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Preface

The 2020s are considered to be a crucial decade for reaching the targets of the Paris Climate Agreement. The global greenhouse gas budget for meeting the 1.5 °C target is rapidly dwindling. According to the IPCC, it still amounted to 300 billion metric tons of CO_2 equivalents in 2021. Every year 42 ± 3 billion metric tons of CO_2 equivalents are released, with 8 billion metric tons of CO_2 equivalents being attributed to the transport sector alone. Depending on the effectiveness of the measures implemented to reduce greenhouse gas emissions, the window of opportunity is just a few years. All the while, the effects of climate change are becoming increasingly visible. Added to this are the global challenges resulting from the COVID-19 pandemic.

When taking stock of what Germany has achieved so far in terms of climate protection in transport, something it began pursuing in the early 2000s through clear goals and measures (significantly reducing final energy consumption supported by renewable energies, alternative drive systems and a modal shift), the results are - to put it kindly – sobering:

Vehicles in use: around 60 million (as of October 2021). Compared with January 2010, this amounts to an increase of over 15 % for cars (approx. 2.5 million cars have alternative drive systems, mainly hybrid electric drives; approx. 0.5 million cars are purely electric vehicles) and 44 % for trucks and semi-trailer trucks (approx. 79 % of trucks are so-called light commercial vehicles of up to 3.5 metric tons). The number of buses and coaches, rail vehicles, inland waterway vessels and aircraft in use is stagnating or partly declining.

Transport volumes: around 1,244 billion passenger kilometers in passenger transport (as of 2019). Approx. 74 % are private passenger vehicles, which has seen an increase of 5 % in ten years; around 2,666 billion metric ton-kilometers in freight transport (incl. ocean-going vessels, as of 2013/2019) which has increased 35 % in ten years without a quantifiable shift from road to rail or ship.

Final energy consumption: approx. 2,789 petajoules (as of 2019) with approx. 83 % in road transport and 16 % in air transport. This has increased 8 % since 2009. The share of renewable energy is only 5 % or, in relation to road transport, approx. 6.6 % and has so far been almost exclusively achieved through biofuels.

Greenhouse gas emissions: around 196 million metric tons (as of 2019) with approx. 51 % from private transport, 30 % from freight transport and public passenger transport by road, and 16 % from aviation. There has been a 6.3 % increase over 2010, and an 8.5 % increase over 1990 levels, despite increasing greenhouse gas abatement through the use of biofuels (approx. 13.2 million metric tons in 2020 to meet the 6 % greenhouse gas reduction quota).

One positive aspect is that the comparatively small biofuel sector has become a pioneer in sustainability over the past decade. Clear sustainability criteria have been established for the production of biofuels thanks to the European Renewable Energy Directive RED of 2009. In addition to there being defined requirements for the agricultural land used to grow biomass, and minimum requirements for specific reductions in greenhouse gases from biofuels, a methodology has been established for calculating the greenhouse gas emissions associated with biofuel production, which must be verified by a certificate. Comprehensive certification schemes have been created which, starting with biofuels, now also certify other biomass-based products. A little-known fact is that, as part of the bioeconomy, biofuels are usually produced in multiproduct plants alongside products such as animal feed, glycerol, etc. which are used by several sectors. For the first time, international market rules have been created that have a positive impact on other application areas as well.

Political framework conditions help to achieve climate protection targets and consequently also influence the development of the market and competition, particularly at European and national levels. The European Green Deal, and its transposition on a national level in Germany, means that a large number of regulations are and will be relevant. With respect to transport for this decade, these include the Climate Change Act (2030 target: permissible annual emission volume of 85 million metric tons of CO_2 equivalents) and the continuation of the greenhouse gas reduction quota that has been in place since 2015 (2030 target: greenhouse gas reduction by at least 25 % with different compliance options, some with minimum and maximum amounts as well as multipliers and adjustment mechanisms for renewable energy carriers, fuels and for electromobility). Added to this are CO_2 fleet regulations for new vehicles (2030 target of 37.5 % for passenger vehicles and 31 % for light commercial vehicles over 2021 levels; 30 % for heavy commercial vehicles over 2020 levels) and, by implication, the Energy Duty Act and Fuel Emissions Trading Act.

“Dare more progress” is the motto of the new German government’s coalition agreement. Its preamble states that one of its top priorities is to meet the Paris climate protection targets and that the energy transition needs to gather more momentum. It cannot be repeated often enough that not only do stakeholders need reliable targets and clear framework conditions, but that effective progress must be made in terms of protecting the climate in the transport sector. Targets for the expansion of electromobility (at least 15 million battery-only electric passenger vehicles by 2030) or quotas for hydrogen and synthetic fuels from renewable electricity (so-called e-fuels or PTX) are undoubtedly important building blocks, but they must also be implemented within realistic timeframes. A canon of all suitable options is needed when it comes to potentials, climate efficiency, costs, and utilization requirements.

In order to meet the climate targets, all obvious and available options for reducing emissions need to be employed and final energy consumption must be reduced significantly. Every building block is required here: emissions avoidance, a modal shift to more climate-friendly options, a switch to renewable fuels and alternative drive systems, and digital networking. In addition to these measures, production volumes for conventional biofuels currently on the market need to be fully utilized and advanced biofuels (including, for example, synthetic fuels with many untapped synergies with PTX) need to be moderately developed, which will help current vehicles protect the environment. In addition, a high gas fuel content can support the energy-efficient and cost-efficient use of renewable resources and, accordingly, reduce the need for advanced and mostly more costly renewable liquid fuels, regardless of whether they are biogenic or non-biogenic. Implementation entails that all components meet a comparable standard of requirements for sustainability. This should be designed and be adaptable within a defined framework so that it can serve as a driving force for practical implementation and thus real climate protection that motivates and engages all stakeholders in society, especially in this day and age. It must also be made transparent that climate protection and climate change are tied to considerable expense and restrictions for everyone. At the same time, this benchmark must be and remain credible – precisely what the arbitrary sustainability requirements - as demonstrated by the European taxonomy on nuclear and gas-fired power plants - are not.

How the individual components contribute to climate protection in transport in real terms - and how they can potentially contribute - must be the subject of continuous monitoring processes. The following report “Monitoring Renewable Energies in Transport” plays an important role in this. Without the extensive expertise of our co-authors, however, it could not be as comprehensive as it is. Therefore, we would like to express our sincere gratitude for their work and for the valuable discourse that arose during the development of the report.

At this point, all that remains is for us to hope that you, our reader, enjoy reading this report. We encourage you, once again, to not only contribute personally to sustainable mobility and climate protection in transport, but also to provide us with your feedback.

Franziska Müller-Langer
Head of Department Biorefineries at the DBFZ, January 2022

Abstract

DBFZ Report-No. 44 examines the monitoring of renewable energy use in transport. The report focuses on renewable biomass-based and electricity-based fuels and electricity within the context of changing framework conditions. The report is an update and expansion of the previous DBFZ Report No. 11 (Monitoring Biokraftstoffsektor, 4th Edition, only available in German language) [Naumann (2019)]. Because the report has been comprehensively revised and its content expanded, it has been given a new title and is being published as a first edition. In future, essential information will be made available online at https://www.dbfz.de/en/monitoring-renewables-transport/. Some of the simplified figures presented in the report will be reproduced here in detail.

The report will start by summarizing the legal framework currently in place and the main policy objectives for renewable energy. It will also present the status quo in the transport sector as well as its infrastructure. The report will go on to cover the steps of the supply and application chain for renewable energy carriers and their use and then classify them in environmental and economic terms. Finally, these aspects will appear in an abridged form in fact sheets on the individual renewable fuel options and on electricity from renewable sources, as well as together in two vehicle-energy matrices for the years 2030 and 2045.

POLITICAL AND LEGAL FRAMEWORK

The political and legal framework has a significant influence on all individual aspects of the supply and application chain of renewable energy in the transport sector as well as on its market development and competitiveness. For example, fuel production from specific feedstocks can be encouraged or limited, chemical and physical material properties can be prescribed through fuel standards, and their targeted application in individual sectors can be controlled.

At the national level, the Federal Climate Change Act (Bundes-Klimaschutzgesetz or KSG) and the quota for reducing greenhouse gas (GHG) emissions, regulated by the Federal Immission Control Act (Bundes-Immissionsschutzgesetz or BImSchG), are important drivers for the integration of renewable energy carriers in the transport sector. The KSG sets out Germany's climate targets until 2045, which include reducing GHG emissions in Germany's transport sector (from 163 million metric tons of CO_2 equivalents (CO_2-eq.) in 2019 to 85 million metric tons by 2030) and requiring Germany to be climate neutral across all sectors from 2045 onwards. The KSG requires that specific measures be taken to achieve targets if individual interim targets are not met, but does not specify these measures. In addition to the CO_2 fleet regulation, the GHG quota, as regulated by the Federal Immission Control Act (BImSchG), is currently the key instrument being used in the transport sector to meet the 2030 targets. Since coming into force in 2015, it has significantly increased GHG abatement for the renewable fuels used in Germany.

The latest amendments to both laws are in reaction to the Paris Climate Agreement as well as to various European directives (such as the Renewable Energy Directive) and European regulations (such as the Effort Sharing Regulation). On an international level, numerous countries, in addition to the European Union, have set mandatory targets for increasing the share of renewable energies in transport, particularly in North and South America and Southeast Asia. A series of further regulatory measures on climate protection will soon follow at the European level under the banner of "Fit for 55". Here, directives on renewable energy in aviation and maritime transport are already being drafted in accordance with a European climate act. Directives on renewable energy, energy taxation, emissions trading, and infrastructure for alternative fuels, as well as guidelines on climate, environmental, and energy subsidies are being further developed which have a direct or indirect link to the transport sector. Because

passenger and freight transport operates across national borders, European-level discussions and a regulatory course-setting are essential for a climate-neutral transformation of the transport sector.

THE TRANSPORT SECTOR AND ITS INFRASTRUCTURE

The transport sector in Germany has one of the highest vehicle densities in the world at 580 vehicles per 1,000 inhabitants. This amounts to around 59 million vehicles out of the more than 2 billion vehicles worldwide. The number of vehicles in use continues to rise. However, there has been a change in the type of drive system used, particularly in passenger cars. Whereas ten years ago almost all new vehicles were equipped with an internal combustion engine, today around 25 % of new passenger cars are battery-electric or at least plug-in hybrid vehicles. Based on various transport scenarios, this must be rigorously expanded in order to achieve the climate policy targets by 2045. A restructuring of the vehicles in use is proceeding very slowly due to the long lifetime of the vehicles. In 2030, more than 40 million vehicles with combustion engines will still be in use, and in 2045, there will still be parts of the transport sector that will be difficult to electrify. As a result, the use of renewable fuels in transport needs to be acelerated.

In 2019, the energy demand in Germany for fuels and electricity in areas of the transport sector such as road, aviation (incl. international aviation), rail and shipping (incl. international shipping) amounted to 2,739 PJ (761 TWh or 65.4 Mtoe) out of the 121 EJ (33,600 TWh or 2,890 Mtoe) needed worldwide. Of this, only 4.4 % came from the renewable fuels bioethanol, fatty acid methyl ester (FAME or colloquially known as biodiesel), HVO diesel, and biomethane, which counted towards the German GHG quota, and 1.5 % came from electricity, only some of which was produced from renewable sources. The majority of this consumption can be traced back to private vehicles, road freight transport, and aviation. According to the National Inventory Report, transport is thus responsible for around 20 % of Germany's GHG emissions. Added to this are the GHG emissions for international air and sea transport departing from Germany. In 2019, GHG emissions from transport totaled 196 million metric tons CO_2-eq. (163 million metric tons CO_2-eq. nationally and 33 million metric tons CO_2-eq internationally). In 2020, emissions decreased by around 11 % to 146 million metric tons CO_2-eq. in domestic transport, largely as a result of the COVID-19 pandemic. With a view to the short-term climate targets up to 2030, electromobility and renewables currently lag behind the assumptions made in transport scenarios. In order to achieve the climate targets, all measures to reduce GHG emissions need to be taken and coordinated with one another. Continuous monitoring and systematic adjustments are essential in this regard.

PRODUCTION TECHNOLOGIES FOR THE PROVISION OF RENEWABLE FUELS

In addition to electricity from renewable sources, the main renewable fuel production technologies available today include:

- the esterification/transesterification of biomass with an oil and fat content, and/or residual and waste materials for the production of FAME,
- the hydrotreatment of biomass with an oil and fat content, or residual and waste materials for the production of paraffinic fuel substitutes for diesel (HVO or HEFA) and kerosene (HEFA-SPK)
- the alcoholic fermentation of biomass with a sugar and starch content for the production of bioethanol
- the anaerobic fermentation (digestion) of agricultural biomass, waste and residuals, and animal excrement for the production of biomethane.

These technologies compete in part for the same resources. In particular, as production capacities of HVO/HEFA fuels increase, pressure on FAME plants will grow. Other technologies (e.g., fermentation of lignocellulosic biomass to bioethanol) already have a high level of technological maturity and are, to some extent, already available on a regional basis; however, they have not yet fully established themselves on the market. Development is currently focusing on purely electricity-based technologies (power-to-X, e-fuels) and electricity- and biomass-based hybrid technologies (SynBioPTX). In principle, different approaches are conceivable here. While there is support for biobased pathways using PTX technology (for example, by incorporating electrolytically produced hydrogen into HEFA processes and synthesis/refinery processes), concepts for using biogenic carbon (e.g., via biogenic carbon dioxide from bioethanol and biomethane plants) in PTX processes are also receiving attention. Which of these options will establish themselves on the market depends not only on regional conditions, but also, to a large extent, on the general conditions and price developments of renewable energies in the transport sector.

Mobilizing feedstocks

Feedstock availability is the first element of the renewable energy supply chain in the transport sector. The biogenic feedstocks suitable for producing biofuels are classified based on their regulatory context and their physical and chemical properties. The latter mainly concerns their suitability with regard to the different production processes. In addition to electricity from renewable sources, the main feedstocks of renewable fuels of non-biogenic origin are primarily water (for producing green hydrogen by electrolysis) and a carbon source (usually CO_2) which can be processed further into fuels that contain carbon.

Up to now, the production of bioethanol has been based almost exclusively on primary agricultural products, although there are already clear signs of efforts to expand the range of raw materials to include lignocellulose-based by-products such as straw. FAME and HVO diesel production also predominantly uses primary products such as rape seed, soy bean, or palm oil; however, used cooking oils (UCO) already account for 20 % of the feedstocks and, increasingly, alternative feedstocks such as tall oil or residues from palm oil production are being used. Around 1.4 EJ of electricity are used in the transport sector worldwide, which amounts to a share of just over 1 %. Of this, about 25 % comes from renewable sources. Electricity-based fuels have yet to play a significant role, however demand and support for them are on the rise.

Quantifying the theoretical, technical, economic, and, above all, the implementation potential of renewable fuels is associated with a considerable degree of range and uncertainty, particularly at the international level. The implementation potential for biogenic feedstocks in the transport sector is believed to be quite low to limited overall. For electricity-based fuels, it is believed to be limited to quite high. Research and development will significantly improve the state of knowledge on the status quo and the prospective developments of renewable resources so that their contribution to a sustainable development in the transport sector can be better evaluated and better managed in terms of a biomass strategy.

Overview of the market

By 2019, global production volumes of renewable energy for the transport sector had increased to about 4 EJ (1.124 TWh or 97 Mtoe), which represents only 3 % of the global energy demand for transport. Currently, the main energy carriers are bioethanol, FAME, and HVO diesel. Production stagnated for the first time in successive years with the onset of the COVID-19 pandemic in 2020. In Europe, production volumes in 2020 amounted to 108 PJ of bioethanol fuel, 409 PJ of FAME, and another 149 PJ for HVO diesel, of which 13 PJ of bioethanol and 126 PJ of FAME were produced in Germany. Biomethane, electricity and hydrogen continue to play a secondary - albeit increasingly important - role as fuels.

The trade in biofuels is highly dependent on both global and regional regulations. The introduction of anti-dumping duties, GHG or fuel quotas, as well as bans on certain feedstocks, can halt established trade routes in the short term and create new ones. The next change is already on the horizon with the ban on palm oil as a feedstock for fuels starting in 2023.

In 2020, Germany was a net importer of bioethanol at 0.87 million m³ (18 PJ) and a net exporter of FAME at 0.88 million metric tons (32 PJ). All of the HVO used in Germany is also imported, which amounted to 1.05 million metric tons (46 PJ) in 2020. Most of the biofuels produced in Germany are exported to Europe. The main bioethanol exporting countries worldwide are the U.S., Brazil, and China; for FAME these are Argentina, Malaysia, and China.

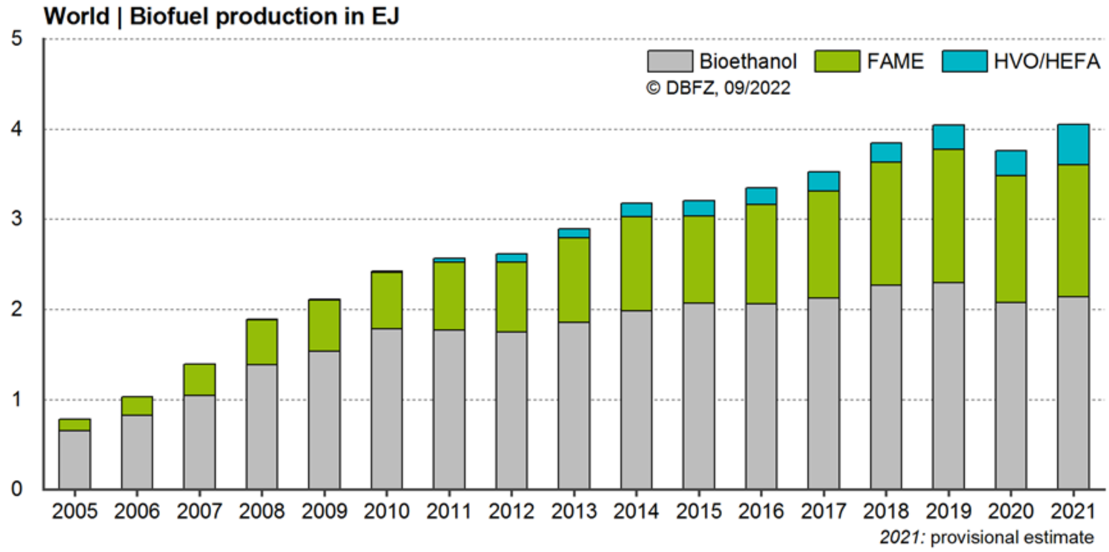


Figure 5-2 Worldwide production volumes of biofuels

ECOLOGICAL AND ECONOMIC ASPECTS OF SUSTAINABILITY

Actual GHG emission figures (based on the corresponding certification systems) and market price information are available for commercially available renewable fuels (bioethanol, FAME, HVO diesel, biomethane) and for electricity from renewable sources. In contrast, for all non-commercially available renewable fuels, which are generally still in the research or demonstration phase, it is only possible to make estimations based on relevant publications. This results in a corresponding level of uncertainty.

In the national transport sector, GHG reductions to date have almost exclusively been achieved through sustainable biofuels (approximately 10 million metric tons in 2019, with an average GHG reduction of 83 % over the fossil reference). The GHG quota, which has been in place since 2015, creates an incentive to use biofuels with a high GHG reduction potential. This has led to an increase in annual GHG emissions avoidance in transport and a simultaneous reduction in the quantities of biofuel required for this. In the future, a range of other renewable options with high GHG mitigation potential may enter the market once the respective technologies become established and a corresponding market demand is created. According to the evaluated studies, e-fuels and fuels based on waste and residual materials show a particularly high potential in terms of GHG emission savings. Electricity-based fuel options are generally associated with very high manufacturing costs and high mobilizable fuel potentials. At the same time, advanced biofuels are associated with lower manufacturing costs and, compared to electricity-based fuels, lower mobilizable fuel potentials. Currently, the technology pathways to methane appear to be the most efficient. Ultimately, the costs for GHG emission avoidance within each area of the transport sector, as well as the technical challenges with respect to infrastructure, will determine which renewable fuels enter the market. Currently, the established fuels biomethane, FAME, and bioethanol have the lowest costs for road applications.

In addition to emissions resulting from the provision of fuels, emissions resulting throughout the vehicle's life cycle (production, use, disposal/recycling) are also taken into consideration. The energy carriers used to power the vehicles decisively affect the vehicles' emission behavior. Electricity and hydrogen in fuel cells have an advantage over other energy carriers in that they do not emit air pollutants and CO_2 emissions during use and are more efficient than internal combustion engines as a result of the high drive efficiencies of electric motors. Other energy carriers, such as methane, methanol and ethanol, can reduce CO_2 emissions and air pollutants as a result of their beneficial chemical properties (e.g., carbon-to-hydrogen ratio or oxygen content). Ultimately, life cycle assessments of vehicles and fuels and evaluations of production, distribution, use, and disposal show that a significant GHG reduction is already possible today if

- renewable pure or blended fuels with a high renewable content are used in vehicles with an internal combustion engine or
- battery-electric vehicles with a high proportion of electricity from renewable sources

are used instead of pure fossil fuels, blended fuels with a low renewable energy content (here mainly E10 and B7), or electricity from fossil energy carriers. However, it will also be crucial to reduce GHG emissions in upstream sectors, for example in the production of vehicle parts made of steel and aluminum or in battery manufacturing. The recyclability of vehicle components is also included in the comprehensive environmental impact assessment.

The aim of an economic evaluation is to assess the economic benefits of concepts or technologies in comparison with reference concepts. As a basis for this, a uniform framework must be established in the form of a system boundary. A direct comparison between energy carriers in the demonstration phase and those that are commercially available is only possible to a limited extent.

THE USE OF RENEWABLE ENERGY IN TRANSPORT

The 10th Ordinance on the Implementation of the Federal Immission Control Act (10th BImSchV) regulates the marketing of fuels and electricity in the transport sector. It specifies fuel qualities with the exception of bunker fuels for aviation and international shipping. For road transport, specific standards for testing and requirements have been specified by the German Institute for Standardization (e.g., DIN EN 228 for gasoline and DIN EN 590 for diesel) in order to ensure a minimum level of fuel quality. In some cases, these standards also regulate the use of renewable fuels in the form of blended fuels made from fossil fuels and renewables as well as pure fuels. These requirements are important in that all parties involved must comply with them in their respective fields of application: Fuel producers have binding specifications for the fulfillment of certain physical and chemical fuel properties which distributors use when evaluating all safety-relevant aspects within the supply chain and which vehicle manufacturers can use to optimize their products for the defined fuel qualities (e.g., with regard to harmful emissions). Consumers can also rely on a minimum level of fuel quality at Germany's filling stations. It is important to comply with the requirements of the 10th BImSchV to ensure maximum material compatibility and fuel performance in the existing infrastructure and vehicles. New fuel options must first be standardized and sufficiently tested before they can be introduced on a widespread scale and included in the 10th BImSchV.

DEVELOPMENT PROSPECTS OF RENEWABLE ENERGY IN TRANSPORT

In the future, a range of renewable energy carriers will be suitable and needed for the transport sector. However, their respective potentials are limited, and their use as fuel competes both with potential use in other sectors (e.g., electricity and heat supply or material use such as in the chemical industry) and between the various modes of transport within the transport sector itself, including road, rail, water, air, and land-based non-road transport. Even the necessary feedstocks are already competing with each other for use. An optimized distribution of these potentials among the modes of transport in terms of provision and use is, therefore, a key challenge for the strategies and measures that need to be developed. One thing is clear: extensive electrification of transport is an essential building block for climate neutrality in the sector. This applies, in particular, to private motorized vehicles and, to a large extent, road freight. Other areas of the transport sector, such as shipping and aviation, heavy interregional freight transport, and even the cars and trucks with internal combustion engines that will still be around in 2045, will continue to depend on liquid or gaseous energy carriers. These energy carriers must be provided in a renewable, climate-neutral manner that is as compatible as possible with the existing vehicles. Figure 9-3 below shows the various renewable options for the year 2045 from the authors' perspective.

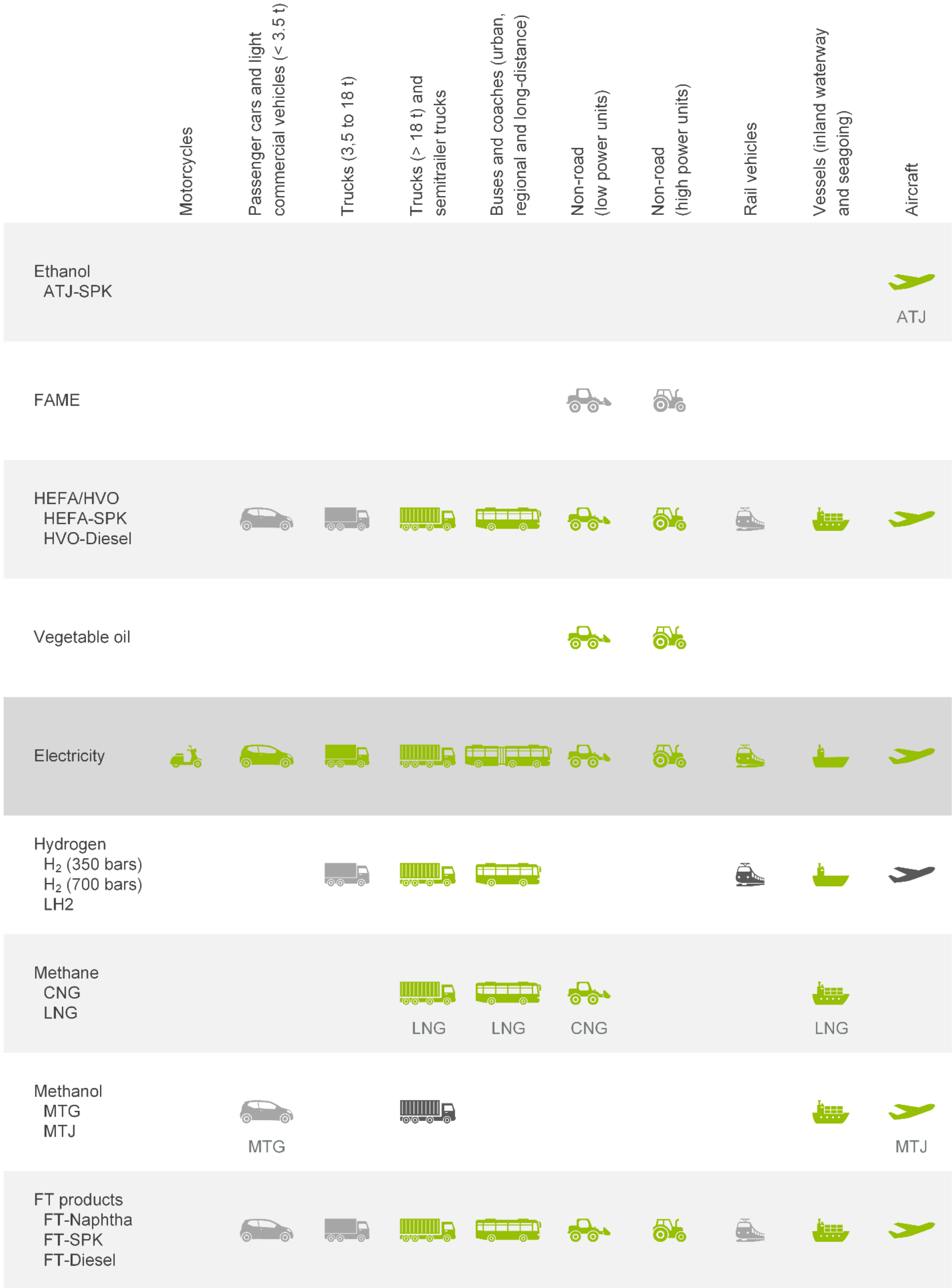


Figure 9-3 Vehicle-energy-matrix for 2045 (green – very probable option, black – possible option, light gray – option for remaining vehicles)

1 Political and regulatory framework

KARIN NAUMANN, NIELS DÖGNITZ AND JÖRG SCHRÖDER

1.1 Classification

For more information:

In recent years the legal framework in the transport sector has had to strike a balance between international agreements, the legal requirements of the European Union, and the transposition of these requirements into national legislation. During this time, the focus has changed again and again. While initially, in addition to climate protection, the focus was on aspects such as regional value creation and security of supply (especially in the national context), the establishment of the European Renewable Energy Directive meant that the target was redefined to include the substitution of fossil energy with renewable alternatives. Starting with the European Fuel Quality Directive and national quotas, for example in Germany and now in Sweden, the key target has been increasingly shifting towards reducing greenhouse gases (GHG) throughout the entire transport sector as a result of the proposal to revise the Renewable Energy Directive.

Figure 1-1 provides an overview of the main framework conditions for renewable energy in transport. In addition to being categorized by region (horizontal), the regulations are categorized by fuel, vehicle and infrastructure (vertical). There are various overarching links and direct dependencies depending on the category. Groupings are also used to illustrate relationships based on content or subordinate positions. Where possible, the scope of application is indicated by symbols for specific modes of transport. These are explained in Section 2. When no symbol is allocated, the regulation refers to all means of transport or the entire transport sector. The overarching climate targets, which relate to all sectors, are globally negotiated and agreed through the United Nations Framework Convention on Climate Change. In the European Union, this agreement is in turn implemented as part of the Green Deal or European Climate Law, and in Germany as part of the Climate Change Act. Most of the legal requirements described below fit into this framework or are even explicitly based on it. The instruments differ with respect to their binding nature. International agreements predominantly relate to transnational means of transport; this particularly applies to agreements in aviation and shipping. Only in the case of the transport of dangerous goods are overarching provisions laid down for all means of transport, which have in turn been integrated into national legislation. The European Union sets the framework for the proportion of renewable energy and fuels used in transport, the GHG emissions avoidance associated with them and their taxation, as well as the framework for the regulations on fuel quality and the handling of chemical substances. It regulates the registration and public procurement of vehicles as well as the infrastructure for adapting them for use with alternative fuels. Many parts of the national legislation refer to international agreements and European requirements, thereby creating the remaining framework for binding regulations (shown as arrows in Figure 1-1). In Germany, these legal regulations may extend beyond the international or European requirements, or set other priorities.

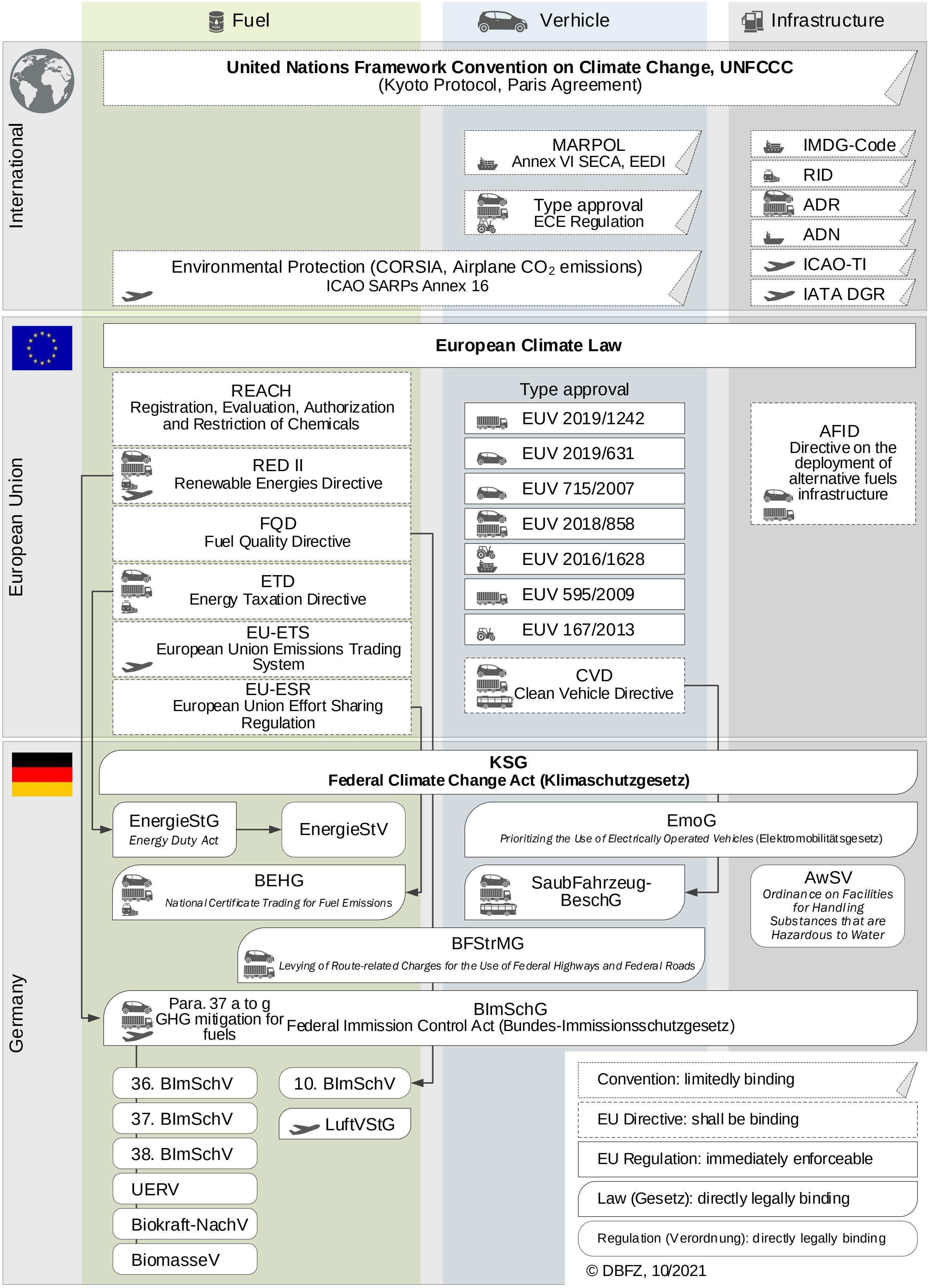


Figure 1-1 Overview of the existing regulatory framework in the transport sector

1.2 Historical overview

The biofuels market is influenced significantly by policy objectives and the resulting regulatory framework. These have changed considerably in recent years and are outlined in detail in the four editions of DBFZ Report 11 [Naumann (2012); Naumann (2014); Naumann (2016); Naumann (2019)]. European directives and national legislation play a crucial role alongside targets for renewable energy quotas, the avoidance of greenhouse gas emissions in the transport sector, and the strategies resulting from this.

In 2001, an EU proposal for a *Directive on the Promotion of the Use of Biofuels* [KOM(2001) 547 (2001)] first recommended a minimum biofuel quota of 2 %. Since this percentage was not assumed to significantly reduce GHG emissions in the transport sector, the percentage was then to increase to over 5 % and mandatory blending was to be introduced. Based on this proposal, *Directive 2003/30/EC on the Promotion of the Use of Biofuels and Other Renewable Fuels for Transport* came into force on May 8, 2003. In it, the European Union's Member States were called upon to cover 2 % of their fuel needs in the transport sector with biofuels by 2005. By 2010, this percentage was to increase to 5.75 %. [Richtlinie 2003/30/EG (2003)]

In order to implement the EU Directive on the Promotion of the Use of Biofuels and Other Renewable Fuels for Transport (2003/30/EC) and the EU Directive on the Restructuring of the Community Framework for the Taxation of Energy Products and Electricity (2003/96/EC), Germany enacted the Biofuels Quota Act in 2006 which introduced a biofuels quota by amending the Federal Immission Control Act (Bundes-Immissionsschutzgesetz, **BImSchG**) and the energy and electricity tax regulations (Biofuels Quota Act, Biokraftstoffgesetz, **BioKraftQuG**). As a result, Section 37a of the BImSchG prescribed a minimum biofuel content in gasoline and diesel for the first time. In addition to the minimum blending quotas, an overall biofuel quota was established, which was to increase to 8 % by 2015. In addition, the BioKraftQuG revised Section 50 in the Energy Duty Act (Energiesteuergesetz) [COM(2016) 767 (2017); EnergieStG (2006)] thereby amending the previous tax relief for biofuels. For biodiesel (FAME) and pure vegetable oil, tax relief was to decrease annually until 2012.

In 2009, the *Act on Amending the Promotion of Biofuels* (Gesetz zur Änderung der Förderung von Biokraftstoffen) [BioKraftFÄndG (2009)] reduced the quota for biofuels in the **BImSchG**. Accordingly, an overall energy-related quota of 5.25 % had to be met. From 2010 to 2014, the biofuel quota was set at 6.25 %. The minimum quota for biofuel content in diesel remained constant at 4.4 %, while the minimum quota for biofuel content in gasoline was reduced from 3.6 % to 2.8 %. An option to use biomethane as a fuel in order to meet the quota was also legally implemented.

Within the course of the BioKraftFÄndG, the quota in Germany was changed in 2015 from achieving a specific percentage of biofuels used for energy to avoiding GHG emissions in transport, the so-called GHG quota. Biofuels remained the main option for meeting the quota, which was initially set at 3 %, then at 4.5 % starting in 2017 and finally at 7 % from 2020 onwards. A further amendment, which went into effect on January 1, 2015, adjusted these levels to 3.5 % starting in 2015, 4 % starting in 2017 and 6 % from 2020 onwards. Because there was a simultaneous increase in the specified avoidance of GHG emissions for these certified biofuels, there was only a slight increase in the absolute demand for biofuels despite the rising quota. At the same time, sustainability requirements were transposed into national legislation in the same way as the RED was. Approved certification systems are used in the verification process, whereby a distinction is made between systems approved at national and EU level.

The quantity of biofuels used in Germany has been greatly influenced by the legal framework. While it had risen sharply in the years up to 2007 due to tax breaks, it subsequently declined significantly as a result of the aforementioned changes and remained at a comparable level between 2009 and 2019. The percentages of the biofuel options used, as well as the feedstocks used to produce them, have also changed alongside the framework conditions.

Directive 2009/28/EC defined for the first time the common EU target of 10 % renewable energy in the transport sector by 2020. It is also known as the **RED** (Renewable Energy Directive). Biofuels must meet extensive sustainability criteria in order to be counted towards the set targets. These were also formulated here in concrete terms for the first time. Accordingly, biofuels had to have a GHG reduction potential of at least 35 % over fossil fuels. This minimum GHG emission savings over the fossil reference increased to 50 % starting in 2017 and 60 % from 2018 onwards for new plants. The calculation framework covers the entire chain – from cultivation to fuel use. [Richtlinie 2009/28/EG (2009)]

The RED was updated for the first time by Directive (EU) 2015/1513. These changes mainly concerned the fulfilment options for the 10 % target in 2020:

- A 7 % cap on biofuels from grains and other crops with a high starch content, sugar crops, oil crops and crops grown primarily for energy production on agricultural land;
- A minimum of 0.5 % and the double counting of renewable non-biogenic fuels and biofuels from feedstocks listed in Annex IX Part A (waste and residues, algae and bacteria, e-fuels, excluding used cooking oil and animal fat)
- Double counting of renewable and biofuels from feedstocks listed in Annex IX (waste and residues, algae and bacteria, e-fuels, and used cooking oil and animal fat)
- 2.5-fold counting (rail transport) and/or 5-fold counting (road transport) of electricity from renewable energy sources.

Building on this, the so-called RED II (Directive 2018/2001, which is commonly referred to as RED II because it replaced the original RED 2009/28/EC) was developed for the period up until 2030. This is described in Section 1.4 f.

1.3 International

The *United Nations Framework Convention on Climate Change (UNFCCC)*, which came into force in 1994, forms the basis for all international efforts to protect the climate [UNFCCC (2021b)] and has so far been ratified by 197 countries – nearly all the countries in the world. In addition to the well-known conferences from Kyoto to Copenhagen, the jointly achieved results of the Paris conference are decisive for the current and future legal framework. This conference concluded with the **Paris Agreement**, which is a legally binding international treaty on climate change [United Nations (2016)]. It was signed by 196 parties and came into force on November 4, 2016. Its goal is to limit global warming to well below 2° C, preferably to 1.5 °C compared to pre-industrial levels [UNFCCC (2021a)]. Even with a global warming of 1.5 °C, heat waves and severe precipitation events which cause flooding will occur much more frequently and be more devastating in many regions of the world. Furthermore, stronger global warming would no longer be able to rule out hitherto improbable but catastrophic events such as the strong changes in the spatial distribution of precipitation patterns or the collapse of the Arctic and Antarctic ice sheets [IPCC (2021)]. The signatory countries therefore aim to achieve a global peak in GHG emissions as soon as possible and a climate-neutral world by the middle of the century. More and more draft legislation has been geared toward these objectives in recent years.

The other international agreements mainly relate to modes of transport that operate internationally such as aircraft and ships. Binding regulations will be essential in the future, but finding the needed consensus is challenging at this level.

Air transport regulations are anchored in the convention of the International Civil Aviation Organization – ICAO) [BAZL (2021)]. *Annex 16 Volume III* outlines the calculations for CO_2 emissions from aircraft [BAZL (2017)]. *Annex 16 Volume IV* is known by the acronym **CORSIA** which stands for the *Carbon Offsetting and Reduction Scheme for International Aviation* [CORSIA (2018)]. This requires all airlines to report their CO_2 emissions once a year starting in 2019. A voluntary pilot phase has been running since January 1, 2021, and international flights are subject to offsetting obligations. In phase 2, which is set to begin in 2027, participation will be mandatory for all countries whose aircraft operators generated more than 0.5 % of global aviation emissions in 2019. All emissions from these operators which exceed the 2019 emissions in the future must be offset through various recognised compensation programmes [IATA (2021b)].

In shipping, the *International Convention for the Prevention of Pollution from Ships* (**MARPOL** Convention) has been in place since 2005 to prevent marine pollution (Annex I-V) and air pollution (Annex VI) from seagoing ships. Annex VI sets limits on nitrogen oxide and sulfur oxide, among other things [MARPOL Annex VI (2021)].

The carriage of dangerous goods and substances is also regulated internationally for all modes of transport. All the regulations listed in Table 1-1 are legally binding in many countries including Germany.

Table 1-1 Overview of international regulations on dangerous goods for various transport sectors

Mode of transport	Regulation	Main aspects	Source
Ship	International Maritime Dangerous Goods Code (IMDG Code)	Regulates the requirements for the respective substances and items, both in terms of content and layout.	[IMDG-Code (1974)]
	European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterways (I)	Contains provisions on hazardous substances and items, as well as provisions on their carriage on board inland vessels. Addresses the requirements and procedures for inspections, the issuance of certificates of approval, and for training and examining experts.	[UNECE (2021)]
Aircraft	ICAO-TI	Establishes the provisions for dangerous goods in air transport.	[ICAO (2021)]
	IATA DGR	Builds on ICAO-TI and is the standard recognized by airlines.	[IATA (2021a)]
Road	European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR)	Regulates the classification of dangerous goods and safety measures as well as labeling and documentation. Requires a special driver's license to transport dangerous goods, stipulates that all parties involved possess expertise, and mandates dangerous goods safety officers in companies.	[ADR (2019)]
Rail	Regulation concerning the International Carriage of Dangerous Goods by Rail (RID)	The content of the regulation largely corresponds to that of the ADR.	[RID (2021)]

1.4 The European Union

The *Directive on the Promotion of the Use of Energy from Renewable Sources* [Richtlinie (EU) 2018/2001 (2018)], generally referred to as **RED II**, expanded the regulatory framework of RED (2009/28/EC) to include the decade up to 2030. It defines a binding target for the overall percentage of energy from renewable sources in the European Union's gross final energy consumption up to 2030. In addition to the use of energy from renewable sources in the heating and cooling sector and in the transport sector, it prescribes the sustainability criteria and criteria for specific GHG savings from biofuels, bioliquids and biomass fuels. In the transport sector, Member States are to ensure, through transposition into national law, that the percentage of renewable energy in road and rail transport amounts to at least 14 % by 2030. Furthermore, a separate target is defined for the percentage of advanced (liquid or gaseous) biofuels used in the transport sector. Advanced biofuels are characterized by the fact that they are produced from biobased residual and waste materials as defined in Annex IX A (see Section 4.1.2). They are to contribute to at least 0.2 % of the final energy demand in road and rail transport by 2022, at least 1 % by 2025, and at least 3.5 % by 2030. In addition, boundary and framework conditions are set to achieve these goals:

- Limiting the percentage of biofuels from food and feed crops to 7 %
- Limiting the percentage of biofuels from used cooking oil and animal fat to 1.7 % (Annex IX B)
- Ending the use of biofuels with a high risk of iLUC (indirect land use change) (i.e., biofuels from palm oil) by 2030
- Increasing the fossil reference value to 94 g CO_2-eq./MJ
- Multiple counting towards the targets:
    - Double counting of advanced biofuels from defined feedstocks (Annex IX A)
    - Double counting of biofuels from used cooking oil and animal fat (Annex IX B)
    - Quadruple counting of electricity from renewable sources used in road transport
    - 1.5 counting of electricity from renewable sources used in rail transport
    - 1.2 counting of renewable fuels used in aviation and shipping.

[Richtlinie (EU) 2018/2001 (2018)]

The European climate targets, which have since been defined or increased, are very ambitious with 55 % GHG savings across all sectors by 2030. A revised draft of the RED II has already been published as part of the Green Deal (Section 1.6.1).

Member States were to have transposed the requirements of the RED II into national law by June 30, 2021. Germany as well as other Member States have failed to meet this deadline [USDA Foreign Agricultural Service (2021)]. Member States have a certain amount of leeway in terms of implementation, which means that the details of the national regulations can differ greatly. For example, Germany and Sweden base their targets on GHG emission avoidance, while the other Member States base their targets on the percentage of renewable energy to be achieved, as Figure 1-2 shows.

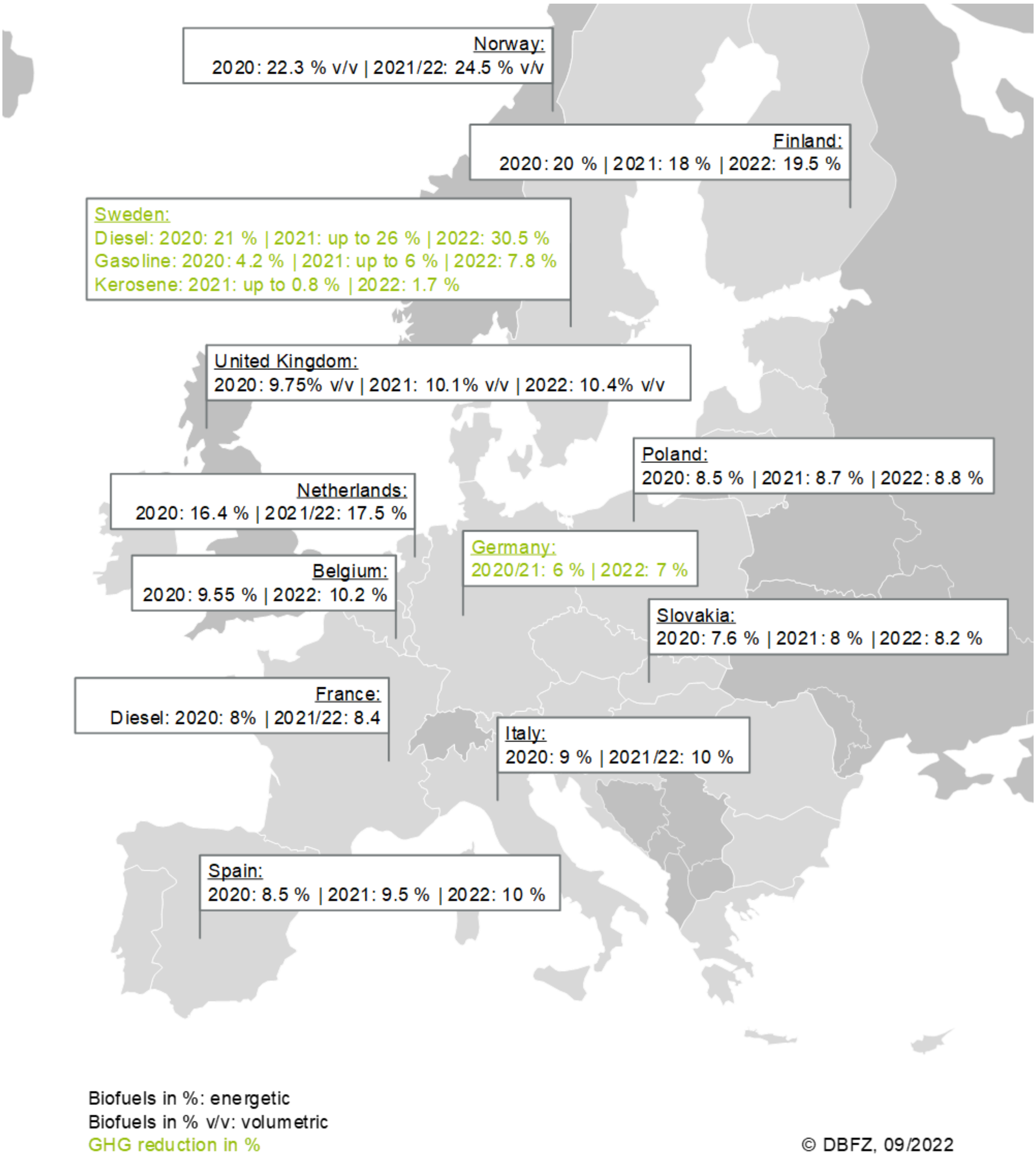


Figure 1-2 Examples of national quotas and targets in Europe from 2020 to 2022. Data based on [IHS Markit (2021d); UFOP (2021)]

The *Regulation on Registration, Evaluation, Authorization and Restriction of Chemicals* (**REACH**) No. 1907/2006 of December 18, 2006 is directly applied by all EU Member States [Verordnung (EG) Nr. 1907/2006 (2021)]. It provides the framework for handling all chemicals circulating in the EU and requires substances to be registered with the European Chemicals Agency (ECHA). This also affects all fuels placed on the market, regardless of their production volume. By the end of 2022, the Commission intends to present a proposal for revision aimed at achieving a pollution-free environment [VCI Online (2021)].

The *Energy Taxation Directive* (**ETD**) *2003/96/EG* regulates the taxation of energy carriers in transport as well as electricity and fossil fuels used for heating [ETD (2021)]. Its main purpose is to set minimum tax rates across the EU. It aims to achieve an overarching taxation system to avoid inequalities in the Union as well as a common taxation system based on climate protection targets. An amendment to this, which is currently being developed, is discussed in Section 1.6.1.

The *European Emissions Trading Scheme* (**EU-ETS**) was established in order to achieve the CO_2 reduction targets. Since 2015, it has primarily focused on reducing emissions in the energy sector and in energy-intensive industries. Since 2012, this has also included aviation – both commercial and non-commercial aircraft operators. However, after significant opposition, the following exemptions to the EU ETS will apply until Dec. 31, 2023:

- Flights to or from airports in countries outside the European Economic Area, and
- Flights from, to and within certain outermost regions of the EU [UBA (2021c)].

Accordingly, aircraft operators must currently provide proof of an emissions allowance for each metric ton of carbon dioxide resulting from their intra-European aviation activities [UBA (2021c)]. Until 2020, they received a free allocation of emission certificates based on their emissions in 2016. From 2021 onwards, the linear reduction factor is to apply – like for stationary equipment – in accordance with Article 9 of the Emissions Trading Directive. This amounts to 2.2 % per year [Richtlinie 2009/29/EG (2009)].

The *Regulation on binding annual greenhouse gas emission reductions by Member States from 2021 to 2030 contributing to climate action to meet commitments under the Paris Agreement* (Effort Sharing Regulation (**ESR**) [Verordnung (EU) 2018/842 (2018)] set targets for Member States that affect most sectors not covered by the EU Emissions Trading Scheme. These national targets (e.g., for the transport, building, agriculture and waste sectors) are based on the relative prosperity of the Member States, which is calculated from their gross domestic product (GDP) per capita. An amendment, which is currently being developed, is discussed in Section 1.6.1.

The *Fuel Quality Directive* (**FQD**) *98/70/EG* was originally introduced to harmonize the quality standards of fossil fuels [Richtlinie 98/70/EG (1998)]. However, since its amendment in 2009, it obligates fuel suppliers to reduce the lifecycle greenhouse gas emissions of fuels by 10 % in addition to setting the technical standards of fuels for road transport. Thus, by 2020, a 6 % reduction was to be achieved through the use of renewable energy and fuels, and an optional further two times 2 % through technical or accounting options such as credits under the Kyoto Protocol.

In addition to the regulatory framework that directly affects the energy carriers in the transport sector and their infrastructure, significant hurdles are indirectly imposed by the effort needed for type approvals. The *European regulations on vehicle approvals* (**TYPE APPROVAL**) require type testing and market surveillance prior to the application of new fuels and fuel blends. The vehicle types shown in Section 2 – with the exception of ocean-going vessels, aircraft and construction machinery – must undergo so-called type approval in Europe. This includes requirements for vehicle safety (e.g., airbags, steering assistance), design (e.g., shape and structure of the truck cabs) and emissions (e.g., European emission standards,

CO_2 emissions) and are defined in the international ECE regulations. Emissions-related type approval is done using special fuels (e.g., spark-igneted passenger cars with fuel in accordance with EN 228). Only by using these reference fuels is the proper operation of the vehicle ultimately ensured (fit for purpose) and guaranteed by the manufacturer. In the case of vehicles with diesel engines, passenger cars and heavy goods vehicles are now occasionally approved for operation with several fuels (EN 590 and EN 15940). France has also taken the route of granting federal type approval for a kit to convert a gasoline vehicle to a flex fuel vehicle (FFV) that runs on E85 fuel. With this system, the warranty remains in place for consumers despite changes in the structure of the drive system (see excursus "Establishing E85 as a renewable fuel in France").

The *Directive on the promotion of clean and energy-efficient road transport vehicles* (Clean Vehicle Directive (**CVD**)) *2019/1161* encourages the further use of low-emission and zero-emission vehicles in public tenders [Richtlinie (EU) 2019/1161 (2019)]. The directive applies to passenger cars, vans, trucks and buses when acquired through purchase, lease, rental or rent-to-own contracts in accordance with the obligations of EU procurement regulations. The directive defines a "clean vehicle" as follows:

- Clean light commercial vehicles: any car or van that meets the following emission limits:
  - until December 31, 2025: no more than 50 g/km CO_2 and up to 80 % of the applicable limits for real driving emissions (RDE) for nitrogen oxide and particle count,
  - from January 1, 2026 onwards: only zero-emission vehicles.
- Clean heavy commercial vehicles: any truck or bus that uses any of the following alternative fuels: hydrogen, electric battery (including plug-in hybrids), natural gas (both compressed natural gas [CNG] and liquified natural gas [LNG], including biomethane), liquid biofuels, synthetic and kerosene fuels, liquefied petroleum gas.

The individual Member States are subject to different targets for the minimum percentage of clean vehicles – mostly 38.5 % for western European countries, less for eastern European countries (ranging from 17.9 % for Bulgaria to 29.7 % for the Czech Republic). In Germany, implementation is governed by the law on the procurement of clean road transport vehicles **SaubFahrzeugBeschG**, which is described in Section 1.5.3.

With regard to the development of an *infrastructure for alternative fuels*, Directive 2014/94 (Alternative Fuel Infrastructure Directive (**AFID**)) calls on Member States to develop a national policy framework for the market development of alternative fuels and their infrastructure [Richtlinie 2014/94/EU (2014)]. According to the requirements, an adequate number of filling stations should be created for:

a) Natural gas for transport:

- LNG in seaports by the end of 2025, in inland ports by the end of 2030, and in the Trans-European Transport Network (TEN-T) for heavy commercial vehicles by the end of 2025 (average distance between filling stations of around 400 km),
- CNG in metropolitan areas by the end of 2020 and in the core network by the end of 2025 (average distance between filing stations of around 150 km),
- Hydrogen for road transport (publicly available, non-binding),

b) Electrical charging points:

- For road transport: in metropolitan areas by the end of 2020 and in the core network by the end of 2025,
- for inland and ocean-going vessels (land-based) in the core network by the end of 2025.

It also stipulates common technical specifications for charging and filling stations and paves the way for the creation of sufficient consumer information on alternative fuels.

The directive includes a regular reporting obligation (every three years, next report due in 2022) on the implementation status of a respective national strategic framework and the achievement of its intended goals. In its latest report from 2019, Germany listed a total of 17,245 electrical charging points and 862 CNG and 4 LNG filling stations for road transport for the year 2018. Accordingly, in 2019 the responsible body – the Federal Ministry of Transport and Digital Infrastructure (BMVI) – regarded the above requirements of the directive as achievable [BMVI (2019)]. The current proposal to amend the directive is discussed in Section 1.6.1.

1.5 Germany

Since 2019, **THE FEDERAL CLIMATE CHANGE ACT** (Bundes-Klimaschtzgesetz) [KSG (2021)] has formed the primary legal basis for Germany's measures for implementing the Paris Climate Agreement. The Federal Government amended the act on May 12, 2021 [Bundesregierung (2021)] in light of the new European climate target for 2030 and as a result of a decision by the Federal Constitutional Court of April 29, 2021, which calls for a binding pathway to climate neutrality. This results in a target for reducing annual greenhouse gas emissions by at least 65 % over 1990 levels by 2030. In addition to this overall target, specific targets have been set for individual sectors in the form of emission limits; these are compared to the status quo in Table 1-3. The annual reduction targets per sector for the years 2031 to 2040 are to be determined in 2024 and the annual reduction targets for the years 2041 to 2045 (2034 per sector) are to be in place no later than 2032. Germany is then expected to achieve greenhouse gas neutrality by 2045.

For the transport sector, the emissions cap in 2030 means emissions need to be reduced in the interim years from 164 (2019) to 85 million metric tons of CO_2 equivalents. The greenhouse gas emissions in the transport sector from 2010 to 2020 and the permitted emission levels for the years 2020 to 2030 are shown in Table 1-2 and Table 1-3.

Table 1-2 Annual emissions in million metric tons of CO_2 equivalents by sector from 2010 to 2020. Data based on [UBA (2021a), (2021b)]

Sector	2010	2012	2014	2016	2018	2019	2020
Energy	368	377	359	344	309	258	221
Industry	188	180	180	192	190	187	178
Buildings	149	131	119	125	116	123	120
Transport	153	154	159	165	163	164	146
incl. road transport	*148*			*160*	*158*		
Agriculture	69	70	72	72	68	68	66
Waste management and other	15	13	12	10	10	9	9

The Federal Environment Agency compiles data on greenhouse gas emissions in the different sectors for the previous calendar year by March 15 of each year. (This was done for the first time for 2020.) For 2020, the (preliminary) data show that all sectors – including the transport sector – remained below the permissible emission levels, i.e., the target was achieved. The massive pandemic-related effects, especially on traffic volumes, played a major role in this. It remains to be seen how this will impact the figures for 2021 and 2022. If the annual emissions data indicate that the permissible annual emission volumes for the transport sector have been exceeded in a reporting year, an assessment of the emissions data is carried out by the Expert Council on Climate Issues. Once this becomes available, the Federal Ministry for Digital and Transport (BMDV) must submit to the federal government an emergency program for the transport sector within three months. This ensures there is an adherence to the permissible annual emission volumes in the following years.

The Climate Change Act provides a framework and acts as a control mechanism for future statutory regulations and ordinances, which have a much greater binding force than the previous provisions.

Table 1-3 Annual permissible emission volumes in million metric tons of CO_2 equivalents by sector from 2020 to 2030. Data based on [Bundesregierung (2021)]

Sector	2020	2021	2022	2024	2026	2028	2030
Energy	368		257				108
Industry	188	182	177	165	149	132	118
Buildings	149	113	108	97	87	77	67
Transport	153	145	139	128	117	105	85
Agriculture	69	68	67	65	62	59	56
Waste etc.	15	9	8	7	6	5	4

1.5.1 Legal framework for fuels from renewable sources

The requirements of the Renewable Energy Directive for the transport sector are transposed in Germany by Article 37a–h of the *Act on the Prevention of Harmful Effects on the Environment Caused by Air Pollution, Noise, Vibration and Similar Phenomena* (Federal Immission Control Act (Bundes-Immissionsschutzgesetz **BImSchG**)) and the lower ordinances for the implementation of the Federal Immission Control Act (**36th, 37th, and 38th BImSchV**). Table 1-4 provides an overview of the greenhouse gas reduction commitments contained therein for fuels for the years 2022 to 2030. As in the RED II, there is a sub-quota for advanced biofuels from biogenic raw materials or feedstocks defined for this purpose, in addition to the overarching target. Furthermore, a binding sub-quota will be defined for aviation starting in 2026. As of yet there are no European requirements, but they will be established in the future, as outlined in Section 1.6.1.

Table 1-4 Targets for the national implementation of the RED II in Germany. Note: PTL stands for power-to-liquid; data based on [THGMQWG (2021)]

Targets	Minimum percentage	2022	2023	2024	2025	2026	2027	2028	2029	2030
GHG quota for liquid fuels	GHG reduction	7.0 %	8.0 %	9.25 %	10.5 %	12.0 %	14.5 %	17.5 %	21.0 %	25.0 %
Advanced biofuels (Annex IX, A)	Road (energy)	0.2 %	0.3 %	0.4 %	0.7 %	1.0 %	1.0 %	1.7 %	1.7 %	2.6 %
PTL kerosine	Air (energy)					0.5 %	0.5 %	1.0 %	1.0 %	2.0 %

The fulfillment of the specified quotas is linked to further framework conditions in terms of the limiting or multiple counting of individual options. These are summarized in Table 1-5. The German GHG quota is based on the RED II framework (Section 1.4), but also deviates from it in the way it is designed.

Table 1-5 Boundary conditions for compliance options within the GHG quota for the transposition of the RED II in Germany. Note: if no information is provided for a specific year, there are no requirements in term of minimum or maximum percentages, data based on [38. BImSchV (2021)]

Fulfillment option	Remarks	Condition
Advanced biofuels in road transport (38th BImSchV, Annex 1)	Quantities over the minimum percentage, except POME	Double counting for amounts over the minimum percentage for energy
Biofuels from used cooking oil (UCO) and animal fat (38th BImSchV, Annex 4)	Percentage for energy	Maximum 1.9 %
Conventional biofuels from feedstocks that also serve the food and feed sectors	Percentage for energy	Maximum 4.4 %
Biofuels from feedstocks with a high risk of indirect land use change (palm oil).		Starting in 2022: maximum 0.9 % Starting in 2023: 0 %
Green hydrogen and derivatives (e-fuels)	Used in refineries and road transport	Double counting
Electricity	Electricity for electric vehicles[1]	Triple counting; adjustment mechanism[2]
Battery-assisted electric drives and fuel cell-assisted electric drives	Factorization of electric power and hydrogen	Adjustment factor for drive efficiency: 0.4
Upstream emission reduction (UER)	GHG avoidance through UER	Until 2026: maximum 1.2 % Starting in 2027: 0 %

1 Electricity from public and private charging points
2 Maximum expansion as stipulated by law; the overall quota is adjusted if this is exceeded

The distributors of gasoline and diesel fuels are obligated to fulfill the GHG quota and must prove this to the quota office in accordance with the legal requirements. The procedure for trading and verifying the GHG quota is illustrated by a schematic diagram in Figure 1-3. Currently, most of the quota is achieved by blending biofuels into gasoline and diesel fuel (in the center of the figure). In this case, the renewable fuel is placed on the market by the obligated party itself as a fulfillment component of the quota, and proof is provided directly to the responsible quota office at the Main Customs Office. If the quota is fulfilled by a fuel, but not by blending it into gasoline or diesel fuel, the obligation to fulfill the quota must be transferred from the obligated party, the petroleum company, to a third party or parties, shown in the right half of the figure. This party, rather than the obligated party, then proves to the quota office that the quota has been fulfilled. This is the case, for example, for biomethane as a renewable substitute for CNG or LNG or for the crediting of pure renewable fuels such as biodiesel or vegetable oil. Electricity in road transport is counted according to the procedure shown in the left half of the figure. The amount of electricity drawn from publicly accessible charging points or from charging points not publicly accessible can be counted towards the GHG quota. The electricity supplier or a third party shall provide evidence of the number of electricity customers with a pure battery-electric vehicle registered to them, combined with an estimated value of 2,000 kWh per year per vehicle for passenger cars, 3,000 kWh for Class N1 light commercial vehicles, and 72,000 kWh for buses and coaches [Bekanntmachung Anrechnung Strom (2021)]. These estimated values are to be applied until further notice starting in calendar year 2022; until 2021, a value of 1,943 kWh per year and vehicle was used for battery-electric passenger cars [Bekanntmachung Anrechnung Strom (2017)]. The resulting reduction can, in turn, be counted towards the quota via a corresponding emissions trade and the formal transfer of the quota obligation to a third party or parties, in this case the electricity suppliers [38. BImSchV (2021)]. The emission factor for electricity for the transport sector is adjusted annually and determined and published by the Federal Environment Agency (UBA) in the previous year. For the calendar year 2021, this was 147 kg CO_2-eq./GJ (UBA 2020), for the calendar year 2022 only 119 kg CO_2-eq./GJ. [Bekanntmachung THG-Minderung (2021)]. A defined method is used to determine the greenhouse gas avoidance (Figure 1-4).

Distributors of liquid or gaseous biogenic fuels can only have these fuels counted towards the quota if they can prove that they meet the sustainability criteria required under the Biofuels Sustainability Ordinance (Ordinance on the Requirements for a Sustainable Production of Biofuels (Biokrafstoff-Nachhaltigkeitsverordnung, Biokraft-NachV)) [Biokraft-NachV (2009)]. This proof is obtained through a governmental web application for sustainable biomass systems (Nabisy), operated by the Federal Office for Agriculture and Food (BLE).

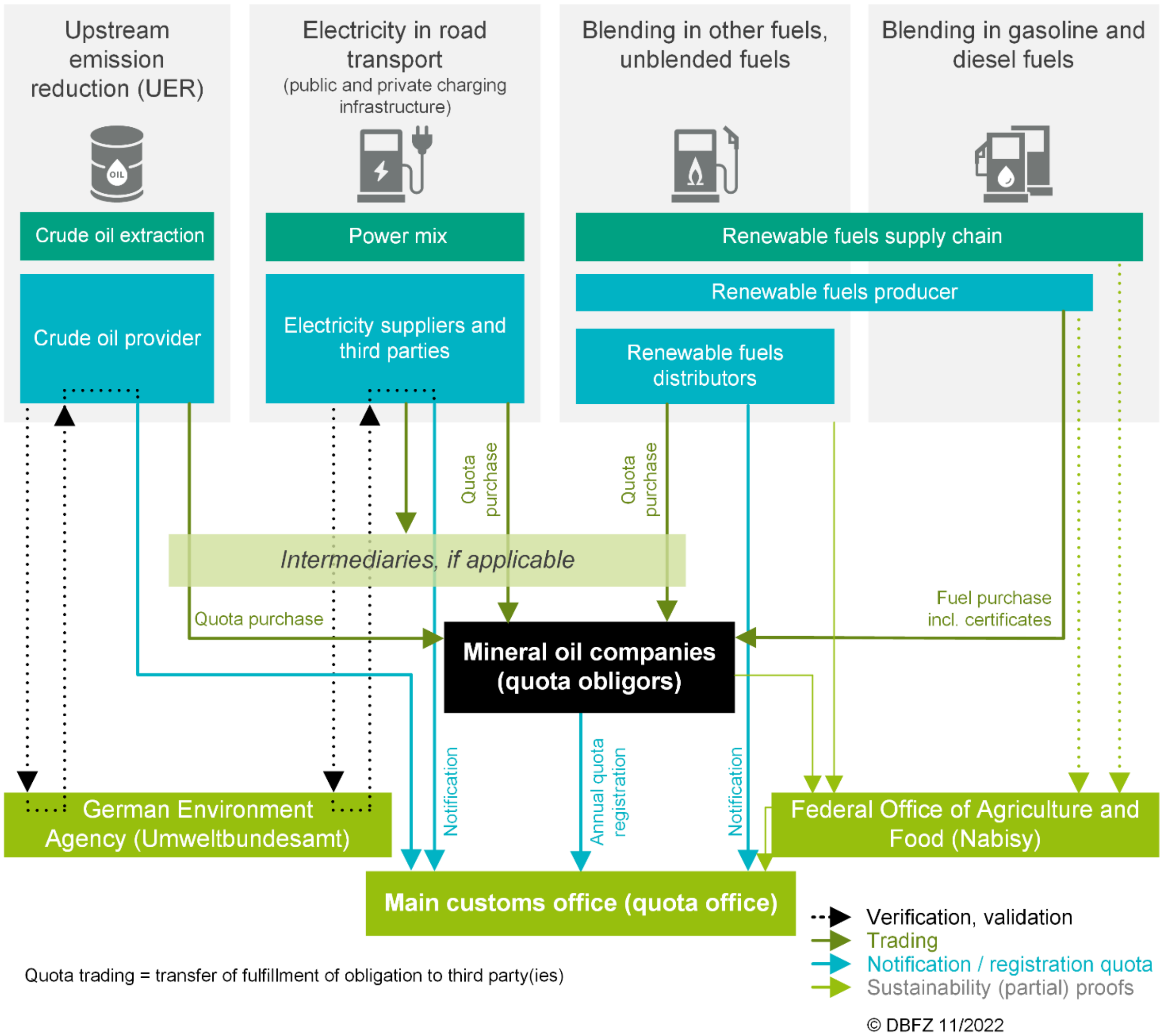


Figure 1-3 Quota verification and trading in Germany, (transferring fulfillment of the obligation to a third party). Note: simplified schematic diagram with no claim to completeness, quota trading corresponds to a transfer of the fulfillment of the obligation to a third party/third parties. For further information see in [DV THG-Quote (2016)]

GHG abatement in accordance with the quota's target is calculated from the ratio of (real) emissions in transport (Figure 1-4, the formula's numerator) over a reference value (the formula's denominator) see also Section 7.3.1. The numerator is the total energy content of the fuel multiplied by its specific emission factor (or a standard value), taking into account multiple counting and possible drive efficiency factors. The denominator, in turn, represents all of the energy content contained in the numerator, including possible multiple counting, multiplied by the reference value of 94.1 kg CO_2-eq./GJ. Upstream emission reductions (UER) up to a maximum of 1.2 % are also taken into account in the quota up to the year 2026.

$$GHG\ quota \leq 100\ \% - \frac{\sum(quantity\ of\ fuel\ used \times emission\ factor \times drive\ factor \times factor\ multiple\ counting) - UER}{\sum(quantity\ of\ fuel\ used \times factor\ multiple\ counting) \times reference\ value}$$

Figure 1-4 Simplified formula for calculating the GHG quota as of 2022. Note: detailed formula can be found at https://www.dbfz.de/Monitoring-EE-im-Verkehr/rahmenbedingungen [Naumann (2021)]

For more information:

The fossil fuel mix initially determines the level of GHG abatement required based on defined emission factors for all fossil liquid fuel options. For example, the current relatively high proportion of diesel fuel actually requires a higher GHG abatement than just the minimum percentage required by the BImSchG. All factors and boundary conditions for the quota are summarized in Table 1-5. The calculation is complex and its formula can be found online. [DBFZ (2022)]

The *Ordinance on the Requirements for a Sustainable Production of Biofuels* (Biofuels Sustainability Ordinance (**Biokraft-NachV**)) came into force in 2009 to meet the requirements of EU Directives 2009/30/EC and 2009/28/EC. Biofuels that count towards the biofuel quota must meet the criteria contained in the ordinance. GHG emissions are calculated in accordance with the methodology set out in the Ordinance. Proof of compliance with these requirements is obtained through certification programs established for this purpose. [Biokraft-NachV (2009)] Since January 2011, all biofuels counted toward the quota in Germany must be certified in accordance with the requirements of the Biofuels Sustainability Ordinance (Biokraft-NachV). Proof of compliance with the requirements is obtained through certification programs, which must be approved at the national level by the Federal Agency for Agriculture and Food (BLE) and at the European level by the European Commission.

The *Ordinance Offsetting the Upstream Emission Reductions against the Greenhouse Gas Quota* (Upstream Emission Reduction Ordinance - Upstream-Emissionsminderungs-Verordnung (**UERV**)) regulates how upstream emission reductions are determined, counted towards the quota, and verified. Upstream emissions are all greenhouse gas emissions that occur before the feedstock for fossil gasoline, diesel, and liquefied petroleum gas fuels enters the refinery or processing plant. Based on the UERV, up to 1.2 % of the greenhouse gas abatement can be counted towards the greenhouse gas reduction target under Section 37a of the BImSchG by reducing upstream emissions in this chain. [UERV (2018)] Emission reductions from UER totaled 783,000 t CO_2-eq for the quota year 2020 (own calculation based on [DEHSt (2021)], as of Dec. 21, 2021), which corresponds to a contribution of about 0.37 % to the GHG quota.

The *Ordinance on the Properties and Labelling of the Quality of Fuels* (10th Ordinance on the Implementation of the Federal Immission Control Act (**10th BImSchV**)) sets out requirements for the quality of gasoline, diesel, biodiesel, ethanol, liquefied gas, natural gas, biogas and vegetable oil in commercial transactions with consumers [10. BImSchV (2019)]. It specifies the content and form of fuel labeling and the requirements directed at vehicle manufacturers or importers with respect to the disclosure of recommended fuel qualities. In some cases, references to specific fuel standards are used (see Section 6.1). For example, diesel fuels sold to consumers must comply with DIN EN 590 or DIN EN 14214 (Section 4(1)). Other diesel fuel standards, such as DIN EN 15940 (paraffinic diesel fuels), under which pure bio-based HVO (hydrotreated vegetable oil) diesel falls, are not approved in Germany according to the 10th BImSchV.

1.5.2 Taxation

The *Energy Duty Act* (Energiesteuergesetz, **ENERGIESTG**) transposes the requirements of the ETD at a national level and regulates the taxation of fossil and renewable energy carriers. Since 2018, it no longer contains a tax cut for pure biofuels in road transport (Section 50); however, additional climate-related taxation has been established via the Fuel Emissions Trading Act, which is described below.

Section 57 regulates the tax relief for energy products used in agriculture and forestry. In accordance with Paragraph 5, this has amounted to the following since January 1, 2013:

1.	Gas oils (diesel):		214.80 EUR/1,000 l
2.	Biofuels:	biodiesel (FAME):	450.33 EUR/1,000 l
		vegetable oil:	450.00 EUR/1,000 l

This tax relief is granted retroactively upon application for (initially fully taxed) fuels [EnergieStG (2015)].

The use of biofuels is indirectly affected by the current preferential treatment of fossil gas fuels, such as CNG, LNG and liquified petroleum gas (LPG), as well as their biogenic substitutes, like biomethane. A reduced tax rate will apply to gaseous hydrocarbons until December 31, 2026 and to non-blended liquefied gases until December 31, 2022 in accordance with Section 2: Tax Schedule, Paragraphs 1 and 2 [EnergieStG (2006)]. However, tax rates are continuously increasing; for gaseous hydrocarbons they will rise from 13.90 EUR/MWh (until 2023) to 27.33 EUR/MWh (2026). Starting January 1, 2027, the regular tax rate of 31.80 EUR/MWh will apply. For liquefied gases, the reduced rate of 363.94 EUR/t in 2022 will be replaced by a regular tax rate of 409 EUR/t from 2023 onwards. The corresponding Ordinance for the Implementation of the Energy Duty Act (Energy Duty Implementation Ordinance (Energiesteuerverordnung, **ENERGIESTV**)) regulates details on the implementation of the Energy Duty Act [EnergieStV (2006)].

Starting in 2021, the *Act on National Certificate Trading for Fuel Emissions* (Fuel Emissions Trading Act – Brennstoffemissionshandelsgesetz, **BEHG**) aims to reduce greenhouse gas emissions in areas that are not yet covered by the European Emissions Trading Scheme (EU ETS) [BEHG (2019)]. Thus, it serves to transpose the EU Effort Sharing Regulation (ESR) [Verordnung (EU) 2018/842 (2018)], which focuses on these areas, as well as the national climate protection targets, particularly in the buildings and transport sectors, whereby European domestic aviation is already subject to the EU-ETS. In doing so, the law establishes a successively increasing price for GHG emissions from fuels and combustibles. For the duration of the sale, the fixed price per emission certificate according to Section 10 of the Fuel Emissions Trading Act amounts to [BEHG (2019)]:

- 2021: 25 EUR,
- 2022: 30 EUR,
- 2023: 35 EUR,
- 2024: 45 EUR,
- 2025: 55 EUR.

From 2026 onwards, the price corridor for the auctioning of certificates is EUR 55 to 65 for one emission certificate.

Currently, the toll on gas-powered vehicles has been reduced, resulting in an impact, albeit not an immediate one, on the use of gas fuels in transportation and thus potentially on the use of their biogenic substitutes. According to the *Act on Levying of Route-related Charges for the Use of Federal Highways* *and Federal Roads* (Bundesfernstraßenmautgesetz (**BFStrMG**)), medium and heavy commercial vehicles must pay a toll for the use of certain roads. This applies to vehicles or vehicle combinations that are intended or used to transport goods by road and whose maximum permissible weight is 7.5 metric tons or more. One exception is for vehicles powered by natural gas, which only have to pay partial toll rates to cover infrastructure costs (0.08 to 0.174 EUR/km) and to cover noise pollution costs (0.002 EUR/km). The partial toll rate to cover air pollution costs of 0.011 to 0.085 EUR/km is waived.

1.5.3 Vehicles and Infrastructure

The German government has set targets for reducing GHG emissions in the transport sector through various action plans. These also include not yet legally binding targets for vehicles and infrastructure. Well-known examples of these action plans include:

- The National Strategic Framework on the Development of Infrastructure for Alternative Fuels from 2016 as part of the transposition of Directive 2014/94/EU (**AFID**) [BMVI (2016)],
- The *German Government's Climate Protection Program 2030 for Implementing the Climate Protection Plan 2050* from 2019, including defining targets for 7 to 10 million electric vehicles by 2030 [BMU (2019)] and
- The *National Hydrogen Strategy* from 2020 with market ramp-up targets for hydrogen use.

An initial binding legal framework for the procurement of zero- or reduced-emission vehicles as well as the associated restructuring of the vehicle fleet and adaptation of the infrastructure has only been developed so far for road transport.

The *Clean Road Vehicles Procurement Act* (Saubere-Fahrzeuge-Beschaffungs-Gesetz – **SaubFahrzeugBeschG**) sets binding minimum targets for low- and zero-emission passenger cars as well as light and heavy commercial vehicles as part of public procurement processes [SaubFahrzeugBeschG (2021)]. The requirements stipulate that, in the future, a part of public sector fleets and the fleets of certain stakeholders organized under private law (e.g., postal and parcel services, waste collection) must consist of low-emission or zero-emission vehicles. Passenger cars as well as light and heavy commercial vehicles must comply with CO_2 and air pollutant emission limits in accordance with the CVD. [SaubFahrzeugBeschG (2021)] With regard to renewable fuels, the law opens up the possibility of using HVO and FT diesel-powered vehicles in Germany for the first time by invoking the fuel standard DIN EN 15940 for paraffinic diesel fuels. However, it remains unclear how this can be reconciled with the restrictions imposed by the 10^{th} BImSchV.

In order to advance the expansion of electromobility and provide further incentives for electromobility, the *Act on Prioritizing the Use of Electrically Operated Vehicles* (Gesetz zur Bevorrechtigung der Verwendung elektrisch betriebener Fahrzeuge, **EmoG**) creates incentives for different classifications of electric vehicles. Subject to individual restrictions, the legislator grants local authorities the power to provide special support for electromobility at the local level. The law is initially in effect until the end of 2026. Under the law, priority measures apply to:

- parking on public streets or roads,
- the use of public streets or roads or parts thereof designated for special purposes,
- allowing exceptions to restricted access and
- charging parking fees on public streets or roads.

The *Ordinance on Facilities for Handling Substances that are Hazardous to Water* (Verordnung über Anlagen zum Umgang mit wassergefährdenden Stoffen, **AwSV**) regulates the protection of bodies of water. It applies, for example, to fixed facilities such as filling stations when handling substances hazardous to water or blends of these, under which all common fuels fall. [AwSV (2017)]

1.6 Future developments

1.6.1 The European Union

A new growth strategy has been developed by the European Union in response to climate change and to the destruction of the environment which are described as "existential threats to Europe and the world" [Europäische Kommission (2019)]. This **European Green Deal** [Europäische Kommission (2021)] aims to create a transition to a modern, resource-efficient and competitive economy by 2050 in which

- no more net greenhouse gas emissions are released,
- economic growth is decoupled from resource use, and
- neither people nor regions are abandoned.

Building on this, a comprehensive package of measures was developed under the slogan **Fit for 55** (referring to the 55 % reduction in greenhouse gases by 2030). A corresponding amendment to the European legal framework is set to be made by the end of 2022, which is why only parts of this framework can be presented and only in draft form; implementation on a national level will still take several years.

As part of the Green Deal, key targets for 2030 and beyond have been adjusted [Europäische Kommission (2021)]:

- Reduction in greenhouse gas emissions by 50 to 55 % (compared to 1990 levels, previously 40 %),
- At least 40 % of energy from renewable sources (previously 32 %),
- Energy savings in final energy and primary energy consumption of 36 to 39 % (previously 32.5 %) and
- Reduction in emissions from cars and trucks by 55 % and 50 % respectively (previously 37.5 % and 30 %), and new zero-emission cars by 2035.

The publication of the Green Deal was announced alongside an extensive amendment of many drafts for new directives (the Commission lists 82 such campaigns [Europäische Kommission (2020)]). The most important proposals currently being made by the European Commission in the context of renewable energy for the transport sector are presented below; however, it will take some time before they can be agreed on and adopted at the European level and subsequently implemented at the national level (see the overview in Table 1-4).

As a key component of the Green Deal, the **European Climate Law** contains the following aspects:

- Climate neutrality: reducing greenhouse gas emissions as a legally binding target for all EU institutions and national governments
  - by 50 to 55 % by 2030 and
  - to net zero by 2050;
- The creation of a predictable business environment for industry and investors that sets the pace of emission reductions from 2030 to 2050 and identifies what needs to be done and at what speed;
- The monitoring of the implementation process through regular progress reporting as well as tools for catching up when someone falls behind;
- Transition to a just and prosperous society with a modern, resource-efficient and competitive economy;
- Adaptation to the effects of climate change. [Europäisches Klimagesetz (2021)]

The revision of the Renewable Energy Directive (revised **RED II**) results from amendments to the proposal by the European Commission and the European Council [COM(2021) 557 (2021)] and increases the overall target for the percentage of renewable energy in the gross final energy consumption of the European Union from 32 % to 40 % by 2030. It also includes the following primary targets for the transport sector:

A. Greenhouse gas emissions in the transport sector are to be reduced by 13 % by 2030 through the use of renewable energy; the trajectory is to be defined by the Member States (this reflects a changed approach to the previously defined relative share of energy of 14 % for 2030 in the current version of the RED II).
B. The share of sustainable advanced biofuels is to increase from at least 0.2 % in 2022 to 0.5 % in 2025 and 2.2 % in 2030 (compared to 1.75 % without double counting in the current version of the RED II).
C. The percentage of renewable fuels of non-biological origin (RFNBO) is to reach 2.6 % by 2030 (including hydrogen).

For the two sub-goals (B and C), each of which relates to the share of energy, the reference value represents the total final energy demand in the transport sector. In relation to these two sub-targets, the use of energy carriers in air or sea transport is counted 1.2 times.

The modified framework conditions listed below must be taken into account in the attainment of the targets:

- No more multiple counting of fulfillment options;
- Consideration of renewable fuels of non-biological origin even when they are used as intermediate products in the production of conventional fuels;
- Possible exemption from sub-quota compliance requirement for advanced biofuels for distributors of electricity and its derivatives in the transport sector;
- The specific GHG reductions for the fulfillment options are calculated as follows:
  - for biofuels and biogas - by multiplying the quantity of these fuels by the calculated emission savings (having different typical regional values for the cultivation of the raw materials is no longer possible); the fossil reference value of 94 g CO_2-eq./MJ shall apply here;
  - for renewable fuels of non-biological origin and recycled hydrocarbons - by multiplying the quantity of these fuels by their emission savings which is to be determined in accordance with delegated acts yet to be adopted;
  - for electricity from renewable energy sources - by multiplying the amount of electricity from renewable sources; the reference value for fossil fuels ECFI of 183 g CO_2-eq./MJ shall apply here.

The following regulations remain unchanged in the RED II:

- The limiting of biofuels from biogenic feedstocks that are also suitable for the food and feed sector, and
- The limiting of biofuels from feedstocks listed in Part B of Annex IX (animal fat and used cooking oil).

The draft amendment to the *Directive for establishing a scheme for greenhouse emission allowance trading within the Community* (**EU-ETS**) [Proposal EU-ETS (2021)] proposes that emissions from the current EU ETS sectors (electricity, manufacturing, aviation, and the expansion of maritime transport) be reduced by 61 % by 2030 over 2005 levels, which corresponds to an increase of 18 %. To achieve this target, a higher annual emissions reduction of 4.2 % (previously 2.2 %) will be imposed. In addition, the free allocation of emission certificates is conditionally tied to a 25 % reduction in free certificates for facilities that do not implement any of the cost-effective decarbonization measures recommended by their energy audits.

The expansion of emissions trading to include the maritime transport sector will only affect CO_2 emissions from large ships, regardless of the country where they are registered. The expansion will cover all emissions from ships calling at EU ports on voyages within the EU (intra-EU), 50 % of emissions from voyages starting or ending outside the EU (extra-EU), and emissions from ships anchored at EU ports.

Under the EU ETS, a new separate emissions trading system will be established for road transport and buildings. As with the RED system, it will encompass distributors of fuels and combustibles and not end users or consumers. An emissions cap will be imposed starting in 2026, which will be lowered annually in order to achieve a 43 % reduction in emissions over 2005 levels by 2030.

In terms of energy taxation, the Energy Tax Directive (**ETD**) defines the EU's common framework and plays a central role in achieving climate protection targets [ETD (2021)]. The adjusted regulations follow a completely revised system. First, the minimum tax rates are restructured. These are now based on the actual energy content and environmental performance of fuels and electricity in euros per gigajoule:

- 10.75 EUR/GJ for conventional fossil fuels as well as non-sustainable biofuels,
- 7.17 EUR/GJ for natural gas, LPG and non-renewable fuels of non-biological origin (for a transitional period of ten years),
- 5.38 EUR/GJ for sustainable but not advanced biofuels and
- 0.15 EUR/GJ for electricity (regardless of its use), advanced sustainable biofuels and biogas, and renewable fuels of non-biological origin; for ten years, this tariff also applies to low-carbon hydrogen and related fuels (e.g., ammonia, bio-LNG).

It also broadens the tax base by including more products and eliminating some of the current exemptions and reductions, resulting in much less leeway for Member States. Kerosene and heavy fuel oil will no longer be fully exempt from energy tax for journeys within the EU.

In accordance with the proposal for a *Regulation to ensure a level playing field for sustainable air transport* (**REFUELEU AVIATION**) [Proposal 2021/0205 (2021)], aviation fuel suppliers must ensure in the future that all aviation fuel provided to aircraft operators at any airport in the Union contains a minimum percentage of sustainable aviation fuel (SAF), including a minimum percentage of synthetic aviation fuel (Table 1-6). In Germany, a minimum percentage of 5 % for 2030 would correspond to 22 PJ based on aviation fuel consumption in 2019 (Section 2.4).

Table 1-6 Minimum percentage of SAF as per ReFuelEU up to 2050. Data based on [Proposal EU-ETS (2021)]

Starting from	Minimum % of SAF	Minimum % of synthetic aviation fuel
1/1/2025	2 %	–
1/1/2030	5 %	0.7 %
1/1/2035	20 %	5 %
1/1/2040	32 %	8 %
1/1/2045	38 %	11 %
1/1/2050	63 %	28 %

Failure to achieve this quota will be subject to a fine that is equivalent to at least double the price delta between fossil kerosene and SAF, and the suppliers concerned must at least make up this shortfall in the subsequent reporting period. Like hydrogen and electricity, biofuels based on food and animal feed are not fulfillment options under this directive.

According to the proposal for a *Regulation on the use of renewable and low-carbon fuels in maritime transport* (**FuelEU Maritime**) [FuelEU Maritime (2021)], greenhouse gas emissions from fuel used in maritime shipping are to be gradually reduced by:

- 2 % starting in 2025,
- 6 % starting in 2030,
- 13 % starting in 2035,
- 26 % starting in 2040,
- 59 % starting in 2045,
- 75 % starting in 2050.

The reference value for this still needs to be defined and will be based on the average greenhouse gas intensity of the energy consumed on board ships in 2020. Furthermore, all container and passenger ships are to be supplied with shore power during their time in port from 2030 onwards.

Compared to the previous regulation, the draft amendment to the *Alternative Fuels Infrastructure Directive* (**AFID**) proposes many concrete specifications and a clearer target for infrastructure improvements for 2030, with some as early as 2025 [Proposal 2021/0223 (COD) (2021)]. The proposals include:

- A total of at least 1 kW of power shall be provided through publicly accessible charging stations for each battery-electric light commercial vehicle
- By 2025, publicly accessible charging pools for battery electric vehicles will be placed throughout the core network[3] at a maximum distance of 60 km.
- By 2030, publicly accessible hydrogen filling stations with a minimum capacity of 2 t/day and a fuel pump with a minimum 700 bar capacity should be placed throughout the core network at a maximum distance of 150 km (liquid hydrogen every 450 km).

According to the draft, a sufficient infrastructure network already exists for LPG and CNG vehicles throughout the Union. As they are to be gradually replaced by zero-emission drives, a limited and targeted policy for the development of an LNG infrastructure, which can also supply decarbonized fuels, is still considered necessary to fill the remaining gaps in the primary networks by 2025.

The implementation of these infrastructure requirements is a matter for the individual EU Member States. During the last regulatory round, the Member States intervened accordingly, so that all AFID requirements were anchored in legislation as non-binding recommendations [Mock (2021)].

As part of the Green Deal, the proposal to amend the *Effort Sharing Regulation* (**EU-ESR**) adjusts the Member States' reduction targets for 2030 which have already been defined. For Germany, the reduction target is to increase from 38 % to 50 % over 2005 levels. [COM/2021/555 (2021)]

The draft of the delegated *Regulation establishing the technical assessment criteria for determining under which conditions an economic activity is deemed to make a significant contribution to climate change mitigation or adaptation [...]* creates a single EU classification system (**Taxonomy**). This regulation is indirectly relevant for renewable energy carriers in the transport sector through its proposal for evaluation criteria to establish whether an economic activity is considered sustainable. Participants in

[3] The core network of the Trans-European Transport Networks (TEN-T) includes the main routes crossing through the countries and is to be completed by 2030. In Germany, this involves the main cross-country highways and a few federal highways (BMVI (2021b)).

the financial market, large companies, the EU and its Member States are affected by these determinations when standards are developed. Thus, all legal and regulatory drafts (in terms of research, funding, taxation, etc.) that will refer to the taxonomy in the future are affected.

Excursus 1: Implementation period of European Regulations (example RED II)

The time required for the process – from defining the targets to consensus building at the European level and implementation, i.e., legislation and implementation at the national level – is of key importance, not least in light of the urgency of action needed on the issue of protecting the climate and reducing greenhouse gases. The example in Table 1-7 shows that about five years passed from the European Commission's first draft of the RED II to its transposition and entry into force at the national level in Germany's transport sector (Section 37a-g BImSchG and associated ordinances). Since the democratic legislative processes in the European Union and Germany can only be accelerated to a limited degree, similar timeframes must also be assumed when adjustments are made in the future. It is therefore all the more important to define long-term targets, establish an appropriate framework, and respond to adjustment needs early on. In light of the 1st draft of the revised RED II [COM(2021) 557 (2021)], published on July 14, 2021, a binding implementation at the national level is therefore not expected before 2025.

Table 1-7 Chronology of the creation of European directives and their transposition into national law using the RED II as an example

Chronology	Implementation steps	Level/party involved
Nov. 30, 2016	Publication of 1st draft of the RED II	European Commission
	Trilogue on consensus building and drafting of resolution version	Commission/Council /Parliament
Dec. 4, 2018	Resolution	European Council
Dec. 24, 2018	Renewable Energy Directive RED II goes into force	European Law
Sept. 22, 2020	1st draft bill for German transposition	German Government
	Public participation and departmental coordination	
Feb. 2, 2021	Cabinet resolution	German Government
May 20, 2021	Parliament resolution	German Parliament
June 30, 2021	Deadline for transposition into national law (not complied with by many countries, including Germany)	State Parliaments
Oct. 1, 2021	National implementation goes into force (with considerable delays)	

1.6.2 Germany

Through various strategies, programs and action plans, Germany's federal government defines the direction of the sustainable development of mobility and transport, above all to reduce transport-related emissions. Although these do not yet have a direct, legally binding nature, they provide support for the political and social discourse and pave the way for concrete, legally binding framework conditions.

The **Climate Protection Plan 2050** (Klimaschutzplan 2050) was adopted in November 2016 and contains the German government's policy principles and targets for climate protection with a view to the long-term goal of a largely CO_2-free economy by 2050. In addition to interim targets (milestones), it also includes specific fields of action and measures for the transport sector:

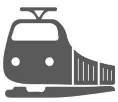
Road transport

- GHG reduction by combining improvements to vehicle efficiency and increased use of GHG-neutral energy

- Passenger cars: Reduction of direct GHG emissions over current vehicles without limiting use through plug-in hybrids, pure electric vehicles with a longer range, and fuel cell vehicles; ambitious advancement of the CO_2 targets for new passenger cars in the 2017 EU Regulation
- Light commercial vehicles: lightweight technologies to increase load capacity and extend e-mobility range

- Heavy-duty vehicles: Further improvement in the efficiency of internal combustion engines and transmissions, hybridization, improved aerodynamics, use of tires with optimized rolling resistance, adjustments to vehicle length and use of hydrogen and liquefied natural gas (LNG) or renewable methane in optimized gas engines, electric drives
- Digitalization: enables, for example, more efficient use of the transport infrastructure

Rail transport



- Targeted investment in the rail network (including electrification of rail lines) and the setting of specific framework conditions for switching from road to rail
- Effective improvement of intermodal competitiveness for climate-friendly rail transport

Bicycles

- Attractive cycling infrastructure in urban and rural areas
- Better links to local public transport
- Greater use of cargo bikes
- Transport reduction through regional production and consumption structures

Pedestrian traffic

- Attractive streets
- Climate-friendly transport options taken into account in the planning process

Air and sea transport

- Emission reductions through alternative drive technologies and designs as well as technical adjustments
- Examination of the possibilities for blending biogenic and renewable electricity-based fuels

General

- Promotion of the use of low-GHG or GHG-neutral transport (non-motorized transport or motorized transport based on renewable energy)

  Examination of the gradual and revenue-neutral restructuring of transport-related charges and levies in order to generate tangible financial benefits from transport behavior that is as low in GHG emissions as possible [BMUB (2016)]

When the Climate Protection Plan is updated in 2022 [BMU (2021)], the milestones and measures will have to be adjusted to reflect the more ambitious Climate Protection Act, which has since been passed and amended.

Hydrogen will play a key role in the further development and completion of the energy transition. Therefore, the German government has drawn up a **National Hydrogen Strategy** (Nationale Wasserstoffstrategie) [BMWi (2020)]. Green hydrogen (from renewable electricity via electrolysis, see Section 3.8.2) will play a particularly important role here:

- Promotion of hydrogen-based mobility
- Use of hydrogen as a basis for synthetic fuels and combustibles
- Hydrogen as an essential element of sector coupling
- New decarbonization pathways via electricity produced from renewables and green hydrogen as well as its downstream products (power-to-X)
- Decarbonization option for key industrial pathways (ammonia, steel, cement).

There are numerous strategies, laws and regulations at various levels that build upon the **German Government's Electromobility Program** (Regierungsprogramm Elektromobilität) [BMVI (2021a)]. These primarily aim to increase the number of electrically powered passenger vehicles and the number of charging points – private, but especially public ones. Some of the 2030 targets include:

- Seven to ten million electric vehicles
- One million publicly accessible charging points
- Installation of 100,000 charging points on automotive production sites and associated dealers
- About one-third of the mileage of heavy road haulage to be electricity based or use e-fuels
- Sufficient fueling and charging infrastructure.

The two electromobility and hydrogen options are accompanied by extensive support measures such as the Environment Premium and the Innovation Premium [BAFA (2021b)] as well as investment grants for public and private charging infrastructure [BMVI (2020)].

The national *Strategic framework for the development of an alternative fuels infrastructure* from 2016 is part of the implementation of Directive 2014/94/EU (**AFID**) [BMVI (2016)]. The development of this infrastructure is not directly enshrined in German law, however it is directly and indirectly promoted through various measures in line with the strategy framework [BMVI (2016)] (Section 1.5.3).

2 Transport and its infrastructure

JÖRG SCHRÖDER AND KARIN NAUMANN

2.1 Stock of vehicles

For more information:

Vehicles can be classified based on various criteria, such as mode of transport, area of use and weight class. Figure 2-1 illustrates the classification used in this report. Agricultural, forestry and construction machinery (with the exception of vehicles such as tractors approved for road use) represent a special case, as they do not fall under the category of transport even though they use the conventional transport energy carriers. The classification is based on the EC vehicle classes in road transport [Verordnung (EU) 168/2013 (2013); Verordnung (EU) 167/2013 (2013); Verordnung (EU) 2018/858 (2018)] and on the criteria of the Federal Ministry of Transport and Digital Infrastructure (BMVI, since December 2021 BMDV) for rail, air and water [KBA (2021m)].

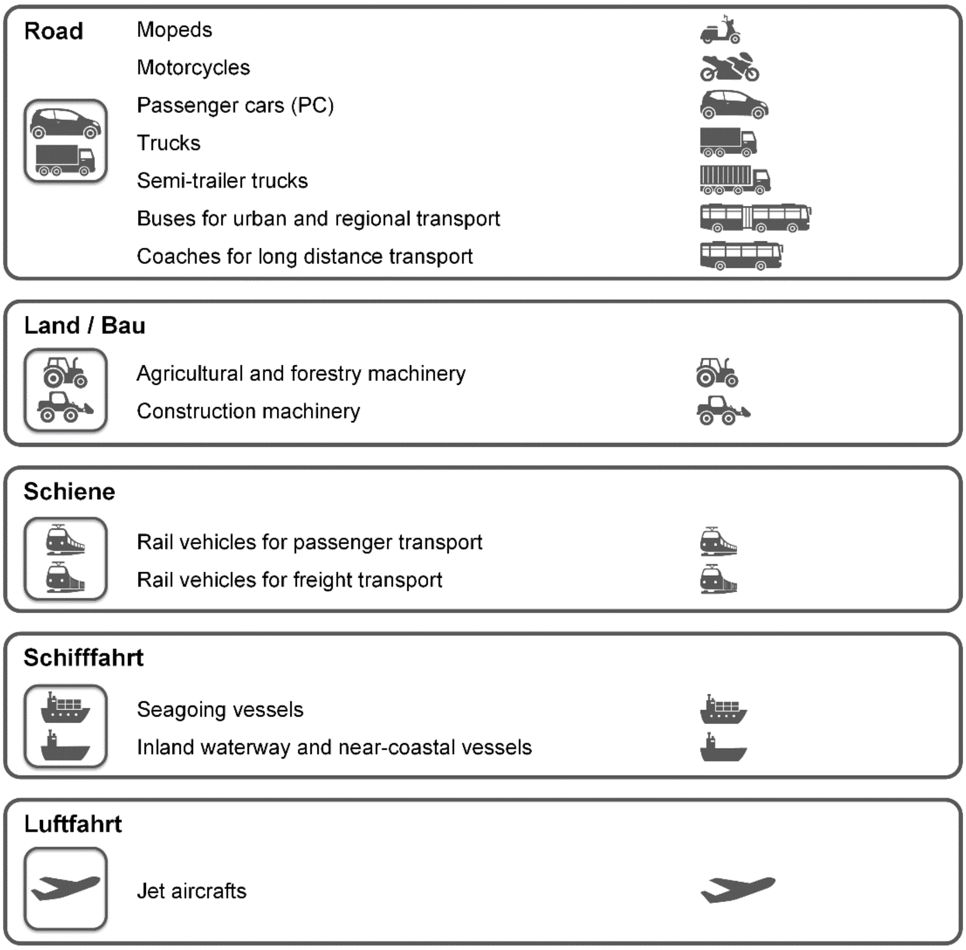


Figure 2-1 Classification of vehicle types by use, data based on [Verordnung (EU) 168/2013 (2013); Verordnung (EU) 167/2013 (2013); Verordnung (EU) 2018/858 (2018); KBA (2021m)]

There are approximately 2 billion vehicles worldwide that are used to move people and goods [Davis (2020); Motorcyclesdata (2021); OICA (2021); UBA (2020)]. The primary segments are passenger vehicles, road-bound commercial vehicles and motorcycles. Around 59 million vehicles operate on Germany's roads (Figure 2-2) [KBA (2021f)]. Globally, the number of vehicles will rise sharply in the coming decades as population figures and mobilization rise. Vehicle density (vehicles per 1,000 inhabitants) can be used as an indicator for individual countries. While vehicle density is above 500 in most countries of the European Union, in North America, Japan and Australia, in the most populous regions of China and India, for example, it is 83 and 18, respectively. The situation in Africa is similar. In Germany, the vehicle density for passenger cars increased from 509 in 2010 to 580 by the end of 2020. [Destatis (2021a); KBA (2021f); Our World in Data (2021)]

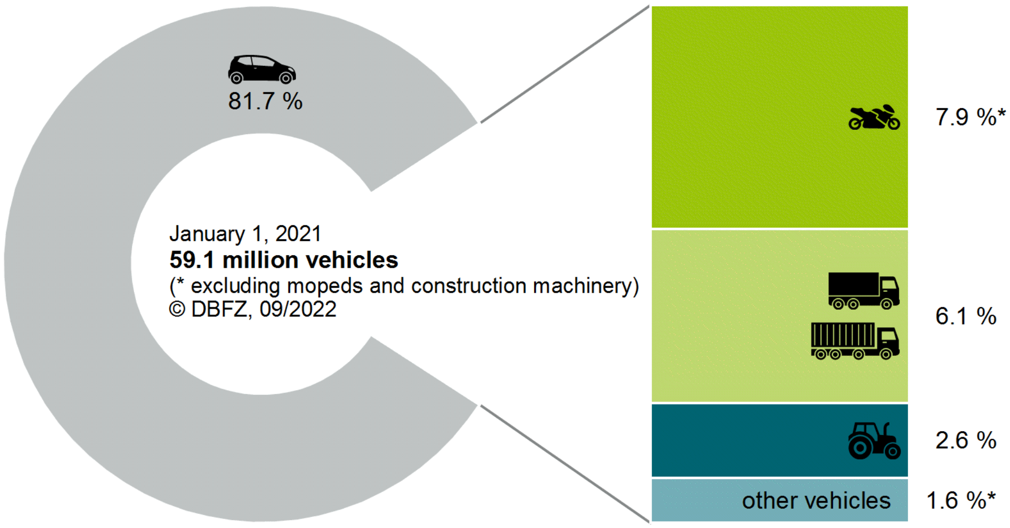


Figure 2-2 Stock of vehicles in Germany. Note: other vehicles are buses and coaches, aircraft, inland waterway vessels, seagoing vessels, railcars and locomotives, data based on [KBA (2021m), (2021b)]

The number of passenger cars, trucks and semi-trailer trucks in Germany has increased significantly in the past ten years (Figure 2-3). At the same time, there has been a stagnation and even a decrease in buses and coaches, railcars, inland waterway vessels and aircraft. Both aspects may be an indication of a contradiction in the goals set by the German government, namely to avoid energy-intensive transport routes, relieve the burden on roads, and ultimately reduce greenhouse gas emissions by shifting traffic from road to rail, both in personal and freight transport.

The age structure of the vehicles in use varies considerably (Figure 2-4). While the stock of road-bound commercial vehicles (trucks and semi-trailer trucks), buses and coaches and passenger cars is rapidly being replaced (average age: less than ten years), the other vehicle segments are over ten years old or, in some cases, over 20 years old. The age structure of the vehicles in use is important in that the introduction of renewables is mostly associated with the replacement or procurement of new vehicles if vehicles cannot be converted or if renewable energy carriers cannot be blended with fossil fuels.

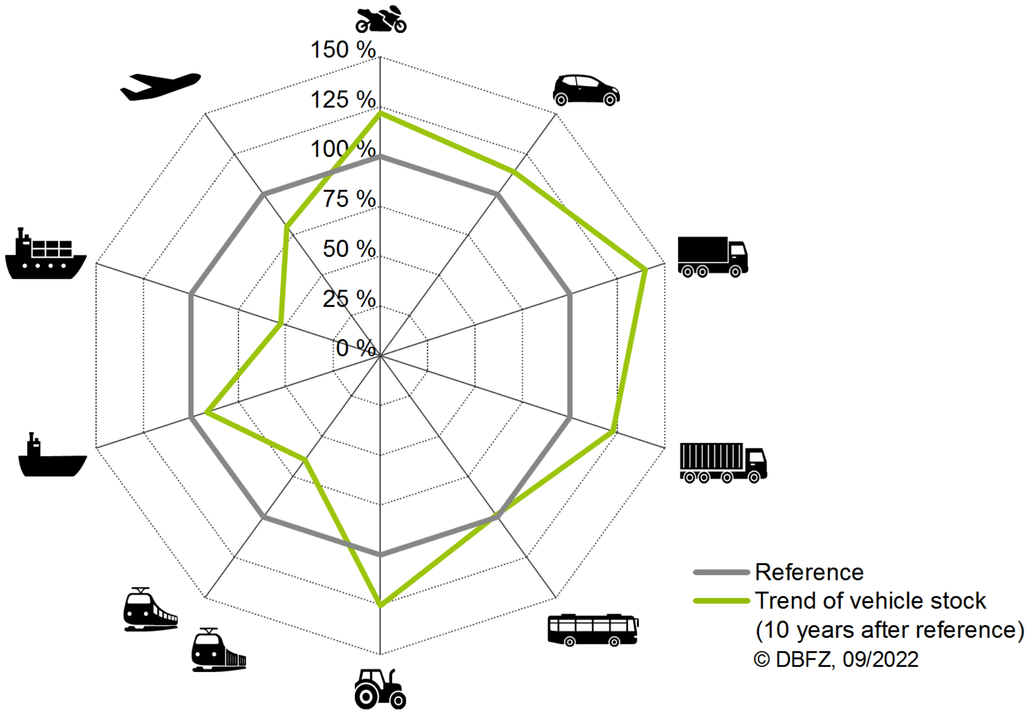


Figure 2-3 Development of the stock of vehicles in Germany over ten years (reference year 2010, reference year rail: 2005). Note: graph does not include mopeds or construction machinery, data based on [KBA (2011), (2021d), (2021m), (2021f)]

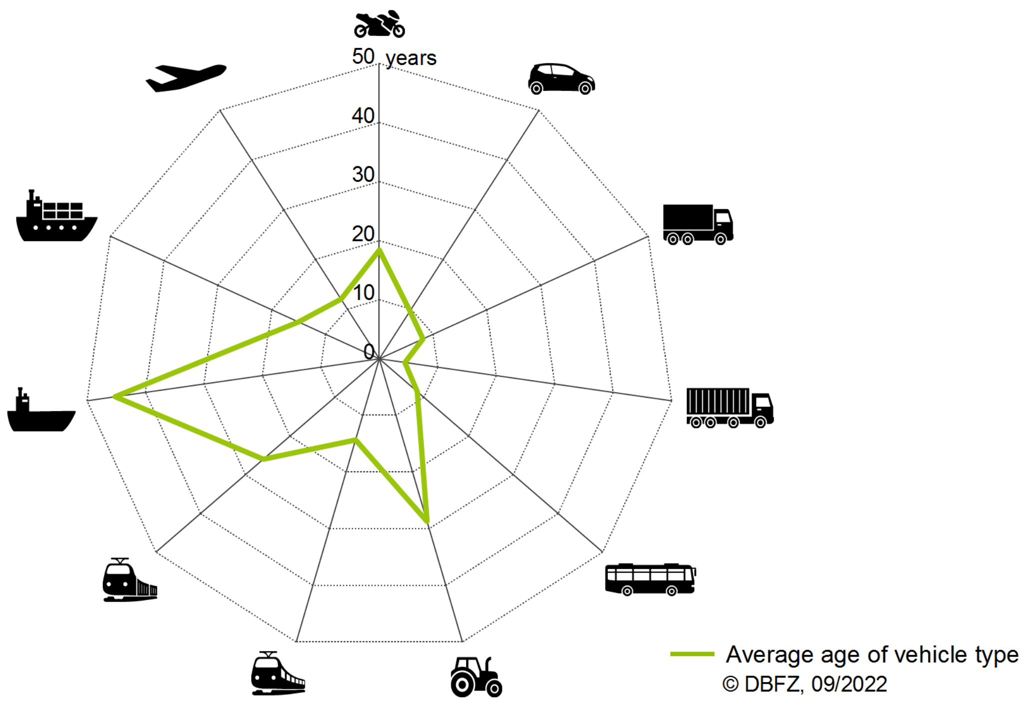


Figure 2-4 Average age of the stock of vehicles in Germany, broken down by vehicle type. Note: graph does not include mopeds or construction machinery, aircraft refers to the aircraft fleet of Lufthansa AG, regional and freight rail refers to the vehicle fleet of Deutsche Bahn AG, data based on [Deutsche Bahn AG (2016); Deutscher Bundestag (2019), (2020); KBA (2010), (2020b); Schönebein (2021); Stoffels (2020)]

The status quo and the current trend for the vehicles in use in Germany, Europe and around the world, as well as the characteristic features of the various types of vehicles, are discussed in detail below.

Motorcycles cover all two- and three-wheeled vehicles. All vehicles requiring registration whose maximum permissible speed is over 45 km/h are included in the statistics. As of January 1, 2021, 4.7 million motorcycles were registered with the Federal Motor Transport Authority (Kraftfahrt-Bundesamt), with approximately 200,000 registrations of new vehicles in 2020. This represents a 24 % increase in the stock of vehicles over the past ten years. Motorcycles were on average 18.7 years old in 2020. [KBA (2021f)]

Motorcycles also include **mopeds (mopeds, motorized bicycles and mopeds with a kick-starter)** whose maximum permissible speed is under 45 km/h. These are not included in the statistics in Germany, however, because they are not registered. It is estimated that there are around 2 million mopeds in Germany. [KBA (2021b)]

Over 22 million motorcycles are registered in the EU (EU-27) and over 300 million worldwide. Over 50 million vehicles are registered each year including mopeds. Motorcycles have established themselves as a primary means of motorized transport, especially in Asia. There is a rapidly growing market there, as in Germany. [Eurostat (2021b); Motorcyclesdata (2021); Rogers (2008)]

While motorcycles typically have an internal combustion engine (gasoline) as a means of propulsion, electric mopeds are gaining traction in many countries [Grand View Research (2021)].

Passenger vehicles are motor vehicles for transporting passengers that have at least four wheels and a maximum of eight seats (excluding the driver's seat). As of January 1, 2021, 48.2 million passenger vehicles were registered with the Federal Motor Transport Authority. This represents a rise of 14 % in the past ten years, with between 2.9 million (2020) and 3.6 million (2019) vehicle registrations per year. Average vehicle age has risen from 8.3 to 9.8 years over the same period. [KBA (2021b)]

There are over 241 million passenger vehicles registered in the EU (EU-27) (as of 2019) and over 1.2 billion worldwide, with over 63 million units sold globally in 2019. [Eurostat (2021a); OICA (2021)]

Germany's stock of passenger vehicles continues to be dominated by internal combustion engine vehicles (ICEVs) that use gasoline and diesel fuels as energy carriers (Figure 2-5). The percentage of alternative drive systems in the passenger vehicle segment is disproportionately high compared to other segments; nevertheless, it remains low at 1.6 million vehicles overall. This includes 724,228 hybrid electric vehicles (HEV) without an external charging option for the traction battery and 346,765 vehicles that use liquefied petroleum gas (LPG) as energy carriers. There has been an upward trend, particularly in the past two years, for battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs), which now amount to 309,083 and 279,861 vehicles respectively. Electrification of passenger vehicles is expected to pick up significantly in the coming years. This is influenced by the various support measures, such as purchase premiums (Figure 2-6). Meanwhile, registrations of new passenger vehicles powered by LPG and natural gas/methane are marginal at under 1,000 vehicles per month, as are registrations of new fuel cell electric vehicle (FCEVs), at under 100 vehicles per month. [KBA (2021a)]

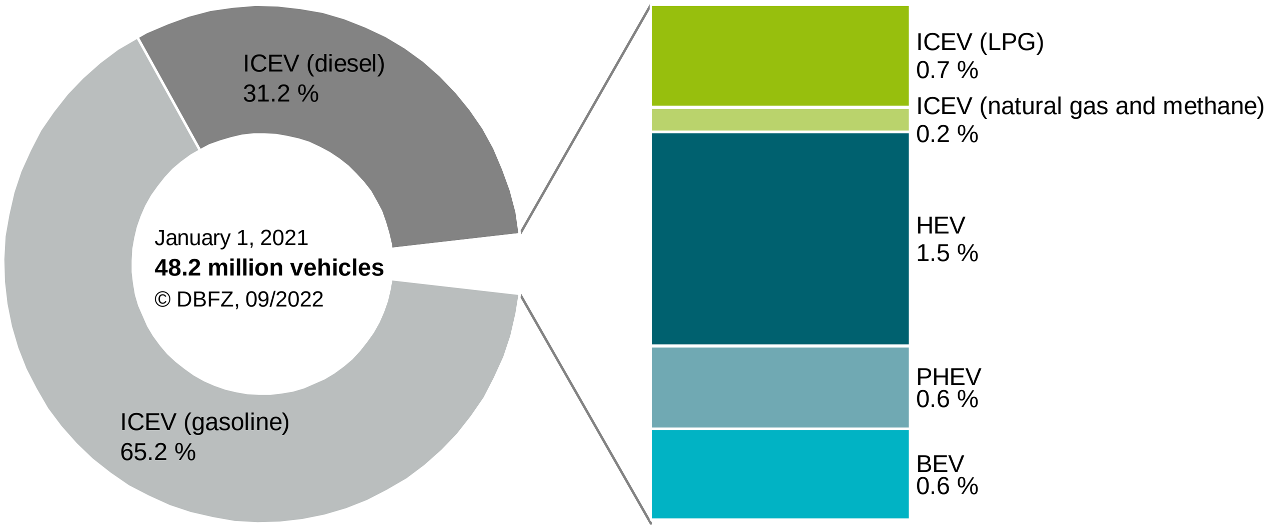


Figure 2-5 Stock of passenger vehicles in Germany, broken down by type of drive and fuel. Data based on [KBA (2020a), (2021e)]

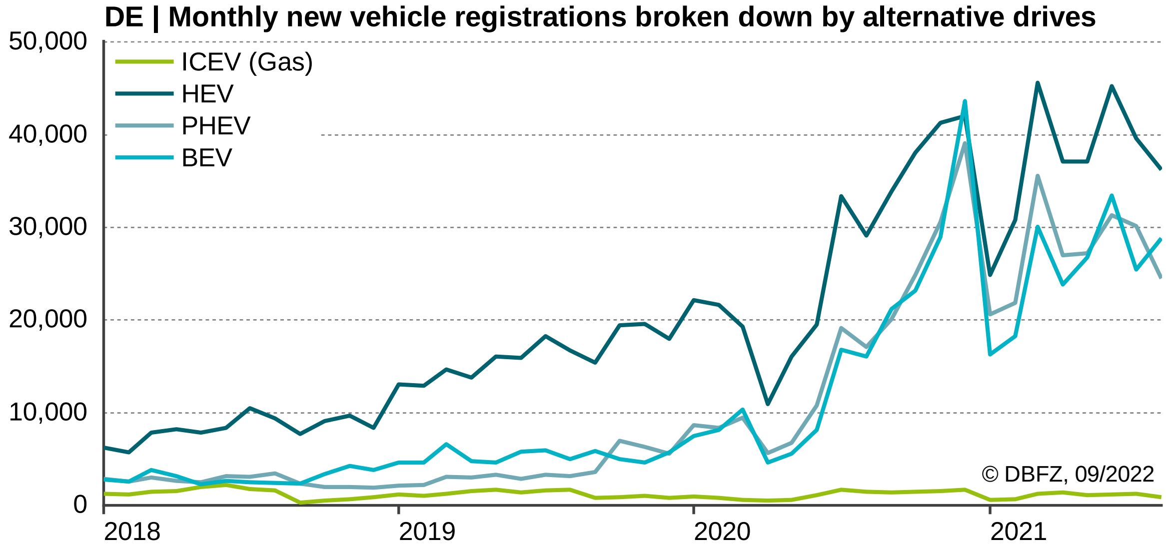


Figure 2-6 New passenger vehicle registrations in Germany, broken down by alternative drives and month. Data based on [KBA (2019), (2021k), (2021l)]

Commercial vehicles for transporting goods include trucks and semi-trailer trucks. Both are commercial vehicles designed and equipped to transport goods by road. Trucks also include vehicles with a total permissible weight of under 3.5 t, so-called light commercial vehicles. As of January 1, 2021, 3.4 million trucks and a further 218,469 semi-trailer trucks were registered with the German Federal Motor Transport Authority (Figure 2-7). This represents a 39 % increase in the past ten years. In 2019, new truck registrations amounted to 343,708 and new semi-trailer truck registrations to 38,620, representing approximately 10.5 % of the vehicles in use. Average vehicle age is currently 8.2 years for trucks and 4.6 years for semi-trailer trucks. [KBA (2020c), (2021g), (2021f), (2021b)]

As of 2019, there were over 36 million registered trucks and semi-trailer trucks in the EU (EU-27) and nearly 400 million worldwide, with approximately 27 million units sold worldwide in 2019 [Davis (2020); Eurostat (2021a)].

The diesel-powered internal combustion engine is the dominant drive system for medium and heavy commercial vehicles. This makes up nearly 100 % of all commercial vehicles. In the past two years, a small stock of vehicles powered by natural gas or biomethane has also emerged in Germany (as of January 1, 2021: 493 LNG and 1,694 CNG). In contrast, light commercial vehicles have a greater range of drive systems (diesel: 89 %, gasoline: 7 %, BEV: 2 %, rest: 2 %). [KBA (2021e), (2021a)]

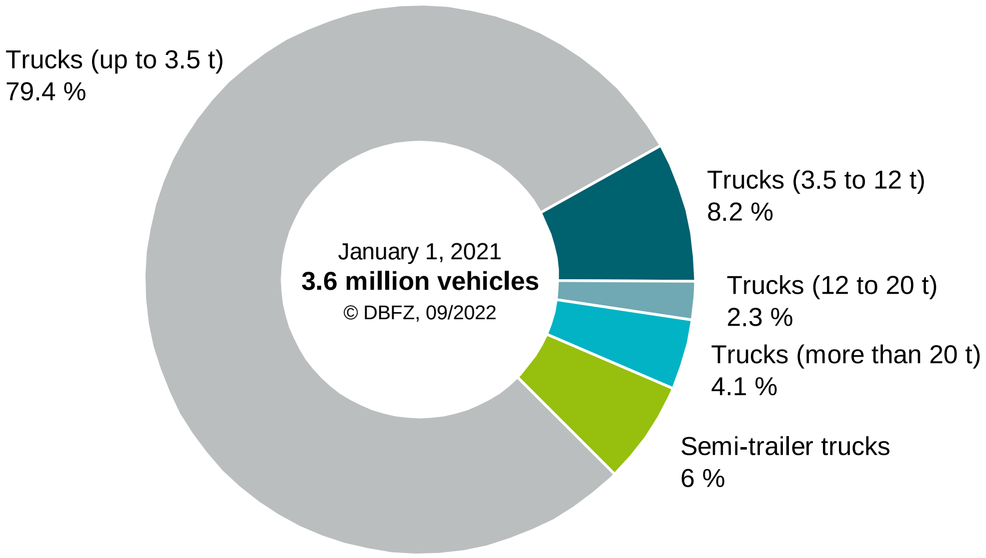


Figure 2-7 Stock of trucks and semi-trailer trucks in Germany, broken down by maximum authorised mass. Data based on [KBA (2021c)]

Unlike passenger vehicles, **BUSES AND COACHES** are designed to carry nine or more passengers. As of January 1, 2021, 75,548 buses and coaches were registered with the Federal Motor Transport Authority. This means that the number of registered vehicles has remained virtually unchanged over the past ten years (down 1 %). In 2020, the number of new vehicle registrations was 6,460 (8.6 % of the stock). The average vehicle age is currently 8.5 years. [KBA (2021b), (2021e)]

In the EU (EU-27), there were approximately 800,000 registered buses and coaches as of 2019, with approximately 44,000 new registrations in 2019 [Eurostat (2021c), (2021a)].

As in the case of commercial vehicles, diesel engines dominate here as well (95 %) compared to alternative drives (CNG: 1 %, BEV: 1 %, HEV: 3 %) [KBA (2021e)].

AIRCRAFT include commercial aircraft and helicopters that are operated by airlines or private operators as part of public transport and whose main purpose is commercial. In 2018, there were 1,134 airplanes and 636 helicopters registered in Germany. In 2018, the number of registered aircraft in the EU was approximately 6,000 and worldwide there were approximately 33,000. Based on the aircraft fleet of Lufthansa AG, the average age is twelve years, but can vary greatly depending on the type of aircraft. [Eurostat (2021f); KBA (2021m); Stoffels (2020)]

Commercial aircraft are normally powered by jet engines and kerosene. Most of the short-haul and cargo aircraft are older propeller models.

INLAND WATERWAY VESSELS include cargo vessels, tugboats, pushers, push-towboats, barges, lighters and passenger vessels used on inland waters such as rivers and lakes. In Germany, around 4,000 vehicles were operated in this category as of 2019. They are powered by an internal combustion engine that uses diesel fuel. The vessels have an average age of 45 years. This makes it very difficult to quickly replace the stock in this segment. It is common to replace or renew the drive system during the lifetime of the vessel. [Deutscher Bundestag (2019); Eurostat (2021g); KBA (2021m)]

Seagoing vessels include all merchant vessels for the carriage of goods (dry cargo vessels and tankers) and for carrying passengers on the high seas. Only 292 ships sailed under the German flag in 2019. Globally, approximately 58,000 vessels sailed in 2017 under the flags of the 20 nations with the most registered seagoing vessels. Today, seagoing vessels are usually powered by internal combustion engines that use marine gasoil (MGO) or heavy fuel oil (HFO). In addition, a small number of vessels are currently being developed that have alternative drive systems which primarily use LNG, but also battery-electric systems. Seagoing vessels have an overall average age of 15 to 20 years, which varies greatly depending on the type of vessel. [KBA (2021m); Schönebein (2021); The Maritime Executive (2017)]

Rail vehicles include locomotives and railcars with electric or diesel-electric drives for long-distance service and regional transport as well as freight transport. At the end of 2015, 4,174 locomotives and 5,743 railcars were operating in Germany. The rail vehicles used for long-distance passenger service are fully electrified, while around half of the fleet used in regional and freight transport is electrified. The remaining vehicles are powered by diesel. In 2019 the average age in regional transport was 14 years; in freight transport it was 26 years. [Deutsche Bahn AG (2016); Deutscher Bundestag (2020); KBA (2021m)]

It is estimated that there are 250,000 locomotives and railcars worldwide [International Union of Railways (2021)].

Agricultural and forestry tractors are commercial vehicles used exclusively or primarily to tow trailers in the agricultural or forestry sector. As of January 1, 2021, 1.6 million such vehicles were registered with the Federal Motor Transport Authority (Figure 2-8). This represents an increase of 25 % in the past ten years. In 2020, 50,766 new vehicles were registered. Agricultural and forestry machinery has an average age of 29 years. The figures suggest that not all vehicles assigned to this vehicle class are being used for professional purposes. The vehicle age must be considered in the context of the performance classes; in particular, the powerful machines used in large agricultural operations are replaced much more quickly due to their high levels of use. In contrast, privately owned tractors are mostly of a lower performance class and are used for much longer and as vintage vehicles. The prevailing drive system is the diesel engine. In addition to this, there is a small stock of battery-electric vehicles and vehicles powered by vegetable oil. In the future, the choice of drive will depend heavily on performance and amount of daily use. [KBA (2021f), (2021h)]

Registration statistics are used to estimate the number of vehicles in use in the non-road mobile machinery (NRMM) sector in the EU-28. In 2019, the reported number of tractors was approximately 3.5 million. There were also around 825,000 harvesters and 274,000 small equipment units. [Mellios (2019)]

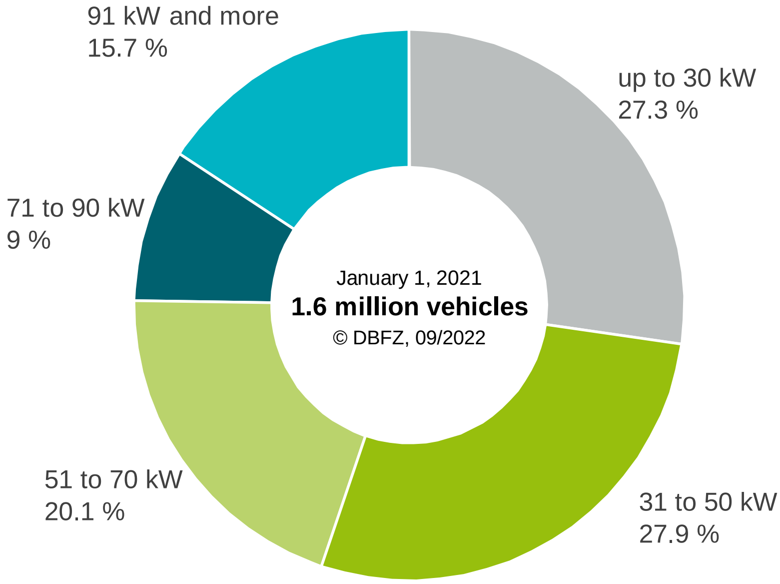


Figure 2-8 Stock of agricultural and forestry tractors in Germany, broken down by performance class. Data based on [KBA (2021g)]

Construction machinery and construction equipment is defined as all stationary, semi-mobile or mobile machines that are powered by an internal combustion engine or electric motor. They are used in the non-road sector to work and process construction materials or for other applications. They are also used in agriculture or in underground and open-cast mining (e.g., excavators, wheel loaders, conveyor belts, lawn mowers, power generators, etc.). Depending on their application profile, construction machinery is powered by electric battery, gasoline or diesel, with diesel engines preferred for high-powered machines.

In Germany, the number of non-electrically powered construction equipment with an engine power greater than 19 kW is estimated at 250,000. A significantly larger number is to be expected with an engine power below 19 kW, as this includes handheld motorized equipment such as compaction machines and lawn mowers. [Bauer (2015)]

The EU-28 recorded approximately 2.4 million units of construction machinery with an engine power lower than 75 kW, approximately 430,000 units of higher-powered heavy machinery, and 720,000 units of small equipment [Mellios (2019)].

2.2 Fueling infrastructure

With the exception of aviation fuels, fuels may only be sold in Germany in accordance with the 10th BImSchV (Section 1.3). This applies both to their distribution at publicly accessible filling stations and at privately owned facilities for vehicle fleets used in road-based transport. The regulatory situation as well as the promotion of an alternative fuel infrastructure and alternative drive systems (e.g., through purchase premiums) are key to their establishment. These incentives are currently leading to a strong expansion of the infrastructure for electromobility, LNG and hydrogen.

Diesel fuel in compliance with DIN EN 590 (B7 and premium fuels) and gasoline fuel in compliance with DIN EN 228 (Super/E5, E10 and premium fuels) were offered at 14,459 publicly accessible filling stations as of 2020 [BFT (2021)]. The number of filling stations offering fuel alternatives is significantly lower (Figure 2-9). At the end of 2020, 837 filling stations offered CNG and 39 offered LNG in compliance with DIN EN 16723-2, 6,767 filling stations offered LPG in compliance with DIN EN 589, and 83 filling stations offered hydrogen in compliance with DIN EN 17124. The number of publicly accessible filling stations providing diesel, gasoline, CNG and LPG for road transport has declined slightly in recent years, while a reverse trend can be seen for LNG and hydrogen. [EAFO (2021b)]

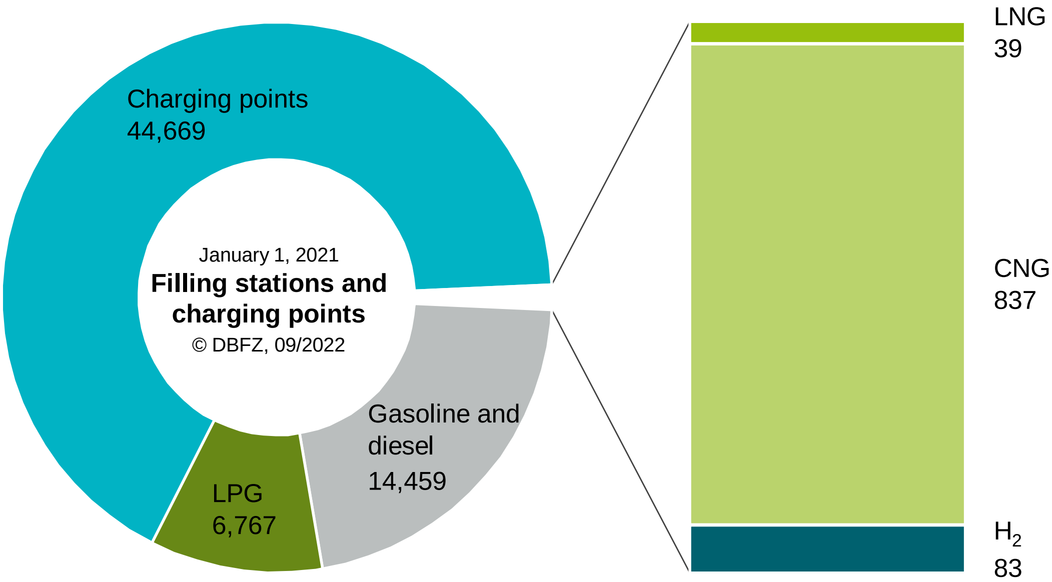


Figure 2-9 Publicly accessible filling stations and charging points for road transport in Germany. Note: charging points include normal and fast charging points, data based on [BFT (2021); EAFO (2021b)]

The following fuel options are currently not offered at publicly accessible filling stations: biodiesel (B100) in compliance with DIN EN 14214, E85 in compliance with DIN EN 15293, and vegetable oil fuels in compliance with DIN 51605 or DIN 51623. Tax policies for pure biogenic fuels and the sharp rise in the price of mineral oil had sparked a demand for these fuels that resulted in the establishment and expansion of structures for the production, distribution and use of alternative fuels by 2006 [UFOP (2006)]. Additional support measures and corresponding economic framework conditions achieved a sufficient degree of planning certainty, so that by 2007 up to 1,900 filling stations for B100 fuel were available and the use of vegetable oil (mostly in agricultural operations or in the haulage industry) was widespread [UFOP (2009)].

The charging infrastructure for electric vehicles has largely developed independently from the conventional filling station infrastructure. There is now a much larger public network, especially at so-called normal charging points with a capacity of up to 22 kW (37,213). A total of 7,456 fast-charging points, important for interregional traffic, were in operation at the end of 2020. [EAFO (2021b)]

In addition to the publicly accessible filling stations for road transport, there is also a large number of private filling stations in Germany, most of which are used for private vehicle fleets (e.g., municipal fleets, haulage companies, agricultural and forestry operations). In the area of electromobility there is also a large number of privately or corporately owned charging points.

Filling stations are in place for the other transport sectors, like rail, shipping and aviation, at least at the larger transfer points (railroad stations, ports and airports). Currently, fuel bunkering at airports often involves local approval for Jet A1 kerosene with a synthetic renewable kerosene blend that conforms to standards [Munich Airport (2021)].

At the end of 2020 Europe had 3,642 CNG filling stations, 332 LNG filling stations, 32,019 LPG filling stations, 125 hydrogen filling stations, approximately 140,000 filling stations for gasoline and diesel, as well as 199,250 normal charging points and 24,987 fast charging points for road transport [EAFO (2021a); WKO (2021)].

2.3 Transport volumes

The stock of vehicles described in Section 2 results in transport volumes for passengers and freight in Germany as shown in Figure 2-10 and Figure 2-11. A total of 1,244 billion passenger kilometers were traveled in 2019. This represents an increase of 5 % in the past ten years. Private motorized transport (cars and motorcycles) accounted for the bulk of passenger traffic, at 73.7 % or 917 billion passenger kilometers. Public transport (public road, rail and air transport) accounted for only a fraction of this, at 20.3 % or 250 billion passenger kilometers. As much as 6.1 %, or 76 billion passenger kilometers, were covered entirely on foot or by bicycle without an external drive. [KBA (2021m)] Volumes for global passenger transport in 2015 amounted to over 50,000 billion passenger kilometers [SuM4All (2017)].

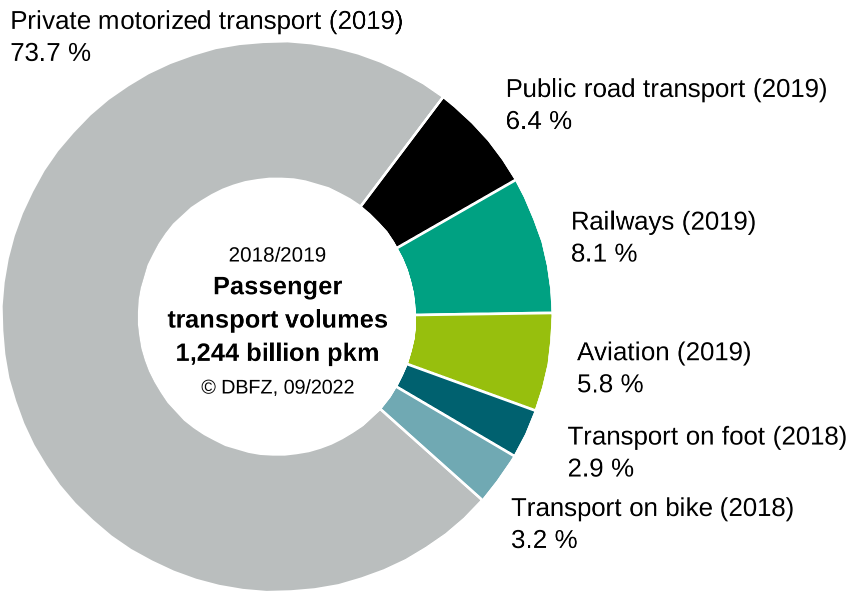


Figure 2-10 Passenger transport volumes in Germany in 2018/2019. Note: pkm stands for passenger kilometer, data based on [KBA (2021m)]

Volumes for freight transport in Germany are dominated by international water-born navigation (between ports in the Federal Republic of Germany and to and from foreign ports, including maritime transport between inland ports). The latest statistics, published in 2013, show transport volumes of 1,983 billion metric ton-kilometers. Road freight made up 18.7 %, amounting to nearly 500 billion metric ton-kilometers in 2019, while the energy-efficient domestic modes of transport, such as rail and domestic water-borne navigation, accounted for only 5 % (133 billion metric ton-kilometers) and 1.9 % (50 billion metric ton-kilometers) respectively. In the past ten years, volumes for freight transport have increased by 35 %. [KBA (2021m)] The volume of global freight transport in 2015 was approximately 120,000 billion metric ton-kilometers [SuM4All (2017)].

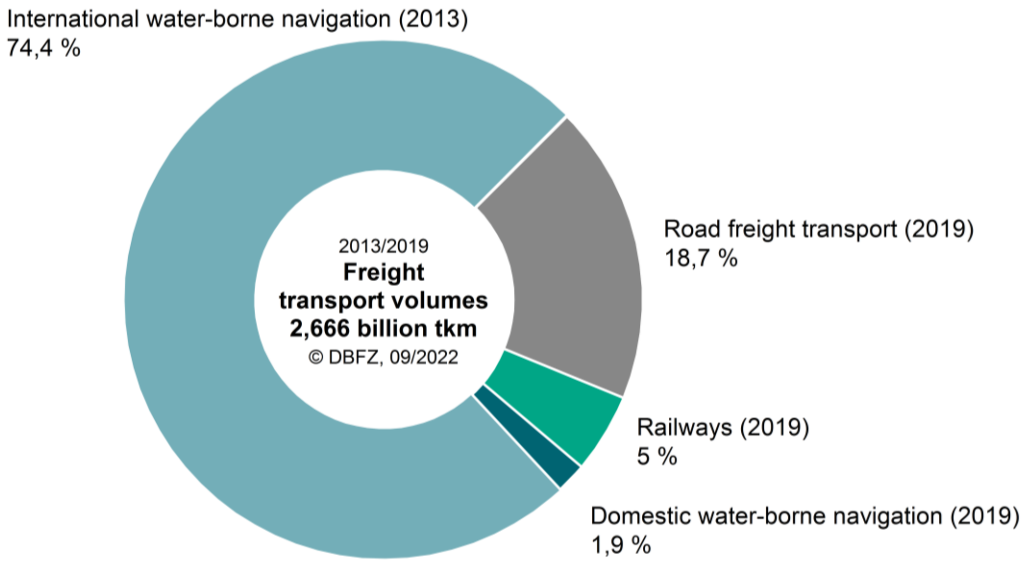


Figure 2-11 Volumes of freight transport in Germany in 2013/2019. Note: tkm means metric ton-kilometer, data based on [KBA (2021m)]

2.4 Final energy consumption

The strong growth in the number of vehicles in use and transport volumes in recent years is only reflected to a limited degree in the final energy consumption of the transport sector. From 2009 to 2019, energy consumption increased by 8 % to 2,739 PJ [KBA (2021m)]. Of this, 465 PJ was consumed by international transport (maritime shipping and cross-border aviation) [Eurostat (2021k)]. Figure 2-12 shows the final energy consumption for transport since the founding of the Federal Republic of Germany. It is easy to see that private motorized transport (cars and motorcycles) has been the particular driving force behind the increase in energy consumption and that a certain stagnation has set in since 2000. This coincides historically with the introduction of the first European regulations that limited fuel consumption (e.g., limiting CO_2 emissions from new passenger cars in accordance with 1753/2000/EC). Road transport made up the highest percentage in 2019 at 83 %, followed by aviation (16 %). When consumption based on mode of transport is compared with transport volumes, the high percentage of aviation and the low percentage of rail transport in final energy consumption is particularly striking.

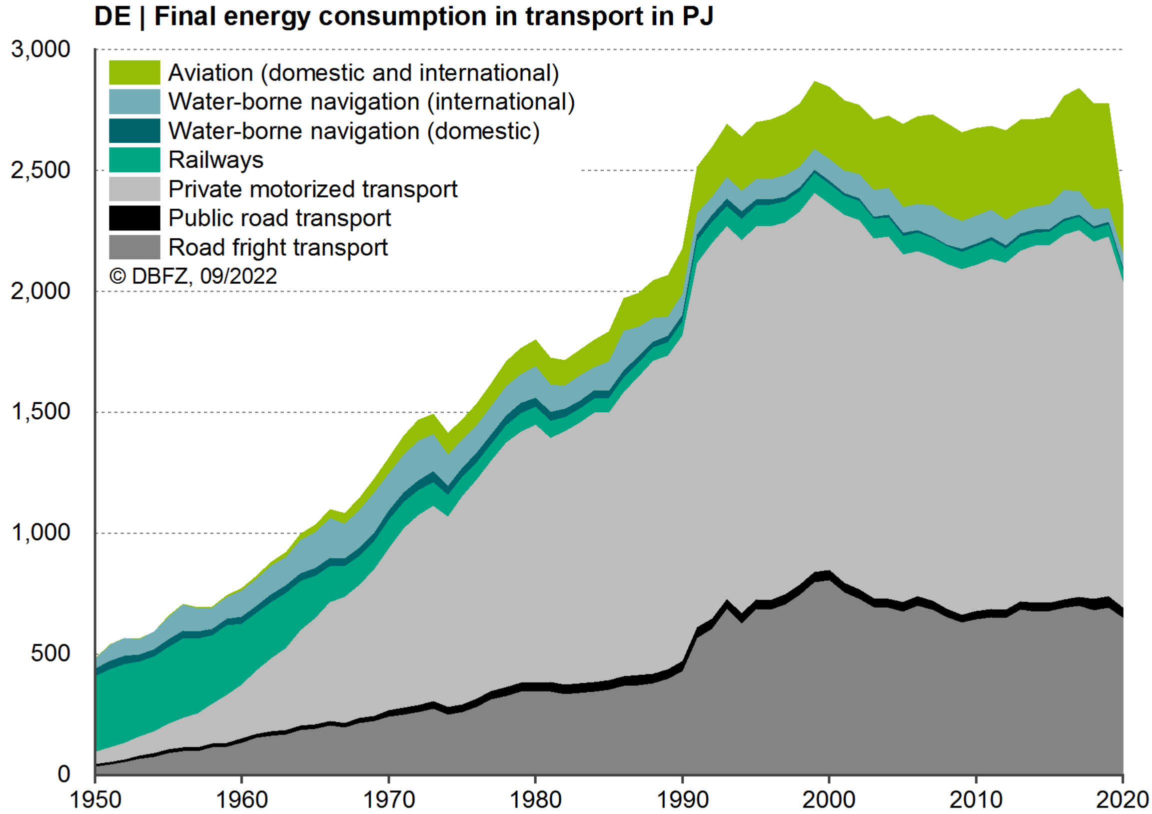


Figure 2-12 Final energy consumption in transport for Germany from 1950 to 2019, broken down by transport sector in Germany incl. international transport for aviation and shipping, up to 1990 for the Federal Republic of Germany. Data based on [Enderlein (1991); KBA (2021m)]

When broken down by energy carrier, only around 5 % of the final energy consumption was of non-fossil origin in 2019 (liquid biofuels, biomethane and electricity from renewable sources). Fossil diesel fuel covers most of the demand from road freight, private motorized transport, and rail and inland waterway transport, at over 1,400 PJ (Figure 2-13). [KBA (2021m)]

Further information on final energy consumption, broken down by energy carrier, can be found in Section 5.5. The distribution of energy carriers at the European and global level is similar. In Europe (EU-27), transport (incl. international transport) consumes 15.7 EJ, with fossil fuels making up 96 %. Globally, this amounts to 121 EJ, with more than 96 % of fossil origin. [Eurostat (2021k); IEA (2021d)]

With a world population of 7.7 billion people, this corresponds to an energy consumption of 15.8 GJ per person per year, or 450 liters of diesel fuel equivalent. In comparison, consumption in Germany is 33.4 GJ or 950 liters of diesel fuel equivalent. [IEA (2021d)]

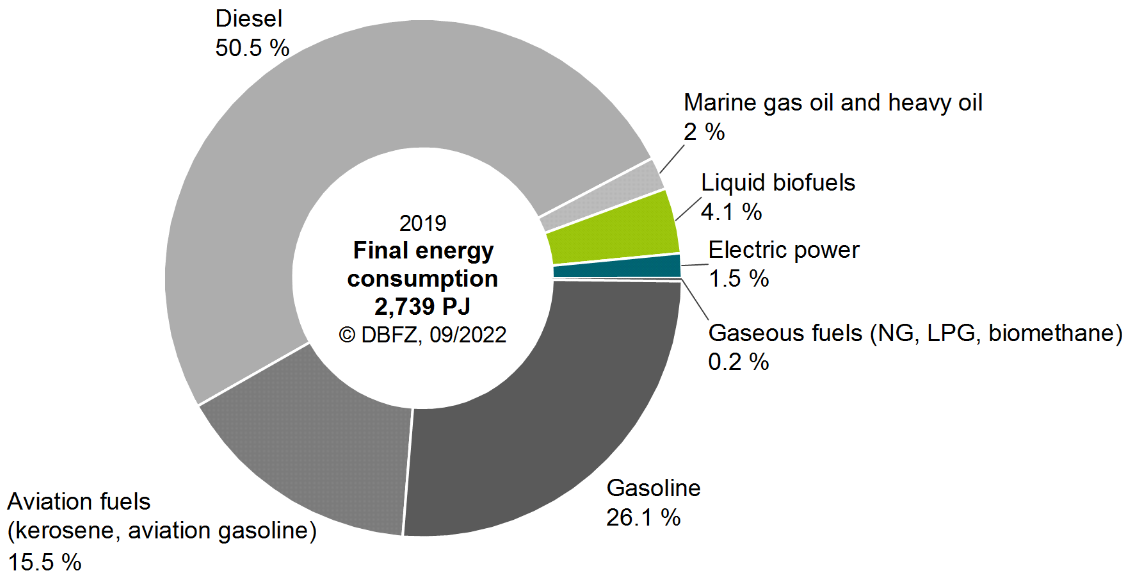


Figure 2-13 Final energy consumption in the transport sector for Germany in 2019, broken down by energy carrier. Data based on [KBA (2021m)]

2.5 Greenhouse gas emissions

GHG emissions from transport are recorded in accordance with the National Inventory Report (NIR) of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC). This means that only CO_2 emissions from fossil fuels and other greenhouse gases (including methane and nitrous oxide) that are directly released by vehicles are recorded. Conversely, GHG emissions that are generated by renewable energy carriers and electricity in the transport sector are not included. In the transport sector, carbon dioxide is the primary greenhouse gas as it, along with water, is the main product of fuel combustion in the internal combustion engine. The other greenhouse gases are air pollutants and are generally in the part per million range after suitable exhaust gas treatment. Further explanations on the distinction between the various system boundaries in the context of the RED II and NIR are presented in Section 7.

Greenhouse gas emissions from domestic transport have remained virtually unchanged since 1990. In 2019, a total of 163 million metric tons of CO_2 equivalents were released by domestic transport (Figure 2-14). This quantity breaks down into 161 million metric tons of CO_2 equivalents for CO_2 and 2 million metric tons of CO_2 equivalents for the remaining greenhouse gases. The percentage for international transport (bunkering for maritime shipping and international aviation) increased by 80 % to 33 million metric tons of CO_2 equivalents over the same period. In the EU-27, a total of 835 million metric tons of CO_2 equivalents were released in 2019 by domestic transport (+24 % compared to 1990), and another 271 million metric tons of CO_2 equivalents were released by international cross-border transport (+74 % compared to 1990). According to the International Energy Agency (IEA), a total of 8.3 billion metric tons of CO_2 were released globally by transport (as of 2018). Based on the current trend, national targets (Climate Change Act) and international targets (EU: Green Deal, global: Paris Climate Agreement) are not achievable, at least by 2030. [Eurostat (2021j); IEA (2021b); UBA (2021a)]

The dominance of road transport is revealed when greenhouse gas emissions are broken down by the various modes of transport (Figure 2-15). Inland shipping, national aviation and rail transport contribute comparatively little to the total amount of greenhouse gas emissions.

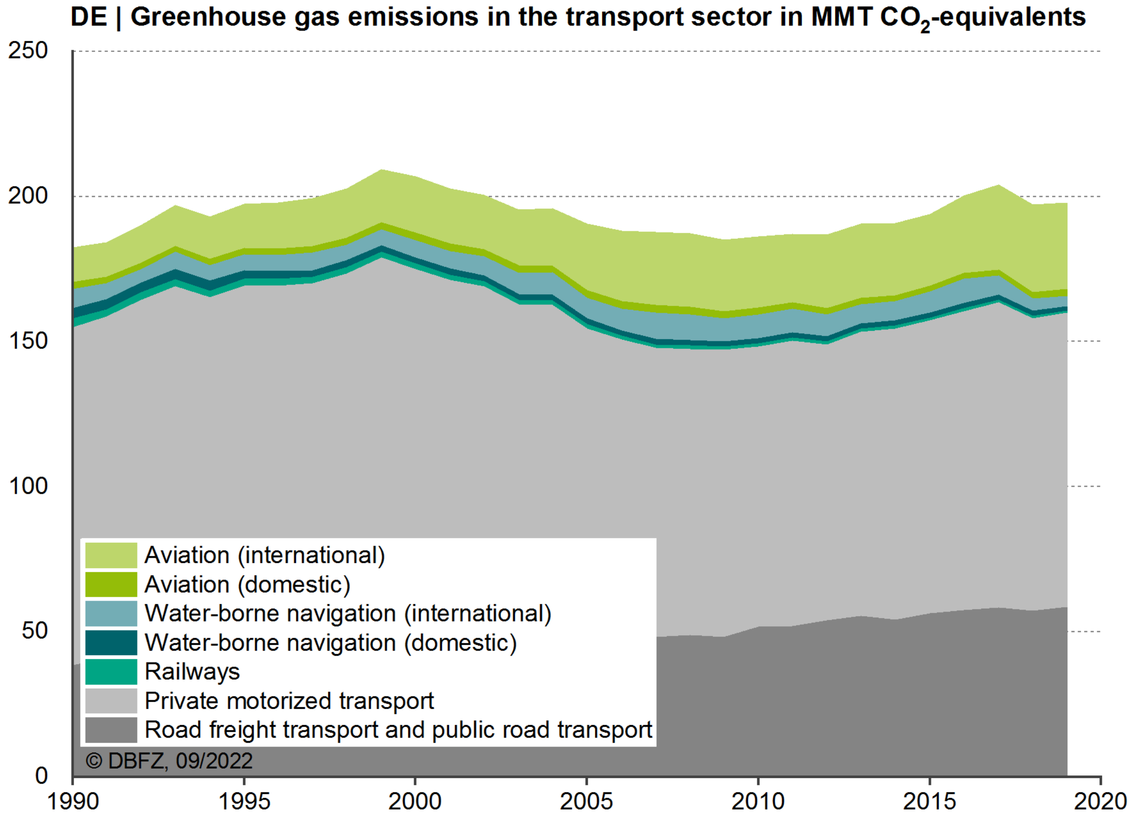


Figure 2-14 Greenhouse gas emissions in the transport sector for Germany, broken down by national and international transport (bunkering for maritime shipping and cross-border aviation). Note: private motorized transport includes passenger vehicles and motorcycles, data based on [Eurostat (2021j)]

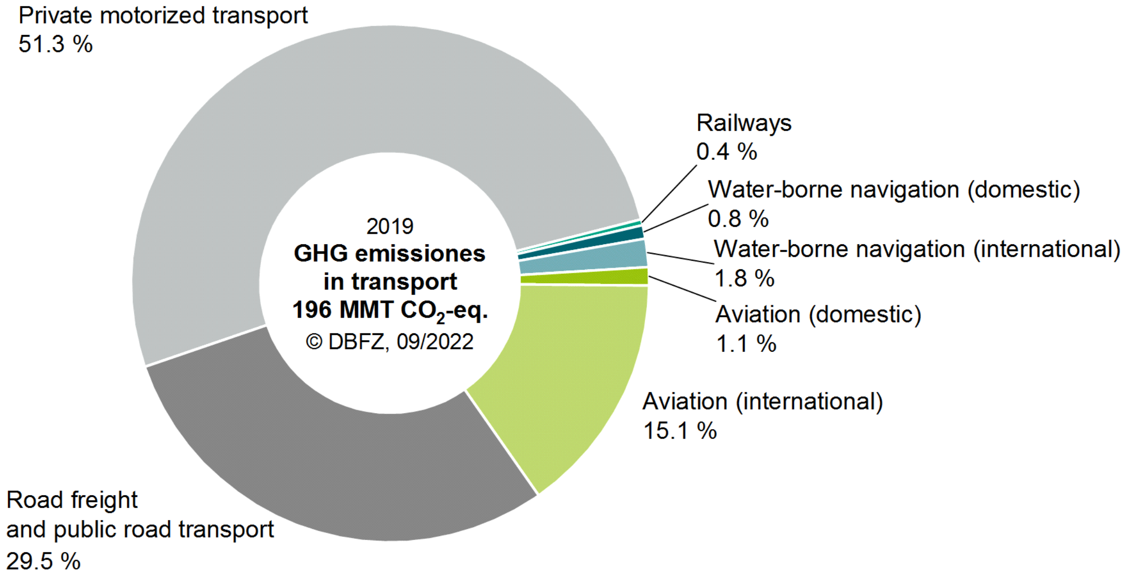


Figure 2-15 Greenhouse gas emissions in transport for Germany, broken down by mode of transport. Note: private motorized transport includes passenger vehicles and motorcycles, data based on [Eurostat (2021j)]

2.6 Future developments

2.6.1 Long-term development prospects | transport scenarios for 2030 and 2050

Numerous studies and investigations examine Germany's energy demand and GHG emissions in a timeframe up until 2050. According to the Climate Change Act, Germany should be climate neutral by then (or according to the amendment of May 12, 2021, by 2045). Modeling usually accounts for the fact that there are varying social, political and legal frameworks and a resulting demand for energy and raw materials.

The results of individual scenarios of the following studies are presented below with regard to energy demand and the development of Germany's stock of vehicles:

- Agora Energiewende: Towards a Climate-Neutral Germany by 2045 [Prognos (2021)],
- UBA: Resource-Efficient Pathways to Greenhouse-Gas-Neutrality – RESCUE (GreenLate and GreenSupreme scenario) [Purr (2019)] and
- dena Study Integrated Energy Transition [Bründlinger (2018)]

The two scenarios with the most extreme assumptions were selected from both the RESCUE study and the dena study. The studies were selected based on the following three criteria:

- Greenhouse gas neutrality by calendar year 2045 or 2050,
- Germany as the region being studied and
- Publication after January 1, 2016.

Figure 2-16 shows the future energy demand of the selected scenarios for the years 2030 and 2045 or 2050. It is evident in all scenarios that energy consumption in transport must drop substantially in order to meet the environmental goals of climate neutrality in 2045 or 2050. In addition, there is an urgent need to implement the individual measures since consumption must be reduced in the next 25 years at the same rate as it increased between 1960 and 1990.

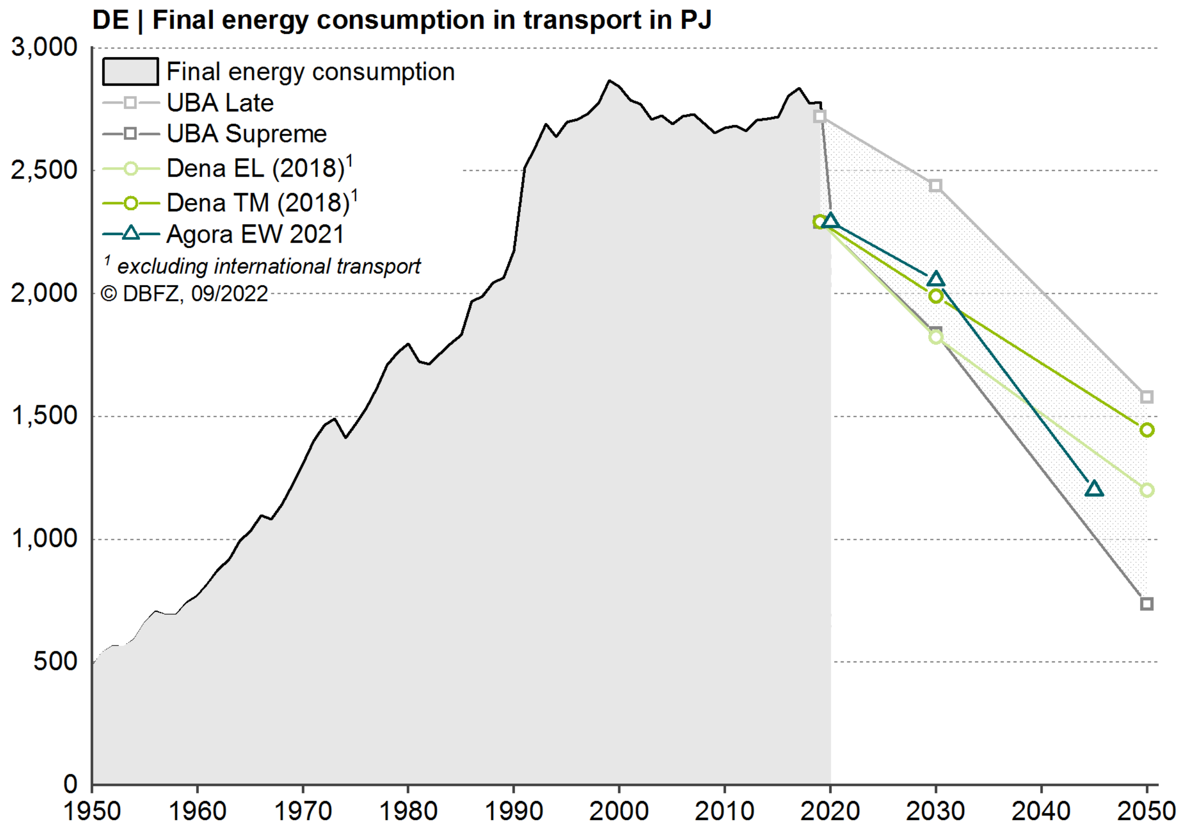


Figure 2-16 Final energy demand in German transport based on various scenarios for the years 2030, 2045 and 2050. Data based on [Bründlinger (2018); KBA (2021m); Prognos (2021); Purr (2019)]

As the study results shown in Figure 2-17 reveal, the direct and indirect electrification (hybridization and fuel cell drive systems) of passenger vehicles is now a largely uncontroversial requirement for achieving greenhouse gas neutrality by 2045 or 2050.

The electrification of road haulage, and here especially of heavy long-distance haulage, represents a significantly greater challenge. One study on this issue assumes that the expansion of a basic network of overhead power lines of 3,200 to 4,000 km in Germany, as well as suitable framework conditions, can encourage the establishment of a stock of 60,000 to 70,000 overhead line hybrid trucks and semi-trailer trucks (BEV and HEV). In 2030, the additional demand of 5 to 6 TWh of electricity resulting from this would be offset by a 1.5 million m^3 reduction in diesel fuel. Investment costs are estimated at 1.9 million euros/km (resulting in 7.6 billion euros for 4,000 km) and depreciation and maintenance costs of 72,600 euros/km/a (plus costs for contact wire wear). [Jöhrens (2020)] Other sources estimate investment costs of 10.2 to 12.2 billion euros for a 4,000 km network [Hacker (2020)]. A European-wide approach, which is urgently needed for heavy road haulage, is only being pursued to a limited degree.

Agora Energiewende's scenario therefore assumes that the percentage of registrations for new trucks and semi-trailer trucks with alternative drive systems will increase sharply from 2025 onward, so that by 2030, 18 % of the vehicles in this segment will be electric and around 3 % will be powered by fuel cells. By 2045, the stock will have leveled off to around 30 % fuel cell and 70 % electric vehicles. Of the electric vehicles, the proportion of battery-electric trucks, overhead line hybrid trucks or a combination of both depends on the policy framework and the development of a corresponding infrastructure (charging points and/or overhead lines). [Prognos (2021)]

Some of the investments and expansion targets called for in the studies have to be implemented by 2030 in order to comply with the pathways to GHG neutrality and stand in contrast to major transport projects currently under construction, such as Stuttgart 21, Berlin Brandenburg Airport, and the northern railway access route to the Brenner Base Tunnel.

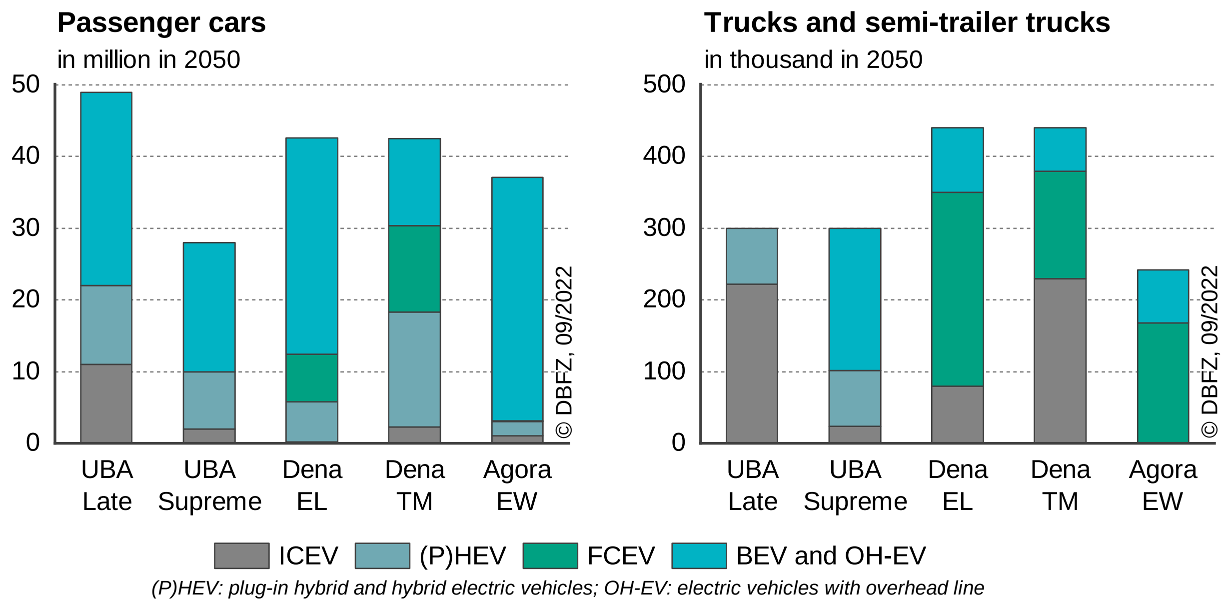


Figure 2-17 Stock of passenger vehicles and trucks (incl. semi-trailer trucks) in 2050, broken down by drive system. Note: own assumption for UBA Late and UBA Supreme of 300 thousand trucks and semi-trailer trucks by 2050, data based on [Bründlinger (2018); Prognos (2021); Purr (2019)]

2.6.2 Short-term climate goals | scenarios up to 2030 in the context of the GHG quota

The goal of climate neutrality by 2045 means that the transport sector faces the specific challenge of enabling sustainable transportation and mobility. Decisive factors here include the development of final energy consumption and the drives and energy carriers used by the various modes of transport. In addition to measures relating to traffic avoidance and modal shifts, the approaches focus on the use of alternative drives and renewable energy carriers.

A key instrument for promoting the use of renewable energy sources in transport is the Renewable Energy Directive (RED, see Section 1.4) and its implementation at the national level in the form of the greenhouse gas quota (GHG quota for short, see Section 1.5.1). It obliges fuel distributors (so-called obligated parties) to measure the GHG emissions of the fuels they place on the market and to reduce these emissions by various means.

The German government decided in 2021 to further develop the GHG quota, which now provides an important framework for renewable energy in the transport sector in Germany until 2030.

Below is a brief description of how the fulfillment of the quota could develop over this period under the transport scenarios outlined in Section 2.6.1. This result is, in turn, compared with the annual emission targets of the Climate Change Act, the RED requirements [Richtlinie (EU) 2018/2001 (2018)], and the current status of the RED amendment [COM(2021) 557 (2021)] (see also Section 1).

The comparison of the scenarios is intended to span a specific corridor up to 2030, if possible, which is why the two selected scenarios show a clear difference in their levels of ambition. The two scenarios are considered in more detail below based on assumptions of two studies about structural development in the transport sector:

a) **LESS AMBITIOUS SCENARIO**: GreenLate scenario from the UBA's RESCUE study [Purr (2019)], which was based on delayed action to avoid climate change, and

b) **AMBITIOUS SCENARIO**: scenario from Agora Energiewende's Climate neutral Germany 2045 [Prognos (2021)].

Both scenarios were extended by the assumption that green hydrogen will be used to a greater extent in 2030: about 2 GW of installed electrolysis capacity in accordance with the hydrogen strategy (equivalent to about 20 PJ[4] of hydrogen), which will be used directly as fuel and in refineries.

The **LESS AMBITIOUS SCENARIO** assumes a moderate reduction in final energy demand in road transport and a moderate increase in electricity use through electromobility to 17 TWh (approx. 60 PJ) in 2030. As Figure 2-18 shows, this results in a rather significant demand for advanced fuels amounting to around 200 PJ. The fulfillment options for this are limited by various factors:

- Biodiesel (FAME) is only marginally suitable for this from a technological point of view and as a result of the defined feedstocks,
- Bioethanol offers a promising option in the form of lignocellulosic ethanol, but numerous commercial-scale plants are still under construction or projected (see Section 3.3). Furthermore, the quantities that can be blended into E5 and E10 in Germany are currently limited,
- HVO/HEFA is well suited from a technological point of view to process some of the defined feedstocks and is much less limited from a technical perspective with regard to blending due to its fuel properties (see Section 6). Significant production capacities have already been established internationally or are under construction and projected,
- Methane can be provided through various technologies that are based on biomass or electricity and blended with up to 100 % fossil-based CNG or LNG. Biomass-based methane via anaerobic digestion is an established technology, especially in Germany, and can also efficiently utilize large portions of the defined feedstocks for advanced biofuels.

Renewable methane can only be deployed in the transport sector and thus be counted towards the quota if it is actually used as a fuel in the form of CNG and LNG.

[4] According to the National Hydrogen Strategy: 4,000 full-load hours per year and 70 % electrolysis efficiency (BMWi (2020)).

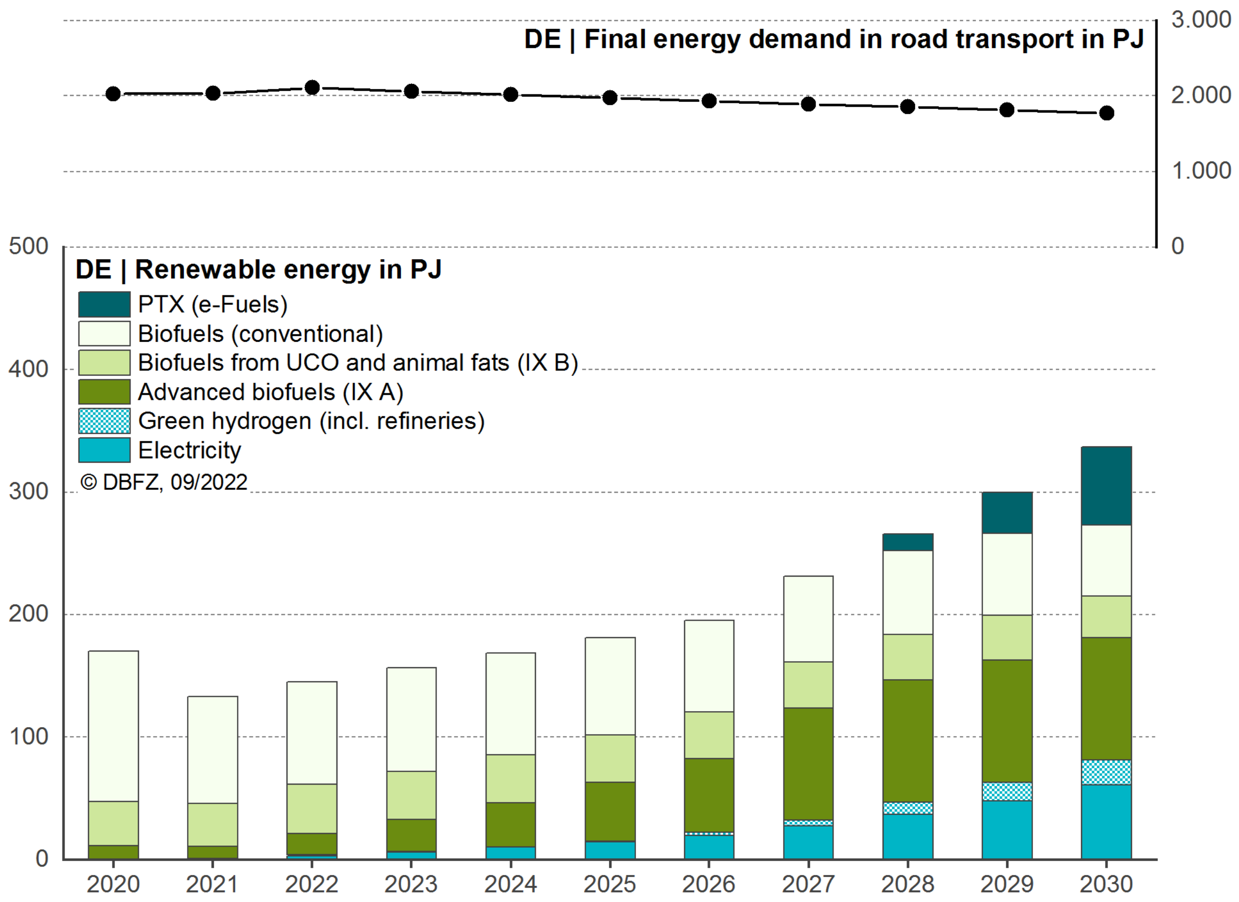


Figure 2-18 Quota fulfillment from 2020 to 2030 in a less ambitious scenario. Note: example calculation based on [Naumann (2022)].

The emission budget, which is defined for the transport sector by the Climate Change Act, totals 1,034 million metric tons of CO_2-eq. for 2022 to 2030. When reduced by 5 million metric tons of CO_2-eq. per year for other forms of national transport (as in the year 2018, see Table 1-2), a budget of 994 million metric tons of CO_2-eq. remains for the years 2022 to 2030 for road transport within the current scope of the GHG quota.

In this scenario, the budget is clearly exceeded for the years 2022 to 2030 by a total of 148 million metric tons of CO_2-eq.

As Table 2-1 clearly shows, the Climate Change Act is also the most relevant benchmark for the GHG quota. While the target of the Climate Change Act is clearly missed, achieving the RED II targets of 14 % renewables in road and rail transport by 2030 and 13 % GHG abatement for the entire transport sector by 2030 [COM(2021) 557 (2021)] is non-critical.

Table 2-1 Key figures and contexts for the example calculation for the possible quota fulfillment in 2020 to 2030 for the less ambitious scenario. Note: example calculation based on [Naumann (2022)]

	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Road transport | energy carrier in PJ											
Energy demand	2,027	2,033	2,109	2,062	2,019	1,975	1,934	1,893	1,852	1,811	1,771
incl. RE[a]	*170* *8 %*	*133* *7 %*	*144* *7 %*	*153* *7 %*	*164* *8 %*	*173* *9 %*	*184* *10 %*	*216* *11 %*	*242* *13 %*	*267* *15 %*	*305* *17 %*
incl. biofuels	*170*	*132*	*142*	*150*	*158*	*165*	*171*	*197*	*199*	*195*	*192*
Context: Climate Change Act (KSG) | GHG emissions in million metric tons of CO_2-eq. for road transport (as per IPCC – World Climate Council)											
GHG as per scenario			146	142	138	134	130	124	119	114	108
KSG target			134	129	123	118	112	107	100	91	80
Difference			*+12*	*+13*	*+15*	*+16*	*+18*	*+17*	*+19*	*+23*	*+28*
Context: Renewable Energy Directive (RED II)											
RE % as per RED			10 %	11 %	13 %	14 %	17 %	21 %	25 %	28 %	33 %
Context: RED recast (recommendation by the European Commission on July 14, 2021) | All transport[b]											
Energy demand											2,400
RE % as per RED											14 %

[a] excl. H_2 in refineries, [b] incl. international transport

The **AMBITIOUS SCENARIO** is based on assumptions about the structural development of the transport sector according to the Agora Energiewende study. However, due to the very strong growth in electromobility, no conventional biofuels would be used from 2025 onwards in accordance with the quota defined in Section 37a of the Federal Immission Control Act (BImSchG). Furthermore, from 2029 onwards only advanced biofuels would be used in accordance with the sub-quota. However, based on the adjustment mechanism defined in Section 37h BImSchG, the quota would be adjusted early on (starting in 2024) to 28.15 % (adjustment factor 0.5) and to 34.09 % (AF 1.5) by 2030. The adjustment factor used to adjust the quota ultimately has a substantial impact on the use of other fulfillment options and thus on the substitution of fossil fuels and the achievability of the climate targets under the Climate Change Act. Figure 2-19 shows an example calculation for the possible fulfillment of the GHG quota by 2030 with an adjustment factor of 1.5.

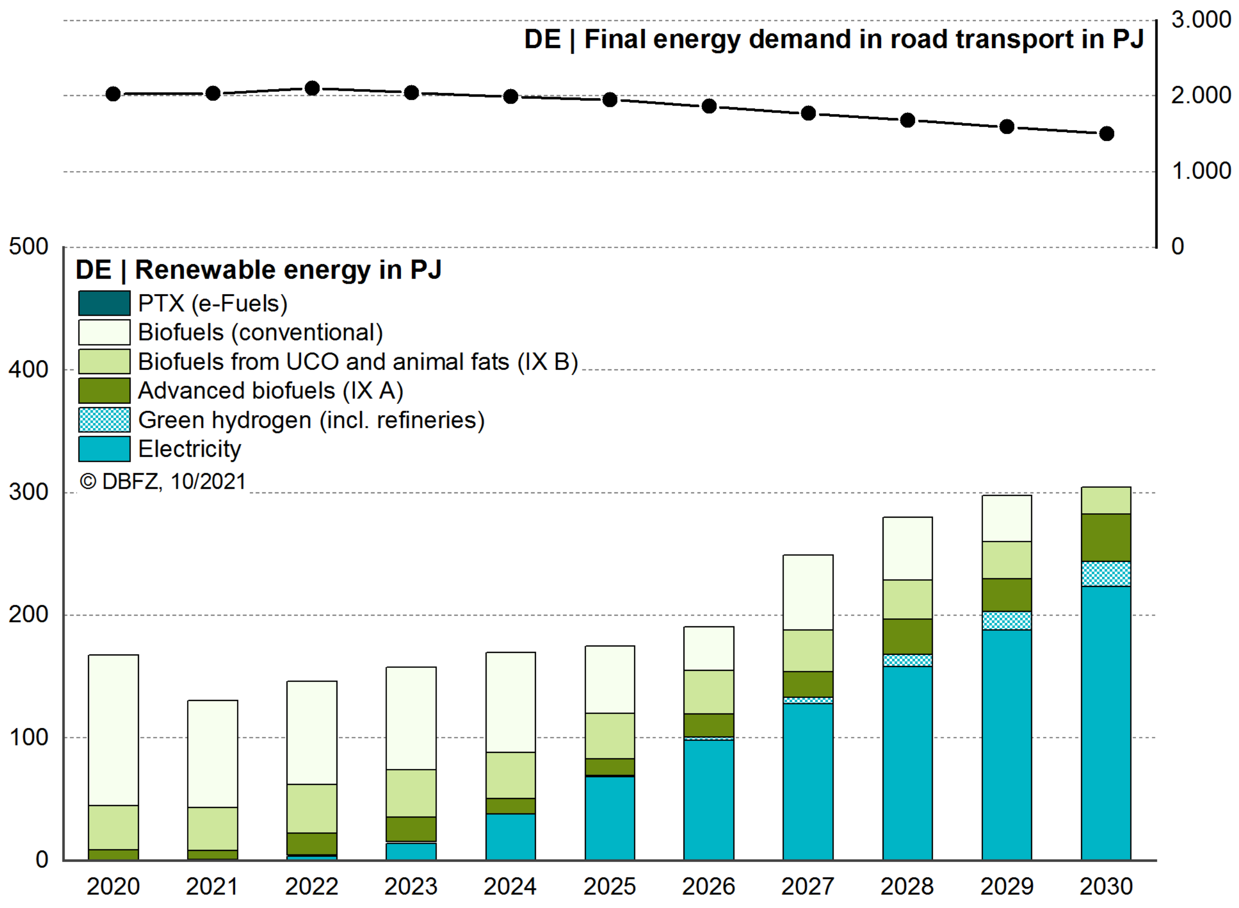


Figure 2-19 Quota fulfillment from 2020 to 2030 in the ambitious scenario. Note: example calculation based on [Naumann (2022)]

The emissions budget for the years 2022 to 2030 under the Climate Change Act is exceeded in every case, even in this ambitious scenario. The degree of this exceedance again depends on the factor used for the adjustment mechanism (between 0.5 and 1.5 according to BImSchG):

- 90 million metric tons of CO_2-eq. exceedance for an adjustment with factor of 0.5,
- 77 million metric tons of CO_2-eq. exceedance for an adjustment with factor of 1.0,
- 65 million metric tons of CO_2-eq. exceedance for an adjustment with factor of 1.5.

Achieving the RED II targets of 14 % renewables in road and rail transport by 2030, and a 13 % GHG abatement for the overall transport sector by 2030 [COM(2021) 557 (2021)] is again non-critical.

Table 2-2 Key figures and contexts for the sample calculation of the possible quota fulfillment in 2020 to 2030 for the ambitious scenario. Note: example calculation based on [Naumann (2022)]

	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Road transport | energy carrier in PJ											
Energy demand	2,027	2,033	2,105	2,044	1,993	1,950	1,860	1,769	1,679	1,589	1,504
incl. RE[a]	*170* *8 %*	*132* *7 %*	*143* *7 %*	*149* *7 %*	*152* *8 %*	*146* *7 %*	*152* *8 %*	*203* *11 %*	*227* *14 %*	*243* *15 %*	*254* *17 %*
incl. biofuels	170	132	141	142	131	106	90	116	112	95	61
Context: Climate Change Act (KSG) | GHG emissions in million metric tons of CO_2-eq. for road transport (as per IPCC)											
GHG scenario			146	140	136	132	124	113	105	97	90
KSG target			134	129	123	118	112	107	100	91	80
Difference			*+12*	*+11*	*+13*	*+14*	*+12*	*+6*	*+5*	*+6*	*+10*
Context: Renewable Energy Directive (RED II)											
RE % as per RED	10 %	9 %	10 %	11 %	13 %	16 %	21 %	29 %	37 %	46 %	57 %
Context: RED recast (recommendation by the European Commission on July 14, 2021) | All transport[b]											
Energy demand											2,053
RE % as per RED											18 %

[a] excl. H_2 in refineries, [b] incl. international transport

Compared to Agora Energiewende, the Dena study [dena (2021c)] assumes an identical total energy demand of about 535 TWh (1,930 PJ) for the year 2030 which includes international transport. On the other hand, it assumes a significantly lower amount of electricity used in transport by 2030: 55 TWh instead of 75 TWh. Accordingly, the challenges relating to the achievement of the quota as well as the climate budget in the years 2022 to 2030 are again likely to be disproportionately higher.

Conclusion

The long-term climate goal of greenhouse gas neutrality in transport by 2045 is tied to concrete and comprehensive infrastructure changes. Experience in recent years of specifically promoting electrification, especially in the passenger vehicle sector, has shown the sluggishness that must be expected for the existing stock of vehicles, even when ambition levels are high. However, in addition to the goal of GHG neutrality by 2045, there is also an overall limited emissions budget until 2045 for the 1.5 °C target, resulting in a very ambitious reduction pathway in the coming years. In addition to all of the measures taken to avoid and shift transport, any available short-term option should be used, especially for areas that are difficult to electrify, above all heavy commercial vehicles as one of the main GHG emitters in transport.

For heavy-duty vehicles with internal combustion engines (ICEVs), for example, emissions can be significantly reduced through

a) (advanced) renewable liquid fuels that directly replace fossil liquid fuels,

b) advanced renewable gas fuels that indirectly replace fossil liquid fuels, but at a low threshold level, and

c) partial electrification of the drive train (e.g., through mild hybrid technologies) and thus an increase in the effectiveness of the drive system.

The aim of a minimum of 2.6 % advanced biofuels by 2030 includes 41 or 45 PJ depending on the scenario. Without a sufficient amount of gas fuel in the transport sector, providing the required quantities of advanced liquid fuels (HVO/HEFA or ethanol based on feedstocks listed in Annex IX A of the RED or Annex 1 of the 38th BImSchV) is likely to become much more difficult. Even if the mobilizability of the high-tech feedstock potentials outlined in Section 4 cannot be conclusively assessed, it remains to be seen how quickly production capacities will be geared to this demand.

With regard to the long-term objectives, policies also set initial priorities for renewable energy carriers in maritime and air transport (Section 1.6.1).

The calculations fundamentally show that, in order to achieve climate targets in the transport sector, all measures, whether subsidies or legal requirements, must be well coordinated if a compliance gap is to be avoided. Continuous monitoring and consistent readjustment will be indispensable, as all options must be deployed ambitiously in order to achieve the targets.

3 Production technologies for supplying renewable fuels

Stephanie Hauschild, Gabriel Costa de Paiva, Ulf Neuling, Tjerk Zitscher, Jakob Köchermann and Kati Görsch

For more information:

Fuels from renewable resources play an important role in achieving national and global climate protection targets. While the main focus of development was initially on the production of bio-based energy sources, today e-fuels made from renewable energy are increasingly finding their way into research and demonstration projects as well.

Biomass-based production technologies are being used to supply significant amounts of the renewable fuels available on the market. Bioethanol, biomethane, biodiesel and HVO/HEFA (hydrotreated vegetable oils and hydroprocessed esters and fatty acids) remain the most important biofuels worldwide. These mature and established processes enable a stable and reliable supply of renewable energy carriers. Biofuels are also already being produced in biorefineries. In many cases, these multi-product facilities produce co-products that are used, for example, in animal feed production, in the chemical industry, and as fertilizers.

There has been a stronger push in recent years to develop and establish advanced biofuels using residual and waste materials. These heterogeneous feedstocks generate multiple challenges for renewable fuel production technologies, which is also reflected in the level of technical readiness of the individual processes. However, with a view to a circular economy, this approach shows great potential for saving valuable resources and cutting avoidable greenhouse gas emissions (GHG emissions).

E-fuels are gaseous and liquid energy carriers generated by renewable energy. In the case of hydrocarbon-based products, there is also a need for a carbon source. One particular challenge for these technologies is load-flexible operation.

3.1 An overview of the technology pathways

Renewable fuels used in transportation can be supplied in a variety of ways. The complexity of these different processes is illustrated in Figure 3-1 below.

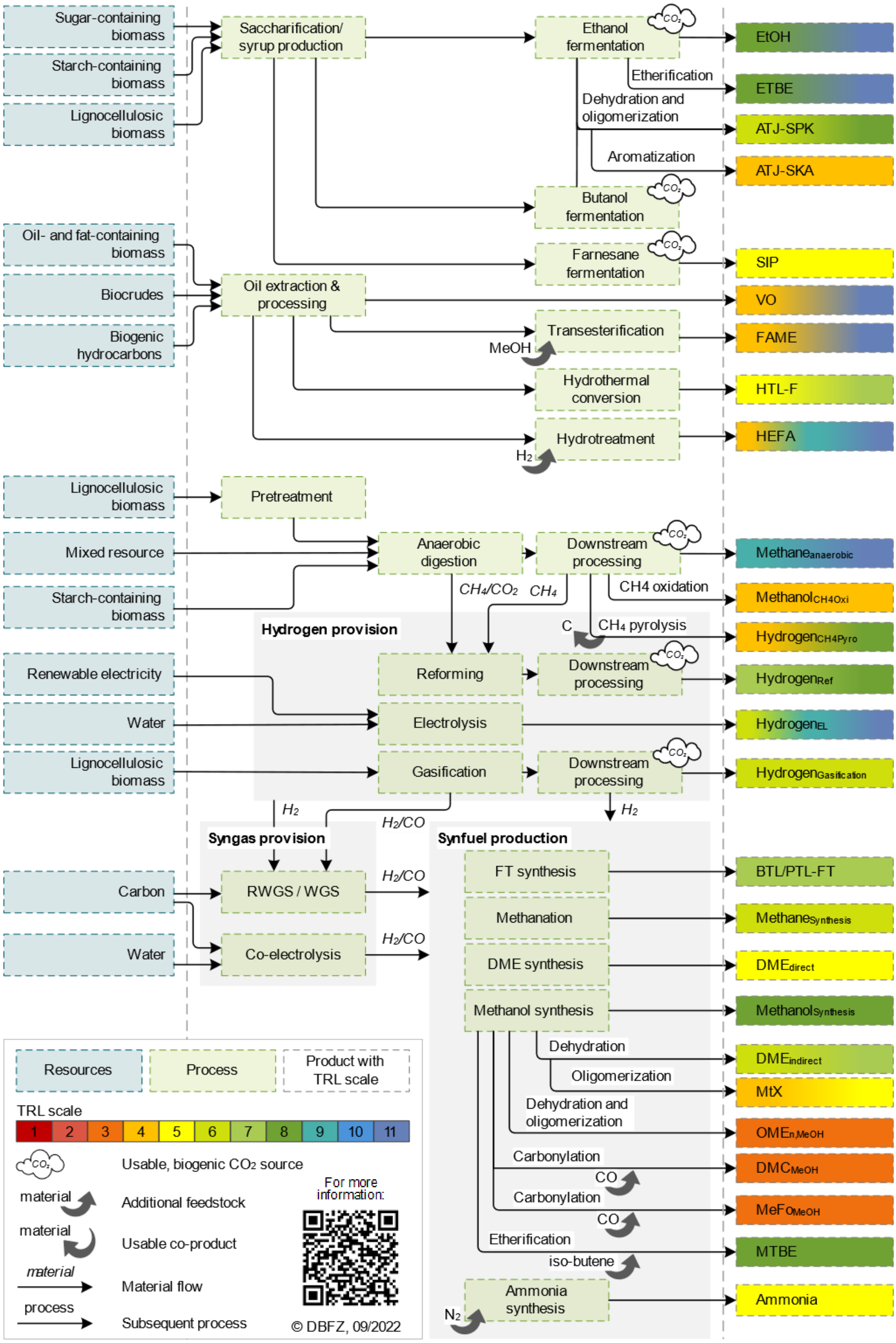


Figure 3-1 Renewable fuel supply options for transport – diagram of the different feedstocks, processes, technology readiness levels (TRL) and generated energy carriers. Note: figure is not exhaustive, CH4Oxi: methane oxidation,

CH4Pyro: methane pyrolysis, Ref: reforming, EL: water electrolysis, EtOH: ethanol, HTL-F: fuel from hydrothermal liquefaction, VO: Vegetable oil

The aim of this diagram is to connect the production technologies with the respective feedstocks, the corresponding level of technical readiness and the energy carriers that are ultimately generated. It also aims to show (potential) points of intersection and connections between the technologies.

After assessing the current level of technical readiness of the fuel production processes, this section will look at a wide range of current and future production technologies and refer to examples of initiatives as well as research and development needs. Building on this range of technologies, further information on potential feedstocks will be provided in Section 4, as well as a detailed analysis of GHG emissions and product manufacturing costs in Sections 7 and 8.

3.2 Technology readiness level

As a technology is developed, it passes through phases of research, testing and establishment on the market. Due to the various resources, stakeholders and risks involved in launching a new technology, the new technology is classified according to the development stage in which it is in. The most widely used system for this is the technology readiness level (TRL) [Héder (2017)]. Developed by NASA to introduce new technologies for its missions, it has been extended to other sectors and is used, for example, by the IEA and in the European Union as part of its Horizon program [Europäische Union (2014); IEA (2020)]. The system is divided into nine stages: basic research (TRL 1 to 2), applied research (TRL 2 to 5), technical development (TRL 5 to 8), and market readiness (TRL 8 to 9) [Frerking (2014)]. The IEA has also introduced two further levels that reflect market integration (TRL 10) and market stability (TRL 11) [IEA (2020)].

When a new fuel is launched on the market, the development process requires additional levels to those described by the TRL, such as fuel certification and testing to ensure it can be used in vehicles ("fit for purpose"). To solve this problem, the Commercial Aviation Alternative Fuels Initiative (CAAFI) developed the fuel readiness level (FRL) to capture the requirements for the development and market launch of alternative aviation fuels [CAAFI (2009)]. The system has nine stages and includes the development cycles for fuel production (FRL 1-5), fuel certification (FRL 6 to 7), suitability and compatibility for use in aircraft (FRL 4 to 7), and commercialization of the production technology (FRL 8 to 9) [CAAFI (2013)].

While the FRL system is specific to the aviation sector, it can also be used, with minor modifications, to describe the progress of fuel development in other sectors. Therefore, TRL and FRL can be jointly used to describe the readiness level of a fuel production process and fuel use. However, the establishment of a fuel's production process and the establishment of a fuel's use do not occur simultaneously; Figure 3-2 shows where they overlap.

This report uses both TRLs and FRLs to describe the status quo of a fuel produced by a manufacturing technology in order to qualitatively classify its development stages. In subsequent sections, technologies and fuels are classified based on the following development stages: research (TRL 1 to 4), demonstration (TRL 5 to 8), and commercialization (TRL 9 to 11).

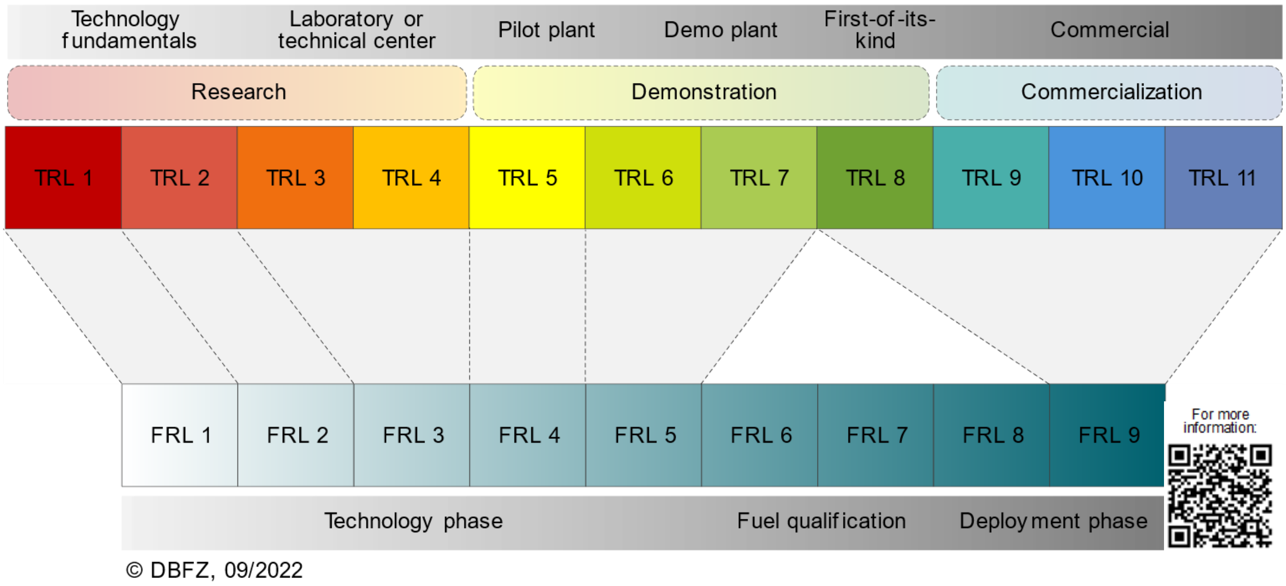


Figure 3-2 Comparison of the technology readiness levels (TRL) according to the IEA and fuel readiness levels (FRL)

3.3 Ethanol fermentation and downstream technologies

Process description

The production of bioethanol through fermentation can be divided into conventional (sugar- and starch-based) and advanced (lignocellulose-based) processes. A general process flow diagram is found in Figure 3-3. The term ethanol fermentation is used here for the processing of biogenic feedstocks under anaerobic conditions using yeast [Faria-Oliveira (2013)]. The yeast most commonly used for industrial applications is *Saccharomyces cerevisiae*, which, in the absence of oxygen, converts sugar (e.g., glucose) into ethanol and carbon dioxide. Other metabolic products, such as aldehydes and esters, are also formed during the process. The reaction temperature is between 20 and 35 °C, with the optimum temperature being around 30 °C [Parapouli (2020); Walker (2016)].

In the pretreatment step, feedstocks containing sugar are milled with water to convert the sugar to an aqueous phase. This liquid is then separated into crystalline sugar (through drying, crystallization and centrifugation) and molasses. The molasses can be used in the fermentation step. If a starch-rich feedstock (e.g., corn or grain) is used, the biomass must undergo saccharification after milling (e.g., by grinding the dry biomass) [Ramirez-Cadavid (2016)]. This process, known as mashing, takes place at increased temperatures; enzymes and water are added. The sugar-rich solutions (molasses or mash) are converted to ethanol during the fermentation process. The ethanol is then concentrated in a subsequent distillation step. The processes for converting sugar- and starch-based feedstocks also differ in terms of the distillation co-product that is to be obtained. While sugar-based processes produce vinasse, starch-based processes produce stillage. The latter can be processed into dried distillers grains with solubles (DDGS) [BDBe (2021); FNR (2021)].

Multi-feedstock plants started being established several years ago, for example in Brazil, in order to ensure that bioethanol plants are not only in use when the cultivated biomass is being harvested. Here, sugar cane is regularly processed during harvest time, and then corn is processed as an intermediate feedstock. Fermentation, distillation, and energy production benefit from higher utilization rates and the internal use of by-products to produce energy (e.g., the use of bagasse and straw from sugar cane instead of other biomass or natural gas to meet internal energy and heat requirements).

As an advanced biofuel, ethanol uses lignocellulosic feedstocks (e.g., wheat straw, bagasse). The main process steps are shown in Figure 3-3. There are many forms of pretreatment for such biomass, with steam explosion being the most advanced form for lignocellulosic biomass. However, acid or alkaline pretreatment, the organosolv process, and mechanical grinding are further examples. After pretreatment, the biomass is processed through hydrolysis of the cellulose. Here, enzymes release the fermentable sugars of the cellulose matrix, which enables subsequent fermentation and distillation [IRENA (2016)].

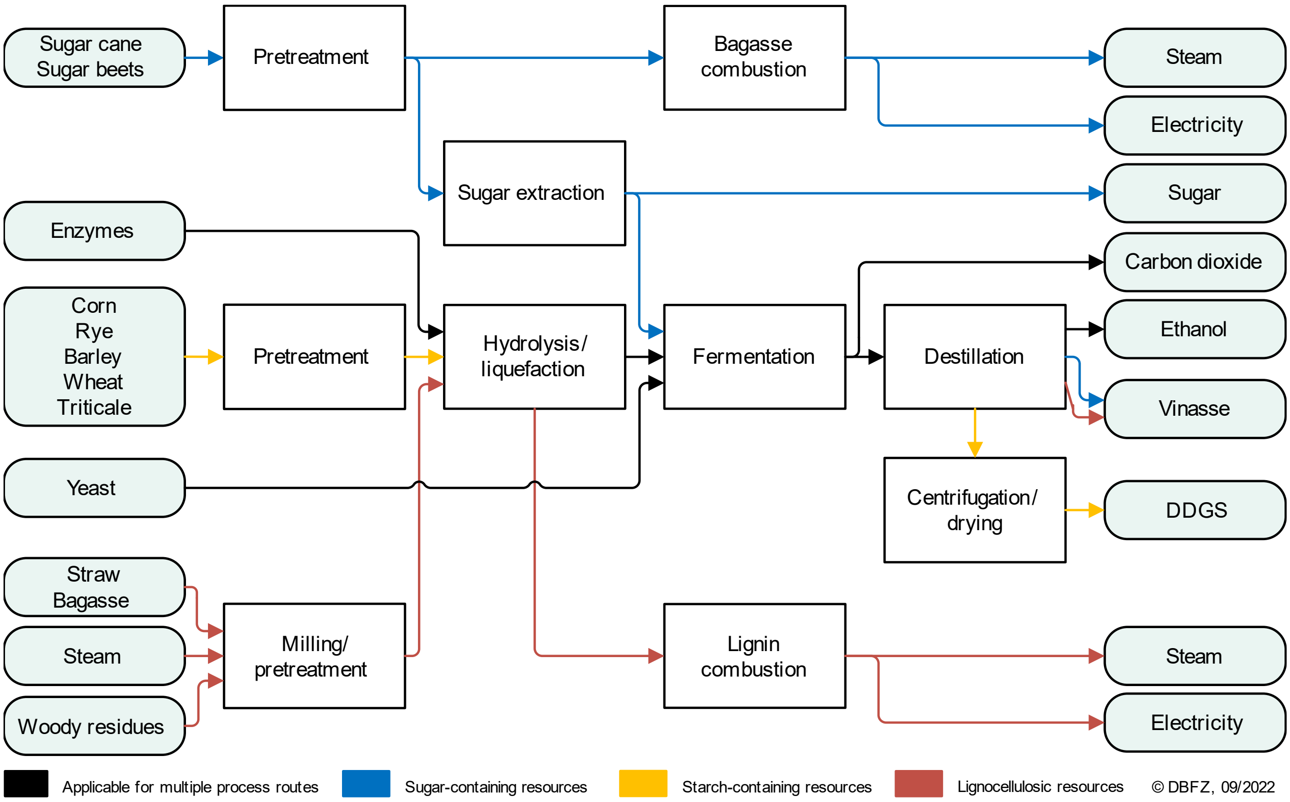


Figure 3-3 Schematic illustration of the routes for processing sugar, starch and lignocellulosic feedstocks into ethanol

Alternatively, yeast cells can be manipulated in such a way to prioritize the processing of biomass that contains sugar or starch as part of alternative metabolic pathways. This enables, for example, the synthesis of butanol or β-farnesene [Wess (2019); Yao (2020)]. β-farnesene is an alkene with 15 carbon atoms whose unsaturated bonds are hydrogenated so that the resulting farnesane can be used as a synthetic paraffinic kerosene (SPK) in accordance with Annex 3 of ASTM D7566 (synthesized iso-paraffins produced from hydroprocessed fermented sugars, SIP) [Gray (2014)]. Butanol can be used in the same way as ethanol in the alcohol-to-jet process (ATJ, Figure 3-4) by converting the alcohol into short-chain alkenes through dehydrogenation and then separating them at low temperatures or by pressure swing adsorption [Mohsenzadeh (2017)]. Oligomerization of alkenes leads to chain elongation of the molecules by a multiple of the carbon number of the respective monomers. For example, if the starting molecule is butene (C_4H_8), the product spectrum includes alkenes such as octene (C_8H_{16}), dodecane ($C_{12}H_{24}$), and higher molecules [Halmenschlager (2016); Toch (2017)]. The maximum percentage of the kerosene fraction in the product blend reported in the scientific literature is around 70 % v/v [Geleynse (2018)]. The paraffinic products, which are still unsaturated, must be treated with hydrogen and ultimately fractionated by distillation [Chuck (2016)].

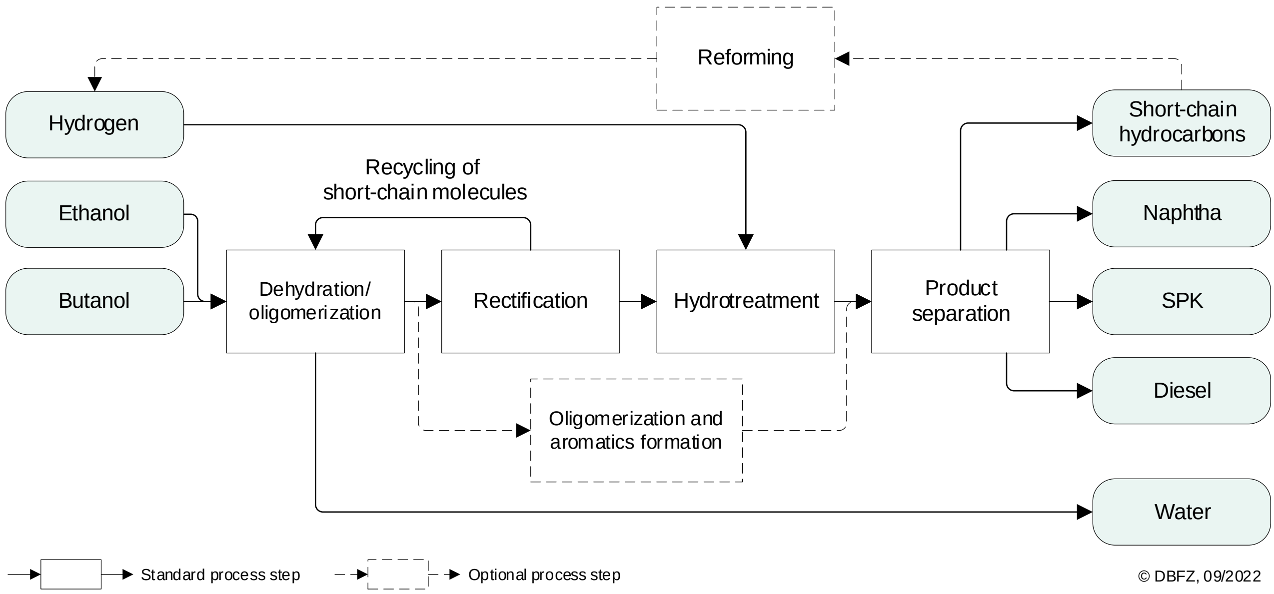


Figure 3-4 Schematic illustration of the alcohol-to-jet process. Data based on [Chuck (2016); Geleynse (2018)]

Ethyl tertiary-butyl ether (ETBE) is produced by a reaction of ethanol with isobutylene. The reaction is an etherification in which ethanol combines with the middle carbon atom of isobutylene. This occurs at low temperatures (30 to 80 °C), at pressures of 5 to 15 bars, and in the presence of an acidic catalyst [Jochen (2005); Menezes (2008)]. When the ethanol is of biogenic origin, the designation "bio-ETBE" is used [ETIP Bioenergy (2021d); Tretbar (2018)].

EXAMPLES OF COMPANIES AND INITIATIVES

One of the largest plants that process sugar cane into ethanol is operated by the company Raizen in Brazil. It has a plant capacity of 256,000 t/a. The U.S. company Poet operates a plant which processes corn into around 419,000 t/a of ethanol [POET (2021)]. Currently, there are two plants in Brazil that produce lignocellulosic ethanol. These are operated by Raizen and Granbio and have production capacities of 40,000 t/a and 65,000 t/a, respectively. Raizen is planning to build a plant with a production capacity of 65,000 t/a. Furthermore, the company POET-DSM Advanced Biofuels owns one plant in the U.S. with a capacity of 75,000 t/a, and the company Longlive Bio-technology operates a plant in China with a capacity of 60,000 t/a [Bioenergy International (2021d); ETIP Bioenergy (2021a); IEA Bioenergy (2021b)]. ENI purchased such a plant in 2018 with an installed capacity of 50,000 t/a, which should go into operation in the near future [ENI (2020); IEA Bioenergy (2021b); Ramos (2020)]. Moreover, SEKAB is known as one of the few companies that specifically uses woody residues in their demonstration plant in Örnsköldsvik/Sweden on a campaign basis [Sekab (2021)]. None of the production facilities are reportedly operating at full capacity. A new lignocellulose-based ethanol plant has been built in Romania using the Sunliq® technology licensed from Clariant. It was completed in October 2021 and has a production capacity of 50,000 t/a [Clariant (2021a)]. Other licenses have already been sold to companies in Poland, Bulgaria and China [Clariant (2021c)].

The main plant producing isobutanol is owned by Gevo in Luverne (USA). It is a corn processing plant that simultaneously produces ethanol and isobutanol (4,500 t/a) [IEA Bioenergy (2021b); Ryan (2021)]. Gevo produces batches (265 m³/a) of ATJ-SPK on a demonstration scale in Silsbee (USA); the construction of a commercial plant with a production capacity of approx. 30,000 m³/a is planned [IEA (2020); IEA Bioenergy (2021b)]. Furthermore, the company LanzaTech is planning to build an ATJ-SPK plant in the

Netherlands with a capacity of 30,000 t/a, which will go into operation in 2024 [CORDIS (2021)], and a plant in Port Talbot (UK) with a capacity of 100,000 m^3/a [IEA Bioenergy (2021b)].

Farnesan had been produced at a sugar cane processing plant owned by Amyris in Brotas, Brazil [Benjamin (2016)]. The plant was sold to Koninklijke DSM N.V. in 2017, after which the production of biofuels was no longer pursued [Lane (2017)].

RESEARCH AND DEVELOPMENT NEEDS

The production of ethanol from starch- and sugar-based biomass is an established technology (TRL 11) and research and development efforts are in the area of utilizing its byproducts (e.g., vinasse or biogenic carbon dioxide) or in optimizing the process. Conversion and retrofitting measures for the production of advanced fuels are also increasingly being discussed at the moment [Rutz (2020)]. The technological development of advanced ethanol plants is currently at stage TRL 8. The utilization of the by-products of these plants (vinasse and excess lignin) is also being addressed.

The processes for producing ATJ-SPK are on their way to market and are between stages TRL 6 and 8 depending on the feedstock. Research is currently focusing on retrofitting existing ethanol plants for the ATJ process [Rutz (2020)]. Byogy Renewables Inc [BYOGY Renewables (2016)] is one company that is currently looking into the integration of a further synthesis step in the ATJ process to produce aromatics. Here, part of the dehydrated alcohol is separated to produce aromatics through oligomerization [Chuck (2016)]. The aim is to produce an alcohol-to-jet synthetic paraffinic kerosene with aromatics (ATJ-SKA).

3.4 Anaerobic fermentation and downstream technologies

PROCESS DESCRIPTION

Biodegradation of organic feedstocks under anaerobic conditions results in a biogas consisting mostly of methane (about 55 to 75 % v/v) and carbon dioxide (about 25 to 45 % v/v). The conversion of organic molecules such as proteins, lipids and carbohydrates through microorganisms [Daniel-Gromke (2017); Kasinath (2021)] occurs in four major steps: i) hydrolysis of complex biopolymers into monomers such as sugars and amino acids; ii) acidogenesis of biomonomers into volatile fatty acids; iii) acetogenesis of the fatty acids into smaller molecules such as hydrogen, carbon dioxide and acetic acid, and iv) methanogenesis, which produces methane and carbon dioxide [Matsakas (2016)]. The biochemical processes can take place under psychrotrophic, mesophilic and thermophilic conditions, with the mesophilic fermentation process being the most commonly used because it is more stable [Kasinath (2021); Matsakas (2016)].

There is a range of suitable feedstocks that can be used to produce biogas. These include municipal solid waste, food scraps, agricultural waste, lignocellulosic biomass, and energy crops. These organic materials can either undergo mono- or co-digestion. Co-digestion is employed to achieve better operating conditions for the microorganisms, with different materials being mixed into the process depending on their pH value, biodegradability and water content. Materials may need to be pretreated (mechanically, thermally, chemically, or biologically) in order, for example, to increase substrate surface and thus improve microorganism accessibility [Kasinath (2021)].

Most of the biogas produced in Germany is converted into electricity (after desulfurization and, if necessary, drying). This is done directly on site via co-generation in combined heat and power plants (CHP). Internal combustion engines, gas turbines and even fuel cells with subsequent production of electricity by generators are used to do this. The raw biogas can also be processed into biomethane.

Processes such as pressure swing adsorption, pressurized water scrubbing, or membrane separation are used. After upgrading, the resulting biomethane can be liquefied or compressed. The latter is required to feed the biomethane into the natural gas grid. The process flow diagram in Figure 3-5 provides an overview of the biogas utilization options.

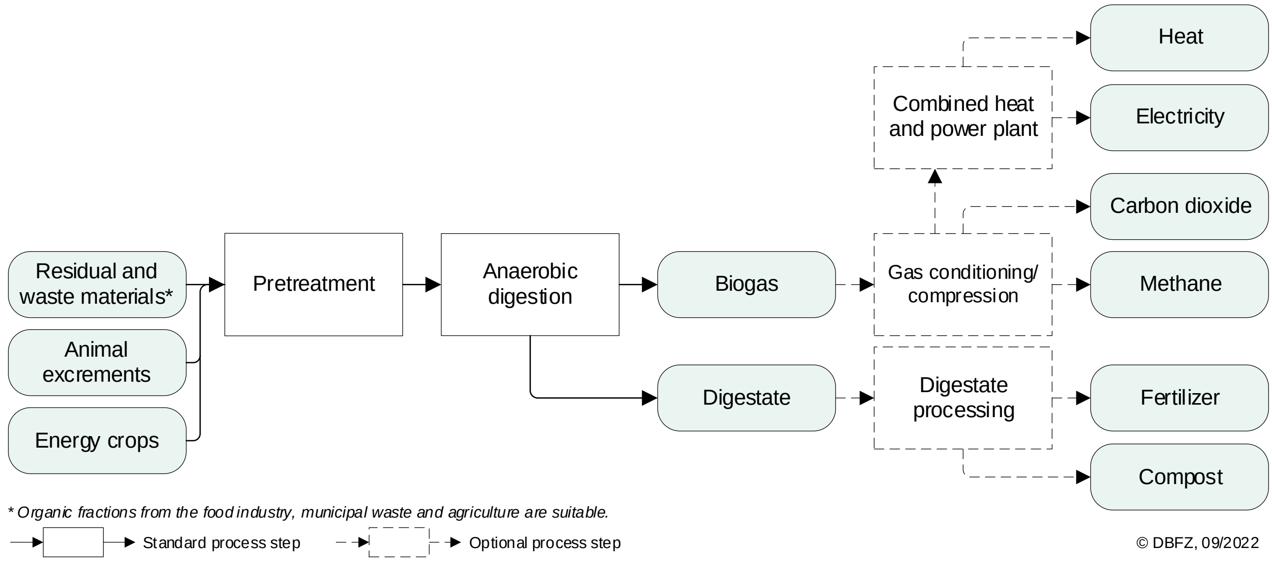


Figure 3-5 Schematic illustration of biogas production and the corresponding derivatives

In addition to methane and carbon dioxide, biogas can also contain low concentrations of hydrogen sulfide and ammonia [Daniel-Gromke (2017); Dannesboe (2021); Kasinath (2021)]. This must be considered, particularly in downstream technologies. One possible way to utilize biogas, which has received increased attention in recent years, is steam reforming to produce biogenic hydrogen. Known as a method to produce hydrogen from natural gas, endothermic steam reforming produces carbon monoxide (CO) and hydrogen with a subsequent water-gas shift reaction (WGS) to increase the hydrogen content in the gas. A final treatment process using pressure swing adsorption purifies the hydrogen fraction.

Dry reforming is the catalytic cracking of methane with CO_2 under high temperatures and pressures. The resulting synthesis gas contains equal proportions of CO and H_2, which is the composition of synthesis gas needed for direct dimethyl ether (DME) synthesis [Kiendl (2018)]. Methanol synthesis, the water gas shift reaction and methanol dehydration occur simultaneously during direct DME synthesis [Dahmen (2012); Kiendl (2018)].

Methane pyrolysis is another technology currently being discussed which can be used to produce bio-based hydrogen. In this process, methane (for example from biogas fermentation) is split into hydrogen and carbon at low pressures and high temperatures [Sánchez-Bastardo (2020)]. The respective temperatures can be generated through an electrically generated plasma (methane plasmalysis), through combustion of a part of the reactant stream, or through liquid metal baths (thermal or catalytic methane pyrolysis) [Abbas (2010)].

In addition to catalytic methanation, which is discussed in Section 3.8.7, biological or microbial methanation is another way to produce methane. Here, microorganisms are used to anaerobically convert carbon dioxide and hydrogen into methane. These microorganisms are highly specialized archaea that carry out methanogenesis at temperatures of up to 65 °C and at pressures of between 5 and 10 bars.

This power-to-gas process (hydrogen is produced via electrolysis) is used, for example, *in situ* or *ex situ* in or at biogas or wastewater treatment plants. Either way, this part of the plant can increase the process's methane yield.

EXAMPLES OF COMPANIES AND INITIATIVES

Biogas is regarded as a precursor for small-scale biofuel production. In Denmark, for example, research activities are focusing on developing small-scale plants for upgrading biogas to methanol with or without adding hydrogen [DTU (2020); IEA Bioenergy (2020a)]. The company Oberon Fuels in the U.S. operates a demonstration plant that produces DME from biogas using the intermediate product methanol [Oberon Fuels (2021)].

In the area of biogas and biomethane steam reforming, a modular pilot-scale plant is currently being constructed by BtX energy GmbH and a test unit for oxidative steam reforming is being planned by the BioROBURplus consortium. In addition, a compact reformer for steam reforming of methane-rich gases is currently being commissioned by the company DBI Gas- und Umwelttechnik GmbH. The company Graforce GmbH has been active in the field of methane plasmalysis for several years and has expanded its hydrogen production portfolio to include wastewater and plastic waste [GRAFORCE (2020)]. A consortium led by BASF is constructing a test facility for methane pyrolysis in Ludwigshafen, which will go into operation by the end of May 2022. It will serve as the basis for the design of a future pilot plant [BASF (2021); BMBF (2019)].

BASF and Linde joined forces to develop a process at a test facility in Germany for the dry reforming of (fossil) methane with further processing into DME (direct DME synthesis) [Linde (2020)]. The biobased production of DME through the dry reforming of biogas is currently at a demonstration scale; an example of this development comes from Gastechnologisches Institut gGmbH in Freiberg [DBI (2019)].

Prominent stakeholders in biological methanation include microbEnergy GmbH and VIESSMANN Climate Solutions SE, which have developed the BiON® process. A corresponding pilot plant has been in operation in Allendorf (Eder) since 2015 [microbEnergy (2020)].

RESEARCH AND DEVELOPMENT NEEDS

Anaerobic fermentation is an established technology (TRL 11). Germany is the leader in Europe with over 8,000 installed plants [Daniel-Gromke (2017)]. In Europe, biogas plants usually generate between 0.5 and 2.7 MW of electricity [IEA (2020)]. The average capacity of a methane processing plant in Germany is 3,420 t/a of biomethane [bdew (2021)]; the average capacity worldwide is 2,530 t/a of biomethane [IEA Bioenergy (2021c)].

When biogas or biomethane are used to produce hydrogen through steam reforming, special attention must be drawn to potential catalyst poisons such as sulfur, silicon and chlorine compounds. Furthermore, in contrast to when only the methane fraction is used, the use of all of the biogas, including the carbon dioxide fraction, affects the plant size, catalyst lifetimes and the separation behavior of the produced gas. The entire process chain is assessed as being at stages TRL 6 to 8. While methane plasmalysis already has a TRL of 8, catalytic and thermal methane pyrolysis still face challenges before they can be implemented on an industrial scale. The catalysts are currently being developed (mainly metal, carbon or molten metal/salt catalysts), the market for the carbon by-product has yet to be established (research is being done on the quality of the carbon produced), and the process/reactor concepts are still under development [Sánchez-Bastardo (2020)]. The technology readiness level is considered to be at stages TRL 3 to 4. The investigations of the Gastechnologisches Institut gGmbH in Freiberg on the dry reforming of biogas with subsequent DME synthesis initially started in the project DME-regenerativ and were concretized in the follow-up project FlexDME. The commissioning of the pilot plant is planned for the year 2022; a TRL of 5 to 6 is currently assumed. [EnArgus (2021); Friedel (2017)]

3.5 Esterification and transesterification

PROCESS DESCRIPTION

Fatty acid methyl esters (FAME) are formed by a reaction of triglycerides with methanol, with glycerol being formed as a by-product. The blend of fatty acid methyl esters is called biodiesel [ETIP Bioenergy (2021e)]. Transesterification is a reversible reaction whose equilibrium is shifted to the product side by an excess of methanol. It uses catalysts such as sodium hydroxide (NaOH), potassium hydroxide (KOH), sodium methylate (CH_3NaO) and potassium methylate (CH_3KO) [Majer (2015)]. Suitable triglycerides are found, for example, in vegetable oils from cultivated biomass (e.g., rape seed, soy bean, oil palm) or in animal fat and used cooking oil (UCO).

Vegetable oil can be obtained from oil seeds in an oil mill, for example. The oil content of the individual seeds can differ significantly. While rape seed and sunflower seeds have an oil content of 40 to 45 % w/w, palm fruits and soy beans have an oil content of 23 % and 21 % w/w, respectively [Bockisch (1993); Kaltschmitt (2016); Majer (2015)]. A distinction is made between extracting oil in small-scale and in large-scale plants. In small-scale plants, the oil is usually extracted mechanically (pressed) without adding heat, followed by solid/liquid separation. When used in fuels, the oil usually undergoes post-treatment similar to the process steps of bleaching and degumming in large-scale plants. For oil seed processed in large-scale plants, either a one- or two-stage final pressing, direct extraction with solvents, or a combination of both is used. To increase the oil yield, heat is usually added to the process. The obtained oil is then processed, i.e., refined or partially refined, by means of degumming, neutralization, bleaching and deodorization [Kaltschmitt (2016)].

When biodiesel is produced from UCO, the feedstock must first be pretreated [Majer (2015)]. Mechanical pretreatment, such as centrifugation and filtration, is suitable for separating solids. Used cooking oils have a higher concentration of free fatty acids than vegetable oils and therefore must be neutralized by esterification [Sarno (2019); Ulfah (2019)]. Neutralization occurs through a reaction of the free fatty acids with methanol [Mazubert (2014)]. Finally, the water content of the oil must be reduced, since water, just like a high acid content, can negatively influence the transesterification process [Bereczky (2017)].

The crude glycerol obtained in the production of biodiesel contains impurities such as methanol, soaps, water and salts. These have to be separated in order to obtain technical-grade glycerol. This can be done through flash evaporation of methanol, neutralization and subsequent filtration of salts, and subsequent distillation of glycerol. To obtain pharmaceutical grade glycerol, further refining steps are required, such as bleaching and adsorption processes [Air Liquide (2021a); Pitt (2019); Wan Isahak (2014)].

Figure 3-6 below illustrates the process for the production of biodiesel.

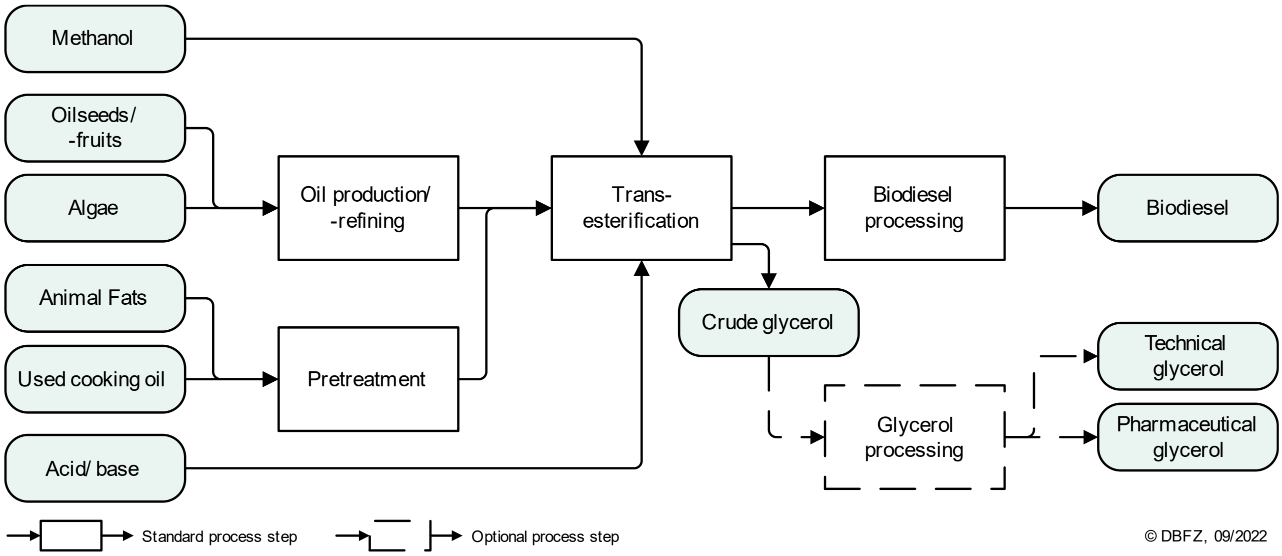


Figure 3-6 Schematic illustration of the production of FAME. Data based on [Majer (2015)]

EXAMPLES OF COMPANIES AND INITIATIVES

The production capacity of FAME plants varies widely. In Germany, for example, installed capacities range from 6,000 t/a (owned by RapSol GmbH) to 350,000 t/a (owned by Archer Daniels Midland Company) [ADM (2006); UFOP (2018)]. Worldwide, the average plant production capacity is around 100,000 t/a. The company Potencial Biodiesel Ltda. in Brazil operates a plant with a production capacity of 800,000 t/a [biodieselbr (2020)].

RESEARCH AND DEVELOPMENT NEEDS

FAME is an established biofuel whose global production in 2019 amounted to 38.84 million t/a [IHS Markit (2020a)]. Thus, it is assumed to have a TRL of 11. Research and development activities are focusing on feedstock upgrading and adapting processes that use low and variable feedstock qualities. Research is also being done on the use of renewable biomass such as jatropha or microalgae [Loh (2021)] and the replacement of fossil methanol with renewable methanol.

3.6 Hydrotreatment

PROCESS DESCRIPTION

The production of HEFA or HVO fuels is chemically and technically similar to the hydrotreatment/ hydrocracking process of fossil reactants. This process is used in petroleum refineries to split off heteroatoms, for example sulfur and oxygen, or for hydrogen-assisted adjustment of the chain length of specific fuel fractions. The HVO/HEFA process[5] uses feedstocks containing esters and fatty acids as well as biocrudes which are catalytically added to hydrogen. This produces a range of paraffinic hydrocarbons in a spectrum comparable to the fractions of petroleum refining. The process can be carried out as a stand-alone process or in existing refineries as a co-refining process with petroleum products (Section 3.9).

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[5] For the sake of simplification, no additional distinction is made for the hydrotreatment of biocrudes and the designation HVO/HEFA is uniformly used in connection with the process and the fuels irrespective of the feedstock.

As shown by Figure 3-7, oil refining (degumming, bleaching and/or neutralization) may need to be carried out depending on the reactant. Used cooking oils and fats may have to be filtered and/or dried, specific salts may have to be separated from tall oil, and biocrudes may need to be conditioned through distillation, cracking and/or a previous hydrotreatment process (Section 3.9). The pretreated oils and fats are heated in a fixed-bed reactor at a hydrogen partial pressure of 40 to 140 bars [Bezergianni (2010); Guzman (2010); Liu (2011); Sotelo-Boyás (2011)] and an operating temperature of between 300 and 450 °C [Arend (2011), (2011); Liu (2011); Sotelo-Boyás (2011)]. The process's stoichiometric hydrogen requirement is between 2 and 3 % w/w depending on the feedstock and process. Hydrogen leads to the saturation of the double bonds and to the elimination of heteroatoms. This results in an oxygen- and aromatic-free mixture of saturated, paraffinic hydrocarbons. Depending on the operating conditions, catalyst and preferred product fraction, isomerization and mild cracking occur after or at the same time as the hydrogenation [Starck (2016)]. The desired fuel properties are determined by the branching and changing of the chain length of the hydrocarbons.

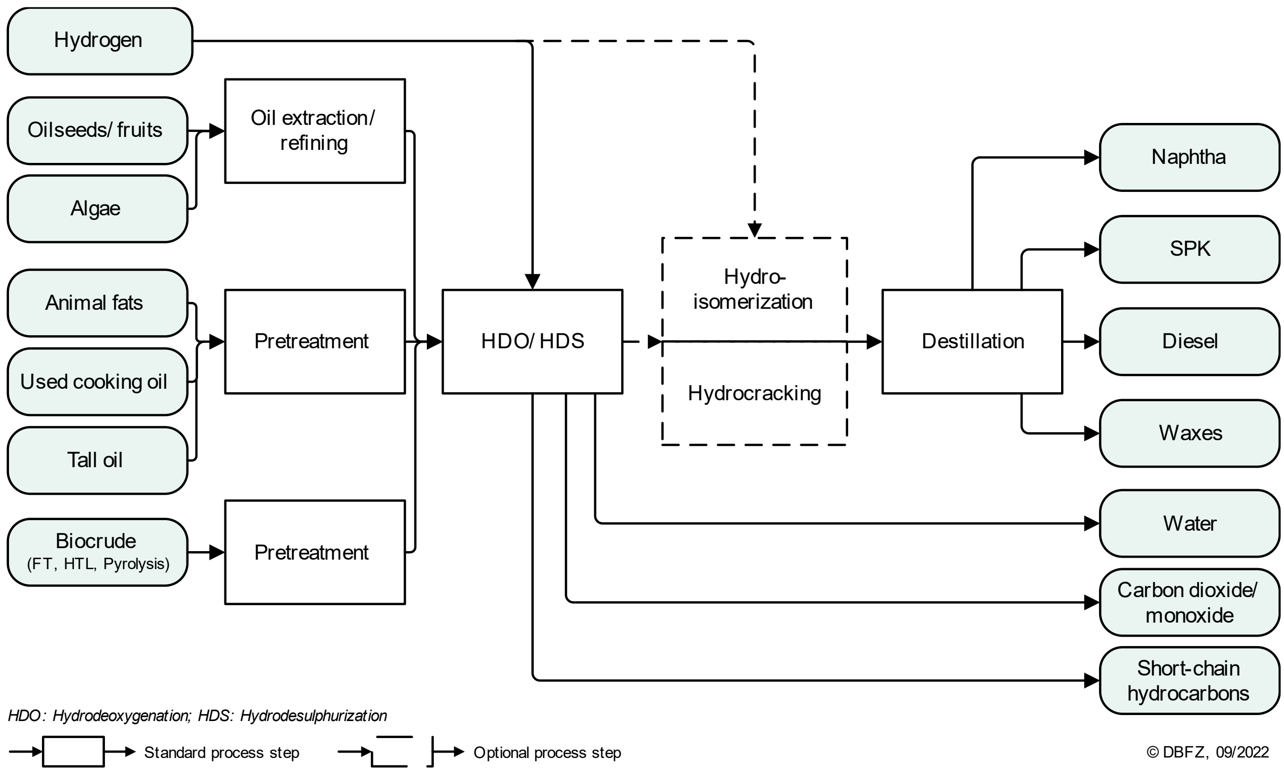


Figure 3-7 Schematic illustration of the production of HVO/HEFA fuels

The main possible products are diesel, gasoline/naphtha, SPK and liquefied petroleum gas (LPG) fractions. The liquid products are separated from each other by distillation. By-products such as carbon dioxide, carbon monoxide and water are removed at a suitable point and, if necessary, upgraded. The light hydrocarbons, for example propane and butane, can be used to generate internal energy or in steam reforming to produce hydrogen.

In accordance with ASTM D7566, HEFA-SPK has been approved as blending component (currently up to 50 % v/v) for fossil JET A/A 1 in commercial aviation since 2011. In May 2020, the seventh pathway for the production of SPK was included in ASTM D7566: HC-HEFA-SPK (synthesized paraffinic kerosene from hydrocarbon-hydroprocessed esters and fatty acids), with a volumetric blending ratio of up to 10 %. It is based on a hydrotreatment process that uses a hydrocarbon-rich oil as the reactant which is obtained through the biosynthesis of a microorganism. Currently, only the microalga species *Botryococcus braunii* has been included in Annex 7.

Examples of companies and initiatives

Neste Oyj was one of the first producers of HVO/HEFA. Various feedstocks (e.g., waste oils) and products (e.g., diesel and SPK) are processed and investigated at the customer's request at its four plants located in three European and Asian countries. The Renewable Energy Group operates a biorefinery in Geismar (Louisiana/USA) which was formerly commissioned by Dynamic Fuels LLC. It uses the Bio-Synfining™ process (supplemented by technologies from Neste Oyj) to produce renewable diesel, naphtha and LPG products [Renewable Energy Group Inc. (2021)]. UPM Biofuels produces HEFA diesel (UPM BioVerno) and naphtha at its biorefinery in Lappeenranta, Finland, using, for the first time, tall oil from its UPM Kaukas Pulp and Paper Mill [UPM Biofuels (2022)]. The Ecofining™ process, developed by Eni S. p. A. and UOP Honeywell, is used in a plant operated by World Energy at its Paramount Refinery (California/USA). This plant has already produced synthetic paraffinic kerosene from beef tallow in accordance with ASTM D7566. Total fuel capacities of stand-alone plants currently range from 130,000 t/a (UPM Biofuels, Lappeenranta refinery) to 500,000 t/a (TOTAL, La Mède refinery) and a future 1.3 million t/a (Neste Oyj, Singapore refinery, planned completion in 2023) [TotalEnergies (2019); UPM Biofuels (2022)].

Employing the Ecofining™ technology, Eni S. p. A. has launched one of the first "Green Refinery" conversion projects at its Venice refinery (Porto Marghera, Italy) [ENI (2021c)]. This involves adapting the existing infrastructure and process technology for the use of biogenic feedstocks. A similar approach is being pursued by TOTAL, which, in 2019, completed the conversion of its former oil refinery in La Mède (France) with the help of the Vegan® hydrotreatment technology from the company Axens [TotalEnergies (2019)].

Research and development needs

The hydrotreatment of biogenic esters and fatty acids is considered an established process and can therefore be considered as having a TRL of 11 for oils from cultivated biomass as well as used cooking oil and animal fat. Only a handful of biorefineries are currently using tall oil as a feedstock, so the technical readiness level for this pathway is classified at TRL 9. Research and development activities tend to focus on the use of sustainable resources and the corresponding adaptation of engineering and control processes. One example of this is the use of algae oils, which is classified at TRL 4. Product-specific investigations are also being carried out, such as a demonstration of the use of unblended HEFA-SPK (non-drop-in) and related compatibility studies which form the basis for certified use in flight operations [Neste (2021)]. Currently, many approaches to improve the market penetration of HEFA fuels are being discussed in terms of retrofitting existing or decommissioned oil refineries. There is also particular interest in retrofitting refineries to co-refine biogenic oils, e.g., biocrudes obtained via pyrolysis[6] or hydrothermal processes. More information on this can be found in Section 3.9.

[6] Pyrolysis is a process for treating (in this case: biogenic) feedstocks at high temperatures in an oxygen-free environment. Moist to wet biomass must be dried and, if necessary, crushed. The resulting pyrolysis gas is separated from the pyrolysis coke and then condensed to obtain the biocrude or pyrolysis oil.

3.7 Hydrothermal liquefaction

Process description

Hydrothermal liquefaction (HTL) is a thermochemical process in which biomass is converted into an energy-rich biocrude in the presence of water at temperatures of 250 to 370 °C and pressures of 100 to 220 bars. Due to the high process pressures, water remains in its liquid or near-critical state. Since water acts both as a solvent and a reactant in the HTL process, the process is particularly suitable for wet biomass such as sewage sludge, animal excrements and organic waste, but also for algae and undried agricultural residues. Under the prevailing reaction conditions, the macromolecular components of the biomass are split into smaller fragments (hydrolysis), converted, and partially recombined into larger molecules (polymerization). While the resulting non-polar compounds (e.g., long-chain, heterocyclic and aromatic hydrocarbons as well as amines and amides) form the biocrude, the polar water-soluble compounds (e.g., alcohols, acids and phenols) accumulate in the process water. [Basar (2021); Castello (2018)]

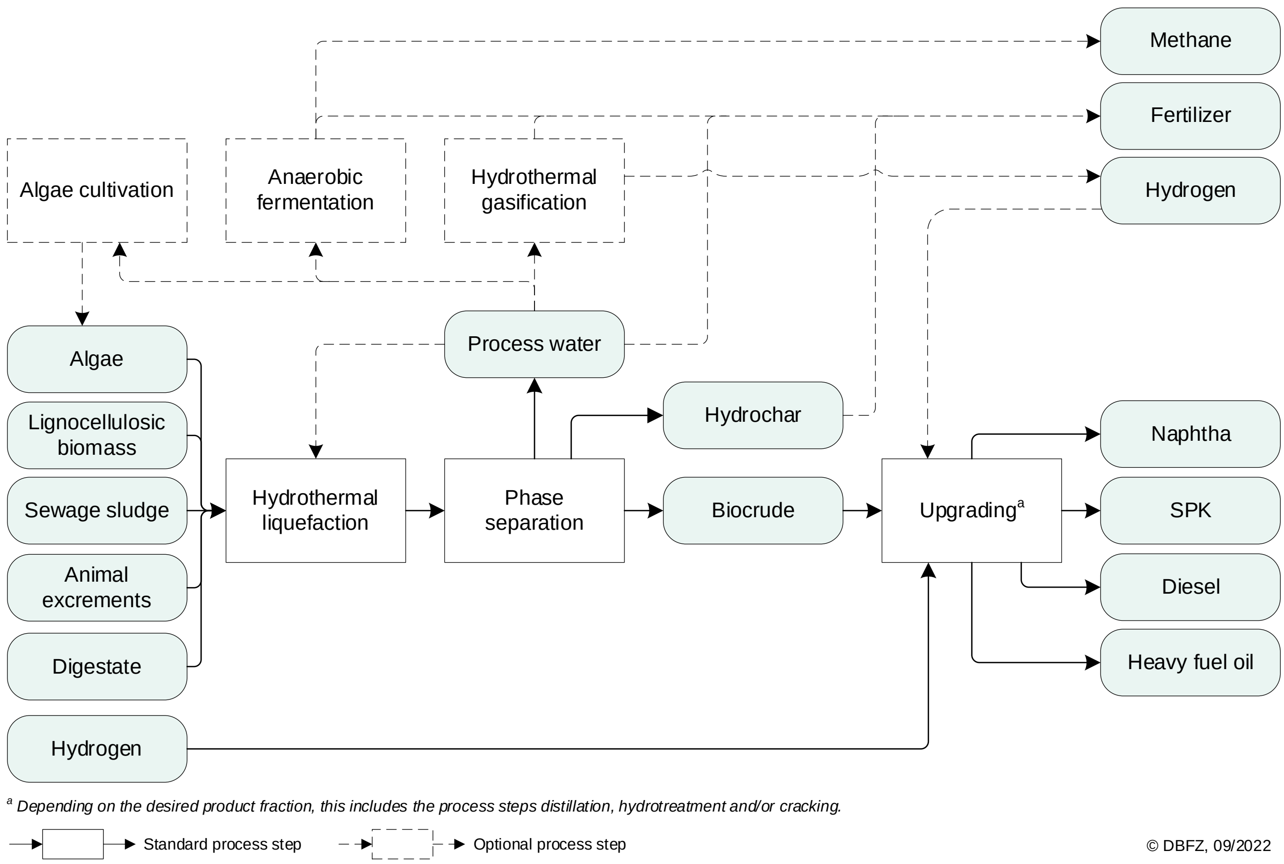


Figure 3-8 Schematic illustration of the production of HTL fuels

The biocrude produced in this way does not meet the requirements of a drop-in fuel and must be refined. During this upgrading process, both the physical (viscosity, higher heating value, color, density) and the chemical properties (presence of heteroatoms) can be modified. The upgrading of the biocrude includes fractional distillation followed by the removal of heteroatoms, for example through hydrotreatment. Distillation residues can be split and refined by catalytic or thermal cracking. [Taghipour (2019)] The process water produced during hydrothermal liquefaction can be converted into biomethane through anaerobic fermentation and can thus provide energy for the overall process [Posmanik (2017); Tommaso

(2015)]. The process water can also undergo hydrothermal gasification, in which the organic components are split into hydrogen and carbon dioxide [Cherad (2016)]. The hydrogen obtained in this way can either be used to produce energy or to process the biocrude. In addition to the two liquid fractions, the HTL process also produces a hydrochar, which is composed of inorganic and recombined water-insoluble molecules, and a process gas, mainly consisting of carbon dioxide, methane and hydrogen. A process flow diagram in Figure 3-8 illustrates the options.

Examples of companies and initiatives

Demonstration-scale HTL plants have been built by various companies in recent years. Licella Holdings Ltd. (Australia) offers a catalytic HTL process called Cat-HTR™. A plant based on this technology was built and commissioned in 2012 at its Somersby site (Australia). It has a total annual biocrude capacity of 9,000 m³. Another demonstration plant (80,000 m³/a) was built and commissioned in 2021 in cooperation with Canfor (Canada). [Lane (2017), (2021); Wijeyekoon (2020)]

Based on the Hydrofraction™ technology from Steeper Energy (Denmark), the Silva Green Fuel joint venture between Statkraft and Sødra has built an HTL demonstration plant in Tofte (Norway) with a total capacity of approx. 1,000 m³/a. Testing began at this plant in 2019 [Wijeyekoon (2020)]. Other companies include Southern Oil Refining (Australia), Muradel Pty Ltd. (Australia), Genifuel Corporation (USA), and Altaca Enerji (Turkey), which are using existing, and working on constructing new, demonstration plants. [Anastasakis (2018); Wijeyekoon (2020)]

In the aviation sector, HTL of fatty acids and fatty acid esters (e.g., animal fats, soy bean oil) was added to Annex 6 of ASTM D7566 in 2020, allowing a blend of up to 50 % v/v with Jet A/A 1 for commercial aviation [CAAFI (2021)]. The “Biofuels Isoconversion (BIC)” process, developed by Applied Research Associates (ARA), uses higher temperatures (450 – 475 °C) than are common for HTL, pressures of up to 210 bars [Wang (2016)], and achieves branched and unbranched cyclic and aromatic hydrocarbons for naphtha, kerosene and diesel fuels [Green Car Congress (2020)]. The corresponding SPK is also known as catalytic hydrothermolysis jet (CHJ). Euglena Co., licensee of the BIC process concept, built a demonstration plant in Yokohama City/Japan in 2018 [BioRefineries Blog (2018)].

Research and development needs

The HTL of biomass is being pursued around the world by various research institutions and companies. Pilot plants and prototypes have been set up and begun operations in recent years in the industrial sector. Therefore, the technology has a TRL of 7. The feedstocks used are mainly agricultural residues, wood residues, residues from the paper and pulp industry, sewage sludge, and algae. Research is still needed to process the resulting biocrude into commercially available drop-in fuels [Castello (2019); Hao (2021)]. Research is also focusing on the disposal and/or recycling of the process water through anaerobic digestion [Dias (2021)] and hydrothermal gasification [Baudouin (2021)]. Another object of current research is the recovery of nutrients from the process, which can accumulate both in the process water and in the hydrocarbon [Ovsyannikova (2020)].

3.8 Production of syngas and downstream technologies

Synthesis gas (or syngas) is a gas consisting mainly of carbon monoxide and hydrogen that can be used to synthesize various fuels and chemicals and to generate electricity [Ernst (2013)]. Synthesis is a chemical, thermochemical or thermocatalytic reaction in which specific reactants are converted into liquid and/or gaseous products. Particularly noteworthy are the so-called gas-to-liquid (GTL) processes, in which gases containing hydrocarbons are synthesized into liquid products [Höök (2014)]. Fuels made from synthesis gas are widely referred to as synthetic fuels.

Depending on the method of production, the syngas may contain small amounts of CO_2, water and traces of nitrogen [van der Drift (2006)]. It can be supplied from both solid hydrocarbon sources, like coal or biomass, and from gaseous hydrocarbon sources such as natural gas or biogas [El-Nagar (2019); Zhao (2020)]. Synthesis gas can alternatively be supplied through the electrolytic production of hydrogen with a subsequent addition of the required carbon monoxide fraction. These approaches are discussed below.

3.8.1 Thermochemical gasification

Process description

Thermochemical gasification can be used to convert carbon-based feedstocks, such as coal or dry biomass, into a synthesis gas [NETL (2021)]. Pyrolysis oil and black liquor can also be used as reactants [Higman (2008)]. The thermochemical process, shown in Figure 3-9, occurs at high temperatures and pressures and uses gasification agents such as air, steam, carbon dioxide or pure oxygen. A distinction is made between autothermal and allothermal processes depending on whether the heat for the gasification reactions is provided by the oxidation of the feedstock in the reactor or by an external source [FLEDGED (2021b); NETL (2021)].

Gasification reactors range from fixed-bed/moving-bed gasifiers, to fluidized bed and double fluidized bed gasifiers and entrained-flow gasifiers. The classification takes into account the difference in gas-solid contact [FLEDGED (2021b); Higman (2008)]. Depending on the type of process, temperatures typically range from 700 to 900 °C or, especially for entrained-flow gasifiers, between 1,200 and 2,000 °C. Pressure can reach up to 20 bars. Prior to the gasification of biomass, pretreatment can be carried out in a similar way to coal by comminuting the feedstock. [Higman (2008)]

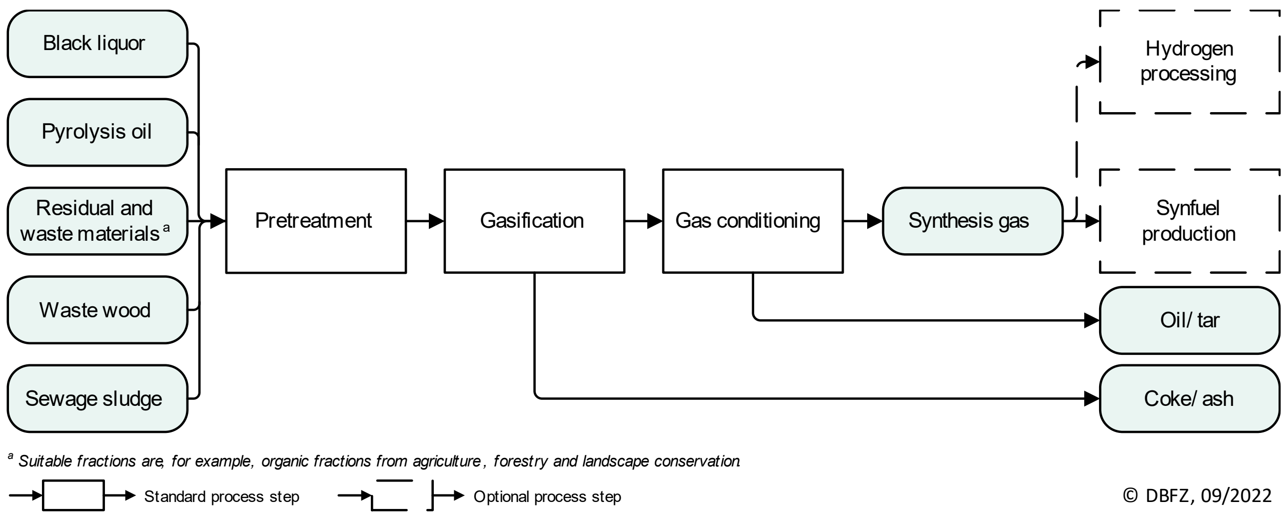


Figure 3-9 Schematic illustration of synthesis gas production using thermochemical gasification

In addition to carbon monoxide and hydrogen, the gaseous product can also contain carbon dioxide, methane, organic molecules, inorganic molecules (e.g., hydrogen sulfide) and particles. The composition of the product depends on various factors such as the design of the reactor, the operating conditions, the feedstock and the gasification agent [Materazzi (2019)]. The synthesis gases obtained in this manner must be treated accordingly before they can be used in downstream synthesis processes (see Section 3.8.5).

Hydrogen can be obtained directly from the syngas. Its concentration in the gas fraction can depend on the type of feedstock, particle size, gasification temperature, catalyst, reaction time and the amount of gasification agent used [Lepage (2021)]. An additional step in the form of a water-gas shift reaction or steam reforming may be necessary to produce an optimum yield. Depending on the composition of the gas, pressure swing adsorption can be used, for example, to ensure that the hydrogen has a high level of purity [Lepage (2021); Spath (2005)].

Examples of companies and initiatives

The gasification of black liquor to produce DME was investigated in a demonstration plant of the "BioDME" project (2008–2013). The company CHOREN Industries GmbH (Germany) developed a gasifier with a 3-phase process (low and high temperature gasification and endothermic fluidized bed gasification). The gasifier was designed to process various feedstocks and was tested in a demonstration plant with a capacity of 13,500 t/a [ETIP Bioenergy (2017)]. The Karlsruhe Institute of Technology has been investigating the gasification of a biocrude produced by pyrolysis in a demonstration plant called bioliq®. Here, the biomass is pyrolyzed as part of a decentralized step and the pyrolysis oil is then gasified in an entrained-flow gasifier [ETIP Bioenergy (2021c)]. A sorption-assisted gasification process was developed up until October 2020 as part of the "FLEDGED" project. The biomass was gasified with steam. Energy was provided by the simultaneous combustion of charcoal, which was produced during the gasification process, and carbon dioxide was removed through adsorption with calcium oxide [FLEDGED (2021a)]. In Canada, the company Enerkem has developed a process for producing ethanol through the gasification of municipal solid waste. A production plant with a capacity of 30,000 t/a of ethanol (converted in 2017 from a former methanol production plant) has been in operation since 2014 [Enerkem (2021b); IEA Bioenergy (2021b)]. A methanation plant based on the thermochemical gasification of wood (20 MW gas capacity) was developed as part of the project "Gothenburg Biomass Gasification (GoBiGas)" which was initiated in 2005 [Larsson (2019)]. According to [Larsson (2019); Materazzi (2019)], the plant ceased operations in 2018. The biomass power plant in Güssing (Austria), run by REPOTEC, has been operating since 2001. Its steam-assisted fluidized bed gasification system has been available for numerous projects that investigate methanation, hydrogen production and the provision of synthetic fuels from biomass [REPOTEC (2018)].

There are few prominent examples of using thermochemical gasification to produce hydrogen. Eni (Italy) is currently investigating the possibility of installing a hydrogen production plant at its Venice site, which would use, among other things, biobased waste streams [ENI (2021b)]. The joint venture Ways2H provides gasifiers for the production of hydrogen from municipal and medical waste, sewage sludge and plastics [Ways2H (2020)].

Research and development needs

A gasifier in Dunkirk (France), installed by TotalEnergies as part of the "BioTfuel" project, and Enerkem's fluidized bed gasifier, in operation since 2014, demonstrate the potential of the process which is classified as having a TRL of 8. In addition, several plants for the gasification of municipal solid waste and biomass are currently under construction [Enerkem (2021a); ENI (2021a); Fulcrum Bioenergy (2021); GIRADA Energy (2021); Overmaat (2019); Velocys (2021b)]. These will further increase the technology readiness level of gasification. Thermochemical gasification as a process for producing biobased hydrogen should actually be regarded as having a TRL of 5 to 7. Research into the thermochemical gasification of biomass must focus in general on avoiding tar production during the process in order to reduce a corresponding loss of product into this fraction [IEA (2019b)].

3.8.2 Electrolysis processes

PROCESS DESCRIPTION

ALKALINE WATER ELECTROLYSIS (AEL) is a technical solution for the electrochemical electrolysis process, in which an electric current splits water into oxygen and hydrogen as part of a chemical reaction. Here, an alkaline water solution of sodium or potassium hydroxide is used as the electrolyte. The hydroxide ion serves as a charge carrier [Rashid (2015)]. Operating temperatures typically range between 60 and 80 °C [IEA (2019b)]. Pressure is moderate at up to 30 bars. Only a few manufacturers allow higher values of up to 60 bars. The electrolysis can occur at a range of 20 to 100 % of the nominal capacity [Buttler (2018)] and is able to vary the relative load at a rate of up to 20 % per second [IRENA (2018)]. Flexible operation with intermittent renewable energy sources, such as photovoltaics or wind energy, is also possible to a limited degree.

POLYMER ELECTROLYTE MEMBRANE ELECTROLYSIS (PEMEL) uses a polymer membrane as the electrolyte, with the protons acting as charge carriers [Rashid (2015)]. Like AEL, PEMEL is a low-temperature electrolysis process with operating temperatures ranging between 50 and 80 °C. The maximum output pressure of the hydrogen varies between 30 and 80 bars [Buttler (2018); IEA (2019b)]. PEMEL is well suited to being used in combination with fluctuating renewable energy sources. In terms of nominal power, the electrolyzer can be operated at 0 to 160 % [Buttler (2018)] with the possibility of a ramp-up and ramp-down of 100 % of the relative load within a few seconds [IRENA (2018)].

SOLID OXIDE ELECTROLYSIS (SOEL) is a high-temperature electrolysis process with operating temperatures of between 600 and 1,000 °C. The process pressure is under 10 bars [IEA (2019b); Sun (2018)]. The electrolyte is solid and consists of zirconium dioxide stabilized with yttrium. Due to the high temperatures, the specific energy requirement per kg of hydrogen is lower than for PEMEL and AEL. Heat provides part of the required energy, so that the hydrogen-specific electricity demand is significantly lower than for low-temperature electrolyzers. In terms of operational flexibility, laboratory-scale studies indicate a high flexibility, however the scientific literature also mentions that large-scale applications could be less flexible [Buttler (2018); Schäfer (2021)]. The process operates at the thermoneutral point, which means that the required heat is provided by internal heat production [Buttler (2018)]. If an external heat source is still required, the additional energy demand must be considered when determining the overall level of efficiency.

A general overview of the electrolysis process can be found in Figure 3-10 below.

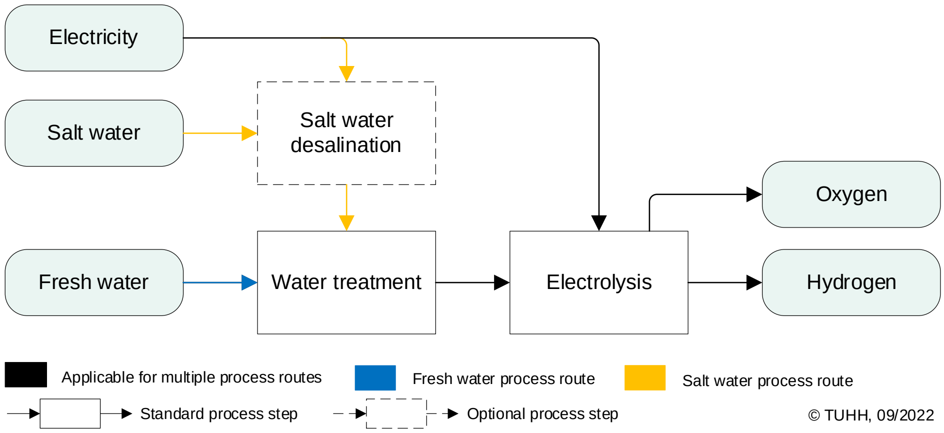


Figure 3-10 Schematic illustration of the electrolysis process using salt water and/or fresh water to produce hydrogen

EXAMPLES OF COMPANIES AND INITIATIVES

Alkaline electrolyzers are sold by various manufacturers for different applications and range from small systems (a few 100 kW) to large-scale modules (5 MW per module). Accordingly, there are electrolysis plants of various dimensions currently under construction or already in operation, both in Germany and abroad. The largest plant in Germany was constructed by McPhy. It has an installed capacity of 6 MW and has been in operation in Werlte since 2013 [McPhy (2015)]. The plant is operated by Audi and the hydrogen is used to produce synthetic methane. The biggest plant currently under construction is in Québec, Canada, where a plant designed and built by thyssenkrupp with an electrical output of 88 MW is scheduled to go into operation by 2023 [ThyssenKrupp (2021)]. The hydrogen will be produced using electricity from Hydro-Québec's hydroelectric power stations and will subsequently be used in a biofuel plant.

The stack size of PEMEL reaches up to 2 MW of rated power [Buttler (2018)]. The largest plant was built by Cummins (formerly Hydrogenics) and is currently located in Bécancour (Canada). It has a total installed capacity of 21 MW and a hydrogen production capacity of up to 8 t/d [Air Liquide (2021b)]. Currently, a 24 MW plant is being built by ITM Linde Electrolysis GmbH as part of the next scaling-up phase in Leuna [Energiewirtschaftliche Tagesfragen (2021)]. The hydrogen will be used to supply various industrial consumers and mobility applications.

In addition to various smaller research initiatives and alliances, high-temperature electrolysis is mainly marketed by Sunfire (Germany). It sells modular electrolyzers under the name Sunfire-Hylink. These have a hydrogen output of 750 m^3/h (STP) and consume 3.6 kWh/m^3 (STP) of electricity per module. Haldor Topsøe A/S has also announced that it will establish capacities for the production of SOEL, but the plants are yet to be commercially available [Frøhlke (2021)].

RESEARCH AND DEVELOPMENT NEEDS

AEL technology is well known and well established. Large commercial AEL plants have been built that range up to 6 MW_{el}, corresponding to 3 t/d [Buttler (2018)]. The technology is thus firmly established on the market and, with a TRL 11, can be regarded as mature. Today, there is a substantial need for research into the flexible-load operation of the electrolysis units, i.e., optimization of the partial load behavior. Furthermore, both cells and stacks are being continually improved to reduce losses, and thereby improve efficiency.

One challenge for PEMEL at present is to reduce the amount of platinum required as a catalyst. However, large-scale plants are now in operation and the first models are being mass-produced. The technology can therefore be regarded as nearly mature and in many cases already established on the market (TRL 9 to 10).

SOEL is not yet mature. The modules offered by Sunfire have a rated power of 150 kW, but the stack size is currently less than 10 kW. The largest plant currently in operation is in Salzgitter with an installed capacity of 720 kW [sunfire (2020)]. The scientific literature regards the technology as being at a pre-commercial and basic research stage [Buttler (2018)], which corresponds to stages TRL 6 to 7. Plant sizes are expected to increase in the coming years [Hauch (2020)].

3.8.3 Supplying carbon dioxide

PROCESS DESCRIPTION

The first step in supplying synthesis gas is to capture carbon dioxide from various sources. Several processes have been developed to do this. These are based on different physicochemical effects and are illustrated in a diagram in Figure 3-11. Carbon dioxide can be captured from concentrated, stationary sources, and diffuse sources. In the case of concentrated, stationary sources, which are usually referred to as point sources, the carbon dioxide is predominantly present in captured gas streams, such as flue or waste gases from industrial production facilities or from energy conversion. Carbon dioxide is an important by-product of bioethanol fermentation and can be obtained as a stream of high-purity gas. Moreover, carbon dioxide is also a product of anaerobic fermentation in the production of biogas and can be recovered and used, for example, after methane capture or after energy recovery. Another advantage of CO_2 capture processes is the possibility of negative emissions generated on balance in the overall process. The most important diffuse source of CO_2 is the atmosphere. Three basic processes for CO_2 point sources and for direct air capture (DAC) are explained below. Examples of some of the technologies available for the capture process are also discussed.

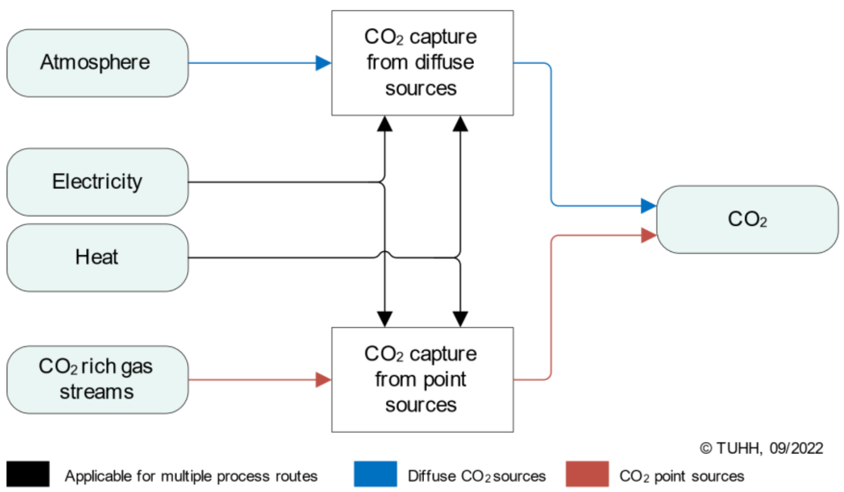


Figure 3-11 Schematic illustration of supplying CO_2 from diffuse and point sources

In the **PRE-COMBUSTION CAPTURE** process, a synthesis gas is produced from a fuel or carbonaceous feedstock through gasification. Here the carbon dioxide is mainly captured through physical absorption. This is done using either the Selexol, Rectisol or Purisol processes, each of which uses a different scrubbing agent. These processes can achieve separation rates of approx. 95 % [Fischedick (2015)]. The process is not suitable for applications in which carbon dioxide occurs in processes downstream from the combustion, for example in the deacidification of carbonates in the mineral industry [acatech (2018); Fischedick (2015)]. Based on the number of plants under construction or in operation, the pre-combustion capture process is assumed to have a TRL of 10 [Gaurina-Međimurec (2018)].

The **POST-COMBUSTION CAPTURE** process is mainly used to capture carbon dioxide after the process step in which it is generated. Usually these are combustion processes in which carbon dioxide is separated from flue gas. In principle, the process can be retrofitted for all processes and industrial plants in which waste gases containing CO_2 are produced. The most economically and technically mature process is amine washing. Other processes, such as physical absorption using Selexol or Rectisol, are also principally possible. In the case of amine scrubbing, the waste gas stream containing CO_2 is fed after flue gas scrubbing into an absorber column in which carbon dioxide is chemically absorbed by the scrubbing agent. In the next process step, the amine solution is heated, whereby carbon dioxide is desorbed and extracted from the column [Fischedick (2015)]. This process is conceivable, for example, for CO_2 extraction from the waste gas stream of biogas combustion in CHP plants [Li (2017)]. The same applies to waste gas streams from biomass co-generation plants [Olsson (2020a)]. Moreover, it would also lend itself as a pre-combustion capture process for the biogas stream during methane processing. Membranes can also be used to capture carbon dioxide from gas mixtures. These are especially used in biogas upgrading. Here, the variable permeability of carbon dioxide (and other compounds) and methane is exploited with respect to the diffusion membrane. The raw biogas passes through several membranes; the methane-rich producer gas is retained, and the CO_2-rich waste gas stream passes through the membranes. The separation process is usually preceded by desulfurization and drying to increase the durability of the membranes. The waste gas stream has a CO_2 concentration of approx. 75 %, which means that it must be post-treated or scrubbed before the carbon dioxide can be used. Biogas upgrading by means of membrane separation has a technical readiness level of TRL 10 [Viebahn (2018)]. Large-scale industrial membrane separation is estimated to have a TRL of 7 [Shahbaz (2021)]. In the case of pressure swing adsorption (PSA), activated carbon or molecular sieves are used to separate the carbon dioxide. The process is based on the variable adsorption behavior of the various gas components. Low temperatures (approx. 5 °C) and increased pressure (2 to 7 bars) facilitate the adsorption process. PSA is an established and mature process for use in biogas upgrading (TRL 11). The CO_2 purity that can be achieved with this separation process is between 87 and 99.9 % [Viebahn (2018)]. The use of PSA on a commercial scale has a TRL of 7 [Shahbaz (2021)].

The **OXY-(FUEL) COMBUSTION CAPTURE** process represents an alternative capture technology. It is based on maintaining a high concentration of carbon dioxide in the waste gas stream and minimizing other components. It is mainly used in incineration processes. Existing incineration plants can be retrofitted, but this is more complex than for the post-combustion process. A high CO_2 concentration in the waste gas is achieved by feeding pure oxygen into the combustion chamber. Oxygen can be obtained from electrolysis by means of an air separation unit or in combination with PTL processes. Since combustion with pure oxygen would exceed the heat resistance of the materials in the combustion chamber, part of the waste gas is circulated. The resulting waste gas stream is mainly made up of water vapor and carbon dioxide. After the removal of impurities through flue gas scrubbing, the condensation of the water vapor produces a highly concentrated CO_2 stream; sulfur and nitrogen oxides remain in the condensate. To obtain carbon dioxide that is as pure as possible, trace gases such as nitrogen, argon or oxygen must be removed; this is achieved by liquefying the gas mixture [Fischedick (2015)]. The technologies that can be used for the oxy-(fuel) combustion capture process have a TRL of 6 [Shahbaz (2021)].

In the **LOW-TEMPERATURE DAC** process, solid sorbents are used to capture carbon dioxide from the atmosphere. The air passes through an adsorber unit where the carbon dioxide is bound to the sorbent under ambient conditions. Desorption takes place in the same unit as adsorption. When the filter is saturated with carbon dioxide, it is regenerated by applying a vacuum and adding heat (45 to 100 °C, depending on the specific process). The resulting carbon dioxide has a purity of approximately 98 to 99.9 %. The TRL ranges widely and is between 1 and 10 depending on the process [Viebahn (2019)]. Due to the electrical and thermal energy required by the adsorption and desorption steps, the energy demand can be higher than for CO_2 capture from point sources.

The **HIGH-TEMPERATURE DAC** process uses an aqueous solution of potassium hydroxide (KOH) to absorb carbon dioxide at ambient air temperatures of around 20 °C and at ambient pressures in an absorption column. This results in the formation of H_2O and potassium carbonate (K_2CO_3). This is regenerated in a pellet reactor (recausticizing unit) by reacting with calcium hydroxide ($Ca(OH)_2$) to form calcium carbonate ($CaCO_3$) and KOH. The hydroxide is then returned to the absorption column. This is the first cycle in the overall process. In the second cycle, $CaCO_3$ is regenerated by deacidification in a furnace (calcination unit). In this step, the carbon dioxide is recovered and can be extracted from the process. The purity of the carbon dioxide is approx. 97 %. The remaining calcium oxide (CaO) is fed into the calcination unit. Here it is remixed with water at a temperature of around 900 °C to form $Ca(OH)_2$, which is returned to the recausticizing unit. The TRL of these processes also ranges widely and is between 1 and 6. The deacidification in the calcination unit demands a high level of heat. The process heat can be supplied through the combustion of natural gas, and a combined gas and steam turbine can be used for integrated power generation [Keith (2018); Viebahn (2019)]. This capture process also requires more energy than when CO_2 is captured from point sources.

In addition to the low-temperature and high-temperature DAC processes, there are other DAC separation processes in which absorption takes place in solutions of NaOH or a mixture of potassium hydrogen carbonate ($KHCO_3$), K_2CO_3 and KOH without needing to add thermal energy. In these processes, the sorbents are regenerated by electrodialysis [Viebahn (2019)].

EXAMPLES OF COMPANIES AND INITIATIVES

Post-combustion capture processes are already being used on a large scale in power plants, for example as part of the Petra Nova Carbon Capture Project (Texas, USA), where approx. 4,800 t/d of CO_2 are recovered at a capture rate of 90 % [Shahbaz (2021)]. The oxy-fuel process has already been trialed on a smaller scale in several coal-fired power plants, such as the Schwarze Pumpe power plant [Fischedick (2015)]. Large-scale CO_2 capture – with CO_2 capture rates of 1 to 3.8 million t/a – is planned using the pre- and oxy-(fuel) combustion processes [Shahbaz (2021)]. Research is also being carried out on the implementation of oxy-fuel processes in cement plants as part of the "ECRA-CCS" and "CEMCAP" projects [Agora Energiewende (2019)].

So far, low-temperature DAC plants have been built that use various sorbents and have different capture capacities. Capacities range from 3.8 kg/d of CO_2 up to 2.46 t/d of CO_2 [Viebahn (2019)]. High-temperature DAC technology is currently being demonstrated at a pilot plant in Squamish, Canada, which has a capacity of 0.6 t/d of CO_2 [Keith (2018)].

Most active CO_2 capture processes at biorefineries are coupled with ethanol plants, with the largest in 2019 being a corn-based ethanol plant run by ADM (USA) with a capture capacity of 1 million t/a [Global CCS Institute (2019)]. Other initiatives include a study of the use of CO_2 capture at a biomass-based co-generation plant in Denmark, a biomass-based electricity plant in the United Kingdom, and a waste-to-energy plant in Norway [IEA Bioenergy (2021a)].

3.8.4 Reverse water gas shift reaction and co-electrolysis

PROCESS DESCRIPTION

The water gas shift reaction is used, for example, in steam methane reforming processes to increase the hydrogen yield. This reaction is reversed in PTL processes to produce a CO-H_2 syngas from carbon dioxide and hydrogen. This is called a reverse water gas shift reaction (RWGS). RWGS is an endothermic reaction that typically uses a nickel- or aluminum-based catalyst [Rezaei (2019)]. The reaction takes place at high temperatures of between 700 and 1,000 °C with pressures of up to 30 bars. A lower process temperature increases the undesirable formation of methane as a result of the Sabatier reaction [König (2016); Wolf (2016)]. Process heat of around 0.28 kWh/kg of CO is required [Rezaei (2019)]. It can be provided by combustion or electricity.

Synthesis gas can also be generated directly from water and carbon dioxide in a single process step by means of high-temperature co-electrolysis (CoEL), as illustrated in Figure 3-12. The electrochemical conversion takes place in a solid oxide electrolyzer at high temperatures of between 600 and 1,000 °C and at pressures below 10 bars [Zheng (2017)]. Inside the electrolyzer, carbon dioxide and water are fed into the cathode side, where water is split and carbon dioxide is activated (mainly by internal RWGS) [Foit (2017)]. Negatively charged oxygen ions pass through the solid electrolyte to the anode side, where the oxygen leaves the cell, usually in a stream of purge gas.

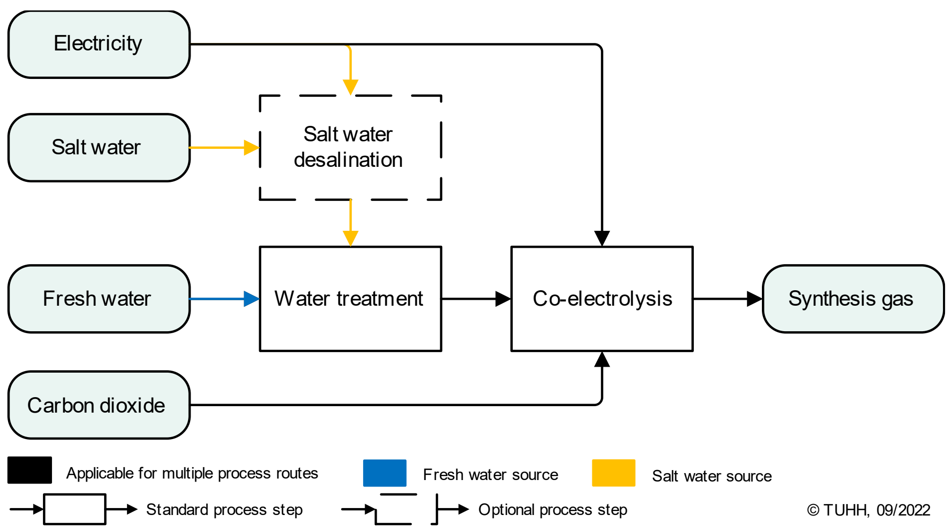


Figure 3-12 Schematic illustration of synthesis gas provision using co-electrolysis

The Gibbs free energy of formation decreases as temperatures increase. This means that less electricity is required for high-temperature electrolysis than for low-temperature electrolysis, which is considered one of its most significant advantages. However, a heat source is needed to bring the feed water (and carbon dioxide) up to the temperature of the CoEL. Most of the heat is needed for evaporating the water, which increases the overall efficiency if waste heat is available at these temperatures. CoEL shows limited susceptibility to feed gas impurities. A fluctuating supply of electricity, which can occur with renewable energy, can be compensated for either by load control of the cells themselves or by switching individual modules on and off. If waste heat is used to cover the thermal energy demand, temperatures must be managed in order to keep the temperature inside the electrolysis stack above a certain level to avoid material stress and degradation [Buttler (2018); Foit (2017); Zheng (2017)].

EXAMPLES OF COMPANIES AND INITIATIVES

As a traditional technology and catalyst developer, Haldor Topsøe A/S (Denmark) has been providing commercial solutions for water gas shift reactors for many years and, based on this experience, can also develop solutions for the reverse reaction. Since these are often tailor-made solutions, no specific modules or systems are offered. Compact modular RWGS plants are also provided by INERATEC GmbH (Germany).

In addition to high-temperature electrolyzers for pure hydrogen production, Sunfire GmbH (Germany) offers co-electrolyzers under the product name Sunfire-SynLink, which are also available as modular systems with an output of 750 m^3/h (STP) and a power consumption of 3.6 kWh/m^3 (STP) per module. The SOEL technology from Haldor Topsøe A/S can be used in co-electrolysis, however these models are also not yet commercially available [Haldor Topsoe (2021)].

RESEARCH AND DEVELOPMENT NEEDS

Some research and demonstration plants do exist, however no RWGS reactors are currently in commercial use. For example, an RWGS reactor is being used in a demonstration of a PTL process via Fischer-Tropsch synthesis (Section 3.8.6), which produces up to 200 l/d of fuel [KIT (2021)]. The technical development status is estimated to be at TRL 6 to 7. Reactors in which electricity is used to provide the required heat have a lower TRL. The challenges faced by the development and operation of large-scale commercial RWGS reactors include preventing soot formation and ensuring real-world catalyst lifetimes. Another research goal is the development of a reactor that can be heated directly by electricity in order to avoid an additional external heat supply, for example from combustion processes. This variant is currently still under development and can be classified as having a TRL of between 4 and 5.

Even though the CoEL technology has been demonstrated, it has not been used commercially. The challenges it is facing along its way to large-scale application include the long-term stability of the material, degradation, and effects such as carbon deposition. The TRL is currently estimated to be at 4 to 5; several pilot plants are planned or already under construction, suggesting a rapid rise in the TRL in the coming years [Buttler (2018); Foit (2017); Schmidt (2016)].

3.8.5 Syngas upgrading

Synthesis gases from the various supply options can contain a range of impurities and contaminants that influence the subsequent synthesis step. These include, for example, solids and tars, undesirable hydrocarbons, and hydrogen sulfide. These must first be removed or converted into utilizable components prior to synthesis.

Various technologies can be used to remove solids and tar. A choice can be made, for example, between cyclones, filters, electrostatic precipitators and water scrubbers, depending on the efficiency requirements, acquisition, operating costs, and the infrastructure needed for the required operating conditions [Brandin (2011)].

In order to adjust the synthesis-specific ratio of hydrogen to carbon monoxide, additional hydrogen can be generated from carbon monoxide through a water gas shift reaction [Brandin (2011)]. The simultaneous production of carbon dioxide must be considered here. Excess methane or other short-chain hydrocarbons in the syngas can be converted into carbon monoxide and hydrogen by steam reforming, for example.

Various technologies are also available for the removal of acid gases, such as hydrogen sulfide. These are mainly based on physical and chemical processes, such as absorption/adsorption, diffusion in membranes or chemical conversion. The process can be selected based on criteria such as gas purity, gas composition, selectivity and economic conditions, among others things [Higman (2008)]. The process technology includes chemical scrubbing with amines or methanol (at cryogenic temperatures), molecular sieves and pressure swing adsorption [Brandin (2011); Higman (2008)].

3.8.6 Fischer-Tropsch synthesis

PROCESS DESCRIPTION

Fischer-Tropsch (FT) is the term used to describe the synthesis of liquid and gaseous hydrocarbons from syngas at high temperatures (200 to 350 °C) and high pressures (20 to 40 bars). A distinction can be made between low-temperature Fischer-Tropsch synthesis and high-temperature Fischer-Tropsch synthesis. The former produces mainly waxes and other long-chain hydrocarbons; the latter primarily produces products of the gasoline fraction. The heterogeneous reaction is controlled by iron or cobalt catalysts. The product spectrum follows the so-called Anderson-Schulz-Flory distribution, which depends on various factors such as reaction temperature, pressure and catalyst. [Albuquerque (2019); Dieterich (2020)]

Thus, the composition of the product depends on the synthesis conditions, and the reaction can theoretically be adjusted to prioritize specific fractions, such as kerosene or diesel. The final product is called biocrude, which must undergo hydrotreatment to adjust the fuel properties. This can be done directly at the plant after Fischer-Tropsch synthesis or in a petroleum refinery, for example through co-refining (see Section 3.9). [Dieterich (2020); Kirsch (2020b)]

EXAMPLES OF COMPANIES AND INITIATIVES

Companies are using a decentralized approach to develop scalable Fischer-Tropsch reactors. For example, INERATEC GmbH (Germany) is developing a microstructured reactor that can better control the temperature of the exothermic synthesis due to the high contact surface for heat and mass transfer [INERATEC (2021); Kirsch (2020a); Loewert (2019)]. The “EnergyLab 2.0” project is implementing this type of reactor in a pilot plant that has a product capacity of 200 l/d. Here, the feedstock is carbon dioxide, which is first converted into carbon monoxide by RWGS [KIT (2021)]. There is a particular focus on the dynamic, flexible-load operation of Fischer-Tropsch synthesis in order to better integrate fluctuating renewable energy into the process.

One example of the application of biomass-based Fischer-Tropsch synthesis was the demonstration plant operated by CHOREN Industries GmbH (Germany), which reported an annual capacity of 13,500 t/a of biocrude in 2009 [IEA Bioenergy (2021b)]. The project was discontinued as a result of the company’s insolvency [USDA Foreign Agricultural Service (2011)]. The technology came from Shell and was later used on a larger scale at the Pear GTL plant (Qatar) [ETIP Bioenergy (2021c)].

Various commercial Fischer-Tropsch production plants are currently under construction [CAAFI (2018)]. For example, Fulcrum BioEnergy Inc. is building a municipal solid waste processing plant in Nevada, USA, with a capacity of nearly 42,000 m^3/a of syncrude[7] [Fulcrum Bioenergy (2021)]. Red Rock Biofuels LLC is building a plant in Oregon (USA) with a capacity of around 60,000 m^3/a for processing various fractions of waste wood [Red Rock Fuels (2021)]. Another example is a plant operated by Velocys Inc in Natchez (USA) that has a biocrude capacity of around 132,000 m^3/a. The plant has already provided FT-SPK for

[7] Fulcrum BioEnergy Inc. is planning various reactants for its plant, of which biobased feedstocks are one possible option. Accordingly, the intermediate product from the Fischer-Tropsch synthesis is more commonly referred to as syncrude.

test flights [Surgenor (2021); Velocys (2021a), (2021b)]. In addition, various PTL plants, especially for the aviation industry, that have a total capacity of approx. 8 million t/a, are either under construction or projected [futurefuels.blog (2021); INERATEC (2022); Norske (2020); WEF (2021)].

Research and development needs

Fischer-Tropsch synthesis is, in and of itself, an established technology for producing syngas from coal or natural gas and has a TRL of 9. One commercial example is the Pear GTL plant mentioned above [ETIP Bioenergy (2021c); Shell (2021a), (2021b)]. The technical readiness of biobased FT pathways only has a TRL of 7, mainly due to the gasification process step. Electricity-based FT processes using RWGS are estimated to have a TRL of 6 to 7, also as a result of this process step.

Decentralized reactor designs are currently in the development phase [Frilund (2021); Loewert (2019)], but other aspects of the process are also in the research or optimization phase. This includes, for example, the utilization of the light gases produced during synthesis [Halmenschlager (2016)] and the process's dynamic operation [Pfeifer (2020)].

Fischer-Tropsch kerosene has been approved by the ASTM D7566 for use in civil aviation at blending rates of up to 50 % v/v. No differentiation is made between the feedstocks, and both fossil and biogenic FT fuels are covered by this regulation [CAAFI (2021)].

3.8.7 Methanation

Process description

Methanation is a heterogeneously catalyzed gas phase reaction in which carbon monoxide or carbon dioxide is thermochemically converted into methane and water through a reaction with hydrogen. It is also called the Sabatier reaction because it was first described by the French chemists Sabatier and Senderens in 1902 [Hänggi (2019); Müller (2013)]. A hydrogen/carbon monoxide ratio of $H_2/CO = 3$ is required for a reaction with pure carbon monoxide. For the methanation of carbon dioxide, a corresponding conversion into carbon monoxide and the associated hydrogen demand must be considered, which means that a stoichiometric ratio of $H_2/CO_2 = 4$ is required here. The WGS reaction – normally an undesirable side reaction of methanation – can be systematically used to adjust the ratio [Materazzi (2019)].

The reaction is thermodynamically facilitated by low temperatures and high pressures, but usually occurs somewhere between 300 to 500 °C and at pressures of up to 100 bars [Ferrari (2021)]. Lower temperatures, despite the thermodynamic benefit, result in increased demands on the material and the catalyst activity [Schlüter (2018)]. Various metal catalysts can be used for methanation reactions. Nickel is typically used on an alumina support due to its good activity and selectivity at a comparatively moderate raw material price [Rönsch (2016)]. In the case of nickel catalysts, particular attention must be paid to the sulfur content of the reactant gas in order to avoid an undesirable deactivation [Materazzi (2019)].

Examples of companies and initiatives

The plant mentioned in Section 3.8.1, which was developed as part of the "GoBiGas" project, was built during an initial expansion stage as a demonstration-scale methanation plant (20 MW of product gas capacity). It was intended to be gradually expanded to a commercial scale with a capacity of 100 MW [Larsson (2019)]. However the plant ceased operations in 2018 [Alamia (2017); Larsson (2019); Materazzi (2019)].

Since 2013, Audi has been operating a pilot plant in Werlte that utilizes carbon dioxide from a biogas plant. The plant produces synthetic methane through methanation. The required hydrogen is produced via electrolysis with the help of solar and wind energy [Audi (2015)]. It has a capacity of around 6,000 kW and produces 1,300 m^3/h of hydrogen, from which 300 m^3/h of synthetic methane are generated [dena (2021a)]. Furthermore, a gasification plant near Lyon (France), which produces 0.1 t/a of synthetic methane, has been in operation since 2017 as part of the "Gaya" project [Gaya (2021); IEA Bioenergy (2021b)].

RESEARCH AND DEVELOPMENT NEEDS

Methanation is estimated to have a TRL of 6 and its technological development seems to stagnate at times. After successful demonstrations in the early 2010s, the step of commercial application of methanation failed. Nevertheless, there is a steady interest and research activities are being conducted as part of various projects. The process is currently being optimized, for example through the development of a transient reactor that uses intermittent energy [Matthischke (2016)]. In 2019, 36 active methanation projects were reported worldwide, most of them in Europe [Thema (2019)].

3.8.8 Methanol synthesis and downstream technologies

PROCESS DESCRIPTION

Methanol is an alcohol with a carbon molecule in its structure that can be synthesized from syngas. This requires syngas that contains a carbon monoxide to hydrogen ratio of 1:4. These components are introduced into a reactor under high pressures and temperatures and in the presence of a copper catalyst. The reactor is available in various commercial designs (e.g. adiabatic, quasi-isothermal, water-cooled or gas-cooled) [Kiendl (2018)]. Methanol can also be synthesized by direct hydrogenation with a CO to H_2 ratio of 1:6 [Marlin (2018)]. Partial oxidation of methane is also possible. Here methane reacts with oxygen to form methanol [Alfadala (2009); Ge (2016); Park (2019)].

Methanol can be used either directly as a fuel or as a base molecule for the production of other fuels. Figure 3-13 provides an overview of the process.

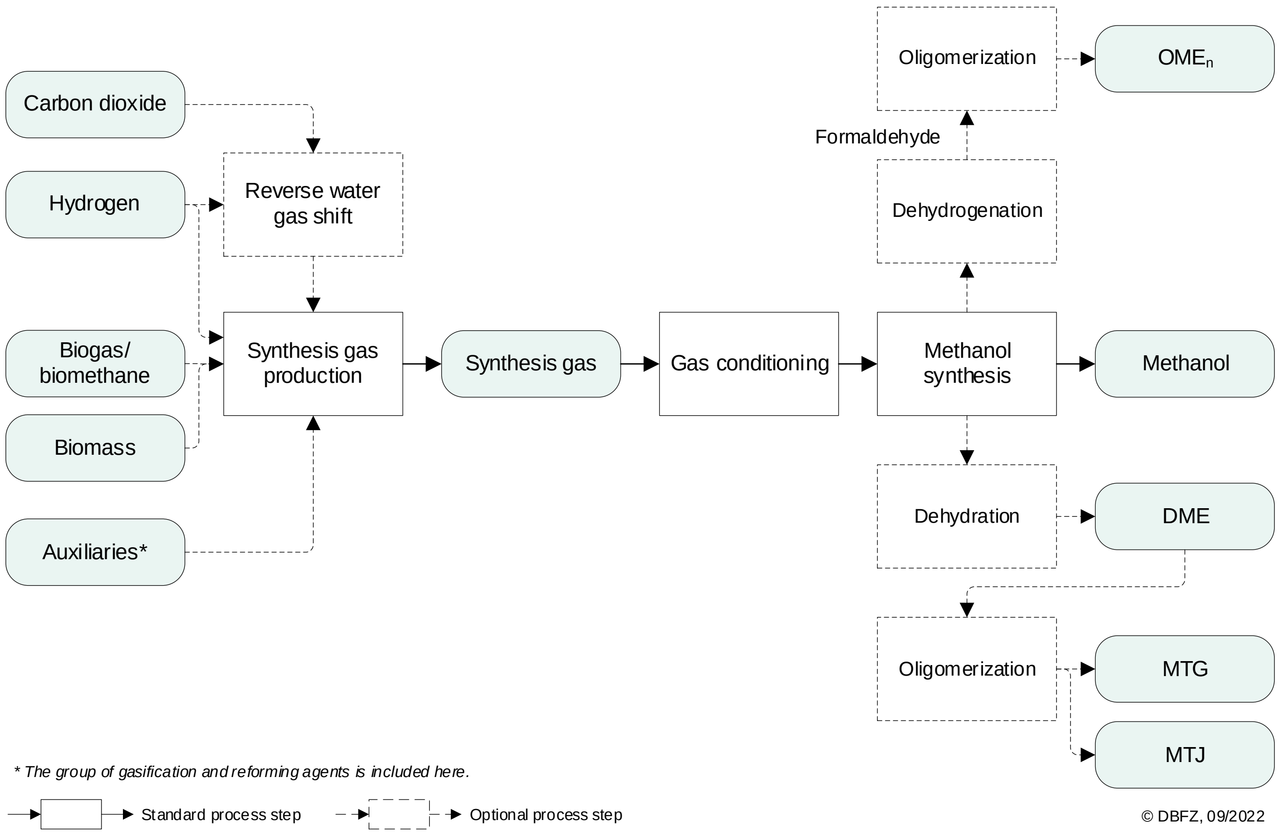


Figure 3-13 Schematic illustration of methanol synthesis and a variety of downstream technologies

DME is the product of methanol dehydration. During synthesis, methanol is split into water and DME in an exothermic reaction. Alumina and aluminosilicate are used as catalysts [Zhou (2016)]. DME can also be synthesized directly from syngas, with reactions of the methanol synthesis, the water gas-shift reaction and methanol dehydration occurring at the same time in the same reactor [Dahmen (2012); Kiendl (2018)]. DME differs significantly from methanol; it has a lower boiling point (-25 °C) than methanol (64.7 °C) and is therefore gaseous at room temperature. Its lower heating value (28.8 MJ/kg) is higher than for methanol (19.6 MJ/kg) [Schröder (2020b)].

Methanol can be further processed into a gasoline fraction as part of a methanol-to-gasoline (MTG) process. In this process, methanol is first partially converted into DME. Methanol and DME react with each other to form light olefins and water. The light olefins react with each other using a zeolite catalyst to form a mixture of paraffins, naphthenes and aromatics [Marsh (1988)]. After the reaction, unconsumed reactants are separated and returned to the reactor. A yield example for the MTG reaction is 1 % gas, 5 % LPG, 38 % synthetic gasoline and 56 % water [ExxonMobil (2017)].

Alternatively, methanol can be further synthesized using the methanol-to-jet (MTJ) process. This is carried out in three process steps: methanol production, synthesis of olefins from methanol (methanol-to-olefins – MTO) and synthesis of paraffinic molecules [Wassermann (2020)]. In the MTO process, methanol is dehydrated as in the MTG process. In this case, the reaction conditions tend to result in the formation of light olefins – mostly ethylene and propylene. These are then converted by oligomerization and hydrotreatment to a kerosene fraction and other products [Bradin (2014); Salkuyeh (2015)].

Other oxygenated molecules are also of interest to researchers for use as fuel substitutes: polyoxymethylene dimethyl ether (oxymethylene ether, OME_n), dimethyl carbonate (DMC) and methyl formate (MeFo). To produce OME_n (where n indicates the number of interconnected OME fragments), methanol is dehydrated to form DME or dehydrogenated to form formaldehyde, which serve as suitable intermediate molecules for oligomerization into OME_n [Schmitz (2015)]. A reaction of methanol with carbon dioxide and carbon monoxide produces DMC and MeFo, respectively. Because of their production process, these fuel substitutes are considered carbon neutral [Härtl (2017); Maier (2019); Tschöke (2019)]. Methyl tertiary-butyl ether (MTBE) can be produced when methanol reacts with iso-butene. It is used as an additive to increase the octane number in gasoline. However, MTBE fell into disrepute due to various cases of groundwater contamination [Grathwohl (2005); Smith (1990)].

Another source of methanol is the kraft process used in the pulp industry. Methanol is produced as a by-product during the kraft pulping of wood. The amount produced depends, among other things, on the type of wood, the temperature, and the cooking time, and can range between 7.3 and 15 kg methanol/t of pulp (oven-dry) [Jensen (2012)]. Crude methanol contains impurities, for example, nitrogen and sulfur, and must be purified before it can be used as a chemical or fuel [Jensen (2012); Warnqvist (2015)].

EXAMPLES OF COMPANIES AND INITIATIVES

In 2020, a methanol plant was installed as an add-on to a pulp mill owned by the company Sødra in Mönsterås (Sweden). It has a capacity of 5,250 t/a of methanol (technology supplied by Andritz AG). Alberta-Pacific Forest Industries Inc. owns a similar plant in Boyle (Canada) with a production capacity of 2,000 – 3,000 t/a of methanol [IRENA (2021c)]. Valmet also sells methanol plants [Valmet (2020b)]. Enerkem's fluidized bed gasification plant, previously built to produce methanol, was converted to an ethanol production facility in 2017 [Enerkem (2022)].

The "KEROSyN 100" project is investigating the production and use of MTJ in Germany. Methanol is produced from carbon dioxide and hydrogen from electrolysis. A pilot plant is being built in Heide (Germany) that will produce MTJ fuel. Its co-refining will be investigated in a fossil fuel refinery [DLR (2020); KEROSyN (2021)].

Siemens and Porsche are planning to build a production plant in the province of Magallanes (Chile) to manufacture synthetic gasoline using the MTG process. Plans are to scale up a pilot plant with an annual production of 130,000 l/a in 2022 to 55 million l/a by 2024 [Porsche (2020); Siemens (2021)]. The Closed Carbon Cycle Mobility project is investigating the use of products derived from methanol (e.g., synthetic gasoline, octanol) that can be used as drop-in fuels [C3-Mobility (2021)].

RESEARCH AND DEVELOPMENT NEEDS

Industrial technologies for methanol synthesis have a TRL of 10 and are available from various technology providers (e.g., Air Liquide, Haldor Topsøe A/S, Linde) [Dieterich (2020)]. However, modular or small-scale production of methanol from biobased feedstocks is only finding its way out of the demonstration phase and is at TRL 8 [ALIGN-CCUS (2019); C2FUEL (2020); CO2FOKUS (2020); FReSMe (2021)].

The production of bio-based methanol with subsequent DME synthesis through the gasification of black liquor was advanced to the demonstration phase and thus to a TRL of 6 to 7 by the "BioDME" project. After this project, however, there was no project which aimed to further improve this technology [ETIP Bioenergy (2021b); Salomonsson (2013)]. The synthesis of DME using steam reforming of biogas was demonstrated by the company Oberon Fuels (USA) on a pilot scale in Brawley (USA) and has a TRL of 7 [Oberon Fuels (2021)]. There are also projects aimed at optimizing the technology for producing DME without using methanol as an intermediate (direct DME synthesis). Depending on their process concept and feedstock, these projects have a TRL of 5, e.g. for the FLEDGED project [FLEDGED (2018)], and a TRL of 8, for the AlignCCUS project fed by fossil CO_2 sources and electrolysis-H_2 [CORDIS (2016)]. The production of oxygenated molecules from methanol (OMEn, DMC, and MeFo) is still mostly in the research phase and must therefore be rated TRL 2 to 3 [Benajes (2020); Rashid (2019), (2019); Zhang (2020)].

3.8.9 Ammonia synthesis

PROCESS DESCRIPTION

Ammonia is produced worldwide, mostly using the Haber-Bosch process in which nitrogen and hydrogen react with each other in the gas phase at high temperatures (approx. 450 °C) and high pressures (approx. 200 bars). An iron catalyst is used for this [Brohi (2014); Kugler (2015)]. The nitrogen used in the process is obtained through an air separation unit, and the hydrogen can come from a variety of sources. Currently, most of the hydrogen used in ammonia production worldwide comes from natural gas and coal.

Green ammonia is the name given to ammonia produced from renewable resources. To minimize the emission of carbon dioxide during the production process, both hydrogen and the necessary heat should come from renewable resources [Brohi (2014)]. For hydrogen production, electrolysis, steam reforming of biomethane (Section 3.4), and biomass gasification (Section 3.8.1) are suitable options. Figure 3-14 illustrates this production process.

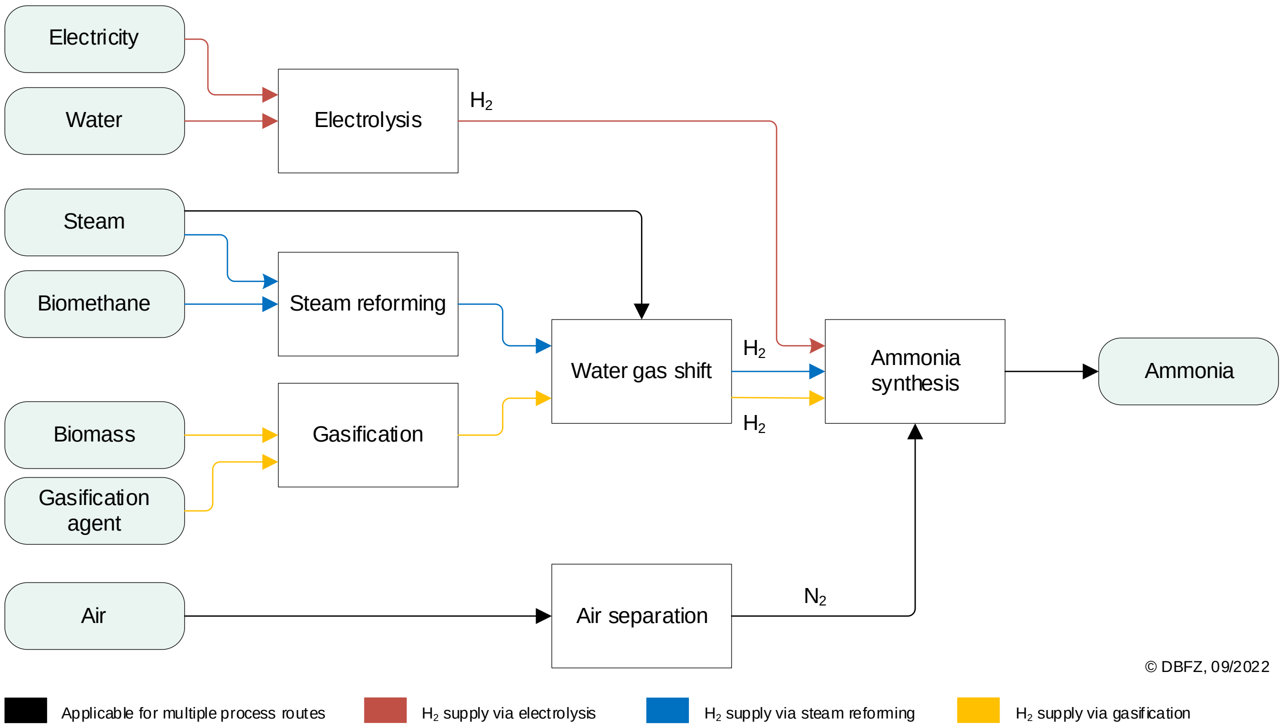


Figure 3-14 Schematic illustration for producing ammonia using biogenic feedstocks

EXAMPLES OF COMPANIES AND INITIATIVES

The theoretical production of ammonia using hydrogen supplied through the gasification of lignocellulosic biomass and black liquor has already been investigated in technical-economic studies. [Akbari (2018); Andersson; Cardoso (2021)] and life cycle assessments [Ahlgren (2012)]. Projects for the production of bio-based ammonia have been announced, but they have yet to be initiated [Ahlgren (2013); Brown (2013)]. In Brazil, Raízen S.A. operates a biogas plant that uses vinasse. The company has signed a contract to supply 20,000 m³/d of biomethane to the company Yara from 2023 onwards to produce hydrogen for ammonia production [NovaCana (2021); Williams (2021); Yara (2021)].

RESEARCH AND DEVELOPMENT NEEDS

It has been reported that production costs would have to be lowered if ammonia from biomass is to be made economically viable [IEA (2020)]. Currently, no overall concepts for the production of ammonia have been piloted or demonstrated, which is why the technology's TRL is 5, irrespective of the process pathway [IEA (2021a)].

3.9 Co-refining

PROCESS DESCRIPTION

Co-refining or co-processing describes the process of simultaneously processing or refining petroleum-based raw materials with biogenic feedstocks using the same infrastructure and reactor technology. These biogenic blends for co-refining include, for example, bio-oils (e.g. vegetable oils, animal fat or used cooking oil) and biocrudes (incl. pyrolysis oils and oils from HTL and FT processes) [van Dyk (2019)]. The advantage of co-refining is that existing infrastructures and experience in oil refineries can be used. Due to current refinery sizes, investment costs and operating costs can be lower in comparison with those of stand-alone plants that process biocrudes. [van Dyk (2021)]

Compared to crude oil, biocrudes and bio-oils often have a significantly higher oxygen and water content, a lower heating value, and, at times, a higher content of free fatty acids [van Dyk (2019)]. In addition, they may have a higher content of alkali and alkaline earth metals (e.g., sodium, potassium and calcium) than petroleum products and may contain other chemical components that are not typical for petroleum refining [Terry Marker (2005)]. This can affect the respective operating conditions, result in a deactivation of the catalysts, and place higher demands on infrastructure materials. A pre-treatment step is often considered in the co-refining of bio-based oils so as not to run the risk of overly influencing the process [van Dyk (2019)]. One example is the esterification of bio-oils with a high acid value to protect the reactor and pipeline materials from corrosive damage. The high oxygen content of biocrudes can be counteracted, for example, by upstream hydrotreatment. The intensity of the pre-treatment of the biogenic streams in co-refining is controversially debated in the literature and depends on the composition and origin of the oil [van Dyk (2021)].

The blending location depends on how similar the biogenic substance is to the fossil-based oil as well as on the desired end product or end use. While petroleum-based crude oil is typically fractionated in refineries in an upstream distillation step before it is processed, the differences in the biogenic oils listed above can hinder this approach [van Dyk (2021)]. Accordingly, hydrocracking, hydrotreatment and fluid catalytic cracking (FCC) units are important co-refining locations after the crude oil has been distilled. Both hydrocracking and hydrotreatment aim to saturate unsaturated bonds and reduce oxygen, sulfur and other heteroatoms. Hydrocracking also modifies the product's chain length due to the harsher operating conditions. As the content of heteroatoms in the processed oil increases (for example nitrogen or oxygen resulting from a biocrude) the unit may demand more hydrogen. A similar situation occurs with regard to the proportion of unsaturated compounds in the feedstock. It is also important to note when using biocrudes that the hydrotreatment and hydrocracker catalyst is sensitive to impurities [van Dyk (2018)]. The term co-processed HVO/HEFA (CP-HVO/HEFA) is used by some publications and statistics for the products of biobased fractions co-refined with petroleum-based raw materials in a hydrotreater or hydrocracker.

The FCC unit is one of the locations being investigated for the co-refining of biocrudes such as pyrolysis oil, Fischer-Tropsch oils and hydrothermal liquefaction products that have longer hydrocarbon molecules and aromatics. Here, aromatics are split into linear hydrocarbon chains, and higher hydrocarbon chains are split into shorter chains. The process is comparatively flexible with regard to the choice of feedstock. Hydrogen demand is not expected to increase and the catalysts are more resistant to catalyst poisons than those used in hydrotreatment [van Dyk (2018)]. Figure 3-15 illustrates the key co-refining locations of biogenic feedstocks in a petroleum-based refinery.

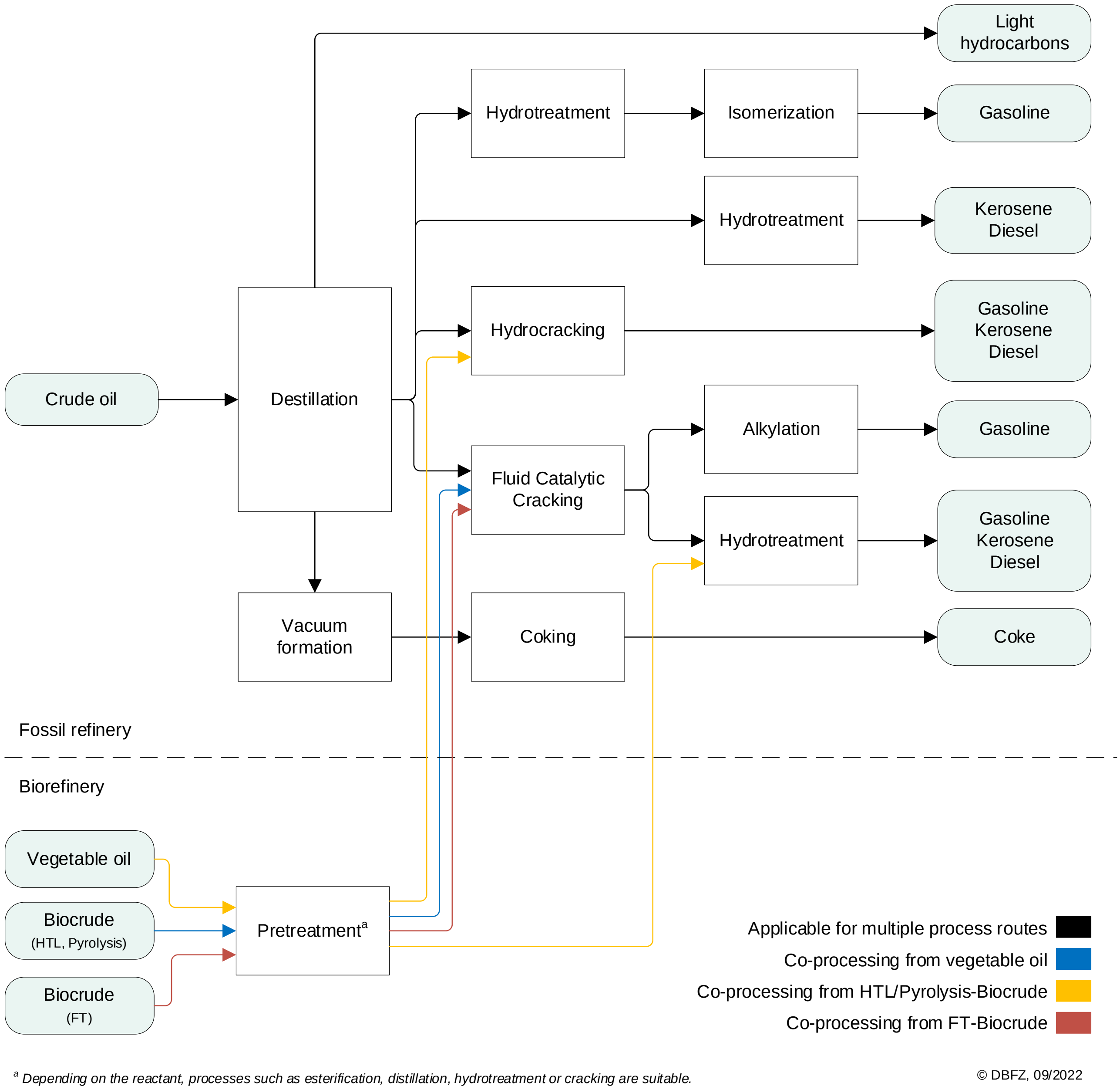


Figure 3-15 Schematic illustration of the co-refining of biogenic feedstocks in fossil refineries. Data based on [van Dyk (2018); van Dyk (2019)]

EXAMPLES OF COMPANIES AND INITIATIVES

The company Petrobras (Petróleo Brasileiro S.A.) has already commercialized gasoline with a small admixture of soy bean oil co-processed in the FCC process [van Dyk (2018)]. The same company has also tested the processing of biocrude from the pyrolysis of sugar cane straw on a demonstration scale of 150 kg/h and has reported on activities that use biocrude from other feedstocks [Rezende Pinho (2014);

Silva (2020)]. In the summer of 2021, Pyrocell Ltd. started a test phase for the initial production of around 50,000 metric tons of pyrolysis oil from sawdust using BTG Bioliquids Technology. Preem Petroleum AB, jointly owned by Pyrocell Ltd. and Setra Group AB, will co-refine this pyrolysis oil in an FCC unit at its refinery in Gävle (Sweden) for two years [Bioenergy International (2021c)].

The "BL2F" project is developing an HTL process for pulp mills to recover biocrude from black liquor which will be refined in oil refineries [BL2F (2021)]. In Norway, the company Silva Green Fuel is building a demonstration plant for the production of biocrude using HTL. The resulting biocrude is to be upgraded in fossil refineries [Silva Green Fuel (2017); Steeper Energy (2017)]. The company Arbios Biotech is planning to build a plant in Prince George (Canada) with a capacity of about 7,950 m^3/a of biocrude using HTL [Bioenergy International (2021a)]. The "KEROSyN 100" project is expected to involve the construction of an MTJ plant, whose product will be co-refined at the Heide Refinery [DLR (2020)]. In Sweden and the U.S., pyrolysis plants with capacities of 24,000 t/a and 75,710 m^3/a of biocrude, respectively, have already been installed, whose products are being processed in petroleum refineries [BTG bioliquids (2021); Ensyn (2021)]. The "Biozin" project is planning to construct a plant with a capacity of 100,000 t/a of biocrude using Shell's IH^2 "Integrated Hydropyrolysis and Hydroconversion" technology [IEA Bioenergy (2021b); Shell (2021c)]. BP's Cherry Point (USA) refinery and Parkland refinery (USA) are co-refining up to 5 % lipids [van Dyk (2021)].

Research and development needs

In the case of civil aviation, ASTM D1655, the "Standard Specification for Aviation Turbine Fuels", has permitted the co-refining of up to 5 % fats and oils since 2018 and, since 2020, the co-refining of up to 5 % biocrude from the FT process [CAAFI (2021)]. Biocrudes from HTL, pyrolysis and other thermocatalytic processes are not certified at this time. These must first be included in ASTM D1655 before they can be commercially use in civil aviation. Co-refining of up to 30 % tall oil has already been investigated by Preem Petroleum AB, but the product has not yet been approved accordingly [van Dyk (2021)]. Due to the (small amount of) biogenic lipid co-refining already taking place, a TRL of 8 to 9 can be assumed. There is still a need for more research in the field of biocrude co-refining. Due to the lack of biocrude volumes, there is little evidence of large-scale activity in this area [van Dyk (2021)]. The technical readiness level is therefore estimated at TRL 5.

3.10 Hybrid technologies

Hybrid technologies take the approach of exploiting the synergies between biomass-based and electricity-based production processes in order to benefit from the advantages they provide and to tackle any challenges. For this purpose, the terms SynBioPTX or power and biomass-to-X (PBTX) have been established [Müller-Langer (2019); Naumann (2019)].

There are two basic overall approaches:

1) The addition of electricity-based processes to biomass-based production pathways (biomass-to-X or BTX)

   Probably the most prominent example of this concept is the use of electrolysis-based hydrogen to process biomass. The synthesis processes for producing HVO/HEFA fuels through hydrotreatment (Section 3.6), synthetic methane through methanation (Section 3.8.7) and methanol through methanol synthesis (Section 3.8.8) should be mentioned here. However, the hydrogen-based processing of specific product fractions, for example through Fischer-Tropsch synthesis (Section 3.8.6) and the alcohol-to-jet process (Section 3.3) using hydrotreatment, are also relevant here. Another hydrogen application is the conditioning of synthesis gas, for example through (steam) reforming (Section 3.4) or thermochemical gasification (Section 3.8.1). The aim here is to obtain the appropriate H_2/CO ratio for an optimum product yield. Electrolytic hydrogen can also be used in bio-based methanation (Section 3.4) to increase the methane content of the product gas. The electrification of process components, such as reactors, represents another way to support biogenic production processes through electricity.

2) The utilization of biogenic carbon in electricity-based production pathways (power-to-X or PTX)

   Processes that use electricity to produce gaseous or liquid energy carriers, heat or reactants for the chemical industry are commonly referred to as PTX processes. In particular, the supply of hydrocarbons as platform chemicals for the fuel sector and selected industries relies on a carbon source. Sources of biogenic carbon in the form of carbon dioxide include fermentation gases from ethanol production, the residual gas stream from the capturing of methane from biogas, and waste gases from the combustion of biogenic feedstocks (Section 4.3.2). For the CO_2- emitting process, carbon-rich gases can be used as a way to reduce the cost of capturing CO_2 (see Section 3.8.3 for the processes). When considering such an approach, the carbon efficiency and product range of the overall process can be increased and/or expanded, which in turn can lead to a reduction in GHG emissions compared to stand-alone plants [Müller-Langer (2016)].

The project “DME-regenerativ” led by Gastechnologisches Institut gGmbH Freiberg (Germany) investigated the production of DME through the dry reforming of biogas. In this project, hydrogen from electrolysis was fed into a single-stage DME process to increase carbon utilization and thus product yield [Friedel (2018)]. While the concept was verified in a first phase of the project, which ran until 2017, the goal of the follow-up project FlexDME is to develop a modular demonstration plant that can produce up to 40 t/a of DME. In addition, the “MeGa-stoRE” project at Aarhus University (Denmark) has developed container-scale biomethane production (10 m^3/h (STP)) by hydrogenating raw biogas (after desulfurization) to produce additional methane from the carbon dioxide contained in the biogas [DTU (2019); Gaikwad (2020)]. The Karlsruhe Institute of Technology (Germany) also investigated the advantages of integrating electrolytically supplied hydrogen based on renewable electricity into biobased processes as part of the bioliq® process. Adding hydrogen to the synthesis step or in an upstream RWGS reaction to convert the remaining carbon dioxide in the syngas has been shown to increase the carbon conversion efficiency by a factor of about 4 for various downstream syngas technologies [Albrecht (2017); DLR (2017)].

Steam reforming of methane, in the form of natural gas or biomethane, is usually gas-fired to operating temperature. Haldor Topsøe A/S is currently commissioning a demonstration-scale, electrically heated steam reforming unit in Foulum (Denmark) [Bioenergy International (2021b)]. The resulting syngas will be used in the project to produce methanol (10 kg/h); however, it also offers the possibility of other downstream syngas technologies.

CAPHENIA GmbH is building a power and biogas-to-liquid (PBTL) facility as part of its innovation hub for CO_2-neutral alternative fuels at the Höchst Industrial Park (Germany) [Frankfurt HOLM (2021)]. Here, biogas is to be converted into syngas and then into synthetic fuels in CAPHENIA’s patented reactor, which will be heated by an electric plasma torch. In July 2021, CAPHENIA also announced its future involvement in the construction of a commercial production plant. This large-scale PBTL plant will be built in Steyerberg (Germany) as part of the “EnZaH2” project in partnership with Oxxynova GmbH, Avacon Natur GmbH and Lühmann GmbH [CAPHENIA (2021)].

Such a hybrid process is being implemented and further developed in the project "Pilot SBG". Within the scope of this project, certain biogenic residues, by-products and waste will be converted into renewable methane. To do this, a pilot plant will be built at the DBFZ site in Leipzig. The plant is designed to combine anaerobic fermentation with innovative pretreatment and upgrading processes. To increase methane yield, the carbon dioxide contained in the biogas is converted to methane in a catalytic methanation process that uses externally supplied hydrogen. This produces an almost pure methane that meets the legal requirements for use as a fuel in the transport sector (DIN EN 16723-2). Depending on the feedstock, the fermentation residues are further treated in a separation cascade. The aim is to recycle all of the by-products generated by the plant and to expand the plant's product portfolio by generating additional products. [DBFZ (2021a)] Figure 3-16 illustrates the synergies of the overall process.

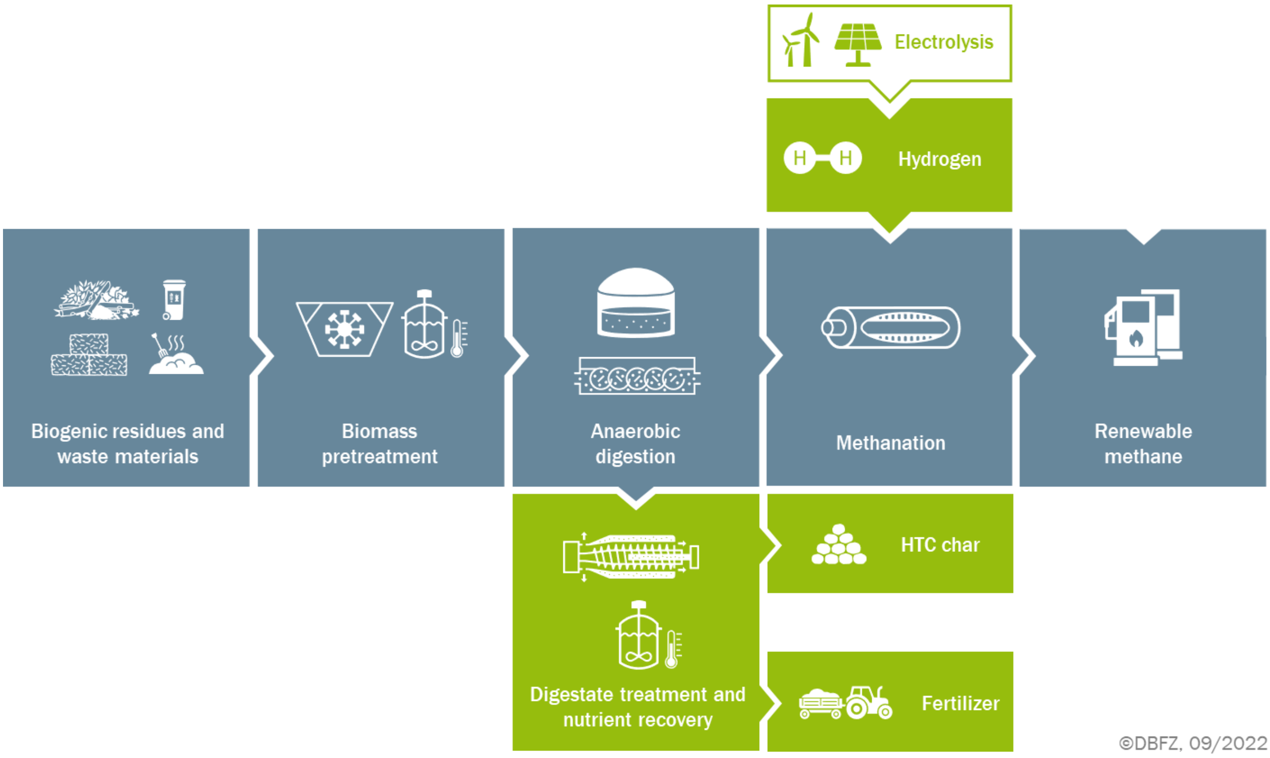


Figure 3-16 Process layout of the pilot plant for the "Pilot SBG" project. Note: no practical implementation of electrolysis [DBFZ (2021a)]

In the future, it will be difficult to separate the bio-based and electricity-based process pathways since a large number of biogenic pathways depend on hydrogen, at least for upgrading the fuel fractions. The aim should be to reduce the use of fossil-based hydrogen down to a minimum in the area of renewable fuels – electrolytic hydrogen can be a useful alternative here. The use of carbon dioxide from biogenic sources makes sense due to its concentrated availability and extensive carbon utilization, thus making a positive contribution to an efficient circular economy. The loss of biogenic carbon – as a valuable resource of many energy carriers and chemical products – in the form of carbon dioxide should primarily be avoided in the future. If this cannot be technically achieved, the carbon dioxide should be recycled downstream from the process step.

4 Resources and their mobilization

Karin Naumann, Gabriel Costa de Paiva, Ulf Neuling, Tjerk Zitscher, Selina Nieß and Karl-Friedrich Cyffka

4.1 Suitable feedstocks at a glance

The supply of feedstock is the first step in the renewable energy supply chain. The biogenic feedstocks suitable for biofuel production can be categorized based on various criteria. Regulations primarily divide these into biogenic products (primarily cultivated or crop plants), biogenic by-products, and wastes and residues. In addition to being categorized by origin, the various biogenic feedstocks can also be differentiated based on their physical and chemical properties. These determine how suitable they are for the various renewable fuel production processes (Section 3).

For more information:

The main raw materials for renewable fuels of non-biological origin (RFNBO) are electricity from renewable sources and water to produce green hydrogen via electrolysis, as well as a carbon source (usually CO_2) so that they can be further processed into fuels that contain carbon. The electricity can be generated from wind and solar energy, biomass, geothermal energy or hydropower, and carbon dioxide can be obtained from either industrial processes (of fossil or biogenic origin) or directly from the air. In addition to fossil-based carbon sources for the production of e-fuels, carbon sources used to produce so-called recycled carbon fuels (RCF) are also expected to play an important role in the future. This can include liquid or solid waste that cannot be recycled (material recycling) or waste gases that are generated by industrial processes and cannot be avoided [Richtlinie (EU) 2018/2001 (2018)].

Figure 4-1 shows examples of feedstocks based on their origin and composition (without weighting them based on proportion of real use).

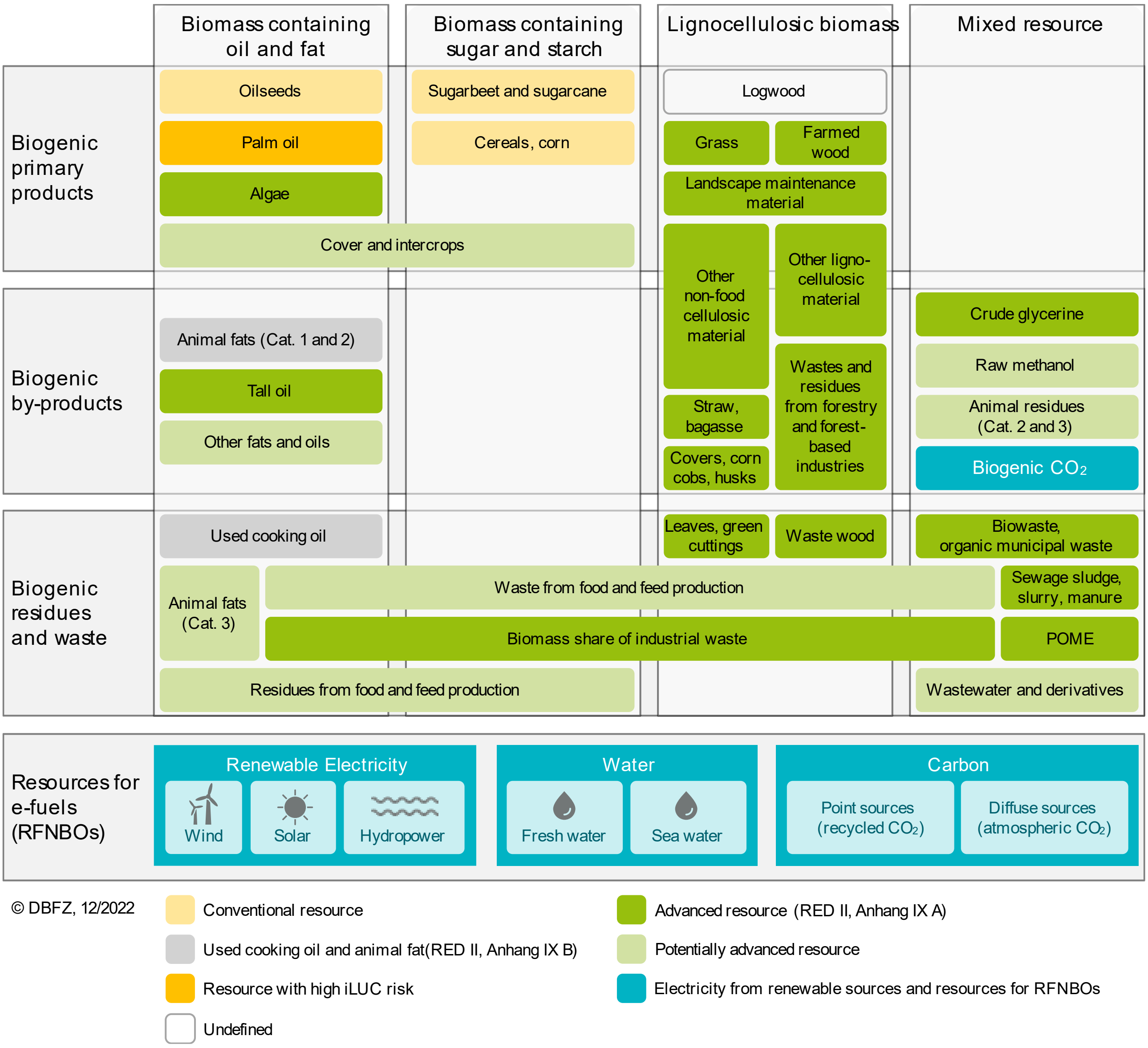


Figure 4-1 Feedstocks used in the production of renewable fuels. Note: not exhaustive, cat. stands for category, potentially advanced feedstocks as per [E4tech (2020)]

The feedstocks are classified based on the European Union's Renewable Energy Directive (RED II)

- Feedstocks for advanced liquid and gaseous biofuels (Annex IX A of RED II),
  - Algae (cultivated on land in ponds or photobioreactors)
  - Biomass fraction of mixed municipal waste
  - Biowaste from private households
  - Biomass fraction of industrial waste (not fit for use in the food or feed chain)
  - Straw
  - Animal manure and sewage sludge
  - Palm oil mill effluent (POME) and empty palm fruit bunches
  - Tall oil pitch, crude glycerol, bagasse, grape marcs and wine lees, nut shells, husks, cobs cleaned of kernels of corn

Biomass fraction of wastes and residues from forestry and forest-based industries (incl. black liquor, lignin and tall oil)

Other non-food cellulosic material and other lignocellulosic material

- Used cooking oil and animal fats classified as Category 1 and 2 in accordance with Regulation (EG) Nr. 1069/2009 (Annex IX B of RED II),
- Conventional feedstocks, i.e., food and feed crops (overwhelming share of established production) with and without a high iLUC risk; and
- Renewables of non-biological origin (RFNBO).

The European Commission has also commissioned a consortium led by E4tech to help it assess potential feedstocks for the production of advanced biofuels that could be included in Annex IX of RED II (EU 2018/2001) or its revised version [E4tech (2020)]. They can be included through a delegated act, taking into account the following aspects:

- Principles of a circular economy and waste hierarchy (in accordance with Directive 2008/98/EG),
- Sustainability criteria as defined by RED,
- Avoidance of waste or residues and avoidance of significant competition-distorting effects on the markets for (by-)products,
- Potential for significant GHG emissions savings over fossil fuels based on the life cycle assessment of the emissions,
- Avoidance of negative impacts to the environment and biodiversity, and
- Avoidance of an additional demand for land.

The feedstocks listed below are on the short list:

- Food-feed processing residues and waste

  (Bakery and confectionery by-products, drink residues and waste e.g., citrus peel and pulp (pressing), fruit /vegetable waste and residues e.g., blemished fruit/vegetables, potato/beet pulp, starchy effluents, sugars (fructose, dextrose) refining residues, molasses, vinasse, alcoholic distillery by-products, whey permeate, olive oil extraction residues)
- Agricultural and forestry residues and waste

  (Raw methanol as a processing residue from pulp production)
- Cover and intermediate crops

  (Oil, beans and meals derived from rotation crops (e.g., silphium perfoliatum, tall wheat grass, camelina, carinata, castor, tobacco)
- Landscape conservation material

  (Biomass from fallow land e.g., hay, legumes, grass, biomass from degraded/polluted land, grass clippings e.g., a mixture of timothy grass, meadow fescue, tall fescue, and clover/leguminous crops, damaged crops)
- Animal residues and waste

  (Animal residues (not fat) that fall under Category 2 and 3, e.g., organs, blood, bones; animal fats that fall under Category 3 (e.g., beef tallow, poultry fat and pork fat)
- Wastewater and derivatives

  (Municipal wastewater and derivatives (other than sludge))

- Fats, oils and grease
  (Soapstocks and derivatives e.g., free fatty acids, brown grease, fatty acid distillates e.g., from palm and oil seeds)
- Other feedstocks
  (Various oils from ethanol production, distillers grain and solubles (DGS), other biowaste).

[E4tech (2020)]

The final decision on the inclusion of new feedstocks in Annex IX lies with the European Commission. According to [E4tech (2020)], feedstocks processed with advanced technologies should be included in Part A and those processed using mature technologies should be included in Part B.

Resources that are not or not yet defined under RED II have neither a limitation nor a special promotion regarding their contribution to the targets.

In **Germany**, sustainability certificates are issued based on the state database Nabisy. The Federal Agency for Agriculture and Food (BLE) is responsible for this and has defined 309 active biomass types (79 of them according to Annex IX A and 30 according to Annex IX B of RED II), which can currently be used to certify biofuels so they can be counted towards the German GHG quota [BLE (2021c)].

4.1.1 Biogenic primary products

In terms of production technologies for biofuels, biogenic feedstocks can be classified based on their main components, as briefly described below.

Biogenic primary products that contain oil and fat, such as the oil seeds of rape, soy beans and sunflowers or the fruit of the oil palm, contain long carbon chains whose fatty acid composition depends on the oil plant [Dieterich (2020)]. The requirements for processing the biomass vary depending on this composition, as does the resulting product composition. In principle, they are suitable for the production of vegetable oil fuel, biodiesel (FAME), and HVO (hydrotreated vegetable oil)/HEFA (hydroprocessed esters and fatty acids) fuels.

Algae are widely being discussed and studied as a promising alternative. As a feedstock, algae have the advantage of being fast growing, of having a high oil content and of not requiring arable land [Ganesan (2020)]. Algae oil yields mainly depend on the species of microalgae used. For example, the species *Nannochloropsis salina* has a lipid content of 31 % to 68 % based on dry weight [Schlagermann (2012)]. Other algae species that have been investigated include *Phaeodactylum tricornutum*, *Nannochloropsis oculta*, *Monodus subterraneus* and *Odontella aurita* [CORDIS (2013); DBU (2010)]. However, there are still some technical challenges associated with algae production, as it requires high levels of electricity, water and nutrients and processing is still at an early stage of development [Moshood (2021)].

Biogenic primary products that contain sugar are particularly suitable for the production of biofuels through fermentation due to the direct availability of glucose. One example is bioethanol. Sugar cane and sugar beets are especially suitable as they have an average glucose content of around 20 % [Pérez (1997)] and 16 % [FAO (1999)] respectively.

In the case of **biogenic primary products that contain starch**, such as corn, wheat or other grains, the carbohydrates that contain starch are converted into a suitable sugar for fermentation through hydroliysis. Corn, for example, has a carbohydrate content of approx. 19 % - about one third of which is starch. It cannot be used in the fermentation process without prior hydrolysis [U.S. Department of Agriculture (2019)].

In 2015, the European Union introduced “Greening”, an agricultural policy instrument to promote the cultivation of **COVER CROPS, SUMMER AND WINTER INTERMEDIATE CROPS**, and undersown crops in the primary crops, thus ensuring more biodiversity in agriculture. In 2016, around 20 % of all arable land in Germany was cultivated with intermediate crops [Henke (2018)]. In the future, these could also play a greater role in the production of advanced biofuels, although the use of such intermediate crops must not lead to an additional demand for agricultural land. One example is Ethiopian mustard (*Brassica carinata*), an oil seed with an oil content of around 27 % [Paula (2019); Sharafi (2014)]. It is used as a feedstock in the production of advanced biofuels because it can more efficiently utilize nutrients, land and water as part of the practice of intercropping [Lal (2019)]. Ryegrass and forage rye are other potential crops as these can be processed into biogas or biomethane through anaerobic fermentation for example [Henke (2018)].

BIOGENIC PRIMARY PRODUCTS THAT CONTAIN LIGNOCELLULOSE, such as grasses, can be used for fermentation following their digestion to sugar. Other woody biomass, above all cultivated wood from short rotation plantations (SRP) is processed without digestion using thermal processes such as pyrolysis and gasification. Investigations are being made into alternative crops like tall wheatgrass (*Agropyron elongatum*) that can be cultivated on land that has special site-related challenges [TFZ (2021)]. Tall wheatgrass is characterized by its robustness and low maintenance, which can be beneficial on marginal land (especially very dry land), reducing nutrient depletion and soil erosion [Cui (2018); Schröder (2018)]. The landscape conservation material from these perennial crops is suitable for biogas or biomethane production [Ciria (2020); Heinz (2018)].

Excursus 2: The plant as a "multi-product system"

Cultivated biomass utilization is, in principle, a multi-product system in which not only a single part of the plant is used, but ideally the entire plant. Almost all established feedstocks for biofuel production, such as corn, grains, palm fruits, sugar cane and rape seed, are utilized based on this system. This holistic utilization approach is shown in Figure 4-2 using sugar cane as an example. In the first processing step, sugar cane leaves (lignocellulosic biomass) are separated from the cane stalk (sugar and lignocellulosic biomass). In the second step, the cane juice (biomass that contains sugar) and the bagasse (lignocellulosic biomass) are again separated by grinding the cane stalk. Apart from the possible direct use for ethanol production, most of the cane juice is refined into sugar. The remainder is separated into molasses that can be used for ethanol production in a downstream aerobic fermentation process. The vinasse produced in the fermentation process can, in turn, be used to produce biogas or biomethane by means of anaerobic fermentation, and the lignocellulosic fractions of the sugar cane can be used to produce cellulosic ethanol (Section 3.4). The entire utilization process of the sugar cane plant thus produces a large number of intermediate and end products, most of which are already being used or can be used in the future. The sugar cane is mostly cultivated for its sugar, which is used in the food and feed sector. The use of the other parts of the plant for material or energy use, i.e., also for fuel production, is a possibility in the production chain, which can, however, be very volatile due to changing market conditions [Czarnikow (2021)].

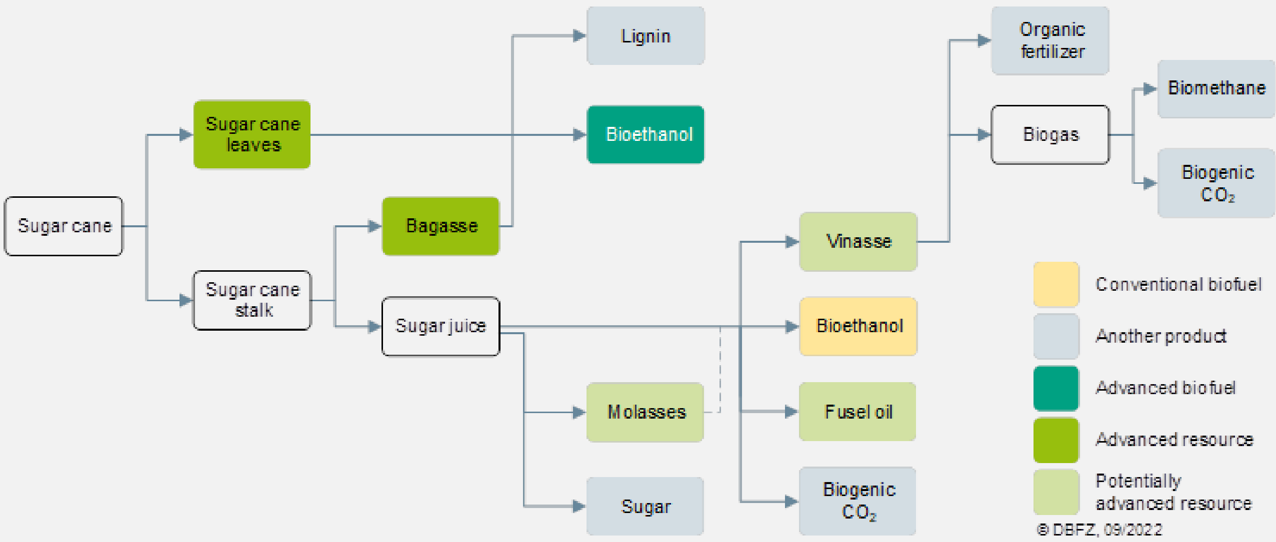


Figure 4-2 Multi-product system using sugar cane processing as an example. Data based on [Formann (2020); Santos (2018)]

4.1.2 Biogenic by-products, waste and residuals

Until now, most of the conventional biofuels are being produced around the world from biogenic primary products. However, policy objectives and legal requirements, especially in the European Union, are shifting the focus towards developing advanced biofuels that are not produced from biogenic primary products.

Biogenic by-products and waste that contain oil and fat are mainly used cooking oil and fats (e.g., frying fat), animal fats that falls under Categories 1 and 2[8], and other by-products such as fusel oil (as a byproduct of ethanol fermentation), tall oil (as a by-product of the pulp industry), and residuals and waste from the food industry that contain oil and fat, for example, from the processing of fruit, vegetables, and grains. Used cooking oil (UCO), which is collected, treated and processed after use in the food industry, is well established and already being used in large quantities.

By-products and waste that contain lignocellulose, such as straw from field crops, bagasse, legumes, leaves, and green waste, as well as forest residues, industrial residues, and waste wood, are feedstocks generated in the agricultural, gardening, landscaping, forestry, and wood processing industries. After appropriate treatment, these lignocellulosic feedstocks are suitable, for example, for anaerobic and ethanol fermentation or for thermochemical gasification. The pulp and paper industry, which processes wood, already has a large number of by-products in its value chain. For example, tall oil is already being processed into HVO/HEFA on an industrial scale through hydrotreatment. Black liquor, which is produced when lignin is separated from pulp, can be refined and upgraded to a higher-value product such as methanol or dimethyl ether (DME) [Rutz (2020)].

The biomass labelled **mixed ressources** in Figure 4-1, which predominantly has a non-specific composition of organic molecules such as proteins, fats and carbohydrates (e.g. food waste, sewage sludge or manure) are feedstocks that are primarily suitable for anaerobic fermentation [Kasinath (2021); Onthong (2017)]. In addition to the already mentioned biofuel technologies used to produce FAME or HVO diesel and bioethanol, **by-products and residuals** that contain sugar, starch and, in some cases, fat from the food industry (e.g., vinasse, baking residues and whey), can also be used to produce biogas and biomethane.

Other biogenic by-products and waste that do not fall under the previous categories can also be used in biofuel production. For example, crude glycerol is listed in Annex IX A of RED II and is a by-product of FAME production. Glycerol itself can be further processed into biogas/biomethane through anaerobic fermentation.

[8] Animal by-products are classified into three “risk to human health” categories. So far, mainly fats from Category 1 (high risk) and Category 2 (medium risk) have been used to produce advanced biofuels under the RED II.

Excursus 3: Cascade use and the circular economy

The production and use of biofuels is closely linked to the concept of a circular economy. The circular economy itself is characterized by the conversion of waste into valuable resources [BMBF (2020); Europäische Kommission (2018)]. Figure 4-3 shows how crops with seeds or fruit that contains oil are grown to produce vegetable oil. The oil seed can be used directly as food, feed, fuel, or as a material, and can be fed back into the cycle through the subsequent use of, for example, frying fat. After this is collected and processed, it is upgraded to FAME or HVO/HEFA, for example, and can be used as a fuel component in the agricultural industry.

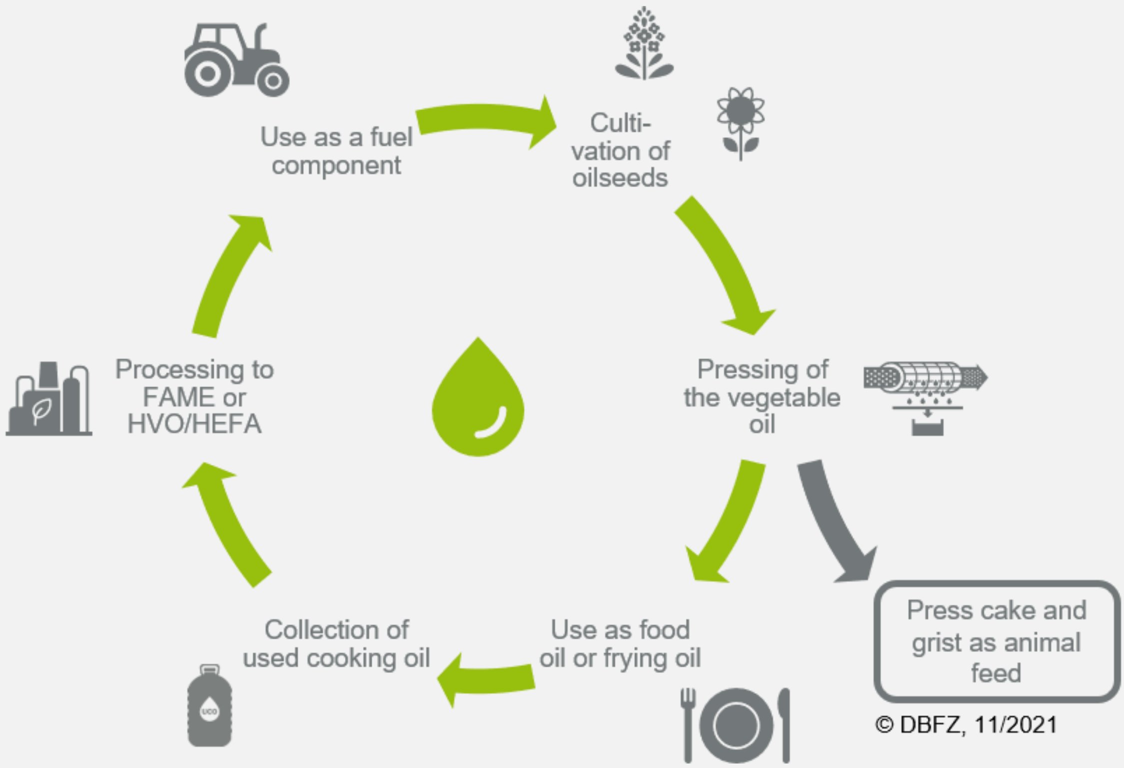


Figure 4-3 The circular economy, using vegetable oil as an example

A practical example of this are the tractors which run on alternative fuels on Bavaria's state-owned farms. In 2020 these farms produced the fuel needed to operate what is Germany's largest vegetable oil-powered tractor fleet of 23 tractors. This saves over 110 metric tons of greenhouse gas emissions a year compared to when diesel is used. Rape seed oil fuel, used to power agricultural machinery, is an example of a regional energy and material cycle. In 2020, the tractors needed 5,000 operating hours to cultivate around 625 hectares of land. This required 59 m³ of rape seed oil fuel. This rape seed oil fuel was produced regionally by cold pressing 160 metric tons of rape seed in decentralized oil mills. In addition to the oil, 110 metric tons of press cake were also produced during the oil pressing process. Press cakes are a valuable domestic protein feed for dairy cows. These cows, in turn, produced around 260 m³ of milk. The manure produced by the cows can be used to generate electricity, fuel, heat and fertilizer in biogas plants. The rape seed, which produced the fuel needed to cultivate the 625 hectares as well as being used as livestock feed, was grown on 41 hectares. After the rape seed harvest, 480 metric tons of rape seed straw and 160 metric tons of roots and stubble remained on the fields – plant residues that return nutrients to the soil and maintain soil fertility. Last but not least, the rape seed flowers helped bees produce 1,200 kg of honey.

4.1.3 Resources for e-fuels

The production of synthetic fuels generally requires the reactants hydrogen and carbon, which are synthesized into hydrocarbons using various processes. Ammonia or the direct use of hydrogen are exceptions as these require, in addition to hydrogen, either nitrogen or no reactant. The hydrogen is produced through electrolysis, which requires water and electricity. Carbon is usually supplied through carbon dioxide or carbon monoxide.

Electrolysis requires fresh water. In principle, this is available in virtually unlimited quantities in coastal regions, since the water quality required for electrolysis can be achieved by seawater desalination plants (e.g., through reverse osmosis) and further treatment steps (e.g., deionization). Brackish water or wastewater can also be used after it has been appropriately treated. It must be remembered that water used as drinking water and in food production competes with the process water used by industry or to produce hydrogen. Its use as drinking water and to produce food should always be prioritized [Khan (2021)].

Electricity from renewable sources can be generated by a variety of conversion technologies. These include plants that use wind power, solar radiation (PV), geothermal energy, hydropower and biomass conversion. These technologies are already used around the world to produce electricity. The share of each technology in total electricity production varies by country depending on regional conditions. These are shaped by natural factors, such as their exploitable potentials, and energy policies in the form of, for example, (financial) support for certain technologies [Kaltschmitt (2020)].

In principle, there are various ways of obtaining carbon. Regenerative biogenic carbon, which can be produced from biomass, is usually more widely available in humid regions (in the form of natural vegetation and cultivated plants) than it is in arid regions. This carbon is a by-product (gaseous carbon dioxide/carbon monoxide or solid carbon) of various conversion processes (e.g., thermochemical or biochemical conversion) [Kaltschmitt (2020)]. Furthermore, various industrial processes emit fossil carbon dioxide, which can be used in a cascade, but not in the sense of a circular economy. Some industrial processes, like those used in the paper or cement industries, also emit a mixture of biogenic and fossil carbon dioxide. Furthermore, in addition to the use of biomass, direct air capture provides regenerative carbon dioxide for use in PTX processes – in the spirit of a circular economy [Zitscher (2020)]. This mixture of fossil and biogenic carbon dioxide has approximately the same concentration in the atmosphere around the world at about 0.04 % [GML (2021)].

4.2 Status quo of the use of feedstocks to produce renewable fuels

4.2.1 Feedstocks for biofuels

Figure 4-4 shows the feedstocks used to produce **BIODIESEL** in Germany, Europe and worldwide in 2020.

The 2.4 million metric tons of FAME and 1.0 million metric tons of HVO diesel used in Germany in 2020 were produced from around 3.6 million metric tons of biogenic oil and fat. The feedstocks used to produce FAME and HVO diesel can be broken down into 41 % palm oil, 32 % used cooking oil (UCO) and other waste fats, 22 % rape seed oil, 3 % sunflower oil, 2 % soy bean oil, and 0.1 % oil from Ethiopian mustard (own calculation based on [BLE (2021b)]). Feedstock use has changed significantly in recent years; while the use of rape seed oil has declined by 64 % since 2011, the amount of UCO has increased about sixfold (Figure A-3) [BLE (2012), (2021b), (2021b)]. For the first time, a high volume of palm oil was also used. This increase can be traced back to a massive increase in the production of HVO diesel due to the raising of the greenhouse gas quota. In total, about 58 PJ [BLE (2021b)] of biofuels were based on palm oil in 2020, which corresponds to 2.9 % of the fuel volume for fulfilling the quota obligation. Also, the approximately 6 PJ of advanced biofuels [Zoll (2021)] contained about 50 % POME [Hahn (2021)], a waste product of palm oil production. In accordance with the requirements of the 38. BImSchV (2021), palm oil will be limited to 0.9 % starting in 2022, and from 2023 onwards it will no longer count towards fulfilling the biofuels quota in Germany.

In the European Union, the feedstocks used for FAME and HVO production in 2020 consisted of rape seed (43 %), UCO (27 %), palm oil (17 %), soy bean oil (6 %), sunflower oil (2 %), and other oils (5 %). Feedstock use has changed substantially; for example, rape seed made up 78 % of the feedstock in 2006 but has gradually decreased since then (Figure A-6). [USDA (2013), (2016), (2018), (2020)]

Globally, palm oil was the most widely used feedstock in 2020 at 31 %, followed by soy bean oil (25 %), UCO (21 %), rape seed (16 %), sunflower oil (1 %), and other oils (6 %), see also Figure A-8. [IHS Markit (2018)-(2020)]

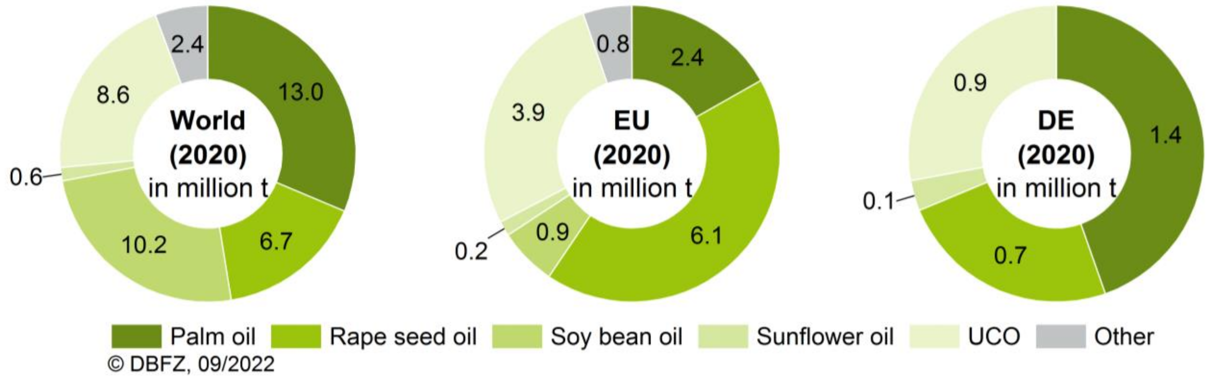


Figure 4-4 Feedstocks for use (Germany) and production (Europe, worldwide) of FAME and HVO diesel. Note: own calculation based on [BLE (2021b); IHS Markit (2020b); Meisel (2015); USDA (2020)]

Figure 4-5 shows the feedstocks used to produce **BIOETHANOL** in Germany, Europe and worldwide in 2020.

The bioethanol used as fuel in Germany in 2020 was produced from the following feedstocks: grains (40 % corn, 9 % wheat, 6 % rye, 3 % triticale, 3 % barley), sugar cane (29 %), sugar beets (5 %), and waste and residual materials (5 %) [BLE (2021b)].

The feedstocks used in ethanol production in the EU in 2020 consisted mostly of corn (39 %), sugar beets (35 %) and wheat (15 %). Other feedstocks played a smaller role, such as triticale (6 %), barley (2 %), rye (2 %) and cellulosic biomass (1 %). Sugar beets used to be the most widely used feedstock, making up 70 % of the feedstocks in 2008, for example. However, corn has dominated since 2019. Figure A-7 provides a full description of the feedstocks used in the EU. [USDA (2013), (2016), (2018), (2020)]

Ninety-four percent of the world's bioethanol feedstocks were processed in the U.S. and Brazil, with this figure having fallen to around 85 % by 2020. The remaining 15 % was mainly composed of 5 % corn from other countries, 3 % sugar cane from other countries, 5 % molasses, 1 % sugar beets, and 1 % cassava. The use of cassava has increased in Asia in recent years, albeit the quantity still not significant [F.O. Licht (2011a), (2011b), (2015a), (2016a), (2017a), (2018a); IHS Markit (2018)-(2020), (2020b)].

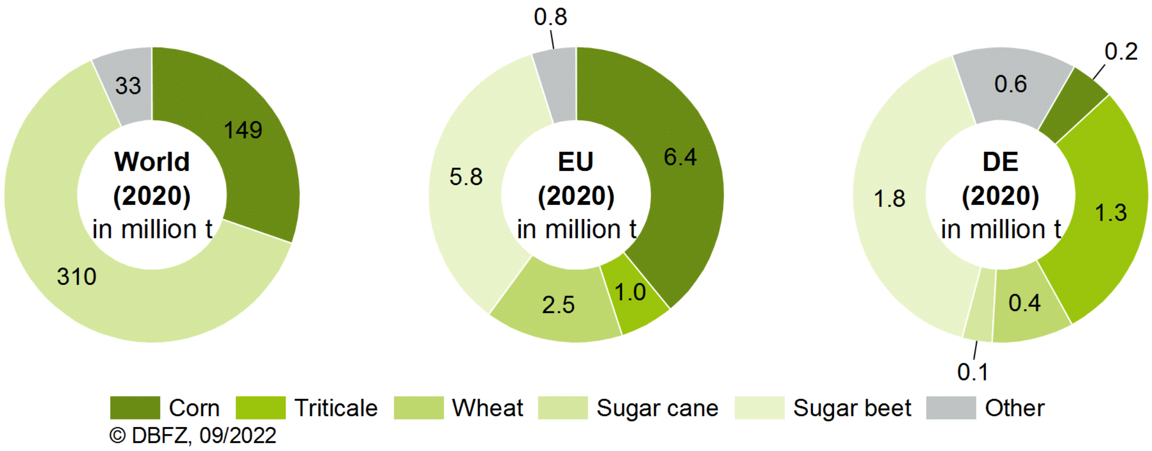


Figure 4-5 Feedstocks for use (Germany) and production (Europe, worldwide) of bioethanol. Note: own calculation data based on [IHS Markit (2020b); USDA (2020)]; for Germany, own calculation based on [BLE (2021b); Meisel (2015)]

The feedstocks used to produce **BIOMETHANE** as a fuel in Germany mainly or exclusively consist of waste and residual materials. The percentage of biomethane from primary agricultural products, especially corn, was comparatively high in 2019 and 2020 at 40 % and 25 %, respectively. As biofuels produced from primary agricultural products can be counted less and less towards the GHG quota, it can be assumed that the percentage from waste and residuals will increase again starting in 2022. [BLE (2017), (2020), (2021b)]

4.2.2 The use of electricity from renewable sources in transport

In **GERMANY**, the electricity used in transport is primarily used in rail transport. Of the approximately 11 TWh (39.6 PJ) of electricity used in rail transport in 2020, around 9.2 TWh (33.1 PJ) were used as traction power in the network of the Deutsche Bahn [AGEEstat (2021)]. Renewable energy made up 61.4 % of Germany's traction power mix in 2020 [Deutsche Bahn (2020)]. Electricity is also used to power urban trams and trains and, for example, for rail-bound port and industrial transport, bringing the total amount of electricity from renewable sources used in rail transport to around 5.9 TWh (21.3 PJ) in 2020.

Road transport used about 0.6 TWh (2.2 PJ) of electricity in 2020 [AGEEstat (2021)]; as a result of the electricity mix, 50.5 % of this came from renewable sources (0.3 TWh) [Fraunhofer ISE (2021)]. Of the total amount of electricity, about 0.4 TWh was used to power battery electric vehicles (BEVs) and the remaining amount for plug-in hybrid vehicles (PHEVs). This figure is based on an estimate for the annual creditable amount of electric power for a battery electric vehicle, amounting to 1,943 kWh/a [Bekanntmachung Anrechnung Strom (2017)]. Compared to previous years, 2020 saw a significant increase in the number of electric vehicles on the road. Nearly 200,000 new BEVs were registered in 2020, bringing the total number of such passenger cars to 309,000 or 358,000 such vehicles overall as of January 1, 2021. A similar number of new PHEVs were registered in 2020 (200,000), amounting to a total of 280,000 such passenger cars or 427,000 such vehicles overall. By July 1, 2021, this figure will have risen further to 495,000 BEVs and 426,000 PHEVs [KBA (2021i), (2021j)]. In addition to the predominantly private charging points, vehicle users currently have access to around 40,000 normal charging points and almost 7,000 fast charging points (as of September 1, 2021) [Bundesnetzagentur (2021)]. In 2020, 115 GWh of electricity could be counted towards the GHG quota. [Zoll (2021)]

Electricity is also used for transport processes inside companies (e.g., electric forklifts, cranes) and for electric bicycles and similar equipment. However, it is difficult to quantify the corresponding amounts of electricity in a reliable way.

The renewable electricity used in transport in Germany (amounting to 22.3 PJ (6.2 TWh)) is around 2.5 % of the total electricity provided from renewable sources (904 PJ (251 TWh)) [Lenz (2021)]. In the transport sector, electricity from renewable sources is expected to continue to be used predominantly in rail transport in the coming years. For example, Deutsche Bahn aims to fulfil its electricity demand entirely from renewable sources by 2038, and this figure is already expected to rise to 80 % by 2030 [Deutsche Bahn (2021)]. The electricity generated from renewable sources in Germany is listed in Table A-3.

The rise in the use of electricity as an energy carrier in road transport is also promoted in Germany by a range of support measures. These include, for example, special depreciation allowances, an environmental premium for private vehicles, as well as tax exemptions/benefits for company cars (BEV and PHEV), charging current, and charging infrastructure. Currently running until 2025 or even 2030, these measures provide a stable framework for the successive development of a publicly accessible charging infrastructure, thereby potentially increasing the percentage of electrically powered vehicles in use. By November 2021, 40,000 new BEVs had been registered – with the trend rising; this corresponds to around 20 % of all new passenger vehicle registrations in Germany [KBA (2021l)]. At 14 %, PHEVs are also at a similar level [KBA (2021l)], with user behavior and the respective vehicle type also playing a decisive role in determining the proportion of electricity or liquid fuels used. The status quo and the historical development of the vehicles being used in Germany are discussed in more detail in Section 2. Assuming there is no change in the incentive regime, it can be assumed that the number of BEVs and PHEVs that make up new passenger car registrations will continue to rise in 2022 and in the coming years, as will the demand for electricity in road transport. Based on current growth, the first milestone of over 1 million electric vehicles (BEV and PHEV) will be reached in 2022.

In the **EUROPEAN UNION**, around 10,651 TJ of electricity was consumed in road transport and 230,771 TJ in rail transport, with 19.7 % of this electricity coming from renewable sources. Electricity consumption has increased only slightly in recent years in rail transport. In 2009, it amounted to 214,304 TJ, i.e., only 7.14 % lower than in 2019. In road transport, electricity consumption was 1,320 TJ in 2009, which corresponds to an increase by a factor of 8 within ten years. Compared to 2018 (6,900 TJ), consumption in road transport grew by 54 % in one year. The electricity generated in Europe from renewable sources is shown in Table A-3. [Eurostat (2021d), (2021e)]

According to [IEA (2021e)], 121 EJ were required **WORLDWIDE** in the transport sector in 2018, of which 1.4 EJ, or 1.16 %, were provided by electricity. In terms of electricity generation, an average of 24.9 % of the world's electricity came from renewable sources in 2018, which included the renewable sources hydropower, PV, wind, geothermal, ocean and biomass [IRENA (2021a)]. The electricity generated from renewable sources worldwide is listed in Table A-3.

Figure 4-6 shows the generation of renewable electricity worldwide broken down by country and based on the respective relative share of total electricity generated for the year 2018. The country with the highest amount of electricity generated from renewables was China at 1,811 TWh (6,5 EJ), which represented 25.9 % of the electricity generated nationwide, followed by the United States at 742 TWh (2.7 EJ, relative share of electricity from renewable sources: 16.7 %) and Brazil at 496 TWh (1.8 EJ, relative share: 82.4 %). The European country with the highest amount of electricity generated from renewables was Germany at 225 TWh (0.8 EJ), which corresponded to 35 % of the electricity generated in 2018. In 2020, the share of electricity generated from renewable sources in Germany increased to

45.4 % [UBA (2021d)]. According to the IEA (2019a), the share of electricity from renewable sources in the transport sector will increase to about 0.5 EJ by 2024.

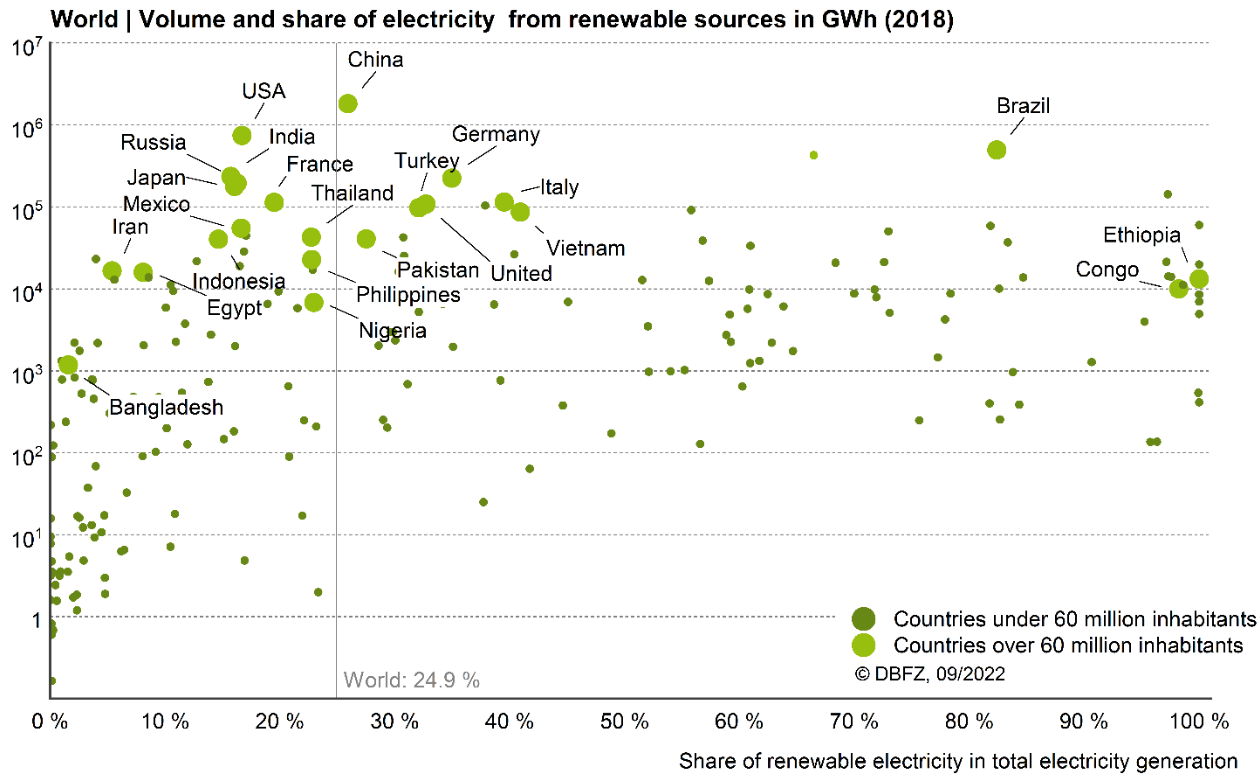


Figure 4-6 Volume and share of electricity from renewable sources worldwide. Data based on [IRENA (2021a); The World Bank (2021)]

4.3 Resource potentials

When biogenic feedstocks are used to produce biofuels, the issue of potential volumes plays an increasingly important role. This not only includes the use of primary products resulting from agricultural cultivation and their associated land use, but also that of all other biogenic by-products, residuals and waste. Quantifying total potentials and reduction aspects, as well as allocating these to existing or planned utilization is important in the context of a bioeconomy.

The use of renewable energy of non-biogenic origin (e.g., wind and solar energy) to supply electricity and its derivatives is also subject to certain restrictions within this cascade.

The status quo of both types of feedstocks with respect to their use in the transport sector is briefly described below, starting with a short, general discussion on the term “potential”.

An analysis of the different types of biomass potentials takes into account a reduction in biomass potential as a result of technical, economic and environmental constraints (Figure 4-7):

- **Theoretical potential** is defined as the maximum amount of terrestrial biomass theoretically available for bioenergy production given the basic biophysical limits.
- **Technical potential** is defined as the amount of theoretical potential that is available based on current technological capabilities, taking into account spatial constraints related to competition with other forms of land use and, for example, other ecological constraints (such as conservation).

- **Mobilizable potential** is the unused portion of the technical potential.
- **Economic potential** is defined as the amount of technical potential that meets the criteria of economic viability under the given conditions
- **Implementation potential** is defined as the amount of economic potential that can be realized within a given timeframe and under specific sociopolitical conditions, including economic, institutional and social constraints, and policy incentives.
- **Sustainable potential** integrates environmental, economic and social sustainability criteria.

Ecological constraints that do not affect nature conservation are not explicitly considered part of the technical potential. Including environmental constraints in the technical potential determines the **ecological potential.** Criteria used to determine the sustainable potential vary depending on the study [Hoefnagels (2017)].

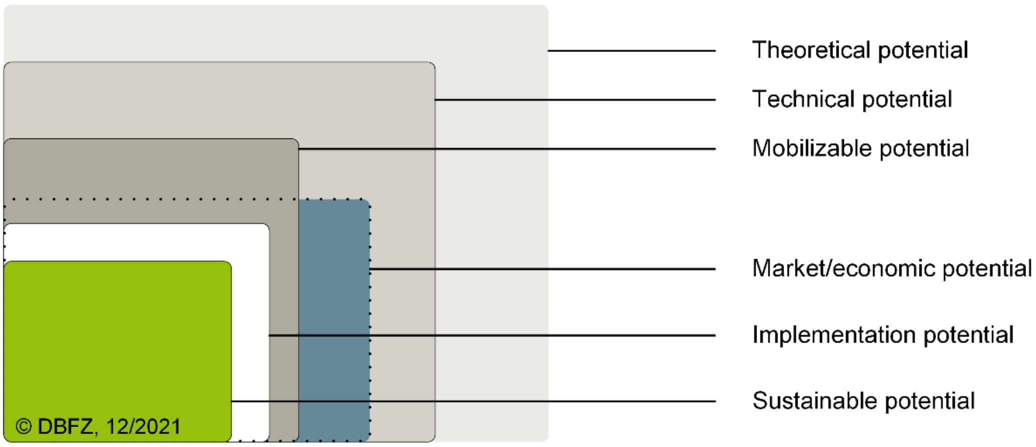


Figure 4-7 Hierarchy and overlapping of the different types of resource potentials. Note: modified illustration based on [Hoefnagels (2017)]

4.3.1 Biogenic resources for renewable energy in transport

The **potential of biogenic resources in Germany** can now be relatively well assessed and estimated, even though numerous questions remain with regard to an efficient and sustainable utilization strategy, for example the quantitative and qualitative differences over time or within a regional context.

The DBFZ resource database[9] includes data on 77 types of biogenic by-products, residuals and waste (for Germany, reference year 2015). These resources can be investigated in terms of various levels of potential: First, the theoretical potential is determined, which is divided into technical potential and an amount that cannot be mobilized for technical reasons (e.g., recovery rate or conversion losses). The technical potential, in turn, is broken down into biomass that is already being used for other purposes (e.g., energy or materials) and biomass that could be mobilized. Finally, the data can be contextualized in terms of its relevance for the transport sector.

Figure 4-8 clearly shows how the resource potential of biogenic by-products and waste decreases along the potential cascade – from a total of 199 to 278 million metric tons of theoretical potential to 86 to 140 million metric tons of technical potential, to 14 to 45 million metric tons of mobilizable potential [DBFZ (2021b)]. Agricultural and forestry by-products account for the largest proportion based on mass.

[9] https://webapp.dbfz.de/

In addition to the development of previously unused by-products and waste, an extended utilization cascade with an energy utilization step is also conceivable, for example in the form of anaerobic fermentation of biogenic waste before it is composted.

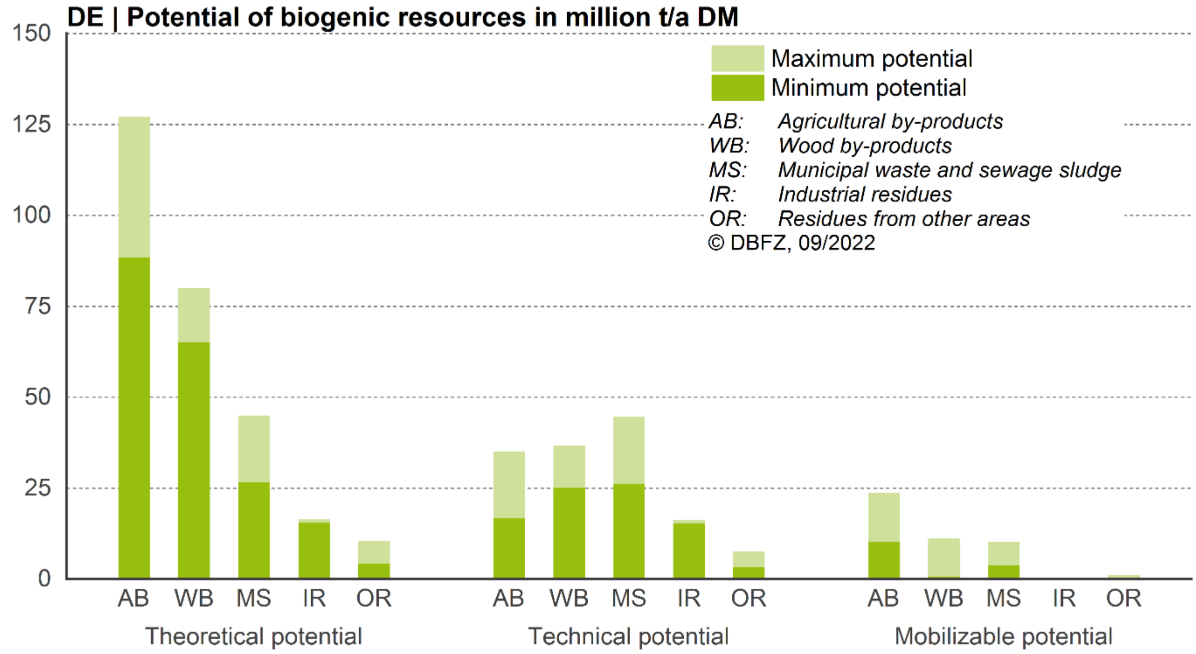


Figure 4-8 Potential of biogenic resources broken down by main feedstock categories in Germany. Note: does not include biogenic primary products, reference year 2015; own calculation, data based on [DBFZ (2021b)]

The **European Union's technical potential of biogenic resources** has already been evaluated as part of numerous studies. Some of these have included estimates of the biomass available for bioenergy purposes. One of the most detailed reviews of the biomass resource assessments in the EU was the Biomass Energy Europe (FP7) project. Updated data from 2015 to 2017 [Hoefnagels (2018)] are illustrated as ranges in Figure 4-9.

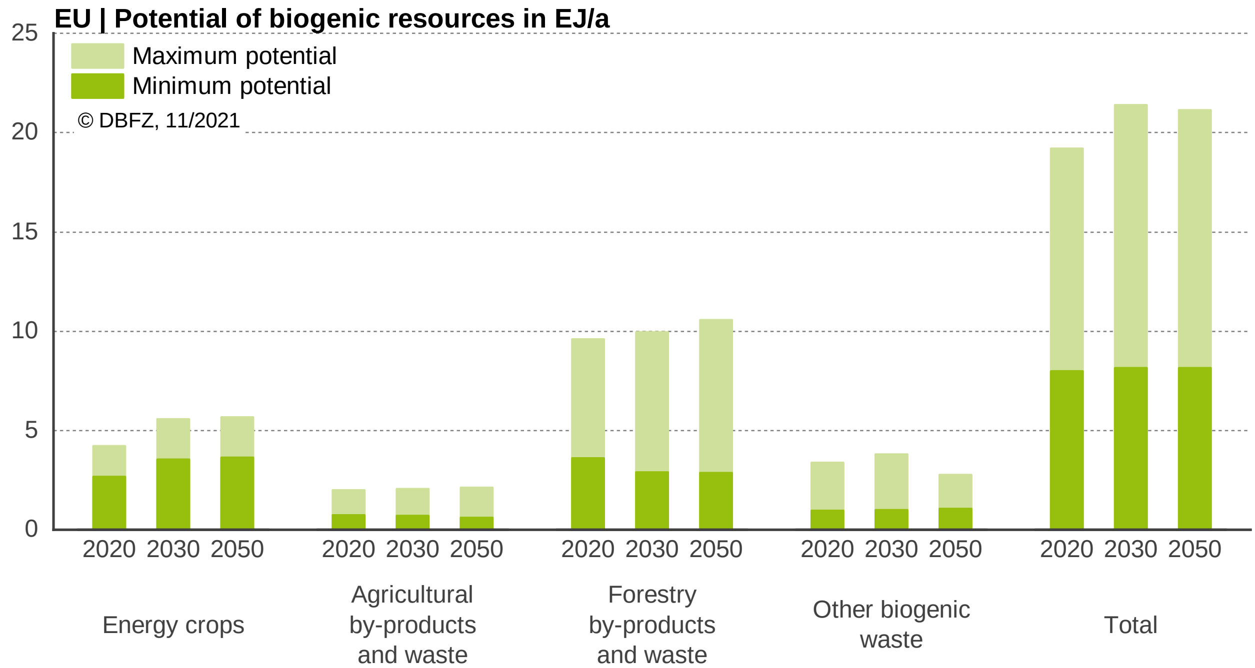


Figure 4-9 Potential of biogenic resources broken down by main feedstock categories in Europe. Note: own illustration, data based on [Hoefnagels (2018)]

Imperial College London analyzed the European bioresource potential from agricultural and forestry by-products, residuals and biowaste and calculated 1.0 to 1.2 billion metric tons of dry matter (DM) in 2030 and 1.0 to 1.3 billion metric tons (DM) in 2050 [Imperial College London (2021)]. The corresponding ranges of 16 to 20 EJ/a in 2030 and 17 to 22 EJ/a in 2050 are thus in the upper limits of the ranges of [Hoefnagels (2018)] as illustrated in Figure 4-10. After subtracting other uses, the biomass potential that can be used for bioenergy amounts to 9 to 14 EJ/a in 2030 and 9 to 15 EJ/a in 2050. A comparison with two other EU-level analyses of biomass potential for bioenergy shows that the lower ranges are relatively similar, at 8 to 9 EJ/a, but the upper limits are either lower for 2030 and 2050, at 11 EJ/a and 13 EJ/a, respectively (Directorate General for Research and Innovation – DG RTD) or significantly higher at 18 EJ/a and 21 EJ/a, respectively (Times Model of the Joint Research Centre – JRC Times) (own calculation based on [Imperial College London (2021)]). The assessment concludes that the data currently available at the European level is still too uncertain and inhomogeneous. This fundamentally promising potential needs to be backed by further research that uses more robust models and more integrated analyses in order to provide a solid basis for sustainable alternative fuels as major contributors to the decarbonization of the transport sector. [Prussi (2022)]

[Bedoić (2019)] focused on agricultural waste and by-products in Europe, examining their volumes from fruit growing and processing, vegetable growing and processing, grain growing (including crop residues), livestock farming and meat processing. When fractions are subtracted that can also be used in the food and animal feed sectors, as well as some material streams that are difficult or impossible to use in the production of energy, the result is a technical potential of 3.25 billion metric tons of fresh matter (FM, reference year 2016), which corresponds to an estimated 0.7 billion metric tons of dry matter (DM) (own calculation). It is difficult to translate these quantities into a corresponding amount of energy without conducting a comprehensive and detailed analysis.

The HyFlexFuel project determined European potentials for eleven different bioresources at the NUT levels NUTS0 to NUTS3 (county level in Germany) and provided information on their availability. The technical potentials, where determinable, refer to source data from the reference years 2009 to 2019. This data will be further updated and harmonized at the DBFZ. [Bellot (2021); HyFlexFuel (2021)]

Current data shows that there is no fully comprehensive and up-to-date potential analysis for European biomass. This is vital, especially when it comes to existing and intended uses of these material flows.

As part of a meta-analysis, the International Renewable Energy Agency (IRENA) evaluated studies published between 2007 and 2014 on the **INTERNATIONAL POTENTIAL OF BIOGENIC RESOURCES**. The studies reveal major differences, primarily due to the methods that were applied and the potential categories that were considered. In summary, the global bioresource potential for the period of 2025 to 2035 is 45 to 375 EJ/a (mean 135 EJ/a). The potential for bioresources from algae is estimated to be relatively low, at 2 to 6 EJ/a. When energy crops (here only non-food) are not included, the result is a (predominantly technical) potential of 35 to 240 EJ/a. [IRENA (2016)] Above all, more in-depth analyses are needed to determine what proportion of the potential can be tapped and to which sectors or cascades sustainable use should be assigned. Estimating a global sustainable biofuel potential requires an overarching biomass strategy, like that which exists at the German or European level (see excursus "The need for a comprehensive biomass strategy").

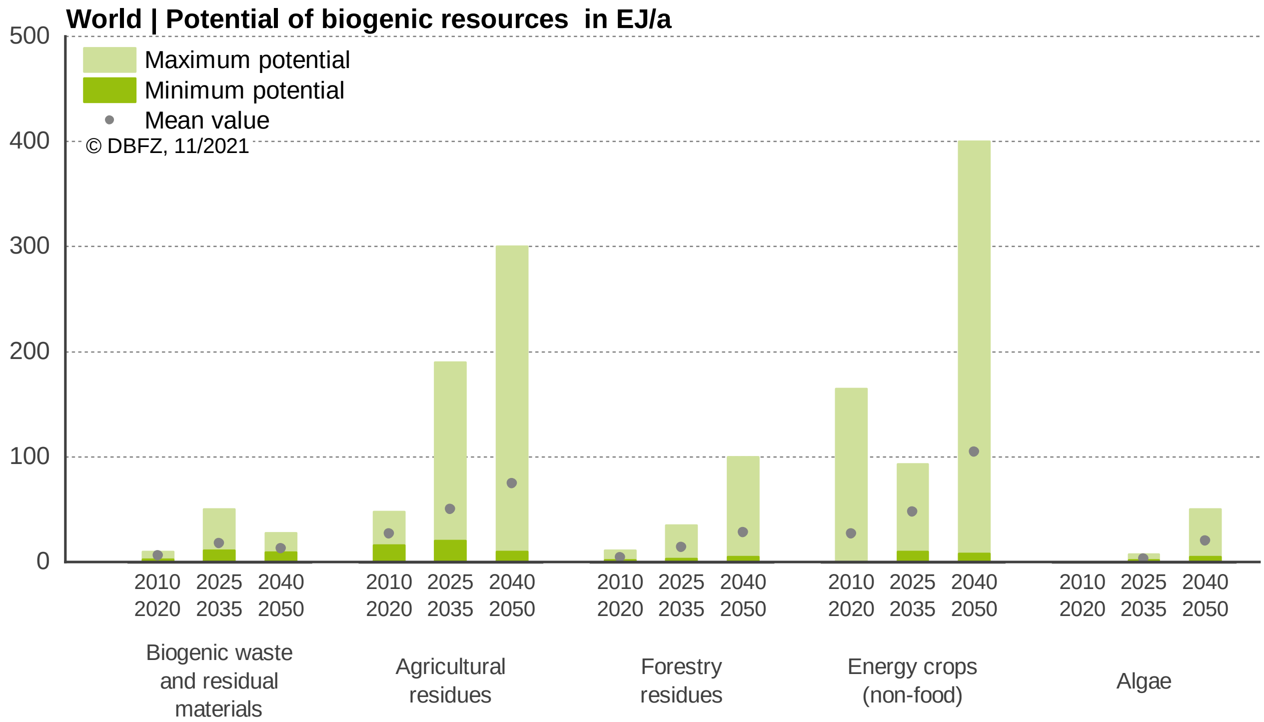


Figure 4-10 Available potential of biogenic resources broken down by main feedstock category worldwide. Note: Annual figures are time spans, predominantly technical potential; own presentation data based on [IRENA (2016)]

China is also increasingly turning to biogas or biomethane made from waste and agricultural residues (Section 5.2). The amount of household waste and other organic waste, such as food waste, is expected to increase significantly in the course of China's urbanization. The sewage sludge generated by China's cities amounted to around 10 million metric tons (DM) in 2017. In addition, there is assumed to be a technical potential of 817 million metric tons of straw (from various crops) and 2.7 billion metric tons of slurry and manure (average values from 2007 to 2011). [Zheng (2020)]

Resource potential and cultivation area of biogenic primary products

The **agricultural area in Germany** that is used to grow energy crops is declining. Most of this area is taken up by the cultivation of crops for biogas plants – about 65 % of the 2.3 million hectares in 2020. Crops for bioethanol production were grown on 212,000 hectares and vegetable oil for biodiesel on 573,000 hectares. The size of both areas has been decreasing in recent years. The total area of 785,000 hectares corresponds to around 4.7 % of the land used for agriculture in Germany. Biofuel that is produced or used in Germany on the basis of imported biomass is not included in these figures on area.

Table 4-1 Cultivation area for bioenergy crops in Germany from 2012 to 2020 in 1,000 hectares. Data based on 2012 to 2014 [BMEL (2019)], for 2015 onwards [BMEL (2021)]

	2012	2013	2014	2015	2016	2017	2018	2019	2020
Rape seed for biodiesel/vegetable oil	786	614	799	805	720	591	590	515	573
Plants for bioethanol	201	173	188	238	259	248	266	215	212
Total plants for fuels	*987*	*787*	*987*	*10,043*	*979*	*839*	*856*	*730*	*785*
Plants for biogas	1,163	1,269	1,354	1,340	1,394	1,430	1,550	1,520	1,480
Plants for solid fuels	11	9	11	11	11	11	11	11	11
Total energy plants	*2,160*	*2,060*	*2,350*	*2,390*	*2,380*	*2,280*	*2,420*	*2,260*	*2,280*
Total agricultural land in use	**16,667**	**16,700**	**16,725**	**16,731**	**16,659**	**16,687**	**16,645**	**16,666**	**16,595**

The crops suitable for biofuel production mainly include oil seeds (soy bean, rape seed) and oil crops (palm), as well as sugar (sugar cane, sugar beet) and starch crops (corn, grains). In recent decades, the **cultivated land worldwide** has expanded significantly for almost all of these crops, and specific yields per hectare have also increased slightly. Figure 4-11 shows the cultivated area worldwide (x-axis) and the specific yields per hectare (y-axis) in 1961 and 2018, with the size of the circles proportionate to the total global yield of the respective crops. It also shows the percentage that was used for biofuel production in 2018. The crop with the lowest increase in yield was sugar cane, at 45 %. Oil palm crops have greatly increased: yields have increased by 285 %, the harvested area has increased by 682 %, and production has increased by 2,912 %. Sugar beets are the only crop whose area has decreased (by 33 %), however this did not affect production (74 % increase) or yield (161 % increase). Overall, the following percentages of crop yields were used for biofuel production worldwide in 2018: 2 % sugar beet, 12 % palm fruit, 14 % soy bean, 15 % corn, 19 % sugar cane, and 24 % rape seed. [FAO (2021)] Crop rotations usually consist of more than one crop. For example, sugar cane is replanted every five to ten years and legumes are grown as an intermediate crop, among other things to protect the soil from erosion and for biological fixation of nitrogen and potassium [Jos (2013)].

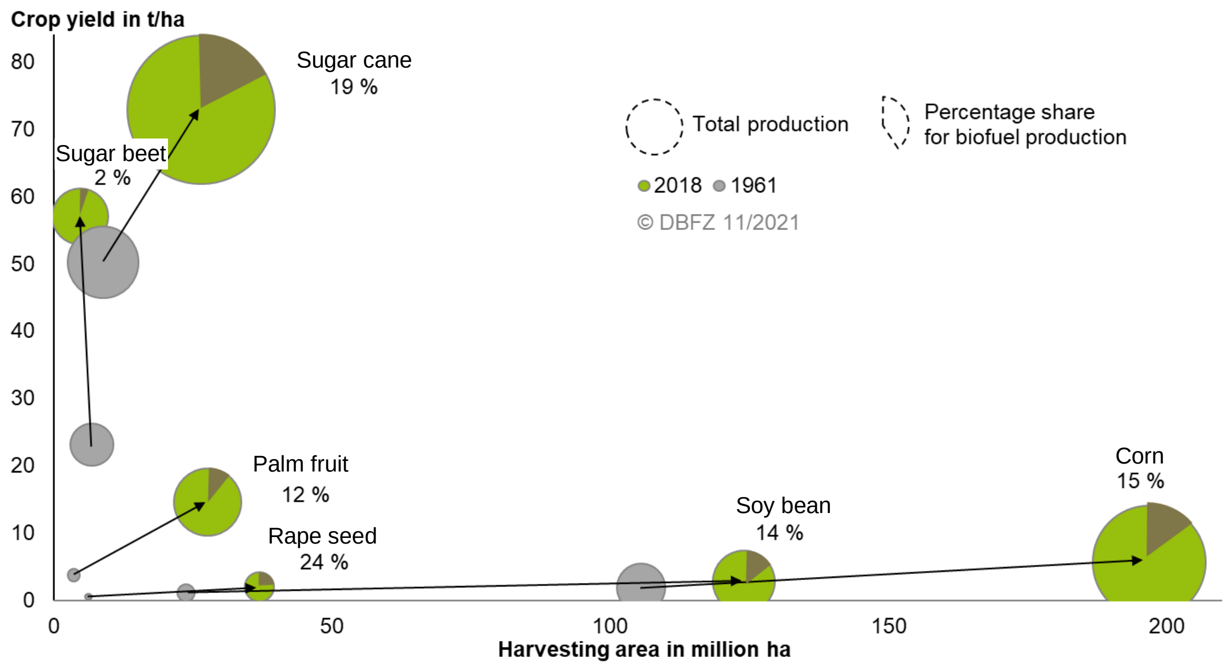


Figure 4-11 Global harvested area, crop yields and total production as well as percentage of use in biofuel production for selected biomasses in 1961 and 2018. Note: own calculation based on [FAO (2021); IHS Markit (2018)-(2020)]; Assumptions: Oil content of soy beans: 21 % w/w, oil content of palm fruits: 23 % w/w, oil content of rape seed: 42.5 % w/w, yields based on dry matter.

Resource potentials of biogenic waste and residues

The potentials for some of the feedstocks that can be used to produce biofuels must be calculated indirectly.

The production of 1 kg of biodiesel (FAME) produces approximately 0.10 kg of **crude glycerol**; the term crude glycerol refers to a concentration of 80 % glycerol [Kaur (2020); Quispe (2013)]. In 2019, 38.84 million metric tons of biodiesel were produced, resulting in a theoretical potential of approximately 3.88 million metric tons of crude glycerol. Glycerol has a market in various sectors and it is estimated that in 2016, 24 % of its end use was for food, 23 % for personal care products, 17 % for oral care products, 11 % in the tobacco industry, 8 % in pharmaceuticals and 17 % for other uses [Greenea (2015)]. Soap and fatty acid production also generates glycerol as a by-product [Kaur (2020)].

Fusel oil is a by-product of ethanol fermentation and consists mainly of isoamyl alcohol (60 to 80 %), an alcohol with a significantly higher energy content than ethanol [Uslu (2020)]. The production of 1 m^3 of ethanol produces approximately 2.0 to 2.5 liter of fusel oil [Bergmann (2018); Montoya Sanchez (2011)]. 80 million metric tons of ethanol was produced globally in 2019, which corresponds to a theoretical production of 0.16 to 0.20 million metric tons of fusel oil.

Tall oil is one of the most important by-products of **pulp production.** Yields vary depending on the mixture of wood and range from 1.25 to 4.00 % [Peters (2017)], with hardwoods (e.g., eucalyptus) producing the lower percentage and softwoods the higher percentage [Peters (2017)]. Even though the market for crude tall oil has not been extensively studied, it is estimated that 1.6 million metric tons were produced in 2008, which had increased to 1.79 million t/a by 2018 [Aryan (2021)]. Crude tall oil is mainly used to generate energy through combustion or it is used in the chemical industry, where its constituents, for example rosin and turpentine, are used as materials [Peters (2017)]. Crude tall oil is used in the biofuel sector primarily to produce HVO/HEFA. It is estimated that 0.32 million metric tons were used for this purpose in 2018 [Aryan (2021); UPM (2021)].

Black liquor is another by-product of cellulose production and is particularly rich in energy and lignin. Yields also depend on a variety of factors, for example the type of wood used as well as the temperature, pressure and reaction time during wood pulping [IEA Bioenergy (2013); Kim (2019)]. The following ratio can be used to estimate the amount of black liquor produced: 1.2 kg (DM) of black liquor per metric ton of unbleached, air-dry pulp and 1.7 kg (DM) of black liquor per metric ton of bleached, air-dry pulp [Swedish Energy Agency (2008)]. Figure A-13 shows an estimate of the total global production of black liquor for the years 1961 to 2019. Of the estimated 229 million metric tons produced in 2019, 55 % were produced in the Americas, 22 % in Asia, 22 % in Europe, and (1 %) in Africa and Oceania. Production over the last ten years has increased by about 2.5 % per year. [FAO (2021)]

Methanol is either used as an end product or as an intermediate in the production of other products. Methanol is used throughout various sectors worldwide and the largest demand does not actually come from the biofuel sector. In 2020, around 29 % of the methanol was used in the fuel sector. Other significant uses for methanol include the production of olefins (methanol-to-olefins) at 31 %, formaldehyde at 23 % and acetic acid at 7 %. In the fuel sector it is blended into gasoline, used to produce biodiesel (3 %), DME (3 %), and methyl tert-butyl ether (10 %), and used in fuel cells (less than 1 %) (Figure A-10). [IRENA (2021c); Methanol Institute (2021)]

4.3.2 Potential of electricity from renewable sources and its derivatives

Renewable energy of non-biogenic origin is regarded as having a relatively high potential. Depending on the type of energy source, there are strong regional differences both internationally as well as within Europe and Germany [Agentur für Erneuerbare Energien (2010)], which must be compensated for by a suitable grid [Kendziorski (2021); NEP 2035 (2021)] or other transport and storage options.

The most efficient form of electricity use is its direct use in transport; this is therefore supported accordingly through policy decisions and legal frameworks, especially for passenger cars (Section 1). In 2020, 251 TWh of Germany's electricity came from renewable sources. In 2019, this amounted to 1,334 TWh in Europe and almost 7,000 TWh worldwide (Figure 4-12).

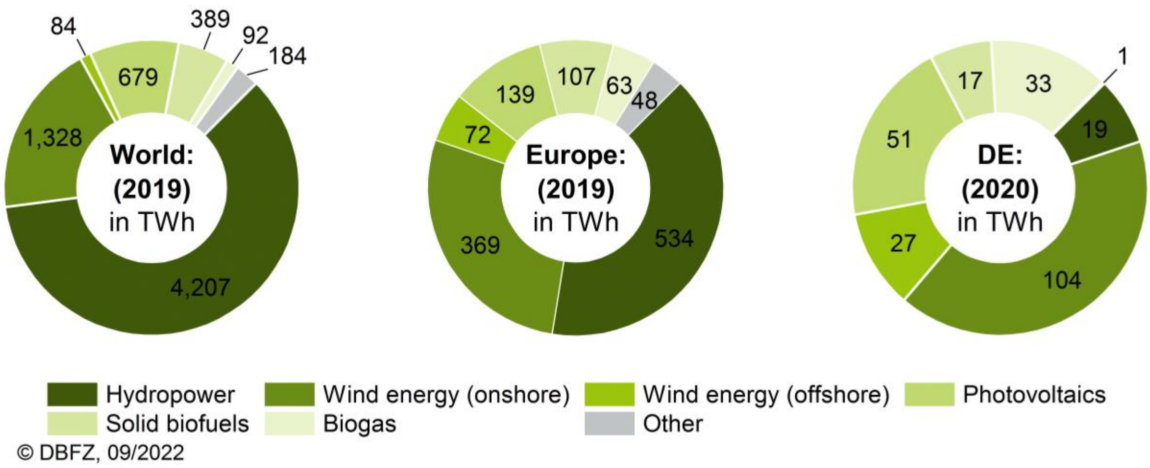


Figure 4-12 Status quo of the provision of electricity from renewable sources worldwide, in Europe and in Germany. Note: own calculation, data based on [IRENA (2021b); Lenz (2021)]

However, for some transport sectors, especially aviation and shipping, electrification is relatively difficult to nearly impossible to implement, so that liquid energy sources will also have to be used here in the medium to long term. Since hydrogen can be produced from electricity via electrolysis and, if necessary, further conversion steps, a large number of different energy carriers can also be produced from electricity. The technologies for producing these fuels are described in more detail in Section 3.

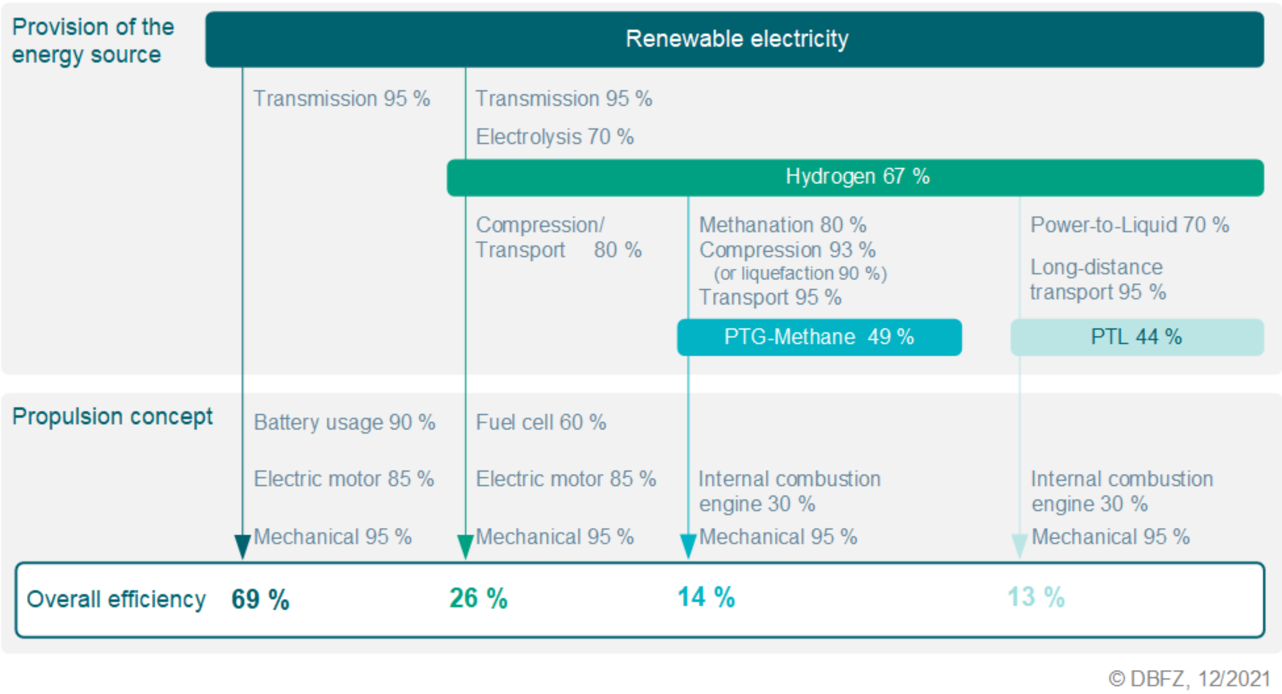


Figure 4-13 Estimation of the overall efficiencies of different electricity-based energy carriers depending on the drive system. Note: modified illustration based on [Agora Verkehrswende (2018)] with no claim to completeness, e.g. with regard to charging and other losses

In addition to the resources needed for electrolysis, the derivatives of green hydrogen also require a carbon source. Up to now, this has mostly been in the form of carbon dioxide, which can be captured from the air. This process is currently still tied to comparatively high costs and the need for large areas of land [Agora Verkehrswende (2018)]. Another option is to use process-related industrial CO_2 emissions as point sources. Figure 4-14 summarizes the status quo of the main point sources, categorized where possible according to fossil and biogenic origin, for Germany and Europe as well as worldwide.

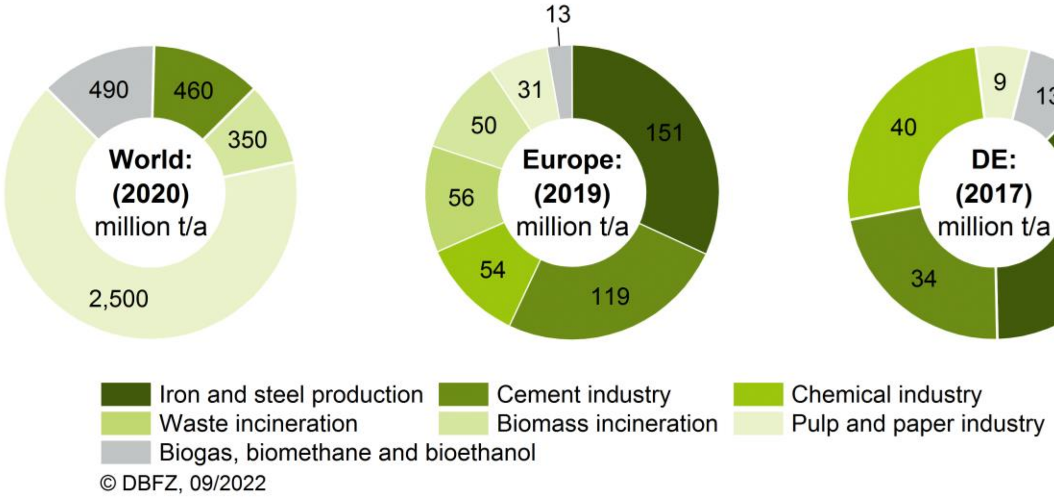


Figure 4-14 Status quo of the technical resource potential of CO_2 point sources worldwide, in Europe and in Germany. Note: cement industry incl. other mineral industries, chemical industry incl. other industrial point sources; with no claim to completeness and for Germany without data on waste and biomass incineration; own illustration based on [Kircher (2020); Olsson (2020b); Zitscher (2020)] and own calculations

ELECTRICITY FROM RENEWABLE SOURCES

Synthetic fuel essentially uses electricity to produce hydrogen via water electrolysis. This can either be used directly as a fuel or converted into hydrocarbons such as methane, kerosene or methanol through further synthesis steps and by adding carbon. Renewably generated energy and green carbon need to be used in order to ensure that these hydrocarbons are produced in a resource- and climate-friendly way. When determining fuel potential, it is therefore crucial to know the potentials of electricity from renewable sources and carbon.

The results of various studies were consolidated in order to determine renewable electricity potentials [AEE (2013); BMVI (2015); DBFZ (2010); DLR (2003)]. The technical potential for generating electricity from renewable energy in Germany varies greatly depending on the individual resource. Onshore wind power has the greatest potential for producing electricity (Figure 4-15). According to the literature, it also has the largest range of possible potential. The differences are mainly due to different assumptions about which areas in Germany are suitable for wind power under which restrictions. The data on usable area varies from 1 % to 13.8 % of Germany's land area. Photovoltaics (PV) has the second largest potential, followed by offshore wind power. Deep geothermal energy and hydropower have a relatively low potential. The minimum total for technical potential for electricity generation in Germany is 537 TWh/a, the maximum total is 3,961 TWh/a.

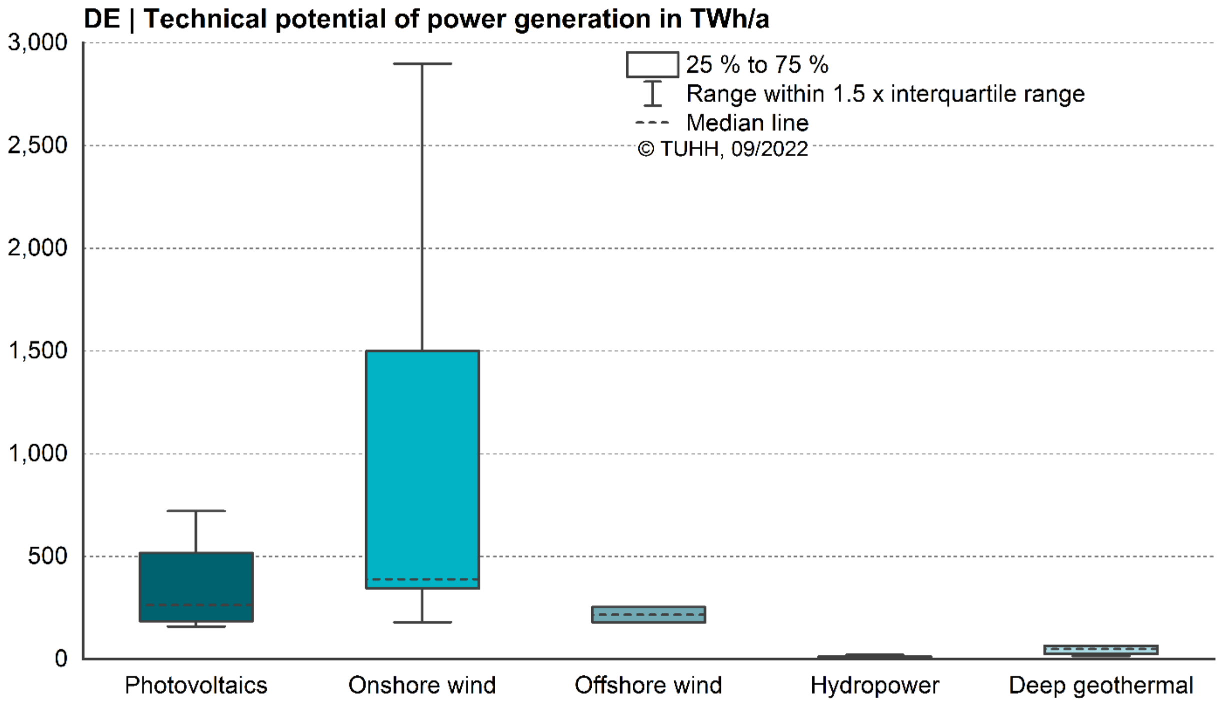


Figure 4-15 Technical potential for electricity generation from renewable sources in Germany. Note: own depiction based on [AEE (2013); BMVI (2015); DBFZ (2010); DLR (2003)]

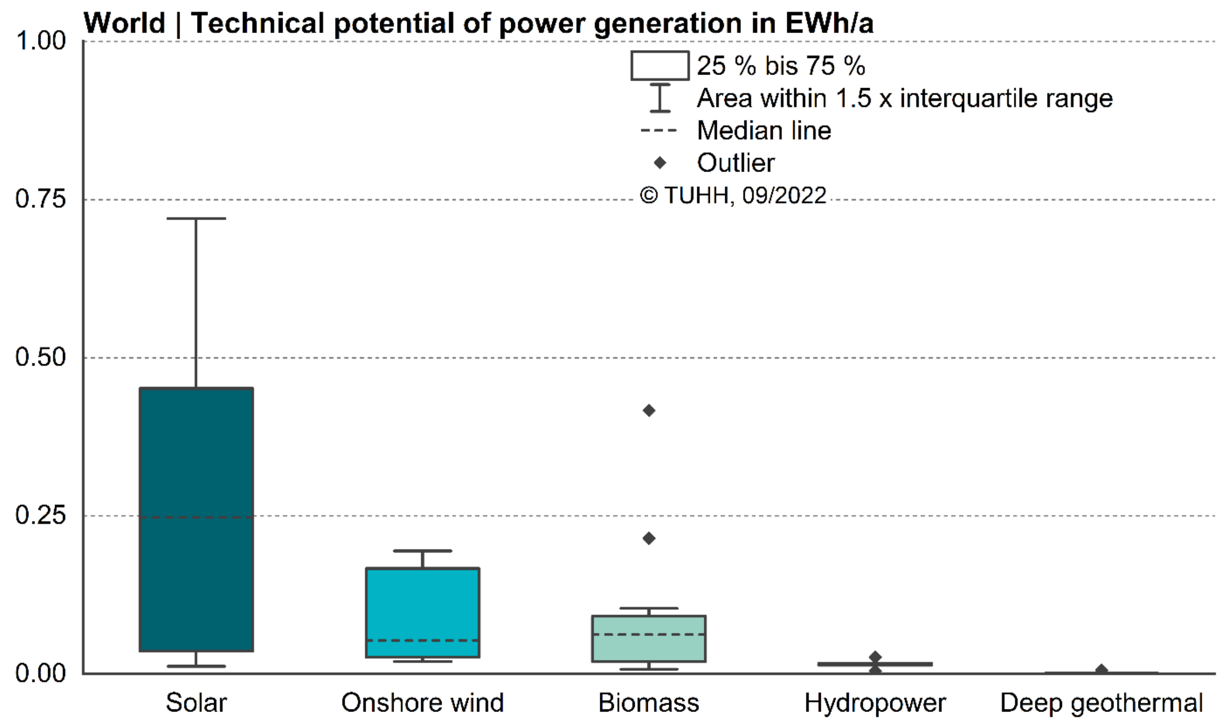


Figure 4-16 Technical potential for electricity generation from renewable sources worldwide. Data based on [AEE (2013); BMVI (2015); DBFZ (2010); DLR (2003)]

From a global perspective, the technical potential for electricity generation is dominated by solar energy, followed by onshore wind power and biomass (Figure 4-16). Hydropower and geothermal energy play a subordinate role. The technical generation potential worldwide also ranges widely and lies between approx. 45 and 1,363 GWh/a. [AEE (2013); BMVI (2015); DBFZ (2010); DLR (2003)]

CO_2 SOURCES FOR THE PRODUCTION OF E-FUELS

Hydrogen and carbon are needed to produce synthetic hydrocarbons, for example kerosene, diesel or methane, which can be used as fuel to power various types of vehicles. Hydrogen can be directly produced, for example through water electrolysis. Carbon is obtained from carbon dioxide by way of a synthesis process, for example Fischer-Tropsch synthesis, methanol synthesis as well as the Sabatier process (methanization). The conversion and synthesis processes are described in Section 3.8.

There are various ways to obtain carbon dioxide: It can either be captured from various industrial processes or from the atmosphere. These options are described below, with the atmosphere considered a diffuse source and industrial processes considered point sources.

INDUSTRIAL CO_2 EMISSIONS AS POINT SOURCES IN GERMANY. Carbon dioxide can be of fossil or biogenic origin if it is generated through the combustion or conversion of fossil carbon carriers or the conversion of biomass. The carbon dioxide contained in the atmosphere is both biogenic and fossil based. Moreover, CO_2 emissions from industry can be divided into energy-related and process-related emissions. Energy-related emissions directly result from the provision and use of energy, for example through the burning of coal. Process-related emissions occur during production processes, primarily through the conversion of feedstocks or auxiliary materials which are essential for creating the properties of the manufactured products. This distinction is necessary because, based on current research, it is assumed that climate-friendly substitution options for energy-related CO_2 emissions can be implemented more easily and effectively (e.g., “renewable” fuels, “renewable” electricity) than alternative technologies that significantly reduce process-related CO_2 emissions while guaranteeing the same product properties. In order to use carbon dioxide as a resource or reactant in synthetic fuel production, it must be available in sufficient quantities. Therefore, the CO_2 potentials from German industry are analyzed and quantified in more detail below [Zitscher (2020)].

Figure 4-17 shows the various CO_2-intensive sectors of the manufacturing industry and their respective process-related and absolute emissions in 2017. The largest emitter was the iron and steel industry at approx. 56.5 million metric tons of CO_2. Of this, around 38 million metric tons were process-related CO_2 resulting from the use of coke as a reducing agent for the iron ore in the blast furnace process. In contrast to primary steelmaking (blast furnace process), relatively small amounts of CO_2 were released in the secondary route through the melting down of scrap in the electric arc furnace. This CO_2 resulted from the burning off of carbon electrodes. The chemical industry produced the second-highest emissions, at just under 40 million metric tons of CO_2. These are mainly caused, for example, by the supply of energy to steam crackers. CO_2 emissions from the mineral industry were largely the result of cement production and the manufacture of quicklime. In the mineral industry, most of the process-related emissions (20 million of the approx 34 million metric tons of CO_2) resulted from the deacidification of carbonates in rotary kilns and shaft furnaces. Only energy-related carbon dioxide – on the order of 9.5 million metric tons – were emitted through the supply of heat and steam in paper and pulp production. Non-ferrous metal production had the lowest level of emissions, totaling just under 2.3 million metric tons of CO_2. Most of these CO_2 emissions are of fossil origin. Biogenic carbon dioxide primarily occurs in paper and pulp production and in the mineral industry. It is produced by the combustion of biogenic waste materials during paper and pulp production (e.g. waste liquor or bark) and by the use of substitute fuels in the cement industry (e.g. used tires, industrial and municipal waste or sewage sludge) [Zitscher (2020)].

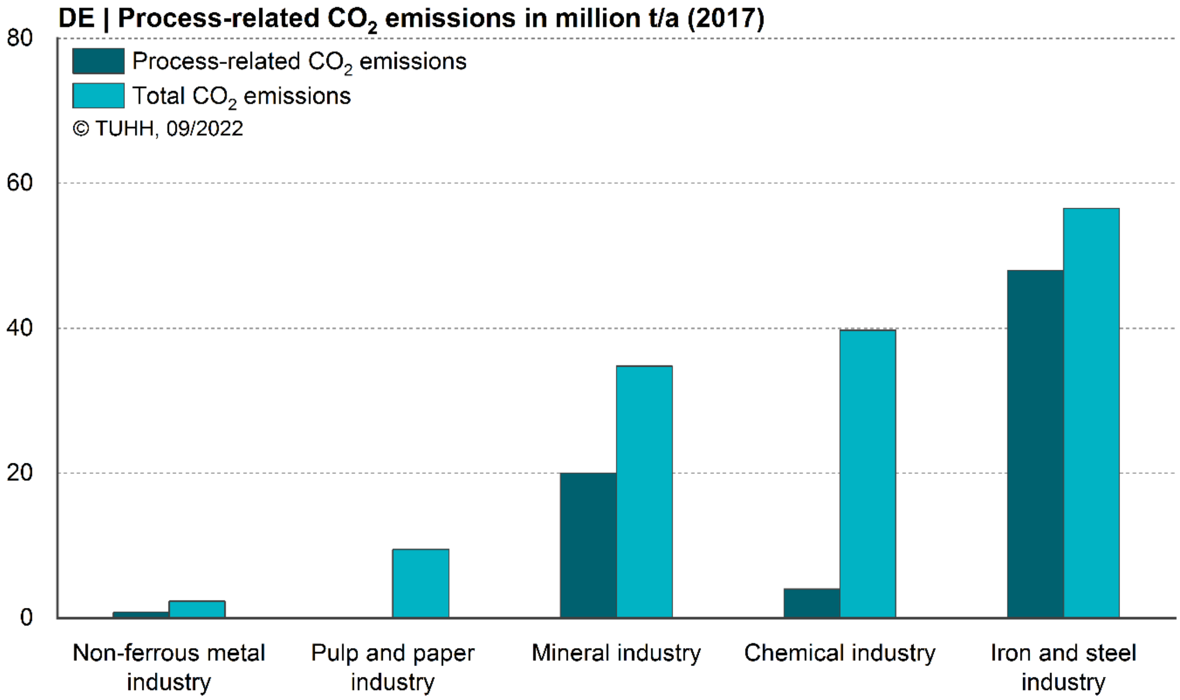


Figure 4-17 Total CO_2 emissions and the proportion of process-related CO_2 emissions in various industrial sectors in Germany for the year 2017. Data based on [Zitscher (2020)]

Figure 4-18 (left) shows the geographic distribution of industrial CO_2 point sources in Germany for 2017. The map provides an overview of how much carbon dioxide was emitted by which locations and shows the proportion of process-related emissions in relation to absolute quantities. Large amounts of carbon dioxide were generated in the Ruhr region due to the high industrial density of various sectors. The paper and pulp industry and the mineral industry showed the lowest degree of agglomeration in relation to the other industrial sectors.

If resource and climate protection are to be seriously pursued in the future, and fossil-based carbon dioxide emissions are to be reduced, industry needs to implement certain process changes and alternative production methods. With this in mind, Figure 4-18 (right) shows possible residual carbon dioxide in 2050 at the industrial sites studied. The values shown under RFS (renewable fuel supply) are based on the assumption that the fossil fuel is substituted by renewably produced methane. ATRES (alternative technologies and renewable energy supply) represents a more drastic conversion process in all of the considered industries by assuming that alternative production processes are used across the board when there are already technologies that produce no or significantly lower CO_2 emissions but which offer the same product properties. Fossil fuel substitution (see RFS) and the use of electricity from renewable sources are also assumed. These measures could reduce the total amount of carbon dioxide from 143 million metric tons in 2017 to 26 or 66 million metric tons of CO_2 in 2050, depending on the extent to which alternative technologies and fuels are used. Accordingly, in 2050, the main source of carbon dioxide would come from the mineral industry since the process-related emissions there can only be reduced to a limited extent. Large-scale industrial use of cement clinker in concrete production or quicklime in various applications would continue [Zitscher (2020)].

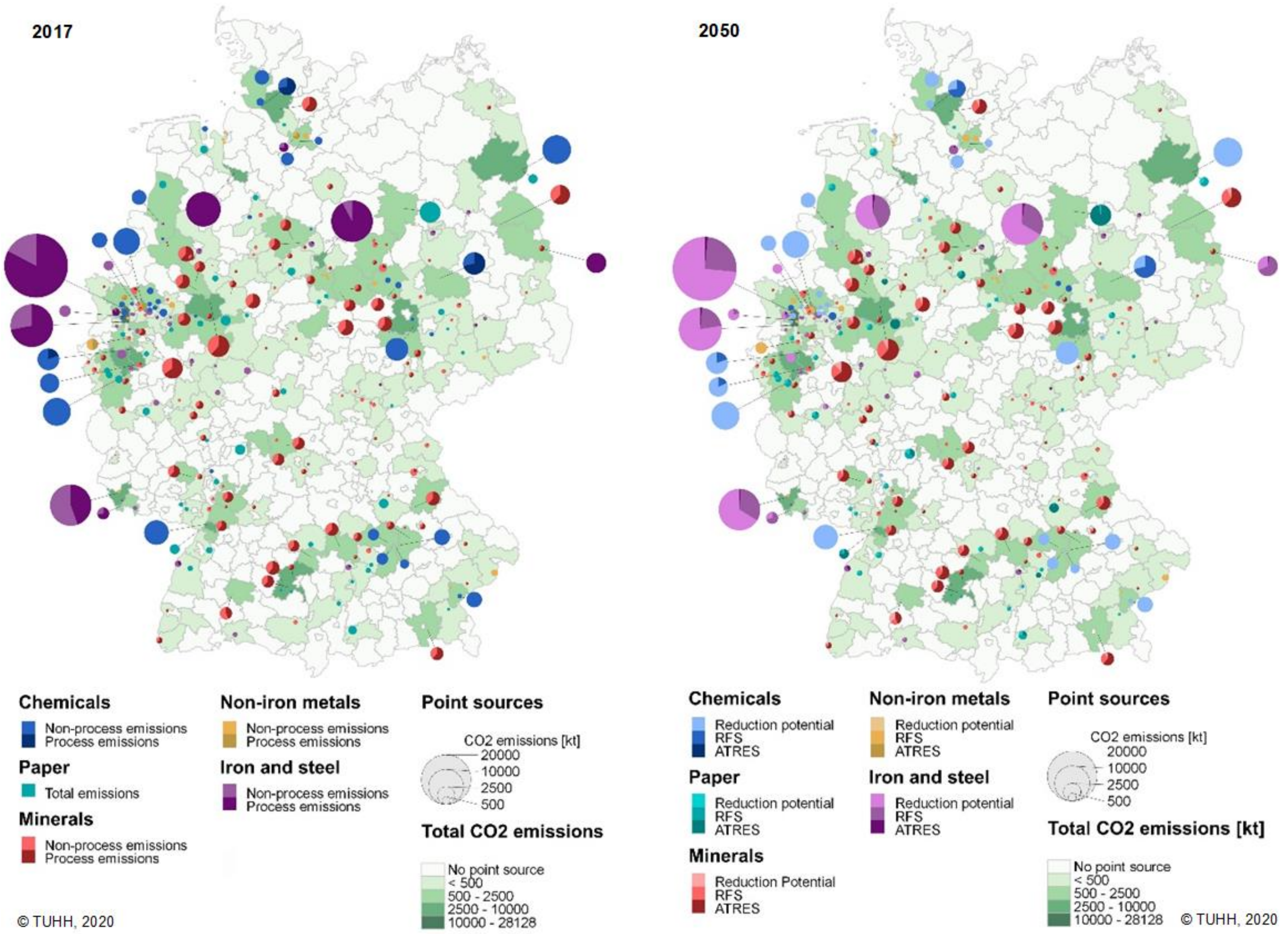


Figure 4-18 Distribution of CO_2 emissions from various industrial sectors in Germany in 2017 (left) and 2050 (right), assuming widespread use of alternative, less carbon-intensive production processes; data based on [Zitscher (2020)]

INDUSTRIAL CO_2 EMISSIONS AS POINT SOURCES IN EUROPE. There are other studies at the European level that determine carbon dioxide potential from industrial processes. In addition to the manufacturing industry, these also include the energy industry, which is not included in the potential analysis. Table 4-2 shows the CO_2 emissions generated in Europe in 2017. [Kircher (2020)]

Table 4-2 CO_2 emissions as point sources by industrial sector in Europe for 2017. Data based on [Kircher (2020)]

Industrial sector	CO_2 emissions in million t/a
Energy	1,066
Chemical	245
Metal	166
Construction	144
Paper production	77.1
Waste	55.5
Mining	7.1
Food and agriculture	5.9

In order to address sustainability and minimize the impact that the production and use of synthetic fuels have on the climate, some of the CO_2 emissions listed in Table 4-2 are attributable to their use as a carbon source. These include emissions from the fossil energy industry. Other sources can only be tapped to a limited degree since the emissions that do occur are emitted in a diffuse form and thus no direct capture and use is possible. This includes, for example, some of the emissions in the agricultural industry. Table 4-3 provides a detailed breakdown of CO_2 emissions by production process for 2016. Only sources with annual emissions of more than 0.1 million metric tons of CO_2 are considered.

Total emissions from the processes under consideration amounted to 356.4 million metric tons in 2016, which is about 2.5 times the emissions from the manufacturing industry in Germany. Based on a future shift towards more a climate-neutral industry, some of the emissions listed in Table 4-3 would no longer be available. This includes from natural gas, hydrogen and ammonia production, a large portion of iron and steel production, and from the integrated gasification combined cycle (IGCC). This would more than halve the total potential in 2016 to approximately 168.5 million metric tons [Zitscher (2020)].

Table 4-3 Suitable industrial CO_2 emissions as point sources (> 0.1 million t/a of CO_2) for the production of synthetic fuels in Europe in 2016. Data based on [Kircher (2020)]

Industrial sector that produces	CO_2 emissions in million t/a
Hydrogen	5.3
Natural gas	5
Ethylene oxide	17.7
Ammonia	22.6
Paper	31.4
IGCC	3.7
Iron and steel	151
Cement	119

Biogenic CO_2 emissions as point sources in Germany. In the biofuel and bioenergy sector, the three main potential point sources for capturing carbon dioxide in Germany are biogas, biomethane and bioethanol plants. It is possible to estimate the theoretical amount of carbon dioxide that could be captured in each state, as shown in Figure 4-19. The carbon dioxide captured from these gas sources differs in the purity of the raw gas. In the biogas sector, the purity of carbon dioxide ranges from 25 to 45 % v/v, which is lower than in the gases from biomethane and bioethanol production, where between 90 and 95 % v/v and 80 to 98 % v/v are achieved respectively [Daniel-Gromke (2018)].

Figure 4-19 shows that total CO_2 emissions from biogas production are estimated to be 10.5 thousand t/a; 0.6 thousand t/a would come from bioethanol production, and 2.0 thousand t/a would be from biomethane production (reference years 2017, 2018, and 2021 for biogas, bioethanol and biomethane). It can be assumed that some of these emissions will decrease in the future. For example, the scenario presented by [Billig (2019)] shows the discontinuation of energy crop-based biogas plants as well as all biomethane plants in Germany. At the same time, the number of waste-based biogas plants would increase. This would reduce estimated emissions from 12.0 thousand t/a of CO_2 (2016 baseline) to about 8 thousand t/a by 2050. In addition, the estimated CO_2 demand in Germany in 2012 was around 5 thousand t/a [Billig (2019)].

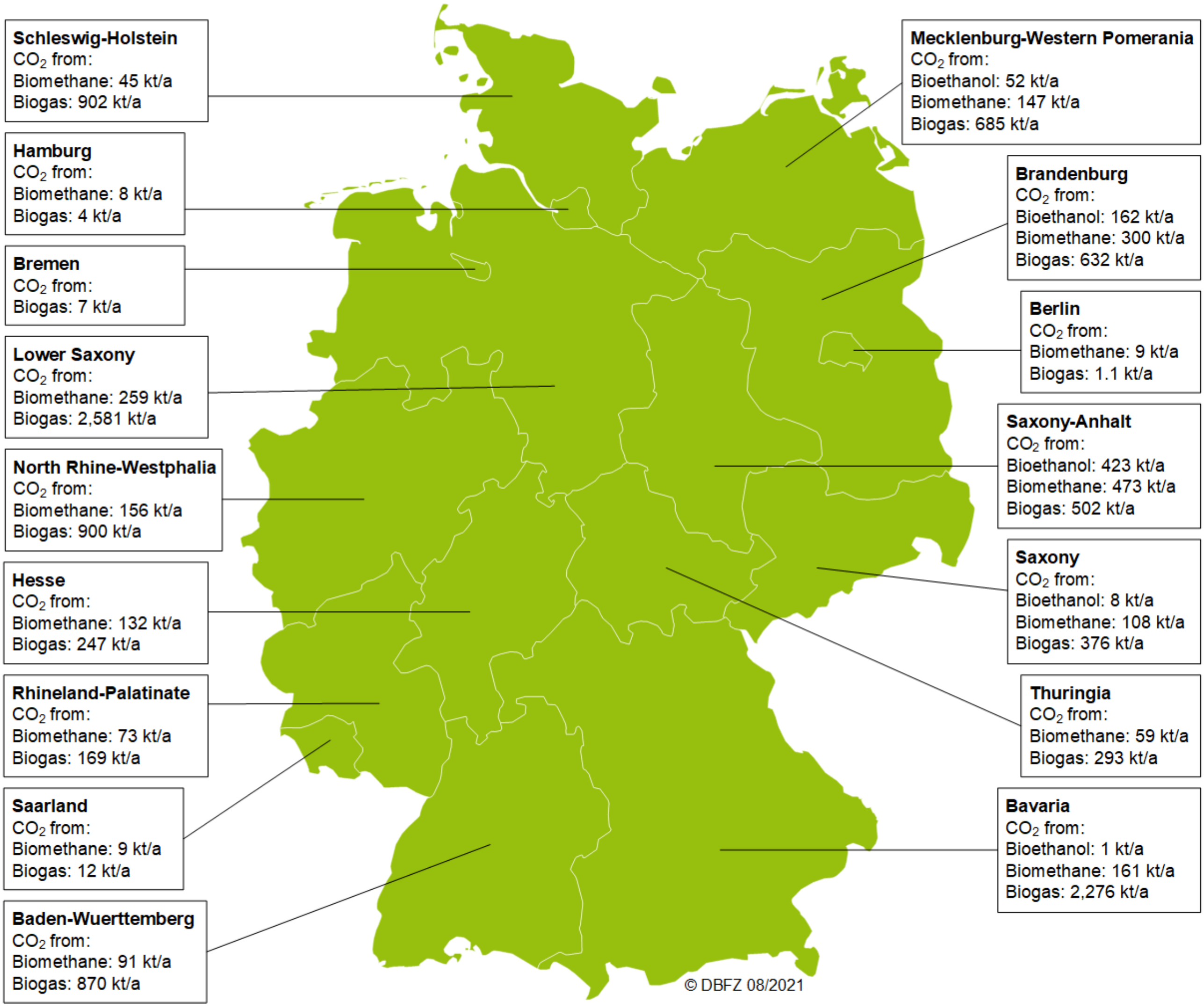


Figure 4-19 Biogenic CO_2 emissions as point sources in Germany broken down by federal state. Note: excluding wood use and processing, own calculation based on [AEE (2021); bdew (2021); Billig (2019)]; assumptions: CO_2 content in biogas: 45 % v/v, energy content in biogas: 6.25 kWh/m³ (STP), efficiency of energy production from biogas: 40.16 %.

Biogenic CO_2 emissions as point sources worldwide. In terms of global potentials, the amount of CO_2 emitted from bioethanol and biomethane production can also be estimated indirectly, as shown in Figure 4-20. The figure shows the world's largest biomethane producers: Germany (which accounts for about half of global production), the U.S. and UK, followed by other European countries. For bioethanol production, the three largest producers in 2019 were the U.S., Brazil and China. The U.S. is the only country with a high potential for CO_2 point sources from both biomethane and bioethanol production. The estimate of the global potential from biogas production was not calculated due to a lack of data. The global emissions from point sources for biomethane and bioethanol production amount to 4.3 and 82.3 million t/a, respectively. The figures for the CO_2 potential from biomethane in Germany deviate from the sum of the values shown in Figure 4-19 due to the inclusion of data from different sources.

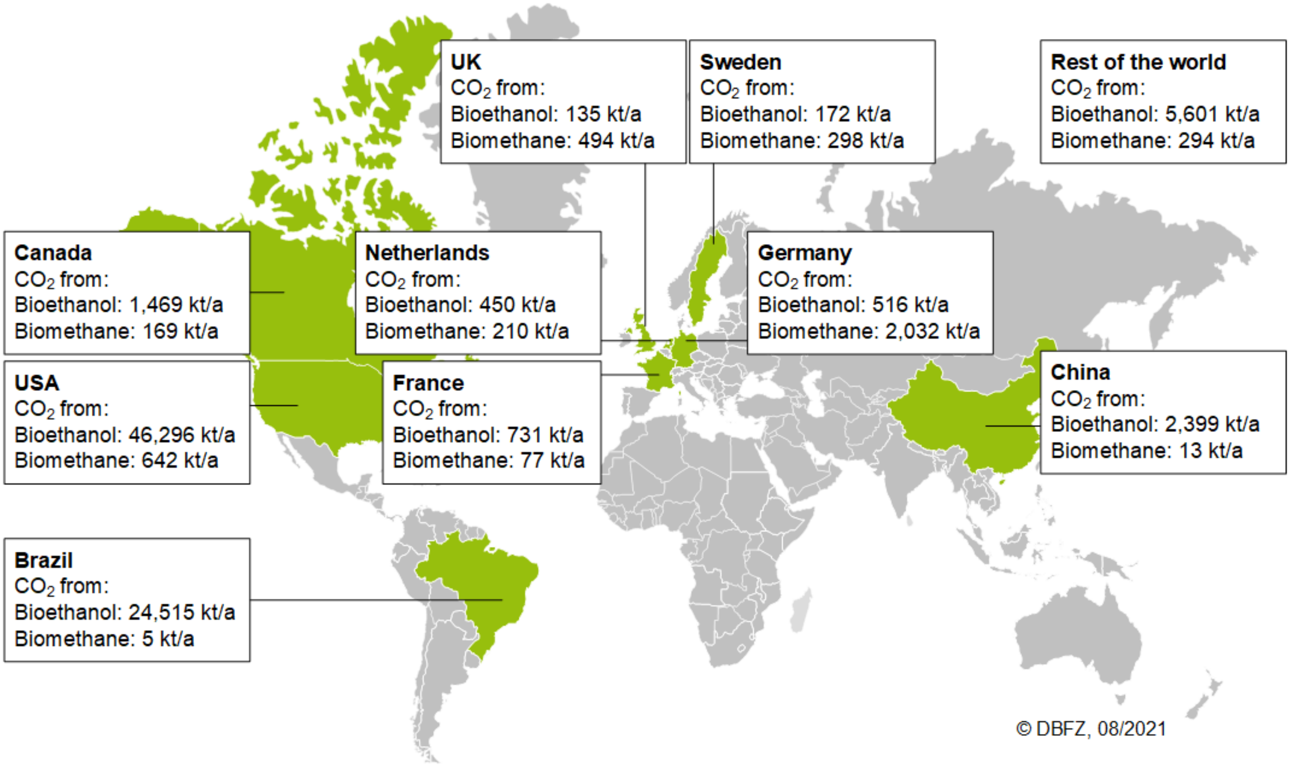


Figure 4-20 Biogenic CO_2 emissions as point sources worldwide. Note: excluding wood use and processing; own calculation based on [IEA Bioenergy (2021c); IHS Markit (2021a)]; assumptions: CO_2 content in biogas: 45 % v/v, energy content in biogas: 6.25 kWh/m³ (STP), efficiency of energy production from biogas: 40.16 %

CO_2 FROM THE ATMOSPHERE. In addition to biogenic and industrial CO_2 sources, CO_2 can also be supplied by capturing it from the atmosphere. Section 3.8.3 describes the various technologies available to do this. This is referred to as direct air capture (DAC). In effect, CO_2 capture is not location-dependent since the concentration of CO_2 is basically distributed uniformly all over the world. There are only minor spatial and temporal fluctuations in the concentration in the atmosphere due to influences such as vegetation, time of day and growing season [Fischedick (2015); Keeling (1996); NASA (2021)]. However, these are of secondary importance when it is to be captured using DAC technologies. Due to low concentrations (400 ppm) compared to industrial or biogenic sources, capturing CO_2 from the atmosphere takes a much greater technical effort, which is marked by a relatively high need for thermal energy to regenerate the sorbents [Fischedick (2015); Viebahn (2019)]. In principle, DAC offers the possibility of supplying CO_2 on-site, independent of any point sources located in the vicinity. This takes advantage, for example, of particularly favorable production conditions for renewable electricity with the goal of producing synthetic fuel. For this supply option, it is important to have a sufficient amount of thermal energy. In the case of PTL production, this can be partially achieved by integrating heat from the synthesis processes [Viebahn (2019)]. Other alternatives include renewable energies, such as solar thermal electricity or deep geothermal energy, which are presumed to be able to provide a high level of thermal energy.

Excursus 4: Geological storage of biogenic carbon dioxide (BECCS)

Bioenergy with carbon capture and storage (BECCS) describes the capture and geological storage of carbon dioxide produced as a by-product from the use of biomass to generate energy [Prognos (2021)]. The technological maturity of BECCS depends on the combination of the bioenergy production technology and the CCS technology used [Royal Society and Royal Academy of Engineering (2018)]. The possibility of integrating CO_2 capture into a biomass conversion pathway depends not only on how ready the technology is for commercial use, but also on the technical effort required to integrate the capture of CO_2 into the respective process, the additional energy required for CO_2 capture, and the additional cost [Witte (2019)]. With the aim of achieving the climate protection goals, the degree of CO_2 capture (capture rate) and the extraction capacity for each technology are important criteria when selecting bioenergy concepts that integrate CO_2 capture. In general, liquid or gaseous fuels can be obtained from biomass through thermochemical, physicochemical, or biochemical conversion (Section 3). Even though carbon dioxide is produced as a by-product in such processes, the use of sustainable biomass is considered carbon neutral. This is based on the fact that the carbon dioxide produced by the process is no higher than the amount of carbon dioxide that the biomass has bound from the atmosphere through photosynthesis in the course of its lifetime [Shahbaz (2021)]. The use of BECCS is therefore limited by the availability of sustainable biomass [Prognos (2021)]. Through its capture and subsequent geological storage, the biogenic carbon dioxide is removed from the carbon cycle over the long term and thus does not contribute to CO_2 accumulation in the atmosphere. BECCS is therefore also referred to as a negative emission technology (NET) [Shahbaz (2021)]. Geological storage of carbon dioxide can occur in deep saline aquifers that can be found on and offshore all over the earth [Fischedick (2007); Olsson (2020a)]. Depleted oil and natural gas fields and unminable coal seams are also suitable for long-term carbon dioxide storage [Fischedick (2007)]. There are only five plants worldwide that use BECCS. Together, they capture about 1.5 million metric tons of CO_2/a [Global CCS Institute (2019); Shahbaz (2021)]. All of these five plants produce bioethanol using aerobic fermentation, which produces a very pure CO_2 waste gas stream. This keeps the cost of CO_2 capture comparatively low [Global CCS Institute (2019)].

Negative emission technologies will play an important role in the future as a way to limit global warming to 1.5 °C and thus reduce the risks caused by global climate change [Olsson (2020a)]. Even with the appropriate abatement measures, residual emissions will occur in the future, particularly in agriculture, industry, and waste management, and these will have to be offset. BECCS is expected to play a particularly important role in addition to the direct capture of carbon dioxide from the air with subsequent geological storage or subsequent synthesis of green polymers [Prognos (2021)]. BECCS not only contributes to the long-term removal of carbon dioxide from the atmosphere, but also provides bioenergy, for example in the form of biofuels, which can be used as alternatives to fossil fuels [Global CCS Institute (2019); Shahbaz (2021)].

4.4 Potential of renewable fuels

A range of emission-reducing measures is required to achieve the climate targets in the transport sector. A key element is to convert as much of the stock of vehicles as possible into electric drives and to switch to renewable fuels in those areas where electrification is difficult or impossible. The renewable fuel requirements resulting from this ambitious transformation of transport and mobility have already been presented in Section 2.6.1.

This section will provide a basic description of the suitable feedstocks needed for renewable fuels. This will be followed by information about the current and potential use of these feedstocks, a comparison of the fuel potentials resulting from these feedstocks, and the future needs of the transport system.

4.4.1 Potential of biofuels

In addition to the different levels of potential (Section 4.3), a strategic, socio-political decision must also be made about which areas should benefit from the limited potentials. In addition to the biogenic primary products from agricultural cultivation, this also applies to all biogenic by-products, residues and wastes, and in a less critical manner, for example, to the point sources of CO_2 for the provision of e-fuels. Various criteria play a role here. System services (positive synergies with other sectors, e.g., the electricity sector) and the lack of technically suitable renewable alternatives are considered alongside efficiency of use. These aspects are also briefly discussed in the excursus "The need for a comprehensive biomass strategy".

The conventional fuel potentials shown in Figure 4-21 are based on 200,000 hectares of domestic land used to grow bioethanol feedstocks and 500,000 hectares for biodiesel feedstocks. This corresponds to 2019 levels as well as to the long-term minimum based on the years 2012 to 2020 [BMEL (2021)].

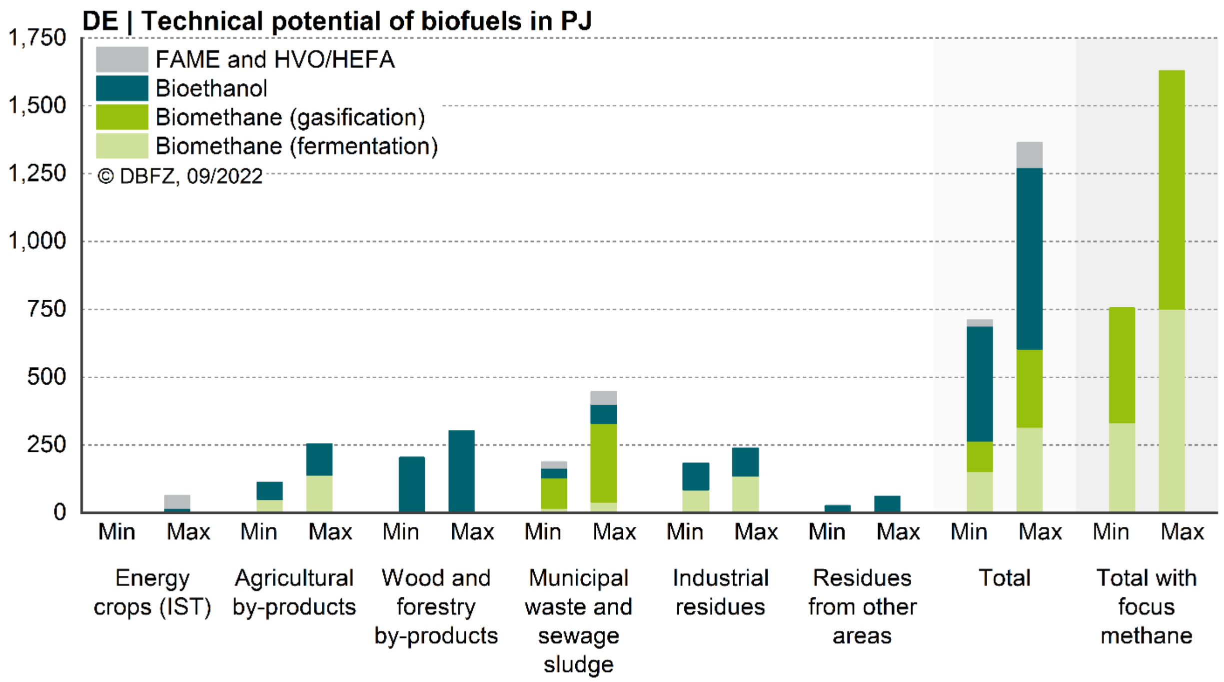


Figure 4-21 Technical potential of biofuels in Germany. Note: own calculation; data based on [DBFZ (2021b)] for advanced bioresources 2015 and the associated conversion, preferably to the liquid biofuels ethanol and FAME, also shown as a total with an alternative focus on methane; [BMEL (2021)] for feedstocks for conventional biofuels from cultivated areas in 2019 and a corresponding conversion.

In accordance with the levels of potential presented in Section 4.3, the technical potential is greater than the mobilizable (i.e., usable) potential. The technical resource potential shown in Figure 4-21 must therefore be adjusted for numerous limiting factors in order to determine the mobilizable potential (Figure 4-22). When tapping this potential, it must be remembered that other sectors will also increasingly be using biogenic feedstocks in the future and that it is therefore very unlikely that the mobilizable potential can be fully utilized for energy in the transport sector.

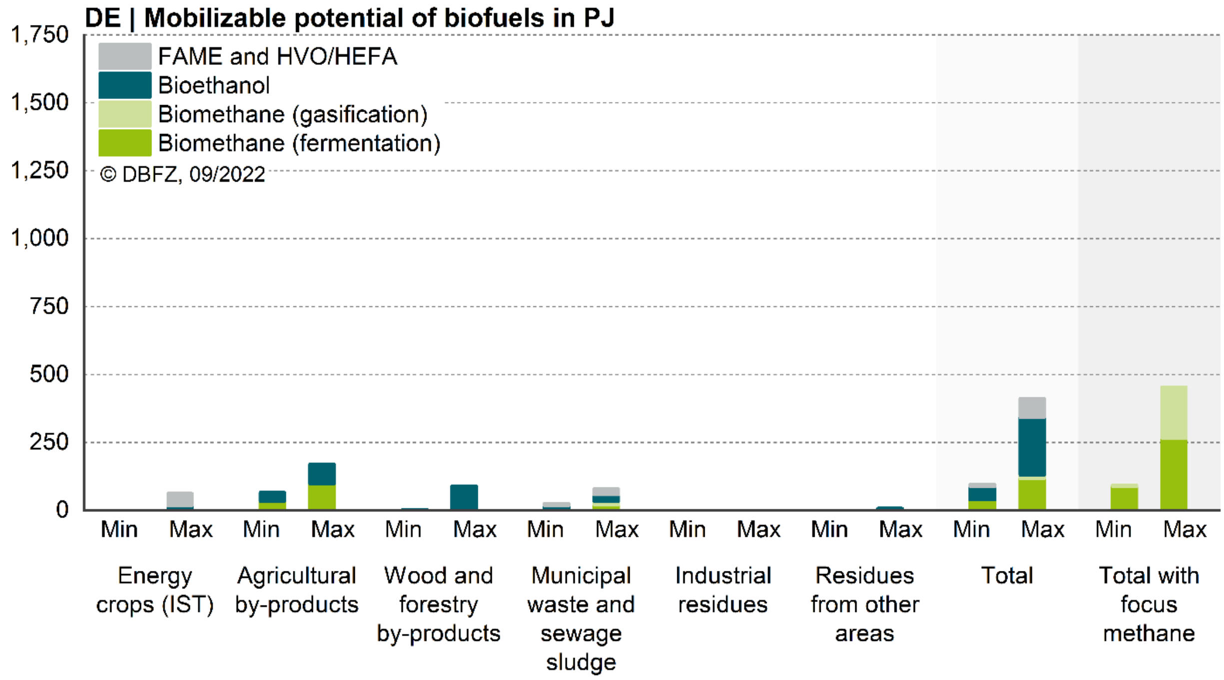


Figure 4-22 Mobilizable potential of biofuels in Germany. Note: own calculation; data based on [DBFZ (2021b)] for advanced bioresources 2015 and the associated conversion, preferably to the liquid biofuels ethanol and FAME, also shown as a total with an alternative focus on methane; [BMEL (2021)] for feedstocks for conventional biofuels from cultivated areas in 2019 and a corresponding conversion

The technical potential of the agricultural by-products and waste generated in **Europe**, estimated at 0.7 billion metric tons of dry matter (DM, reference year 2016 Section 4.3.1), corresponds to a technical biomethane potential of 3.8 to 5.8 EJ for anaerobic fermentation plus 240 to 290 PJ of biomethane from the gasification of mainly non-fermentable woody or fruit tree cuttings (own calculation based on [Bedoić (2019)]). Forestry residues or, for example, landscape conservation materials, are not included. The estimate was based on biomethane since a wide range of advanced bioresources can be utilized here, even though other sustainable utilization routes to biogenic fuels are certainly possible for individual material flows. Furthermore, it must be assumed that only a significantly smaller portion of the technical potential will even be tapped at all and that, in addition to the production of fuels for transport, other material or energy uses can also be conceivable and sustainable. When utilizing the bioresources through anaerobic fermentation or gasification to produce biomethane, further process steps may also be required in order to supply this as a fuel in the form of bio-CNG, bio-LNG or, for example, bio-GTL. Each of these options is accompanied by specific losses in efficiency – in other words, the usable energy in the form of fuel correspondingly goes down.

Excursus 5: The need for a comprehensive biomass strategy

According to the coalition agreement of the current federal government, “Bioenergy in Germany is to have a new future. We will develop a sustainable biomass strategy in order to achieve this.”

The challenges in moving towards climate neutrality by 2045 also include the optimal integration of all biogenic resources into a target-oriented carbon cycle. In addition to reducing GHG emissions, it is essential to understand the quality and quantity of all utilizable biogenic resources as well as their intended optimized use in the required sectors.

This biomass utilization strategy must consider both the energy and material use of biomass as well as its sink performance. The investigation and evaluation of conflicting goals, for example with regard to land availability and competing uses, should serve as a basis for a well-balanced use of biomass, which is a key factor for all sectors. [dena (2021c)]

The established use of biomass for energy in various sectors (as well as its increasing material use in the course of an emerging bioeconomy) requires a uniform and sufficiently high CO_2 price and a comprehensive sustainability certification of all forms of biomass [Witte (2019)]. In addition, and most importantly, there needs to be a sustainable strategy for the use of limited resources.

Furthermore, there is also an important relationship between the agricultural sector and food supply. Achieving the climate targets in Germany is linked, among other things, to the fundamental premise of larger market shares for plant protein products than for animal protein products in the period after 2030 [Prognos (2021)]. A significant reduction in livestock farming would also lead to a corresponding reduction in the land required for growing animal feed, even though an expansion of organic farming and the associated reduction in land yields would reduce this effect.

Zech et al. shows, for example, that a (healthier) diet in Europe, which contains less meat, can also free up significant potentials for other uses. Agriculture is responsible for a large percentage of global GHG emissions, with livestock farming accounting for the largest proportion. Limiting average daily meat consumption per capita in Europe to the maximum level recommended by the World Health Organization (WHO) would roughly correspond to halving the current amount (from more than 200 g/d to 100 g/d per capita). This would increase biofuel potentials from a total of 9.5 million metric tons (2007 – 2011 average for biodiesel and bioethanol) to almost 69 million metric tons (biodiesel, bioethanol and biomethane). Furthermore, direct emissions from livestock farming would widely be avoided. [Zech (2019)]

According to preliminary figures from the Federal Office for Agriculture and Food, 84.5 kg of meat per capita was available for consumption in Germany in 2020. In addition to the actual amount of meat consumed of 57.3 kg/capita (down 1.3 % from 2019), this also includes the consumption of feed, industrial utilization, and all losses. In contrast, the average per capita consumption of meat in the EU-28 was 80.0 kg in 2019, up 0.6 % from the previous year. Global per capita meat consumption was 42.9 kg in 2018, up 28 % over 1990 levels. [BLE (2021a)]

4.4.2 Potential of e-fuels

The direct use of electric power is, as already shown in Figure 4-13, the most efficient use of renewable non-biogenic resources compared to various other drive systems. Furthermore, renewable hydrogen can be provided via electrolysis using electricity from renewable sources and water. Various processes can be used to process this hydrogen further, which is combined with carbon to produce electricity-based hydrocarbons such as methane (Figure 4-23), methanol (Figure 4-24) and Fischer-Tropsch fuels. A more detailed description of this is provided in Section 3.

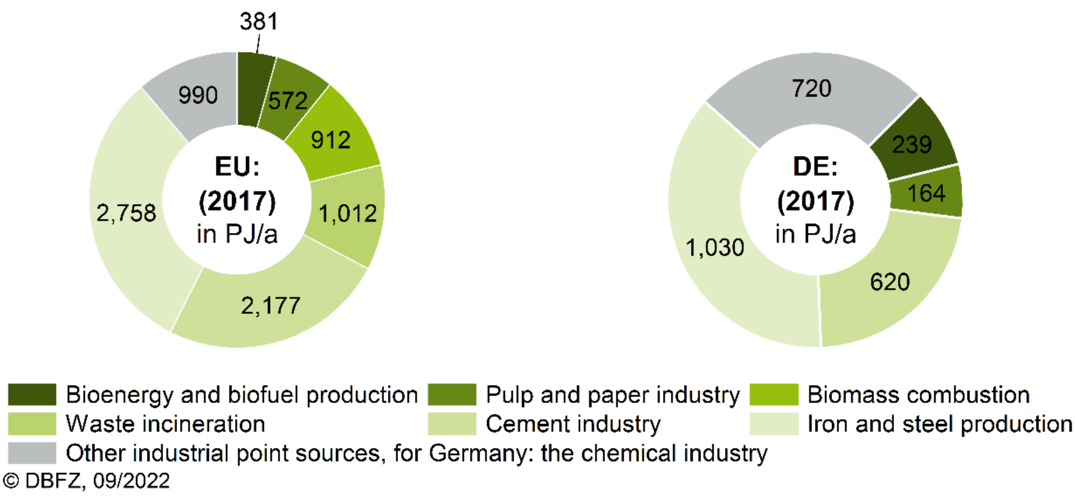


Figure 4-23 Potential of electricity-based methane in Germany and Europe based on CO_2 point sources in 2017. Note: own calculation based on data from Figure 4-14

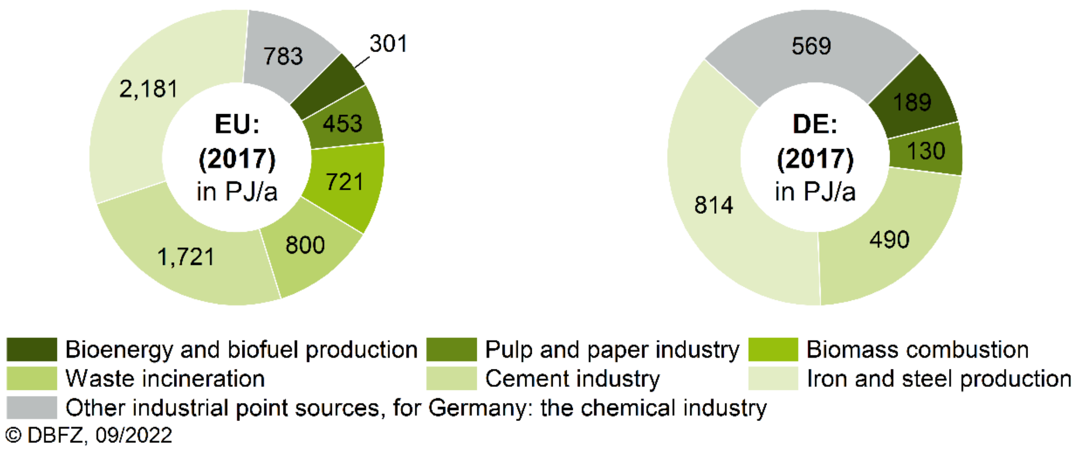


Figure 4-24 Potential of electricity-based methanol in Germany and Europe based on CO_2 point sources in 2017. Note: own calculation based on data from Figure 4-14

The production of e-fuels is primarily associated with the need for a considerable amount of (renewable) electricity. These generation capacities – mainly from wind and solar energy – as well as the electrolysis plants and PTX plants require a correspondingly large amount of land. Numerous studies therefore widely agree that the production of e-fuels will essentially take place in non-European countries due to the greater land potential there and the assumption that production costs will be significantly lower. [Schmieder (2021)]

4.4.3 Summary and conclusions

With regard to **GERMANY'S** biofuel potential, Figure 4-25 shows the range of mobilizable potential for advanced feedstocks. However, it can be assumed that this will not be exclusively used for fuel production in the future. This is based on a limited use of land in Germany for conventional fuels (Section 4.4.1). For e-fuels, it is based on the current stock of selected CO_2 point sources. Accordingly, the two options of e-fuels (PTG and PTL) cannot be added together. Regardless of this, carbon dioxide can also be captured from the air, for example. The availability of electricity from renewable sources and water for electrolysis, which is likely a strong limiting factor, is not considered in this scenario. The requirements shown on the right in the figure represent only two example scenarios from a wide range of development possibilities: the result of delayed action (GreenLate scenario [Purr (2019)]) and the achievement of the 2045 climate target (Agora Energiewende [Prognos (2021)]).

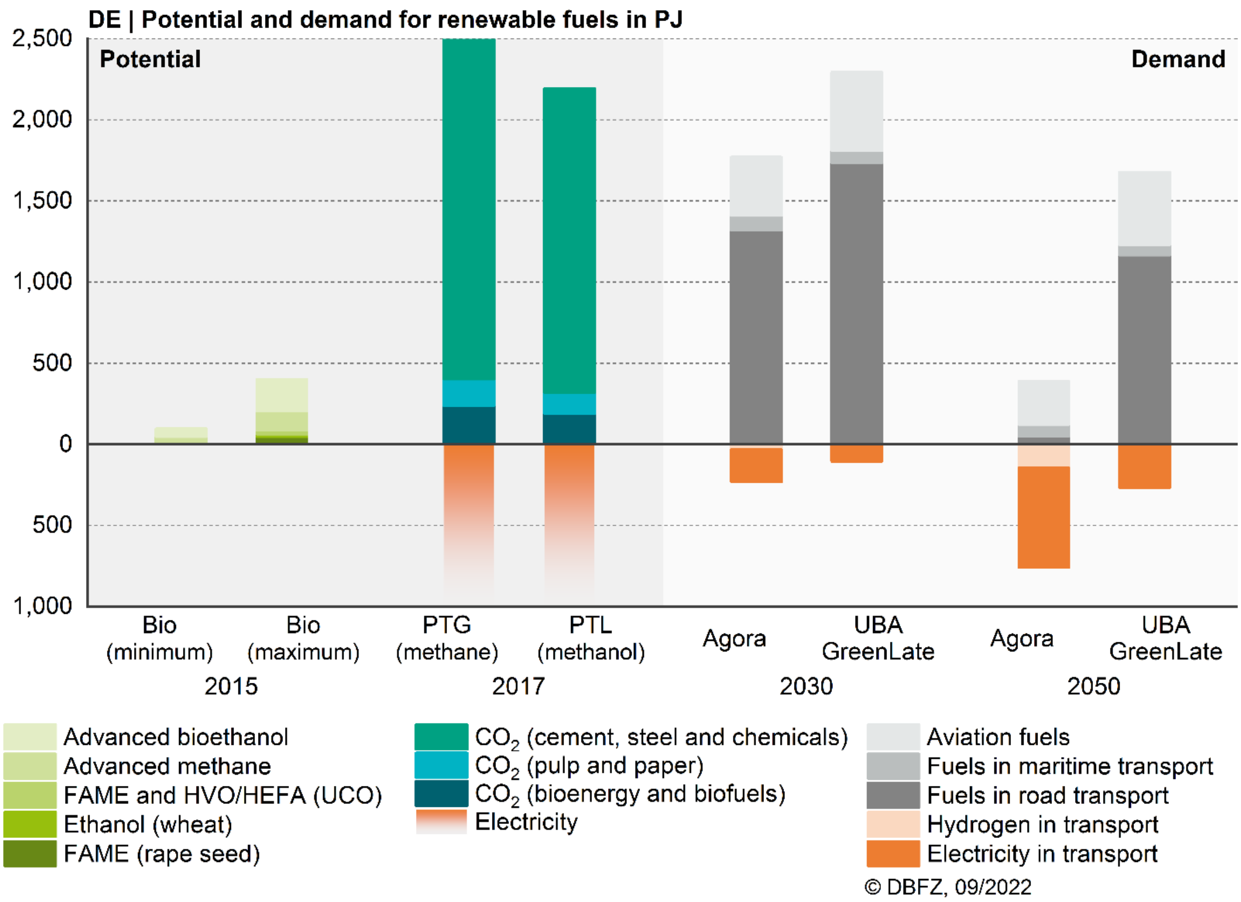


Figure 4-25 Mobilizable potential of biofuels (2015) and technical potential of e-fuels based on CO_2 point sources (2017) as well as the demand for renewable fuels in Germany (2030 and 2050). Note: own calculation and illustration; data based on Figure 4-22 for ranges for biofuels based on mobilizable potential, potential of e-fuels (PTX) based on point sources (Figure 4-23 and Figure 4-24); examples of demand scenarios according to [Purr (2019)] with late action, and according to [Prognos (2021)] with ambitious measures [DBFZ (2021b); Kircher (2020); Prognos (2021); Purr (2019)]

In terms of biofuel potential in the **European Union**, Figure 4-26 shows the technical potential, in other words restrictions are largely not taken into account here and the mobilizable potential is likely to be significantly lower. For e-fuels this is again based on CO_2 point sources. Like in Figure 4-25, methane and methanol cannot be added together, and the limited influence of the availability of electricity from renewable sources and water is not taken into account. The two demand scenarios for 2030 and 2050 are taken from the *impact assessment report* for the draft revision of the RED II [COM(2021) 557 (2021)]. The EU Reference Scenario (REF) contains projections for energy demand and supply under the current policy framework of the European Union and its Member States. It particularly takes into account the current framework conditions for achieving the climate target of a 40 % minimum reduction in greenhouse gas emissions in 2030 over 1990 levels, but not the achievement of the revised climate target for 2030 of a 55 % minimum reduction. The REG scenario, on the other hand, relies on a very strong intensification of energy and transport policies.

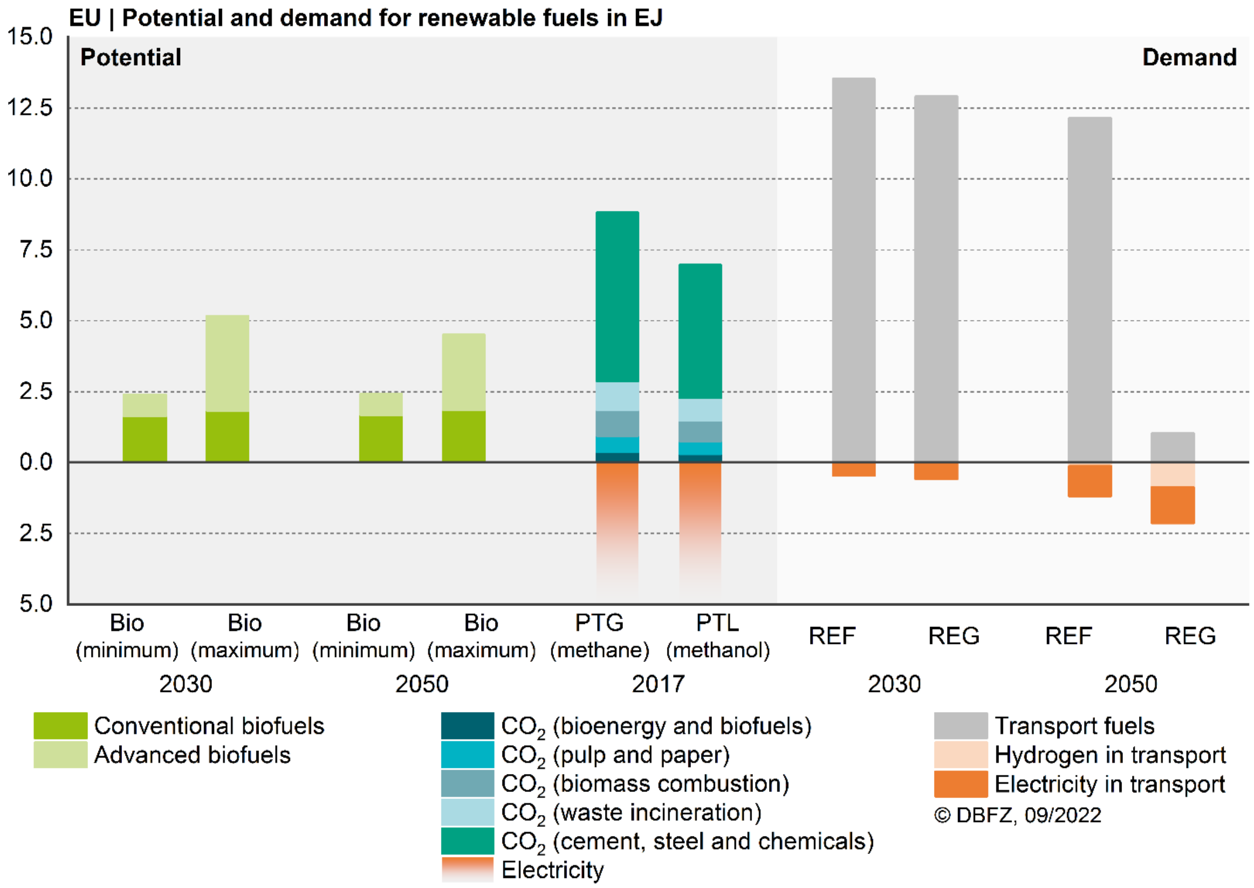


Figure 4-26 Technical potential (2017, 2030, 2050) and demand (2030, 2050) for renewable fuels in the European Union. Note: own calculation and illustration; data based on according to [Hoefnagels (2018)] for bioresource potential excluding forestry biomass, [Kircher (2020)] for potential of e-fuels (PTX) based on the CO_2 potential, [COM(2021) 557 (2021)] for the reference (REF) demand scenario and the demand scenario "strong intensification of energy and transport policy" (REG)

However, the comparison of current potentials and future demands in Figure 4-25 and Figure 4-26 can also be regarded as having only a limited significance overall. Uncertainties or ranges exist at various levels of the analysis, which are listed in Table 4-4.

Table 4-4 Uncertainties and/or ranges in the analysis of potentials and demands

Category	Description	Indicator
Potential of biofuels		
Biogenic primary products	Prospects	
	Limitation or exclusion of agricultural and forestry feedstocks for selected purposes, social and political discourse required	*Strategy*
Biogenic by-products, residues and biogenic waste	Status quo	
	Availability and quality of the data for determining historical and current theoretical potentials of advanced bioresources, also including, for example, temporal, regional and qualitative fluctuations	*Data basis*
	Availability and quality of data for identifying all limiting factors and already established uses of advanced bio-feedstocks (quantification of mobilizable potential)	*Restriction*
	Processes and corresponding conversion factors in the production of bio-based fuels and energy carriers, e.g., biomethane instead of bioethanol, etc., including efficiency losses in downstream products such as ATJ from ethanol or LNG from biomethane	*Conversion*
	Prospects	
	Future development of relevant influencing factors for quantifying and limiting potentials, including cascade factor [Indufor (2013)]	*Data basis, restriction*
	Future (further) development of suitable conversion technologies and associated parameters	*Conversion*
	The more longer-term the determination of the prospective potential, the greater the uncertainties	
	Mobilizing and utilizing potentials by building up corresponding capacities in production, infrastructure and use ultimately require appropriate framework conditions	*Strategy,* *Legislation*
Potential of electricity from renewable sources and e-fuels		
Electricity from renewable sources	Status quo	
	Availability and quality of the data for determining the theoretical potentials of renewable energy, also including, for example, seasonal and regional fluctuations	*Data basis*
	Availability and quality of the data for identifying all limiting factors as well as other uses in other sectors (quantifying mobilizable potential)	*Restriction*
	Prospects	
	Future development of relevant influencing factors for quantifying and limiting potentials	
E-fuels	Status quo	
	Availability and quality of the data for determining the theoretical potential of resources for e-fuels, especially with regard to electricity from renewable sources, water and CO_2 as a carbon source	*Data basis*
	Availability and quality of the data for identifying all limiting factors and other uses (e.g., also CO_2 for BECCS)	*Restriction*
	Processes and corresponding conversion factors in the production of bio-based fuels and energy carriers, e.g., biomethane instead of	*Conversion*

Category	Description	Indicator
	bioethanol, etc., including efficiency losses in derivatives such as ATJ from ethanol or LNG from biomethane	
	Prospects Future development of relevant influencing factors for quantifying and limiting potentials Future (further) development of suitable conversion technologies and associated parameters	*Data basis, restriction* *Conversion*
	Mobilization and use of the potentials The development of corresponding capacities in production, infrastructure and utilization ultimately requires appropriate framework conditions	*Strategy,* *Legislation*
Demand in the transport sector		
Total energy demand	Significant reduction in total final energy demand in the transport sector ▪ Crucial for achieving climate targets – in the short, medium and long term ▪ Need for ambitious measures to avoid transport, shift transport (e.g., road-rail), and improve transport (e.g., drive systems and energy sources)	*Strategy* *Legislation*
Specific need for energy carriers	Decisive orientation for energy supply in transport 2030/2050: ▪ Convertible potential of all suitable energy ▪ Allocation of the implementable potential to the different modes of transport based primarily on technical criteria ▪ Forcing and controlling corresponding changes to systems and/or drives	*Strategy,* *legislation*

As Table 4-4 shows, the range of resource potentials is offset by the scope for implementing transport policy measures. While research and development can improve knowledge of the status quo and the future development of renewable resources, their development (keyword: biomass strategy) and type of use are largely determined by legal and economic framework conditions. The same applies to the development of the specific demand for renewable energy sources in the transport sector.

These ranges therefore do not allow for a conclusive quantification of the (sustainable) implementation potential of renewable energy sources in the transport sector. In summary and with a view to what is presented in Section 9, their potentials are therefore qualitatively classified in Table 4-5. This classification, like all previous remarks, takes into account a regionally delimited resource potential. The established international trade in feedstocks and products, as described in Section 5.4, and the resulting potential imports are not included in this analysis.

Table 4-5 Qualitative classification of the potentials of renewable resources for energy carriers in the transport sector in Europe . Note: the evaluation scale has three levels: low – limited – high

Category	Feedstock group	Feedstock examples	Theoretical potential	Implementation potential in the transport sector
Biogenic primary products	Primary agricultural products	Seeds and fruit containing sugar, starch and oil	High	Low to limited
		Intermediate crops, cultivated wood	Low to limited	Low to limited
	Primary forestry products	Logs	High	Low
Biogenic by-products, residues and waste	Agricultural by-products	Straw, herbage	Limited	Low to limited
	Forestry by-products	Branches, bark etc.	Limited	Low
	Industrial by-products and waste	Black liquor, tall oil	Low to limited	Low
		Sludge, water, etc.	Limited	Low
		Animal by-products	Limited	Low
	Other residues and waste	Waste wood	Low to limited	Low
		Used cooking oil	Low	Low
		Municipal waste	Low	Low
		Green clippings	Low	Low
Resources for e-fuels	Electricity from renewable sources	Wind, sun, water	High	Limited to high
	CO_2 point sources	Fossil and bio-based processes/industries	Limited to high	Low to limited
	Diffuse CO_2 sources	Air	High	Limited to high

The feedstocks and potentials considered here are exclusively related to the supply of energy carriers suitable for the transport sector. Not included in the analysis are all infrastructure expenditures, i.e., all resources required for production (production facilities), distribution (grids), and use (vehicles).

Section 7.8 looks in more detail at the lifecycle greenhouse gas emissions of vehicles with different drive systems in relation to their mileage. A comprehensive resource and sustainability assessment of mobility and transport concepts requires that all parts of the supply and application chain be considered accordingly.

5 Market overview

KARIN NAUMANN, JÖRG SCHRÖDER AND GABRIEL COSTA DE PAIVA

5.1 Background

For more information:

The long-term global trend in the transport sector is characterized by a high and fast-growing demand for energy. As shown in Figure 5-1, this demand has almost doubled in the past 30 years since 1990. Even though the use of biofuels has increased fivefold to about 3.8 EJ over the same period, only about 3 % of the energy demand can be substituted by a biogenic alternative. In comparison, the rate of growth of electricity over the past 30 years has been significantly lower (1.6 times). Overall, these two energy carriers, which are key to the energy transition, cover just 4.3 % of the energy demand in global transport [IEA (2021e), (2021c)].

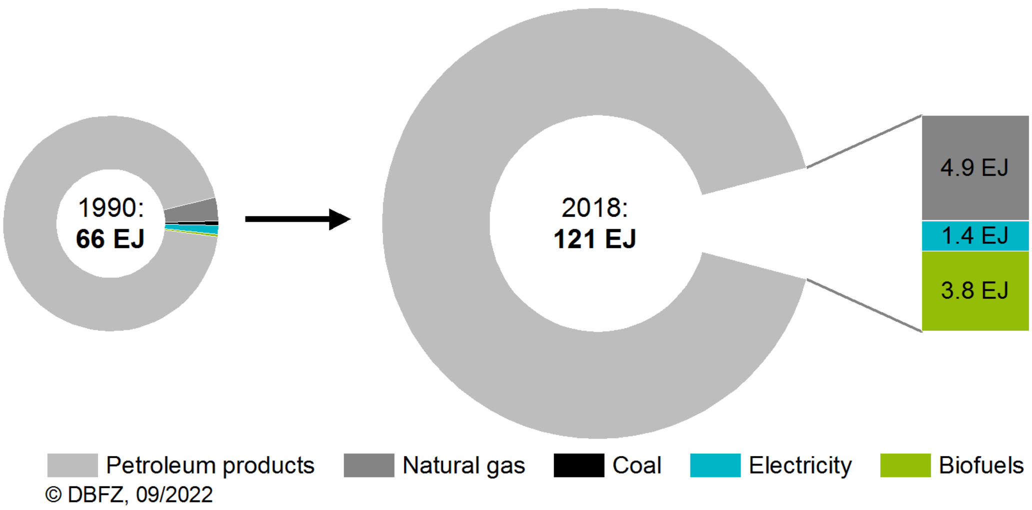


Figure 5-1 Global final energy consumption in the transport sector by energy source in 1990 and 2018. Data based on [IEA (2021e), (2021c)]

The sugar cane processing industry in Brazil had already begun in the 20th century to produce bioethanol as a fuel in addition to processing sugar; in the 1990s, it produced about 10 million m³ annually, making Brazil the main global producer of bioethanol. As Figure 5-2 shows, global bioethanol production increased to 85 million m³/a (1.8 EJ/a) by 2010 and then to around 110 million m³/a (2.3 EJ/a) by 2019. Production declined by around 10 % in 2020, whereas slight growth is expected again in 2021. [IHS Markit (2021d)] Since 2006, biodiesel (FAME) has made up a relevant proportion of the biofuels used worldwide. Following continuous growth, the volume produced in 2019 was around 40 million metric tons (1.5 EJ) of FAME [IHS Markit (2021c)]. HVO/HEFA (hydrotreated vegetable oils or hydroprocessed esters and fatty acids) has also been produced as a paraffinic diesel substitute in industrial-scale plants since 2007. This volume had increased to about 6 million t/a (0.3 EJ/a) worldwide by 2019.

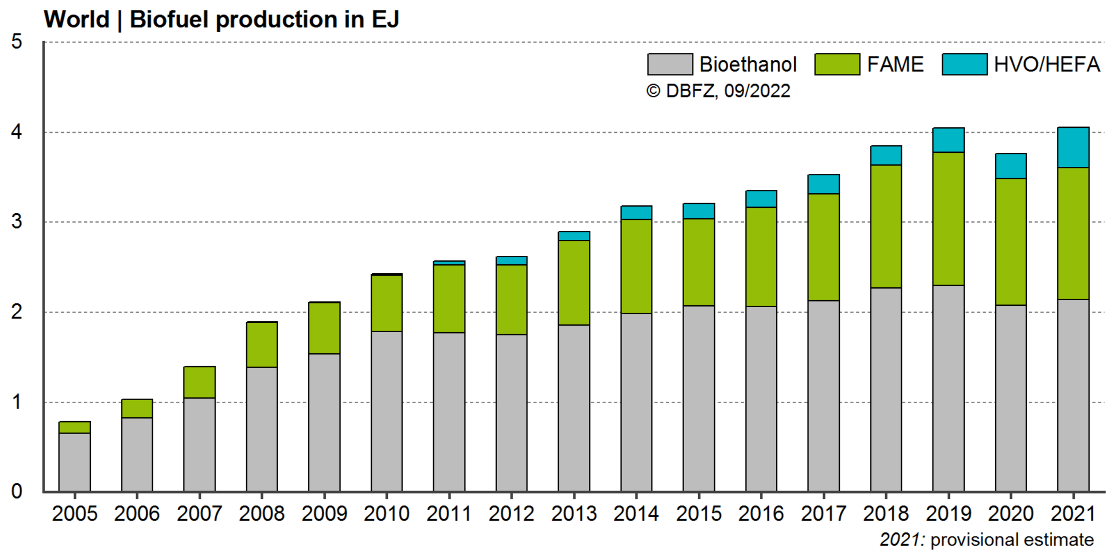


Figure 5-2 Development of global biofuel production volumes. Note: own calculation; data based on [F.O. Licht (2009), (2012a), (2014a), (2015b), (2015d); IHS Markit (2021c), (2021d)]

5.2 Production

In 2020, the situation caused by the COVID-19 pandemic significantly changed the demand for fuels and thus the global need for renewable energy in transport. The effects were still noticeable in 2021 and may continue to be felt in the coming years. At the global level, bioethanol remains the most important renewable fuel in the transport sector. Global bioethanol production in 2020 was lower than originally expected as a result of COVID-19. The U.S. and Brazil were particularly hard hit, as their bioethanol markets are dominated by fuel ethanol. The global production of bioethanol declined by about 10 % in 2020. Bioethanol as a fuel is expected to grow by 4 % in 2021 and 5 % in 2022. This would leave the available volume below 2019 levels even in the third year after the outbreak of the pandemic. [IHS Markit (2021d), (2021i)] In the short to medium term, focus on the global scale will be on new sales markets for biofuels in general and on those of previously insignificant feedstocks in particular. In addition to the historically established centers for the production of FAME and HVO/HEFA, Asian producers are currently expanding their role as suppliers of advanced biofuels. These suppliers of advanced FAME and HVO/HEFA are also targeting European and U.S. import markets, spurred on by decarbonization targets for road, air, and maritime transport in Europe and the U.S. and their preferences for advanced feedstocks (Section 1).

In the Member States of the European Union, COVID-19 measures restricting personal contact reduced mobility and fuel consumption in road transport, with a much greater reduction in gasoline than in diesel. As a result of this decline, bioethanol fuel production in Europe also fell by 8 % in 2020 over the previous year. The levels seen in 2019 will probably not be reached again until 2022. [IHS Markit (2021d), (2021e)] The demand for diesel fell by 4 % in 2020 over the previous year. Diesel demand is also expected to be below average in 2021. These COVID-19-related market developments coincide with decarbonization efforts by the European Union. Successively increasing targets for renewable energy and greenhouse gas reduction (RED/FQD/ESR) offset the decline in the fuel demand for road transport in 2020 and has also allowed some rise in the demand for FAME (estimated at 19.5 million metric tons in 2020 compared to 18.9 million metric tons in 2019). In 2021 and 2022, demand may increase to 20.8 and 22.6 million metric tons, respectively. [IHS Markit (2021f)]

The following general development trends are currently emerging on the European biofuels market:

- **Focus on biofuels from residues and waste:** Biofuels from specific feedstocks are promoted through the multiple counting of certain options as outlined in the RED. Despite some bottlenecks in the availability of feedstocks, the share of these biofuels (so far mainly biodiesel from used cooking oil and animal fat) has increased significantly in the last decade. The total demand for FAME under Annex IX Part B of the RED II was about 3.3 million metric tons in 2020. This corresponds to about 1.3 % of the demand for liquid road fuels and is thus below the upper limit of 1.7 % specified by the RED II. [IHS Markit (2021b)] As a result, the use of FAME from used cooking oil and fat could continue to rise to the upper limit in the short to medium term. The generation of energy from waste has generally become an attractive business, leading to the establishment of global trading networks.
- **Promotion of alternative renewable energy in transport:** Renewable energy policies for the transport sector are no longer just limited to liquid biofuels. In some Member States, other options include compressed or liquefied biomethane as well as electricity from renewables or hydrogen. In Germany, refineries are even allowed to use upstream emission reduction (UER) projects to a certain extent to fulfil their greenhouse gas quota (Section 1.5.1).
- **Focus on HVO/HEFA:** Renewable diesel in the form of HVO/HEFA offers better physical and chemical properties (cetane number, energy content) and a higher blending limit than FAME. It has therefore become an important option in many European countries in recent years (Figure 6-1). In addition, mineral oil companies are under pressure to decarbonize their value chains. Converting an existing refinery (possibly partially at first) into a plant for renewable diesel presents an interesting option. [IHS Markit (2021f)]
- **Excess credits for renewable energy and/or GHG reductions:** Like in Germany, credits from the pre-2020 commitment periods still exist in a number of other EU Member States, and it is likely that these credits have continued to increase in the past year, as some biofuel volumes were purchased prior to COVID-19 under more optimistic demand forecasts. The resulting surpluses can be counted towards the 2021 commitment period and subsequent years, thereby reducing the need for renewable fuels and electricity.

The status quo (generally with 2020 as the reference year) of production volumes of commercially available biofuels and the existing and foreseeable production capacities of renewable fuels for transport are presented below. Commercially available fuels are those that have a TRL of 10 to 11 according to the classification presented in Figure 3-2, i.e., they are produced on a large industrial scale. Accordingly, bioethanol, FAME, HVO/HEFA diesel and, to a lesser extent, biomethane fall under this category. The current production volumes of liquid biofuels available on a commercial scale are shown for the year 2020 in Figure 5-3, Figure 5-4 and Figure 5-5. Global **bioethanol** production fell by about 8 % in 2020 over the previous year to 119 million m³ (2,485 PJ) following many years of growth. In addition to 99 million m³ of bioethanol used as a fuel, a further 20 million m³ of industrial ethanol was used as a material in 2020. The most important global markets are the U.S., Brazil and increasingly China; in Europe it is France [IHS Markit (2021d)].

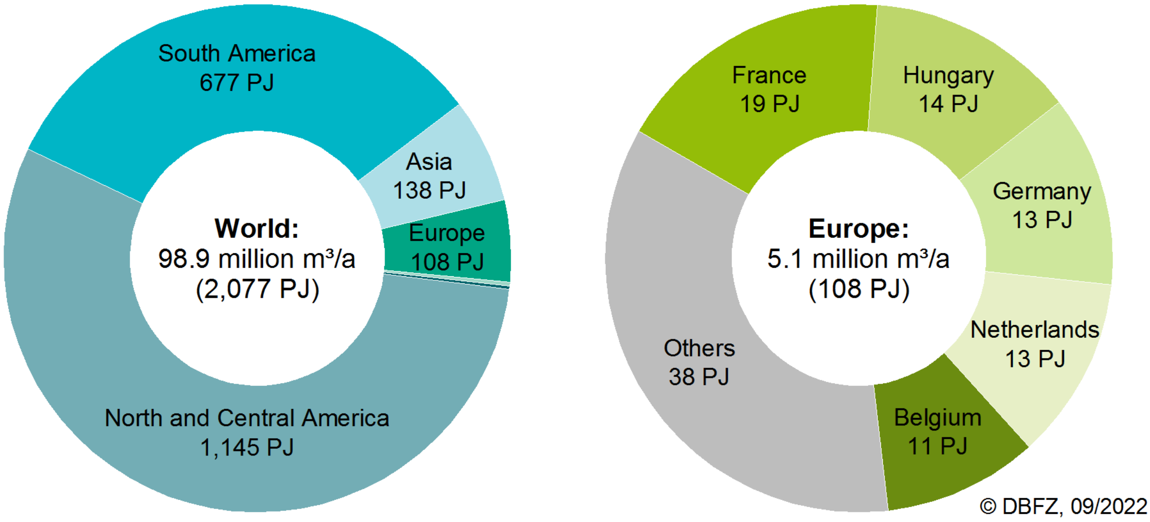


Figure 5-3 Bioethanol fuel – global and European production volumes in 2020. Note: no claim to completeness; own calculation; data based on [IHS Markit (2021d)]

Global production of **FAME** also decreased by 4 % in 2020 over the previous year to 38 million metric tons (1,411 PJ). While the majority of bioethanol production takes place in North and South America, FAME production is very homogeneously distributed worldwide. The largest producers are Indonesia, the U.S. and Argentina; in Europe it is Germany. [IHS Markit (2021c)]

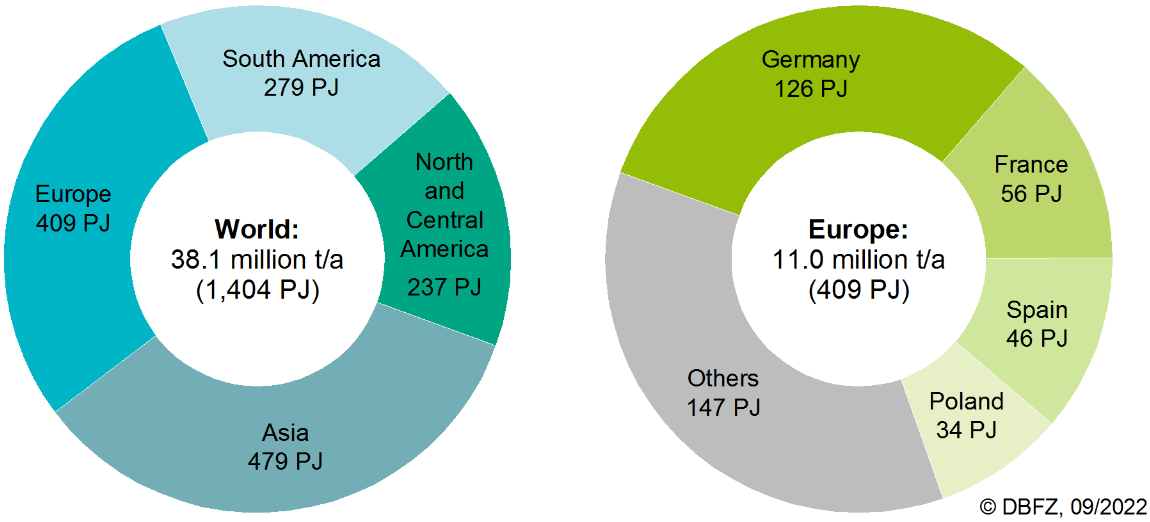


Figure 5-4 FAME – global and European production volumes in 2020. Note: no claim to completeness; own calculation; data based on [IHS Markit (2021c)]

Only **HVO/HEFA DIESEL** saw an increase in production in 2020 compared to the previous year – to 6.2 million metric tons (274 PJ) – despite the pandemic (Figure 5-5). The main producers here are the U.S., Singapore and the Netherlands [IHS Markit (2021c)].

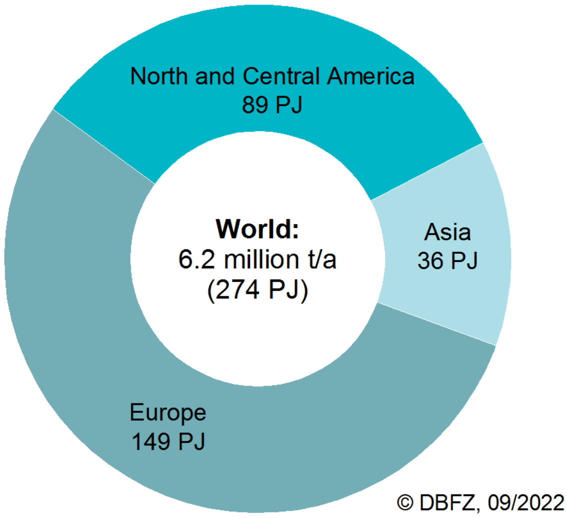


Figure 5-5 HVO/HEFA diesel – global production volumes in 2020. Note: no claim to completeness; own calculation; data based on [IHS Markit (2021c)]

5.3 Capacities

The production capacities of commercially available fuel options are usually significantly higher than the quantities actually produced. Production capacities for **BIOETHANOL** (Figure 5-6), for example, amount to 168 million m³/a worldwide, of which 16 million m³/a are not being utilized. Currently 1,804 production plants are operating worldwide. With a total production volume of 119 million m³/a, this corresponds to an average utilization rate of 78 %. In addition to these available capacities, a further 3.5 million m³/a are under construction worldwide and 33.3 million m³/a are projected. Existing plants are not use-specific and therefore have capacities to produce bioethanol for both material and fuel use. In Europe and Germany, the available capacities are significantly lower, with 170 plants producing 11.0 million m³/a in Europe and 13 plants producing 1.4 million m³/a in Germany.

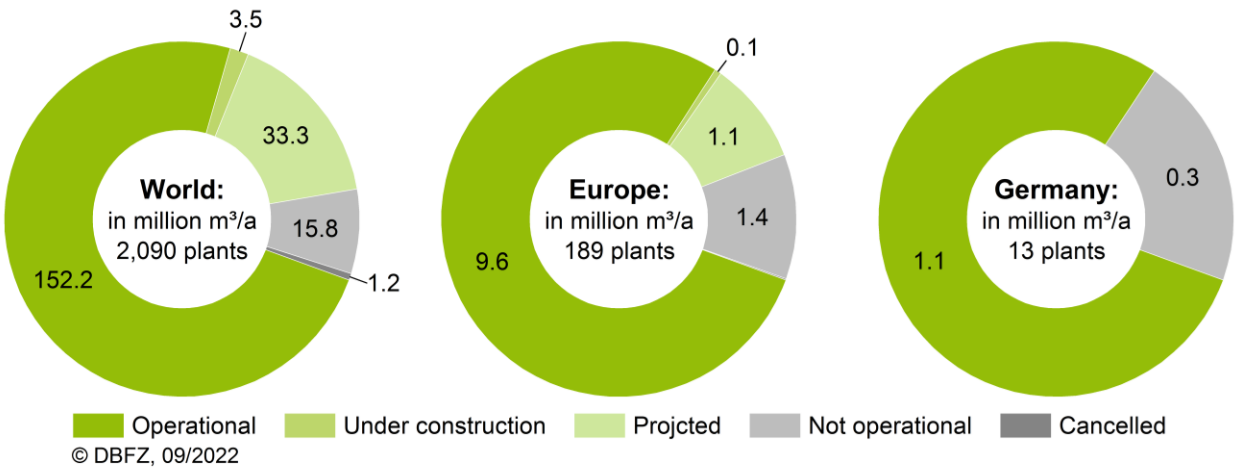


Figure 5-6 Bioethanol – worldwide, European and German production capacities in existing and planned plants in 2021. Note: excluding planned plant expansions; no claim to completeness; data based on [IHS Markit (2021a)]

Production capacities of **FAME** (Figure 5-7) amount to around 79.1 million t/a worldwide. Of this, however, only 60.6 million t/a are being utilized. The current capacities are covered by 914 plants worldwide. These plants produced 40 million metric tons in 2019 and 38 million metric tons in 2020, operating, on average, at only 62 % capacity. A further 1.1 million t/a worldwide are under construction and 12.0 million t/a are projected. European capacities are provided by 277 plants and amount to 28.4 million t/a. In Germany 53 plants produce 5.4 million t/a.

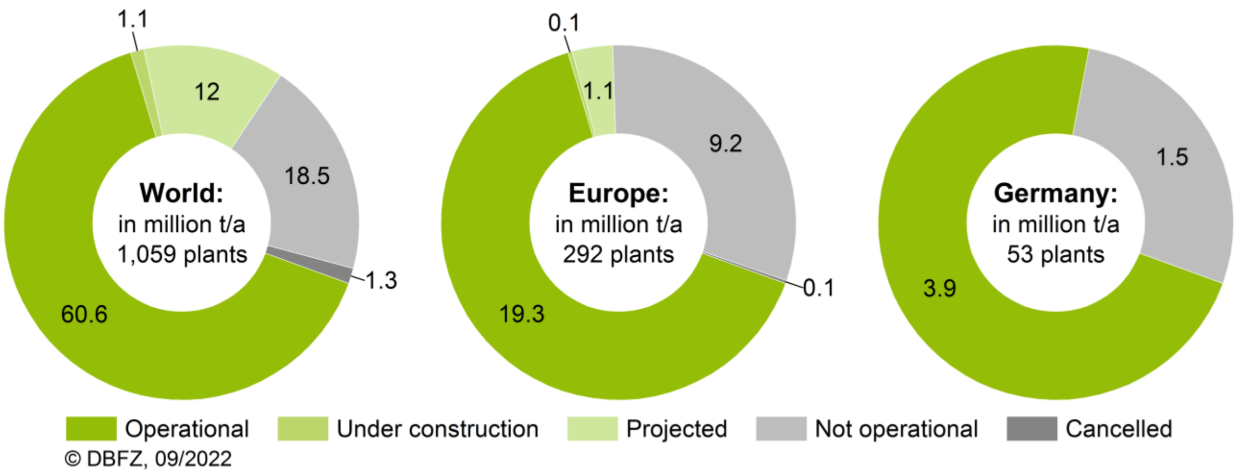


Figure 5-7 FAME – worldwide, European and German production capacities in existing and planned plants in 2021. Note: excluding planned plant expansions; no claim to completeness; data based on [IHS Markit (2021a)]

There are currently twenty-nine **HVO/HEFA DIESEL** plants worldwide (Figure 5-8) with an annual production capacity of 8.0 million metric tons. Further plants are under construction which will produce 0.2 million t/a, and capacity expansions totaling almost 6 million t/a are either being planned or are being implemented at around ten existing HVO/HEFA plants. [IHS Markit (2021a)] In the U.S. alone, HVO/HEFA production capacities are expected to increase from around 5 million t/a in 2021 to more than 20 million t/a in 2025 [IHS Markit (2021h)]. In Europe, 14 plants are in operation with a capacity of 4.8 million t/a. With a view to advanced biofuels, HVO/HEFA technology is well suited for processing challenging feedstocks. Most plants are so-called multi-feedstock plants, which can utilize a range of different feedstocks – apart from a few plants in Scandinavia that process only tall oil

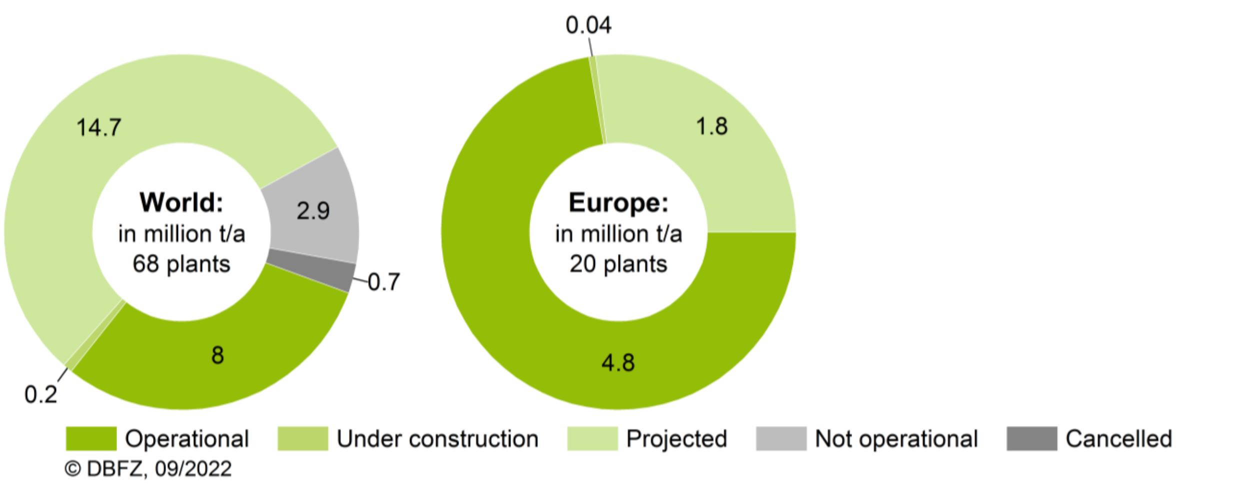


Figure 5-8 HVO/HEFA diesel – worldwide and European production capacities in existing and planned plants in 2021. Note: excluding planned plant expansions; no claim to completeness; data based on [IHS Markit (2021a)]

Up to now, **BIOMETHANE** has been supplied as a fuel (Figure 5-9) primarily via the commercially available technology of anaerobic digestion. The installed production capacities as well as the possibilities for use in transport vary greatly from region to region. Biomethane is not only available as a fuel, but can also replace fossil natural gas as a renewable substitute in every application segment. In the countries where is it currently being produced, it is still primarily used for stationary applications to supply electricity and heat. Total biomethane production capacities are presented in the next paragraph.

In Germany, there are 232 biomethane plants in operation at 222 locations. These use the process of anaerobic biomass fermentation to produce biogas, upgrade it to natural gas quality, and feed it into the natural gas grid. These plants have a feed-in capacity of over 147 thousand m³/h at STP. Of the more than 10 TWh_{HS} of biomethane sold in Germany in 2020, about 10 % was used as fuel. [dena (2021b)]

Anaerobic fermentation, which is used to produce biogas or biomethane, is able to utilize a wide variety of feedstocks as well as feedstock mixtures and therefore a large portion of the biogenic waste and by-products defined as advanced. Plants can vary widely in terms of installed capacity depending on the availability of feedstock to the site (for example, the plants in Germany have capacities of between 0.5 and 20 MW). Most of the world's installed biomethane capacities are in Europe and/or at the European level, with 1.9 billion m³/a of the world's 2.4 billion m³/a being produced there. In Germany, this amounts to around 1 billion m³/a. [IHS Markit (2021a)] China is one of the largest growth markets – in 2015, the central government began funding large-scale biomethane projects (with biogas capacities > 500 m³ per plant). The government financed the construction of 25 biomethane demonstration projects in 2015, and approved another 22 projects in 2016 and 18 projects in 2017. [Zheng (2020)]

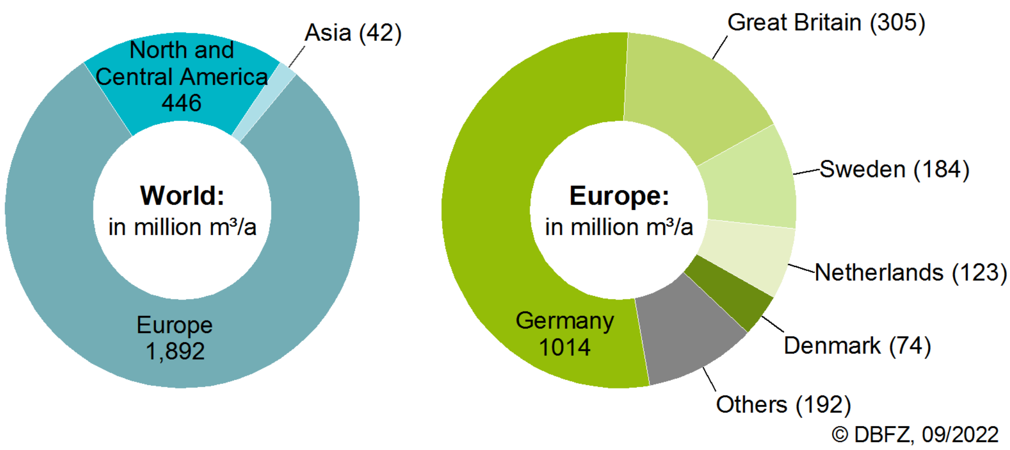


Figure 5-9 Biomethane – worldwide and European production capacities in existing and planned plants in 2019. Note: excluding plants under construction or planned plants and plant expansions; no claim to completeness; data based on [IEA Bioenergy (2021c)] as well as own research

Against the backdrop of climate protection, decarbonization in the transport sector, and limited renewable resources (Section 4.3), policies are aiming to expand and, at the same time, diversify the provision of renewable energy sources for transport. In addition to the already established, commercially available production technologies for biofuels and their increasing adaptation to advanced feedstocks, a strong focus is also on

- the development of new technologies for the efficient and sustainable production of biofuels from advanced feedstocks and
- a greater electrification of suitable modes of transport and the production and use of fuels that are based on electricity from renewable sources.

Information is given below about the available capacities of selected fuel options that are neither at the established level of the previously described fuel options, nor are they still in the demonstration phase. These fuels are mostly traded bilaterally and not on trading exchanges. They have a technological readiness level of 9 as described in Figure 3-2.

In addition to the already established and commercially available technologies HVO/HEFA and biomethane, **LIGNOCELLULOSIC ETHANOL** (Figure 5-10) represents the most developed technology option for advanced biofuels. Even though large quantities are not yet being produced and traded, production capacities are being successively expanded. In addition to numerous smaller-scale pilot and demonstration plants, more and more larger scale production facilities have been built in recent years, especially in the U.S. and China. Thus, production capacities have increased from around 0.1 million m³/a in 2010 to around 2.5 million m³/a in 2020. Plants with capacities totaling 0.5 million m³/a were not in operation. In Europe and Germany, the achieved capacities are significantly lower at 0.15 million m³/a and 0.001 million m³/a, respectively. As Figure 5-10 shows, additional plants totaling at least 0.5 million m³/a are under construction and 3 million m³/a are currently projected. [IHS Markit (2021a)]

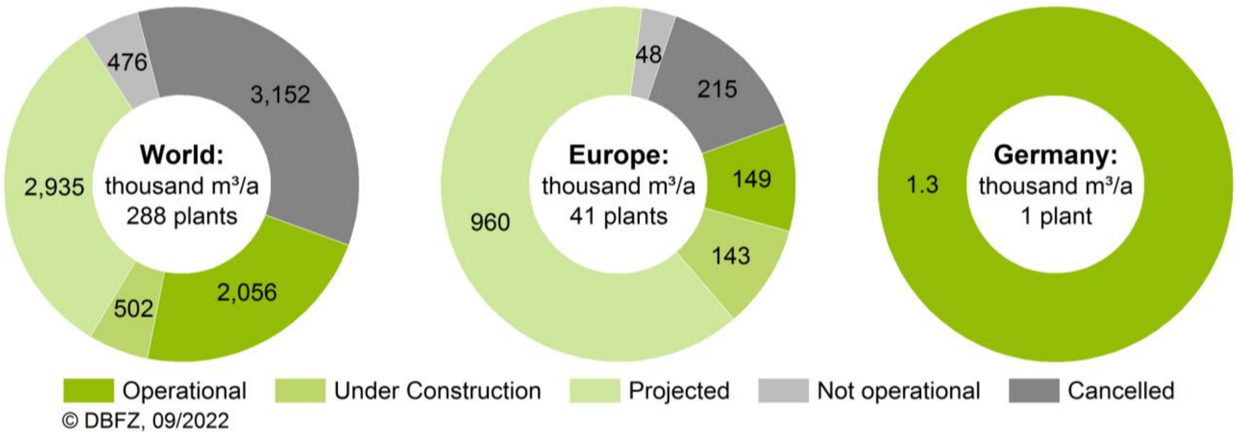


Figure 5-10 Lignocellulosic ethanol – worldwide, European and German production capacities in existing and planned plants in 2020. Note: excluding cancelled projects and plants with capacities under 1,000 m³/a; no claim to completeness; data based on [IHS Markit (2021a)] as well as own research

Worldwide production capacities of **RENEWABLE KEROSENE** (Figure 5-11) are clearly on the rise. Plants that are currently in operation have capacities totaling only 8 PJ, of which 5 PJ use the HEFA process and 3 PJ use the ATJ process. At the same time, additional plants with capacities totaling 45 PJ are being planned or are under construction. The capacities described in Figure 5-11 relate to 18 plants, including plants in which the technology that is being used could not be identified (marked as “unknown technology” in the figure). As decarbonization targets continue to be binding in aviation, capacities will also have to increase steadily and be supplemented by electricity-based options.

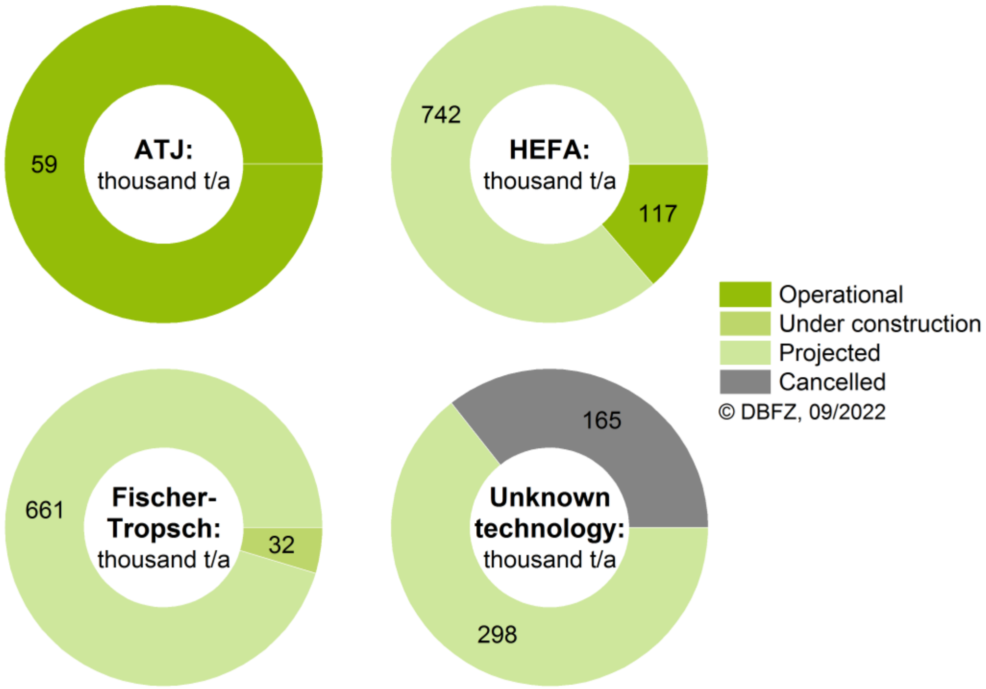


Figure 5-11 Renewable jet fuel – worldwide production capacities in existing and planned plants in 2020. Note: data based on [IHS Markit (2021a)] as well as own research

Green, electricity-based **HYDROGEN** is being produced in Europe, mainly in Germany, although not all is intended for use in transport; some of this hydrogen is being processed into its derivatives methane and methanol (Figure 5-12). According to Wulf et al., 8 MW of the 78 MW of electrolysis capacity is used for methanol production and 18 MW for methane production. [Wulf (2020)] The largest electrolyzer installed to date has a capacity of 10 MW and can thus produce up to 1,300 t/a of hydrogen, equivalent to around 156 TJ [Refhyne (2019)]. It is difficult to obtain a clear picture of the current situation as the development of a green hydrogen infrastructure is being strongly promoted worldwide and accordingly new projects are being implemented on a daily basis. Many more nationally and internationally funded projects are underway to advance the expansion of electrolysis capacities, for example 100 MW in Hamburg [Stadt Hamburg (2021)], and 1,000 MW [SeaH2Land (2021)] and 200 MW [Scheuermann (2021)] in the Netherlands. Other giga-scale projects are being implemented outside Europe, mainly in wind- and sun-rich regions, for example in Australia, or in Argentina where Fortescue Future Industries aims to build up hydrogen capacities equivalent to 15 million t/a by 2030 [Kempkens (2021); Newbery (2021)].

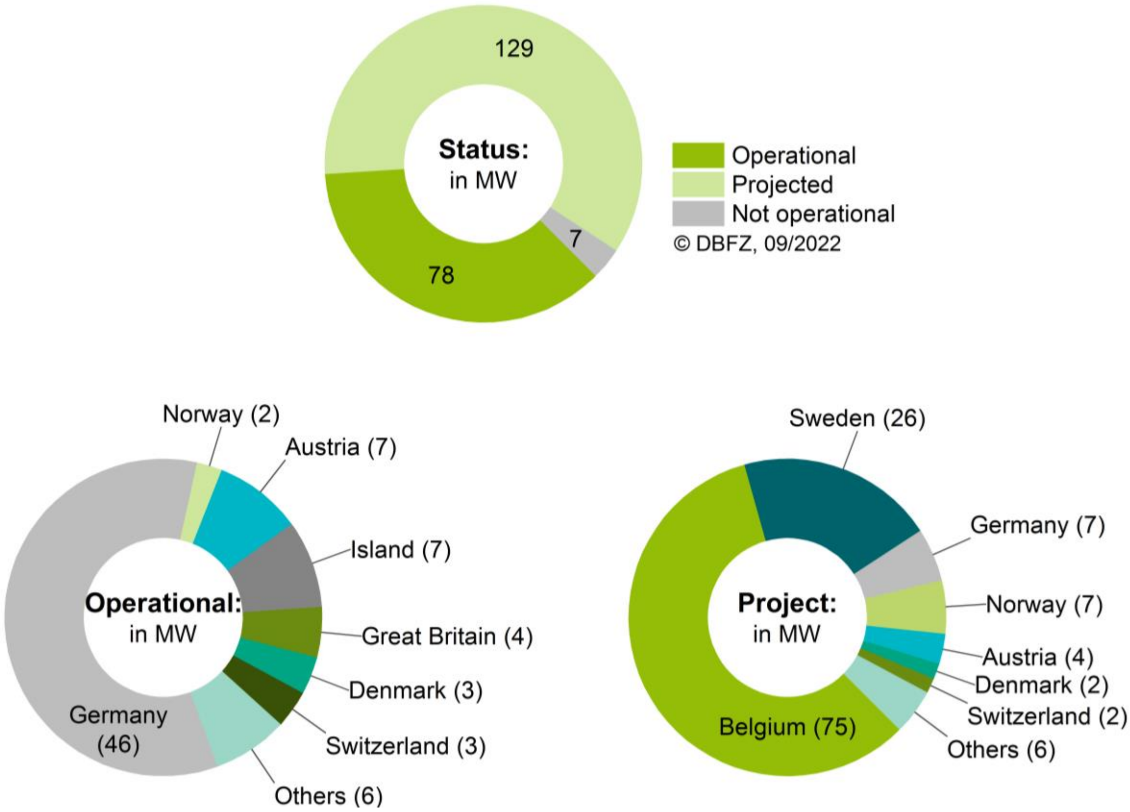


Figure 5-12 Renewable hydrogen and its derivatives – European electrolysis capacities in 2020. Note: capacities not exclusively used in the transport sector; data based on [Wulf (2020)]

METHANOL as a fuel and especially its derivatives methanol-to-gasoline (MTG) and methanol-to-jet (MTJ) are suitable energy carriers for the transport sector. Even though there is currently a lack of corresponding standards and, hence, approvals in the transport sector, extensive production capacities are already being established and/or planned. This is because methanol also serves as a promising renewable energy carrier in many other industries. Figure 5-13 shows that each of the seven existing plants mostly produce a few thousand metric tons of biobased methanol per year. The six plants under construction will have industrial-scale capacities of more than 100,000 t/a. The largest plant under construction, with a capacity of 875,000 t/a, is scheduled to come online in Florida in 2023 [Landälv (2020)]. Further plants, including BTL, PTL and SynBioPTL plants are projected (Section 3.10). For example, a PTL plant with an annual MTG capacity of 130 m³ (0.1 t/a) is to be built in Chile in 2022. It will be expanded in 2024 to enable the production of 55,000 m³/a (43.5 thousand t/a). The synthetic gasoline fuel will be produced using wind energy, electrolysis and CO_2 captured from the air [Siemens Energy (2021)].

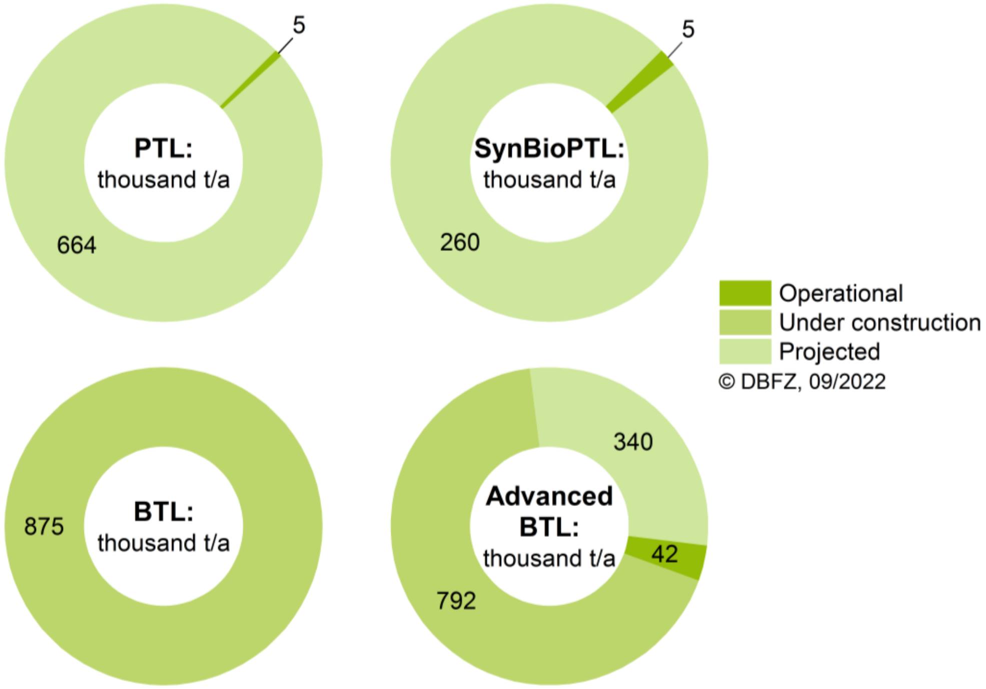


Figure 5-13 Renewable methanol – worldwide production capacities in existing and planned plants in 2020. Note: advanced BTL only from feedstocks listed in RED II Annex IX Part A; no claim to completeness; data based on [IHS Markit (2021a)] as well as own research

In addition, there are numerous pilot- and demonstration-scale plants under construction or projected for the production of bio-based fuels. They serve to further the technical development of innovative technologies. These include, for example, hydrothermal processes, gasification and pyrolysis. [IEA Bioenergy (2021b)]

The development of biobased Fischer-Tropsch fuels has already had a checkered history. Fulcrum Bioenergy Inc. in Nevada (USA) is taking the next step towards commercializing the technology, albeit using mixed, not just biological municipal waste. The plant is expected to be operational by the end of 2021, converting 175,000 metric tons per year of processed solid municipal waste into approximately 42,000 m³/a of syncrude, which is then processed into aviation fuel, diesel and gasoline. In addition to its current location, Fulcrum plans to set up eight more locations in the U.S., which will have an annual capacity of more than 400 million U.S. gallons (around 1.5 million m³) of drop-in-capable fuel. [Fulcrum Bioenergy (2021)]

The first PTL Fischer-Tropsch plant is in operation in Werlte and has a capacity of 350 t/a. Further PTL plants are under construction or are being planned, in particular for the aviation industry, with capacities totaling around 8 million t/a [futurefuels.blog (2021); INERATEC (2022); Norske (2020); WEF (2021)].

Contextualizing European development goals with available advanced fuel capacities

The demand for necessary production facilities can be roughly estimated based on the European goals for providing advanced fuels. Assuming that air transport in the European Union in 2030 will have the same consumption levels as in 2019 (2,566 PJ), a target of 5 % advanced aviation fuels implies an energy demand of about 128 PJ in 2030. At the same time, road transport is expected to consume 12,932 PJ in 2030 (equivalent to 2019 consumption levels) and, at a minimum rate of 2.2%, will require around 284 PJ of advanced fuels. This adds up to 421 PJ of advanced fuels, if the maritime sector is not included. [Eurostat (2021k)] Examples of projects to build facilities for advanced fuels include:

- Clariant (Romania): 50,000 t/a (1.3 PJ/a) of bioethanol from straw [Clariant (2021b)] and
- Verbio (Germany): 16.5 MW (0.5 PJ/a) of biomethane from straw [VERBIO Schwedt GmbH (2021)].

Achieving the 412 PJ of advanced fuels calculated above will require at least 300 Clariant or 900 Verbio plants by 2030, whereby at least a percentage of this would be further processed into renewable kerosene. Taking into account the required construction times (e.g., approx. four years for the Clariant plant) as well as further constraints such as planning, finding construction companies/personnel and investors, it appears doubtful [Clariant (2021a)] that the goals of the European Union can be achieved within the few remaining years based solely on the need for production capacities. [Clariant (2021b)]

In 2020, the proportion of biofuels made from the residues of palm oil production (POME) in Germany increased sharply to 3 PJ [[Hahn (2021)]. Here, a strong lever can be provided very quickly when needed, which can cover enormous percentages of the set targets of advanced biofuels even without the development and implementation of innovative technologies. Even though biofuel from POME is not counted double like other advanced biofuels[10], it currently remains questionable whether this disadvantage necessarily leads to comparable competitive conditions for the other advanced biofuels.

5.4 Trade

In recent years the European Union has imported more biofuels than it has exported (net import). Net imports of the two biofuels with the largest market shares declined, with net imports of bioethanol going from more than 1 million m^3 in 2012 to 174,000 m^3 in 2018. FAME decreased from 2 million metric tons in 2011 to 165,000 metric tons in 2016. In subsequent years, net imports of both fuels increased again (Figure 5-14 and Figure 5-16).

Net imports of bioethanol (including bioethanol used as a material) increased after 2018 to up to 0.7 million m^3 in 2020. This corresponded to about 9 % of the EU's total bioethanol fuel consumption. From 2017 onwards, the UK was no longer listed in the trade balances as an EU Member State, which is why these export surpluses shifted the picture yet again. Up until 2010, Brazil, as a country of origin, accounted for a significant share of the import volumes. In the following year (2011), import volumes from the USA increased sharply, but declined again between 2013 and 2018, nearly returning to previous levels. The import volumes in 2019 and 2020 again mainly came from Brazil and the U.S., with these countries achieving by far the largest national production volumes in 2020, followed by China.

As the consumption of bioethanol as a fuel increased in Germany, so did its import volumes. In 2020, about 1.4 million m^3 were covered by imports. At the same time, about 0.5 million m^3 of bioethanol were exported. Imports were mainly from the Netherlands, Belgium, Hungary and Sweden. Exports were mainly made within the EU to the Netherlands, Sweden, Denmark and France. The Netherlands is only considered a stopover for exports leaving the ethanol terminal in Rotterdam to non-European countries. The resulting net import of 0.9 million m^3 (F.O. Licht 2018b) corresponded to the trade volumes of bioethanol including industrial alcohol and potable alcohol for material use. [IHS Markit (2021c)]

[10] For volumes beyond the minimum volume of advanced biofuels, which is defined annually up until 2030 (BImSchG)

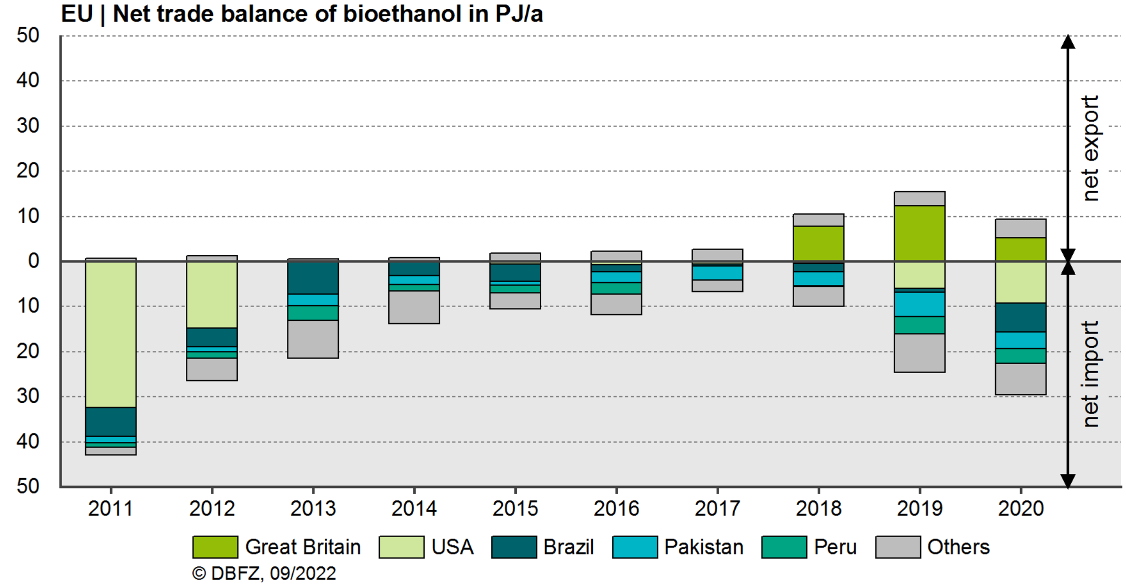


Figure 5-14 Bioethanol – net trade balances of the European Union. Note: graph also includes bioethanol used as a material; own calculation based on data from [F.O. Licht (2014b), (2016b), (2017b), (2018b), (2019); IHS Markit (2021k), (2021j), (2021l)]

Internationally traded bioethanol has risen in recent years from 9.1 % of overall consumption in 2014 to 13.4 % in 2020. Bioethanol is thus also predominantly traded and used within the domestic market. As Figure 5-15 shows, South America (Brazil) and North America (USA) are net exporters, while the net importers are the European Union and Asia (in addition to China and Japan, this also includes South Korea, the Philippines and India).

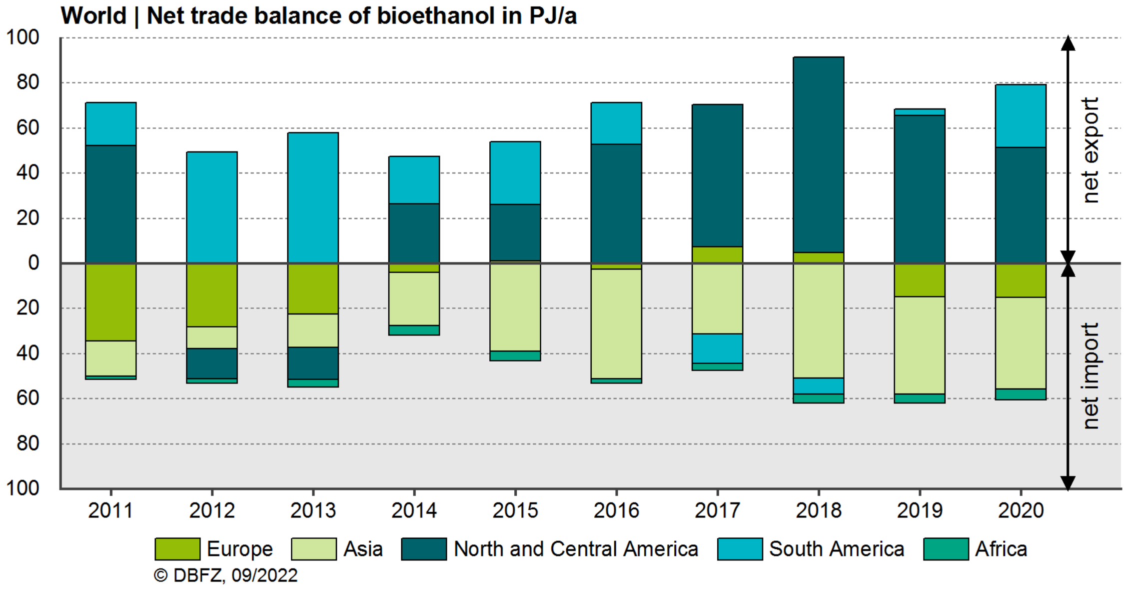


Figure 5-15 Bioethanol – worldwide net trade balances. Note: graph also includes bioethanol used as a material; own calculation based on data from [F.O. Licht (2012b), (2015c), (2016c); IHS Markit (2020c)]

At the European level, net imports of FAME amounted to 2.5 million metric tons in 2018, representing about 18 % of total EU FAME consumption (Figure 5-16). Major importers of FAME are Argentina, Malaysia, China and Indonesia. The use of used cooking oil has been steadily rising. In 2020, a total of about 2.5 million metric tons of FAME made from used cooking oil were imported into Europe, of which about 1.1 million metric tons came from China alone [IHS Markit (2021g)].

Regulatory measures with anti-dumping duties have accounted for the volatile trade balances over the years. In order to prevent double funding (in the country of origin and within the EU), the EU imposed anti-dumping duties on FAME from Argentina and Indonesia on May 27, 2013 [Verordnung (EU) 490/2013 (2013)] and defined supplementary anti-dumping duties for both countries of origin in September 2017 [Durchführungsverordnung (EU) 2017/1578 (2017)]. While import volumes of FAME from Argentina and Indonesia were still very high in 2012 at 1.4 million t/a and 1.1 million t/a, respectively, they plummeted in subsequent years. Further anti-dumping duties were imposed on FAME from the U.S. for five years starting in 2021 [Durchführungsverordnung (EU) 2021/1266 (2021)].

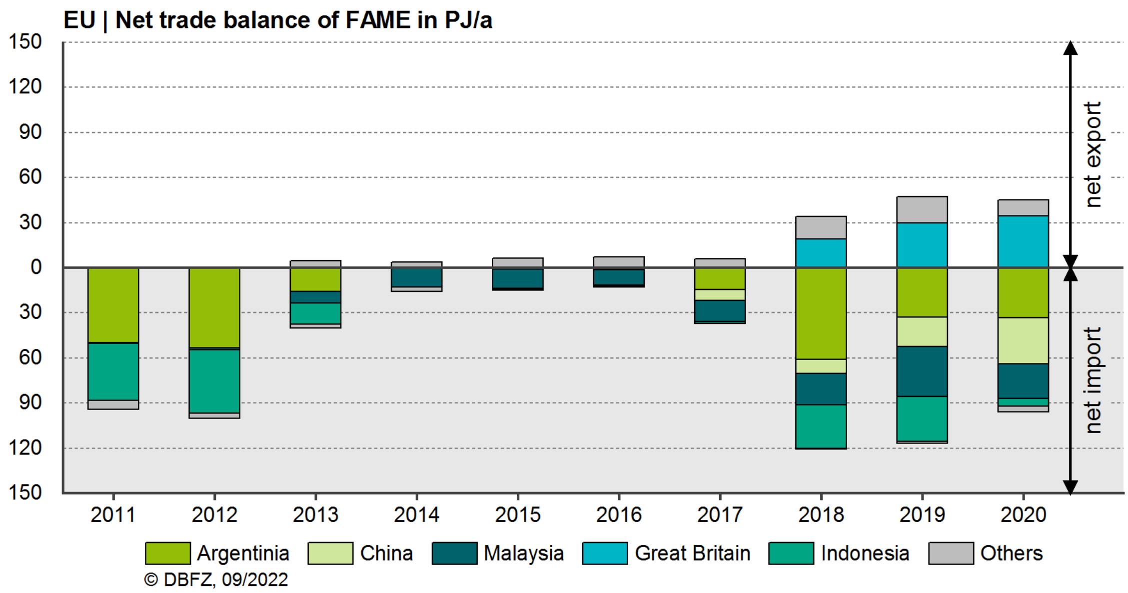


Figure 5-16 FAME – net trade balances of the European Union. Own calculation based on data from [F.O. Licht (2014b), (2016b), (2017b), (2018b), (2019); IHS Markit (2021k), (2021j), (2021l)]

Significant quantities of the biofuels produced or used in Germany were and are traded internationally. The main customers are the Netherlands (incl. exports via Rotterdam), Belgium, Poland, the U.S. and Austria. Imports are mainly from the Netherlands, Belgium, Great Britain and Poland. In the overall trade balance for Germany for the year 2020, this resulted in FAME exports totaling 2.3 million metric tons and FAME imports amounting to 1.4 million metric tons (F.O. Licht 2018b). All of the HVO/HEFA diesel used in Germany was imported [IHS Markit (2021c)].

In recent years, the percentage of globally traded FAME and HVO/HEFA diesel (Figure 5-17) has fluctuated between 15 and 20 % of the total volume of FAME and HVO/HEFA diesel[11]. Accordingly, the majority of this is also used directly as fuel in the producing countries. The European Union exported about 1.9 million metric tons of FAME and HVO/HEFA diesel in 2020, which included about 1.6 million metric tons of FAME and 0.3 million metric tons of HVO/HEFA diesel. Almost all of the 0.7 million metric tons of HVO/HEFA diesel produced in Singapore is estimated to have been exported, while the U.S. imported a total of about 0.9 million metric tons of HVO/HEFA in 2020. [IHS Markit (2020a)]

[11] Trade volumes within the EU were not taken into account.

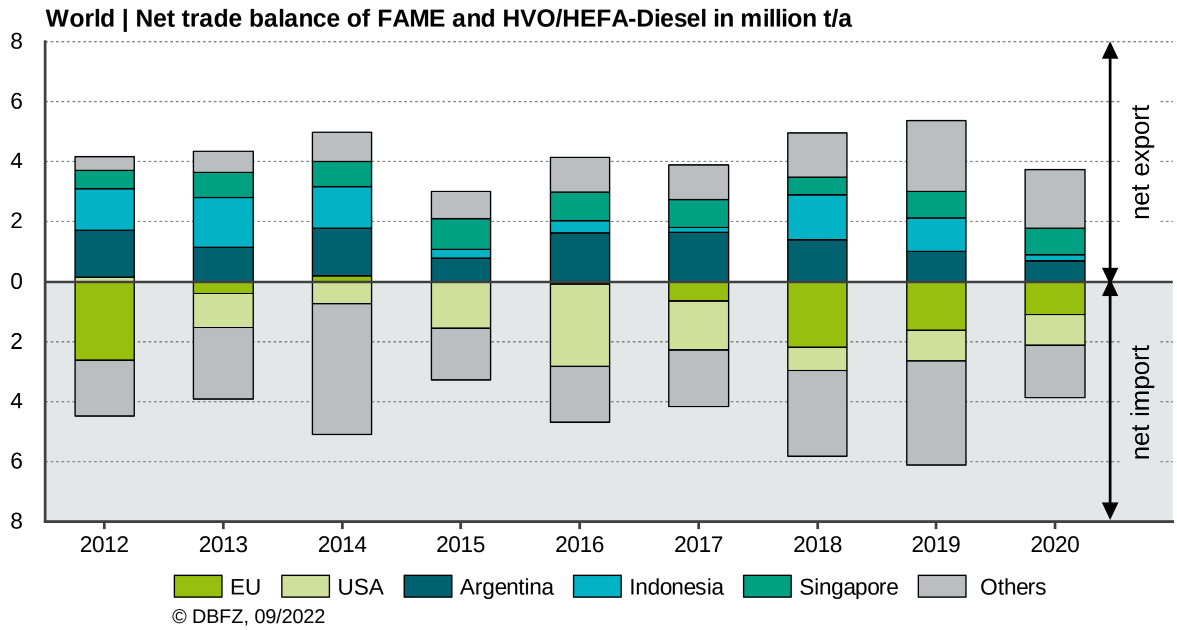


Figure 5-17 FAME and HVO/HEFA diesel – worldwide net trade balances. Own calculation based on data from [IHS Markit (2020a)]

THE ORIGIN OF BIOFUEL FEEDSTOCKS IN THE CONTEXT OF THE GHG QUOTA

Germany's Federal Office for Agriculture and Food (BLE) publishes an annual evaluation and progress report for certified biofuels that count towards the German GHG quota. In contrast to the previously mentioned data, which specify the first or last trading partners for the import and export of the traded fuels, this report can be used to identify which countries the feedstocks originated from. The data published in the report provide no indication of the country in which the respective fuel is produced. Theoretically, feedstocks can be converted into fuels in the country of origin, in Germany or in a third country. Thus, the report acts as a supplementary indicator of the trade routes of the renewable fuels that count towards the GHG quota in Germany.

Currently, fuels made from plant-based feedstocks (biogenic primary products) and feedstocks based on biowaste and (agricultural) residues count toward the GHG quota in Germany (Section 4.2.1). The biogenic primary products are typical energy crops such as rape seed, corn, wheat and palm oil. The main countries of origin in this category (Figure 5-18) are Indonesia (palm oil for 20.0 PJ of fuel), Germany (rape seed for 13.8 PJ of fuel), Ukraine (corn for 10 PJ of fuel), Hungary (corn for 5.2 PJ of fuel), and Poland (rape seed for 1.9 PJ, corn for 1.8 PJ, triticale for 1.2 PJ of fuel). A largely new feedstock, *Brassica carinata*, which may be declared an advanced feedstock in the future, has been added in recent allocation years, with small amounts (equivalent to 0.1 PJ of fuel) coming from Uruguay and the United States. [BLE (2020), (2021d)]

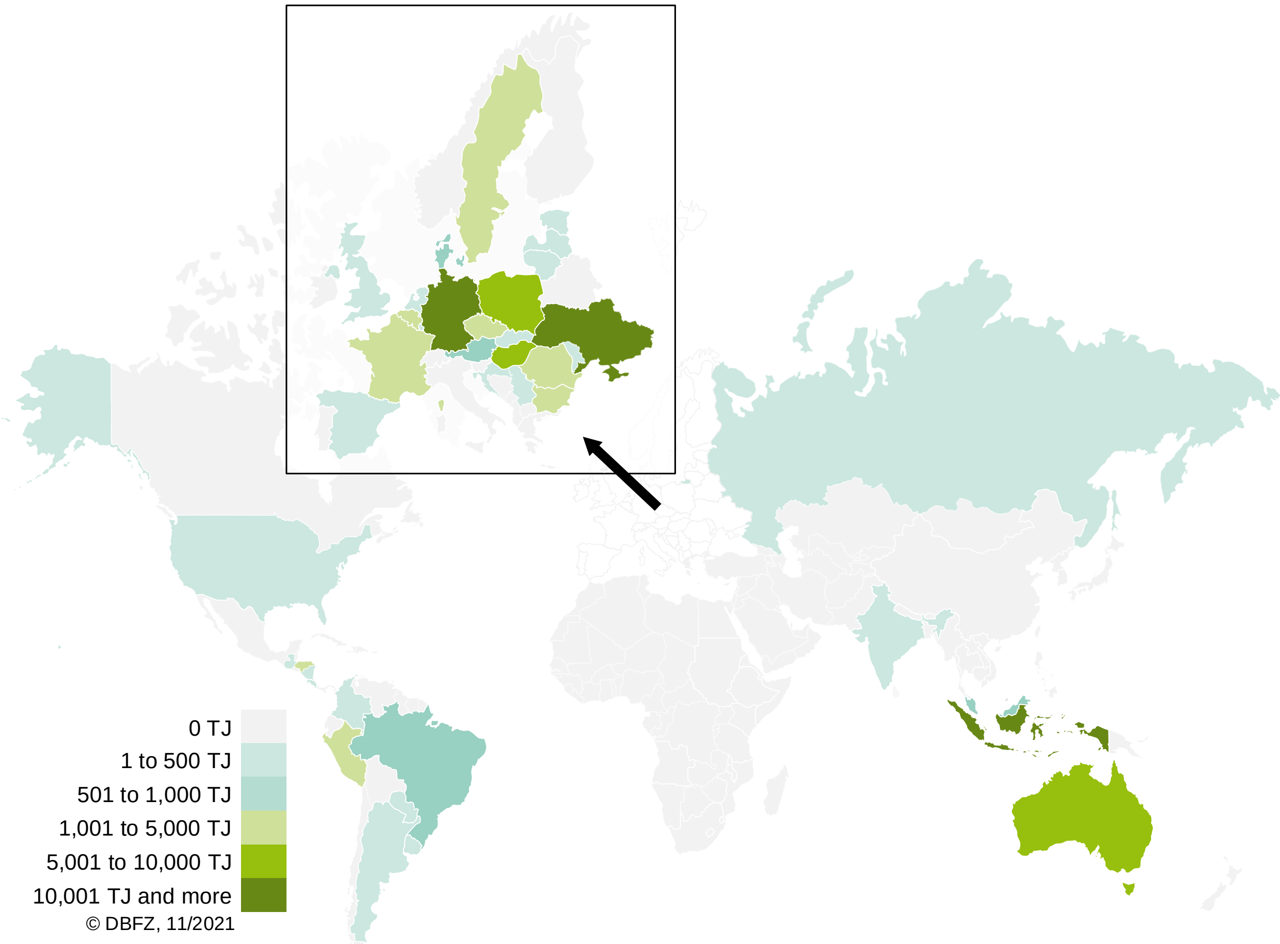


Figure 5-18 Countries of origin of the biogenic primary products for fulfillment of the German GHG quota in 2019, Data based on [BLE (2020), (2021d)]

As can be seen in Figure 5-19, there are significantly more countries involved with biowaste and (agricultural) residuals (Section 4.2.1) than with biogenic primary products (Figure 5-18). This may be due in part to the fact that UCO is also used in large HVO/HEFA refineries, which once again source their feedstocks much more broadly than individual ethanol and FAME plants. The leading countries for waste and residual materials are China (equivalent to 9.5 PJ of fuel), Germany (7.2 PJ of fuel), Poland (2.6 PJ of fuel), the Netherlands (2.2 PJ of fuel), and Indonesia (1.4 PJ of fuel). [BLE (2020), (2021d)]

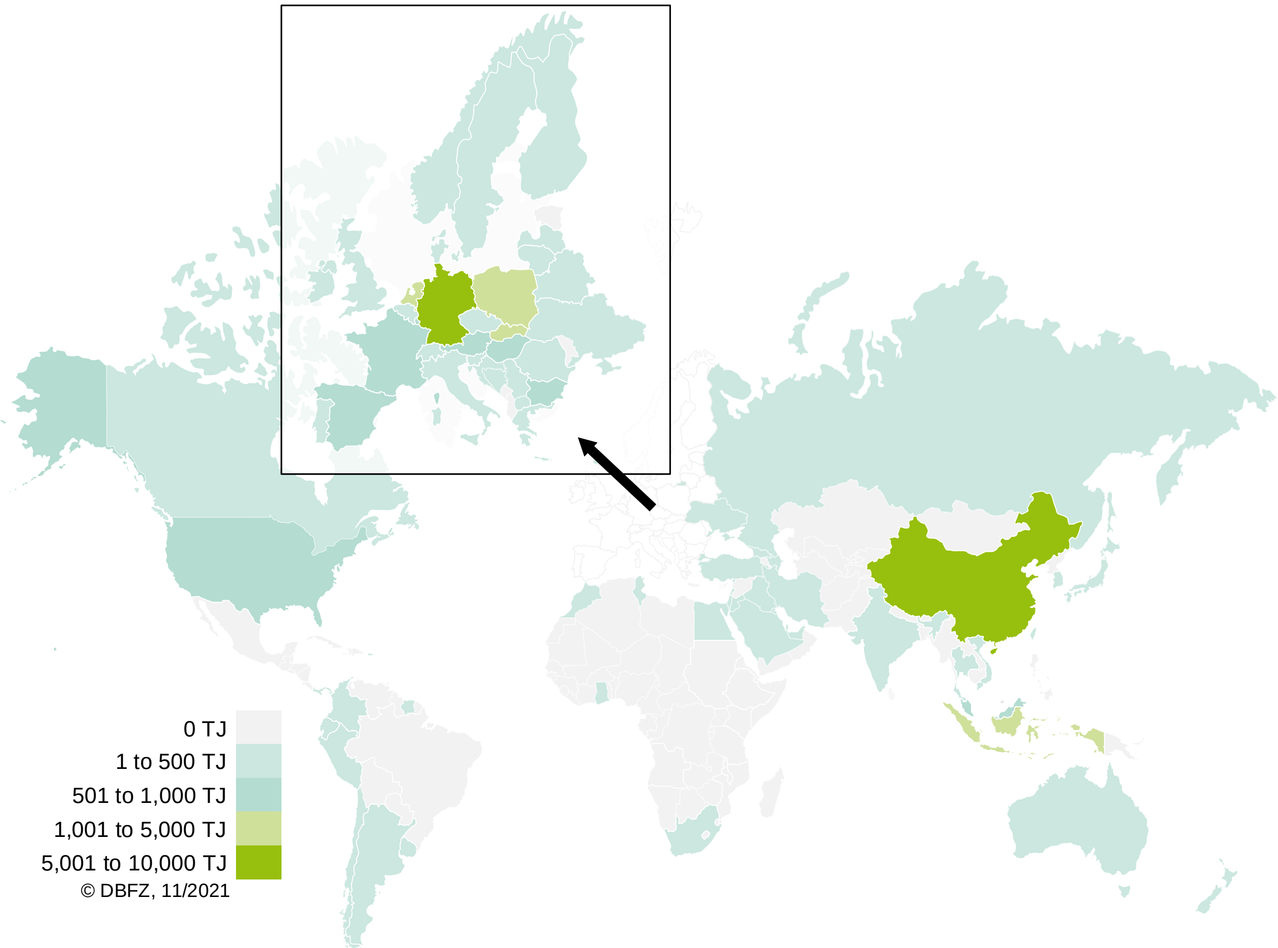


Figure 5-19 Countries of origin of biowaste and (agricultural) residuals for fulfillment of the German GHG quota in 2019. Data based on [BLE (2020), (2021d)]

5.5 Utilization

The transport sector is characterized more than any other by its use of fossil petroleum as a feedstock and, at the same time, by enormous global growth in final energy demand, as already shown in Figure 5-1.

In **Germany**, the greenhouse gas quota increased from 4 % to 6 % in 2020 [THGMQWG (2021)], prompting a significant increase in the use of biofuels. As Figure 5-20 shows, around 168 PJ of the approximately 2,018 PJ of energy used in road transport in 2020 came from renewable sources. This corresponds to 7.3 %. FAME and HVO play a major role as diesel substitutes, with FAME making up the largest share at 89 PJ. While the amount of FAME remained almost identical to 2019 levels, HVO diesel use increased significantly from 2 PJ in the previous year, to 44 PJ in 2020. This figure is also about twice the previous all-time high of 21 PJ in 2013 [BLE (2014)]. The use of bioethanol as a fuel component (including the ethyl tert-butyl ether content) was down on the previous year at 30 PJ. Biomethane (2.6 PJ), electricity (0.4 PJ) and hydrogen (0.01 PJ) continue to be of minor - albeit increasing - importance for the greenhouse gas quota. In addition, certain fossil fuels with a greenhouse gas advantage can still be counted toward the quota until 2021. In 2020, this included 14.7 PJ of LPG and 944 GWh (3.4 PJ) of CNG and LNG. In 2020, a 6 PJ biofuel content met the requirements for being counted toward the separate quota for advanced fuels. Since only about 1 PJ would have been required to meet the 0.05 % quota target in 2020, the remaining 5 PJ can be applied to the following year [Zoll (2021)].

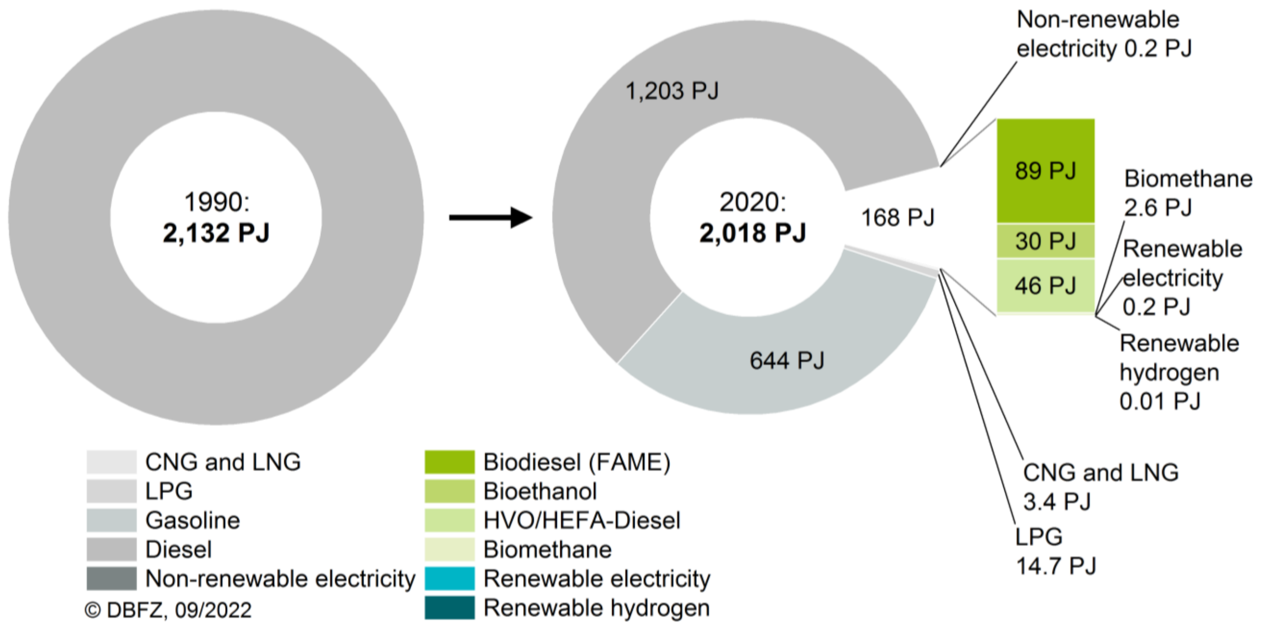


Figure 5-20 Use of energy carriers in road transport in Germany. Note: own graph with data based on [BAFA (2021a)] for fossil diesel and gasoline; [BLE (2021b)] for biofuels; [Zoll (2021)] for all others; gasoline and diesel volumes are reduced by an estimated value (totaling 110 PJ) for the portion of total volumes not used in road transport

The development of biofuel production and use in Germany is characterized by ever-changing legal framework conditions. Initially (i.e., in the years up to 2007), pure fuels in the form of FAME and vegetable oil were mainly used due to significantly reduced tax rates (Figure 5-21). Between 2004 and 2007, volumes rose particularly sharply in relative terms from around 40 PJ to 166 PJ. In subsequent years, pure fuel volumes declined rapidly again with the decrease in tax incentives. Now pure fuels are only used in niche applications. Most of the biofuels are now blended with fossil gasoline and diesel.

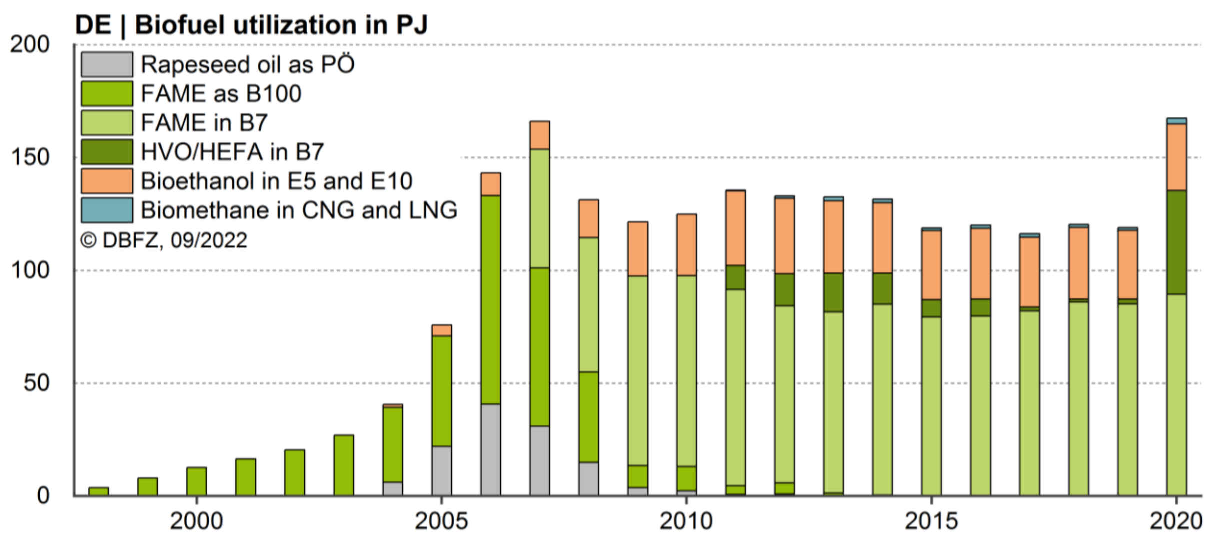


Figure 5-21 Biofuel utilization in Germany. Note: PÖ means plant oil; own calculation based on data from: [BLE (2013), (2016), (2019), (2021b); Lenz (2021)]

In the Member States of the **European Union**, the use of renewable energy in the transport sector is strongly guided and supported by corresponding framework conditions. Figure 5-22 shows the energy carriers used in road transport in the EU 28 for the year 2019. The share of renewable energy was 5.7 % in 2019. For 2020, the RED defined a target of 10 % renewables in EU road and rail transport, with some options being counted multiple times. This approach is intended to prop up options deemed eligible for support; however, it leads to a distorted balancing of the target figure. In addition, the theoretical target of 10 %, for example, can already be achieved with lower amounts in real terms. Nevertheless, it can be assumed that the relative share of renewable energy in road and rail transport will have increased again in the European Union in 2020, in line with developments in Germany.

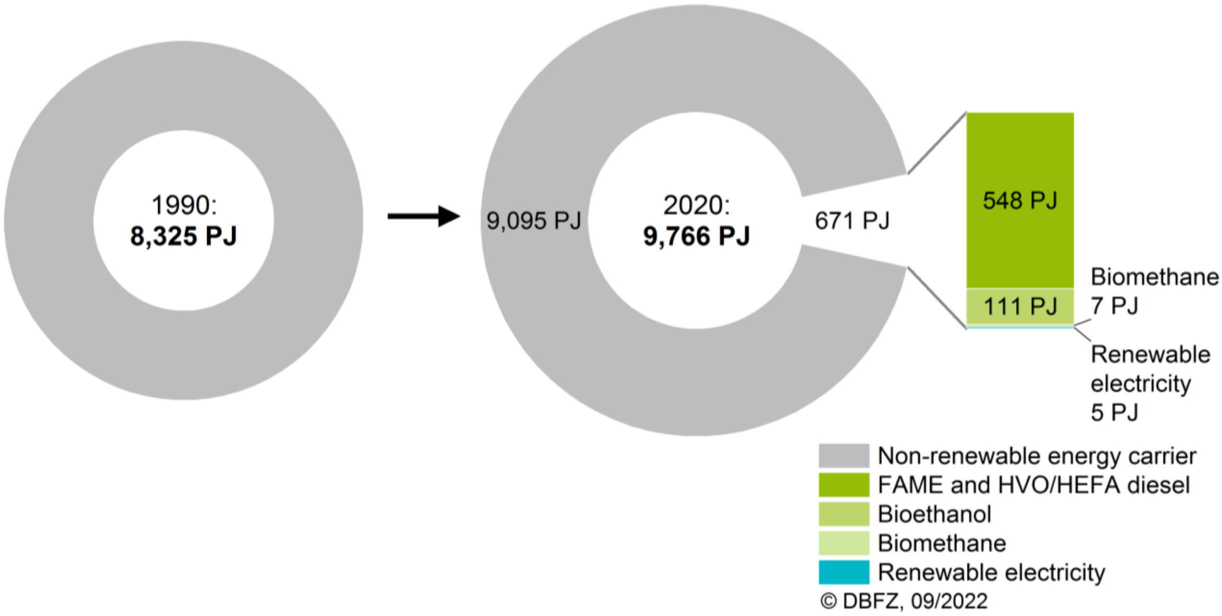


Figure 5-22 Use of non-renewable and renewable energy carriers in road transport in the European Union. Note: EU-27; data based on [Eurostat (2021h)]

The **USE OF BIOFUELS WORLDWIDE** largely corresponds to the annual production, give or take possible year-on-year shifts due to a decrease or increase of stocks. In addition, there is a regional shift of feedstocks and fuels between producer and consumer countries. This international trade is discussed in Section 5.4.

Excursus 6: The use of bioethanol as a fuel in Brazil

In Brazil, the fuel market for passenger cars is largely based around bioethanol and gasoline. Electric vehicles and vehicles powered by natural gas only play a minor role. In addition, diesel engines have been banned in passenger cars in Brazil since 1976 due to the high oil import rates at the time and supply problems [Motoki (1994)]. Since 1975, the Brazilian government has encouraged the development of engines that run on hydrous ethanol (water content of about 6.8% v/v) or a mixture of anhydrous ethanol (water content of less than 0.7 % v/v) and gasoline, since it was able to produce bioethanol as a by-product of an already extensive sugar production industry [Geisel (1975); Lael, Manoel Regis Lima Verde (2020)]. Since then, the percentage of anhydrous ethanol in gasoline has changed frequently, having remained as 27 % v/v since 2014 (E27) [Ministério da Agricultura (2015)].

In 2003, Brazil registered its first flex-fuel vehicles (FFVs) with a reliable fuel detection system. As they were developed further, the market share of flex-fuel vehicles increased from 3.5 % in 2003 to 96.5 % in 2019 [ANFAVEA (2008); Joseph Jr (2013); UNICA (2020)].

In practice, the availability of the two fuel options allows the end consumer to make purchase decisions based on consumer prices. Figure 5-23 shows the development of monthly consumption of E27 (broken down by gasoline and bioethanol content) and hydrous ethanol (E100), as well as the prices of the two fuel options for Brazil from 2001 to 2019, which have been adjusted for inflation [Banco Central do Brasil (2022); Ministério de Minas e Energia (2021)].

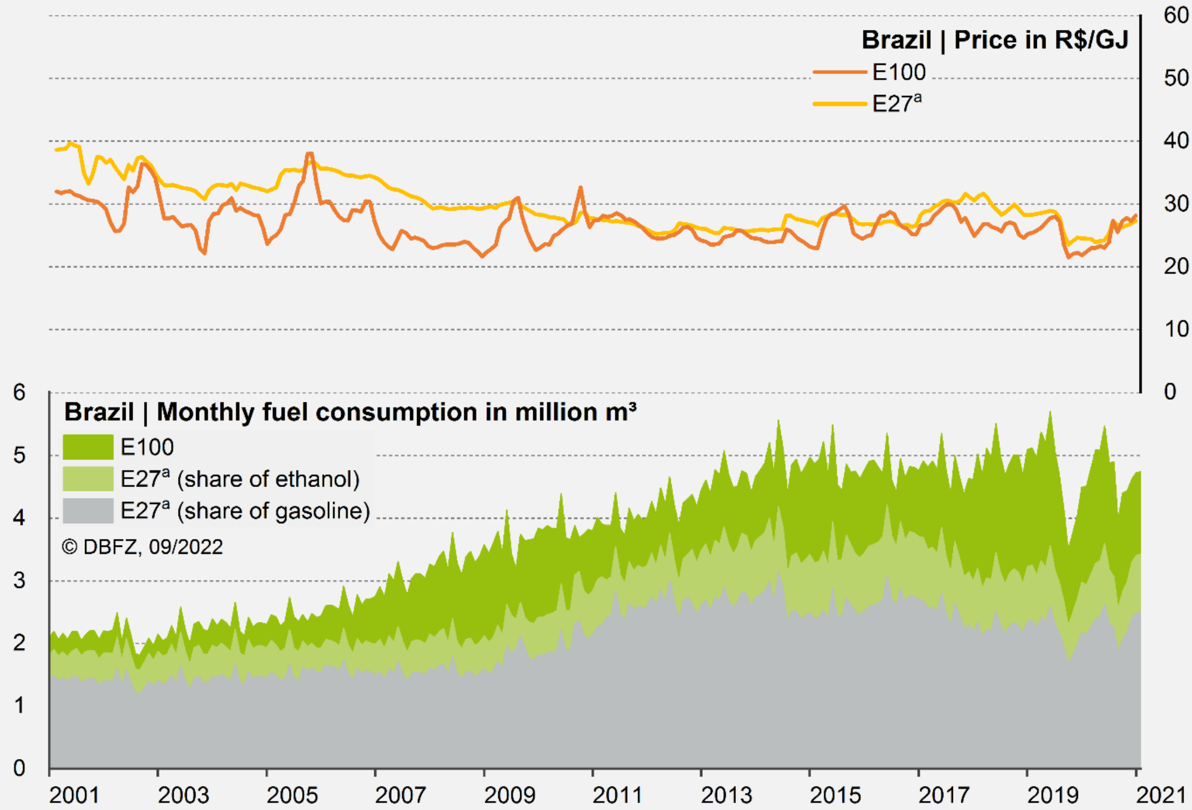


Figure 5-23 Monthly consumption and price of gasoline and bioethanol in Brazil between 2001 and 2021. Note: prices have been adjusted for inflation; [a] E27 corresponds to: E27 from 2014 to 2021, E25 in 2002 to 2005 and 2007 to 2010, E23 in 2006 and E20 in 2011 and 2012; own graph based on data from [Banco Central do Brasil (2022); Ministério de Minas e Energia (2021)]

Fuel prices in Brazil fluctuate according to fuel supply and the supply chain. The ability to utilize both fuel options in flex-fuel vehicles is reflected in sale volumes, such as in 2018/2019, when the lower price of E100 led to a significant increase in its market share. However, there are also regional differences. For example, in February 2011, gasoline and ethanol had the same median price in Brazil (R$26.7/GJ). However, in the state of Mato Grosso, gasoline and ethanol cost R$29.7/GJ and R$29.09/GJ respectively, while in the state of Roraima they cost R$28.4/GJ and R$33.63/GJ respectively. This makes it financially advantageous for the end user to fill up with E27 gasoline in one state and E100 ethanol in the other.

6 Use of renewable energy in transport

JÖRG SCHÖDER, EDGAR REMMELE AND KLAUS THUNEKE

For more information:

Renewable energy carriers are currently being blended with fossil fuels in the 27 EU member states in order to achieve the European targets for renewable energy in the transport sector. The most widespread blending proportions used in road transport are as follows:

- a maximum of 7 % v/v biodiesel (FAME) in fossil diesel (B7),
- a maximum of 5 % v/v bioethanol in gasoline (E5),
- a maximum of 10 % v/v bioethanol in gasoline (E10),
- an undefined proportion up to a total replacement of natural gas by renewable methane, and
- an undefined proportion up to a total substitution of the national electricity supply with electricity from renewable sources.

Some Member States also use higher blending proportions or pure renewable energy sources. Well-known examples are the use of hydrotreated vegetable oils (HVO) and/or hydroprocessed esters and fatty acids (HEFA) in Sweden [Sherrard (2017)], Finland [Neste Oyj (2021)] and the Netherlands [OrangeGas (2021)] as well as E85 in France and Sweden [Sherrard (2017)]. Figure 6-1 provides an overview.

The blending of bioethanol with gasoline and the blending of biodiesel (FAME) with diesel are also common practices worldwide. In Brazil, bioethanol has established itself as the main fuel alongside conventional gasoline in private motorized transport. Here, the bioethanol content of gasoline is at least 27 % v/v and this can increase to 100 % depending on the current daily supply [Queensland University of Technology (2020)]. Other countries with blend mandates for bioethanol over 20 % v/v are Paraguay and Argentina (both E25) [Ioannis Pappis (2021); Queensland University of Technology (2020)]. The USA, which has the strongest market for ethanol fuel, now uses E10 and, regionally, E15 and E85 [Queensland University of Technology (2020); Wright (2020)]. Costa Rica and Indonesia both mandate the highest proportion for FAME at 20 % v/v. The strongest biodiesel markets – the U.S., China, Brazil and France – have imposed blend mandates of between 5 and 10 % v/v [Queensland University of Technology (2020); Wright (2020)].

Renewable energy is not currently used in aviation or maritime shipping except in a few demonstration projects or local supply contracts. However, it can be assumed that, at least in aviation, the number of flights using SAF as an admixture will increase in the coming years. Los Angeles International Airport (LAX, since 2016) and San Francisco International Airport (SFO, since 2020), among others, are vanguards in this respect [Greenair (2019), (2020b), (2020a); Wright (2020)].

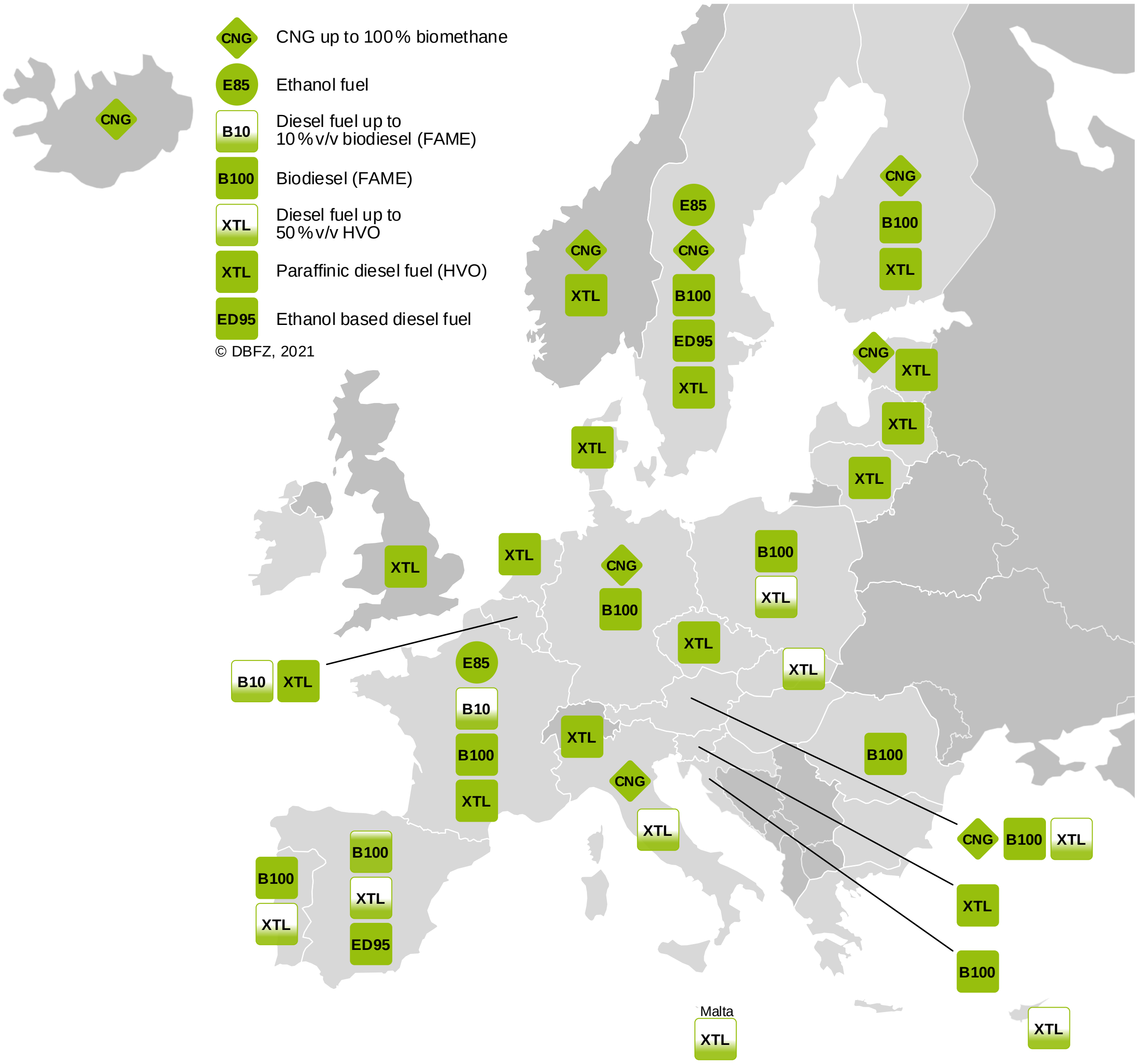


Figure 6-1 Fuel options for road vehicles with significant percentages of renewable fuels above the EN 228 and EN 590 standards according to country. Note: no claim to completeness; data based on [Eurostat (2021i)]

In addition to the already established energy carriers, many other energy carriers are being discussed for the various drive concepts which use the technologies described in Section 3. In Figure 6-2 below, the options are classified according to their compatibility with diesel, gasoline, turbine and electric engines (using fuel cells, batteries/overhead lines): highly compatible (✓), compatible (✓) and not compatible (white).

	Diesel engine	Gasoline engine	Turbines	Electric engine (fuel cell)	Electric engine (battery or overhead line)
Electricity					✓ (highly compatible)
Hydrogen	✓ (compatible)	✓ (compatible)		✓ (highly compatible)	
Methane (CNG)	✓ (compatible)	✓ (highly compatible)			
Methane (LNG)	✓ (highly compatible)	✓ (highly compatible)			
Methanol	✓ (highly compatible)	✓ (highly compatible)		✓ (compatible)	
MTG		✓ (highly compatible)			
MTJ					
Ethanol	✓ (compatible)	✓ (highly compatible)		✓ (compatible)	
ATJ			✓ (highly compatible)		
Vegetable oil	✓ (highly compatible)				
FAME	✓ (highly compatible)				
HVO/HEFA	✓ (highly compatible)	✓ (compatible)	✓ (highly compatible)		
DME/OME	✓ (highly compatible)		✓ (highly compatible)		
Fischer-Tropsch	✓ (highly compatible)	✓ (highly compatible)	✓ (highly compatible)		

Figure 6-2 Energy carrier compatibility according to type of drive. Legend: highly compatible (✓), compatible (✓) and not compatible (white)

6.1 Fuel standards and labels

Fuel standards define the requirements for fuel quality. They ensure a high engine reliability and compliance with emission limits. They also serve as a reference for fuel trading. Fuel standards specify the parameters that determine fuel quality through limit values and test methods and take into account the quality of the measurement methods. Fuel standards provide legal certainty and are therefore a basic requirement for the market introduction and distribution of alternative fuels.

Standards have been set at European and national level for a large number of fossil fuels that contain a biogenic blending component, as well as for pure biofuels or blended fuels that can be used to power diesel and gasoline engines as well as aircraft turbines. These are listed in Sections 6.1.1 to 6.1.4. Some of the necessary requirements for fuel combinations currently under discussion in the scientific community are shown in Table 6-1.

Table 6-1 Fuel options where no European or German standardization activities are known to be occurring. Note: no claim to completeness

Fuel	Area of application
Ethanol-gasoline blend (E20)	Road (combustion engine)
Ethanol-diesel fuel (ED95)	Road (combustion engine)
HEFA/FT-gasoline	Road (combustion engine)
Methanol (M100)	Road (fuel cell)
Methanol (M100)	Maritime (combustion engine)
Methanol as a blending component	Road (combustion engine)
Methanol-gasoline blend (M5 to M85)	Road (combustion engine)
Methanol-ethanol-gasoline blend (A20)	Road (combustion engine)
Methanol-to-Gasoline (MTG)	Road (combustion engine)
Methanol-to-Jet (MTJ)	Aviation (turbine)

In Germany, only the fuels listed in the 10th BImSchV may be placed on the market (Section 1.5.1). These fuels must be labeled at filling stations in accordance with DIN EN 16942 (Fuels – Identification of vehicle compatibility – Graphical representation for consumer information; German version EN 16942:2016+A1:2021) [DIN EN 16942 (2021)]. Unlike in other European countries, the fuel portfolio may not be expanded for private vehicle fleets with their own fueling infrastructure (business-to-business application) with the exception of aviation fuels, or this can be applied for on a case-by-case basis for research and testing purposes.

6.1.1 Gaseous fuels

DIN EN 589

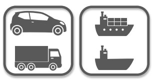
LPG

Automotive fuels – LPG – Requirements and test methods; German version EN 589, 2019-03 edition. This document specifies the requirements and test methods for liquefied petroleum gas (LPG) that is being traded and supplied for motor vehicles. It applies to the LPG used to operate vehicles that are compatible with this fuel. According to the 10th BImSchV, fuels complying with this standard may be marketed in Germany. Only fossil LPG is being used today. [DIN EN 589 (2019)]

DIN EN 16723-2

CNG LNG

Natural gas and biomethane for use in transport and biomethane for injection in the natural gas network – Part 2: Automotive fuels specification; German version EN 16723-2, 2017-10 edition. This standard contains the requirements for test methods for natural gas and biomethane and the requirements that the blends of natural gas and biomethane must fulfill at the supply point (filling station) in order to be used as fuels in motor vehicles. According to the 10th BImSchV, fuels complying with this standard may be marketed in Germany. [DIN EN 16723-2 (2017)]



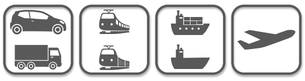
ISO 16861

Petroleum products – Fuels (class F) – Specifications for Dimethyl ether (DME); German and English version ISO 16861:2015-05. This standard specifies the quality of dimethyl ether of fossil or biogenic origin for use as a fuel. A pre-standard is currently being developed for the standardization of DME (DIN/TS 51698). [ISO 16861 (2015)]

DIN EN 17124

H2

Hydrogen fuel – Product specification and quality assurance – Proton exchange membrane (PEM) fuel cell applications for road vehicles; German version EN 17124, 2019-07 edition. This document provides specifications for hydrogen used as a fuel to operate road vehicles whose electric motors are powered by PEM fuel cells. Due to the sensitive nature of these drive systems, this document gives special consideration to the quality assurance surrounding the purity of the hydrogen fuel. According to the 10th BImSchV, fuels complying with this standard may be marketed in Germany. [DIN EN 17124 (2019)]



6.1.2 Liquid fuels for engines with a spark ignition – “gasoline engines”

DIN EN 228

E5 E10

Unleaded petrol; German version EN 228:2012+A1:2017, 2017-08 edition. This document specifies requirements and test methods for unleaded gasoline supplied and placed on the market. It governs its use in gasoline engines that run on unleaded gasoline. It describes, among other things, one grade of gasoline containing a maximum of 5 % v/v ethanol (E5) and a second grade of gasoline containing a maximum of 10 % v/v ethanol (E10). According to the 10th BImSchV, fuels complying with this standard may be marketed in Germany. [DIN EN 228 (2017)]

DIN EN 15376

Ethanol as a blending component for petrol; German Version EN 15376:2014, 2014-12 edition. This standard specifies the requirements and test methods for delivered and/or marketed ethanol used as a fuel extender in vehicles with gasoline engines in accordance with the requirements of EN 228. The standard applies to the entire blend range of ethanol up to and including 85 % v/v ethanol. [DIN EN 15376 (2014)]

DIN EN 15293

E85

Automotive ethanol (E85) fuel – Requirements and test methods; German version EN 15293:2018, 2018-10 edition. This document specifies the requirements and test methods for traded and delivered ethanol fuel (E85). It applies to E85 for use in vehicles with gasoline engines equipped to use this fuel. Fuels that are in line with this standard may be placed on the market in Germany in accordance with the 10th BImSchV. [DIN EN 15293 (2018)]

6.1.3 Liquid aviation turbine fuels

ASTM D1655

Standard Specification for Aviation Turbine Fuels, 2018 edition. This ASTM standard specifies the requirements for the jet fuel “Jet A-1”; no ISO or EN standard exists. [ASTM D1655-20D (2020)]

ASTM D7566

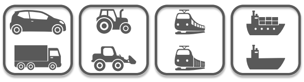
Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons, 2019 edition. ASTM standard D7566 describes the quality of jet fuel (Jet A-1) containing a proportion of synthetic hydrocarbons. The fuels produced by the individual technology processes are described in the corresponding annexes. Currently, it covers seven different processes. [ASTM D7566-20C (2020)]

6.1.4 Liquid fuels for engines with a compression ignition – “diesel engines”

DIN EN 590

B7

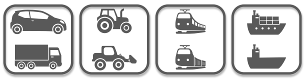
Diesel fuel containing 7 % v/v fatty acid methyl ester (FAME); German version EN 590:2013+A1:2017, 2017-10 edition. This standard describes a fuel that may contain up to 7 % v/v of FAME. In addition, paraffinic hydrocarbon components may be included, for example from hydrotreatment processes (HVO) or Fischer-Tropsch processes (GTL, BTL) as well as from the co-refining of renewable energy carriers, provided that the blended product complies with the requirements of this standard. For example, a DIN EN 590 compliant diesel “R33” (a blend of 67 % v/v diesel fuel, 26 % v/v HVO and 7 % v/v FAME) was tested in a field trial and is now being used by Volkswagen in fleet applications [DIN EN 590 (2017); Götz (2015); Reichel (2018)]. According to the 10th BImSchV, fuels complying with this standard may be marketed in Germany. Fuels that are compliant with DIN EN 590 are also typically used for inland shipping.



DIN EN 14214

B100

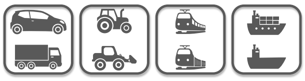
Fatty acid methyl esters (FAME) for use in diesel engines and heating applications; German version EN 14214:2012+A2:2019, 2019-05 edition. DIN EN 14214 specifies the quality of FAME, also known as biodiesel, for use as the pure fuel B100 in vehicles developed or adapted for this purpose, and as a blending component to diesel fuel in accordance with the requirements of the relevant standards and as a heating oil substitute. According to the 10th BImSchV, fuels complying with this standard may be marketed in Germany. [DIN EN 14214 (2019)]



DIN EN 16734

B10

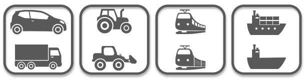
Diesel fuel containing 10 % v/v fatty acid methyl esters (FAME); German version EN 16734:2016+A1:2018, 2019-02 edition. This standard describes a diesel fuel that may contain up to 10 % v/v of FAME and can be used in compatible vehicles within private vehicle fleets. It may include other biogenic components, such as HVO and BTL, provided that the requirements of this standard are met. The standard is not mentioned in the 10th BImSchV. Accordingly, this fuel may not be used in road transport. [DIN EN 16734 (2019)]



DIN EN 16709

B20 **B30**

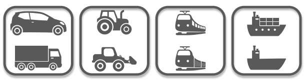
Diesel fuel blends with a high FAME content (B20 and B30); German version EN 16709:2015+A1:2018, 2019-02 edition. This standard describes a diesel fuel that may contain up to 20 or 30 % v/v of FAME and can be used in compatible vehicles within private vehicle fleets. It may include other biogenic components, such as HVO and BTL, provided that the requirements of this standard are met. The standard is not referred to in the 10th BImSchV. Accordingly, the fuel may not be used in road transport. [DIN EN 16709 (2019)]



DIN EN 15940

XTL

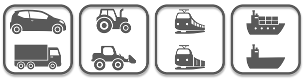
Paraffinic diesel fuel from synthesis or hydrotreatment; German version EN 15940:2016+A1:2018+AC:2019, 2019-10 edition. This standard defines the quality of diesel fuel based on synthesis gas or hydroprocessed oils. These fuels can be used in compatible vehicles within private vehicle fleets [DIN EN 15940 (2019)]. In its pure form, this paraffinic diesel fuel does not meet the current requirements of the diesel fuel specification DIN EN 590, but it can be used as an admixture in diesel fuel, provided that the requirements of DIN EN 590 are met. It can be distributed as a pure fuel to public filling stations in most European countries. This does not apply to Germany, because it is not listed in the 10th BImSchV.



DIN 51605
DIN 51623

PÖ

DIN 51605: rape seed oil fuel, 2020-11 edition and DIN 51623: vegetable oil fuel, 2020-11 edition. These two standards describe fuels made from vegetable oils that can be used in specially manufactured vehicles or vehicles adapted to run on vegetable oil. The standards differ in the feedstock that the fuel is based on: Whereas DIN 51623 permits all parts of the plant that contain oil, DIN 51605 relates exclusively to rape seed. According to the 10th BImSchV, fuels complying with this standard may be marketed in Germany. [DIN 51623 (2020); DIN 51605 (2020)]



DIN/TS 51699 The German Institute for Standardization (DIN) is currently drafting a standard for the use of polyoxymethylene dimethyl ether (oxymethylene ether – OME) as a fuel. The draft standard will specify the quality of the OME as a pure fuel or as a blending component.

DIN ISO 8217 Fuels and combustible fuels (class F) requirements for marine fuels (ISO 8217:2017), 2018-10 edition. This document specifies the requirements for fuels for marine diesel engines and boilers prior to conventional onboard treatment. The specifications for fuels in this document can also be applied to fuels used in stationary diesel engines of the same or similar type as those used for maritime purposes. These are subdivided into heavy fuel oils (HFO) and distillates (marine gas oil, MGO) as well as the subcategories low sulfur fuel oil (LSFO), ultra-low sulfur fuel oil (ULSFO), high sulfur fuel oil (HSFO), marine diesel oil (MDO) and intermediate fuel oil (IFO). [DIN ISO 8217 (2018)]

MARPOL Annex VI MARPOL Annex VI of the International Convention for the Prevention of Pollution from Ships regulates air pollution from ships. Regulation 18 sets out requirements for fuel quality – in particular for the sulfur content of the fuels used (0.5 % w/w globally, 0.1 % w/w within the so-called “Sulfur Emission Control Area”). [IMO (2019)]

6.2 Fuel quality parameters

The fuel properties that are used to describe a fuel’s quality are influenced by the feedstock used to produce it, its production process, the blending components, the additives that are introduced, as well as its storage and transport. Establishing certain limits for these properties ensures trouble-free operation of the engine and the exhaust gas aftertreatment system. Emissions that are toxic to humans and the environment can also be lowered, which is also done indirectly by maintaining the functionality of exhaust gas aftertreatment systems, and through quality-preserving storage and safe transport of the fuel. The Federal Immission Control Act and the Ordinance on the Properties and Labeling of the Quality of Fuels (10th BImSchV, Section 1.5.1) serve as the national legal framework for the quality and GHG reduction of fuels. Quality assurance systems are commonly used by fuel manufacturers and distributors to guarantee that the quality of the fuels is in line with the requirements of the standards (FQD, Section 6.1).

Selected fuel properties are explained in more detail below.

Acid number: The acid number is a measure of the free fatty acid content of vegetable oils and fatty acid methyl esters and describes the amount of caustic potash required to neutralize the free fatty acids. The acid number depends on the quality of the processed oil seed as well as on an oil's degree of refinement and aging. Water, microorganisms and enzymes in the oil can cause hydrolytic cleavage of the triglycerides and raise the acid number. Acidic compounds in the fuel lead to corrosion, wear and residue formation in the engine. Free fatty acids can also react with basic components of the engine oil.

Alkali metals: Alkali metals, such as sodium and potassium, can cause hot corrosion and deposits on injectors during combustion, act as catalyst poisons and are deposited as ash in the soot particulate filter. The naturally occurring alkali metal content in vegetable oil is very low. However, caustic soda or caustic potash is used as a catalyst for transesterification in the production of FAME. Catalyst residues may remain in the FAME.

Ammonia and amines: Ammonia and amines can occur naturally when methane is produced from biogas and elevated levels can occur, especially when the gas is treated with amine scrubbers. Ammonia has a strong corrosive effect.

Aromatic content: Aromatics are organic compounds with a single or multiple ring system with conjugated double bonds. Aromatics are formed primarily during fuel refinement and have a positive effect on the fuel's anti-knock quality. However, a high proportion of aromatics in the fuel contributes to the formation of polycyclic aromatic hydrocarbons (PAHs) in the exhaust gas, which are harmful to human health.

Ash content: The ash content describes the total proportion of inorganic solids in the fuel. A high ash content can be caused, for example, by dust entering the fuel or by catalyst residues from transesterification. As ash content increases, so does the risk of abrasion in the injection pump, in the injectors, and in the combustion chamber. It can also impair the operation of exhaust gas aftertreatment systems such as oxidation catalysts, catalysts based on the selective catalytic reduction (SCR) principle, and particulate filters.

Biodegradability: Since fuels can be released into the environment, for example, during refueling or in the event of an accident, biodegradability is an important quality aspect. Biodegradabilty is understood to mean the decomposition of fuels by living organisms or enzymes, ideally to the point of mineralization. Various standardized test methods are available depending on the properties of the fuels undergoing testing.

Blending proportion: The blending proportion describes the mass, volume or energy fraction of a fuel that has been blended to another fuel. For example, the blending proportion of ethanol in E10 gasoline is no greater than 10 % v/v.

Carbon residue: The carbon residue of diesel fuel and FAME is determined by carbonizing the last 10 % of the distillation residue. Determining the carbon residue simulates the combustion of fuel on a surface without oxygen. The carbon residue consists of organic and inorganic components and is an indicator of the fuel's tendency to carbonize at the injection nozzles and to form a residue in the combustion chamber. Fuel additives, such as ignition accelerators, can increase the carbon residue and lead to an inaccurate interpretation.

Carbonyl sulfide: Carbonyl sulfide is a strong-smelling, gaseous sulfur compound that occurs in natural gas and biogas and is therefore regulated by the quality requirements for CNG. See also “Sulfur content”.

Cetane index: The cetane index can be calculated from the fuel density and boiling behavior. It allows the ignitability to be assessed without having to measure the cetane number. The theoretical principle is that as density increases, caused by a rise in the proportion of cracking products with double bonds, the cetane number decreases. As the high-boiling components increase (greater chain length of the molecules) the cetane number increases. The formula must be constantly adapted to changing refinery standards. Deviations between the calculated cetane index and the measured cetane number result both from inaccuracies in the empirical formula and from scattered measurements of the cetane number. The cetane index is unable to represent the cetane number of fuels that have been mixed with ignition accelerators.

Cetane number: The cetane number is an indicator of the ignitability of fuels in compression ignition engines. The standardized measurement of the cetane number is carried out in a single-cylinder test engine (CFR or BASF test engine). The measurement of the cetane number is only partially suitable in determining the ignitability of fuels with a biogenic component due to the test engine used. Alternatively, the ignition delay can be measured or the derived cetane number (DCN) or cetane index (CI) can be determined in a constant volume combustion chamber. Fuels with a low ignitability, i.e., lower cetane number, produce a higher ignition delay, which can result in poorer cold-start behavior, higher pressure peaks and thus higher exhaust gas and noise emissions. Depending on the operating condition of the engine, the ignitability of biogenic fuels may have its own properties that cannot be compared with those of diesel fuel.

CFPP (cold filter plugging point): The CFPP predicts the temperature at which a fuel will still flow smoothly and be filterable. The requirements for the CFPP vary with the season. When fuel filters are heated by engine waste heat or filter heating, safe operation is possible even at temperatures that are lower than those indicated by the CFPP. Often there is no apparent correlation between the operability of diesel passenger cars in the vehicle test and the CFPP parameter.

Cloud point: The cloud point describes the temperature at which paraffin crystals first become visible (like a “cloud”) when diesel fuel is cooled. The pumpability and filterability can only be determined if no additives have been added to the fuel to improve flow. The cloud point can only be used to a limited degree to draw conclusions about the low-temperature behavior of diesel fuels in vehicles.

Compressor oil: Compressor oil can be introduced into gaseous fuels during compression. Its content should be kept as low as possible in the gaseous fuel. Oil separation filters are used for this purpose.

Corrosion effect on copper: The copper strip corrosion test is used to determine a fuel’s corrosion effect on copper. A pre-treated copper strip is stored for a certain period of time and at a certain temperature in a sample container with the fuel. Afterwards it is optically evaluated for discoloration using a reference scale.

Density: Density describes the mass of a volume of fuel at a certain temperature. In the case of vegetable oil fuels, for example, the density increases as the carbon content goes up, i.e., with increasing chain length and an increasing number of double bonds. Fuel is mostly traded based on volume. Density can be used to distinguish between fuels and to identify fuel blends.

Diglyceride: The diglyceride content indicates the completeness of the transesterification of triglycerides to FAME. A high diglyceride content, indicating a low degree of transesterification, can lead to deposits in the injection system and combustion chamber.

Distillation or boiling behavior: Diesel fuel consists of hydrocarbon mixtures that boil at temperatures between 170 and 380 °C. In the standard for diesel fuel, distillation describes the key points of the boiling process, such as the volume fraction that has evaporated when the liquid is heated to a certain temperature and the temperature at which a certain volume fraction of the liquid has evaporated. The final boiling point influences deposits, particle emissions and smoke formation. It is difficult to determine a boiling curve for vegetable oils and FAME, since cracking processes disturb the boiling behavior.

Dust-related impurities: Dust-related impurities in methane fuel can cause deposits or lead to blockages in the fuel system. Corresponding filters are used for gas purification.

Earth alkaline content: The content of calcium and magnesium in vegetable oils is mainly influenced by seed quality and the processing of the oil seed. Calcium and magnesium are introduced into the vegetable oil through phospholipids. They can lead to deposits in the combustion chamber and on injection nozzles and valves, affect the operation of catalytic converters and, as they form ash, can clog particulate filters.

Electrical conductivity: In jet fuel, the content of additives that can conduct electricity is regulated to prevent short circuits.

Ester: The ester content is used to describe FAME, to unambiguously characterize it, and to detect blends with other fuels.

Ethanol content: Ethanol can be blended with fossil gasoline. The standard has established proportions of up to 5 or 10 % v/v and, in the case of E85, up to 85 % v/v. An excessively high ethanol content can have a negative impact on the material resistance of the parts of the tank and injection system that carry fuel, especially in older vehicles. In addition, the oxygen content in ethanol, and the reduced lower heating value associated with this, increase fuel consumption. On the other hand, ethanol has advantages over gasoline in terms of exhaust emissions and enables a gasoline engine to operate more efficiently as a result of its better knock resistance.

Fatty acid methyl ester content: Fatty acid methyl esters can be blended with fossil diesel fuel at rates of 7, 10, 20 or 30 % v/v in compliance with the standards. If blending rates are exceeded, material incompatibilities, cold-start problems or changes in emission behavior may occur. In addition, biogenic fuel components may accumulate in the engine oil when fuel is injected later for the purpose of regenerating the particulate filter.

Fatty acid pattern: The fatty acid pattern provides information about which and what proportions of fatty acids are present in a fuel derived from vegetable oil. This enables information to be obtained, for example, about oxidation and polymerization susceptibility, possible interactions with the engine oil and the tendency for deposits to form in the combustion chamber. The fatty acid pattern helps to determine the structure-related parameters MC (mean number of carbon atoms) and MD (mean number of double bonds) for vegetable oils. These enable an approximate calculation of parameters such as iodine value, saponification value, kinematic viscosity, density, lower heating value, surface tension and elemental composition. [Emberger (2013)]

Flash point: The flash point is the temperature at which fuel in an open or closed vessel is converted to such a gaseous state that a gas-air mixture is ignitable by an external ignition. The flash point is important in order to be able to classify liquids as hazardous substances according to their ignitability, resulting in safety measures for storage and transport. Even slight mixtures of different fuels, for example during transport, can result in deviations from the characteristic flash point of the pure fuels.

Freezing point: The freezing point is the temperature at which a fuel changes from a liquid to a solid.

GLYCERIDE CONTENT: The content of mono-, di- and triglycerides is an indicator of the completeness of the transesterification process during FAME production. A high glyceride content can cause deposits in the injection system and in the combustion chamber.

GLYCEROL CONTENT: Similar to the glyceride content, the total glycerol content is an indicator of the completeness of the transesterification of triglycerides to FAME. The free glycerol content is an indicator of the quality of the phase separation of glycerol and fatty acid methyl esters during transesterification. A high glycerol content in a fuel can lead to deposits in the injection system and in the combustion chamber.

HYDROCARBON DEW POINT TEMPERATURE: The hydrocarbon dew point temperature describes the condensation behavior of natural gas or biomethane. It is the temperature at which the liquid phase begins to form at a given pressure.

HYDROGEN CONTENT: The hydrogen content in natural gas and biomethane fuels is regulated, for example to prevent corrosion of steel tanks in vehicles. The hydrogen can come from synthesis gas or from PTG processes.

HYDROGEN IMPURITIES/HYDROGEN PURITY: Hydrogen, especially as an energy storage medium for fuel cells, requires a high degree of purity due to the high sensitivity of fuel cells. With respect to damage, a distinction is made between damage to hydrogen-carrying components, such as tanks and pipelines, and reversible and irreversible damage to the fuel cell. Irreversible damage to fuel cells is caused by sulfur, ammonia and halogens, therefore concentrations must be kept as low as possible. Reversible damage is caused by hydrocarbons, CO_2, carbon monoxide, formaldehyde and formic acid. Components that carry hydrogen can be affected by water, CO_2, sulfur, formaldehyde, formic acid, ammonia, halogens, and solid and liquid suspended particles. The total content of non-hydrogen gases is also limited due to dilution effects. [EMCEL GmbH (2018)]

HYDROGEN SULFIDE: Hydrogen sulfide can come from natural gas or can occur in CNG through the methane supplied from biogas. Hydrogen sulfide has a very strong odor that is reminiscent of rotten eggs. See also "sulfur content".

IODINE VALUE: The iodine value is a measure of the number of double bonds of the fatty acid molecules in vegetable oil fuels. The parameter indicates how many grams of iodine are bound by 100 g of oil or fatty acids. The lower the iodine value, the higher the degree of saturation of the molecules. The iodine value is a way to distinguish between different types of vegetable oils. It provides information on the tendency for deposits to form in the combustion chamber and on injectors. In addition, an increasing proportion of unsaturated fatty acids increases the risk of polymerization of the motor oil when the fuel is introduced into it. The iodine number can also be used to estimate the risk of oxidative spoilage of the fuel during storage.

LEAD CONTENT: All gasoline that has been sold in Germany since 1996 has been lead free. Previously, additives containing lead (tetraethyl lead and tetramethyl lead) were used to improve the gasoline's anti-knock quality and to support the lubrication of gasoline engines. Traces of lead can build up in the combustion chamber and in the exhaust aftertreatment system, accelerating engine wear. Lead is also considered a cytotoxin that reduces oxygen uptake in the blood.

LOWER HEATING VALUE: The lower heating value is the measure of the heat (energy) that can be released per volume or mass during total combustion of a substance. In contrast, the higher heating value includes the energy released during condensation of the water vapor produced during combustion and is therefore higher than the lower heating value. The lower heating value is calculated from the higher heating value minus the evaporation heat of the water.

Lubricity: A fuel's lubricity must be tested because the fuel in diesel injection systems must also act as a lubricant. A high frequency reciprocating rig (HFRR) is used to determine a fuel's lubricity. In this test, a steel ball with a defined force, frequency and path length moves for a certain time over a steel plate containing a certain amount of tempered fuel. The diameter of the flattened area on the ball is the so-called HFRR value.

Manganese content: Manganese primarily enters the fuel through the additive (methylcyclopentadienyl)manganese tricarbonyl. (Methylcyclopentadienyl)manganese tricarbonyl has been used since the 1950s as an additive to improve knock resistance.

Methane number: The methane number is comparable to the octane rating of gasoline and describes the knock resistance of gaseous fuels. The methane number is the proportion by volume of methane in a methane-hydrogen mixture that produces the same knocking behavior in a test engine as the gaseous fuel being tested.

Methanol content: Like ethanol, methanol influences fuel consumption, exhaust emissions, corrosion, and the engine's cold start behavior and is capped by the standard at 3 % v/v [DIN EN 228 (2017)]. When using fuels containing methanol, care must be taken to ensure that there is no contact with water, as otherwise phase separation may occur in the fuel. Currently, the methanol content in gasoline is very low, as the use of methanol in the refining process is not economical.

Octane number (research octane number and motor octane number): The octane number is a measure of the knock resistance of fuels in an engine with a spark ignition. The standardized measurement of the octane number is carried out in a single-cylinder test engine (CFR or BASF test engine). Fuels with a low octane number or low knock resistance can cause spontaneous ignition and uncontrolled combustion, which, in the worst case, can lead to engine damage. Fuels with increased knock resistance (e.g., ethanol or methane) allow the combustion chamber charge to be optimized towards high compression ratios, thereby improving thermodynamic efficiency.

Olefins: Olefins are acyclic and cyclic hydrocarbons with one or more carbon double bonds. They can range from 0 to 18 % v/v depending on the refinery configuration. Olefins influence a fuel's anti-knock quality. Olefins exhibit positive properties, especially at low and medium engine speeds, and are therefore used primarily in normal and super unleaded gasoline. A lower proportion of olefins in gasoline can lead to reduced nitrogen oxide emissions and a simultaneous increase in hydrocarbons. [Hitzler (2000)]

Oxidation stability: Oxidation stability is a parameter that describes a fuel's aging condition and its storage capability. When fuels are stored, oxidation and polymerization processes can set in leading to the formation of insoluble compounds that clog filters. If unburned fuel with low oxidation stability enters the engine oil, this leads to a faster depletion of multi-functional additives and thus to shorter periods between oil changes. The test methods for determining the oxidation stability of diesel fuel and biofuels differ.

Oxygen content: The oxygen content indicates the amount of oxygen bound in the fuel. A high oxygen content in the fuel reduces its lower heating value and thus influences fuel consumption. The oxygen bound in the fuel reduces the oxygen demand during combustion and thus counteracts the formation of particle emissions in rich, low-oxygen combustion zones.

Phosphorus content: Phosphorus is present in vegetable oils in the form of phospholipids. As the proportion of phospholipids increases, oxidation stability decreases. In addition, phospholipids tend to hydrate (swell in the presence of water) and, for example, can clog fuel filters. Phosphorus lowers the combustion temperature and leads to deposits in the combustion chamber, on valves and on injectors, thereby indirectly causing higher exhaust emissions. Catalytic converters are also highly sensitive to phosphorus compounds with respect to their conversion rate or long-term operation.

Polycyclic aromatic hydrocarbons (PAH): According to DIN EN 590, PAHs are defined as the total content of aromatic hydrocarbons reduced by the content of mono-aromatic hydrocarbons. The analysis is carried out using high-performance liquid chromatography. Polyaromatics in diesel fuel lead to an increase in particle emissions.

Polyunsaturated fatty acid methyl ester: Polyunsaturated fatty acid methyl esters – as components of biodiesel – especially linolenic acid methyl esters and fatty acid methyl esters with more than three double bonds, can lead to deposits in the combustion chamber and on injectors. There is also a risk of engine oil incompatibility (tendency to polymerize) if a fuel with a high proportion of unsaturated fatty acids is introduced into the engine oil. Analysis of the proportion of polyunsaturated methyl esters in FAME allows more precise statements to be made than can be concluded from the iodine value.

Pour point: The pour point describes the temperature at which the fuel, which has been cooled under specific conditions, is still able to flow. The flowability is checked at temperature increments of 3 K. Special pour point vessels are used as sample containers. As the mineral oil cools, paraffin wax crystals form, which affect the flowability. The pour point is considered to have been reached when no movement of the fuel can be observed for more than five seconds when the sample container is held in a horizontal position. The pour point can be subject to large deviations due to prior heat treatment of the fuel.

Sulfated ash: Sulfated ash is the mineral residue that remains as sulfate after incineration and treatment with sulfuric acid. The sulfated ash originates from inorganic foreign substances. When analyzing FAME, it is not the ash, but the sulfated ash that is determined in order to measure the sodium and potassium residues that can originate from the catalyst during transesterification.

Sulfur content or total sulfur content: During fuel combustion, more than 95 % of the sulfur is converted into sulfur dioxide (SO_2). The remaining sulfur accumulates on particles. In the oxidation catalyst, the proportion of sulfur converted to sulfur trioxide (SO_3) increases depending on the type of catalyst and temperature. Sulfuric acid droplets form from SO_3 and water vapor, which attach to soot and lead to an increase in the total particle mass. Sulfur compounds can also irreversibly damage the catalytically active layer of the catalyst. Catalyst concepts for reducing particle emissions therefore require either catalyst technologies that are not sensitive to sulfur, or an extremely low sulfur content in the fuel. Sulfur in the fuel can also contribute to acidification of the motor oil. Sulfur content also affects engine longevity. The acidic compounds formed during combustion lead to corrosive wear and tear. This is counteracted by motor oil additives that neutralize acidic reaction products. Strong-smelling organic sulfur compounds are added to methane fuel during odorization so that gas leaks can be detected by smell.

Thermal stability: Testing the thermal stability assesses a fuel's tendency to form deposits in the fuel system. The fuel is aged at a specific temperature over a specific period of time. In order to assess the tendency to form deposits, the differential pressure during filtration of the fuel is measured before and after aging. Filtration is used to gravimetrically compare the sediment content before and after aging, and the deposits in the heating pipe are examined or visually assessed.

Total contamination: Total contamination is the mass fraction of undissolved solids (particles) in the fuel. A high level of solids can clog fuel filters, impair the function of injectors and cause abrasion on the injection system and deposits in the combustion chamber.

Total volatile silicon: The silicon content is a quality parameter for CNG and LNG when methane is produced completely or in part from biogas or landfill gas. As a rule, natural gas does not contain any silicon. Silicon oxide from combustion can, for example, lead to deposits in the engine combustion chamber and on lambda sensors, cause abrasion, and reduce the efficiency of catalytic converters.

Toxicity: Toxicity refers to the harmful effect of substances on organisms. In the case of fuels, this includes human toxicity, in the sense of protecting the user, but also, aquatic toxicity in the event of leaks or accidents. Specific test methods are available for testing the toxic effect of fuels.

Viscosity: A fuel's viscosity influences the delivery behavior in the fuel system and atomization at the injection nozzles (droplet spectrum and geometry of the injection jet). Viscosity is highly dependent on temperature and pressure. This must be taken into account, especially with the high pressures that prevail in modern injection systems. High viscosities lead to cold start problems due to deteriorated flow, pumping and atomization behavior. Viscosities that are too low make hot starting more difficult and lead to loss of performance at high temperatures and to wear and tear on the pump. A distinction is made between dynamic and kinematic viscosity. The kinematic viscosity is determined for fuels. This is the quotient of the dynamic viscosity and the density of the liquid.

Water content: A fuel's water content is mainly influenced by fuel production and storage. At low temperatures, free water can clog filters due to crystal formation. The high pressures in modern injection systems can cause free water to form, which can damage the injection system, for example through cavitation. During storage, microorganisms can multiply at the boundary layer between the free water and fuel, which can clog filters. Microorganisms also accelerate oil aging. Water is required for hydrolytic cracking to occur. An elevated water content in the fuel can cause corrosion, for example on the chromate layer of chrome-plated brass components. This can attack the brass alloy. This in turn has a catalytic effect on polymerization processes in vegetable oil. Water is not generally a disadvantage in engine combustion. When fuel-water emulsions are burned, the combustion temperature drops, which results in a reduction in NO_X emissions (nitrogen oxides – NO_X).

Water vapor dew point: The water vapor dew point is used to track the condensation of water vapor from natural gas or methane fuel on cold surfaces, and/or the stability of the condensate on cold surfaces, which must be avoided. The water vapor dew point describes the temperature and pressure for a state of equilibrium between the gaseous and liquid phase, and is a quality parameter for CNG and LNG. The water content can be calculated from the water vapor dew point.

Wobbe Index: The Wobbe index is a measure of the heating load supplied to a gas appliance. It enables a comparison to be made between gases with different compositions, taking into account their respective heating values and densities. The Wobbe index is based on volume.

6.3 Safety aspects for handling renewable energy carriers

Regulations divide the handling of fuels into three main processes: transport, storage and transfer/filling. These three processes are regulated by various laws, ordinances and technical rules in order to ensure safe handling at all times and to avoid harming people and the environment. The following regulations must be observed when storing, transferring and filling fuels: the Operational Safety Ordinance [BetrSichV (2021)], the Water Resources Act [WHG (2021)] including the Ordinance on Facilities for Handling Substances that are Hazardous to Water [AwSV (2020)], the Federal Immission Control Act [BImSchG (2019)] and its ordinances, as well as the Technical Rules for Operational Safety (TRBS) and Technical Rules for Hazardous Substances (TRGS). These regulations define the permissible storage quantities, the requirements for the storage sites, and the risk assessments the employer must make. During transport, the regulations concerning the (inter)national carriage of dangerous goods must also be observed (road: ADR, rail: RID, inland waterways: ADN, ocean-going vessels: IGMD, civil aviation: ICAO-IATA and DGR). The key data for fuels are typically summarized in safety data sheets (SDS).

Fuels have different physical, chemical and toxicological properties under normal/ambient conditions and when in use. These are summarized below. The analysis is based on the available safety data sheets.

GASOLINE AND ITS BLENDS WITH ETHANOL (E0, E5, E10, E85), METHANOL (M15, M56, M85), METHANOL/ETHANOL (A20), HVO NAPHTHA OR FT NAPHTHA, AND MTG

The specifications for handling ethanol-gasoline blends are based on those of gasoline as this has higher, or at least equivalent, safety requirements.

Gasoline is a colorless to light yellow liquid with a phenol-like odor. Its high flammability and hazardous effects on human health and the environment must be taken into consideration when handling it properly. Due to its low flash point of under 23 °C (typical values below -20 °C), gasoline is classified as an extremely flammable and highly volatile hazardous substance. The vapors are heavier than air and can spread out near the ground, resulting in a high risk of explosion. Direct contact can cause severe eye and skin irritation as well as genetic defects in humans. Inhalation of gasoline vapors can also cause drowsiness and dizziness. It can be fatal if ingested or if it enters the respiratory tract. Furthermore, it has long-term effects on the environment and is considered toxic, for example, to aquatic organisms. A phase separation forms when gasoline comes into contact with water. In ethanol-gasoline blends, water mixes with ethanol and the gasoline phase floats above the ethanol-water phase. Therefore, ethanol-gasoline blends that have a high ethanol content (e.g., E85) must comply with different requirements for the water separators at filling stations.

The safety requirements for gasoline and ethanol-gasoline blends are very high. For example, storage is prohibited under the WHG within zones I and II of drinking water protection areas. Under TRGS 510, only volumes of up to 10 kg may be stored outside proper in storage facilities. Storage facilities are required to have containment systems and storage tanks above 200 l must have a double-walled design. Packing group II requirements must be observed during transport, and a dangerous goods driver’s license is required to transport quantities of 333 l or more. Transfer and filling operations of gasoline and ethanol-gasoline blends must be conducted outdoors or in well-ventilated rooms, and the equipment and devices used should always be up-dated in accordance with the Operational Safety Ordinance (Betriebssicherheitsverordnung).

The handling of ethanol-gasoline blends at publicly accessible filling stations is straightforward and familiar to consumers. During the refueling process, protective gloves should be worn and sources of ignition should be avoided. Passenger cars are usually refueled in less than ten minutes.

These safety precautions apply equally to gasoline blended with methanol (M15, M56, M85) or with ethanol and methanol (A20), HVO naphtha and FT naphtha, and MTG. However, here there are no specific safety data sheets available for the analysis. The flash point, explosion limits and solubility, as listed in Table 6-2, will vary depending on the mixing ratios between the gasoline and the blending component. M85 is not classified as “dangerous for the environment” according to the Globally Harmonized System (GHS) of Classification and Labelling of Chemicals.

Table 6-2 Safety data for gasoline and its mixtures with ethanol (E0, E5, E10, E85). Note: standard temperature and pressure (STP); data based on [Aral AG (2018b)]

Property	Description
Product definition	Blend according to DIN EN 228 (E0, E5, E10) and DIN EN 15293 (E85)
Physical state (STP)	Liquid
State in vehicle tank	Liquid, unpressurized, ambient temperature
Color	Colorless to light yellow
Odor	E0/E5/E10: phenol-like (aromatic); E85: slightly sweet
Flash point	Under −20 °C
Explosion limits	E0/E5/E10: 0.6 to 8 % v/v in air; E85: 1.4 to 19 % v/v in air
Solubility	Gasoline is very slightly soluble in water, ethanol is very soluble in water
Hazard symbols	 only for E0/E5/E10: 
UN number	E0/E5/10: UN 1203; E85: UN 3475
Transport of dangerous goods class	3 (flammable liquid)
Dangerous goods number	33 (highly flammable liquid (flash point under 23 °C))
Packing group	II (substances presenting medium danger)
Temperature class	T3 (200 to 300 °C)
Explosion group	II A
Storage class	3
Water hazard class	3 (very hazardous to water)

ETHANOL (E100)

Ethanol is a clear, colorless liquid with a slightly sweet odor and burning taste. Ethanol is hygroscopic, highly flammable and volatile. It can cause severe eye irritation on contact. Unlike gasoline, ethanol is an environmentally friendly product.

The safety requirements for handling ethanol are comparable to those for gasoline and ethanol-gasoline blends. This is mainly due to its low flash point of less than 23 °C and the explosion protection requirements associated with this. One difference lies in its hazardousness to water. Ethanol is classified as Water Hazard Class 1 (slightly hazardous to water), which means that it is easier to handle in the context of the Water Resources Act. From a toxicological point of view, fewer requirements also have to be observed. For example, the occupational exposure limits (OEL) for ethanol are higher than those for individual gasoline components such as benzene.

For consumers, handling ethanol at filling stations is simple and comparable to gasoline or ethanol-gasoline blends. During the refueling process, protective gloves should be worn and sources of ignition should be avoided. It usually takes less than ten minutes to refuel a passenger car.

Table 6-3 Safety data for ethanol (E100). Data based on [Carl Roth GmbH (2021)]

Property	Description
Product definition	Pure substance (or mixture of substances if combined with water)
Physical state (STP)	Liquid
State in vehicle tank[12]	Liquid, unpressurized, ambient temperature
Color	Colorless
Odor	Slightly sweet
Flash point	12 °C
Explosion limits	3.1 to 27.7 % v/v in air
Solubility	Very soluble in water and gasoline
Hazard symbols	
UN number	UN 1170
Transport of dangerous goods class	3 (flammable liquid)
Dangerous goods number	33 (highly flammable liquid (flash point under 23 °C))
Packing group	II (substances presenting medium danger)
Temperature class	T1 (max. permitted 450 °C)
Explosion group	II B
Storage class	3
Water hazard class	1 (slightly hazardous to water)

Methanol (M100)

Like ethanol, methanol is a clear, colorless liquid with a sweet odor. It is also a hygroscopic, highly flammable and volatile substance. Methanol is not categorized as "environmentally hazardous". Unlike ethanol, methanol is toxic when it is ingested, inhaled or comes into contact with the skin, all of which can result in death.

The safety requirements are comparable to those for ethanol. In addition, further safety measures are necessary due to the toxic effect of methanol on humans; for example, bitter compounds and odorants are added to methanol. Protective gloves and eye protection must be worn as a minimum requirement for handling methanol.

For consumers, the handling of methanol at filling stations would be straightforward and comparable to that of gasoline or ethanol-gasoline blends. During the refueling process, protective gloves should be worn and sources of ignition should be avoided. A passenger car would typically be refueled in less than ten minutes. Any future use of methanol as a fuel should only take place in combination with educational campaigns to raise awareness of the need for greater caution and to reduce any existing hesitancies.

[12] In Brazil aqueous ethanol is used as an E100 fuel. According to specifications, the water content can amount to 4.9 % v/v.

Table 6-4 Safety data for methanol (M100). Data based on [Carl Roth GmbH (2020)]

Property	Description
Product definition	Pure substance (or mixture of substances if combined with water)
Physical state (STP)	Liquid
State in vehicle tank	Liquid, unpressurized, ambient temperature
Color	Colorless
Odor	Sweet
Flash point	9.7 °C
Explosion limits	5.5 to 44 % v/v in air
Solubility	Almost completely miscible with water
Hazard symbols	
UN number	UN 1230
Transport of dangerous goods class	3 (flammable liquid)
Dangerous goods number	336 (highly flammable, liquid and toxic substance)
Packing group	II (substances presenting medium danger)
Temperature class	T1 (max. permitted 450 °C)
Explosion group	II A
Storage class	3
Water hazard class	2 (hazardous to water)

DIESEL AND ITS BLENDS WITH FAME, HVO AND FT DIESEL (B0, B7, B10, B20, B30, R33)

The specifications for handling FAME diesel or FAME-HVO/FT blends are modeled after diesel or HVO/FT fuel, as these have higher or at least equivalent safety requirements.

Diesel is a yellow liquid with a characteristic odor. Its fire load and hazardous effects on health and the environment must be taken into consideration when handling it properly. Diesel is flammable above its flash point (typically between 56 and 61 °C). Prolonged or repeated skin contact may cause irritation. Contact with diesel vapors or mists may irritate mucous membranes - especially the eyes. Inhalation or ingestion can result in brief nausea, headache, drowsiness, and even vomiting or death. Individual components are known to cause depression and possibly cancer. The environmental toxicology of diesel and HVO/FT diesel is that an oil film can form on the surface of water which prevents oxygen exchange. FAME components also form a film on the surface of water, but this dissolves in the water and is rapidly biodegraded.

The safety requirements for diesel and its blends with FAME and HVO/FT diesel are lower than for gasoline, ethanol, methanol and methane, in particular due to its significantly higher flash point. Up to 100 kg of diesel and its blends can be stored in suitable containers; for larger quantities, special storage facilities with containment systems must be used. The WHG does not permit it to be stored within zones I and II of drinking water protection areas. During transport, the requirements of packing group III must be complied with, and a dangerous goods license is also required to transport quantities of 1,000 l or more.

Transfer and filling operations must be conducted outdoors or in well-ventilated rooms, and the work equipment used should always be kept up to date in accordance with the Operational Safety Ordinance (Betriebssicherheitsverordnung).

Handling FAME/HVO/FT diesel blends at publicly accessible filling stations is straightforward and familiar to consumers. Protective gloves should be worn during the refueling process and it usually takes less than ten minutes to refuel a passenger car. Filters can clog when summer diesel, and in particular its blends with FAME, is used at low outdoor temperatures in winter.

Table 6-5 Safety data for diesel and its blends with FAME, HVO and FT diesel (B0, B7, B10, B20, B30 und R33). Data based on [Aral AG (2018a); TotalEnergies (2020)]

Property	Description
Product definition	Mixture of substances according to DIN EN 590 (B0, B7, R33), DIN EN 16734 (B10) and DIN EN 16709 (B20, B30)
Physical state (STP)	Liquid
State in vehicle tank	Liquid, unpressurized, ambient temperature
Color	Yellow
Odor	Characteristic
Flash point	Over 56 °C
Explosion limits	B0: 0.6 to 6.5 % v/v in air
Solubility	Diesel, HVO and FT diesel nearly insoluble in water, FAME soluble in water (ca. 1,500 mg of water per kg of FAME)
Hazard symbols	
UN number	UN 1202
Transport of dangerous goods class	3 (flammable liquid)
Dangerous goods number	30 (flammable liquid (flash point from 23 °C to 61 °C))
Packing group	III (substances presenting slight danger)
Temperature class	T3 (200 to 300 °C)
Explosion group	II A
Storage class	3
Water hazard class	2 (hazardous to water)

PARAFFINIC DIESEL FUELS (HVO, FT DIESEL)

Paraffinic diesel fuels are colorless and odorless liquids at ambient temperatures and can be handled like diesel fuel. Unlike diesel fuel based on mineral oil, paraffinic diesel fuels have a flash point above 61 °C and do not fall under the hazard categories “flammable” (GHS02), “irritant” (GHS07) and “dangerous for the environment” (GHS09).

Despite their lower hazard potential, safety precautions like those for fossil diesel should also be taken when handling paraffinic diesel fuels.

Consumers are currently unable to obtain HVO and FT blends at publicly accessible filling stations as they are not included in the 10th Ordinance for the Implementation of the Federal Immission Control Act (10th BImSchV). If approved, paraffinic diesel fuels should be handled like conventional diesel fuel when refueling. Passenger cars can usually be refueled in under ten minutes.

Table 6-6 Safety data for paraffinic fuels (HVO and FT diesel). Data based on [Neste Oyj (2019)]

Property	Description
Product definition	Mixture of substances according to DIN EN 15940
Physical state (STP)	Liquid
State in vehicle tank	Liquid, unpressurized, ambient temperature
Color	Colorless
Odor	Odorless
Flash point	Over 61 °C
Explosion limits	0.5 to 5.0 % v/v in air
Solubility	Nearly insoluble in water
Hazard symbols	
UN number	UN 1202
Transport of dangerous goods class	3 (flammable liquid)
Dangerous goods number	N/A
Packing group	III (substances presenting slight danger)
Temperature class	T3 (200 to 300 °C)
Explosion group	II A
Storage class	3
Water hazard class	1 (slightly hazardous to water)

Fatty acid methyl esters (FAME, "biodiesel", B100)

FAME is a flammable, yellowish liquid with a faint odor. FAME does not fall under the CLP; therefore, there is no classification according to the GHS categories.

Because it is classified as Water Hazard Class 1, safety measures like those for facilities for handling substances hazardous to water (AwSV) must be observed (containment systems for storage) and permits must be obtained. Despite its lower hazard potential, similar safety precautions to those for handling conventional diesel fuel should be taken.

FAME was available as a pure fuel at many filling stations up until 2010 with safety precautions comparable to those for diesel fuel. Passenger cars can usually be refueled in under ten minutes.

Table 6-7 Safety data for FAME (B100). Data based on [Calpam Mineralöl-Gesellschaft mbH (2018); Mabanaft (2021)]

Property	Description
Product definition	Mixture of substances according to DIN EN 14214
Physical state (STP)	Liquid
State in vehicle tank	Liquid, unpressurized, ambient temperature
Color	Light yellow to brownish
Odor	Faint
Flash point	Over 101 °C
Explosion limits	Unknown
Solubility	Slightly soluble in water
Hazard symbols	N/A
UN number	N/A
Transport of dangerous goods class	N/A
Dangerous goods number	N/A
Packing group	N/A
Temperature class	T3 (200 to 300 °C)
Explosion group	N/A
Storage class	10
Water hazard class	1 (slightly hazardous to water)

Vegetable oil fuel

Pure vegetable oils are liquid at room temperature. As temperatures decrease, viscosity increases depending on the fatty acid composition. As a foodstuff, vegetable oils are very safe and easy to handle. They pose no danger in terms of explosiveness or toxicological risk to humans or the environment. Vegetable oils are the only type of liquid fuel that can be used in water conservations areas without any special requirements other than the duty of care that always applies. Until 2010, vegetable oils were used as fuel, for example, in the agricultural sector or as fuel for combined heat and power plants. The refueling process for vegetable oil fuel is comparable to that of conventional diesel fuel. Tractors can usually be refueled in less than ten minutes.

Table 6-8 Safety data for vegetable oil. Data based on [Bunge Deutschland GmbH (2018); Carl Roth GmbH]

Property	Description
Product definition	Mixture of substances according to DIN 51605 or DIN 51623
Physical state (STP)	Liquid to solid (depending on feedstock)
State in vehicle tank	Liquid, unpressurized, ambient temperature
Color	Yellow
Odor	Odorless
Flash point	Over 101 °C
Explosion limits	Unknown
Solubility	Insoluble in water
Hazard symbols	N/A
UN number	N/A
Transport of dangerous goods class	N/A
Dangerous goods number	N/A
Packing group	N/A
Temperature class	N/A
Explosion group	N/A
Storage class	10
Water hazard class	Generally hazardous to water

Methane (CNG, LNG)

Methane is a colorless, odorless and flammable gas. When combined with air, it forms an extremely explosive mixture. To prevent unnoticed leakage, an odorant is added to CNG. Methane, in the form of gaseous CNG, is compressed to 250 bars (200 bars in the vehicle itself). No odorant is added to liquid LNG due to cryogenic liquefaction. The temperature of LNG is around -162 °C. Above the liquid phase, a gas phase forms in LNG tanks with maximum pressures of 15 to 18 bars (above this pressure range, safety measures such as reliquefaction or pressure regulation must be introduced).

Due to its explosive properties when mixed with air, as well as its high global warming potential, special safety precautions must be taken when handling methane. For example, according to Technical Instructions on Air Quality Control (TA Luft), methane emissions are, in many respects, directly or indirectly regulated as total hydrocarbons, so that state-of-the-art aftertreatment processes (e.g., exhaust gas aftertreatment, thermal afterburning or reliquefaction) must be carried out. The most important explosion protection measure during transport and storage is to avoid contact with air or oxygen.

Consumers are partly familiar with handling CNG due to the infrastructure already in place. Refueling takes place at special pumps with special high-pressure nozzles. The pumps are mostly located away from liquid fuel pumps. Refueling at publicly accessible filling stations usually takes a maximum of ten minutes. So-called “slow fill” stations can also be used in both the private and commercial sectors. Here, refueling takes place directly from the natural gas grid and usually takes several hours (typically overnight). In contrast, LNG is exclusively used in the commercial sector (heavy-duty transport and shipping). Here, users must be appropriately trained and instructed in the use of the refueling equipment. It usually takes around 15 minutes to refuel a truck. Insulated gloves and a face shield/eye protection must be worn during this process.

Table 6-9 Safety data for methane (CNG, LNG). Data based on [Küppers Engineering (2021); Linde Gas GmbH (2021); Shell (2016)]

Property	**Description**
Product definition	Mixture of substances according to DIN EN 16723-2
Physical state (STP)	Gaseous
State in vehicle tank	CNG: gaseous, pressurized (up to 250 bars), ambient temperature LNG: liquid, pressurized (up to 15 bars), cryogenic
Color	Colorless
Odor	CNG: odorized; LNG: odorless
Flash point	−187 °C
Explosion limits	4.4 to 17 % v/v in air
Solubility	Slightly soluble in water
Hazard symbols	
UN number	1972
Transport of dangerous goods class	2
Dangerous goods number	CNG: 23; LNG: 223
Packing group	N/A
Temperature class	T1 (over 450 °C)
Explosion group	I
Storage class	2A
Water hazard class	Not hazardous to water

Hydrogen (H_2)

Hydrogen is a colorless and odorless flammable gas. It is also extremely flammable when combined with air. When used as a fuel, it is usually a pressurized gas (350 bars or 700 bars) that can explode when heated. Hydrogen can also be supplied as a fuel in liquid form by cooling it to a temperature as low as – 253 °C, so that it can be transported in vehicles. In this case, however, evaporation losses usually occur when the hydrogen is reheated in the insulated tank.

The high explosiveness of hydrogen and its pressurized storage are two of its most important safety aspects. The explosiveness of hydrogen when combined with air can be controlled by avoiding sources of ignition and specifying that hydrogen must not be stored or transported in combination with air/oxygen. In addition, pressurized hydrogen may only be handled in specially approved containers. The equipment used to handle hydrogen must comply with Explosion Group II C.

Consumers are still unfamiliar with handling hydrogen as a fuel at filling stations, but it tends to be comparable with the use of CNG. Refueling a passenger car usually takes less than ten minutes. No special precautions need to be taken.

Table 6-10 Safety data for hydrogen. Data based on [Linde Gas GmbH (2018)]

Property	Description
Product definition	Mixture of substances according to DIN EN 17124
Physical state (STP)	Gaseous
State in vehicle tank	Gaseous, pressurized (350 bars or 700 bars), ambient temperature
Color	Colorless
Odor	Odorless
Flash point	−253 °C
Explosion limits	4 to 77 % v/v in air
Solubility	Slightly soluble in water
Hazard symbols	
UN number	1049
Transport of dangerous goods class	2
Dangerous goods number	23
Packing group	N/A
Temperature class	T1 (over 450 °C)
Explosion group	II C
Storage class	2A
Water hazard class	Not hazardous to water

Renewable kerosene (FT-SPK, HEFA-SPK and ATJ-SPK)

The types of synthetic paraffinic kerosene described here (also called renewable kerosene or SPK) are liquid and colorless at ambient temperature and have the characteristic smell of kerosene.

To ensure product integrity, synthetic paraffinic kerosene should be treated in the same manner as the final product (Jet A/A-1 according to ASTM D1655 or DEF STAN 91-091) after production and until it is blended with Jet A/A-1, as specified in Section 6.5 of ASTM D7566. However, the safety requirements of the SPK depend on its chemical and physical properties and may partly deviate from those of Jet A/A-1. According to ASTM D7566, adaptations within the framework of change management for the production site, distribution and storage are allowed.

SPK can only be handled by personnel who have been appropriately trained and instructed and is comparable to conventional JET A/A-1.

Table 6-11 Safety data for renewable kerosene (FT-SPK, HEFA-SPK, ATJ-SPK). Data based on [Bullerdiek (2019b); Müller-Langer (2020); Neste Oyj (2020)]

Property	Description
Product definition	Mixture of substances according to ASTM D7566, Annexes 1, 2 or 5
Physical state (STP)	Liquid
State in vehicle tank	Liquid, unpressurized, ambient temperature
Color	Colorless
Odor	Kerosene-like
Flash point	Over 38 °C (depending on the type)
Explosion limits	0.6 to 6 % v/v in air (depending on the type)
Solubility	Slightly soluble in water
Hazard symbols	 , only ATJ-SPK/HEFA-SPK:  
UN number	Same as JET A/A-1: 1863 (jet fuel) As a chemical: 3295 (hydrocarbons, liquid)
Transport of dangerous goods class	3
Dangerous goods number	30
Packing group	III (substances presenting slight danger)
Temperature class	T3 (over 450 °C)
Explosion group	II C
Storage class	2A
Water hazard class	2 (hazardous to water)

ELECTRICITY FROM RENEWABLE SOURCES

The handling of electricity cannot be assessed and classified in the same way as the fuels mentioned above. From a physical point of view, electricity is not an energy carrier but a form of energy. Only when the storage medium (e.g., a traction battery) is combined with the electricity does it become an energy carrier. Accordingly, electricity is not addressed in some of the safety-related laws such as the WHG, nor can it be classified according to REACH or CLP.

The fundamental safety precautions for handling electricity – and also for generating it – are well known. For this reason, only the challenges related to the vehicle are discussed below. Battery electric vehicles use both direct current (within the traction battery) and alternating current (on-board grid, drive). Depending on the vehicle type, the voltage level is in the low-voltage range[13] of 400 to 850 V with amperages of over 500 A in some cases. Electric vehicles use alternating current (at normal charging points) or direct current (at fast charging points) to charge. In contrast, the voltage level of the "starter battery" in vehicles with combustion engines is in the low-voltage range of between 6 and 48 V; the battery itself is charged by the combustion engine. These different power ranges bring about new workplace environments, particularly in automotive workshops and for fire and rescue service personnel in the event of an emergency. Thus, trained personnel are required. Electric vehicles must be marked at suitable points with the warning symbol shown in Figure 6-3. [ZVEI (2013)]

Figure 6-3 Warning symbol to mark the high-voltage of electric vehicles

From the end user's point of view, the recharging of traction batteries with electric current, as it is done in battery-powered vehicles, is basically familiar from the daily environment.. Specifically, other types of electrical plugs are used, so that barriers in dealing with electric vehicles may have to be removed. The safety technology integrated in vehicles prevents the vehicle from being (unintentionally) operated incorrectly. Cars can be recharged at fast charging points within approx. 30 minutes and at normal charging points within approx. 8 hours.

6.4 Requirements for fueling infrastructure and fuel distribution

The existing fueling infrastructure described in Section 2.2 can continue to be used for many of the fuels described here, although some technical adjustments will have to be made. For other fuels, new distribution and fueling infrastructures will have to be built; in some cases, this has already begun. The equipment and facilities along the entire distribution chain that come into contact with the fuels require, at minimum, approval for the respective fuel.

[13] In the automotive sector, voltages over 60 V are referred to as "high-voltage", which corresponds to voltage class B (low voltage).

The fuel options described in Section 6.3 will be evaluated below in the context of the filling station and distribution infrastructure. An initial overview is presented in Table 6-12. Options that are compatible with the established infrastructure will not be discussed further.

Table 6-12 Compatibility with existing fueling infrastructure. Note: no claim to completeness; data based on [Grope (2018)]

Fuel	Remarks
Biodiesel (FAME)	Technical adjustments needed for existing fueling infrastructure; global and local distribution infrastructure in place and compatible
Renewable kerosene	Compatible with existing fueling and distribution infrastructure
Ethanol	Technical adjustments needed for existing fueling infrastructure; global and local distribution infrastructure in place and compatible
HEFA/FT diesel	Compatible with existing fueling and distribution infrastructure
HEFA/FT naphtha	Compatible with existing fueling and distribution infrastructure
Methane (CNG)	Compatible with existing global and local distribution infrastructure; expansion of refueling and distribution infrastructure required
Methane (LNG)	Refueling and distribution infrastructure under development, not compatible with existing CNG infrastructure
Methanol	Technical adjustments needed for existing fueling infrastructure; global distribution infrastructure available and compatible; development of local distribution infrastructure necessary
Methanol-to-gasoline	Compatible with existing refueling and distribution infrastructure
Vegetable oil	Compatible with existing refueling and distribution infrastructure; expansion of local distribution infrastructure necessary
Electricity	Charging infrastructure under development, not compatible with existing infrastructure
Hydrogen	Refueling and distribution infrastructure under development, not compatible with existing infrastructure

ETHANOL: Existing gasoline distribution infrastructure in road transport is designed for gasoline with a maximum ethanol content of 10 % v/v. If the blended ethanol content increases in the future (e.g., E20 with 20 % v/v ethanol content) or if E85 is again established as a fuel alternative, further regulations will be needed, especially at filling stations. For example, filling stations have underground containment basins to catch spilled fuel as a preventive measure to protect water. When it rains, fuel blends and rainwater mix here. To ensure that the rainwater is fed into the sewage system, a light liquid separator is used to separate the fuel and collect it. When gasoline fuels have a high ethanol content, the separation efficiency of the installed light liquid separators may be limited under certain circumstances due to the solubility of ethanol with water and gasoline [Baumeister (2006)]. Furthermore, all equipment that comes into contact with the fuel must be approved for use with the ethanol-gasoline blend, which has not been the case for all of the existing equipment [Baumeister (2006)]. The filling station equipment must therefore be converted in accordance with the existing regulatory framework. The fuel is usually transported to the filling station by tanker (truck or rail) or ship. This infrastructure is already established for ethanol and there should be no compatibility issues in this regard. Comparable requirements must be met for the use of aqueous ethanol as a pure fuel, like that which is used in Brazil, or for ethanol in diesel fuel (ED95). [UPEI (2021)]

In the future, **METHANOL** will be used as a fuel for both road and maritime transport, for internal combustion engines as well as for fuel cells. The distribution structure depends on the target segment. Currently, ships and tanker trucks are used throughout the world to transport conventional IMPCA-grade methanol from the few methanol plants to storage tanks at ports or industrial parks. This globally established distribution infrastructure can, in principle, be used to introduce methanol as a fuel. A distribution infrastructure from tank farms to refineries and filling stations still needs to be established. The effort required to convert existing road transport filling stations so that they can be used with methanol is comparable to the effort required to convert them for ethanol use. The affected equipment must be approved for the respective blend. Based on current experience, methanol-compatible seals must be installed in existing systems. Alternatively, special flex-fuel tank systems can be retrofitted at filling stations. The bunkering of methanol for maritime transport can be done using the existing tank facilities at ports. Before they can be approved, they may have to receive a new coating, which can be applied at regular maintenance intervals. An additional aspect that needs to be taken into consideration is the methanol quality. Fuel cell applications will require a higher quality of methanol than that which is used in maritime applications. Accordingly, parallel infrastructures must be established for different methanol qualities [Schröder (2020b)].

BIODIESEL (FAME) has an established distribution infrastructure. Refueling facilities generally do not have to be modified to use FAME as a pure fuel; however, biodiesel-compatible seals may have to be installed. In addition, maintenance intervals must be shortened to limit sludge formation at the bottom of tanks [UPEI (2021)].

VEGETABLE OIL is highly compatible with the existing fueling infrastructure due to its preferential use in the agricultural and forestry sectors as well as in inland shipping. However, no distribution infrastructures currently exist. As a rule, fuel will not be supplied through public filling stations, but through on-farm filling stations. It should be noted that at very low temperatures, cold-flow additives must be added to the vegetable oil, or it must be warmed up before use to keep the fuel in a liquid state.

METHANE AS CNG can rely on an established fueling and distribution infrastructure with over 800 CNG stations. It is connected to the natural gas grid in Germany and is fully compatible with fossil natural gas. However, CNG must be made much more widely available at filling stations in order to compete with other fuel options and electricity. In particular, filling stations along highways usually do not offer CNG because they are not connected to the natural gas grid. In contrast **METHANE AS LNG** is not dependent on the natural gas grid. Fossil LNG is currently distributed from LNG port terminals to the more than 60 LNG stations already installed in Germany and the more than 400 in Europe which are used in heavy-duty transport and inland shipping (bunker ships are also used here in some instances). Further expansion of the fueling infrastructure is absolutely essential for widespread use in heavy, interregional freight transport. The liquefaction of biomethane or electricity-based methane must also be established. There are various projects that use a centralized (e.g., Rheinland Raffinerie) or decentralized approach (e.g., EnviTec Biogas AG) which will be carried out in the next few years. The technical complexity of distributing LNG is very high, as the release of methane emissions (e.g., boil-off gas through venting at the LNG tank or during the refueling process itself) must be avoided at many points along the distribution chain.

The infrastructure that would enable **HYDROGEN** to be used as a fuel is not yet been fully established in either Germany or Europe, even though individual hydrogen filling stations have already been installed, especially for use in passenger vehicles. As with methane as LNG, this must be expanded, especially for heavy commercial vehicles and buses and coaches in order to create alternatives to conventional drive concepts. The local and global distribution of renewable hydrogen will pose a challenge in the future. Currently, hydrogen is primarily produced in refineries from natural gas and used for industrial purposes.

It is distributed over short distances, for example through pipelines within chemical parks. In contrast, renewable electricity-based hydrogen cannot be produced as a fuel in sufficient quantities in Germany or in Europe. Production will have to take place primarily in wind- or sun-rich regions such as South America or North Africa, and transport distances will automatically increase. Transporting hydrogen over long distances is complex. Hydrogen is the smallest molecule and can therefore diffuse through seals or become embedded in metals (hydrogen embrittlement). Furthermore, due to its low density, even cryogenic liquefied hydrogen requires very large tank volumes to transport. For example, there are currently no suitable ships for transporting cryogenic liquefied hydrogen by sea and no suitable hydrogen bunkers available at ports. As an alternative to the direct transport of hydrogen, various storage media are currently being investigated, such as ammonia, methanol or liquid organic hydrogen carriers (LOHC), which are easier to transport. With such concepts, however, there will be energy loss during conversion.

Renewable kerosene currently includes all types of synthetic paraffinic kerosenes certified as drop-in fuels according to ASTM D7566. Their properties require that they first be blended with fossil JET A/A-1 according to ASTM D1655 or DEF STAN 91 -091. Blending must be performed in accordance with EI/JIG 1530 prior to entry into the airport supply infrastructure; blending at the airport fuel depot is not permitted [EI/JIG 1530]. ASTM D7566 stipulates that once the blends have been certified in accordance with Table 1 of ASTM D7566, they are considered to be JET A/A-1 (in accordance with ASTM D1655 or DEF STAN 91-091) and will be treated as such. The existing infrastructure for distributing fossil kerosene can and should be used without limitation from this point onwards. Because the volumes of SPK currently in use remain small and because there is limited experience in handling it, the individual components are mainly supplied by dedicated tanker trucks, tank containers or tank cars. To ensure product integrity, these individual components are to be handled in the same way as the final product Jet A/A-1 up until the blending process. Deviations in handling, for example due to safety aspects, are possible and sometimes necessary within the context of change management for the production site, distribution and storage [ASTM D7566-20C (2020)].

6.5 Motor-related use of renewable energy carriers

Renewable fuels can be produced and marketed in one of two ways: as a blended fuel made from renewable and fossil components, or as a pure renewable fuel. Even though renewable fuels are already being used in the various transport sectors, the use of blended fuels has prevailed in recent years for pragmatic reasons, despite their disadvantages. However, this use of blended fuels made from renewable and fossil energy carriers will not be enough for a complete defossilization by 2045 in Germany or 2050 in Europe.

6.5.1 Renewable energy carriers as blended fuels

The advantage of blended fuels made from renewable and fossil components is that they can be easily marketed nationwide using the existing distribution and filling station infrastructure (Section 6.4), provided they meet the fuel standard for which the respective vehicle has been approved (e.g., B7 as per DIN EN 590 and E5 or E10 as per DIN EN 228). This means that proportions of renewable energy can be integrated relatively quickly into the transport sector (Table 6-13). Because the fuel must be compatible with the vehicle's engine system, the proportion of the renewable component is often low. Particularly in view of end-of-life vehicles, increasing the blend ratio (e.g., of biodiesel to diesel to more than 7 % v/v and ethanol to gasoline to more than 10 % v/v) is not entirely straightforward. If the aim is to increase the proportion of the renewable component (e.g., E20, B20 or B30), vehicles must have appropriate manufacturer approvals that ensure that these fuels are compatible with the fuel-carrying components and take into account how the fuel influences motor oil and exhaust gas aftertreatment. In addition, trouble-free combustion and emission behavior must be guaranteed under all operating conditions (see type approval in Section 1.4).

Blended fuels generally do not have the environmentally friendly properties of most renewable components, such as high biodegradability (Section 6.3). In addition, the advantageous properties of renewable fuels with respect to efficient and low-emission engine operation (e.g., oxygen content, simple molecular structure) can either not be utilized at all or only to a limited degree. At the same time, the addition of renewable fuels can lead to an improvement or deterioration in the quality of fossil fuels. Improved quality includes, for example, increased lubricity by adding FAME to desulfurized diesel, higher ignitability by adding HVO diesel to diesel fuel, or improved anti-knock properties by adding ethanol or methanol to gasoline. In contrast, material incompatibilities with the fuel-carrying components, lower energy densities, and the resulting increase in volumetric fuel consumption often lead to uncertainty.

For the best possible combustion and emission behavior, fuels, combustion engines and exhaust gas aftertreatment systems must be compatible with each other. If varying proportions of different fuels or the admixture of renewable components are used beyond the vehicle manufacturer's approvals, adjustments usually have to be made to the vehicle's hardware and software. Typical examples include the retrofitting of sensors to detect the fuel composition, injection and tank systems for blending a second fuel option, and adaptations to the engine control system. The technical effort required varies depending on the fuel option and internal combustion engine used.

As a rule, renewable energy carriers that are largely or completely identical in chemical structure to the fossil energy source, and have correspondingly comparable properties, are shown to be technically uncritical with regard to their use in existing vehicles. These are, for example, paraffinic fuels that are blended into diesel fuel, renewable methane and renewable hydrogen that are blended into natural gas, renewable hydrogen that is combined with fossil-generated hydrogen, and electricity from renewable sources that is added to fossil-generated electricity.

Table 6-13 Maximum blending rates of alternative fuels in established fuels

Energy carrier	Maximum blending rate	Standard	Criterion
Ethanol	10 % v/v	DIN EN 228	Ethanol content limited by standard
FT naphtha	ca. 80 % v/v	DIN EN 228	Octane number, distillation behavior
HVO naphtha	ca. 80 % v/v	DIN EN 228	Octane number, distillation behavior
Methanol	3 % v/v	DIN EN 228	Methanol content limited by standard
MTG	ca. 80 % v/v	DIN EN 228	Octane number, distillation behavior
DME	cannot be blended	DIN EN 590	"Fit for purpose" criterion
FAME	10 % v/v	DIN EN 590	FAME content limited by standard
FT-Diesel	ca. 26 % v/v	DIN EN 590	Density
HVO-Diesel	ca. 26 % v/v	DIN EN 590	Density
OME	cannot be blended	DIN EN 590	"Fit for purpose" criterion
Hydrogen	2 % v/v	DIN 16723-2	Hydrogen content limited by standard
ATJ-SPK	50 % v/v	ASTM D 7566	ATJ-SPK content limited by standard
FT-SPK	50 % v/v	ASTM D 7566	FT-SPK content limited by standard

Energy carrier	Maximum blending rate	Standard	Criterion
HEFA-SPK	50 % v/v	ASTM D 7566	HEFA-SPK content limited by standard

6.5.2 Renewable energy carriers as pure fuels

In the future, all energy carriers used in the various transport sectors must be of renewable origin in order to meet climate policy targets. This implies that the renewable energy carrier be a pure fuel or a blended fuel made from different renewable options. Today, pure renewable fuels are used in various applications, enabling optimized use while leveraging advantages and avoiding adverse effects. The fact that increasingly stringent emission requirements can also be met by the pure fuels FAME, HVO diesel and rape seed oil fuel as well as E85 (E85 is generally listed as a pure fuel, although at least 15 % v/v fossil gasoline fuel is still permitted) is demonstrated by manufacturer approvals for various vehicles (FAME: https://www.agqm-biodiesel.de/f-und-e/freigaben, HVO/FT diesel: https://toolfuel.eu/freigaben-fuer-care-diesel/, E85: Ford Kuga Flexfuel [Quartier (2019)]), by practical examples (see excursus "Bio-CNG in urban public transport – a practical example from Augsburg") and by various studies [Demuynck (2021); Ettl (2016); Harndorf (2019); Huber (2015); Schröder (2019)].

Key technical differentiators between the respective fuel options are:

- Energy content per unit volume and/or mass (tank volume needs),
- Local emissions (pollutants and CO_2 emissions),
- Hazardous substance classification (according to international GHS system),
- Compatibility with established fuel options,
- Material compatibility with polymers and metals (no harm) and
- Cold properties.

In some sectors, there is severely limited space for storing the energy carrier, for example in aviation, for vehicles that transport bulky goods, or in high-performance machines that are used off-road on a continuous basis. Here, the **ENERGY CONTENT PER UNIT VOLUME** is an important characteristic. In general, liquid fuels contain more energy per unit volume than gaseous fuels. The gaseous energy carriers methane, hydrogen, dimethyl ether and ammonia only become practical alternatives through compression or liquefaction, but at the cost of increased technical and energy outlay for fuel preparation and for the refueling system. Fuels with a high volumetric energy density include the various aviation fuels ATJ, HEFA and FT SPK as well as HVO gasoline and diesel, FT gasoline and diesel, biodiesel and vegetable oils. In comparison, other liquid fuels such as ethanol, methanol, and oxymethylene ether have a significantly lower energy density due to their high oxygen content. Battery-electric vehicles require even more space and available mass to store the energy carrier and/or electricity due to the heavy accumulators that take up space. Table 6-14 shows the energy densities of individual renewable energy carriers and/or their typical blends, as well as the amount of fuel needed to cover the same driving distance as one liter of diesel. This illustrates the strong disparity described above between oxygen-free liquid fuels and oxygenated gaseous fuels and electricity. Energy carriers that have a 1.0 range equivalency tend to be more suitable for transport routes with long driving distances and/or for high transport loads than energy carriers with a range equivalency greater than 1. (Note: the data for electricity are related to the volume and mass of a typical battery [Wissenschaftliche Dienste Deutscher Bundestag (2020)].)

Table 6-14 Typical energy densities of various energy carriers and their blends. Note: range equivalency as a ratio of the volumetric energy density and drive efficiency of an energy carrier and its drive to the volumetric energy density of diesel and the efficiency of a diesel engine; assumptions: drive efficiency of 0.24 for diesel engines (ICE-CI), 0.22 for gasoline engines (ICE-SI), 0.36 for FCEV and 0.65 for BEV; data based on [Bauer (2021); Bullerdiek (2019a); Wissenschaftliche Dienste Deutscher Bundestag (2020)]

Fuel	Drive	Density at 15 °C	Gravimetric energy density	Volumetric energy density	Range equivalency
		kg/m	MJ/kg	MJ/l	–
Diesel	ICE-CI	830	43	36	1.0
FAME	ICE-CI	890	37	33	1.1
B30	ICE-CI	848	41	35	1.0
B7	ICE-CI	835	42	35	1.0
HVO/FT diesel	ICE-CI	780	44	34	1.0
Vegetable oil (rape seed)	ICE-CI	925	38	35	1.0
OME	ICE-CI	1050	19	20	1.8
DME	ICE-CI	671	28	19	1.8
Gasoline	ICE-SI	740	43	32	1.3
Ethanol		793	27	21	
E85	ICE-SI	785	29	23	1.7
E10	ICE-SI	745	40	30	1.3
Methanol		796	20	16	
M85	ICE-SI	788	23	18	2.2
M10	ICE-SI	746	40	30	1.3
HVO/FT/MTG naphtha	ICE-SI	730	44	32	1.2
Natural gas					
CNG	ICE-SI	148	45	7	5.0
LNG	ICE-CI	430	49	21	1.7
Methane					
CNG	ICE-SI	162	50	8	5.0
LNG	ICE-CI	450	50	23	1.5
Kerosene	Jet	810	43	34	1.0
ATJ-SPK	Jet	760	44	33	1.0
HEFA/FT-SPK	Jet	750	44	33	1.0
MTJ	Jet	750	44	33	1.0
H_2					
350 bars	FC	24	120	3	7.9
700 bars	FC	40	120	5	4.7
LH2 (liquefied hydrogen)	FC	71	120	9	2.6
Electricity[14]	BEV	–	< 1	1	13.4

[14] The energy densities of electricity are related to the mass or volume of a traction battery (Wissenschaftliche Dienste Deutscher Bundestag (2020)).

Harmful local emissions are now a crucial criterion in evaluating the internal combustion engine, exhaust gas aftertreatment, and fuel system. The requirements are high, both for on-road and off-road applications. Of particular importance here are the pollutants regulated by legislation (such as nitrogen oxides), particle number, particle mass, unburned hydrocarbons, and carbon monoxide. Other notable pollutants are methane, ammonia and nitrous oxide. Vehicles and mobile machinery and equipment powered by the two carbon-free energy carriers hydrogen (in fuel cells) and electricity do not cause any harmful local emissions. They should therefore be preferentially used in areas where human exposure to exhaust gases cannot be ruled out, provided that no other restrictions prevent their use. Fuels for spark-ignition internal combustion engines or fuels with a high oxygen content, including, above all, newly developed synthetic fuels (oxymethylene ether and dimethyl ether), burn very cleanly in combination with a relatively simple exhaust gas aftertreatment system (e.g., three-way catalytic converter). In contrast, most compression ignition diesel substitutes require complex exhaust gas aftertreatment systems (combination of oxidation catalyst, particulate filter and SCR catalyst) in order to comply with current emission limits. This aspect is described in more detail in Section 7.7.

Fuels that do not pose a direct threat to the environment are particularly suitable for use in environmentally sensitive areas such as nature reserves or on permeable surfaces. These include, for example, vegetable oils and, at times, biodiesel. These have a high biodegradability and low ecotoxicity. Other fuels, such as CNG, LNG and hydrogen, do not pose a risk to soil and water, but they do pose an occupational safety risk that necessitates certain safety requirements for the tank system, vehicle and fueling infrastructure. Fuels are labeled in accordance with the **classification of hazardous substances** GHS. These include: explosivity, ignitibility, gases under pressure, corrosion to skin, severe eye damage, acute toxicity, risk of chronic damage to health, and water hazard. This aspect is outlined in more detail in Section 6.3 for the fuels discussed here.

Ideally, renewable fuels are, from a technical point of view, fully **compatible with established fuel options** such as B7, E10 and CNG. This means that the existing vehicles in use can continue to be used and costly applications can be avoided. These fuel options include renewable methane in CNG and LNG, and renewable hydrogen and electricity blended with their fossil counterparts. In addition, paraffinic fuels from the HVO/HEFA and Fischer-Tropsch processes and MTG are also technically compatible, but, as a pure fuel, do not meet the fuel standards for the established options. This is usually accompanied by a lack of a regulatory framework (10th BImSchV). For all other options, the conditions described in Section 6.5.1 must be met. For compatibility with the vehicles themselves, additional aspects regarding **material compatibility (no harm)** with the polymers and metals contained in the vehicle must be taken into account. Various fuels can influence the properties of the materials that carry the fuel, so that these have to be substituted. Table 6-15 shows the compatibility of selected alternative pure fuels with conventional internal combustion engines (diesel, gasoline and gas-powered engines and power units).

Table 6-15 Compatibility of selected pure fuels with conventional internal combustion engines. Data based on [Grope (2018)]

Fuel	Engine	Compatibility
FAME (B100)	ICE-CI	Adjustments necessary for materials that carry the fuel and for engine applications [Schröder (2019); UPEI (2021)]
HVO/FT diesel	ICE-CI	Software adjustments may be necessary to meet exhaust gas aftertreatment requirements; incompatibilities may exist due to lack of aromatics in fuel [UPEI (2021)]
Vegetable oil	ICE-CI	Adjustments necessary for materials that carry the fuel and for engine applications
OME	ICE-CI	Material incompatibility with existing polymers and copper; adjustments to internal combustion engine necessary (injection system); simplified exhaust gas aftertreatment system [Schröder (2020a)]
DME	ICE-CI	Adjustments to internal combustion engine necessary (injection system); pressurized tank necessary; possible corrosive effect on existing materials
Ethanol (E85)	ICE-SI	Adjustments necessary for materials that carry the fuel and for engine applications [Schröder (2020b); UPEI (2021)]
Methanol (M85)	ICE-SI	See ethanol
HVO naphtha	ICE-SI	Possible corrosive effect on existing materials
FT naphtha	ICE-SI	See HVO naphtha
MTG	ICE-SI	See HVO naphtha
Methane	ICE-SI	No adjustments necessary for CNG/LNG engines; adjustments necessary for gasoline engines (modification of injection system, pressurized tank) and possible material incompatibility if combustion temperatures are too high
Hydrogen	ICE-SI	Adjustments necessary for conventional internal combustion engines (modification of injection system, pressurized tank) and possible material incompatibility at excessively high combustion temperatures
HEFA-SPK	Jet	Possible incompatibilities due to the absence of aromatics in the fuel
ATJ-SPK	Jet	See HEFA-SPK
FT-SPK	Jet	See HEFA-SPK

Fuels can also be classified according to their **SUITABILITY FOR USE AT COLD TEMPERATURES.** For example, fuels for internal combustion engines with both a spark ignition and compression ignition are divided into summer, winter and transition grades, which must be offered at filling stations during the respective seasons. In the case of fuels used in internal combustion engines with a compression ignition, the cold behavior is usually defined using the cold filter plugging point (CFPP, see Section 6.2). Fuels with a high paraffinic content of hydrocarbons (HVO diesel and FT diesel) have better cold properties than other fuels such as fossil diesel, FAME, vegetable oil fuel and OME. The cold behavior of FAME and vegetable oils, for example, depends on the feedstock used. In contrast, for fuels used in internal combustion engines with a spark ignition, vapor pressure is an indicator of the cold behavior. Vapor pressures must be higher in winter than in summer. In the case of ethanol and methanol, this is achieved by increasing the proportion of fossil gasoline in winter. In the case of hydrogen and electricity, temperature does not directly influence their suitability as a fuel or operating energy, but low ambient temperatures sometimes significantly reduce the capacities of lithium-ion batteries.

In addition, the **REFUELING OR CHARGING BEHAVIOR** of the various energy carriers is a way to differentiate between the different drive concepts and thus also the different energy carriers. Liquid fuels have a particular advantage in this respect, as refueling is quick and easy. With cryogenic or compressed fuels, the refueling process itself is fast, but certain safety aspects (e.g., protective gloves, face protection) must be taken into consideration. The use of electricity as an energy carrier is by far the most time-consuming alternative with respect to recharging. These aspects are described for the different options in Section 6.3.

FUEL OPTIONS AND VEHICLES IN USE

In principle, all liquid and gaseous fuels can be used as energy carriers in vehicle drive systems. However, for many, the effort required to implement them in the specific application is too high (Figure 6-2). Based on the transport scenarios described in Section 6.2, all urban and regional transport routes for passenger and freight transport will be electrified in the future. Transport routes with a transregional range and light payloads will also tend to be electrified. Here, however, fuel cell drives that use hydrogen are in strong competition with internal combustion engines that use diesel substitutes because they are easier to handle (especially with regard to refueling times and vehicle mass). In maritime transport, aviation, agriculture, forestry and construction, liquid fuels will continue to be used as energy carriers in the future as a result of the high range and load requirements. The outlook for heavy-duty transregional road haulage is unclear. Here, many options are currently being discussed (conventional internal combustion engines using renewable energy carriers, hydrogen fuel cells, or (hybrid) electric drives with a battery or overhead line).

Despite all efforts to electrify drive systems, millions of vehicles with conventional, hybrid or plug-in hybrid drives will still be in use in Germany in 2045, some of which will require the fuel options currently available today. Renewable fuels must also be provided for these vehicles by 2045. Therefore, ways must be found to adapt vehicles to alternative fuels through relatively simple means (see excursus “Establishing E85 as a renewable fuel in France”) or, conversely, to adapt fuels to the requirements of the vehicles in use (e.g., synthetic fuels such as MTG).

The focus on electromobility is not as strong worldwide as it is in Germany. Accordingly, by 2045 and 2050, the proportion of vehicles with internal combustion engines will be significantly higher than in Germany [Laurikko (2020)]. This makes it clear that an even stronger and faster expansion of renewable energy in transport is called for that does not compete with electrification.

Excursus 7: Establishing E85 as a renewable fuel in France

A significant stock of E85 compatible vehicles has been established in recent years in France as a possible drive system option, along with the corresponding fuel. The background to this development is that France gradually increased the proportion of renewable energy in the transport sector to 8.6 % by 2021 and created various incentives for using E85:

- Reduction in VAT for E85 fuel,
- Reduction in the cost to register vehicles,
- Tax-free acquisition of company vehicles with E85 hybrid drives when these emit less than 100 g CO_2/km and
- 40 % discount on the counting of CO_2 emissions towards the vehicle-specific CO_2 tax [Demoures (2020)].

The restructuring of the stock of vehicles is further promoted through the government approval (homologation) of "E85 conversion boxes", which enable conventional gasoline-powered vehicles to be converted for use with E85 fuel. This required a state decree by the French government (E85 Box Regulation). These measures were accompanied by an advertising and communication campaign for flex-fuel vehicles by industry and the government.

Status quo of E85 in France:

- 3.5 % market share of E85 in transport as of 09/2020 [Porter (2020)]
- 129,000 E85 vehicles [ePure ASBL (2020)] with 1,000 new vehicle registrations every month [Demoures (2020)]
- Nine available flex-fuel vehicle models as of 09/2021 [Leblanc (2021)]
- Four E85 conversion boxes with approval/homologation on the market, with around 4,000 units sold per month as of 01/2020 [Demoures (2020)]
- 2,562 public filling stations that offer E85 as of 09/2021 [bioethanolcarburant.com (2021)]
- Fuel price of 0.67 EUR/l, as of 09/2021 [bioethanolcarburant.com (2021)]

7 Environmental aspects of sustainability

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7.1 Background

For more information:

As outlined above, the fuel sector is strongly subject to national and European policy regulations. These also impose environmental requirements on the use of renewable energy carriers, especially in road transport. The requirements are set out in the EU 2018/2001 Directive (RED II for short) [Richtlinie (EU) 2018/2001 (2018)], which has been in force since 2018 at the European level and transposed at a national level through the Biofuels Sustainability Ordinance [Bio-NachAnpV (2021)]. These continue the objectives of Directive 2009/28/EC (RED for short) [Richtlinie 2009/28/EG (2009)] and the Biofuels Sustainability Ordinance [Biokraft-NachV (2009)], which were in force from 2009 to 2020. Accordingly, biofuels require sustainability certification before they can be counted towards the national GHG reduction quota and be included in the minimum share of renewable energy as required by the EU. In addition to the requirement that biofuels must reduce GHG emissions over a fossil reference, other sustainability requirements are intended to minimize the risk of biomass negatively impacting biodiversity and other ecosystem functions. The Annex of the RED II [Richtlinie (EU) 2018/2001 (2018)] and the Biofuels Sustainability Ordinance [Bio-NachAnpV (2021)] define a default value for GHG emissions and the resulting GHG reduction for each biofuel as proof of the required GHG reduction. These default values and the biofuel producer's own GHG calculation can be used for verification. The calculation rule for determining one's own GHG emissions and GHG reductions is also specified in the annexes of the RED II and the Biokraft-NachV (see Section 7.3).

Liquid or gaseous renewable fuels of non-biogenic origin (hereafter referred to as e-fuels) are also subject to a GHG reduction requirement [Richtlinie (EU) 2018/2001 (2018)]. For the GHG calculation methodology as well as for further requirements for these fuels, a draft delegated act to Directive EU 2018/2001 was submitted by the European Commission in May 2022 [Europäische Kommission (2022a), (2022b)], which has not yet been adopted. In addition to a structurally changed calculation methodology compared to the GHG calculation for biofuels, the delegated act regulates requirements for the additionality of renewable non-biogenic electricity production and the temporal and geographical correlation between electricity production from renewable sources and fuel production.

When counting the electricity in road transport within the context of the GHG reduction quota, the emission factor of Germany's power generation mix is used, as specified by the UBA and, in the special case of electricity generation from renewable sources, the emission factor is set as zero. In the context of implementing the RED II, no further requirement is placed on GHG reduction for the electricity mix.

In addition to road transport, a sub-quota for aviation fuels is anchored in the law to further develop the GHG reduction quota as part of the national transposition of the RED II. However, this is reserved for e-fuels [Richtlinie (EU) 2018/2001 (2018)]. As mentioned, the GHG calculation methodology for demonstrating the required GHG savings for these fuels has not yet been finalized. In addition, the International Civil Aviation Organization (ICAO) has established an international aviation program for offsetting and reducing carbon called the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), which calls for carbon-neutral growth beginning in 2020 and a 50 % reduction in net carbon emissions from aviation by 2050. While the CORSIA requirements are voluntary for ICAO member states until 2026, they will become mandatory from 2027 onwards [ICAO (2019)]. The use of sustainable aviation fuels is one way to achieve these climate protection targets. The ISCC CORSIA certification system [ISCC System GmbH (2020a)] was developed to assess the sustainability criteria, as defined by CORSIA, in the use of sustainable aviation fuels. Based on the RED II, there are minimum requirements for reducing GHG emissions and for the sustainable production or extraction of biomass. In order to verify the minimum GHG requirements, the ISCC-CORSIA certification system defines standard GHG emissions values as well as a calculation rule for offsetting the GHG emissions of bio-based aviation fuels [ISCC System GmbH (2020a), (2020b)].

For the shipping industry, the International Maritime Organization (IMO) has drawn up a self-commitment strategy to reduce GHG emissions overall. It aims to achieve a minimum 40 % reduction in CO_2 emissions over 2008 levels by 2030 and a 70 % reduction by 2050 [IMO (2018)]. International shipping does not have concrete calculation rules or sustainability requirements for the provision of biomass like in road and air transport.

Calculating GHG emissions in accordance with the RED/RED II and the Biofuels Sustainability Ordinance covers the entire process chain or the entire life cycle of renewable fuels. All required material and energy quantities and their associated GHG emissions along the life cycle must be counted. The biogenic CO_2 emissions released during the combustion of biofuels are considered climate-neutral because of the short-circuited CO_2 cycle and are not included in the calculation. In contrast, the calculation method used by the Intergovernmental Panel on Climate Change (IPCC) [IPCC (2006)] includes a different frame of reference. Here, only the direct emissions are counted that are directly emitted by the individual sectors such as transport (e.g., fossil CO_2 emissions from combustion), industry, agriculture (e.g., methane and nitrous oxide emissions) and forestry. This calculation is used, for example, to check whether the targets of the Paris Climate Agreement and the sector-specific climate protection targets under the German Climate Change Act are being met. For the transport sector, the directly emitted biogenic CO_2 emissions from the combustion of biofuels in engines are also considered climate-neutral and count as zero. All other renewable energy carriers, such as renewable electricity or hydrogen, also count towards zero emissions for the transport sector, while fossil greenhouse gases from the combustion of fossil fuels are counted. This means that when the IPCC method is used, the upstream emissions, which are a part of the fuel process chain according to the RED/RED II and the Biofuels Sustainability Ordinance, are not counted in the transport sector, but rather for agriculture and forestry (cultivation), industry (manufacturing process) and energy (electricity for the manufacturing process). It follows that the resulting GHG emissions of both calculation methods cannot be compared. Which counting method is used depends on the purpose: GHG emissions are calculated according to the RED/RED II and Biofuels Sustainability Ordinance when fuels are counted towards the national GHG reduction quota and towards the minimum share of renewable fuels required by the EU. The IPCC method is used to verify the achievement of climate protection targets in the sectors (see Figure 7-1). Only the calculation of GHG emissions in accordance with the RED II and the Biokraft-NachV will be discussed below.

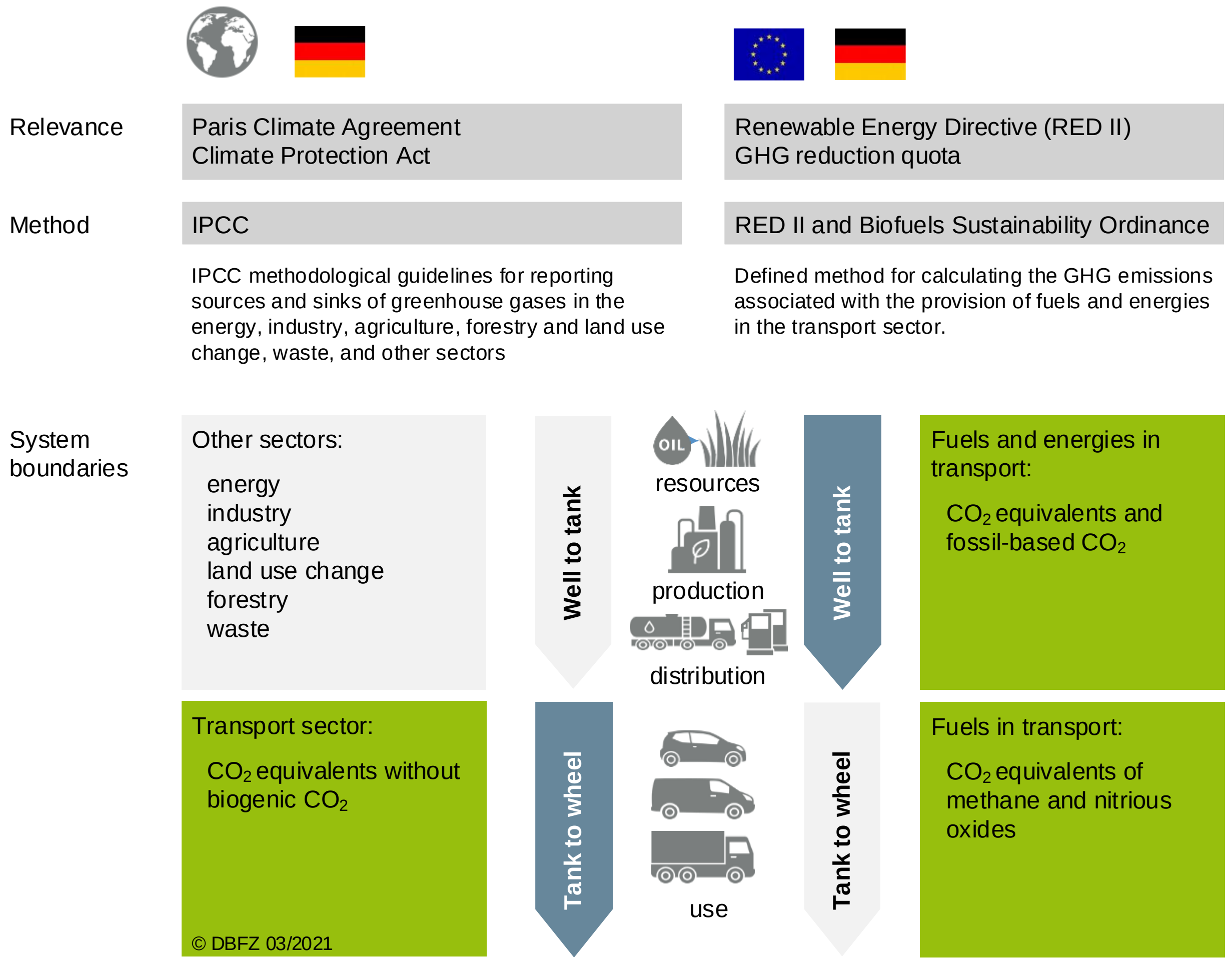

Figure 7-1 System boundaries for calculating greenhouse gas emissions according to the IPCC und RED II/Biokraft-NachV. Note: the calculation or counting of the GHG emissions for the air pollutants methane and nitrous oxide (vehicle exhaust) are not comparable for the two methods

7.2 Sustainability requirements

7.2.1 Requirements for renewable fuels in road transport

The sustainability requirements of the RED/RED II and the Biofuels Sustainability Ordinance can be divided into the requirement of a minimum GHG reduction over a fossil reference and further sustainability requirements pertaining to the production, extraction and traceability of biomass.

RED II raised the RED's fossil reference value from 83.8 g CO_2-eq./MJ to 94 g CO_2-eq./MJ [Richtlinie (EU) 2018/2001 (2018)], [Richtlinie 2009/28/EG (2009)]. With respect to this value, the following minimum GHG requirements apply to biofuels starting in 2021:

- Plants commissioned before October 5, 2015: at least 50 %
- Plants commissioned between October 6, 2015 up to December 31, 2020: at least 60 %
- Plants commissioned after January 1, 2021: at least 65 % [Richtlinie (EU) 2018/2001 (2018)]

Biofuels that were counted toward the GHG reduction quota and included in the EU's renewable energy share requirement up until 2020 were subject to the following minimum RED requirements:

- Plants commissioned before October 5, 2015 up to December 31, 2017: at least 35 %
- Plants commissioned before October 5, 2015, starting January 1, 2018: at least 50 %
- Plants commissioned since October 6, 2015: at least 60 % [Richtlinie (EU) 2015/1513]

The options for demonstrating the required GHG savings are presented in more detail in Section 7.3.

The required GHG savings of liquid or gaseous e-fuels will be at least 70% from 1/1/2021 onwards, although, as mentioned, the methodology for GHG accounting of these fuels already presented in the draft has yet to be adopted by the EC. In this draft, there are no explicit sustainability requirements apart from the required GHG savings. General requirements do exist by way of the condition that there be an additional as well as temporally and geographically correlated generation of the renewable non-biogenic electricity to produce e-fuels. In contrast, there are no restrictions for the carbon source. It can be both biogenic and fossil-based [Europäische Kommission (2022a), (2022b)].

Additional sustainability requirements are only imposed on biofuels. The essential aspects include:

- For biofuels made from agricultural residues and wastes, operators and national authorities must establish monitoring and management plans to address deterioration of soil quality and carbon stocks.
- Biofuels may not be produced from feedstocks grown on land with a high level of biodiversity. These include primary forests and other forested areas with undisturbed environmental processes, forests with a high level of biodiversity, other non-degraded forested areas with a high level of biodiversity, designated protected areas, and grasslands > 1 hectare with a high level of biodiversity.
- Biofuels may not be produced from feedstocks that originate from areas with high carbon stocks. This includes wetlands and continuously forested areas (areas > 1 hectare with trees over 5 m tall and a canopy cover of 10 to 30 % and > 30 %).
- Biofuels may not come from feedstocks extracted from peat bogs [Richtlinie (EU) 2018/2001 (2018)].

A new aspect that was not included in the original RED and Biofuel Sustainability Ordinance is a separate listing of sustainability requirements for biofuels from forestry biomass. The following criteria must therefore be met:

- Legal harvesting
- Reforesting on harvested areas
- Designated areas are protected for conservation purposes
- During the harvest, care is taken to preserve soil quality and biodiversity
- Harvesting activities maintain or improve the long-term production capacity of the forest
- Land use, land-use change and forestry (LULUCF) requirements: The country or organization of origin is a Party to the Paris Agreement, has communicated a nationally determined contribution (NDC) to the United Nations Framework Convention on Climate Change (UNFCC), and the reported emissions from the LULUCF sector shall not exceed emission reductions in the harvested area.

A so-called risk-based approach is used for verification. First it is examined whether the criteria are fulfilled by the legislation of the respective country. If this is not the case, verification takes place at the level of the forest area where product is extracted [Richtlinie (EU) 2018/2001 (2018)].

Another amendment to the RED II is a phase-out by 2026 of biofuels from feedstocks with a high risk of indirect land use change [Richtlinie (EU) 2018/2001 (2018)]. In other words, these biofuels may not count toward the EU's required minimum share of renewable energy after 2026. In Germany, the phase-out will already take effect in 2023 through the Act on the Further Development of the GHG Reduction Quota [THGMQWG (2021)]. If these biofuels are to count toward the GHG quota after 2023, the GHG emissions would be based on the reference value 94.1 g CO_2-eq./MJ. The methodology for determining the risk for indirect land use change is defined in the European Commission's Delegated Act [Deligierte Verordnung (EU) C(2019)2055 (2019)]. So far, only palm oil has been identified as a feedstock with a high risk of land use change. Direct land use changes, on the other hand, must be taken into account in the GHG calculation when demonstrating a biofuel's required GHG savings, as already stipulated by the RED [Richtlinie (EU) 2018/2001 (2018)] (see Section 7.3).

As in the original RED and Biokraft-NachV, economic operators must commit to using a mass balance system when demonstrating compliance with sustainability requirements. The requirements for this mass balance system are specifically defined in the two legal acts mentioned above. Compliance with the sustainability criteria is verified through recognized certification systems and bodies. If all requirements are met, the biofuel receives the sustainability certificate so that it can be counted towards Germany's GHG reduction quota and included in the share of renewable energy as required by the EU.

7.2.2 Requirements for renewable fuels in air transport

So far, the only way renewable fuels in air transport can be counted towards the aviation fuel sub-quota is if they reduce GHG emissions by 70 % over the fossil reference [Richtlinie (EU) 2018/2001 (2018)]. However, this only applies to e-fuels as only they have been able to meet the sub-quota until now.

It is possible to count biokerosenes towards the general GHG reduction quota. In this case, the mandatory sustainability requirements described in Section 7.3.1 apply. The ISCC CORSIA certification system is another way to verify sustainable aviation fuels; however, it will not be required by ICAO member states until 2027. The system covers all types of feedstocks and residues from the agriculture, forestry and fishery industries and is strongly aligned with the sustainability requirements of the RED II. For example, a minimum GHG savings of 10 % compared to the fossil reference of 89 g CO_2-eq./MJ must be met. This can be demonstrated using the default values listed in the Annex of the ISCC-CORSIA system document [ISCC System GmbH (2020a)] or by calculating actual values. The ISCC CORSIA specifically excludes land from which biomass cannot be extracted for biokerosene. Furthermore, good agricultural and forestry practices are required for the production of biomass to prevent pollution, degradation and destruction of the environment. Unlike in the RED II, the GHG default values in CORSIA that can be used to demonstrate the required 10 % GHG reduction include indirect land use change (iLUC) factors for biokerosene made from cultivated biomass that can potentially be used for food and feed purposes. The defined iLUC factors must also be accounted for in the calculation of one's actual GHG emissions if this cultivated biomass is used [ISCC System GmbH (2020a), (2020b)].

7.3 Calculating GHG emissions for renewable fuels

7.3.1 Calculating GHG emissions for renewable fuels in road transport

Biofuels in road transport are alone in having defined default values for specific GHG emissions and GHG reductions. They also have a binding method for calculating the actual values that can be counted towards the national GHG reduction quota and towards the minimum share of renewable energy as required by the EU.

There are three different ways to demonstrate the required GHG reductions. Firstly, the default GHG reductions listed in the annexes of the RED II and the Biofuel Sustainability Ordinance can be used. However, biofuel producers can, themselves, use the calculation methodology described in the annexes to calculate their actual GHG emissions and the GHG savings based on these. The third verification method is a combination of both approaches. Here, disaggregated default values as defined in the annex and own calculation values can be used for the different terms in the formula.

Unlike in the RED, new biofuel pathways with default values for GHG emissions and GHG reductions were included in the RED II for existing and future biofuels. In some instances, existing production pathways were specified and their default values were adjusted. Biomethane now has new default values due to the inclusion of corn feedstock. Default values from mixing different proportions of manure, biowaste and corn have also been added for biomethane. When different ratios of feedstocks are mixed in a biogas or biomethane plant, operators can calculate new GHG emissions values based on the defined default values using a calculation rule listed in the annexes of the RED II and the Biofuel Sustainability Ordinance. There is also a new calculation rule for determining actual GHG emissions from biomethane when feedstocks undergo co-digestion [Biokraft-NachV (2021); Richtlinie (EU) 2018/2001 (2018)].

The annexes to the RED II and the Biofuels Sustainability Ordinance also specify the method for calculating actual GHG emissions and GHG reductions. This GHG calculation rule is a much simpler version of the standardized life cycle assessment methodology. The LCA methodology according to DIN ISO 14040 and 14044 offers a variety of methodological freedoms, for example with regard to the functional unit, the system boundaries, the choice of allocation methodology, the environmental impact categories, etc.[DIN EN ISO 14040 (2006)] [DIN EN ISO 14044 (2006); DIN EN ISO 14040 (2006)]. These methodological freedoms were severely limited in the RED calculation rule in order to harmonize the GHG results of biofuels as part of the certification process and to make them more comparable. Thus, the functional unit is set at one megajoule, the allocation between products in a product system is based on the lower heating value, the system boundary extends from feedstock extraction or cultivation to fuel use, and only the three greenhouse gases CO_2, CH_4 and N_2O are considered. The calculation takes into account changes in carbon stocks as a result of direct land use change, while ignoring indirect land use changes [Richtlinie (EU) 2018/2001 (2018)]. However, biofuels with a high risk of indirect land use change will be phased out starting in 2023, as described in Section 7.2.1.

The calculation formula for actual GHG emissions from biofuels is as follows:

$$E = e_{ec} + e_l + e_p + e_{td} + e_u + e_{sca} + e_{ccs} + e_{ccr}$$

with

E Total emissions from the use of the fuel

e_{ec} Emissions from the extraction or cultivation of raw materials

e_l Annualized emissions from carbon stock change caused by land-use change

e_p Emissions from processing

e_{td} Emissions from transport and distribution

e_u Emissions from the fuel in use
e_{sca} Emission savings from soil carbon accumulation via improved agricultural management
e_{ccs} Emission savings from CO_2 capture and geological storage
e_{ccr} Emission savings from CO_2 capture and replacement

Using the calculation formula for determining GHG emissions, the actual GHG savings are determined as follows:

$$THG - saving = \frac{(E_{F(t)} - E_B)}{E_{F(t)}}$$

with
E_B Total emissions from the fuel in use
$E_{F(t)}$ Total emissions from the fossil fuel comparator for transport

The calculation formula of the actual GHG emissions for the production of biomethane from co-fermentation is:

$$E = \sum_{1}^{n} S_n * (e_{ec,n} + e_{td,feedstockf,n} + e_{l,n} - e_{sca,n}) + e_p + e_{td,product} + e_u + e_{ccs} - e_{ccr}$$

with
E Total emissions from the production of biomethane before energy conversion
S_n Share of feedstock n in the fraction of input into the digester
$e_{ec,n}$ Emissions from the extraction or cultivation of feedstock n
$e_{td, feedstock,n}$ Emissions from transport of feedstock n to the digester
$e_{l,n}$ Annualized emissions from carbon stock changes caused by land-use change, for feedstock n
$e_{sca, n}$ Emission savings from improved agricultural management of feedstock n
e_p Emissions from processing
$e_{td, product}$ Emissions from the transport and distribution of the biomethane
e_u Emissions from the fuel in use, that is GHG emitted during combustion
e_{ccs} Emission savings from CO_2 capture and storage
e_{ccr} Emission savings from CO_2 capture and replacement [Richtlinie (EU) 2018/2001 (2018)]

Compared to the original RED and Biofuels Sustainability Ordinance, the term e_{ee} (emission savings from surplus electricity from cogeneration) has been omitted from the GHG calculation formula. In addition, the greenhouse gases N_2O and CH_4 must now be included in the GHG calculation when biofuels are used. Biogenic CO_2 continues to be considered climate-neutral and is not included in the calculation [Richtlinie (EU) 2018/2001 (2018)].

A further simplification over the LCA methodology is to only consider the three greenhouse gases carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) and the resulting global warming potentials (see Table 7-1). These were raised slightly from the original RED and Biofuels Sustainability Ordinance, which listed factors 296 for nitrous oxide and 23 for methane in accordance with the Fourth Assessment Report of the IPCC from 2007 [IPCC (2007)]. The global warming potential (GWP) defined in the RED II refers to the climate impact of greenhouse gases within the first 100 years (GWP 100). However, it should be noted that the climate impact of some greenhouse gases is higher when the observation period is shorter, such as only 20 years (GWP 20). Thus, the global warming potential of methane in the first 20 years corresponds to three times the global warming potential in the first 100 years. GWP 20 is accordingly relevant for shorter observation periods.

Table 7-1 Global warming potentials of the greenhouse gases included in the RED II

Greenhouse gas	Global warming potential (GWP 100)
Carbon dioxide (CO_2)	1
Nitrous oxide (N_2O)	298
Methane (CH_4)	25

For e-fuels, there is currently a draft of the calculation methodology for GHG emissions [Europäische Kommission (2022a), (2022b)] via a delegated act to EU Directive 2018/2001 [Directive (EU) 2018/2001 (2018)]. Since this has not yet been adopted, only essential core elements of the calculation will be discussed below. As with GHG accounting for biofuels, GHG emissions from processing, transport, distribution, and use must be accounted for. Crediting via capture and geological storage of CO_2 is also allowed. In contrast to the GHG calculation for biofuels, the GHG emissions from the extraction or cultivation of the raw materials must no longer be given, but the GHG emissions from the input materials and energies must be listed separately for elastic and rigid input materials or energies. While the production of elastic feedstocks/energies can be increased to meet additional demand, rigid feedstocks/energies are produced in a fixed product ratio so that their supply cannot be increased to meet additional demand. To account for this aspect, the GHG emissions from the existing use of the input materials are deducted for the rigid input materials or energies.

7.3.2 Calculating GHG emissions from biofuels in air transport using ISCC CORSIA

The ISCC CORSIA Certification System [ISCC System GmbH (2020b)] follows the RED II by defining both default values and calculation rules when determining actual GHG emissions and GHG reductions. The following aviation fuels have different GHG default values depending on the world region and feedstock:

- FT-SPK
- HEFA-SPK
- ATJ (isobutanol and ethanol-to-jet)
- SIP

These standard GHG emissions consist of a core GHG emissions value for the process chain and a defined iLUC value.

The calculation formula defined in the RED II is used to calculate the actual GHG emissions from aviation fuels. However, in the ISCC-CORSIA Certification System, the iLUC factor, which is defined in the annex of the system document, must be added to the calculated value when cultivated biomass is used [ISCC System GmbH (2020b)]. As in the RED II, only the greenhouse gases CO_2, CH_4 and N_2O are considered in the calculation. However, the global warming potentials from the 5th IPCC Assessment Report of 2013 do apply here [IPCC (2013)].

Table 7-2 Global warming potentials of the greenhouse gases considered in the ISCC CORSIA, according to the 5th IPCC Assessment Report

Greenhouse gas	Global warming potential (GWP 100)
Carbon dioxide (CO_2)	1
Nitrous oxide (N_2O)	265
Methane (CH_4)	28

The actual GHG reduction for aviation fuels is calculated in the ISCC-CORSIA Certification System as follows:

$$ER_y = FCF * \left[\sum_f MS_{f,y} * \left(1 - \frac{LS_f}{LC}\right)\right]$$

with

ER_y	GHG emissions reductions of the aviation fuel under consideration
FCF	Conversion factor as a fixed value of 3.16 kg CO_2/kg for Jet-A fuels and 3.10 kg CO_2/kg for Jet-B fuels
$MS_{f,y}$	Total mass of the fuel in year y for fuel type f
LS_f	GHG emissions from the fuel
LC	Baseline emissions, fixed value of 89 g CO_2-eq./MJ for Jet-A fuels and 95 g CO_2-eq./MJ for Jet-B fuels [ISCC System GmbH (2020b)]

7.4 GHG emissions and GHG reduction potential of commercially available renewable energy

Figure 7-2 shows the GHG emissions of the commercially available renewable fuel options in road transport for which a request to be counted towards the GHG quota was submitted in 2018, 2019 and 2020. Accordingly, the values are from fuels that have received a sustainability certificate [BLE (2021b)]. Only the GHG emissions values for 2020 are shown for the renewable fuels biomethanol and bio-LNG. Small quantities of both fuel types were counted towards the GHG quota for the first time in 2020. The figure also shows the default values for commercially available bio-based aviation fuels from the ISCC-CORSIA system document [ISCC System GmbH (2020b)]. The GHG emissions from the use of electricity are reflected in the GHG emissions values of the German electricity mix for the years 2018 to 2020, and the GHG emissions value from offshore wind, onshore wind, and photovoltaic electricity generation for 2020 [Hengstler (2021); Icha (2021); Lauf (2019); Lauf (2021)]. The GHG emissions only relate to the energy content of the fuel. The use in the different drive systems is taken into account through the drive factors (DF) in the Annex of the 38th BImSchV. This is 1 for the use of fuels in internal combustion engines and 0.4 for the use of electricity in electric motors and hydrogen in fuel cells [38th BImSchV (2021)]. The figure also shows the minimum GHG reductions for biofuels compared to the fossil reference of 83.8 g CO_2-eq./MJ, which was in place until 2020 (Directive 2009/28/EG). In the case of biofuels which could be counted toward the GHG quota or included in the minimum share of renewables as required by the EU until 2020, this amounts to 50 % for plants commissioned by the end of 2016 and 60 % for plants commissioned since 2017 [Richtlinie (EU) 2015/1513]. The required GHG savings for sustainable aviation fuels of 10 % over the fossil reference of 89 g CO_2-eq./MJ from the ISCC-CORSIA Certification System [ISCC System GmbH (2020b)] is also included.

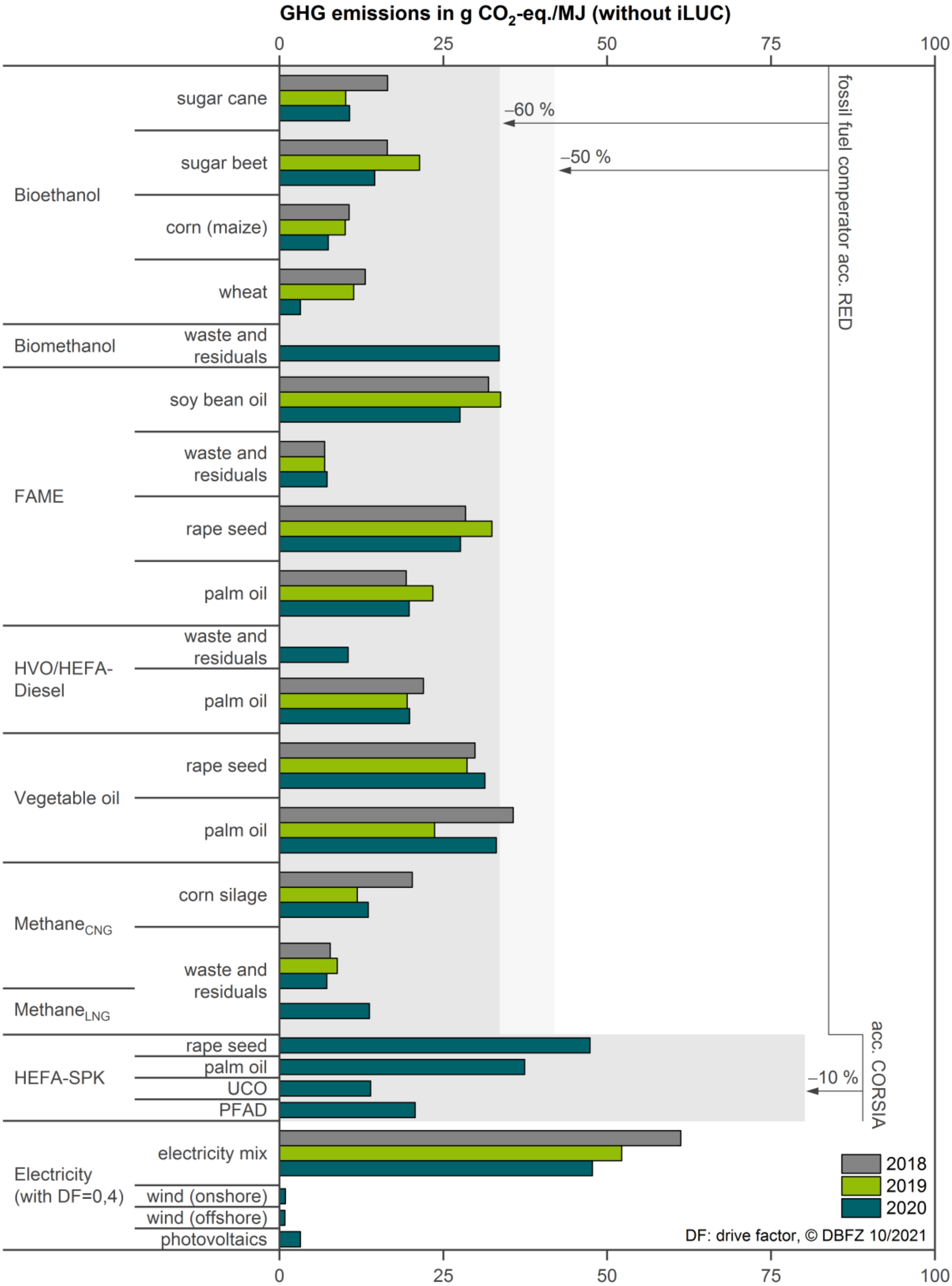

Figure 7-2 GHG emissions for commercially available fuels. Data based on [BLE (2019), (2019), (2020), (2021b); Hengstler (2021); Icha (2021); ISCC System GmbH (2020b); Lauf (2019); Lauf (2021)]

Since the introduction of the GHG quota, overall biofuel GHG reductions have risen sharply from 70 % in 2015 to 84 % in 2018, and then remained at a consistently high level of 83 % since 2019. Nevertheless, there is no correspondingly consistent trend for each individual biofuel [BLE (2021b)]. Figure 7-2 clearly shows that GHG emissions fluctuated between 2018 and 2020. Palm oil-based vegetable oil fluctuated strongly in 2019. These fluctuations could be caused by the fact that calculating actual GHG emissions acted as an incentive to optimize process chains and that biofuels from other feedstocks and/or from other plants with different costs have now been included in the GHG quota. The low average GHG emissions value of bioethanol from wheat in 2020 is also striking. It is likely that some plant operators have taken credit for capturing and using the biogenic CO_2.

In principle, the GHG emissions for biofuels from residues and waste materials are generally lower than those for cultivated biomass-based biofuels. A comparison also shows that the highest GHG reductions are from biomethane as CNG, ahead of bioethanol (with the exception of 2020, where bioethanol from wheat achieved the highest GHG savings) and biomethane as LNG. This is due to its high proportion of residue- and waste-based feedstocks. FAME exhibits a medium reduction in GHG emissions overall. The lowest GHG reductions are achieved by HVO, vegetable oils, and biomethanol, the latter of which has been recently included in the quota. However, all commercially available biofuels in road transport meet the required minimum GHG reductions – otherwise they could not have been counted towards the GHG quota. The highest GHG reductions among biofuels from 2018 to 2020 were achieved by biomethane from residues and waste, bioethanol from wheat, sugar cane and corn, and FAME from used cooking oil (UCO). The default GHG emissions of HEFA aviation fuels are shown in Figure 7-2; however, they cannot be compared with the actual GHG emissions for road transport biofuels as they represent generic average values. Nevertheless, within these default values for bio-based aviation fuels, it is also clear that the residual and waste-based aviation fuels have potentially lower GHG emissions than those made from crop-based biomass. All HEFA aviation fuels can achieve the required GHG savings of the ISCC-CORSIA Certification System based on their default values. In an overall comparison of commercially available renewable energy carriers, electricity from renewable sources, such as wind power for electric mobility, has the lowest GHG emissions. However, when the electricity generation mix is used instead of pure renewable electricity, this results in the highest level of GHG emissions.

If the road transport biofuels under consideration were produced in new plants (commissioned after January 1, 2021), some palm oil-based vegetable oils and some FAME fuels made from soy bean oil would not count towards the GHG reduction quota or the minimum share of renewable energy as required by the EU. Even though a new higher reference of 94.1 [Richtlinie (EU) 2018/2001 (2018)] replaced the reference of 83.8 g CO_2-eq./MJ [Richtlinie 2009/28/EG (2009)] starting in 2021, a higher minimum GHG requirement of 65 % [Richtlinie (EU) 2018/2001 (2018)] also applies.

In general, the calculated GHG reductions relative to the standard fossil reference of 83.8 (or 94.1 g CO_2-eq./MJ starting in 2021) do not correspond to the GHG emissions purportedly avoided since biofuels replace their fossil counterparts. The specific GHG emissions currently defined for fossil gasoline and natural gas are below the fossil reference of 94.1 g CO_2-eq./MJ, while those of diesel are above it. This means that gasoline and natural gas substitutes have lower – and diesel substitutes slightly higher – GHG reductions than those shown in Figure 7-2. However, this approach also falls short since conventional fuels will not be substituted on a one-to-one basis because the future transport sector will be characterized by new fuels, alternative drive systems, and modified mobility behavior.

7.5 GHG emissions and GHG reduction potential of renewable energy in the demonstration phase

Figure 7-3 shows the GHG emissions of renewable fuels in the demonstration phase. These are essentially advanced biofuels and e-fuels for road and maritime transport. Biofuels from cultivated biomass that is potentially used for food and feed purposes and biofuels from residual materials are both listed under bio-based aviation fuels. In addition, the figure shows the minimum GHG requirements over the fossil reference of 94.1 g CO_2-eq./MJ, which applies from 2021 onwards. This is 65 % for biofuel plants starting operation in or after 2021, and 70 % for e-fuels starting in 2021 [Richtlinie (EU) 2018/2001 (2018)]. The required GHG savings for sustainable aviation fuels of 10 % over the fossil reference of 89 g CO_2-eq./MJ [ISCC System GmbH (2020b)] from the ISCC-CORSIA Certification System is also shown.

GHG emissions for biofuels that can be used in road and maritime transport were taken from the default GHG emissions values in Annex V of the RED II and the Biofuel Sustainability Regulation [Biokraft-NachV (2021); Richtlinie (EU) 2018/2001 (2018)]. There is no default value for biomethane from solid biomass gasification. The GHG emissions value is derived from calculations made as part of the GoBiGas research project [Alamia (2017)]. The GHG emissions values for aviation fuels were taken from the ISCC-CORSIA system document [ISCC System GmbH (2020b)]. They represent the default values defined there based on the RED II methodology. The defined default values for hydrogen and methane that are electrolytically generated from renewable electricity were taken from the Annex of the 37th BImSchV [37. BImSchV (2020)]. The GHG emissions values for hydrogen from the gasification of lignocellulosic material were taken from the 2016 publication by Hajjaji et al. [Hajjaji (2016)]. GHG emissions from electricity-based methanol and DME are from the 2018 publication by Bongartz et al [Bongartz (2018)]. As mentioned above, there is currently no standardized method for calculating GHG emissions from e-fuels and no default values for them. Hence, the GHG emissions shown in Figure 7-3 are only comparable to a limited degree, as not every value has been generated using the RED II calculation method.

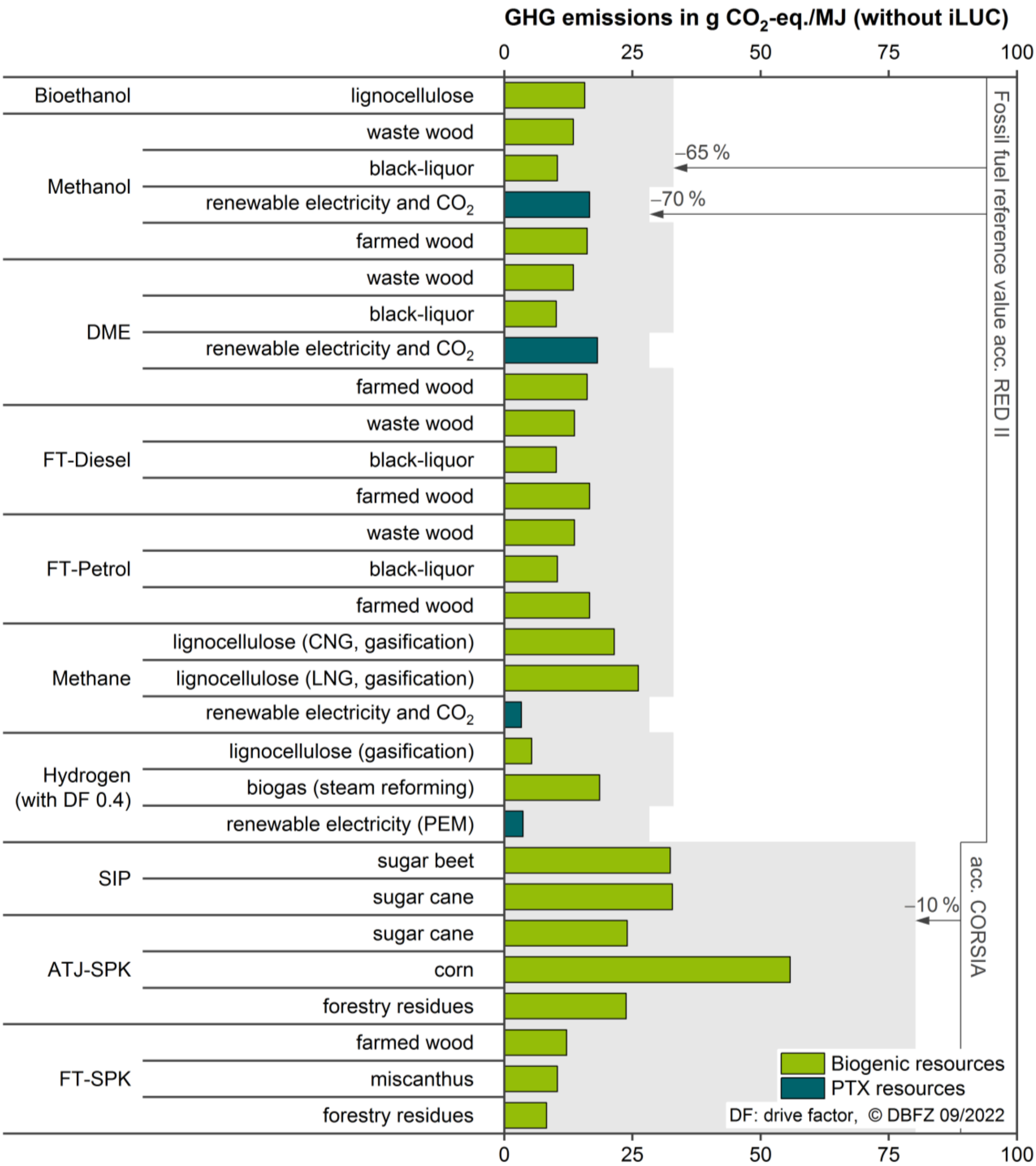

Figure 7-3 GHG emissions for future energy carriers Data based on [Alamia (2017); Bongartz; 37. BImSchV (2020); Bongartz (2018); Richtlinie (EU) 2018/2001 (2018); Hajjaji (2016); ISCC System GmbH (2020b)]

In principle, all renewable fuels presented here can achieve the required GHG reductions. The highest GHG emissions would come from the use of aviation fuels made from crop biomass which is potentially used for food and feed purposes and from biomethane from the gasification of lignocellulosic biomass. The lowest GHG emissions would come from hydrogen and methane that are electrolytically produced from renewable electricity, FT-SPK from forestry residues, and black-liquor-based methanol, DME, FT-diesel and FT-gasoline.

7.6 GHG emissions and GHG reduction potential of renewable energy at the research level

The renewable fuels identified in this report as being in the research phase have poor and inconsistant data due to the stage of development that they are in. Scientific publications only occasionally consider the environmental impact of these fuels. In some of these studies, the methodological framework, such as system boundaries, allocation methodology, or allocation of credits, is not presented in a transparent and comprehensible way. Sometimes the methodological framework varies so much between publications that the results cannot be directly compared. As a result, the sporadically published results are not presented here in a diagram or table.

7.7 Exhaust emissions from the use of renewable fuels

Exhaust emissions resulting from the combustion of liquid and gaseous fuels have a variety of negative effects on human health and the environment, including damage to the respiratory and cardiovascular systems and an increased risk of cancer and death [Geupel (2021); WHO (2021)].

Legislation on exhaust emissions

To protect human health and the environment, the EU introduced standardized exhaust gas legislation in the early 1990s that contained binding emission standards. These initially applied to road vehicles and were later expanded to include mobile machinery and equipment as well as inland waterway vessels. Since then, the legal limits for exhaust emissions, which are determined by standardized emission test cycles, have continued to tighten. Emissions from ocean-going vessels are regulated by the International Maritime Organization (IMO) and emissions from aircraft by the International Civil Aviation Organization (ICAO). The main air pollutants from transport that are limited by legislation include: particulates, nitrogen oxides (NO_X), hydrocarbons (HC) including methane, and carbon monoxide (CO). The legal requirements differ depending on the means of transport, drive system and performance, etc.

For example, for non-road mobile machinery (NRMM) in the 56 to 560 kW range, nitrogen oxide (NO_X) limits were lowered by more than 95 % and limits for particulate matter by more than 97 % between 1999 and 2019. In order to better reflect dynamic engine operation, a non-road transient cycle (NRTC) has been required since 2011 in addition to a non-road steady cycle (NRSC). Furthermore, since the introduction of Stage V in the emission standards, binding emission limits now apply to all engine sizes, starting with the smallest engines from 0 to 8 kW and extending to large engines with a rated power of over 560 kW. At the same time, a new limit on the number of particulates has been introduced for vehicles between 19 and 560 kW [Verordnung (EU) 2016/1628 (2014)].

Despite an extensive lowering of the limits for exhaust emissions for road vehicles and mobile machinery and equipment, continuous monitoring of air quality revealed no corresponding improvement for a long time, especially for nitrogen oxides [Kessinger (2021); Löschau (2019); Lutz (2021)].

One reason for this is the long-standing lack of coordination between emission standards for transport and air quality standards [Lutz (2021)]. In addition, the exhaust gas values recorded on the test bench under ideal testing conditions sometimes differ significantly from the emissions released under real operating conditions.

As a result, the so-called in-service conformity test was introduced in 2013 for heavy-duty commercial vehicles with the introduction of the Euro IV emission standard and higher. This involves determining the exhaust emissions of operated vehicles at regular intervals over the lifetime of the vehicle and under real driving conditions. Portable emission measurement systems (PEMS) are used to determine real driving emissions. The legal requirements for this are described in detail in EU Regulations 582/2011, 64/2012 and 2016/1718 [Verordnung (EU) Nr. 582/2011 (2011); Verordnung (EU) 64/2012 (2012); Verordnung (EU) 2016/1718 (2016)].

For passenger cars and light commercial vehicles, new guidelines for determining real driving emissions (RDE) were introduced in 2016, which were later revised and expanded. Initially, a conformity factor for nitrogen oxide emissions of 2.1 applied for the transition phase. This means that the value determined in an RDE measurement may be no more than 2.1 times the threshold for the test bench measurements. In January 2020, the conformity factor was reduced to 1.5, which means that the test bench threshold may only be exceeded by a maximum of 50 %. Exceedance is tolerated in order to take into account the measurement tolerance of the PEMS. The conformity factor for the particle count has been 1.5 since its introduction. RDE measurements are to be carried out on a random basis for new vehicles at the time they are type-approved and for existing vehicles after a certain period of operation. This is intended to monitor compliance with the emission limits under real-world operating conditions.

With the introduction of the Stage V emission standard in 2019, emissions for non-road mobile machinery (NRMM) must now also be recorded and reported under actual driving conditions using portable emission measurement systems (PEMS). However, mandatory emission limits and conformity factors have not yet been defined for this [Verordnung (EU) 2017/655 (2016); Verordnung (EU) 2016/1628 (2014)].

It should be noted that emission measurements under real operating conditions can only be compared with each other to a limited degree due to the great variability in the boundary conditions. However, RDE measurements can provide information about when emission peaks occur under real operating conditions and whether a vehicle or machine can also comply with the statutory emission limits over its lifetime when used as intended.

Emissions legislation applies equally to fossil and renewable fuels.

LOWERING EXHAUST EMISSIONS

Emission reduction measures have been introduced in order to comply with increasingly stringent emission legislation. Emissions are most effectively reduced through a combination of in-engine measures and exhaust gas aftertreatment systems (EATS). Examples of EATS include the three-way catalytic converter (reduction of NO_X, HC and CO) and the gasoline particulate filter (separation of particulates) for spark-ignition engines, and the oxidation catalytic converter (reduction of CO and HC), the diesel particulate filter (separation of particulates) and the SCR catalytic converter (NO_X reduction) for engines with a compression ignition. Additional catalysts are used, such as ammonia slip catalysts, to avoid, under unfavorable operating conditions, secondary emissions such as ammonia or nitrous oxide, which can be generated when the reducing agent urea is introduced into the exhaust system.

Fuel has played less of an influential role in exhaust emissions in recent years with the rise in EATS [Ettl (2019); Nylund (2018)]. This applies both to the emission of exhaust gas elements that have been limited (CO, HC, NO_X, particulates) and to many health-relevant elements that have not been limited, for example aldehydes and polycyclic aromatic hydrocarbons (PAH). However, for vehicles without EATS or for those using low-grade fuels with a high sulfur content, such as maritime fuel, the influence of the fuel on emission performance is significant.

Here, low-sulfur or oxygenated diesel substitutes, such as vegetable oil and biodiesel, usually have a favorable effect on CO, HC and particulate emissions. However, this often goes hand in hand with higher

NO_X emissions as a result of higher peak temperatures during combustion. HVO (hydrotreated vegetable oil) also has very good combustion properties due to its paraffinic structure and therefore also leads to lower CO, HC and particulate emissions than fossil diesel. In addition, HVO also has the potential to simultaneously mitigate NO_X emissions to a small extent [Nylund (2018)]. The higher ethanol content of gasoline leads to lower particulate emissions, especially during acceleration, and in some cases also to a reduction in CO and NO_X [Huber (2019)]. The use of methanol in motors leads to lower CO and HC and, in some cases, NO_X emissions due to its chemical structure, with oxygen bound to the molecule and the absence of carbon-carbon bonds. However, methanol that hasn't been completely burned can also cause higher aldehyde emissions unless these are catalytically oxidized again in the exhaust system. When used as a maritime fuel, for example, methanol can lead to a significant reduction in particulate emissions (black carbon) and sulfur oxides compared with conventional maritime fuels, without the need to retrofit costly exhaust gas purification systems [Schröder (2020b)]. The use of the oxygenated synthetic fuel OME as a pure fuel or blending component also generally leads to a decrease in particulate mass in the exhaust gas and to a reduction in the particulate-NO_X-trade-off [Härtl (2015); Omari (2017)]. Grope et. al. provide an overview of the emission behavior of renewable fuels in modern internal combustion engines. [Grope (2018)]

Alternative fuels can also indirectly contribute to reducing exhaust emissions over fossil fuels if, for example, they allow optimized engine settings. For example, knock resistance can be improved by a higher ethanol content in gasoline and the engine can be operated with a higher compression ratio, which has a favorable effect on combustion efficiency and the degree of pollutant formation. In addition, oxygenated fuels usually allow higher exhaust gas recirculation rates, which can reduce NO_X emissions and reduce the trade-off between particulate emissions and NO_X. In contrast, there could be an increase in exhaust emissions over the operating time if renewable fuels are insufficiently aligned with the engine and EATS. It has yet to be conclusively determined whether renewable fuels have a positive or negative impact on the effectiveness of EATS in continuous operation. Studies have shown that different biodiesel qualities (FAME) can have a varying influence on the long-term stability of EATS [AGQM (2018); Schröder (2017)].

Conclusions

For a long time, the lowering of emission limits for particulate matter and nitrogen oxides did not bring about a sufficient improvement in air quality. Only with the increasingly widespread use of particulate filters and SCR catalytic converters, progressive emissions legislation (above all real emission measurements), and the introduction of low emission zones and 30 km/h zones has the trend strongly declined. Fewer and fewer threshold violations have been recorded in recent years at the numerous air quality monitoring stations. Nevertheless, additional efforts are needed to further reduce the impact on people and the environment [Kessinger (2021); Löschau (2019); Lutz (2021)].

When different fuels are used to operate modern internal combustion engines with an EATS, the difference between emission behavior on the test bench and during actual operation is slight. Engine type and EATS, as well as engine condition and mode of operation, outweigh the influence of fuel type and quality. However, renewable fuels can make an important contribution to reducing emissions when the EATS is inactive (e.g., outside the working temperature of the catalytic converter) or in older engines without an EATS. The extent to which new fuels can contribute to the development of more effective and lower-emission engine combustion processes (e.g., homogeneous charge compression ignition (HCCI)) remains to be seen. In this context, the question also arises as to whether combustion processes and internal combustion engines will continue to be developed to the same extent if the passenger car industry, which is the main driving force here, focuses primarily on electromobility.

One undisputed advantage of renewable fuels over fossil fuels is their contribution to reducing greenhouse gas emissions. Depending on the type of feedstock, production process, distribution route and engine use, greenhouse gas emissions from renewable fuels are mostly well below those from fossil fuels.

7.8 Greenhouse gas emissions from vehicles and fuels

The GHG emissions in the transport sector encompass the air pollutants methane (CH_4) and nitrous oxide (N_2O) caused by fuel combustion and, in the case of fossil fuels, also the release of CO_2 from a fossil source (see system boundaries of the National Inventory Report). As a result, it "only" takes avoiding methane and nitrous oxide emissions and using renewable energy carriers to reduce greenhouse gas emissions in the transport sector. However, greenhouse gas emissions from the production, distribution and disposal of vehicles and fuels are not ascribed to the transport sector itself. These emissions are an integral part of the agriculture, energy and industry sectors. Accordingly, GHG emissions may be transferred from one sector to another when diesel and gasoline are replaced by renewable fuels or when vehicles with an internal combustion engine are replaced by battery electric or fuel cell vehicles. The best-known example are the GHG emissions generated from the production of electricity to power electric vehicles. These emissions are currently substantial when the German electricity mix is used to power them due to the high proportion of electricity generated from coal-fired power plants. However, these emissions are not ascribed to the transport sector. In order to sustainably reduce the total GHG emissions related to transport, both the emissions resulting from the energy carriers (production, distribution, use) and the emissions resulting from the vehicles themselves (production, distribution, use, disposal) must be considered. This approach is known as a "life cycle assessment" (LCA).

The approach is presented below for different vehicle types using the fuel-specific GHG emissions outlined in Sections 7.4 to 7.6. The calculations were performed for today's compact passenger cars and 40-ton trucks. They are based on the freely available LCA calculation tools "carculator"[15] and "carculator_truck"[16], which are also documented in related publications [Sacchi (2021b); Sacchi (2021a)].

All components are included in the life cycle assessments of the vehicles, i.e., the vehicle body, powertrain, energy storage system, as well as maintenance and disposal. Greenhouse gas emissions caused by the construction and maintenance of the road infrastructure are also taken into account, as are refrigerant emissions from air conditioning systems, which impact the climate. The source of the background inventory data is the life cycle inventory database "ecoinvent"[17], more precisely version 3.7 of its system model "allocation, cut-off by classification" [Wernet (2016)].

Passenger cars are assumed to travel 200 thousand km over their entire lifetime. The vehicle weight ranges from approx. 1,350 to 1,500 kg, depending on the type of powertrain. The battery electric vehicle is equipped with a battery which has a storage capacity of 43 kWh that can be used until the end of the vehicle's lifetime. Energy consumption while driving is calculated using the WLTP driving cycle. Trucks in the 40-ton category have a vehicle weight of around 15 metric tons. The calculations were carried out with an average load of around 9 metric tons and the vehicles are assumed to travel 350 thousand km over their entire lifetime.

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15 https://carculator.psi.ch
16 https://github.com/romainsacchi/carculator_truck
17 https://ecoinvent.org/

Life cycle GHG emissions of cars are shown in Figure 7-4, and those of trucks in Figure 7-5. The climate impact of the GHG emissions was calculated using the global warming potentials of the individual GHGs over 100 years in accordance with the IPCC's 5th Assessment Report. Methane and nitrous oxide, the most important greenhouse gases besides CO_2, have global warming potentials of 28 and 265, respectively, which means they have a correspondingly greater impact on the climate than CO_2 [IPCC (2013)].

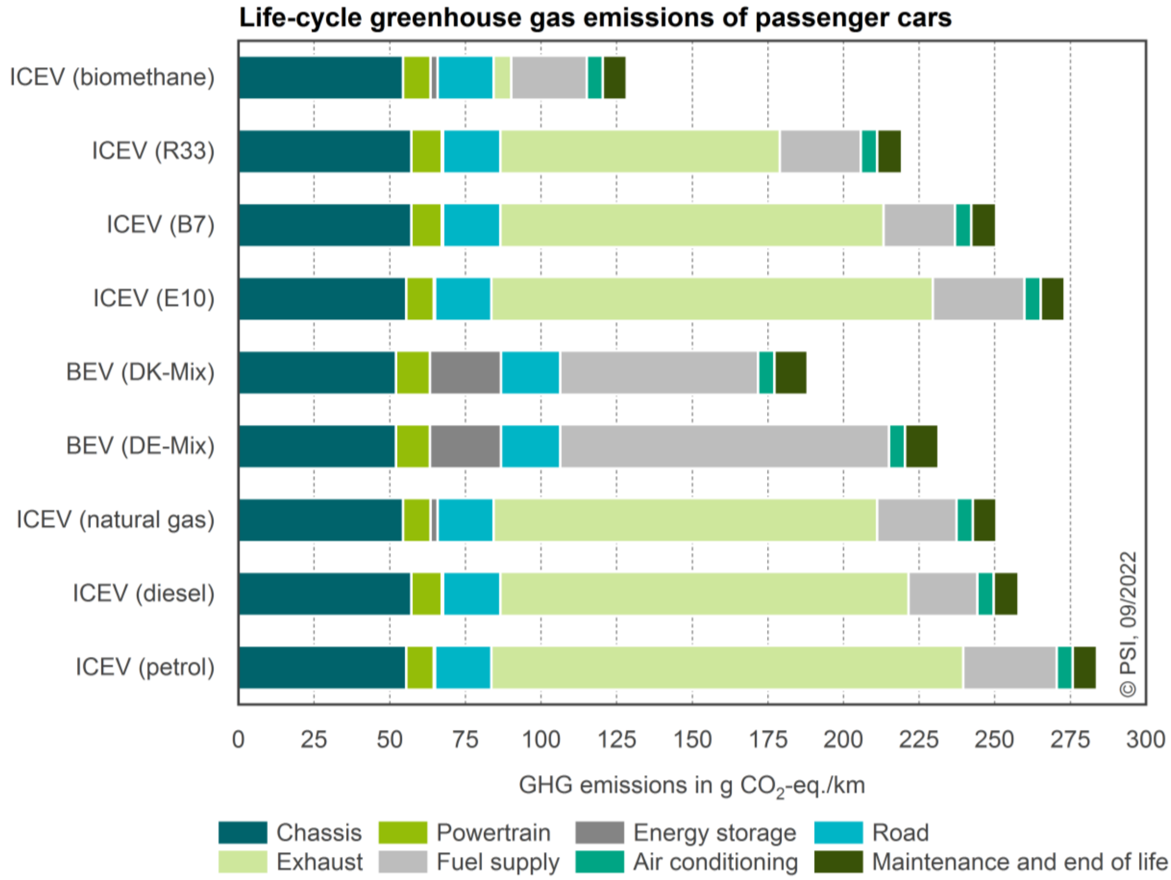

Figure 7-4 Life-cycle greenhouse gas emissions for compact passenger cars, broken down by manufacturing (body, powertrain, energy storage and road), operation (exhaust, energy carrier, air conditioning), maintenance and disposal of the vehicle, as well as the supply of operating energy (fuel or electricity); Note: DE/DK mix: low-voltage electricity mix in Germany/Denmark.

For vehicles powered by fossil fuels (gasoline, diesel, natural gas), most of the GHG emissions occur during the combustion of these fuels ("tailpipe" contribution). Since biogenic CO_2 emissions (i.e., CO_2 emissions from the combustion of renewable fuels) are not assessed as impacting the climate, renewable fuels only contribute slightly to emissions during vehicle operation, namely, low methane emissions when biomethane is used as a fuel and, likewise low emissions of the climate-impacting refrigerant from the air conditioning system. In the case of battery electric vehicles, substantial GHG emissions come from the production of the battery as well as the production of the electricity used to charge the battery if a significant proportion of the electricity is generated in coal or gas-fired power plants. This is currently the case in Germany, which means that the battery electric vehicle produces only slightly lower GHG emissions than gasoline and diesel vehicles. As all of the vehicle bodies compared here are similar, the GHG emissions caused by their production and disposal are also similar. Their generally quite high contribution to overall emissions shows that these high GHG emissions are currently associated with the production of steel and aluminum (the main components of the vehicle bodies). GHG emissions from road infrastructure are calculated as a function of the weight of the vehicle – accordingly, the battery-powered vehicle causes slightly higher emissions here because the battery increases the weight of the vehicle.

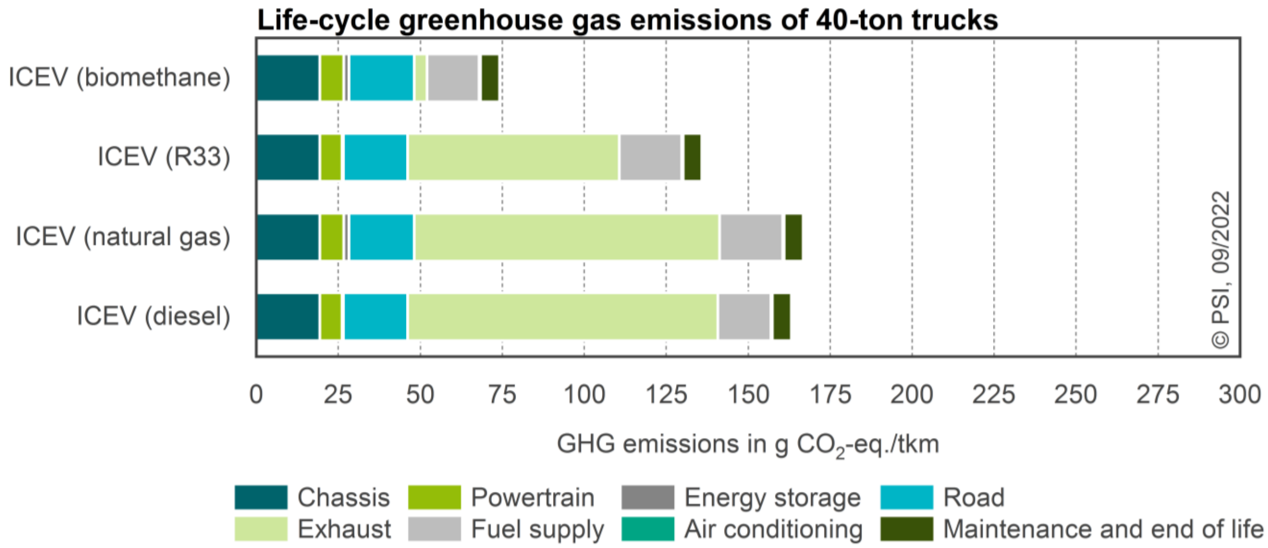

Figure 7-5 Life-cycle greenhouse gas emissions for 40-ton trucks, broken down by manufacturing (body, powertrain, energy storage and road), operation (exhaust, energy carrier, air conditioning), maintenance and disposal of the vehicle, as well as the supply of operating energy (fuel or electricity); Note: DE/DK mix: low-voltage electricity mix in Germany/Denmark.

In general, vehicles that run on 100 % biomethane produced from residual materials have the lowest greenhouse gas emissions from a life cycle assessment perspective; they are about half as high for both cars and trucks as the emissions from vehicles powered by fossil fuels. In the case of passenger cars, natural gas is by far the most climate-friendly fossil fuel, as combustion produces fewer CO_2 emissions than diesel and gasoline. However, the energy efficiency of natural gas engines today is lower than that of gasoline and especially diesel engines. Therefore, for trucks that consume large quantities of fuel, the GHG emissions of diesel trucks are even slightly lower than those of natural gas-powered trucks. When comparing GHG emissions of passenger cars and trucks, trucks are shown to have a slightly higher relative share of tailpipe emissions than passenger cars, which is due to a truck's higher mileage over its lifetime.

The results of the life cycle assessment presented here clearly show that biofuels, which are produced from biogenic residues and thus do not cause substantial GHG emissions during fuel production (i.e., biomethane, for example), are currently the most climate-friendly alternative in Germany – for both cars and trucks. This will be the case until coal and gas-fired power plants only contribute to a minor extent to the German electricity mix. The example of the BEV car with the electricity mix from Denmark shows that higher renewable shares in the electricity mix have a swift impact on GHG emissions. The results also show that no significant effects on GHG emissions are achieved with the current strategy of blending small amounts of renewable fuels with fossil fuels (B7 and E10). On the other hand, the limited potential of climate-friendly energy carriers must be taken into account here, as well as the fact that all renewable energy can be used for other purposes, which results in competition over its use.

A look to the future suggests that, based on current trends in the vehicle sector, vehicle electrification, which includes fuel cell cars, is set to increase. It can be assumed that there will be a rise in battery electric and fuel cell trucks, at least in regional freight transport. To ensure a positive effect on the climate, electricity and hydrogen with low production-related GHG emissions must be available in appropriate quantities. Residue-based fuels, whose production is already associated with low GHG emissions today, have a comparatively low potential for improvement. From an LCA perspective, it will be crucial to reduce GHG emissions in other sectors, such as steel and aluminum production. This would reduce GHG emissions overall for all vehicles.

Excursus 8: Bio-CNG in urban public transport – a practical example from Augsburg

The city of Augsburg, which today has a population of almost 300,000, committed to operating climate-friendly buses as early as 1995. Since 2006, Augsburg's public utility company has primarily procured natural-gas powered buses so that the entire bus fleet has been running on natural gas since 2010. Since 2011, the buses have been powered by climate-friendly biomethane made from residual and waste materials, which is purchased and counts towards the GHG target.

In 2021 the fleet of buses consisted of 82 vehicles, including 14 articulated buses with a hybrid module. These are particularly efficient because they reduce biomethane consumption with the help of an electric engine through energy recovery during braking and drive support when the buses start up. By 2025, a further 35 CNG buses – then 15 years old on average – will be replaced by hybrid buses. The annual mileage of the bus fleet is approx. 5 million km with a gas consumption of approx. 2,350 metric tons of biomethane per year. The gas consumption of the new hybrid buses is about 20 % lower than that of the older CNG buses.

The biomethane bus fleet of the city of Augsburg reduces greenhouse gas emissions by 6,000 to 6,500 metric tons annually compared to a fleet that is powered by diesel. Augsburg's public utility company has received several awards for its environmental commitment and serves as a role model and advisor to many municipalities who wish to convert their public transport to one that is powered in a climate-friendly way.

8 Economic aspects of sustainability

Niels Dögnitz, Hendrik Etzold and Kathleen Meisel

8.1 Economic evaluation

For more information:

The aim of an economic evaluation is to test the economic benefit of concepts or technologies on the basis of reference concepts. This requires a uniform framework in the form of a system boundary. Without a defined system boundary, no adequate comparison of several options be made. The relevant boundaries for the concepts considered here are generally identified as feedstock provision, biomass conversion and production, distribution, and utilization.

These system boundaries are defined in Figure 8-1, whereby the results of prior system boundaries are included in subsequent ones. The first system boundary encompasses supply and includes all steps in supplying the feedstocks. All costs pertaining to the supply of feedstocks can be derived from this. The most common target value of the evaluation is the manufacturing cost. This includes all incurred costs (capital, consumption, operating and other costs) as well as revenues from the production process. Distribution costs are calculated by adding the cost of distribution to the manufacturing cost. In order to determine the consumer price, other cost items must be included, mainly taxes, profit and fees.

The data analysis below is based on the following system boundaries:

- the product manufacturing costs for energy carriers in the demonstration phase and
- the distribution costs (which were equated here to wholesale prices) for commercially available energy carriers.

This distinction means that the aforementioned costs can only be compared fairly within the same system boundary. A comparison between energy carriers in the demonstration phase as well as between commercially available energy carriers is only possible to a limited degree. A comparison outside the different system boundaries is further complicated by the fact that other conditions for market introduction must be met in addition to the pure manufacturing costs. Such hurdles to a market launch can include, for example, the adaptation or development of engines, the establishment of suitable production capacities and their associated capital expenditures, the development of distribution routes and refueling or charging infrastructure, and the development of a consumer market.

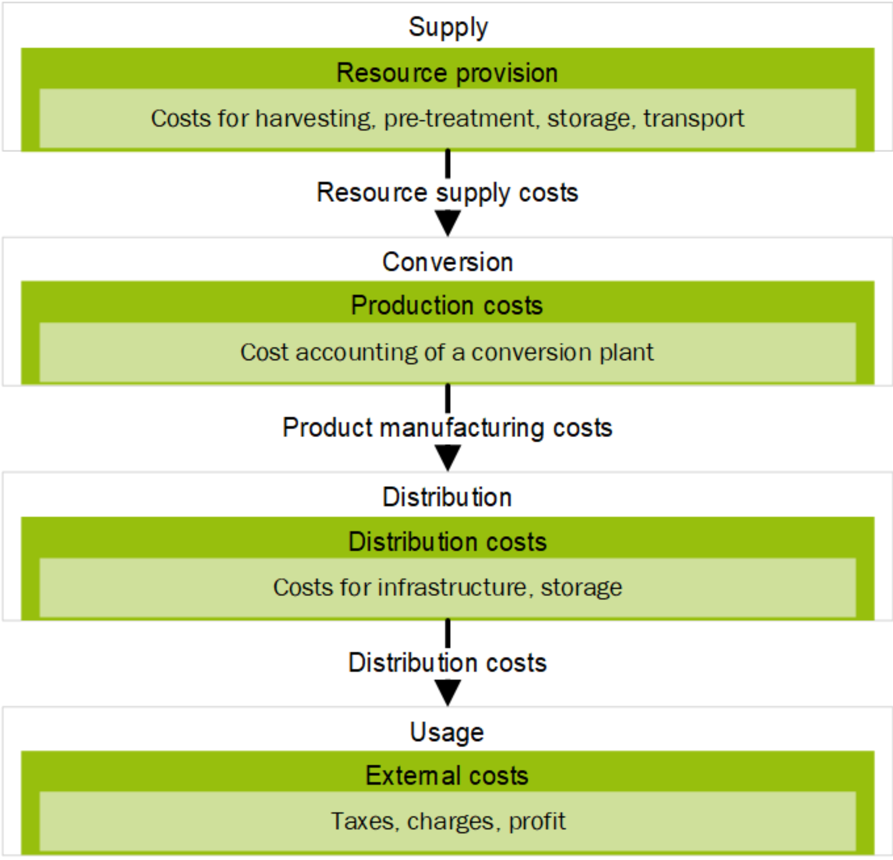

Figure 8-1 Simplified illustration for defining the system boundaries in the economic evaluation

8.2 Costs and prices of commercially available renewable energy

Currently, various types of commercially available biofuels are being traded on the global market. The costs of these biofuels usually highly depend on feedstock costs; when produced in large-scale plants, they can constitute 80 to 90 % of the total cost [Naumann (2019)]. Therefore, the development of specific feedstock and product prices for the commercially available fuels is also discussed below. Prices for agricultural feedstocks are generally very volatile. The seasonal fluctuations and regional differences result from a fluctuating supply (e.g., due to strong or weak harvest years) and from the varying intensity of demand in the sectors where they are used (above all food, animal feed, energy). In addition, there are special effects that can also affect the entire global economy, such as the COVID-19 pandemic in 2020. Further cost items relating to feedstocks and fuels were taken from selected studies and can be found in Table A-4.

8.2.1 Bioethanol

Figure 8-2 summarizes the price developments for bioethanol (U.S.) and bioethanol (EU). It also compares the prices of fossil gasoline (energy in EUR/GJ) and of wheat as a feedstock as well as the by-product DDGS (mass in EUR/t). The U.S. price for bioethanol is consistently lower than the EU price due to lower production costs and higher feedstock availability. This difference had grown significantly by mid-2020 but had disappeared completely by mid-2021. While it was less than 10 EUR/GJ in 2018, it had widened to more than 20 EUR/GJ by 2020. The prices for wheat and DDGS tend to run in parallel, with the price of DDGS feed averaging about 50 EUR/t more than the price of wheat.

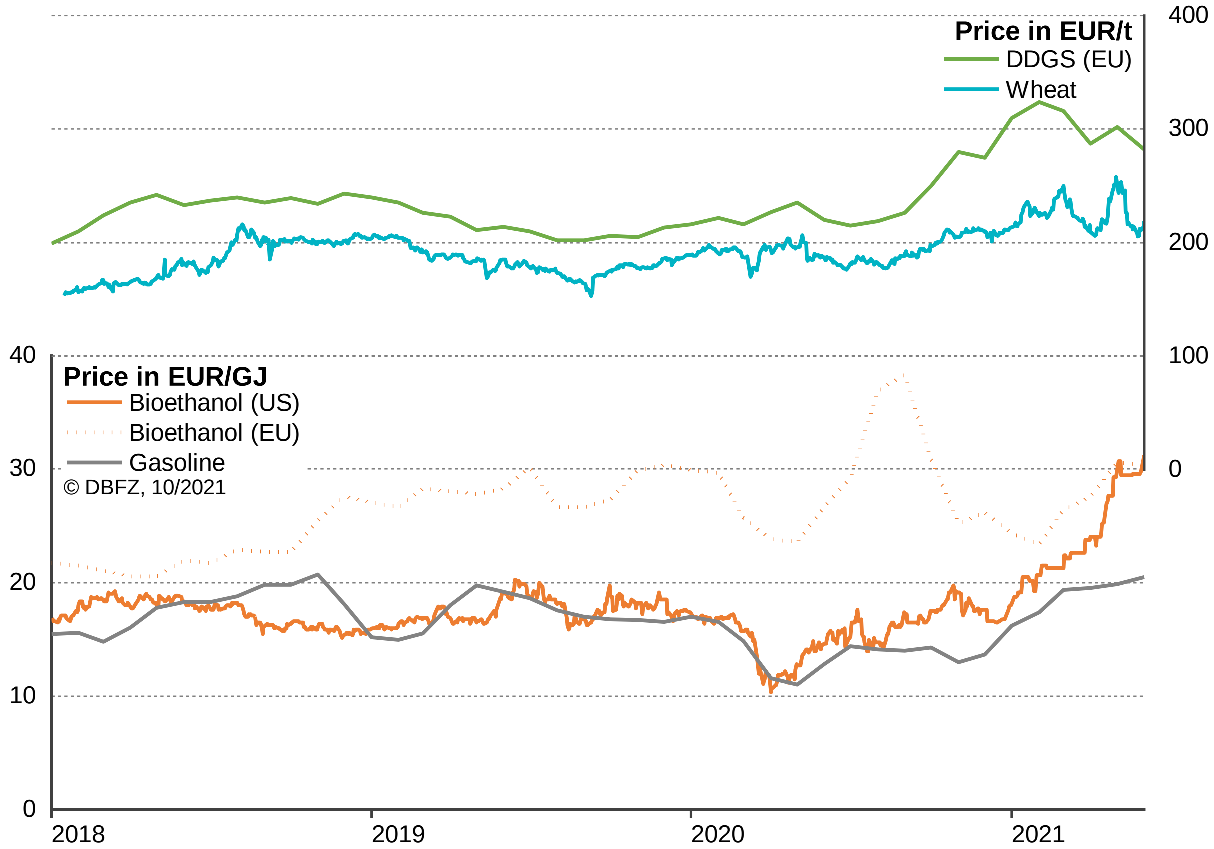

Figure 8-2 Price development of bioethanol and fossil gasoline (wholesale prices excluding taxes) as well as wheat and DDGS from January 2018 to June 2021. Data based on [finanzen.net (2020a), (2020b); IHS Markit (2018)-(2020); Mineralölwirtschaftsverband e.V. (2020)]

8.2.2 FAME

Vegetable oil, which is the main feedstock used to produce FAME and HVO/HEFA (hydrotreated vegetable oils/hydroprocessed esters and fatty acids) has been subject to moderate price fluctuations in recent years. The nominal (i.e., not adjusted for inflation) price development of rape seed, soy bean and palm oil used in biodiesel production as well as used cooking oil (UCO) is summarized in Figure 8-3. All feedstock prices (mass in EUR/t) remained at a more or less constant level until mid-2019. They were 700 to 800 EUR/t for rape seed oil, 600 to 700 EUR/t for soy bean oil and UCO, and 450 to 600 EUR/t for palm oil. In June 2019, the FAO price index for oil seeds began rising steadily, driven mainly by palm oil prices. The reason for the sharp increase was high demand, especially from the biodiesel sector, coupled with a shrinking supply. [AMI (2020)] The subsequent fluctuations were mainly related to the effects of the COVID-19 pandemic. After a sharp drop during lockdown in the second quarter of 2020, prices rose continuously almost without exception until 2021 with no foreseeable peak at the time of printing. It should be noted that, unlike vegetable oils, UCO is currently not yet being traded on a commodity exchange; instead, it is being traded bilaterally. However, the UCO price has historically been at about the same level as crude rape seed and soy bean oil. The impact of the COVID-19 pandemic is also reflected in the price of fossil crude oil, which is also included here as an indicator of global economic development. It dropped sharply in spring 2020 and was around 300 EUR/t in the second half of 2020. Before then, the crude oil price had remained relatively constant for years.

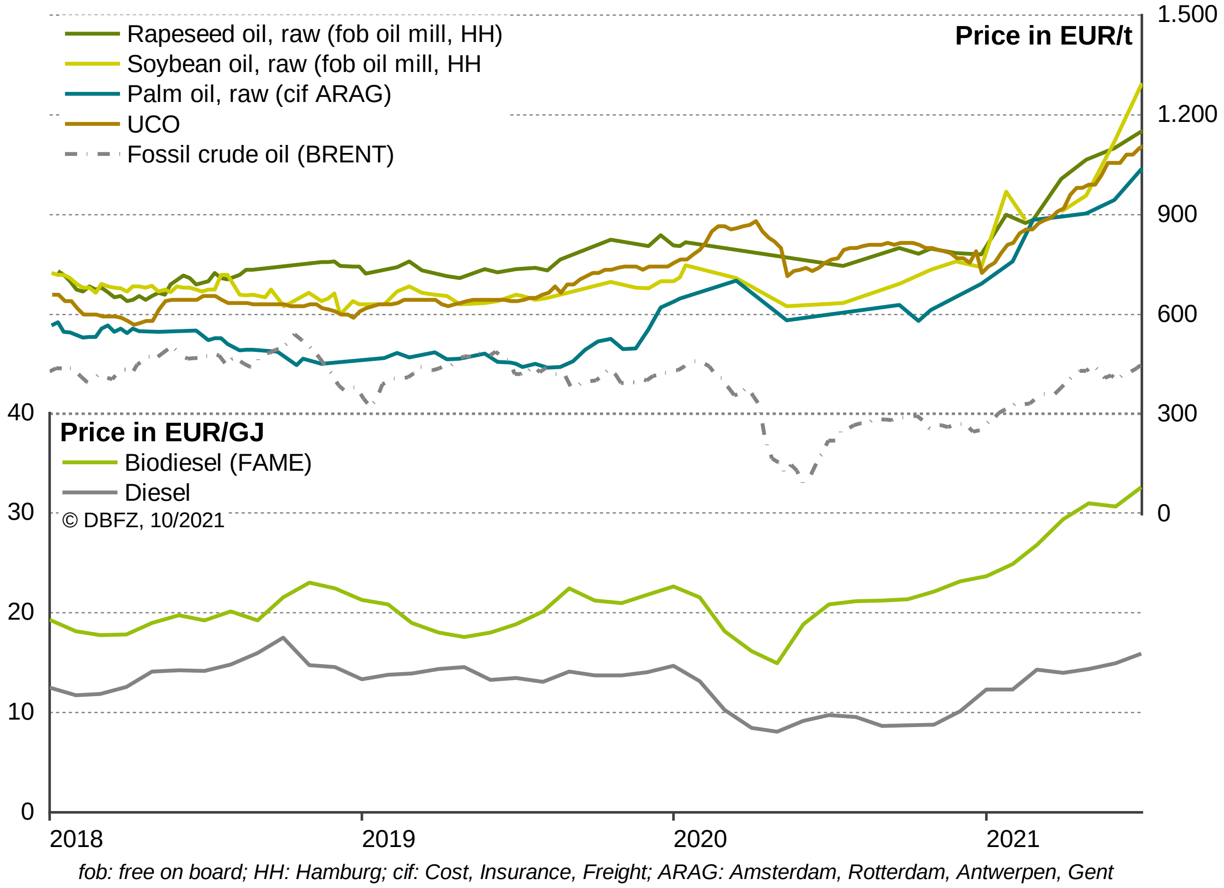

Figure 8-3 Price development of various vegetable oils, used cooking oil (UCO) and fossil crude oil as well as of FAME and fossil diesel from January 2018 to June 2021. Note: wholesale prices excluding taxes for FAME and diesel; data based on [AMI (2020); Greenea (2020); Mineralölwirtschaftsverband e.V. (2021)],

Using the vegetable oil directly as vegetable oil fuel, for example in agriculture and forestry, is the most economic option. Costs can be kept low through self-production and direct utilization without conversion.

Figure 8-3 also shows the wholesale prices for biodiesel and fossil diesel (energy in EUR/GJ). The price for FAME has been relatively constant for years at slightly above 30 EUR/GJ (1,000 to 1,300 EUR/t). While the difference between fossil diesel and FAME ranged from 3 to 7 EUR/GJ until 2020, this increased to up to 13 EUR/GJ in 2020. Prior to this, both prices fell sharply in the second quarter of 2020 in line with commodity prices; a key aspect here is likely to be the much lower fuel sales as a result of the COVID-19 lockdown. While the price of FAME made a strong recovery over the course of the year - even reaching its ten-year high, the price of fossil diesel remained low and had only increased slightly by the end of the year.

8.2.3 HVO/HEFA diesel

The established conversion pathways for HVO and HEFA still only make up a small proportion of the fuel market. Market prices for these products are often only determined on a bilateral basis. There is no trading platform with publicly available prices, so product unit costs from study data are used (broken down by three feedstocks in Figure 8-4). While fuels made from residues, waste and UCO are attractively priced fuel options, plant-based HVO/HEFA (see figure for various feedstocks) cannot compete with the other commercially available biofuels.

In Europe, the sales market for the residual and waste materials listed in Annex IX A of RED II will be good in the coming years due to the successively increasing sub-quotas for these fuels. This advantage will be magnified in Member States where there is multiple counting towards the total quota - such as in Germany (Section 1.5.1).

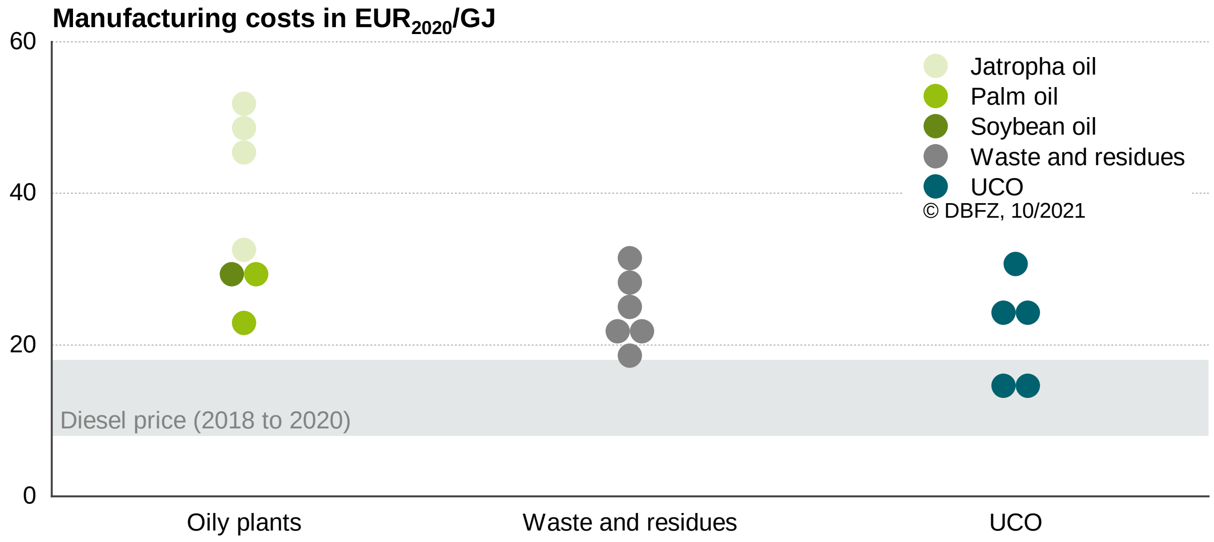

Figure 8-4 Product manufacturing costs of established conversion pathways for HEFA and HVO broken down by feedstock. Note: costs from the studies are adjusted for inflation to the year 2020; own calculation based on data from [aireg (2015); Bullerdiek (2019a); Capaz (2021); Hamelinck (2021); IEA Bioenergy (2020b); Jafri (2019); Jong (2015); Kalligeros (2018); Lorenzi (2019); Neuling (2018)]

8.2.4 Biomethane

The wholesale prices of biomethane can fluctuate strongly depending on the feedstock used and the type of trade (short-term/long-term). Feedstock dependency also varies according to the sector in which it is utilized and the framework conditions established there (electricity: Renewable Energy Sources Act EEG/RED, fuel in transport: GHG quota in BImSchG), which provide special compensation for biomethane made from certain biomasses. According to a study by the German Energy Agency (dena), the average purchase prices of biomethane from different feedstocks without direct assignment to the respective market were:

- for short-term trading in 2021:
  16.00 EUR/GJ (manure), 14.30 EUR/GJ (waste) and 14.30 EUR/GJ (renewable resources)
- for long-term trading in 2021:
  19.00 EUR/GJ (manure), 15.00 EUR/GJ (waste) and 17.30 EUR/GJ (renewable resources)

[dena (2021b)]

The data from the German Energy Agency are based on survey data from a limited group of participants and are therefore only partially reliable. Landwärme GmbH, which is both a producer and trader of biomethane, indicates an average wholesale price of 15.54 EUR/GJ for 2021 (January to September) for biomethane based on waste and residual materials. For advanced biomethane, the price is around 22.40 EUR/GJ (August to September 2021).

According to the BMWi, the price of biomethane-based CNG between June 2020 and June 2021 averaged 1.097 EUR/kg or 21.94 EUR/GJ (Group H Gas) and is thus at the same level as natural gas CNG at 1.098 EUR/kg [BMWi (2021)]. When the VAT of 3.50 EUR/GJ and the energy tax of 3.86 EUR/GJ are deducted, the price of biomethane excluding tax amounts to 14.58 EUR/GJ. Additional cost items such as biomethane compression, financing the filling station infrastructure, and profit margins result in a deficit between the average purchase price of biomethane and the price of biomethane when it is sold as a fuel. The biomethane is thus passed on to the end customer at prices than are lower than were paid to purchase it. This deficit can only be compensated for by additional revenue from the marketing of the low emission values of biomethane, so-called quota trading (Section 1.5.1).

8.2.5 Electricity

As electromobility increases in the transport sector, the electricity price for end consumers needs to be regarded in the same way as prices for renewable fuels. For the years 2018 to 2020, the Federal Statistical Office calculates an end consumer price of between 28.78 and 30.88 cents/kWh including all taxes, with slight fluctuations over the years [Destatis (2021b)]. This corresponds to 80 to 86 EUR/GJ. The German Federal Ministry for Economic Affairs and Energy (BMWi, renamed Federal Ministry for Economic Affairs and Climate Action in December 2021) published an average price of 27.4 cents/kWh (76 EUR/GJ) for 2020 [BMWi (2021)]. It is not possible to make a direct comparison with other fuel options as the energy can be used more efficiently in electric cars. The RED II established an adjustment factor for drive efficiency of 0.4 (see Section 1.5.1), which reflects this higher energy efficiency. Taking this into account, the above-mentioned cost of 80 EUR/GJ could be lowered to around 32 EUR/GJ when comparing it other renewable energy carriers in transport. A figure in euros per km would be a good comparative parameter to make individual, model-related comparisons.

Costs range widely for the provision of renewable energy as this is influenced quite significantly by external circumstances. Costs for photovoltaics range from 10 to 32 EUR/GJ, for wind (onshore) 11 to 23 EUR/GJ and for wind (offshore) 21 to 39 EUR/GJ. [Fraunhofer ISE (2018)]

Charging at public charging points is also becoming increasingly important, especially in large cities. There is currently no overview of the average cost of the public infrastructure for these electricity prices. The charging station providers do not use comparable fee structures. In some cases, billing is based only on consumption, while in other cases there is a subscription model for frequent drivers or there is a basic fee combined with lower rates for electricity. Prices vary between 32 cents/kWh and 49 cents/kWh, while charging stations not tied to a contract sometimes charge much higher prices [ADAC (2020)].

8.3 Cost of renewable energy in the demonstration phase

The competitiveness of renewable energy carriers in the demonstration phase depends on many factors, one important one being manufacturing costs. There are also legal regulations that can sometimes compensate for any economic disadvantages of these options and increase competitiveness, for example, the GHG abatement quota and the sub-quota for advanced biofuels (Section 1.5). Flexible use of energy carriers and the cost of investment in new facilities can also play an important role.

Figure 8-5 shows the product manufacturing costs for the individual forms of renewable energy. More than 60 international studies published after 2015 were evaluated. These studies performed independent and comprehensive calculations to determine the manufacturing costs. The results were normalized to the year 2020, taking inflation and currency conversion into account, and then compared. In addition, corresponding reference lines were inserted for better comparability with the price range for fossil fuels. These can vary widely depending on the state of the art, the site-specific plant concepts and the associated costs for investments, reactants and plant operation, as well as the methodology used to calculate cost. The different assumptions lead to large fluctuations, especially for concepts with a low TRL. The median can serve as an orientation for a weighted value from all cited studies. The most favorable fuel costs often result from pathways that use residual and waste materials. These are usually calculated with very low feedstock prices, however the limited availability of these feedstocks should be taken into account. The cost of pathways that use lignocellulosic feedstocks are often two to four times higher than for the fossil reference. Pathways that use electricity from renewable sources as an energy carrier are usually (much) higher than this value. Only a handful of studies have identified pathways that can compete at current fossil fuel prices. For all options, a subsidy or CO_2 price is therefore necessary before they can be established. The graph therefore only provides an indication of how individual options can be classified in terms of their manufacturing costs. In addition to the investments, the costs for providing the biomass or the electricity are usually the determining factors. An overview of the range of the various fuel options is also provided by the impact assessment from the draft revision of the RED II; this largely reproduces the ranges shown below [COM(2021) 557 (2021)].

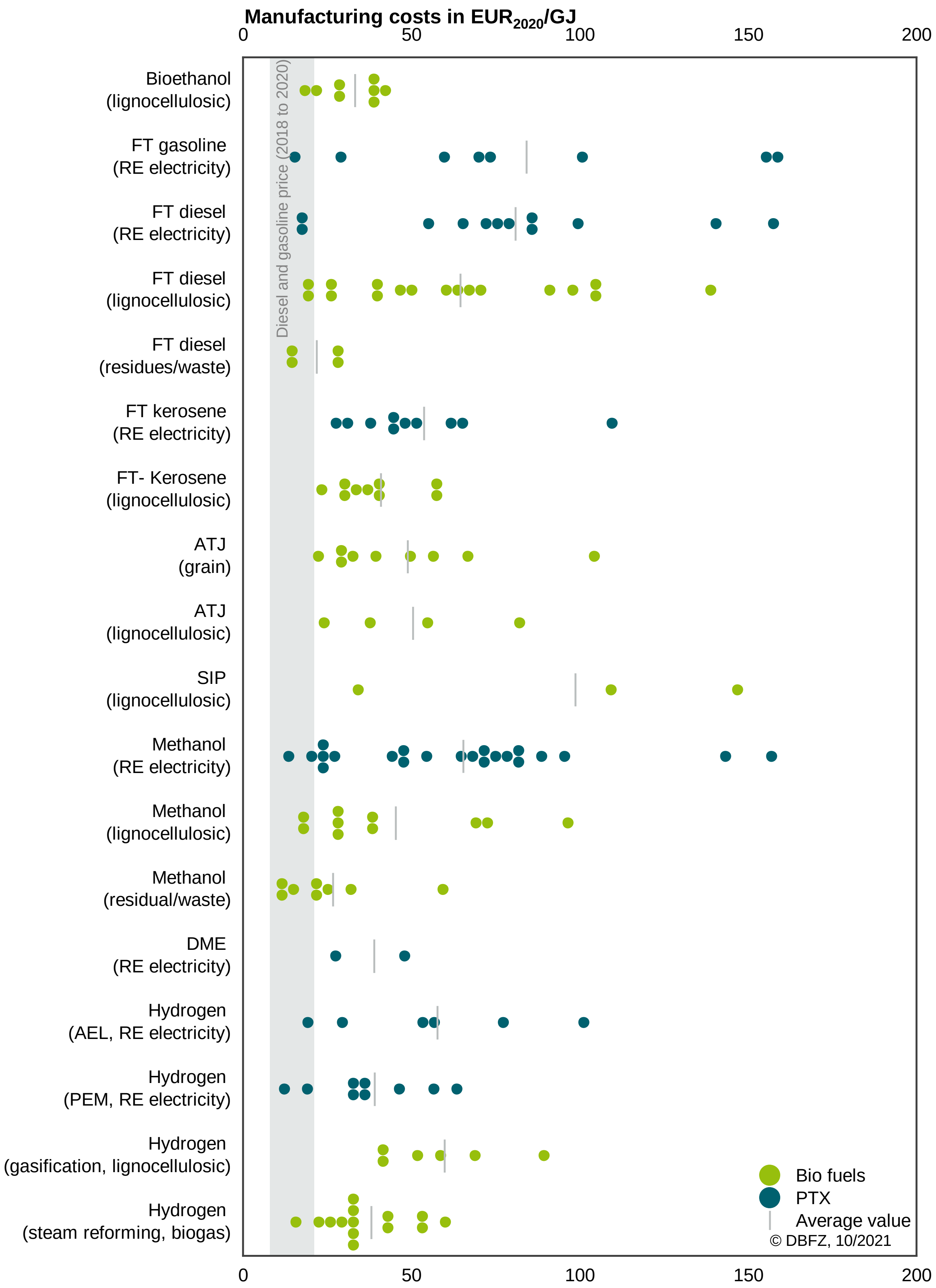

Figure 8-5 Product manufacturing costs of future energy carriers. Note: costs from the studies shown adjusted for inflation to the year 2020; own calculation; data based on [Aierzhati (2021); aireg (2015); Albrecht (2017); Atsonios (2016); Becker (2012); Buddenberg (2016); Bullerdiek (2019a); Butera (2021); Capaz (2021); Chen (2021);

Cihlar (2020); Di Marcoberardino (2018); Fasihi (2016); Fernández-Dacosta (2019); Gröngröft (2014); Guzmán (2020); Heneka (2020); IEA Bioenergy (2020b); Jafri (2019); Jong (2015); Kalligeros (2018); Kang (2017); Kenkel (2020); Klein-Marcuschamer (2013); König (2015); König (2016); LBST (2016); Lepage (2021); Liebich (2020); Macrelli (2012); Mauerhofer (2020); Millinger (2017); Millinger (2021); Minutillo (2020); Moretti (2021); Neuling (2018); Ordóñez (2020); Peters (2020); Rajabihamedani (2018); Reeve (2020); Ricardo Energy & Environment (2016); Timmerberg (2019); Tremel (2015); UBA (2016); Uddin (2020); Valente (2019); Varone (2015); Veipa (2020); Wang (2014); Yan (2020); Yao (2017); Yates (2020); Zech (2015); Zech (2016)]

8.4 Greenhouse gas abatement costs

The instrument of a GHG quota creates a separate market in Germany for the options approved to fulfil this target. Here, one of the decisive criteria for establishing competitiveness are the GHG abatement costs of these fulfillment options. Taking into account other market conditions, renewable fuels that exhibit the highest GHG savings compared to the fossil reference and have the lowest additional costs are the ones that are placed on the market first. The renewable energy carriers that have contributed to meeting the GHG quota in recent years - or are likely to do so in the near future - are FAME, bioethanol, HVO/HEFA, biomethane and electricity [Zoll (2020)]. Market prices, the actual GHG emissions calculated during the sustainability certification process (BLE) and fixed emission factors (UBA) and/or actual average reported GHG emissions (UBA) are available for these energy carriers. GHG abatement costs are calculated as follows:

$$k_{GHGA} = \frac{P_{renewable} - P_{reference}}{e_{reference} - e_{renewable}}$$

k_{GHGA}	GHG abatement cost of the renewable fulfillment option [EUR/t CO_2-eq.]
$P_{renewable}$	Market price of the renewable fulfillment option [EUR/GJ]
$P_{reference}$	Market price of the fossil reference [EUR/GJ]
$e_{renewable}$	GHG emissions of the renewable fulfillment option [g CO_2-eq./MJ]
$e_{reference}$	GHG emissions of the fossil reference [94.1 g CO_2-eq./MJ until 2020]

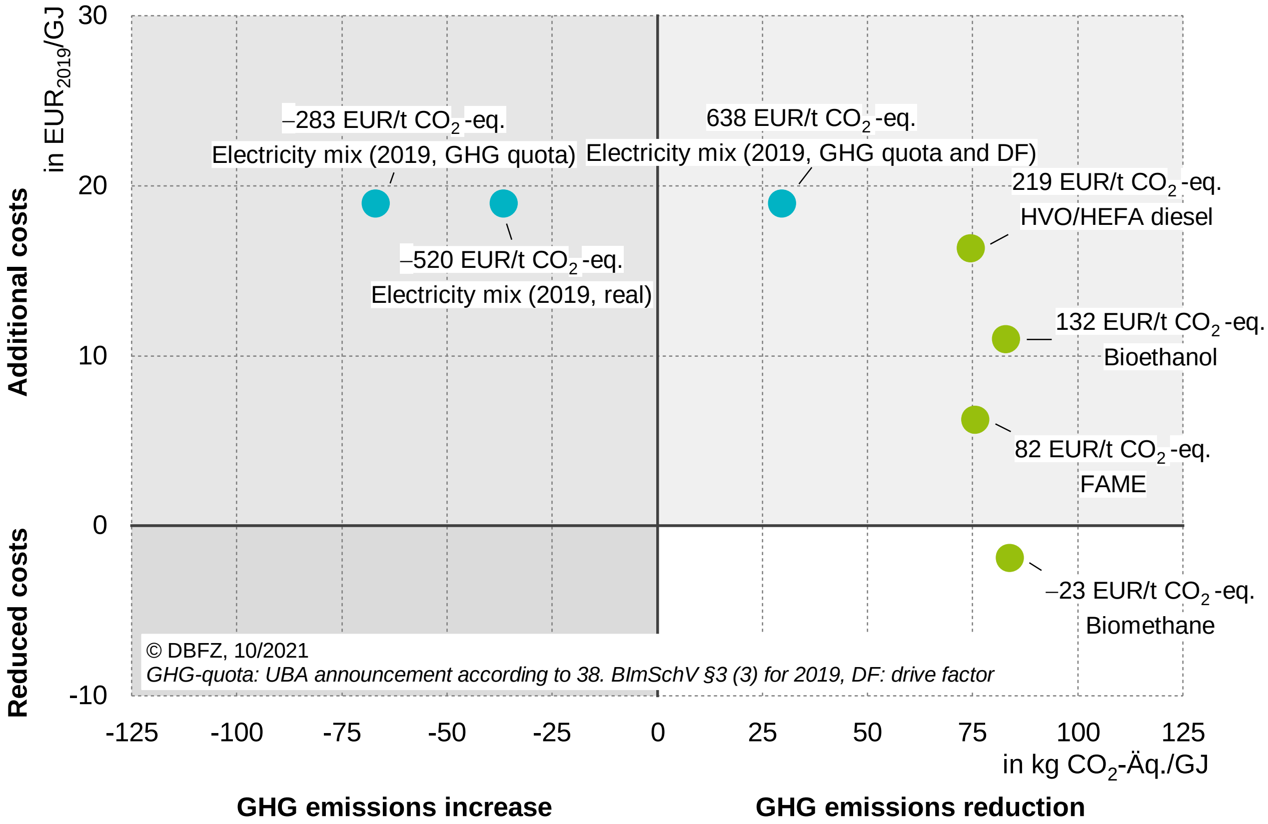

Figure 8-6 Selected GHG abatement costs based on additional costs and GHG savings relative to the fossil reference. Note: base year 2019; data as averages; based on data from Figure 7-2, Figure 8.2.4, Figure 8.2.5, Figure 8-3, Figure 8-4 and Figure 8-5

Figure 8-6 shows the GHG abatement costs for selected renewable energy carriers. The parameters GHG savings and additional costs (each relative to the fossil reference) span four different quadrants. Both additional costs (positive values) and reduced costs (negative values) are possible in comparison to the respective fossil reference. Similarly, the renewable options can have both lower GHG emissions (positive GHG savings values) and higher GHG emissions (negative GHG savings values) compared to the respective fossil reference. There are three different GHG abatement costs for electricity use in 2019. Similarly, the renewable options can have both lower GHG emissions (positive GHG savings values) and higher GHG emissions (negative GHG savings values) compared to the respective fossil reference. There are three different GHG abatement costs for electricity use in 2019. Taking into account the adjustment factor of 0.4 for the drive efficiency of electric engines (Section 8.2.5), these amount to 638 EUR/t CO_2-eq. They are significantly higher compared to the other renewable energy carriers. Thus, higher additional costs have to be spent to achieve GHG savings. If this drive factor is not taken into account, there are no GHG savings, but rather additional emissions compared to the fossil reference and negative GHG abatement costs of -283 EUR/t CO_2-eq. and -520 EUR/t CO_2-eq. respectively. Since the preliminary estimate of the GHG emissions of the electricity mix for 2019 was higher than the actually emitted GHG emissions, excess emissions are higher than the fossil reference and there is a lower negative value for the GHG abatement costs from the preliminary estimate. Of the fuel options not based on electricity, biomethane has the lowest (and even negative) GHG abatement costs of -23 EUR/t CO_2-eq. because the biomethane price is lower than the natural gas price. Here, the negative costs indicate a very favorable savings option since a high GHG saving can even be achieved at a reduced cost compared to the fossil reference. In the ranking of GHG abatement costs, FAME follows at 84 EUR/t CO_2-eq., bioethanol at 131 EUR/t CO_2-eq. and HVO/HEFA at 219 EUR/t CO_2-eq. It is also clear from the figure that, while bioethanol has higher GHG savings compared to FAME, it also has higher additional costs and thus higher overall GHG abatement costs compared to FAME. In an overall comparison, HVO/HEFA fuels are associated with the lowest GHG savings and highest additional costs among the biofuels. However, the ranking of renewables based on GHG abatement costs is obscured by many regulatory measures in the market; thus, other factors (e.g., blending limits, double counting, existing fuel markets and infrastructures in Germany and Europe, etc.) also play a role.

9 Technology fact sheets and overview

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9.1 Technology fact sheets

For more information:

The technology fact sheets below provide a summary of the information presented in the previous sections. The fact sheets are structured according to the type of energy carrier, with a focus on usage. The top half of the fact sheet looks at the supply context of these energy carriers and the correspondingly suitable technologies along with their possible feedstocks and implementation potentials, existing and planned production volumes, GHG emissions, and manufacturing costs or prices. The bottom half of the fact sheet includes the application aspects of these energy carriers in the transport sector. Table 9-1 describes the system and structure of the fact sheets.

Table 9-1 Legend for technology fact sheet

ENERGY CARRIER	(biomass-based)	(electricity-based)
Production technology	Brief description of the main process steps used to produce the energy carrier; Section 3 (technology options in the research phase - TRL 1 to 4 - are not presented in the fact sheet)	
Commercialization (TRL 9–11)	Listing of the process steps	Listing of the process steps
Demonstration (TRL 5–8)	Listing of the process steps	Listing of the process steps
Products	Listing of the products and potential derivatives	
Feedstocks	Identification of suitable energy carrier feedstocks; Section 4	
Commercialization (TRL 9–11)	Listing of potential feedstocks	Listing of potential feedstocks
Demonstration (TRL 5–8)	Listing of potential feedstocks	Listing of potential feedstocks
Potential	Listing of all feedstock potentials; Section 4.4	
Biogenic primary products	3-stage qualitative assessment of the utilizable feedstock potential for the transport sector (implementation potential based on Table 4-5)	
Biogenic by-products, residuals and waste		
Resources for e-fuels		
Production volumes	Listing of production volumes; Section 5.2	
Germany	t/a or m³/a or TWh and PJ/a	t/a or m³/a or TWh and PJ/a
Europe (incl. Germany)	t/a or m³/a or TWh and PJ/a	t/a or m³/a or TWh and PJ/a
World (incl. Europe)	t/a or m³/a or TWh and PJ/a	t/a or m³/a or TWh and PJ/a
Plant capacities	Listing of plant capacities incl. those that are existing, under construction and projected; Section 5.3	
Germany	t/a or m³/a and PJ/a	t/a or m³/a and PJ/a
Europe (incl. Germany)	t/a or m³/a and PJ/a	t/a or m³/a and PJ/a
World (incl. Europe)	t/a or m³/a and PJ/a	t/a or m³/a and PJ/a
GHG emissions	Listing of GHG emissions for the energy carrier, broken down by feedstock (does not include the entire range of feedstocks); Source data: BLE for certified annual averages in the GHG quota, the RED or RED II for default values, ISCC for guideline/standard values specifically for kerosene, and other sources for theoretical values from scientific publications using the RED methodology; Section 7	
Biogenic primary products	from … to …(feedstocks) [source]	
Biogenic by-products, residuals and waste	from … to …(feedstocks) [source]	
Resources for e-fuels	from … to …(feedstocks) [source]	

ENERGY CARRIER	(biomass-based)	(electricity-based)
Manufacturing costs	Listing of the manufacturing costs for the energy carrier, broken down by selected feedstocks (does not include the entire range of feedstocks, possible ranges also depend on available data); theoretical values from scientific publications; Section 8	
Biogenic primary products	from … to …(feedstocks)	
Biogenic by-products, residuals and waste	from … to …(feedstocks)	
Resources for e-fuels	from … to …(feedstocks)	
Trade prices	from … to … (for ethanol, FAME, vegetable oil and methane)	
Application	Application relates to the fuels defined as products	
Transport sector	Classified according to Figure 6-2, also for derivatives	
Fuel standard	Classified according to Section 6.1, also for derivatives Note: Fuel standards in **bold** are listed in the 10th BImSchV	
Hazard symbols	GHS symbols and warning labels (Section 6.3)	
Fueling infrastructure	Compatibility of the energy carrier with the existing infrastructure (Table 6-12), also for derivatives	
Vehicles in use	Compatibility of the energy carrier with the vehicles in use (Table 6-15), also for derivatives	
Vehicle emissions	Vehicle emissions for the energy carrier in relation to the fuels commonly used today (Section 7.7), also for derivatives	
Energy density	Energy density according to Table 6-14, also for derivatives	
Range equivalency	Range equivalency according to Table 6-14, also for derivatives	

Technology Fact Sheet 1: Bioethanol

Bioethanol		
Production technology		
Commercialization (TRL 11)	Sugar or starch-based: milling – (mashing) – fermentation (C6 yeasts) – distillation – by-product utilization	
Demonstration (TRL 8)		Lignocellulose-based: milling – pretreatment – hydrolysis – fermentation (C5/C6 yeasts) – distillation – by-product utilization
Products	Ethanol, (CO_2), derivatives: ATJ, ETBE	
Feedstocks		
Commercialization (TRL 11)	Biogenic primary products: (parts of) plants containing sugar and starch Suitable biogenic by-products (e.g., molasses), residuals and waste	
Demonstration (TRL 8)		Suitable biogenic by-products, residuals and waste (e.g., straw)
Potential		
Biogenic primary products	Primary crops and intermediate crops: low to limited	
Biogenic by-products, residuals and waste	Biogenic by-products, residuals and waste: limited	Biogenic by-products, residuals and waste: limited
Production volumes in 2020		
Germany	0.6 million m³/a or 13 PJ	
Europe (incl. Germany)	5 million m³/a or 108 PJ	
World (incl. Europe)	99 million m³/a or 2,077 PJ	
Plant capacities in 2021		
Germany	1 million m³/a or 23 PJ/a	0.001 million m³/a or 0.03 PJ/a
Europe (incl. Germany)	11 million m³/a or 227 PJ/a (incl. 25 PJ/a under construction/projected)	1 million m³/a or 27 PJ/a (incl. 23 PJ/a under construction/projected)
World (incl. Europe)	189 million m³/a or 3,965 PJ/a (incl. 769 PJ/a under construction/projected) ATJ-SPK: 0.06 million t/a or 3 PJ/a (incl. all suitable forms of alcohol as a feedstock)	6 million m³/a or 115 PJ/a (incl. 72 PJ/a under construction/projected)
GHG emissions		
Biogenic primary products	3 to 20 kg CO_2-eq./GJ (parts of plants containing sugar and starch) [BLE (2021b)] ATJ-SPK: 24 to 56 kg CO_2-eq./GJ (sugar cane, corn) [ISCC System GmbH (2020b)]	
Biogenic by-products, residuals and waste	5 kg CO_2-eq./GJ (residuals and waste) [BLE (2021b)]	16 kg CO_2-eq./GJ (wheat straw) [Richtlinie (EU) 2018/2001 (2018)]

BIOETHANOL		
Manufacturing costs		
Biogenic primary products	13 to 23 EUR_{2020}/GJ (sugar cane, sugar beets)	
Biogenic by-products, residuals and waste		18 to 43 EUR_{2020}/GJ (lignocellulose)
Trade prices (2020)	Bioethanol (EU): 24 to 38 EUR/GJ Bioethanol (US): 10 to 20 EUR/GJ	
Application		
Transport sector	Moped, passenger vehicles, light commercial vehicles, small land-based non-road vehicles ATJ-SPK: aviation	
Fuel standard	Ethanol: **DIN EN 15293** (E85), **DIN EN 228** (E5 and E10) ATJ-SPK: ASTM D7566 (max. 50 % v/v)	
Hazard symbol	Ethanol: ATJ-SPK:	
Fueling infrastructure	E85: Technical adjustments to established fueling infrastructure needed, global and local distribution infrastructure exists and is compatible ATJ-SPK: Compatible, but rarely approved by airport operators	
Vehicles in use	E85: Adjustments needed to materials that carry fuel and application in the engines of existing vehicles ATJ-SPK: Approved for blends up to 50 % v/v	
Vehicle emissions	E85: Comparable with gasoline according to EN 228 ATJ-SPK: Comparable with jet fuel according to ASTM D1655	
Energy density	E85: 29 MJ/kg and 23 MJ/l; ATJ-SPK: 44 MJ/kg and 33 MJ/l	
Range equivalency	E85: 1.7 ATJ-SPK: 1.0	

Technology Fact Sheet 2: Biodiesel (FAME)

FAME		
Production technology		
Commercialization (TRL 11)	Vegetable oil-based: oil production (extraction/pressing) – oil refining – transesterification – product separation – glycerol upgrading	Oil-based residuals: filtration – (oil refining) – esterification and transesterification – product separation – glycerol upgrading
Products	FAME, derivatives: possibly CP-HVO/HEFA via co-refining in petroleum refineries	
Feedstocks		
Commercialization (TRL 11)	Vegetable oils and fats from oil seeds or oil plants	Used cooking oils and fats, animal fats
Potential		
Biogenic primary products	Primary crops and intermediate crops: low to limited	
Biogenic by-products, residuals and waste		Industrial by-products and waste: low Other waste and residuals: low
Production volumes in 2020		
Germany	3 million t/a or 126 PJ	
Europe (incl. Germany)	11 million t/a or 409 PJ	
World (incl. Europe)	38 million t/a or 1,404 PJ	
Plant capacities in 2021		
Germany	4 million t/a or 144 PJ/a	
Europe (incl. Germany)	21 million t/a or 759 PJ/a (incl. 44 PJ/a under construction/projected)	
World (incl. Europe)	74 million t/a or 2,727 PJ/a (incl. 485 PJ/a under construction/projected)	
GHG emissions		
Biogenic primary products	20 to 28 kg CO_2-eq./GJ (soy bean oil, rape seed, palm oil) [BLE (2021b)]	
Biogenic by-products, residuals and waste		7 kg CO_2-eq./GJ (used cooking oil/fat) [BLE (2021b)]

FAME		
Manufacturing costs		
Biogenic primary products	8 to 23 EUR_{2020}/GJ (rape, soy bean, palm oil)	
Biogenic by-products, residuals and waste		18 to 30 EUR_{2020}/GJ (used cooking oil/fat)
Trade prices (2020)	15 to 23 EUR/GJ	
Application		
Transport sector	Passenger vehicles, light commercial vehicles, trucks, semi-trailer trucks, buses and coaches, land-based non-road vehicles, rail, inland waterway vessels	
Fuel standard	**DIN EN 14214** (B100), **DIN EN 590** (B7), DIN EN 16734 (B10), DIN EN 16709 (B20 and B30), DIN EN 15940 (B7)	
Hazard symbol	None	
Fueling infrastructure	B100: Technical adjustments to established fueling infrastructure needed, global and local distribution infrastructure exists and is compatible	
Vehicles in use	B100: Adjustments needed to materials that carry the fuel and application in the engines of existing vehicles	
Vehicle emissions	B100: Comparable with diesel according to EN 590	
Energy density	B100: 37 MJ/kg and 33 MJ/l	
Range equivalency	B100: 1.1	

Technology Fact Sheet 3: HVO/HEFA fuels

HVO/HEFA		
Production technology		
Commercialization (TRL 11)	Vegetable oil-based: Oil production (extraction/pressing) – hydrotreatment – (hydroisomerization/cracking) – product separation	Oil-based residuals: Filtration/dehydration/desalination – hydrotreatment – (hydroisomerization/hydrocracking) – product separation
Demonstration (TRL 8)		Biocrudes: Filtration/dehydration/desalination – (multi-stage) hydrotreatment – (hydroisomerization/ hydrocracking) – product separation
Products	Naphtha, SPK, diesel and other gaseous, liquid and solid paraffinic hydrocarbons	
Feedstocks		
Commercialization (TRL 9-11)	Vegetable oils and fats from oil seeds or oil plants	Used cooking oils and fats, animal fats, PFAD/POME, tall oil
Demonstration (TRL 7-8)		Biocrudes (supplied e.g., via pyrolysis or HTL)
Potential		
Biogenic primary products	Primary crops and intermediate crops: low to limited	
Biogenic by-products, residuals and waste		Industrial by-products and waste: low to limited Other waste and residuals: low
Production volumes in 2020		
Germany	None	
Europe (incl. Germany)	HVO: 3 million t/a or 149 PJ/a HEFA-SPK: unknown	
World (incl. Europe)	HVO: 6 million t/a or 274 PJ/a HEFA-SPK: unknown	
Plant capacities in 2021		
Germany	None	
Europe (incl. Germany)	HVO: 7 million t/a or 289 PJ/a (incl. 80 PJ/a under construction/projected) HEFA-SPK: unknown	
World (incl. Europe)	HVO: 23 million t/a or 1,009 PJ/a (incl. 81 PJ/a under construction/projected) HEFA-SPK: 0.9 million t/a or 38 PJ/a (incl. 33 PJ/a under construction/projected)	
GHG emissions		
Biogenic primary products	HVO: 19 kg CO_2-eq./GJ (palm oil) [BLE (2020)] HEFA-SPK: 37 to 47 kg CO_2-eq./GJ (rape seed and palm oil) [ISCC System GmbH (2020b)]	
Biogenic by-products, residuals and waste		HVO: 10 kg CO_2-eq./GJ (used cooking oil/fat and PFAD) [BLE (2021b)] HEFA-SPK: 14 to 21 kg CO_2-eq./GJ (used cooking oil/fat and PFAD) [ISCC System GmbH (2020b)]

HVO/HEFA		
Manufacturing costs		
Biogenic primary products	23 to 56 EUR_{2020}/GJ (palm oil, soy bean and jatropha)	
Biogenic by-products, residuals and waste		15 to 32 EUR_{2020}/GJ (used cooking oil/fat)
Application		
Transport sector	Passenger vehicles, light commercial vehicles, trucks, semi-trailer trucks, buses and coaches, land-based non-road vehicles, rail, ships, aviation	
Fuel standard	HVO: DIN EN 15940 (HVO100), **DIN EN 590** (ca. 26 % v/v) HEFA-SPK: ASTM D7566 (max. 50 % v/v)	
Hazard symbol	HVO:  HEFA-SPK: 	
Fueling infrastructure	HVO and HEFA-SPK: Compatible with established fueling and distribution infrastructure	
Vehicles in use	HVO: Software adjustments may be necessary in existing vehicles; possible incompatibilities due to lack of aromatics in the fuel HEFA-SPK: Possible incompatibilities due to lack of aromatics in the fuel	
Vehicle emissions	HVO: Comparable with diesel according to EN 590 HEFA-SPK: Comparable with jet fuel according to ASTM D1655	
Energy density	HVO: 44 MJ/kg and 34 MJ/l	HEFA-SPK: 44 MJ/kg and 33 MJ/l
Range equivalency	HVO: 1.0	HEFA-SPK: 1.0

Technology Fact Sheet 4: Vegetable oil

VEGETABLE OIL	
Production technology	
Commercialization (TRL 9-11)	Vegetable-oil based: Oil production (extraction/pressing) – oil refining
Products	Vegetable oil, derivatives: FAME, HVO/HEFA, possibly CP-HVO/HEFA via co-refining in petroleum refineries
Feedstocks	
Commercialization (TRL 9-11)	Vegetable oils and fats from oil seeds or oil plants
Potential	
Biogenic primary products	Primary crops and intermediate crops: low to limited
Plant capacities and production volumes	
Germany Europe (incl. Germany) World (incl. Europe)	Production capacities and volumes are very large and are increasing worldwide (Figure 4-11). Currently no significant use of vegetable oil as a fuel.
GHG emissions	
Biogenic primary products	31 to 33 kg CO_2-eq./GJ (rape seed, palm oil) [BLE (2021b)]
Prime costs	
Biogenic primary products	21 to 25 EUR/GJ (rape seed oil)
Trade prices (2020)	20 to 24 EUR/GJ (rape seed oil) 17 to 26 EUR/GJ (soy bean oil) 16 to 21 EUR/GJ (palm oil) 19 to 24 EUR/GJ (UCO)
Application	
Transport sector	NRMM
Fuel standard	**DIN 51605** (rape seed oil), **DIN 51623** (vegetable oil)
Hazard symbol	None
Fueling infrastructure	Compatible with established fueling and distribution infrastructure, local distribution infrastructure needs to be developed
Vehicles in use	Small number of vehicles exists Adjustments to materials that carry the fuel and application in engines needed
Vehicle emissions	Comparable with diesel according to EN 590
Energy density	38 MJ/kg and 35 MJ/l
Range equivalency	1.0

Technology Fact Sheet 5: Electricity

ELECTRICITY	
Production technology	
Commercialization (TRL 11)	Solar energy (photovoltaics) Wind energy (onshore) Wind energy (offshore) Hydroelectric power Geothermal energy Bioenergy
Demonstration (TRL 5-8)	Solar energy (solar power plants), tidal power plants
Products	Electricity, derivatives: hydrogen
Potential	
	Limited to high
Product volumes in 2019	
Germany	Electricity from renewable energy totaling 248 TWh (894 PJ), amount of electricity used in transport: 6.2 TWh (22.3 PJ)
Europe (incl. Germany)	Electricity from renewable energy totaling 1,485 TWh (5,344 PJ), electricity used in EU transport: 67 TWh (241 PJ)
World (incl. Europe)	Electricity from renewable energy totaling 7,159 TWh (25,772 PJ), electricity used in transport: 399 TWh (1,436 PJ)
GHG emissions	
Electricity (with DF = 0.4)	52 kg CO_2-eq./GJ (electricity mix 2019) [Icha (2021)] 3 kg CO_2-eq./GJ (photovoltaics) [Hengstler (2021)] 1 kg CO_2-eq./GJ (onshore wind) [Hengstler (2021)] 1 kg CO_2-eq./GJ (offshore wind) [Hengstler (2021)]
Manufacturing costs	
Electricity	10 to 32 EUR_{2020}/GJ (photovoltaics) 11 to 23 EUR_{2020}/GJ (onshore wind) 21 to 39 EUR_{2020}/GJ (offshore wind)
Application	
Transport sector	Moped, passenger vehicles, light commercial vehicles, semi-trailer trucks, buses and coaches, small land-based non-road vehicles, inland waterway vessels
Fuel standard	Not necessary
Warning symbol	(High-voltage symbol for electric cars)
Fueling infrastructure	Charging infrastructure (normal and fast charging points) under development, not compatible with established infrastructure
Vehicles in use	Vehicles under development Not compatible with established internal combustion engine vehicles
Vehicle emissions	None
Energy density	< 1 $MJ/kg_{battery}$ and 1 $MJ/l_{battery}$
Range equivalency	13.4

Technology Fact Sheet 6: Hydrogen

HYDROGEN	(biogenic)	(biogenic)	(electricity)
Production technology			
Commercialization (TRL 9-11)			AEL and PEMEL: electricity production – water treatment – electrolysis
Demonstration (TRL 5-8)	Steam reforming: mechanical pretreatment – (two-stage) reforming to synthesis gas with steam – WGS – gas purification (PSA)	Thermochemical gasification: mechanical and thermal pretreatment – thermochemical gasification – WGS – gas purification (PSA)	AEL and PEMEL: electricity production – seawater desalination – water treatment – electrolysis
Products	Hydrogen, (CO_2), derivatives: methane, methanol, FT products, DME, ammonia		
Feedstocks			
Commercialization (TRL 9-11)			Water, (renewable) electricity
Demonstration (TRL 5-8)	Biogas or biomethane	Logs, cultivated or waste wood, black liquor	Water, (renewable) electricity
Potential			
Biogenic primary products	See biomethane in Technology Fact Sheet 7	Primary forestry products: low	
Biogenic by-products, residuals and waste		Forestry by-products: low Industrial by-products and waste: low to limited	
Resources for e-fuels			Limited to high
Plant capacities in 2020			
Germany			46 MW electrolysis output (incl. 7 MW under construction/projected)
Europe (incl. Germany)			207 MW electrolysis output (incl. 129 MW under construction/projected)
GHG emissions			
Biogenic primary products	47 kg CO_2-eq./GJ (biogas) [Hajjaji (2016)]		
Biogenic by-products, residuals and waste		13 kg CO_2-eq./GJ (lignocellulose) [Hajjaji (2016)]	
Resources for e-fuels			PEMEL: 9 kg CO_2-eq./GJ renewable electricity [37. BImSchV (2020)]

Hydrogen			
Manufacturing costs			
Biogenic primary products	18 to 63 EUR_{2020}/GJ	42 to 93 EUR_{2020}/GJ	
Biogenic by-products, residuals and waste			
Resources for e-fuels			AEL: 19 to 104 EUR_{2020}/GJ PEMEL: 12 to 66 EUR_{2020}/GJ
Application			
Transport sector	Trucks, semi-trailer trucks, buses and coaches, rail, ships, aviation		
Fuel standard	**DIN EN 17124**		
Hazard symbol			
Fueling infrastructure	Fueling and distribution infrastructure for 350 bars and 700 bars under construction, not compatible with established infrastructure		
Vehicles in use	Vehicles being developed for 350 bars and 700 bars Adjustments needed to gasoline engines (modification of injection system, pressure tank) and possible material incompatibility if temperatures in combustion chamber are too high		
Vehicle emissions	None		
Energy density	120 MJ/kg, 3 MJ/l at 350 bars, 5 MJ/l at 700 bars and 9 MJ/l for LH2		
Range equivalency	7.9 at 350 bars, 4.7 at 700 bars and 2.6 for LH2		

Technology Fact Sheet 7: Methane

METHANE	(biomass)	(biomass)	(electricity)
Production technology			
Commercialization (TRL 9-11)	Anaerobic fermentation: (milling) – fermentation – gas upgrading – gas conditioning – (processing of fermentation residues)		
Demonstration (TRL 6)		Catalytic methanation: thermochemical gasification – WGS – gas conditioning – methanation – product separation	Catalytic methanation: electrolysis – CO_2 provision – RWGS – gas conditioning – methanation – product separation
Products	Methane, (CO_2), derivatives: hydrogen, methanol, FT products		
Feedstocks			
Commercialization (TRL 9-11)	Primary agricultural products, by-products and residues (including corn, slurry, straw). Biogenic waste: biowaste and green clippings, sewage sludge		
Demonstration (TRL 6)		Logs, cultivated or waste wood, black liquor, sewage sludge, pyrolysis oil, forestry by-products.	Water, (renewable) electricity, diffuse CO_2 sources and CO_2 point sources
Potential			
Biogenic primary products	Agricultural primary crops and intermediate crops: low to limited	Logs and cultivated wood: low to limited	
Biogenic by-products, residuals and waste	Biogenic by-products and waste: low to limited	Industrial by-products and waste: low to limited, Other waste and residuals: low	
Resources for e-fuels			Renewable electricity: limited to high, CO_2 point sources: low to limited, diffuse CO_2 sources: limited to high
Plant capacities in 2019			
Germany	1,014 million m³/a or 36 PJ/a		
Europe (incl. Germany)	1,892 million m³/a or 68 PJ/a		
World (incl. Europe)	2,380 million m³/a or 100 PJ/a		

METHANE			
GHG emissions			
Biogenic primary products	CNG: 14 kg CO_2-eq./GJ (silage corn) [BLE (2021b)]	CNG: 22 kg CO_2-eq./GJ LNG: 26 kg CO_2-eq./GJ (lignocellulose) [Alamia (2017)]	
Biogenic by-products, residuals and waste	CNG: 7 kg CO_2-eq./GJ (residuals and waste) [BLE (2021b)] LNG: 13.7 kg CO_2-eq./GJ (residuals and waste) [BLE (2021b)]		
Resources for e-fuels			CNG: 3 kg CO_2-eq./GJ (renewable electricity) [37. BImSchV (2020)]
Manufacturing costs			
Biogenic primary products	17 EUR_{2020}/GJ (renewable raw materials)		
Biogenic by-products, residuals and waste	16 to 19 EUR_{2020}/GJ (waste and slurry)		
Resources for e-fuels			32 to 62 EUR_{2020}/GJ (electricity)
Trade prices (2020/2021)	15 EUR_{2020}/GJ		
Application			
Transport sector	Trucks (> 12 t), semi-trailer trucks, buses and coaches, land-based non-road vehicles, ships		
Fuel standard	**DIN EN 16723-2** (CNG and LNG)		
Hazard symbol			
Fueling infrastructure	CNG: compatible with established global and local distribution infrastructure, expansion of fueling and distribution infrastructure needed LNG: fueling and distribution infrastructure under development, not compatible with established CNG infrastructure		
Vehicles in use	Small number of CNG vehicles exists, LNG vehicles under development No adjustments needed to CNG/LNG engines; adjustments needed to gasoline engines (modification of injection system, pressure tank) and possible material incompatibility if combustion temperatures are too high		
Vehicle emissions	No particle emissions		
Energy density	CNG: 50 MJ/kg and 8 MJ/l	LNG: 50 MJ/kg and 23 MJ/l	
Range equivalency	CNG: 5.0	LNG: 1.5	

Technology Fact Sheet 8: Methanol

METHANOL	(biogenic)	(electricity-based)
Production technology		
Demonstration (TRL 6–8)	Mechanical and thermal pretreatment – thermochemical gasification – WGS – gas conditioning – methanol synthesis – product separation	Electrolysis – CO_2 provision (diffuse and point sources) – RWGS – gas conditioning – methanol synthesis – product separation
Products	Methanol, derivatives: DME, MTG, MTJ, OME_n, DMC, MeFo, MTBE	
Feedstocks		
Demonstration (TRL 6–8)	Logs, cultivated or waste wood, black liquor, sewage sludge, forestry by-products	Water, (renewable) electricity, diffuse CO_2 sources and CO_2 point sources
Potential		
Biogenic primary products	Logs, cultivated wood: low to limited	
Biogenic by-products, residuals and waste	Industrial by-products and waste: low to limited Other waste and residuals: low	
Resources for e-fuels		Renewable electricity: limited to high, CO_2 point sources: low to limited, diffuse CO_2 sources: limited to high
Plant capacities in 2020		
World	2 million t/a or 33 PJ/a (incl. 32 PJ/a under construction/projected) an additional 0.3 million t/a or 4 PJ/a as SynBioPTL	0.7 million t/a or 11 PJ/a under construction/projected
GHG emissions		
Biogenic primary products	16 kg CO_2-eq./GJ (cultivated wood) [Richtlinie (EU) 2018/2001 (2018)]	
Biogenic by-products, residuals and waste	14 kg CO_2-eq./GJ (waste wood) [Richtlinie (EU) 2018/2001 (2018)] 10 kg CO_2-eq./GJ (black liquor) [Richtlinie (EU) 2018/2001 (2018)] 34 kg CO_2-eq./GJ (residual and waste materials) [BLE (2021b)]	
Resources for e-fuels		17 kg CO_2-eq./GJ (renewable electricity and CO_2 from biogas) [Bongartz (2018)]
Manufacturing costs		

METHANOL		
Biogenic feedstocks	18 to 97 EUR_{2020}/GJ (lignocellulose, note: not possible to differentiate between primary products and by-products) 12 to 62 EUR_{2020}/GJ (residual and waste materials)	
Resources for e-fuels		14 to 160 EUR_{2020}/GJ
Application		
Transport sector	Ships MTX: passenger vehicles, light commercial vehicles, land-based non-road vehicles, aviation	
Fuel standard	Methanol: **DIN EN 228** (M3) MTG: **DIN EN 228** (approx. 80 % v/v) MTJ: no existing standard	
Hazard symbol	Methanol: 	
Fueling infrastructure	M85/M100: Technical adjustments to established fueling infrastructure needed, global distribution infrastructure exists and is compatible, development of local distribution infrastructure necessary	
Vehicles in use	M85: Adjustments needed to materials that carry the fuel and application in the engines of existing vehicles	
Vehicle emissions	M85/M100: no particle emissions MTJ: Comparable to jet fuel according to ASTM D1655	
Energy density	M85: 23 MJ/kg and 18 MJ/l	
Range equivalency	M85: 2.2 MTG: 1.2 MTJ: 1.0	

Technology Fact Sheet 9: Fischer-Tropsch fuels

Fischer-Tropsch		
Production technology		
Demonstration (TRL 6–7)	Mechanical and thermal pretreatment – thermochemical gasification – WGS – gas conditioning – FT synthesis – fractionation and hydrotreatment	Electrolysis – CO_2 provision (diffuse and point sources) – RWGS – gas conditioning – FT synthesis – fractionation and hydrotreatment
Products	Naphtha, kerosene, diesel and other gaseous, liquid and solid paraffinic hydrocarbons	
Feedstocks		
Demonstration (TRL 6–7)	Logs, cultivated or waste wood, black liquor, sewage sludge, forestry by-products.	Water, (renewable) electricity, diffuse CO_2 sources and CO_2 point sources
Potential		
Biogenic primary products	Logs and cultivated wood: low to limited	
Biogenic by-products, residuals and waste	Industrial by-products and waste: low to limited Other waste and residual materials: low	
Resources for e-fuels		Renewable electricity: limited to high, CO_2 point sources: low to limited, diffuse CO_2 sources: limited to high
Plant capacities in 2021		
World	2 million t/a or 90 PJ/a under construction/projected	8 million t/a or 347 PJ/a under construction/projected
GHG emissions		
Biogenic primary products	FT diesel: 17 kg CO_2-eq./GJ (cultivated wood) [Richtlinie (EU) 2018/2001 (2018)] FT-SPK: 10 to 12 kg CO_2-eq./GJ (cultivated wood, miscanthus) [ISCC System GmbH (2020b)]	
Biogenic by-products, residuals and waste	FT diesel: 10 to 14 kg CO_2-eq./GJ (black liquor, waste wood) [Richtlinie (EU) 2018/2001 (2018)] FT-SPK: 8 kg CO_2-eq./GJ [ISCC System GmbH (2020b)]	
Resources for e-fuels		No known data based on the RED II methodology

Fischer-Tropsch		
Manufacturing costs		
Biogenic feedstocks	FT diesel: 15 to 141 EUR_{2020}/GJ FT SPK: 23 to 61 EUR_{2020}/GJ	
Resources for e-fuels		FT naphtha: 15 to 160 EUR_{2020}/GJ FT SPK: 28 to 113 EUR_{2020}/GJ FT diesel: 18 to 88 EUR_{2020}/GJ
Application		
Transport sector	Passenger vehicles, light commercial vehicles, trucks, semi-trailer trucks, buses and coaches, land-based non-road vehicles, rail, ships, aviation	
Fuel standard	FT diesel: DIN EN 15940, **DIN EN 590** (ca. 26 % v/v) FT naphtha: **DIN EN 228** (ca. 80 % v/v) FT-SPK: ASTM D7566 (max. 50 % v/v)	
Hazard symbol	FT diesel: FT naphtha: FT-SPK:	
Fueling infrastructure	FT diesel and FT-SPK: Compatible with established refueling and distribution infrastructure	
Vehicles in use	FT diesel: Software adjustments may be necessary to vehicles and incompatibilities may exist due to a lack of aromatics in the fuel FT-SPK: Incompatibilities may exist due to a lack of aromatics in the fuel	
Vehicle emissions	FT diesel: Comparable with diesel according to EN 590 FT-SPK: Comparable with kerosene according to ASTM D1655	
Energy density	FT diesel: 44 MJ/kg and 34 MJ/l FT-SPK: 44 MJ/kg and 33 MJ/l	
Range equivalency	FT diesel: 1.0 FT naphtha: 1.2 FT-SPK: 1.0	

9.2 Overview of the renewable energy carriers for the years 2030 and 2045

As things stand, a number of different energy carriers can be classified as "renewable" in accordance with the Renewable Energies Directive RED II. The type of feedstock determines which technology must be used to convert the energy carrier and which fulfillment option (that can be counted towards the GHG reduction quota) forms the basis. Table 9-2 illustrates the feedstock-based but technology-open approach of the RED II.

Table 9-2 Energy carriers broken down by production technology, feedstock and compliance with the RED II

Fulfillment option	Feedstocks (Figure 4-1)	Technologies (Section 3)	Energy carrier
Advanced biofuels and biogas according to Annex IX A	Algae, tall oil, biomass from food industry residues that contain oil and fat	(Trans)esterification	FAME
		Hydrotreatment	HVO/HEFA (naphtha, kerosene, diesel); HC-HEFA
		Hydrothermal liquefaction	HTL (naphtha, diesel); CHJ
	Residuals from the food industry that contain sugar and starch	Alcoholic fermentation	Ethanol and its derivatives ATJ-SPK, ETBE; SIP
		Anaerobic fermentation	Methane and its derivative H_2
	Lignocellulosic biomass	Anaerobic fermentation	Methane and its derivative H_2
		Alcoholic fermentation	Ethanol and its derivatives ATJ-SPK, ETBE; SIP
		Thermochemical gasification	Hydrogen, synthesis gas as an intermediate
		Methanization via thermochemical gasification	Methane
		Methanol synthesis via thermochemical gasification	Methanol and its derivatives DME, MTBE, MTG, MTJ, OME
		Fischer-Tropsch synthesis via thermochemical gasification	FT (naphtha, kerosene, diesel)
		Dimethyl ether synthesis via thermochemical gasification	DME
	Food and municipal waste, sewage sludge, liquid manure, crude glycerol	Anaerobic fermentation	Methane and its derivative H_2
		Hydrothermal liquefaction	CHJ
Biofuels and biogas according to Annex IX B	Used cooking oil/fat, animal fat (Categories 1 and 2)	Processing of used cooking oil	UCO
		(Trans)esterification	FAME
		Hydrotreatment	HVO/HEFA (naphtha, kerosene, diesel); HC-HEFA
		Hydrothermal liquefaction	HTL (naphtha, diesel); CHJ

Fulfillment option	Feedstocks (Figure 4-1)	Technologies (Section 3)	Energy carrier
Conventional biofuels	Primary biomass containing oil and fat	Mechanical and chemical extraction	Vegetable oil
		(Trans)esterification	FAME
		Hydrotreatment	HVO/HEFA (naphtha, kerosene, diesel); HC-HEFA
	Primary biomass containing sugar and starch	Alcoholic fermentation	Ethanol and its derivatives ATJ-SPK, ETBE; SIP
		Anaerobic fermentation	Methane and its derivative H_2
Electricity from renewable sources	Wind, solar, biomass, geothermal and hydropower	Various	Electricity
Green hydrogen	Electricity from renewable sources and water	Electrolysis	Hydrogen
e-fuels	Green hydrogen and carbon dioxide	Methanization via RWGS	Methane
		Methanol synthesis via RWGS	Methanol and its derivatives DME, MTBE, MTG, MTJ, OME
		Fischer-Tropsch synthesis via RWGS	FT (naphtha, kerosene, diesel)

The diagram in Figure 9-1 provides information on the fuels contained in the fact sheets based on various evaluation criteria (Table 9-3) and interpreted with respect to a possible classification by application area for Germany in the years 2030 (Figure 9-2) and 2045 (Figure 9-3). With a view to becoming climate neutral by 2045, electrification is to be preferred in all areas of transport due to the high potential for energy savings. However, for areas in which complete electrification is not possible - even in the long term - it is clear that pure renewable fuels must be used in a targeted manner alongside at least partial electrification of the drive systems. By 2030, well over 40 million vehicles will still have internal combustion engines that run on blended fuels made up of a fossil and a renewable component, similar to today's conventional fuels E10 and B7. By 2045, a much smaller percentage of vehicles with internal combustion engines will run on renewable energy carriers. The type of energy carrier depends heavily on the transport sector and the power required by the drive system.

The importance of electric **MOTORCYCLES** as a means of transport is set to increase by 2045, especially for short distances. **PASSENGER VEHICLES** and **LIGHT COMMERCIAL VEHICLES** (up to 3.5 t) can also be powered almost exclusively by electric battery. Other drive systems (combustion engine or electric drive with fuel cell) should no longer be competitive in these three segments due to their significantly poorer drive efficiency. From today's perspective, vehicles with internal combustion engines in 2030 will mainly run on today's conventional blended fuels, which will be made of a fossil and a renewable fuel component (ethanol: up to 10 % v/v, FAME: up to 7 % v/v, hydrotreated vegetable oils (HVO): up to 25 % v/v) and a new option, methanol-to-gasoline (MTG, also as a blended fuel). Appropriate regulatory adjustments (especially to the 10th BImSchV) would enable new options with a higher proportion of renewable resources or new pure fuel options to enter the market (e.g., HVO). At the same time, there will be a smaller number of hydrogen vehicles with fuel cells by 2030. The federal government aims to run most of these fuel cell vehicles on renewable hydrogen by then.

ROAD FREIGHT TRANSPORT is also expected to be electrified to a large extent by 2045. By then, battery-electric drive systems should be able to power commercial vehicles with a total weight of up to approx. 18 metric tons since the energy density of batteries continues to rise and charging points are becoming more widespread. The same applies to articulated and semi-trailer trucks in regional transport. A much broader range of drive systems and energy carriers can be expected for interregional heavy-duty transport. Currently, electric drives with fuel cells (hydrogen) or overhead lines, as well as internal combustion engines that use renewable liquefied methane (LNG), hydrogen and diesel substitutes such as Fischer-Tropsch and HVO diesel are under discussion. It is difficult to estimate which of these technologies will prevail or whether all options will coexist. In view of the fact that this segment involves a very high level of transnational transport, solutions will have to be found at the European level. By 2030, the same diesel substitutes used in passenger cars will probably be available for road-bound commercial vehicles with internal combustion engines; biomethane (LNG) and the first electric vehicles (battery and fuel cell) will also be available. The drive systems for **BUSES AND COACHES** will be very heterogeneous in the years 2030 and 2045, similar to road freight transport. While urban and regional transport can be electrified to a large extent (battery or fuel cell) by 2045, renewable liquid fuels (including LNG) are expected to rise in interregional transport, oriented towards heavy-duty road freight transport. By 2030, additional biomethane (CNG)-powered vehicles will be in use, especially for public buses. The liquid fuels in 2030 will be very similar to the options available today.

When it comes to non-road mobile machinery (NRMM), including **AGRICULTURAL, FORESTRY** and **CONSTRUCTION MACHINERY**, the choice of drive system and energy carrier highly depends on the performance requirements, as is the case with road freight transport, as well as buses and coaches. While low-powered NRMM will be able to have a high degree of electrification by 2030, more powerful machines will not be electrified to a large extent until 2045. Special machines will still have to run on liquid energy carriers in 2045, since they must achieve very high outputs on a seasonal basis (e.g., harvesters) and, for example, a fast recharging of batteries or refilling of hydrogen tanks is not possible due to local conditions (e.g., in forests or on construction sites). For all machines that cannot be electrified in the future, the same energy carrier options as in road freight transport are available. In addition, regionally produced vegetable oil fuel is an attractive option for agricultural and forestry machinery.

The majority of **RAIL VEHICLES** are already electrified today. They are powered by overhead lines over an extensive part of the rail network. Further rail lines are to be upgraded with overhead lines by 2045 so that only vehicles on a few branch lines and, for example, shunting locomotives or similar vehicles with independent drive systems will still be needed. Here, either battery- or fuel cell-powered rail vehicles can be used and, for the remaining stock of vehicles, renewable liquid diesel substitutes such as HVO or FT diesel. In both cases, rail vehicles can be quickly converted to renewable drives since there is a modest stock of vehicles and because rail transport mostly operates independently of other transport sectors.

MARITIME TRANSPORT AND AVIATION are cited as the most difficult transportation systems to electrify due to their high requirements for power and their international scope of activity. Smaller inland waterway vessels or light aircraft used for short distances, for example, are the most likely to be electrified. From today's perspective, most ships and aircraft will continue to require liquid fuels, which will be predominantly blended fuels with renewable components until 2030 and will only be fully renewable in the long term (possibly well after 2045). Renewable aviation fuels such as ATJ-SPK, hydrogen, HEFA-SPK or FT-SPK, as well as maritime fuels such as methanol, hydrogen, LNG, HVO-diesel and FT-diesel are possible candidates.

Looking ahead to 2045, it is conceivable that renewable options such as FAME or bioethanol, which are established today and will still be urgently needed in 2030, will become less important. The feedstocks used today for FAME - vegetable oils, waste and residual materials - can also be used, for example, in HVO/HEFA plants, which can produce a wider range of renewable fuel options (primarily diesel and kerosene) that are also suitable for the transport sectors that are difficult to electrify. Ethanol fuel, on the other hand, is mainly used today as a blended fuel in gasoline engines for passenger cars. These engines are expected to be the first to be displaced by electric drives, so there will be no need for bioethanol in road-based transport. The freed-up capacity could then be used for the production of ATJ kerosene or other applications.

In all transport sectors, other renewable energy carriers are being discussed as future options, for example ammonia in maritime transport or dimethyl ether (DME), oxymethylene ether (OME) and hydrogen as diesel substitutes. These energy carriers are currently still in a very early stage of development and are therefore not considered here.

Table 9-3 Assessment criteria for Figure 9-1. Note: reference manufacturing costs correspond to the average price of diesel in 2020

Criterion	0	1	2	3	4
Technology readiness level according to IEA	1 – 4		5 – 8		9 – 11
Potential	Low		Limited		High
GHG emissions (kg CO_2-eq./GJ)	> 50	30 – 50	20 – 30	10 – 20	< 10
Manufacturing costs (EUR_{2020}/GJ)	> 50	30 – 50	20 – 30	10 – 20	< 10
Standards and regulations for blended and pure fuel	None	Standard as blended or pure fuel	Standard as blended or pure fuel and listed in 10th BImSchV	Standard as blended and pure fuel	Standard as blended and pure fuel as well as pure fuel listed in 10th BImSchV
Hazardous substance classification for pure fuel (number of GHS symbols)	> 3	3	2	1	0
Fueling infrastructure for pure fuel	None	New infrastructure under development	Major adjustments to established infrastructure are necessary	Minor adjustments to established infrastructure are necessary	No adjustments to established infrastructure are necessary
Vehicle fleet for pure fuel	None	New vehicle fleet under development	Major adjustments to established vehicle fleet are necessary	Minor adjustments to established vehicle fleet are necessary	No adjustments to established vehicle fleet are necessary
Air pollutants (exhaust gas) for pure fuel in relation to gasoline, kerosene or diesel	All pollutants worse	Individual pollutants worse	No major differences	Individual pollutants omitted	No emissions
Range equivalency for pure fuel	> 10	5 – 10	1.5 – 5	1.2 – 1.5	1.0 – 1.2

	Resources	Technology readiness level	Potential of available energy	GHG emissions	Production costs		Standardization and regulation	Hazard classification	Filling station infrastructure	Vehicle fleet	Air pollutants (exhaust)	Vehicle range equivalent
Ethanol	biogenic primary products	4	0 to 2	0 to 4	2 to 3	Ethanol	4	2	3	3	2	2
	biogenic by-products	2 to 4	0 to 2	3 to 4	1 to 3	ATJ-SPK	2	1	4	4	2	4
FAME	biogenic primary products	4	0 to 2	2	2 to 4	FAME	4	4	3	2	2	4
	biogenic by-products	4	0	4	1 to 3							
HEFA/HVO	biogenic primary products	4	0 to 2	1 to 3	0 to 2	HEFA-SPK	2	1	4	4	2	4
	biogenic by-products	2 to 4	0	2 to 3	1 to 3	HVO-Diesel	4	3	4	4	2	4
Vegetable oil	biogenic primary products	4	0 to 2	1	2	Vegetable oil	2	4	3	2	2	4
Electricity	mixture DE 2019	4	2 to 4	0		Electricity	4	4	1	1	4	0
	photovoltaics	4	2 to 4	4	1 to 3							
	wind (onshore)	4	2 to 4	4	2 to 3							
	wind (offshore)	4	2 to 4	4	1 to 2							
Hydrogen	biogenic primary products	2	0 to 2	1	0 to 3	H_2 (350 bars)	4	2	1	1	4	1
	biogenic by-products	2	0 to 2	3		H_2 (700 bars)	4	2	1	1	4	2
	PTX feedstocks	2 to 4	2 to 4	4	0 to 3	LH2	4	2	0	0	4	2
Methane	biogenic primary products	2 to 4	0 to 2	2 to 3	3	CNG	4	2	3	1	3	2
	biogenic by-products	2 to 4	0 to 2	3 to 4	3							
	PTX feedstocks	2	2 to 4	4	0 to 1	LNG	4	2	1	1	3	3
Methanol	biogenic primary products	2	0 to 2	3	0 to 3	Methanol	2	1	1	3	3	2
	biogenic by-products	2	0	1 to 3		MTG	2	0				4
	PTX feedstocks	2	2 to 4	3	0 to 3	MTJ	0				2	4
FT fuels	biogenic primary products	2	0 to 2	3	0 to 3	FT-Naphtha	2	0				4
	biogenic by-products	2	0	3 to 4		FT-SPK	2	1	4	4	2	4
	PTX feedstocks	2	2 to 4		0 to 3	FT-Diesel	4	3	4	4	2	4

Figure 9-1 Assessment of available or soon-to-be available energy carriers in relation to their properties. Note: criteria according to Table 9-3 as of 2020; biogenic by-products incl. biogenic residuals and waste materials.

Figure 9-2 Vehicle-energy-matrix for Germany in 2030. Note: green – very probable option, dark gray – possible option, light gray – option for remaining stock of conventional drive systems; blend indicates blended fuels made of renewable and fossil energy carriers

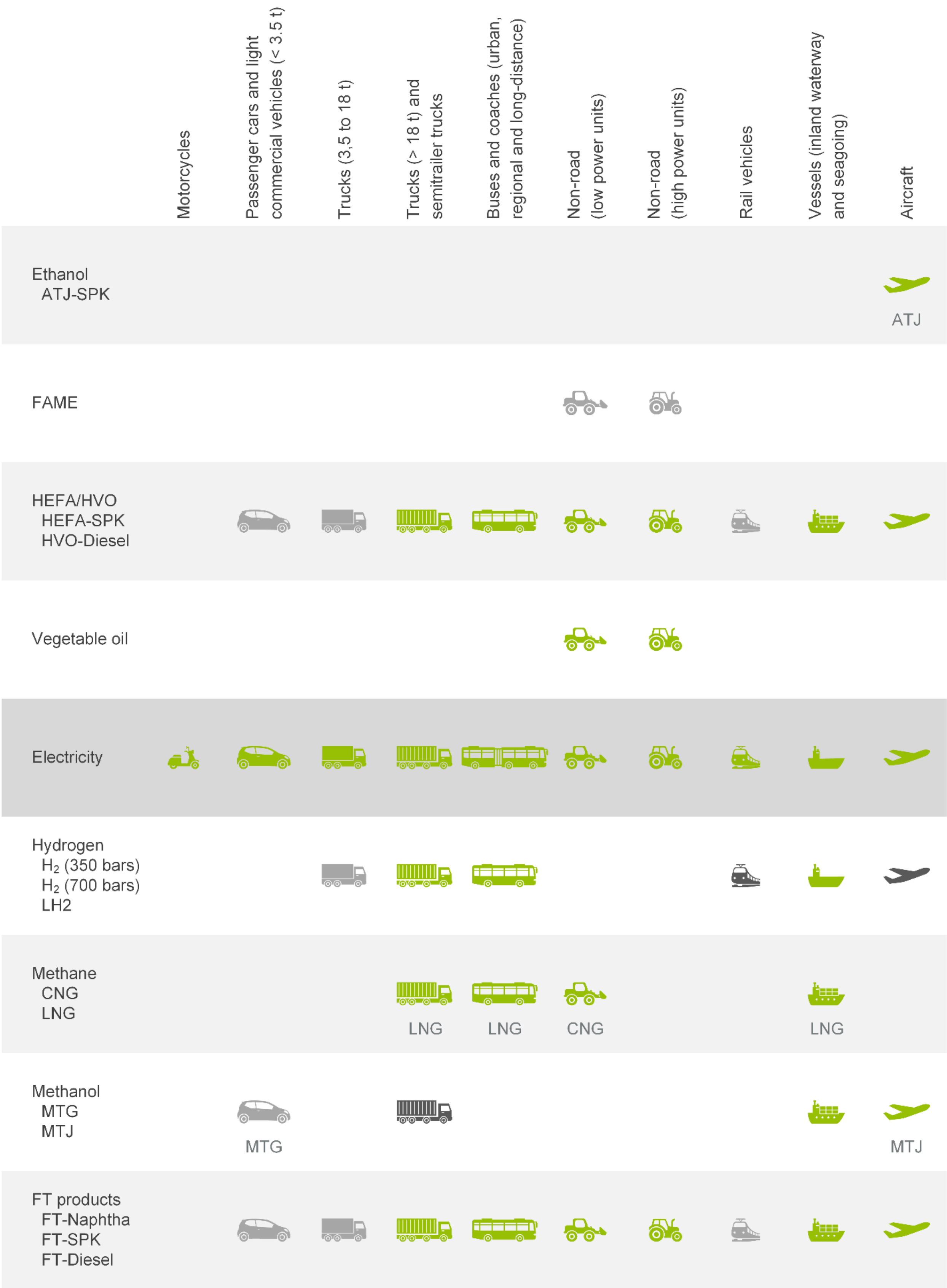

Figure 9-3 Vehicle-energy-matrix for Germany in 2045. Note: green – very probable option, dark gray – possible option, gray – option for remaining stock of conventional drive systems

Glossary

Term	Meaning
(Advanced and conventional) biofuels	Biofuels are fuels produced directly or indirectly from biomass. Examples are bioethanol, FAME and biomethane. Advanced biofuels are fuels produced from feedstocks listed in Annex IX Part A of the European Renewable Energy Directive RED II (2018/2001). Conventional biofuels are produced from parts of starch-rich crops, sugar crops or oil crops produced on agricultural land (and forestry plantations) as a primary product.
Annex IX Parts A and B	The Part A (feedstocks for the production of advanced biofuels and biogas for transport) and Part B (waste fats for the production of biofuels and biogas for transport) of Annex IX of the European Renewable Energy Directive RED II (2018/2001) define feedstocks for the production of promoted or regulated biofuels and biogas for transport. In Germany, these are defined in a legally binding manner in Annexes 1 and 4 of the 38th BImSchV.
CO_2-equivalent	Unit of measurement used to standardize the climate impact of different greenhouse gases. CO_2 equivalents are a way to show the quantity of a gas that is needed to have the same greenhouse gas effect as carbon dioxide (CO_2) over a certain period of time, e.g., 20, 100 or 500 years. [NPM (2021)]
Commercialization phase	In this report, energy carriers in the commercialization phase are all those that can be assigned to Technology Readiness Levels 9 to 11 as illustrated in Figure 3-2. These are energy carriers that are already commercially available.
Delegated act (European Union)	Delegated acts are non-legislative acts adopted by the European Commission that serve to amend or supplement non-essential elements of the legislation. Delegated acts are typically used when legislative acts - including their Annexes - have to be (regularly) amended to take account of technical and scientific progress. [EUR-Lex (2021a)]
Demonstration phase	In this report, energy carriers in the demonstration phase are all those that can be assigned to Technology Readiness Levels 5 to 8, as shown in Figure 3-2. These are energy carriers that are not yet commercially available but are being produced in industrial demonstration plants or in initial pilot plants.
Directive (European Union)	A directive is a legislative act adopted by the EU institutions, which is addressed to the EU Member States and is binding as to the result to be achieved. A directive is part of the EU's secondary law, the body of laws that derives from the principles and objectives set out in the EU Treaties (primary law). The national authorities of each EU country to which the directive is addressed determine the form and the methods they use to incorporate the directive into national law (formally known as "transposition"). [EUR-Lex (2021b)]
e-fuels	E-fuels are fuels produced from electricity, water and potentially other feedstocks such as carbon dioxide. The EU defines e-fuels as renewable fuels of non-biological origin (RFNBO). In Germany, these fuels are referred to as power-to-fuel (PTX) and, depending on whether gaseous or liquid fuels are synthesized, are produced using power-to-gas (PTG) or power-to-liquid (PTL) technology. [NPM (2021)]
Energy carrier	Energy carriers are substances whose energy content can be harnessed in conversion processes. In this report, the term energy carrier is used in the context of fuels and electricity.
Federal law (Germany)	Only the German Bundestag has the power to enact federal laws. The states participate in passing federal legislation through the Bundesrat. A law is promulgated in the Federal Law Gazette following a resolution by the Bundestag, approval by the Bundesrat, a countersignature by the federal government and a signature by the president. [Deutscher Bundestag (2022a)]

Term	Meaning
Greenhouse gas abatement costs	Greenhouse gas abatement costs are the effective costs of a climate protection measure per unit of weight of avoided CO_2 emissions. While added investment reflects the sums to be invested in the period under consideration, abatement costs provide a more comprehensive view of the costs that also includes operating costs. Unlike the usually positive added investment, abatement costs can be negative for some instruments or instrument packages. This occurs when, for example, higher spending on vehicles is more than offset by savings in energy and maintenance costs. In most cases, however, abatement costs are positive.
Greenhouse gas reduction quota (GHG quota)	The GHG quota is a market-based instrument for reducing the emission of climate-damaging gases in the German transport sector. The quota obligates the distributors of fuels to take emission-reduction measures. [NPM (2021)]
Greenhouse gases (GHG)	Greenhouse gases are atmospheric trace gases that contribute to the greenhouse effect. They can be of both natural and anthropogenic origin. The most important greenhouse gases are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). [NPM (2021)]
Legal ordinance (Germany)	A legal ordinance is not enacted by the Bundestag as the legislative branch, but by the executive branch, i.e., the federal government, a federal minister, or a state government. A legal ordinance requires statutory authorization with a defined content, purpose and scope. Even though a legal ordinance is not enacted as part of a legislative procedure, it is nevertheless binding. While a legislative procedure is usually relatively lengthy, ordinances can be issued and amended more quickly. [Deutscher Bundestag (2022b)]
Modes of transport	Transport medium for the carriage of passengers, goods and services. Modes of transport include land transport (rail and road), shipping (inland and maritime) and aviation. [NPM (2021)]
Regulation (European Union)	European regulations have general application, are binding in their entirety and are directly applicable in all European Union (EU) Member States. A regulation is part of the EU's secondary law, the body of laws that derives from the principles and objectives set out in the EU treaties (primary law). A regulation is addressed to abstract categories of persons - EU institutions, EU Member States or individuals - and not to identified persons. It is binding in its entirety. [EUR-Lex (2021c)]
Renewable energy carriers	Renewable energy carriers are all energy carriers made from renewable resources. These include biofuels, e-fuels and electricity from renewable sources.
Research phase	In this report, energy carriers in the research phase are all those that can be assigned to Technology Readiness Levels 1 to 4, as illustrated in Figure 3-2. These are energy carriers that are not yet commercially available and are only produced in a research context, e.g., on a laboratory scale.
Resources	The term resources is used in the report to refer to input materials for renewable fuel production and includes biogenic primary products from agriculture and forestry, biogenic by-products and biogenic residues and waste, as well as other carbon sources (point and diffuse CO_2 sources), sustainably generated electricity and water. As an alternative for biogenic resources, 'feedstock' and 'raw material' are also used.
Synthetic fuels	Synthetic fuels or "synfuels" are all types of fuels produced from a synthesis gas using catalytic synthesis technologies. Synthesis is a combination of several groups of molecules, which can either be made from bio-based feedstocks (e.g., biomass-to-liquid, BTL), be electrochemically derived (e-fuels), or be produced from fossil resources (e.g., gas-to-liquids, GTL).

List of abbreviations and symbols

Abbreviation	Description
A20	Gasoline containing 20 % v/v alcohol (methanol, ethanol)
ADN	Accord européen relatif au transport international des marchandises dangereuses par voie de navigation intérieure (European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterways)
ADR	European Agreement concerning the International Carriage of Dangerous Goods by Road
AEL	Alkaline water electrolysis
AFID	Alternative Fuel Infrastructure Directive
Agora	Agora Energiewende gemeinnützige GmbH
ASTM	American Society for Testing and Materials (standards organization)
ATJ	Alcohol-to-jet (conversion of alcohol to jet fuel)
AwSV	Ordinance on Facilities for Handling Substances that are Hazardous to Water
B10	Diesel containing 10 % v/v biodiesel (FAME)
B100	Biodiesel (FAME)
B20	Diesel containing 20 % v/v biodiesel (FAME)
B30	Diesel containing 30 % v/v biodiesel (FAME)
B7	Diesel containing 7 % v/v biodiesel (FAME)
BASF test engine	Single-cylinder test engine to determine the ignitibility of diesel fuels
BECCS	Bioenergy with carbon capture and storage
BEHG	Fuel Emissions Trading Act
BetrSichVO	Operational Safety Ordinance
BEV	Battery electric vehicle
BFStrMG	Act on Levying of Route-related Charges for the Use of Federal Highways and Federal Roads
BIC	Biofuels Iso-Conversion (method for producing naptha, kerosene and diesel fuels)
BImSchG	Federal Immission Control Act
BImSchV	Ordinance for implementing the Federal Immission Control Act
BioKraftFÄndG	Act on Amending the Promotion of Biofuels
Biokraft-NachV	Biofuels Sustainability Ordinance
BioKraftQuG	Biofuels Quota Act
BiomasseV	Ordinance on the Generation of Electricity from Biomass
BLE	Federal Office for Agriculture and Food
BMDV	Federal Ministry for Digital and Transport
BMU	Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (renamed Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection in December 2021)
BMVI	Federal Ministry of Transport and Digital Infrastructure (renamed Federal Ministry for Digital and Transport in December 2021)
BMWi	Federal Ministry for Economic Affairs and Energy (renamed Federal Ministry for Economic Affairs and Climate Action in December 2021)

Abbreviation	Description
BTL	Biomass-to-liquid (conversion of biomass to a liquid fuel)
BTX	Biomass-to-X (conversion of biomass to an energy carrier)
CAAFI	Commercial Aviation Alternative Fuels Initiative
CCS	Carbon capture and storage
CFPP	Cold filter plugging point
CFR test engine	Single-cylinder test engine to determine the octane number of gasoline
CHJ	Catalytic hydrothermolysis jet (jet fuel that is produced using the BIC process)
CLP	European regulation on the classification, labelling and packaging of substances and mixtures (Regulation (EC) 1272/2008)
CNG	Compressed natural gas
CO_2-eq.	CO_2-equivalent
CoEL	Co-electrolysis
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation (global, market-based climate protection measure to limit aviation emissions)
COVID-19	Coronavirus SARS-CoV-2
CP-HVO/HEFA	Co-processed or co-refined HVO/HEFA
CVD	Clean Vehicles Directive (directive on the promotion of clean and energy-efficient road transport vehicles)
DAC	Direct air capture (capturing of CO_2 from the atmosphere)
DBFZ	DBFZ Deutsches Biomasseforschungszentrum gemeinnützige GmbH
DDGS	Dried distillers grains with solubles
DE	Germany
DEHSt	German Emissions Trading Authority
DGS	Distillers Grains with Solubles
DIN	German Institute for Standardization
DK	Denmark
DMC	Dimethyl carbonate
DME	Dimethyl ether
E10	Gasoline containing 10 % v/v ethanol
E100	Ethanol fuel
E15	Gasoline containing 15 % v/v ethanol
E20	Gasoline containing 20 % v/v ethanol
E25	Gasoline containing 25 % v/v ethanol
E27	Gasoline containing 27 % v/v ethanol
E5	Gasoline containing 5 % v/v ethanol
E85	Gasoline containing 85 % v/v ethanol
e-fuels	(Renewable) electricity-based fuels, alternative abbreviation for PTX
EATS	Exhaust gas aftertreatment system
ECE	Economic Commission for Europe

Abbreviation	Description
ECHA	European Chemicals Agency
ED95	Ethanol fuel for diesel engines, mixed with 5 % ignition improver and lubricant
EC	European Community
EEG	Renewable Energy Sources Act
EmoG	Act on Prioritizing the Use of Electrically Operated Vehicles
EN	European norm
EnergieStG	Energy Duty Act
EnergieStV	Ordinance for the Implementation of the Energy Duty Act
ESR	Effort Sharing Regulation
ETBE	Ethyl tertiary-butyl ether
ETD	Energy Taxation Directive
EU-27	European Union from February 1, 2020 onwards (United Kingdom leaves the EU)
EU-28	European Union between July 1, 2013 and January 31, 2020
EU-ETS	European Emissions Trading Scheme
EURO	European emissions standard of vehicles
FAME	Fatty acid methyl ester, known colloquially as biodiesel
FC	Fuel cell
FCEV	Fuel cell electric vehicle
FFV	Flex fuel vehicle (vehicle that can flexibly run on blends of gasoline, methanol and ethanol)
FQD	European Fuel Quality Directive
FRL	Fuel readiness level
FT	Fischer-Tropsch
FuelEU Maritime	EU Initiative for the decarbonization of international maritime transport
GHG	Greenhouse gas
GHS	Globally harmonized system (Globally Harmonized System of Classification and Labelling of Chemicals)
GTL	Gas-to-liquid (conversion of gaseous energy carriers to synthetic liquid fuel)
HC	Hydrocarbons
HCCI	Homogeneous charge compression ignition
HEFA	Hydroprocessed esters and fatty acids
HEV	Hybrid electric vehicle
HFO	Heavy fuel oil
HFRR	High frequency reciprocating rig (measured value for lubricity)
HH	Hanseatic City of Hamburg
HSFO	High sulfur fuel oil
HTL	Hydrothermal liquefaction
HVO	Hydrotreated vegetable oils
IATA DGR	IATA Dangerous Goods Regulations (dangerous goods regulations for the transport of dangerous goods by air)

Abbreviation	Description
ICAO	International Civil Aviation Organization
ICAO-TI	ICAO technical instruction
ICE	Internal combustion engine
ICE-CI	Internal combustion engine with compression ignition (diesel engine)
ICE-SI	Internal combustion engine with spark ignition (gasoline engine)
ICEV	Internal combustion engine vehicle
IEA	International Energy Agency
IGCC	Integrated gasification combined cycle
iLUC	Indirect land use change
IMDG-Code	International Maritime Dangerous Goods Code
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change ("World Climate Council")
ISCC CORSIA	International Sustainability and Carbon Certification for CORSIA-eligible fuels (certification system to verify the sustainability criteria set out in CORSIA for the use of sustainable aviation fuels)
IUE	Institute of Environmental Technology and Energy Economics at the University of Technology Hamburg-Harburg
IX A	Part A of Annex IX of the Renewable Energy Directive RED II (2018/2001)
IX B	Part B of Annex IX of the Renewable Energy Directive RED II (2018/2001)
JET A/A-1	Aviation fuel
KSG	Climate Change Act
LCA	Life cycle assessment
LH2	Liquefied hydrogen
LCV	Light commercial vehicle
LNG	Liquefied natural gas
LOHC	Liquid organic hydrogen carrier
LPG	Liquefied petroleum gas
LSFO	Low sulfur fuel oil
LuftVStG	German Aviation Tax Act
LULUCF	Land use, land-use change and forestry
M100	Methanol
M15	Gasoline containing 15 % v/v methanol
M56	Gasoline containing 56 % v/v methanol
M85	Gasoline containing 85 % v/v methanol
MARPOL	International Convention for the Prevention of Pollution from Ships
MDO	Marine diesel oil
MeFo	Methyl formate (methyl methanoate, methyl ester of formic acid)
MGO	Marine gas oil
MMT	Million metric tons
MTBE	Methyl tertiary-butyl ether

Abbreviation	Description
MTG	Methanol-to-gasoline (conversion of methanol to gasoline)
MTJ	Methanol-to-jet (conversion of methanol to jet fuel)
Nabisy	Sustainable biomass systems
NDC	Nationally determined contributions
NET	Negative emissions technology
NIR	National Inventory Report
NO_X	Gaseous oxides of nitrogen (nitrogen oxides)
NRMM	Non-road mobile machinery
NRSC	Non-road steady cycle (steady test cycle for NRMM)
NRTC	Non-road transient cycle (transient test cycle for NRMM)
OH	Overhead line hybrid
OICA	Organisation Internationale des Constructeurs d'Automobiles (International Organization of Motor Vehicle Manufacturers)
OME	Polyoxymethylene dimethyl ether (oxymethylene ether for short)
OME_n	Polyoxymethylene dimethyl ether with a chain length of n
PAH	Polycyclic aromatic hydrocarbons
PBTL	Power-and-biomass-to-liquid (conversion of electricity and biomass to liquid fuels), the report also refers to power-and-biogas-to-liquid in the context of the CAPHENIA process.
PBTX	Power-and-biomass-to-X (conversion of electricity and biomass to an energy carrier)
PEM	Proton exchange membrane
PEMEL	Polymer electrolyte membrane electrolysis
PEMS	Portable emissions measurement system
PFAD	Palm fatty acid distillates
(P)HEV	Both plug-in-hybrid and hybrid vehicles
PHEV	Plug-in hybrid electric vehicle
POME	Palm oil mill effluent
PSA	Pressure swing adsorption
PSI	Paul Scherrer Institute
PT	Public transport
PTL	Power-to-liquid (conversion of electricity to liquid fuel)
PTX	Power-to-X (conversion of electricity to an energy carrier)
PV	Photovoltaics
R33	Diesel fuel with 26 % v/v HVO-diesel and 7 % v/v FAME
RCF	Recycled carbon fuel
RDE	Real driving emissions
RE	Renewable energy
REACH	EU chemical regulation (EC) 1907/2006
RED	Renewable Energy Directive 2009/28
RED II	Renewable Energy Directive 2018/2001

Abbreviation	Description
RFNBO	Renewable fuels of non-biological origin
RID	Regulation concerning the International Carriage of Dangerous Goods by Rail
RRM	Renewable raw materials
RWGS	Reverse water gas shift reaction
SAF	Sustainable aviation fuels
SaubFahrzeugBeschG	Law on the procurement of clean road transport vehicles
SCR	Selective catalytic reduction
SDS	Safety data sheet
SIP	Synthesized iso-paraffins produced from hydroprocessed fermented sugars
SKA	Synthetic kerosene with aromatics
SOEL	Solid oxide electrolysis
SPK	Synthetic paraffinic kerosene
SRP	Short rotational plantation
STP	Standard temperature and pressure
SynBioPTL	Combination of biomass and electricity-based technologies to produce liquid fuels
SynBioPTX	Combination of biomass and electricity-based technologies to produce energy carriers
Syngas	Synthesis gas
TA Luft	Technical Instructions of Air Quality Control
TEN-T	Trans-European Transport Network
TFZ	Technologie- und Förderzentrum with headquarters in Straubing
TRBS	Technical Rules for Operational Safety
TRGS	Technical Rules for Hazardous Substances
TRL	Technology readiness level
TUHH	Hamburg Technical University
UBA	Federal Environment Agency
UCO	Used cooking oils
UER	Upstream emission reduction (upstream emission reduction in the overall process)
UERO	Ordinance Offsetting the Upstream Emission Reductions against the Greenhouse Gas Quota
ULSFO	Ultra low sulfur fuel oil (oil with max. 0.1 % sulfur)
UNFCCC	United Nations Framework Convention on Climate Change
v/v	Volume fraction
w/w	Mass fraction
WGS	Water gas shift reaction
XTL	X-to-liquid (conversion of an energy carrier to a liquid fuel)

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10. BImSchV (2019): Verordnung über die Beschaffenheit und die Auszeichnung der Qualitäten von Kraft- und Brennstoffen. 10. BImSchV from 13.12.2019. In: *BGBl*.

37. BImSchV (21.12.2020): Verordnung zur Anrechnung von strombasierten Kraftstoffen und mitverarbeiteten biogenen Ölen auf die Treibhausgasquote. In: BGBl.

38. BImSchV (2021): Verordnung zur Festlegung weiterer Bestimmungen zur Treibhausgasminderung bei Kraftstoffen. 38. BImSchV from 12.11.2021. In: *BGBl* (Heft I Nr. 79), p. 4932.

Abbas, Hazzim F.; Wan Daud, W.M.A. (2010): Hydrogen production by methane decomposition. A review. In: *International Journal of Hydrogen Energy* 35 (3), p. 1160–1190. DOI: 10.1016/j.ijhydene.2009.11.036.

acatech (2018): CCU und CCS – Bausteine für den Klimaschutz in der Industrie. München. Available online at https://www.acatech.de/wp-content/uploads/2018/09/acatech_POSITION_CCU_CCS_WEB-002_final.pdf, last updated 09.2018, last checked on 15.10.2021.

ADAC (2020): Ladestationen für Elektroautos: Das kostet der Strom. Available online at https://www.adac.de/rund-ums-fahrzeug/elektromobilitaet/laden/elektroauto-ladesaeulen-strompreise/, last updated 06.10.2020, last checked on 14.10.2021.

ADM (2006): ADM Announces Expansion of Hamburg Oil Refinery and Storage Facility. Available online at https://www.adm.com/news/news-releases/adm-announces-expansion-of-hamburg-oil-refinery-and-storage-facility, last updated 05.11.2006, last checked on 12.10.2021.

ADR (30.11.2019): International Carriage of Dangerous Goods by Road. ADR.

AEE (2013): Bundesländer mit neuer Energie. Jahresreport Föderal-Erneuerbar 2013. Jahresreport Föderal-Erneuerbar 2013. Available online at https://www.unendlich-viel-energie.de/mediathek/publikationen/bundeslaender-mit-neuer-energie-der-jahresreport-foederal-erneuerbar-2013, last checked on 28.10.2021.

AEE (2021): Bundesländer-Übersicht zu Erneuerbaren Energien. Available online at https://www.foederal-erneuerbar.de/uebersicht/bundeslaender/BW%7CBY%7CB%7CBB%7CHB%7CHH%7CHE%7CMV%7CNI%7CNRW%7CRLP%7CSL%7CSN%7CST%7CSH%7CTH/kategorie/bioenergie, last checked on 12.10.2021.

AGEEstat (2021): Erneuerbare Energien in Deutschland. Daten zur Entwicklung im Jahr 2020. Daten zur Entwicklung im Jahr 2020. Available online at https://www.umweltbundesamt.de/sites/default/files/medien/5750/publikationen/2021_hgp_erneuerbareenergien_deutsch_bf.pdf.

Agentur für Erneuerbare Energien (Publisher) (2010): Erneuerbare Energien 2020. Potenzialatlas Deutschland. Potenzialatlas Deutschland. Available online at https://www.unendlich-viel-energie.de/media/file/319.Potenzialatlas_2_Auflage_Online.pdf.

Agora Energiewende; Wuppertal Institut (2019): Klimaneutrale Industrie. Schlüsseltechnologien und Politikoptionen für Stahl. Published by Chemie und Zement. Schlüsseltechnologien und Politikoptionen für Stahl. Berlin. Available online at https://www.agora-energiewende.de/veroeffentlichungen/klimaneutrale-industrie-hauptstudie/, last updated 11.2019, last checked on 15.10.2021.

Agora Verkehrswende; Agora Energiewende; Frontier Economics (2018): Die zukünftigen Kosten strombasierter synthetischer Brennstoffe. Available online at https://www.agora-verkehrswende.de/fileadmin/Projekte/2017/Die_Kosten_synthetischer_Brenn-_und_Kraftstoffe_bis_2050/Agora_SynCost-Studie_WEB.pdf.

AGQM (2018): Biodiesel-Analytik. Die wichtigsten Qualitätsparameter und ihre Bedeutung. Published by Arbeitsgemeinschaft Qualitätsmanagement Biodiesel e.V. Die wichtigsten Qualitätsparameter und ihre Bedeutung. Berlin. Available online at https://www.agqm-biodiesel.de/application/files/6715/4710/7996/Merkblatt_Analytik.pdf, last checked on 12.10.2021.

Ahlgren, Serina (2013): Production of Ammonia and Nitrogen Fertilizers based on Biomass – Research Efforts in Sweden. Published by Swedish University of Agricultural Sciences. Available online at https://www.ammoniaenergy.org/paper/production-of-ammonia-and-nitrogen-fertilizers-based-on-biomass/, last checked on 12.10.2021.

Ahlgren, Serina; Baky, Andras; Bernesson, Sven; Nordberg, Åke; Norén, Olle; Hansson, Per-Anders (2012): Consequential Life Cycle Assessment of Nitrogen Fertilisers Based on Biomass – a Swedish perspective. In: *Insciences J.*, p. 80–101. DOI: 10.5640/insc.020480.

Aierzhati, Aersi; Watson, Jamison; Si, Buchun; Stablein, Michael; Wang, Tengfei; Zhang, Yuanhui (2021): Development of a mobile, pilot scale hydrothermal liquefaction reactor. Food waste conversion product analysis and techno-economic assessment. In: *Energy Conversion and Management: X*, p. 100076. DOI: 10.1016/j.ecmx.2021.100076.

Air Liquide (2021a): Glyzerindestillation und -bleichung. Erzeugung von Glycerin in Pharmauqalität. Erzeugung von Glycerin in Pharmauqalität. Available online at https://www.engineering-airliquide.com/de/glyzerindestillation-und-bleichung, last checked on 20.10.2021.

Air Liquide (2021b): Inauguration of the world's largest PEM electrolyzer. to produce decarbonized hydrogen. to produce decarbonized hydrogen. Available online at https://www.airliquide.com/magazine/energy-transition/inauguration-worlds-largest-pem-electrolyzer, last checked on 12.10.2021.

aireg (2015): Abschätzung eines möglichen Beitrags Deutschlands zur Senkung der CO2-Emissionen im Luftverkehr durch den Einsatz von Biokraftstoffen. Forschungsvorhaben Nr. 50.0354/2012. Forschungsvorhaben Nr. 50.0354/2012. Available online at https://aireg.de/wp-content/uploads/2015/07/150407_1218_schlussbericht.pdf, last checked on 05.01.2022.

Akbari, Maryam; Oyedun, Adetoyese Olajire; Kumar, Amit (2018): Ammonia production from black liquor gasification and co-gasification with pulp and waste sludges. A techno-economic assessment. In: *Energy* 151 (9a), p. 133–143. DOI: 10.1016/j.energy.2018.03.056.

Alamia, Alberto; Larsson, Anton; Breitholtz, Claes; Thunman, Henrik (2017): Performance of large-scale biomass gasifiers in a biorefinery, a state-of-the-art reference. In: *Int J Energy Res* 41 (14), p. 2001–2019. DOI: 10.1002/er.3758.

Albrecht, Friedemann G.; König, Daniel H.; Baucks, Nadine; Dietrich, Ralph-Uwe (2017): A standardized methodology for the techno-economic evaluation of alternative fuels – A case study. In: *Fuel* 194, p. 511–526. DOI: 10.1016/j.fuel.2016.12.003.

Albuquerque, Jonas S.; Costa, Franciele O.; Barbosa, Bianca V. S. (2019): Fischer–Tropsch Synthesis. Analysis of Products by Anderson–Schulz–Flory Distribution Using Promoted Cobalt Catalyst. In: *Catal Lett* 149 (3), p. 831–839. DOI: 10.1007/s10562-019-02655-4.

Alfadala, Hassan E.; Reklaitis, G. V. Rex (Publisher) (2009): Proceedings of the 1st Annual Gas Processing Symposium. 10 - 12 January 2009, Doha, Qatar. 10 - 12 January 2009, Doha, Qatar. 1. ed. Amsterdam: Elsevier (Advances in gas processing, 1). Available online at http://site.ebrary.com/lib/alltitles/docDetail.action?docID=10264134.

ALIGN-CCUS (2019): Making fuels from CO2: RWE unveils new synthesis pilot plant in Germany. Available online at https://www.alignccus.eu/news/making-fuels-co2-rwe-unveils-new-synthesis-pilot-plant-germany, last updated 29.11.2019, last checked on 12.10.2021.

AMI (2020): Marktwoche Ölsaaten und Biokraftstoffe. Wöchentlicher Newsletter. Published by Agrarmarkt Informations-Gesellschaft mbH. Wöchentlicher Newsletter.

Anastasakis, Konstantinos; Biller, Patrick; Madsen, René B.; Glasius, Marianne; Johannsen, Ib (2018): Continuous hydrothermal liquefaction of biomass in a novel pilot plant with heat recovery and hydraulic oscillation. In: *Energies* 11 (10), p. 2695.

Andersson, Jim; Lundgren, Joakim: Techno-Economic Analysis of Ammonia Production via Integrated Biomass Gasification. Published by International Conference on Applied Energy. Available online at https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.933.2608&rep=rep1&type=pdf, last checked on 12.10.2021.

Andritz (2020): ANDRITZ Lignin Recovery technology for kraft mills. Available online at https://www.andritz.com/products-en/group/pulp-and-paper/pulp-production/kraft-pulp/lignin-recovery, last checked on 12.10.2021.

ANFAVEA (2008): Vehicles – Production, Domestic Sales and Exports. Associação Nacional dos Fabricantes de Veículos Automotores. Available online at http://www.anfavea.com.br/anuario2008/capitulo2a.pdf, last checked on 29.10.2021.

Aral AG (2018a): Aral Diesel, Aral LKW-Diesel, Aral SuperDiesel. Sicherheitsdatenblatt. Published by Aral AG. Sicherheitsdatenblatt. Available online at https://www.aral.de/content/dam/aral/business-sites/de/global/retail/pdfs/sicherheitsdatenblaetter/Kraft_und_Brennstoffe/deutsch/AralDieselAralLKW-DieselAralSuperDiesel_de.pdf, last checked on 06.10.2021.

Aral AG (2018b): Aral Super E5, Aral Super E10, Aral SuperPlus 98. Safety Data Sheet. Published by Aral AG. Safety Data Sheet. Available online at https://www.aral.de/content/dam/aral/business-sites/de/global/retail/pdfs/sicherheitsdatenblaetter/Kraft_und_Brennstoffe/englisch/AralSuperE5AralSuperE10AralSuperPlus98_en.pdf, last checked on 06.10.2021.

Arend, Matthias; Nonnen, Thomas; Hoelderich, Wolfgang F.; Fischer, Jürgen; Groos, Jeremie (2011): Catalytic deoxygenation of oleic acid in continuous gas flow for the production of diesel-like hydrocarbons. In: *Applied Catalysis A: General* 399 (1-2), p. 198–204. DOI: 10.1016/j.apcata.2011.04.004.

Aryan, Venkat; Kraft, Axel (2021): The crude tall oil value chain. Global availability and the influence of regional energy policies. In: *Journal of Cleaner Production* 280 (4), p. 124616. DOI: 10.1016/j.jclepro.2020.124616.

ASTM D1655-20D (2020): Specification for Aviation Turbine Fuels (2020).

ASTM D7566-20C (2020): Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons (2020).

Atsonios, Konstantinos; Panopoulos, Kyriakos D.; Kakaras, Emmanuel (2016): Investigation of technical and economic aspects for methanol production through CO2 hydrogenation. In: *International Journal of Hydrogen Energy* 41 (4), p. 2202–2214. DOI: 10.1016/j.ijhydene.2015.12.074.

Audi (2015): Audi e-fuels. Available online at https://www.audi-mediacenter.com/en/audi-future-performance-days-2015-5097/audi-e-fuels-5104, last updated 11.09.2015, last checked on 12.10.2021.

AwSV (18.04.2017): Verordnung über Anlagen zum Umgang mit wassergefährdenden Stoffen.

AwSV from 19.06.2020 (2020): Verordnung über Anlagen zum Umgang mit wassergefährdenden Stoffen. In: *Bundesgesetzblatt* 2020 (Teil 1 Nr. 29).

BAFA (2021a): Amtliche Mineralöldaten für die Bundesrepublik Deutschland. 2012 bis 2021. Published by Bundesamt für Wirtschaft und Ausfuhrkontrolle. 2012 bis 2021 (2012-2021). Available online at https://www.bafa.de/SiteGlobals/Forms/Suche/Expertensuche/Servicesuche_Formular.html?templateQueryString=Amtliche+Daten+Mineral%C3%B6ldaten&sortOrder=dateOfIssue_dt+desc, last checked on 21.10.2021.

BAFA (2021b): Elektromobilität - Neue Richtlinie zum Umweltbonus. Kombi-Förderung und Staffelung bei Leasing ab 16. November 2020. Kombi-Förderung und Staffelung bei Leasing ab 16. November 2020. Available online at https://www.bafa.de/SharedDocs/Kurzmeldungen/DE/Energie/Elektromobilitaet/20201104_neue_richtlinie_umweltbonus.html, last updated 15.10.2021, last checked on 15.10.2021.

Banco Central do Brasil (2022): Sistema Gerenciador de Séries Temporais. Available online at https://www.bcb.gov.br/?SERIESTEMP, last checked on 11.01.2022.

Basar, Ibrahim Alper; Liu, Huan; Carrere, Helene; Trably, Eric; Eskicioglu, Cigdem (2021): A review on key design and operational parameters to optimize and develop hydrothermal liquefaction of biomass for biorefinery applications. In: *Green Chem.* 23 (4), p. 1404–1446. DOI: 10.1039/D0GC04092D.

BASF (2021): Stimmen aus der Forschung. Ein echter Meilenstein. Ein echter Meilenstein. Available online at https://www.basf.com/global/de/who-we-are/sustainability/we-produce-safely-and-efficiently/energy-and-climate-protection/carbon-management/interview-methane-pyrolysis.html, last checked on 15.10.2021.

Baudouin, David; Salionov, Daniil; Vogel, Frédéric; Bjelić, Saša (2021): Advanced Analytical Study of Process Streams for a Rational Optimization of Hydrothermal Gasification. In: *ACS Engineering Au*.

Bauer, Christian; Mutel, Chris; Cox, Brian; Zhang, Xiaojin; Treyer, Karin; Sacchi, Romain (2021): PSI carculator. Published by Paul Scherrer Institut. Available online at https://carculator.psi.ch/, last checked on 12.10.2021.

Bauer, Ulrich; Winz, Gerald (2015): Ermittlung des Baumaschinenbestandes in Deutschland. Published by Forschungsvereinigung Bau- und Baustoffmaschinen e. V. Kempten (Schriftenreihe der Forschungsvereinigung Bau- und Baustoffmaschinen e. V., 47). Available online at https://fvb.vdma.org/documents/6296991/19334646/47_FVB_Baumaschinenbestand_2015.pdf/cd6e62cb-abe5-437f-9f76-47452b1c6243, last checked on 10.06.2021.

Baumeister, Stefan (2006): Anforderungen an Ethanol Tankstellen (2006). Available online at https://docplayer.org/47921368-Anforderungen-an-ethanol-tankstellen-stefan-baumeister-ford-werke.html, last checked on 20.07.2021.

BAZL (2017): Annex 16, Environmental Protection, Volume III – Aeroplane CO2 Emissions. ICAO Annex 16 V III. Published by Bundesamt für Zivilluftfahrt. ICAO Annex 16 V III. Available online at https://www.bazl.admin.ch/dam/bazl/de/dokumente/Fachleute/Regulationen_und_Grundlagen/icao-annex/icao_annex_16_environmentalprotectionvolumeiii_co2.pdf.download.pdf/icao_annex_16_environmentalprotectionvolumeiii-co2.pdf, last updated 2017, last checked on 08.11.2021.

BAZL (2021): Anhänge zur Konvention der Int. Zivilluftfahrtorganisation (ICAO). ICAO Annex. Published by Bundesamt für Zivilluftfahrt. ICAO Annex. Available online at https://www.bazl.admin.ch/bazl/de/home/fachleute/regulation-und-grundlagen/rechtliche-grundlagen-und-richtlinien/anhaenge-zur-konvention-der-internationalen-zivilluftfahrtorgani.html, last updated 20.05.2021, last checked on 12.10.2021.

BDBe (2021): Verfahren. Available online at https://www.bdbe.de/bioethanol/verfahren, last checked on 12.10.2021.

bdew (2021): Interaktive Karte "Gas kann grün". Available online at https://www.bdew.de/energie/erdgas/interaktive-karte-gas-kann-gruen/, last checked on 12.10.2021.

Becker, W. L.; Braun, R. J.; Penev, M.; Melaina, M. (2012): Production of Fischer–Tropsch liquid fuels from high temperature solid oxide co-electrolysis units. In: *Energy* 47 (1), p. 99–115. DOI: 10.1016/j.energy.2012.08.047.

Bedoić, Robert; Ćosić, Boris; Duić, Neven (2019): Technical potential and geographic distribution of agricultural residues, co-products and by-products in the European Union. In: *The Science of the total environment* 686, p. 568–579. DOI: 10.1016/j.scitotenv.2019.05.219.

BEHG (2019): Gesetz über einen nationalen Zertifikatehandel für Brennstoffemissionen. BEHG from 12.12.2019.

Bekanntmachung Anrechnung Strom (2017): Bekanntmachung des Schätzwertes der anrechenbaren energetischen Menge elektrischen Stroms für ein reines Batterieelektrofahrzeug gemäß § 7 Absatz 3 der Verordnung zur Festlegung weiterer Bestimmungen zur Treibhausgasminderung bei Kraftstoffen (38.BImSchV). Bekanntmachung Anrechnung Strom from 21.12.2017. Source: BAnz AT 29.12.2017 B8.

Bekanntmachung Anrechnung Strom (2021): Bekanntmachung des Schätzwertes der anrechenbaren energetischen Menge elektrischen Stroms für ein reines Batterieelektrofahrzeug gemäß § 7 Absatz 3 der Verordnung zur Festlegung weiterer Bestimmungen zur Treibhausgasminderung bei Kraftstoffen. Bekanntmachung Anrechnung Strom from 02.12.2021. Source: BAnz AT 16.12.2021 B3.

Bekanntmachung THG-Minderung (28.10.2021): Bekanntmachung nach § 5 Absatz 3 der Verordnung zur Festlegung weiterer Bestimmungen zur Treibhausgasminderung bei Kraftstoffen. Bekanntmachung THG-Minderung from 04.10.2021. Source: BAnz AT 28.10.2021 B10.

Bellot, Franz-Fabian; Horschig, Thomas; Brosowski, André (2021): Quantifizierung europäischer Biomassepotenziale. In: *Open Agrar*. Available online at https://www.openagrar.de/receive/openagrar_mods_00073600, last checked on 13.01.2022.

Benajes, Jesús; García, Antonio; Monsalve-Serrano, Javier; Martínez-Boggio, Santiago (2020): Potential of using OMEx as substitute of diesel in the dual-fuel combustion mode to reduce the global CO2 emissions. In: *Transportation Engineering* 1 (6), p. 100001. DOI: 10.1016/j.treng.2020.01.001.

Benjamin, Kirsten R.; Silva, Iris R.; Cherubim, João P.; McPhee, Derek; Paddon, Chris J. (2016): Developing Commercial Production of Semi-Synthetic Artemisinin, and of β-Farnesene, an Isoprenoid Produced by Fermentation of Brazilian Sugar. In: *Journal of the Brazilian Chemical Society. DOI:* 10.5935/0103-5053.20160119.

Bereczky, Akos (2017): Effect of the use of waste vegetable oil based biodiesel on the landscape in diesel engines. In: *Therm sci* 21 (1 Part B), p. 567–579. DOI: 10.2298/TSCI150630280B.

Bergmann, Jessica C.; Trichez, Débora; Sallet, Lunalva P.; Silva, Flávia Cristina de Paula; Almeida, Joao, R. M. (2018): Technological Advancements in 1G Ethanol Production and Recovery of By-Products Based on the Biorefinery Concept. In: *Advances in Sugarcane Biorefinery* 2018, p. 73–95. Available online at https://www.sciencedirect.com/science/article/pii/B9780128045343000045?via%3Dihub, last checked on 22.06.2021.

BetrSichV from 28.05.2021 (2021): Verordnung über Sicherheit und Gesundheitsschutz bei der Verwendung von Arbeitsmitteln. In: *Bundesgesetzblatt* 2021 (Teil Nr. 49).

Bezergianni, Stella; Dimitriadis, Athanasios; Sfetsas, Themistoklis; Kalogianni, Aggeliki (2010): Hydrotreating of waste cooking oil for biodiesel production. Part II. Effect of temperature on hydrocarbon composition. In: *Bioresource technology* 101 (19), p. 7658–7660. DOI: 10.1016/j.biortech.2010.04.043.

BFT (2021): Daten und Fakten zur Entwicklung des Tankstellenmarktes bzw. der Tankstelenbranche. Published by Bundesverband freier Tankstellen e. V. Available online at https://www.bft.de/daten-und-fakten/entwicklung-tankstellenanzahl, last updated 22.06.2021, last checked on 22.06.2021.

Billig, E.; Decker, M.; Benzinger, W.; Ketelsen, F.; Pfeifer, P.; Peters, R. et al. (2019): Non-fossil CO2 recycling—The technical potential for the present and future utilization for fuels in Germany. In: *Journal of CO2 Utilization* 30 (6331), p. 130–141. DOI: 10.1016/j.jcou.2019.01.012.

BImSchG (2019): Gesetz zum Schutz vor schädlichen Umwelteinwirkungen durch Luftverunreinigungen, Geräusche, Erschütterungen und ähnliche Vorgänge. BImSchG from 08.04.2019. In: *BGBl* (Heft I Nr. 12), p. 432.

biodieselbr (2020): ANP autoriza Potencial a participar do L76 como a maior usina do Brasil. Available online at https://www.biodieselbr.com/noticias/regulacao/leilao/anp-autoriza-potencial-a-participar-do-l76-como-a-maior-usina-do-brasil-021020, last updated 02.10.2020, last checked on 11.08.2021.

Bioenergy International (2021a): Arbios Biotech to build commercial-scale biocrude plant in Prince George. With collaboration of Alan Sherrard. Available online at https://bioenergyinternational.com/biofuels-oils/arbios-biotech-to-build-commercial-scale-biocrude-plant-in-prince-george, last updated 06.10.2021, last checked on 20.10.2021.

Bioenergy International (2021b): Haldor Topsoe begins commissioning of eSMR Methanol demo plant in Foulum. Available online at https://bioenergyinternational.com/research-development/haldor-topsoe-begins-commissioning-of-esmr-methanol-demo-plant-in-foulum, last updated 28.10.2021.

Bioenergy International (2021c): Preem's Lysekil refinery begins producing renewable petrol from pyrolysis oil. Available online at https://bioenergyinternational.com/biofuels-oils/preems-lysekil-refinery-begins-producing-renewable-petrol-from-pyrolysis-oil, last updated 21.06.2021, last checked on 15.10.2021.

Bioenergy International (2021d): Raízen reveals plans for second cellulosic ethanol plant in Brazil. Available online at https://bioenergyinternational.com/biofuels-oils/raizen-reveals-plans-for-second-cellulosic-ethanol-plant-in-brazil, last updated 01.07.2021, last checked on 15.10.2021.

bioethanolcarburant.com (2021): Trouver une station Superéthanol-E85. Available online at https://www.bioethanolcarburant.com/trouver-une-station-e85/, last checked on 29.09.2021.

BioKraftFÄndG (2009): Gesetz zur Änderung der Förderung von Biokraftstoffen. BioKraftFÄndG from 15.07.2009. In: *BGBl* (I Nr. 41), p. 1804.

Biokraft-NachV (2009): Verordnung über Anforderungen an eine nachhaltige Herstellung von Biokraftstoffen. Biokraft-NachV from 05.10.2009. In: *BGBl* 2009 (Teil I Nr. 65), p. 3182.

Biokraft-NachV (2021): Referentenentwurf zur Neufassung der Biomassestrom-Nachhaltigkeitsverordnung und der Biokraftstoff-Nachhaltigkeitsverordnung. Biokraft-NachV from 31.03.2021.

Bio-NachAnpV (2021): Verordnung zur Neufassung der Biomassestrom-Nachhaltigkeitsverordnung und der Biokraftstoff-Nachhaltigkeitsverordnung und zur Änderung der Besonderen Gebührenverordnung BMEL. Bio-NachAnpV from 02.12.2021.

BioRefineries Blog (2018): euglena completes the construction of its demonstration plant to produce renewable fuels in Japan. Available online at https://biorrefineria.blogspot.com/2018/11/euglena-completes-construction-of-its-demonstration-plant-to-produce-renewable-fuels-japan-HVO-algal-biorefinery.html, last checked on 27.09.2022.

BL2F (2021): About the project. Available online at http://www.bl2f.eu/about-the-project/, last checked on 15.10.2021.

BLE (2012): Evaluations- und Erfahrungsbericht für das Jahr 2011. Biomassestrom-Nachhaltigkeitsverordnung. Biokraftstoff-Nachhaltigkeitsverordnung. Published by Bundesanstalt für Landwirtschaft und Ernährung. Biomassestrom-Nachhaltigkeitsverordnung. Biokraftstoff-Nachhaltigkeitsverordnung. Bonn. Available online at https://www.ble.de/SharedDocs/Downloads/DE/Klima-Energie/Nachhaltige-Biomasseherstellung/Evaluationsbericht_2011.pdf?__blob=publicationFile&v=1, last checked on 15.10.2021.

BLE (2013): Evaluations- und Erfahrungsbericht für das Jahr 2012. Biomassestrom-Nachhaltigkeitsverordnung. Biokraftstoff-Nachhaltigkeitsverordnung. 2. überarbeitete Auflage. Published by Bundesanstalt für Landwirtschaft und Ernährung. Biomassestrom-Nachhaltigkeitsverordnung. Biokraftstoff-Nachhaltigkeitsverordnung. Bonn. Available online at https://www.ble.de/SharedDocs/Downloads/DE/Klima-Energie/Nachhaltige-Biomasseherstellung/Evaluationsbericht_2012_2_Auflage.pdf;jsessionid=F83723B2944228AD3C163782F8AEBF89.2_cid335?__blob=publicationFile&v=1, last checked on 15.10.2021.

BLE (2014): Evaluations- und Erfahrungsbericht für das Jahr 2013. Biomassestrom-Nachhaltigkeitsverordnung. Biokraftstoff-Nachhaltigkeitsverordnung. Published by Bundesanstalt für Landwirtschaft und Ernährung. Biomassestrom-Nachhaltigkeitsverordnung. Biokraftstoff-Nachhaltigkeitsverordnung. Bonn. Available online at https://www.ble.de/SharedDocs/Downloads/DE/Klima-Energie/Nachhaltige-Biomasseherstellung/Evaluationsbericht_2013.pdf;jsessionid=F83723B2944228AD3C163782F8AEBF89.2_cid335?__blob=publicationFile&v=1, last checked on 15.10.2021.

BLE (2015): Evaluations- und Erfahrungsbericht für das Jahr 2014. Biomassestrom-Nachhaltigkeitsverordnung. Biokraftstoff-Nachhaltigkeitsverordnung. Published by Bundesanstalt für Landwirtschaft und Ernährung. Biomassestrom-Nachhaltigkeitsverordnung. Biokraftstoff-Nachhaltigkeitsverordnung. Bonn. Available online at https://www.ble.de/SharedDocs/Downloads/DE/Klima-Energie/Nachhaltige-Biomasseherstellung/Evaluationsbericht_2014.pdf;jsessionid=F83723B2944228AD3C163782F8AEBF89.2_cid335?__blob=publicationFile&v=1, last checked on 15.10.2021.

BLE (2016): Evaluations- und Erfahrungsbericht für das Jahr 2015. Biomassestrom-Nachhaltigkeitsverordnung. Biokraftstoff-Nachhaltigkeitsverordnung. Published by Bundesanstalt für Landwirtschaft und Ernährung. Biomassestrom-Nachhaltigkeitsverordnung. Biokraftstoff-Nachhaltigkeitsverordnung. Bonn. Available online at https://www.ble.de/SharedDocs/Downloads/DE/Klima-Energie/Nachhaltige-Biomasseherstellung/Evaluationsbericht_2015.pdf?__blob=publicationFile&v=1, last checked on 15.10.2021.

BLE (2017): Evaluations- und Erfahrungsbericht für das Jahr 2016. Biomassestrom-Nachhaltigkeitsverordnung. Biokraftstoff-Nachhaltigkeitsverordnung. Published by Bundesanstalt für Landwirtschaft und Ernährung. Biomassestrom-Nachhaltigkeitsverordnung. Biokraftstoff-Nachhaltigkeitsverordnung. Bonn. Available online at https://www.ble.de/SharedDocs/Downloads/DE/Klima-Energie/Nachhaltige-Biomasseherstellung/Evaluationsbericht_2016.pdf;jsessionid=D0914B16717DA3641645C832122839C3.1_cid325?__blob=publicationFile&v=3, last checked on 15.10.2021.

BLE (2018): Evaluations- und Erfahrungsbericht für das Jahr 2017. Biomassestrom-Nachhaltigkeitsverordnung Biokraftstoff-Nachhaltigkeitsverordnung. Published by Bundesanstalt für Landwirtschaft und Ernährung. Biomassestrom-Nachhaltigkeitsverordnung Biokraftstoff-Nachhaltigkeitsverordnung. Bonn. Available online at https://www.ble.de/SharedDocs/Downloads/DE/Klima-Energie/Nachhaltige-Biomasseherstellung/Evaluationsbericht_2017.pdf;jsessionid=D0914B16717DA3641645C832122839C3.1_cid325?__blob=publicationFile&v=3, last checked on 15.10.2021.

BLE (2019): Evaluations- und Erfahrungsbericht für das Jahr 2018. Biomassestrom-Nachhaltigkeitsverordnung, Biokraftstoff-Nachhaltigkeitsverordnung. Published by Bundesanstalt für Landwirtschaft und Ernährung. Biomassestrom-Nachhaltigkeitsverordnung, Biokraftstoff-Nachhaltigkeitsverordnung. Bonn. Available online at https://www.ble.de/SharedDocs/Downloads/DE/Klima-Energie/Nachhaltige-Biomasseherstellung/Evaluationsbericht_2018.pdf, last checked on 21.10.2021.

BLE (2020): Evaluations- und Erfahrungsbericht für das Jahr 2019. Biomassestrom-Nachhaltigkeitsverordnung, Biokraftstoff-Nachhaltigkeitsverordnung. Published by Bundesanstalt für Landwirtschaft und Ernährung. Biomassestrom-Nachhaltigkeitsverordnung, Biokraftstoff-Nachhaltigkeitsverordnung. Available online at https://www.ble.de/SharedDocs/Downloads/DE/Klima-Energie/Nachhaltige-Biomasseherstellung/Evaluationsbericht_2019.pdf, last checked on 21.10.2021.

BLE (2021a): Bericht zur Markt- und Versorgungslage mit Fleisch 2021. Published by Bundesanstalt für Landwirtschaft und Ernährung. Available online at https://www.ble.de/SharedDocs/Downloads/DE/BZL/Daten-Berichte/Fleisch/2021BerichtFleisch.pdf?__blob=publicationFile&v=2, last checked on 02.01.2022.

BLE (2021b): Evaluations- und Erfahrungsbericht für das Jahr 2020. Biomassestrom-Nachhaltigkeitsverordnung, Biokraftstoff-Nachhaltigkeitsverordnung. Published by Bundeministerium für Landwirtschaft und Ernährung. Biomassestrom-Nachhaltigkeitsverordnung, Biokraftstoff-Nachhaltigkeitsverordnung. Bonn. Available online at https://www.ble.de/SharedDocs/Downloads/DE/Klima-Energie/Nachhaltige-Biomasseherstellung/Evaluationsbericht_2020.pdf;jsessionid=E4B37F25CA48344B01D7917DC1A922C3.2_cid335?__blob=publicationFile&v=3, last checked on 04.01.2022.

BLE (2021c): Information über die Attribute der in der staatlichen Datenbank Nabisy hinterlegten Biomassearten. Published by Nabisy. Available online at https://www.ble.de/SharedDocs/Downloads/DE/Klima-Energie/Nachhaltige-

Biomasseherstellung/Nabisy/Biomassecodeliste.xlsx;jsessionid=6CB397FE5890627C12ECC742B96B245C.1_cid335?__blob=publicationFile&v=8, last checked on 13.01.2022.

BLE (2021d): Report Monitoring Biokraftstoffsektor - detaillierte Informationsbereitstellung zu den verwendeten Biomassen für die Bereitstellung von Biokraftstoffen in Deutschland 2019. Leipzig (2021). E-Mail to DBFZ.

BMBF (2019): Methanpyrolyse: Klimafreundlicher Wasserstoff. Published by Bundesministerium für Bildung und Forschung. Available online at https://www.fona.de/de/massnahmen/foerdermassnahmen/wasserstoff-aus-methanpyrolyse.php, last updated 01.04.2019, last checked on 15.10.2021.

BMBF (2020): Nationale Bioökonomiestrategie. Published by Bundesministerium für Bildung und Forschung. Available online at https://biooekonomie.de/sites/default/files/files/2020-06/bmbf_nationale_biooekonomiestrategie_langfassung_deutsch.pdf, last updated 03.2020, last checked on 15.10.2021.

BMEL (Publisher) (2019): Statistisches Jahrbuch über Ernährung, Landwirtschaft und Forsten der Bundesrepublik Deutschland 2018 (62. Jahrgang). Available online at https://www.bmel-statistik.de/fileadmin/SITE_MASTER/content/Jahrbuch/Agrarstatistisches-Jahrbuch-2018.pdf, last checked on 14.01.2022.

BMEL (Publisher) (2021): Statistisches Jahrbuch über Ernährung, Landwirtschaft und Forsten der Bundesrepublik Deutschland 2020 (64. Jahrgang). Available online at https://www.bmel-statistik.de/fileadmin/SITE_MASTER/content/Jahrbuch/Agrarstatistisches-Jahrbuch-2020.pdf, last checked on 14.01.2022.

BMU (2019): Klimaschutzprogramm 2030 der Bundesregierung zur Umsetzung des Klimaschutzplans 2050. Published by Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit. Available online at https://www.bundesregierung.de/resource/blob/974430/1679914/e01d6bd855f09bf05cf7498e06d0a3ff/2019-10-09-klima-massnahmen-data.pdf?download=1, last checked on 15.10.2021.

BMU (2021): DOPPLUNG Klimaschutzplan 2050 – Die deutsche Klimaschutzlangfriststrategie. Available online at https://www.bmu.de/themen/klima-energie/klimaschutz/nationale-klimapolitik/klimaschutzplan-2050/, last updated 14.06.2021, last checked on 14.06.2021.

BMUB (2016): Klimaschutzplan 2050. Klimaschutzpolitische Grundsätze und Ziele der Bundesregierung. Published by Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit. Klimaschutzpolitische Grundsätze und Ziele der Bundesregierung. Berlin.

BMVI (2015): Räumlich differenzierte Flächenpotentiale für erneuerbare Energien in Deutschland. Available online at https://www.bbsr.bund.de/BBSR/DE/veroeffentlichungen/ministerien/bmvi/bmvi-online/2015/DL_BMVI_Online_08_15.pdf;jsessionid=F5487ACB7B04788249146C71ABBD974C.live21303?__blob=publicationFile&v=2, last updated 08/2015, last checked on 28.10.2021.

BMVI (2016): Nationaler Strategierahmen über den Aufbau der Infrastruktur für alternative Kraftstoffe. als Teil der Umsetzung der Richtlinie 2014/94/EU. Published by Bundesministerium für Verkehr und digitale Infrastruktur. als Teil der Umsetzung der Richtlinie 2014/94/EU. Berlin. Available online at https://www.bmvi.de/SharedDocs/DE/Anlage/G/MKS/mks-nationaler-strategierahmen-afid.pdf?__blob=publicationFile, last checked on 15.10.2021.

BMVI (2019): Erster Bericht über die Umsetzung des nationalen Strategierahmens in Deutschland. (AFID-Bericht). Published by Bundesministerium für Verkehr und digitale Infrastruktur. (AFID-Bericht). Available online at https://www.bmvi.de/SharedDocs/DE/Anlage/G/MKS/afid-erster-bericht.pdf?__blob=publicationFile, last checked on 14.10.2021.

BMVI (2020): Bekanntmachung der Richtlinie über den Einsatz von Bundesmitteln im Rahmen des Programms „Ladeinfrastruktur an Wohngebäuden – Investitionszuschuss“. Published by Bundesministerium für Verkehr und digitale Infrastruktur. Available online at https://www.bmvi.de/SharedDocs/DE/Anlage/G/richtlinie-private-ladeinfrastruktur.pdf?__blob=publicationFile, last checked on 21.10.2021.

BMVI (2021a): Gesetzeskarte Elektromobilität. Zentrale Strategien, Gesetze und Verordnungen. Published by Bundesministerium für Verkehr und digitale Infrastruktur. Zentrale Strategien, Gesetze und Verordnungen. Available online at https://www.bmvi.de/SharedDocs/DE/Anlage/G/buendnis-fuer-moderne-mobilitaet-gesetzeskarte-elektromobilitaet.pdf?__blob=publicationFile, last checked on 21.10.2021.

BMVI (2021b): Transeuropäische Verkehrsnetze (TEN-V). Published by Bundesministerium für Verkehr und digitale Infrastruktur. Available online at https://www.bmvi.de/SharedDocs/DE/Artikel/G/transeuropaeische-verkehrsnetze.html, last checked on 21.10.2021.

BMWi (2020): Die Nationale Wasserstoffstrategie. Published by Bundesministerium für Wirtschaft und Energie. Berlin. Available online at https://www.bmwi.de/Redaktion/DE/Publikationen/Energie/die-nationale-wasserstoffstrategie.html.

BMWi (2021): Bekanntmachung zur Pkw-Energieverbrauchskennzeichnungsverordnung. Published by Bundesministerium für Wirtschaft und Energie. Berlin. Available online at https://www.bmwi.de/Redaktion/DE/Downloads/B/bekanntmachung-zur-pkw-energieverbrauchskennzeichnungsverordnung-preisliste.pdf?__blob=publicationFile&v=4, last checked on 12.10.2021.

Bockisch, Michael (1993): Nahrungsfette und -öle. Stuttgart: Ulmer (Handbuch der Lebensmitteltechnologie).

Bongartz, D.; Doré, L.; Eichler, K.; Grube, T.; Heuser, B.; Hombach, L. E. et al.: Comparison of light-duty transportation fuels produced from renewable hydrogen and green carbon dioxide.

Bongartz, Dominik; Doré, Larissa; Eichler, Katharina; Grube, Thomas; Heuser, Benedikt; Hombach, Laura E. et al. (2018): Comparison of light-duty transportation fuels produced from renewable hydrogen and green carbon dioxide. In: *Applied Energy* 231, p. 757–767. DOI: 10.1016/j.apenergy.2018.09.106.

Bradin, David (2014): Process for producing renewable jet fuel compositions. Registered through David Bradin. Registration no: US201261667605P. Publication no: WO2014008337A1. Priority data: 03.07.2012.

Brandin, Jan; Liliedahl, Truls (2011): Unit operations for production of clean hydrogen-rich synthesis gas from gasified biomass. In: *Biomass and Bioenergy* 35 (5), S8-S15. DOI: 10.1016/j.biombioe.2011.05.025.

Brohi, Emtiaz Ali (2014): Ammonia as fuel for internal combustion engines? An evaluation of the feasibility of using nitrogen based fuels in ICE. An evaluation of the feasibility of using nitrogen based fuels in ICE. Available online at https://publications.lib.chalmers.se/records/fulltext/207145/207145.pdf, last checked on 21.10.2021.

Brown, Trevor (2013): Renewable Ammonia from Biomass: SynGest, BioNitrogen, Agrebon. Available online at https://nh3fuelassociation.org/2013/04/24/ammonia-from-biomass/, last updated 24.04.2013, last checked on 21.10.2021.

Bründlinger, Thomas; König, Julian Elizalde; Frank, Oliver; Gründig, Dietmar; Jugel, Christoph; Kraft, Patrizia et al. (2018): dena-Leitstudie Integrierte Energiewende. Impulse für die Gestaltung des Energiesystems bis 2050. Published by Deutsche Energie-Agentur GmbH (dena). Impulse für die Gestaltung des Energiesystems bis 2050. Berlin. Available online at https://www.dena.de/fileadmin/dena/Dokumente/Pdf/9261_dena-Leitstudie_Integrierte_Energiewende_lang.pdf, last checked on 06.10.2021.

BTG bioliquids (2021): From sawdust to tank. Available online at https://www.btg-bioliquids.com/plant/pyrocell-gavle-sweden/, last checked on 20.10.2021.

Buddenberg, Torsten; Bergins, Christian (2016): Capturing of CO2 in Waste Incineration Plants towards Power2Fuel. Published by MHPS Mitsubishi Hitachi Power Systems.

Bullerdiek, Nils; Buse, Joachim; Dögnitz, Niels; Feige, Andreas; Halling, Ann-Marlen; Hauschild, Stephanie et al. (2019a): Einsatz von Multiblend-JET-A-1 in der Praxis. Zusammenfassung der Ergebnisse aus dem Modellvorhaben der Mobilitäts- und Kraftstoffstrategie. Zusammenfassung der Ergebnisse aus dem Modellvorhaben der Mobilitäts- und Kraftstoffstrategie. Leipzig.

Bullerdiek, Nils; Buse, Joachim; Kaltschmitt, Martin; Pechstein, Jan (2019b): Regulatory Requirements for Production, Blending, Logistics, Storage, Aircraft Refuelling, Sustainability Certification and Accounting of Sustainable Aviation Fuels (SAF). Report within the Research and Demonstration Project on the Use of Renewable Kerosene at Airport Leipzig/Halle (DEMO-SPK). Published by Bundesministerium für Verkehr und digitale Infrastruktur. Report within the Research and Demonstration Project on the Use of Renewable Kerosene at Airport Leipzig/Halle (DEMO-SPK). Available online at https://www.bmvi.de/SharedDocs/DE/Anlage/G/MKS/demo-spk-recommendation-paper.pdf?__blob=publicationFile, last checked on 21.10.2021.

Bundesnetzagentur (2021): La-de-säu-len-kar-te. Available online at https://www.bundesnetzagentur.de/DE/Sachgebiete/ElektrizitaetundGas/Unternehmen_Institutionen/E-Mobilitaet/Ladesaeulenkarte/start.html, last checked on 28.10.2021.

Bundesregierung (2021): Generationenvertrag für das Klima. Klimaschutzgesetz 2021. Klimaschutzgesetz 2021. Available online at https://www.bundesregierung.de/breg-de/themen/klimaschutz/klimaschutzgesetz-2021-1913672, last updated 27.08.2021, last checked on 21.10.2021.

Bunge Deutschland GmbH (2018): Pflanzenöl. Sicherheitsdatenblatt. Published by Bunge Deutschland GmbH. Sicherheitsdatenblatt. Available online at https://www.bunge-deutschland.de/fileadmin/user_upload/downloads/sicherheitsdatenblaetter/SDB_Pflanzenoel_2018.pdf, last checked on 06.10.2021.

Butera, Giacomo; Jensen, Søren H.; Ahrenfeldt, Jesper; Clausen, Lasse R. (2021): Techno-economic analysis of methanol production units coupling solid oxide cells and thermochemical biomass conversion via the TwoStage gasifier. In: *Fuel Processing Technology* 215, p. 106718. DOI: 10.1016/j.fuproc.2020.106718.

Buttler, Alexander; Spliethoff, Hartmut (2018): Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids. A review. In: *Renewable and Sustainable Energy Reviews* 82 (3), p. 2440–2454. DOI: 10.1016/j.rser.2017.09.003.

BYOGY Renewables (2016): Renewable fuels for all modes of transport. Available online at https://www.energy.gov/sites/prod/files/2016/09/f33/weiss_alternative_aviation_fuels_workshop.pdf, last checked on 21.10.2021.

C2FUEL (2020): Project concept and objectives. Available online at https://c2fuel-project.eu/about-c2fuel/, last checked on 21.10.2021.

C3-Mobility (2021): C3-Mobility - Ausgewählte Projektergebnisse. Available online at http://www.c3-mobility.de/abgeschlossene-arbeitspakete/, last checked on 21.10.2021.

CAAFI (2009): Declaration and Recommendations. Conference on Aviation and Alternative Fuels. Conference on Aviation and Alternative Fuels. Available online at https://www.icao.int/Meetings/caaf2009/Documents/CAAF-09_WP024_en.pdf, last checked on 21.10.2021.

CAAFI (2013): CAAFI Fuel Readiness Level Pass/Fail Criteria List. Available online at https://www.caafi.org/information/pdf/PassFailCriteria_Alternative%20Fuel%20FRL%202013_06_26.pdf, last updated 26.06.2013, last checked on 21.10.2021.

CAAFI (2018): Alternative Jet Fuel Production Facilities Status. Available online at https://www.caafi.org/focus_areas/docs/Alternative_Jet_Fuel_Production_Facilities_Status.pdf, last checked on 21.10.2021.

CAAFI (2021): Fuel Qualification. Available online at https://www.caafi.org/focus_areas/fuel_qualification.html, last checked on 22.06.2021.

Calpam Mineralöl-Gesellschaft mbH (2018): FAME (Biodiesel). Sicherheitsdatenblatt. Published by Calpam Mineralöl-Gesellschaft mbH. Sicherheitsdatenblatt. Available online at https://calpam.com/wp-content/uploads/2019/10/SDB-Calpam-FAME-Biodiesel_2018-neu.pdf, last checked on 21.10.2021.

Capaz, Silva R. (2021): Alternative aviation fuels in Brazil. Environmental performance and economic feasibility. Environmental performance and economic feasibility.

CAPHENIA (2021): CAPHENIA produziert E-Fuels in Niedersachsen. Available online at https://caphenia.tech/caphenia-produziert-e-fuels-in-niedersachsen/, last updated 28.10.2021.

Cardoso, João Sousa; Silva, Valter; Chavando, José Antonio Mayoral; Eusébio, Daniela; Hall, Matthew J.; Costa, Mário (2021): Small-Scale Biomass Gasification for Green Ammonia Production in Portugal. A Techno-Economic Study. In: *Energy Fuels* 35 (17), p. 13847–13862. DOI: 10.1021/acs.energyfuels.1c01928.

Carl Roth GmbH (2020): Methanol ≥99 %, zur Synthese. Sicherheitsdatenblatt. Published by Carl Roth GmbH. Sicherheitsdatenblatt. Available online at https://www.carlroth.com/medias/SDB-8388-DE-DE.pdf?context=bWFzdGVyfHNlY3VyaXR5RGF0YXNoZWV0c3wzNzYzNjZ8YXBwbGljYXRpb24vcGRmfHNlY3VyaXR5RGF0YXNoZWV0cy9oNzIvaDczLzkwMzE2NDY2MDk0MzgucGRmfGY1MTQwNzEzZWI5NTBmZjFmNjc3YzExZmQ5NTBmZDNjZDNkMDAzYmU3MWIxMTM5OTNkMzkwNjFlNGY2MzA0YTE, last checked on 06.10.2021.

Carl Roth GmbH (2021): Ethanol 96%, Ph.Eur., reinst. Sicherheitsdatenblatt. Published by Carl Roth GmbH. Sicherheitsdatenblatt. Available online at https://www.carlroth.com/medias/SDB-P075-BE-DE.pdf?context=bWFzdGVyfHNlY3VyaXR5RGF0YXNoZWV0c3wyNzgxODl8YXBwbGljYXRpb24vcGRmfHNlY3VyaXR5RGF0YXNoZWV0cy9oZDcvaDVlLzkwMjc3OTk0NDk2MzAucGRmfDQwZjZkMDlmYzEyNTJkODQ5ZDY2NWNlYzA2YTE4YzU4ZTJlNzgyZGFlYTYxMzIzODZiYmY2ODA1NTE2YzYzYTk, last checked on 06.10.2021.

Carl Roth GmbH: Rapsöl. Sicherheitsdatenblatt. Published by Carl Roth GmbH. Sicherheitsdatenblatt. Available online at https://www.carlroth.com/medias/SDB-6964-DE-DE.pdf?context=bWFzdGVyfHNlY3VyaXR5RGF0YXNoZWV0c3wyMTg1NDZ8YXBwbGljYXRpb24vcGRmfHNlY3VyaXR5RGF0YXNoZWV0cy9oODYvaGNiLzg5MTMwNjEzMTQ1OTAucGRmfDNlMzM3MTQwMjU0NmFiZDU3MmRiNTg3YWFmMDBkNDg2MWRmYTAwMzc2NGQzZDg5OTU1MDVmYTA1OGI1MzJmOGU, last checked on 21.10.2021.

Castello, Daniele; Haider, Muhammad Salman; Rosendahl, Lasse Aistrup (2019): Catalytic upgrading of hydrothermal liquefaction biocrudes. Different challenges for different feedstocks. In: *Renew. Energy* 141, p. 420–430.

Castello, Daniele; Pedersen, Thomas; Rosendahl, Lasse (2018): Continuous Hydrothermal Liquefaction of Biomass. A Critical Review. In: *Energies* 11 (11), p. 3165. DOI: 10.3390/en11113165.

Chen, Peter H.; Quinn, Jason C. (2021): Microalgae to biofuels through hydrothermal liquefaction. Open-source techno-economic analysis and life cycle assessment. In: *Applied Energy* 289, p. 116613. DOI: 10.1016/j.apenergy.2021.116613.

Cherad, Ramzi; Onwudili, J. A.; Biller, Pratrick; Williams, P. T.; Ross, A. B. (2016): Hydrogen production from the catalytic supercritical water gasification of process water generated from hydrothermal liquefaction of microalgae. In: *Fuel* 166, p. 24–28.

Chuck, Christopher J. (Publisher) (2016): Biofuels for aviation. Feedstocks, technology and implementation. Feedstocks, technology and implementation. London, UK, San Diego, CA: Academic Press.

Cihlar, J.; Lejarreta, A. V.; Wang, A.; Melgar, F.; Jens, J.; Rio, P. (2020): Hydrogen Generation in Europe. Overview of Key costs and Benefits. Published by European Commission. Overview of Key costs and Benefits. Available online at https://op.europa.eu/de/publication-detail/-/publication/7e4afa7d-d077-11ea-adf7-01aa75ed71a1/language-en, last checked on 05.01.2022.

Ciria, Carlos S.; Barro, Ruth; Sanz, Marina; Ciria, Pilar (2020): Long-Term Yield and Quality Performance of Perennial Energy Grasses (Agropyron spp.) on Marginal Land. In: *Agronomy* 10 (7), p. 1051. DOI: 10.3390/agronomy10071051.

Clariant (2021a): Clariant completes construction of first commercial Sunliquid® cellulosic ethanol plant in Podari, Romania. Available online at https://www.clariant.com/en/Corporate/News/2021/10/Clariant-completes-construction-of-first-commercial-sunliquid-cellulosic-ethanol-plant-in-Podari-Rom, last updated 15.10.2021, last checked on 29.10.2021.

Clariant (2021b): sunliquid® Cellulosic Ethanol Plant in Romania. Available online at https://www.clariant.com/de/Corporate/Events/2021/10/Global-Media-Call-sunliquid-Cellulosic-Ethanol-Plant, last updated 13.10.2021, last checked on 21.10.2021.

Clariant (2021c): Welcome at Clariant in Romania. Commercial-scale flagship plant for the production of cellulosic ethanol. Commercial-scale flagship plant for the production of cellulosic ethanol. Available online at https://www.clariant.com/pt/Company/Contacts-and-Locations/Key-Sites/Romania, last checked on 21.10.2021.

CO2FOKUS (2020): Our Approach. Available online at https://www.co2fokus.eu/our-approach/, last checked on 21.10.2021.

COM(2016) 767 (2017): Vorschlag für eine Richtlinie des Europäischen Parlaments und des Rates zur Förderung der Nutzung von Energie aus erneuerbaren Quellen (Neufassung). COM(2016) 767 from 23.02.2017.

COM(2021) 557 (2021): Proposal for a Directive of the European Parliament and oft he Council amending Directive (EU) 2018/2001,Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652. COM(2021) 557 from 14.07.2021.

COM/2021/555 (14.07.2021): Vorschlag für eine Verordnung zur Änderung der Verordnung (EU) 2018/842 zur Festlegung verbindlicher nationaler Jahresziele für die Reduzierung der Treibhausgasemissionen im Zeitraum 2021 bis 2030 als Beitrag zu Klimaschutzmaßnahmen zwecks Erfüllung der Verpflichtungen aus dem Übereinkommen von Paris. COM/2021/555 from 14.07.2021.

CORDIS (2013): FTE-Erfolgsstorys - Potenzial von Algen als Biokraftstoff erwecken. Available online at https://cordis.europa.eu/article/id/90176-rtd-success-stories-unlocking-the-biofuel-potential-of-algae/de, last updated 16.12.2013, last checked on 04.11.2021.

CORDIS (2016): FLExible Dimethyl ether production from biomass Gasification with sorption-enhancED processes (FLEDGED). Available online at https://cordis.europa.eu/project/id/727600, last updated 27.06.2017, last checked on 25.10.2021.

CORDIS (2021): Fuel via Low Carbon Integrated Technology from Ethanol. Available online at https://cordis.europa.eu/project/id/857839, last updated 22.07.2021, last checked on 25.10.2021.

CORSIA (2018): Annex 16, Environmental Protection, Volume IV. CORSIA.

Cui, Lei; Ren, Yongkang; Murray, Timothy D.; Yan, Wenze; Guo, Qing; Niu, Yuqi et al. (2018): Development of Perennial Wheat Through Hybridization Between Wheat and Wheatgrasses. A Review. In: *Engineering* 4 (4), p. 507–513. DOI: 10.1016/j.eng.2018.07.003.

Czarnikow (2021): Ethanol vs sugar: the price relationship that keeps Brazil's sugar market guessing. Available online at https://www.czarnikow.com/blog/brazil-sugar-market-ethanol-sugar, last updated 08.02.2021, last checked on 08.11.2021.

Dahmen, Nicolaus; Henrich, Edmund; Dinjus, Eckhard; Weirich, Friedhelm (2012): The bioliq® bioslurry gasification process for the production of biosynfuels, organic chemicals, and energy. In: *Energ Sustain Soc* 2 (1), p. 327. DOI: 10.1186/2192-0567-2-3.

Daniel-Gromke, Jaqueline; Kretzschmar, Jörg; Stinner, Walter; Barchmann, Tino; Denysenko, Velina; Rensberg, Nadja; Liebetrau, Jan (2018): Beitrag von Biogas im Rahmen der Sektorkopplung. Expertenfrühstück "Die Rolle des Gassektors in der Energiewende". Berlin (2018).

Daniel-Gromke, Jaqueline; Rensberg, Nadja; Denysenko, Velina; Trommler, Marcus; Reinholz, Toni; Völler, Klaus et al. (2017): Anlagenbestand Biogas und Biomethan - Biogaserzeugung und -nutzung in Deutschland. Leipzig: DBFZ Deutsches Biomasseforschungszentrum gemeinnützige GmbH (DBFZ Report, Nr. 30).

Dannesboe, Christian; Hansen, John Bøgild; Johannsen, Ib (2021): Removal of sulfur contaminants from biogas to enable direct catalytic methanation. In: *Biomass Conv. Bioref.* 11 (5), p. 1823–1834. DOI: 10.1007/s13399-019-00570-7.

Davis, Stacy C.; Boundy, Robert G. (2020): Transportation Energy. Data Book. 38.2. Ed. Published by Oak Ridge National Laboratory. Data Book. Available online at https://www.inist.org/library/2020-08.Davis_Boundy.TransportationEnergyDataBook_Ed_38.US_DOE.pdf, last checked on 25.10.2021.

DBFZ (2021a): Pilotanlage Synthetisiertes Biogas. Bioressourcen und Wasserstoff zu Methan als Kraftstoff – Konzeptionierung einer Anlage im Pilotmaßstab. Bioressourcen und Wasserstoff zu Methan als Kraftstoff – Konzeptionierung einer Anlage im Pilotmaßstab. Available online at https://www.dbfz.de/projektseiten/pilot-sbg, last checked on 25.10.2021.

DBFZ (2021b): Ressourcendatenbank. Available online at https://webapp.dbfz.de/resource-database/?lang=de, last checked on 25.10.2021.

DBFZ (2022): Monitoringbericht erneuerbare Energien im Verkehr. Published by DBFZ Deutsches Biomasseforschungszentrum gemeinnützige GmbH. Available online at https://www.dbfz.de/Monitoring-EE-im-Verkehr/, last updated 15.12.2021, last checked on 15.12.2021.

DBFZ; ZALF; DLR; DFD; ILB; vTI (2010): Globale und regionale räumliche Verteilung von Biomassepotenzialen. Statuos Quo und Möglichkeit der Präzisierung. Statuos Quo und Möglichkeit der Präzisierung. Available online at https://www.unendlich-viel-energie.de/media/file/255.DBFZ_ZALF_DLR_VTI_Globale_Regionale_Biomassepotenziale_mar10.pdf, last updated 03.2010, last checked on 25.11.2021.

DBI (2019): Verbundvorhaben FlexDME - Entwicklung einer flexibel operierenden Demonstrationsanlage zur Erzeugung von Dimethylether aus Biogas und Wasserstoff. Available online at https://www.dbi-gruppe.de/files/PDFs/Projekte/82_Projektsteckbrief_FlexDME_03EIV121D.pdf, last updated 03.06.2019, last checked on 25.10.2021.

DBU (2010): Abschlussbericht Aktenzeichen 13224-32. „Förderschwerpunkt-Biotechnologie: ChemBioTec: Integrierter Prozess zur Produktion von Omega-3-EPA mittels Mikroalgen im Photobioreaktor, Entwicklung von Aufschlussund Extraktionsverfahren". „Förderschwerpunkt-Biotechnologie: ChemBioTec: Integrierter Prozess zur Produktion von Omega-3-EPA mittels Mikroalgen im Photobioreaktor, Entwicklung von Aufschlussund Extraktionsverfahren“. Available online at https://www.dbu.de/OPAC/ab/DBU-Abschlussbericht-AZ-13224.pdf, last checked on 04.11.2021.

DEHSt (2021): Projekte im Kraftstoffsektor. Published by Umweltbundesamt. Available online at https://www.dehst.de/DE/Klimaschutzprojekte-Seeverkehr/UERV/upstream-emissionsminderungen_node.html, last checked on 22.01.2021.

Deligierte Verordnung (EU) C(2019)2055 (2019): COMMISSION DELEGATED REGULATION (EU) C(2019) 2055 of 13.3.2019 supplementing Directive (EU) 2018/2001 as regards the determination of high indirect land-use change-risk feedstock for which a significant expansion of the production area into land with high carbon stock is observed and the certification of low indirect landuse change-risk biofuels, bioliquids and biomass fuels. Deligierte Verordnung (EU) C(2019)2055 from 13.03.2019.

Demoures, Sylvain (2020): French success story on E85: can it be replicated across Europe ? Fuels of the Future 2020. Fuels of the Future 2020. Berlin.

Demuynck, Joachim (2021): Advanced emission controls and renewable fuels for future-proof engines with low pollutants and lifecycle CO2 emissions. 9th Intern. Conf. “Fuel Science - From Production to Propulsion”. 22-24 June 2021. 9th Intern. Conf. “Fuel Science - From Production to Propulsion” (2021). Available online at https://www.aecc.eu/wp-content/uploads/2021/06/210623-AECC-presentation-FSC-conference-final.pdf, last checked on 25.10.2021.

dena (2021a): Audi e-gas Projekt. Available online at https://www.powertogas.info/projektkarte/audi-e-gas-projekt/, last checked on 25.10.2021.

dena (2021b): Branchenbarometer Biomethan 2021. dena-ANALYSE. With collaboration of Toni Reinholz und Klaus Völler. Published by Deutsche Energie-Agentur GmbH (dena). dena-ANALYSE.

dena (2021c): dena-Leitstudie Aufbruch Klimaneutralität. Eine gesamtgesellschaftliche Aufgabe. Published by Deutsche Energie-Agentur GmbH. Eine gesamtgesellschaftliche Aufgabe. Available online at https://www.dena.de/fileadmin/dena/Publikationen/PDFs/2021/Abschlussbericht_dena-Leitstudie_Aufbruch_Klimaneutralitaet.pdf, last checked on 25.10.2021.

Destatis (2021a): Bevölkerung nach Nationalität und Geschlecht (Quartalszahlen). Bevölkerungsstand. Published by Destatis. Bevölkerungsstand. Available online at https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Bevoelkerung/Bevoelkerungsstand/Tabellen/liste-zensus-geschlecht-staatsangehoerigkeit.html, last checked on 25.10.2021.

Destatis (2021b): Elektrischer Strom. Abgabe an private Haushalte. Published by Statistisches Bundesamt (Destatis). Abgabe an private Haushalte. Available online at https://www.destatis.de/DE/Themen/Wirtschaft/Preise/Publikationen/Energiepreise/energiepreisentwicklung-pdf-5619001.pdf?__blob=publicationFile, last checked on 03.12.2021.

Deutsche Bahn (2020): Integrierter Bericht 2020. Available online at https://ibir.deutschebahn.com/2020/fileadmin/downloads/pdf/DB_IB20_d_web_01.pdf, last checked on 28.10.2021.

Deutsche Bahn (2021): DB Energie - Treiber der Energiewende für die Mobilität der Zukunft. Available online at https://www.dbenergie.de/dbenergie-de/nachhaltigkeit, last checked on 28.10.2021.

Deutsche Bahn AG (2016): DB-Konzern - Unsere Flotten und Netzwerke 2015. Published by Deutsche Bahn AG. Available online at https://ir.deutschebahn.com/fileadmin/Deutsch/2015/Berichte/IB_2015_Flotte_de.pdf, last checked on 25.10.2021.

Deutscher Bundestag (2019): Luftverschmutzungen durch die Binnenschifffahrt. Antwort der Bundesregierung auf kleine Anfrage. Drucksache 19/7510. Published by Deutscher Bundestag. Antwort der Bundesregierung auf kleine Anfrage. Available online at https://dip21.bundestag.de/dip21/btd/19/075/1907510.pdf, last checked on 25.10.2021.

Deutscher Bundestag (2020): Beschaffung von rollendem Material bei der Deutschen Bahn AG. Antwort der Bundesregierung auf kleine Anfrage. Drucksache 19/22478. Published by Deutscher Bundestag. Antwort der Bundesregierung auf kleine Anfrage. Available online at http://dip21.bundestag.de/dip21/btd/19/224/1922478.pdf, last checked on 25.10.2021.

Deutscher Bundestag (2022a): Gesetze. Parlamentsbegriffe A – Z. Published by Deutscher Bundestag. Parlamentsbegriffe A – Z. Available online at https://www.bundestag.de/services/glossar/glossar/G/gesetze-245434, last checked on 18.01.2022.

Deutscher Bundestag (2022b): Rechtsverordnung. Parlamentsbegriffe A – Z. Published by Deutscher Bundestag. Parlamentsbegriffe A – Z. Available online at https://www.bundestag.de/services/glossar/glossar/R/rechtsverord-245520, last checked on 18.01.2022.

Di Marcoberardino, Gioele; Foresti, Stefano; Binotti, Marco; Manzolini, Giampaolo (2018): Potentiality of a biogas membrane reformer for decentralized hydrogen production 129, p. 131–141. DOI: 10.1016/j.cep.2018.04.023.

Dias, M. E.; Oliveira, G. H.D.; Couto, P. T.; Dussán, K. J.; Zaiat, M.; Ribeiro, R. et al. (2021): Anaerobic digestion of hydrothermal liquefaction wastewater from spent coffee grounds. In: *Biomass and Bioenergy* 148, p. 106030.

Dieterich, Vincent; Buttler, Alexander; Hanel, Andreas; Spliethoff, Hartmut; Fendt, Sebastian (2020): Power-to-liquid via synthesis of methanol, DME or Fischer–Tropsch-fuels. A review. In: *Energy Environ. Sci.* 13 (10), p. 3207–3252. DOI: 10.1039/d0ee01187h.

DIN 51605 (2020): Kraftstoffe für pflanzenöltaugliche Motoren - Rapsölkraftstoff - Anforderungen und Prüfverfahren (2020).

DIN 51623 (2020): Kraftstoffe für pflanzenöltaugliche Motoren - Pflanzenölkraftstoff - Anforderungen und Prüfverfahren (2020).

DIN EN 14214 (2019): Flüssige Mineralölerzeugnisse - Fettsäure-Methylester (FAME) zur Verwendung in Dieselmotoren und als Heizöl - Anforderungen und Prüfverfahren; Deutsche Fassung EN 14214:2012+A2:2019 (2019).

DIN EN 15293 (2018): Kraftstoffe - Ethanolkraftstoff (E85) - Anforderungen und Prüfverfahren; Deutsche Fassung EN 15293:2018 (2018).

DIN EN 15376 (2014): Kraftstoffe für Kraftfahrzeuge - Ethanol zur Verwendung als Blendkomponente in Ottokraftstoff - Anforderungen und Prüfverfahren; Deutsche Fassung EN 15376:2014 (2014).

DIN EN 15940 (2019): Kraftstoffe - Paraffinischer Dieselkraftstoff aus Synthese oder Hydrierungsverfahren_- Anforderungen und Prüfverfahren; Deutsche Fassung EN_15940:2016+A1:2018+AC:2019 (2019).

DIN EN 16709 (2019): Kraftstoffe - Dieselkraftstoffmischungen mit hohem FAME-Anteil (B20 und B30)_- Anforderungen und Prüfverfahren; Deutsche Fassung EN_16709:2015+A1:2018 (2019).

DIN EN 16723-2 (2017): Erdgas und Biomethan zur Verwendung im Transportwesen und Biomethan zur Einspeisung ins Erdgasnetz - Teil 2: Festlegungen für Kraftstoffe für Kraftfahrzeuge; Deutsche Fassung EN 16723-2:2017 (2017).

DIN EN 16734 (2019): Kraftstoffe - Dieselkraftstoff (B10) - Anforderungen und Prüfverfahren; Deutsche Fassung EN 16734:2016+A1:2018 (2019).

DIN EN 16942 (2021): Kraftstoffe - Identifizierung der Fahrzeug-Kompatibilität - Graphische Darstellung zur Verbraucherinformation; Deutsche Fassung EN 16942:2016+A1:2021 (2021).

DIN EN 17124 (2019): Wasserstoff als Kraftstoff_- Produktfestlegung und Qualitätssicherung_- Protonenaustauschmembran(PEM)-Brennstoffzellenanwendungen für Straßenfahrzeuge; Deutsche Fassung EN_17124:2018 (2019).

DIN EN 228 (2017): Kraftstoffe - Unverbleite Ottokraftstoffe - Anforderungen und Prüfverfahren; Deutsche Fassung EN 228:2012+A1:2017 (2017).

DIN EN 589 (2019): Kraftstoffe - Flüssiggas - Anforderungen und Prüfverfahren; Deutsche Fassung EN 589:2018 (2019).

DIN EN 590 (2017): Kraftstoffe - Dieselkraftstoff - Anforderungen und Prüfverfahren; Deutsche Fassung EN 590:2013+A1:2017 (2017).

DIN EN ISO 14040 (2006): Umweltmanagement – Ökobilanz – Grundsätze und Rahmenbedingungen (ISO 14040:2006); (2006).

DIN EN ISO 14044 (2006): Umweltmanagement – Ökobilanz – Anforderungen und Anleitungen (ISO 14044:2006) (2006).

DIN ISO 8217 (2018): Mineralölerzeugnisse - Kraft- und Brennstoffe (Klasse_F) - Anforderungen an Schifffahrtsbrennstoffe (ISO_8217:2017) (2018).

DLR (2003): Ökologisch optimierter Ausbau der Nutzung erneuerbarer Energien in Deutschland. Available online at https://www.ifeu.de/fileadmin/uploads/landwirtschaft/pdf/Oekologisch_optimierter_Ausbau_Langfassung.pdf, last updated 03.2003, last checked on 28.10.2021.

DLR (2017): A standardized methodology for the techno-conomic evaluation of alternative fuels – A case study. Available online at https://elib.dlr.de/109190/, last checked on 05.11.2021.

DLR (2020): Wind-strom als Bei-trag für kli-maf-reund-li-ches Flie-gen. Available online at https://www.dlr.de/content/de/artikel/news/2020/03/20200820_windstrom_als_beitrag_fuer_klimafreundliches_fliegen.html, last updated 24.08.2020, last checked on 25.10.2021.

Dressler, Daniela; Engelmann, Karsten; Serdjuk, Martina; Remmele, Edgar (2016): Rapsölkraftstoffproduktion in Bayern. Analyse und Bewertung ökologischer und Analyse und Bewertung ökologischer und ökonomischer Wirkungen nach der ExpRessBio-Methode nach der ExpRessBio-Methode. Published by TFZ Technologie- und Förderzentrum. Analyse und Bewertung ökologischer und Analyse und Bewertung ökologischer und ökonomischer Wirkungen nach der ExpRessBio-Methode nach der ExpRessBio-Methode.

DTU (2019): Final report. MeGa-stoRE 2 - Phase 2. MeGa-stoRE 2 - Phase 2. Available online at https://energiforskning.dk/sites/energiforskning.dk/files/slutrapporter/megastore2.2_final_report_27-jun_19_1_16072019_13021.pdf, last updated 30.06.2019, last checked on 05.11.2021.

DTU (2020): Biogas into methanol in a container. Available online at https://www.dtu.dk/english/about/press-room/articles/2020/06/biogas-into-methanol-in-a-container?id=81048c4e-9d28-4a41-a059-6a881f8b1989, last updated 04.06.2020, last checked on 25.10.2021.

Durchführungsverordnung (EU) 2017/1578 (2017): Durchführungsverordnung (EU) 2017/1578 der Komission vom 18. September 2017 zur Änderung der Durchführungsverordnung (EU) Nr. 1194/2013 des Rates zur Einführung eines endgültigen Antidumpingzolls und zur endgültigen Vereinnahmung des vorläufigen Zolls auf die Einfuhren von Biodiesel mit Ursprung in Argentinien und Indonesien. Durchführungsverordnung (EU) 2017/1578 from 18.09.2017. In: *Amtsblatt der Europäischen Union* 60 (L 239), p. 9–24.

Durchführungsverordnung (EU) 2021/1266 (2021): Durchführungsverordnung (EU) 2021/1266 der Kommission vom 29. Juli 2021 zur Einführung eines endgültigen Antidumpingzolls auf die Einfuhren von Biodiesel mit Ursprung in den Vereinigten Staaten von Amerika im Anschluss an eine Auslaufüberprüfung nach Artikel 11 Absatz 2 der Verordnung (EU) 2016/1036 des Europäischen Parlaments und des Rates. Durchführungsverordnung (EU) 2021/1266 from 02.08.2021. In: *Amtsblatt der Europäischen Union* 64 (L 277), p. 34–61.

DV THG-Quote (2016): Verbrauchsteuern / Ordnungsrechtliche Förderung von Biokraftstoffen durch die Biokraftstoffquote; Veröffentlichung der vorläufigen Fassung der „Dienstvorschrift zur Überwachung der Einhaltung der Treibhausgasminderung nach § 37a Absatz 4 des Bundes-Immissionsschutzgesetzes (DV THG-Quote)". DV THG-Quote from 21.01.2016. In: *Elektronische Vorschriftensammlung Bundes-Finanzverwaltung* (N 04 2016 Nr. 22).

E4tech (2020): Assessment of the potential for new feedstocks for the production of advanced biofuels (Renewable Energy Directive – Annex IX). Available online at https://www.e4tech.com/resources/239-assessment-of-the-potential-for-new-feedstocks-for-the-production-of-advanced-biofuels-renewable-energy-directive-annex-ix.php, last updated 08.2020, last checked on 06.08.2021.

EAFO (2021a): EU-27 | Alternative Fuels and Infrastructure. Country detail. Published by European Alternative Fuels Observatory. Country detail. Available online at https://www.eafo.eu/countries/european-union/23640/summary, last updated 22.06.2021, last checked on 25.10.2021.

EAFO (2021b): Germay | Alternative Fuels and Infrastructure. Country detail. Published by European Alternative Fuels Observatory. Country detail. Available online at https://www.eafo.eu/countries/germany/1734/summary, last updated 22.06.2021, last checked on 25.10.2021.

EI/JIG 1530: EI/JIG Standard 1530 Quality assurance requirements for the manufacture, storage and distribution of aviation fuel to airports (A4).

El-Nagar, Raghda Ahmed; Ghanem, Alaa Ali (2019): Syngas Production, Properties, and Its Importance. Available online at https://www.intechopen.com/chapters/69842, last updated 21.11.2018, last checked on 25.10.2021.

Emberger, Peter (2013): Zünd-, Verbrennungs- und Emissionsverhalten verschiedener Pflanzenöle. Dissertation, Halle (Saale).

EMCEL GmbH (2018): Wie wirkt sich Wasserstoffverunreinigung auf eine Brennstoffzelle aus? Available online at https://emcel.com/de/wasserstoffverunreinigung-in-brennstoffzellen/, last updated 16.04.2018, last checked on 25.10.2021.

EnArgus (2021): Verbundvorhaben: FlexDME - Entwicklung einer flexibel operierenden Demonstrationsanlage zur Erzeugung von Dimethylether aus Biogas und Wasserstoff. Teilvorhaben DBI: Design des Synthesegas-Reaktors und des Katalysatortests. Published by Projektträger Jülich. Teilvorhaben DBI: Design des Synthesegas-Reaktors und des Katalysatortests. Available online at https://www.enargus.de/pub/bscw.cgi/?op=enargus.eps2&q=%2201183342/1%22&v=10&id=936405, last checked on 27.09.2022.

Enderlein, Heinz; Schrader, Bernhard (1991): Verkehr in Zahlen. 20. Ed. Published by Der Bundesminister für Verkehr. Bonn. Available online at https://www.bmvi.de/SharedDocs/DE/Publikationen/G/verkehr-in-zahlen_1991-pdf.pdf?__blob=publicationFile, last checked on 25.10.2021.

EnergieStG (2006): Energiesteuergesetz. EnergieStG from 15.07.2006. In: *BGBl* (I Nr. 33), p. 1534.

EnergieStG (2015): Energiesteuergesetz. EnergieStG from 03.12.2015. In: *BGBl* (I), p. 2178.

EnergieStV (2006): Verordnung zur Durchführung des Energiesteuergesetzes. EnergieStV from 31.07.2006.

Energiewirtschaftliche Tagesfragen (2021): In Leuna entsteht die größte PEM-Elektrolyse-Anlage der Welt. Published by Martin Czakainski. Available online at https://www.energie.de/et/news-detailansicht/nsctrl/detail/News/in-leuna-entsteht-die-groesste-pem-elektrolyse-anlage-der-welt, last updated 19.01.2021, last checked on 25.10.2021.

Enerkem (2021a): Repsol to join Enerkem and Agbar to build a waste to chemicals plant in Tarragona. Available online at https://enerkem.com/news-release/repsol-to-join-enerkem-and-agbar-to-build-a-waste-to-chemicals-plant-in-tarragona/, last updated 27.04.2021, last checked on 25.10.2021.

Enerkem (2021b): Technology comparison. Reducing greenhouse gas emissions and making everyday products greener while offering a sustainable alternative to landfilling, incineration, and other technologies. Reducing greenhouse gas emissions and making everyday products greener while offering a sustainable alternative to landfilling, incineration, and other technologies. Available online at https://enerkem.com/process-technology/technology-comparison/, last checked on 06.07.2021.

Enerkem (2022): Methanol. Available online at https://enerkem.com/products/methanol/, last updated 2022, last checked on 13.01.2022.

ENI (2020): Versalis: biomass power plant restarted at Crescentino and bioethanol production onstream within the first half of the year. Available online at https://www.eni.com/en-IT/media/press-release/2020/02/versalis-biomass-power-plant-restarted-at-crescentino-and-bioethanol-production-onstream-within-the-first-half-of-the-year.html, last updated 08.02.2020, last checked on 25.10.2021.

ENI (2021a): Hydrogen, the potential of an energy vector. Available online at https://www.eni.com/en-IT/operations/hydrogen-clean-energy-strategy-eni.html, last updated 23.03.2021, last checked on 25.10.2021.

ENI (2021b): Hydrogen, the potential of an energy vector. Waste-to-Hydrogen. Waste-to-Hydrogen. Available online at https://www.eni.com/en-IT/operations/hydrogen-clean-energy-strategy-eni.html, last updated 28.10.2021.

ENI (2021c): Website - Biorefineries, a solid example of circular economy. Venice and Gela, two major refineries converted in line with new standards, are emblematic of our work on environmental sustainability. Venice and Gela, two major refineries converted in line with new standards, are emblematic of our work on environmental sustainability. Available online at https://www.eni.com/en-IT/operations/biorefineries.html, last updated 19.10.2021, last checked on 25.10.2021.

Ensyn (2021): Georgia Project. Dooley County, Georgia, U.S. - First Production Expansion Project in the U.S. for Fuels. Dooley County, Georgia, U.S. - First Production Expansion Project in the U.S. for Fuels. Available online at http://www.ensyn.com/georgia.html, last checked on 25.10.2021.

ePure ASBL (2020): E85. An ethanol blend to fuel Europe's clean mobility. Published by ePure ASBL. An ethanol blend to fuel Europe's clean mobility. Available online at https://www.epure.org/wp-content/uploads/2020/08/200803-DEF-PP-E85-factsheet-Single-pages.pdf, last checked on 29.09.2021.

Ernst, Stefan (Publisher) (2013): Preprints of the DGMK-Conference "New Technologies and Alternative Feedstocks in Petrochemistry and Refining", October 9 - 11, 2013, Dresden, Germany. (authors' manuscripts). (authors' manuscripts). Als Ms. gedr. Hamburg: DGMK (Tagungsbericht / DGMK, 2013,2). Available online at https://www.osti.gov/etdeweb/servlets/purl/22176029.

ETD (2021): Proposal for a Directive restructuring the Union framework for the taxation of energy products and electricity. ETD.

ETD (31.05.2021): Community framework for the taxation of energy products and electricity. ETD.

ETIP Bioenergy (2017): Updated and expanded databases. Available online at https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5b4c4768d&appId=PPGMS, last updated 21.07.2017, last checked on 06.07.2021.

ETIP Bioenergy (2021a): Cellulosic Ethanol (CE). Available online at https://www.etipbioenergy.eu/value-chains/products-end-use/products/cellulosic-ethanol, last checked on 25.10.2021.

ETIP Bioenergy (2021b): Demonstration of BioDME - Dimethyl ether as an advanced biofuel at industrial scale. Available online at https://www.etipbioenergy.eu/value-chains/products-end-use/products/biodme, last checked on 25.10.2021.

ETIP Bioenergy (2021c): Discontinued BtL Projects. Available online at https://www.etipbioenergy.eu/value-chains/conversion-technologies/advanced-technologies/biomass-to-liquids/discontinued-btl-projects, last checked on 25.10.2021.

ETIP Bioenergy (2021d): ETBE. Available online at https://www.etipbioenergy.eu/value-chains/products-end-use/products/etbe, last checked on 21.06.2021.

ETIP Bioenergy (2021e): Fatty Acid Methyl Esters (FAME) Fact Sheet. Available online at https://www.etipbioenergy.eu/fact-sheets/fatty-acid-methyl-esters-fame-fact-sheet#prod, last checked on 25.10.2021.

Ettl, Johannes; Emberger, Peter; Thuneke, Klaus; Remmele, Edgar (2016): Pflanzenöltaugliche Traktoren der Abgasstufen I bis IIIB. Begleitforschung zum Einsatz pflanzenöltauglicher Traktoren auf bayerischen Versuchsgütern. Published by Technologie- und Förderzentrum im Kompetenzzentrum für Nachwachsende Rohstoffe. Begleitforschung zum Einsatz pflanzenöltauglicher Traktoren auf bayerischen Versuchsgütern. Straubing (Berichte aus dem TFZ, 47).

Ettl, Johannes; Thuneke, Klaus; Emberger, Peter; Remmele, Edgar (2019): Langzeitmonitoring pflanzenöltauglicher Traktoren der Abgasstufen I bis IV. Published by Technologie- und Förderzentrum im Kompetenzzentrum für Nachwachsende Rohstoffe (Berichte aus dem TFZ, 60 (in Vorbereitung)).

EUR-Lex (2021a): Delegierter Rechtsakte. Glossare von Zusammenfassungen. Published by Europäische Union. Glossare von Zusammenfassungen. Available online at https://eur-lex.europa.eu/summary/glossary/delegated_acts.html?locale=de, last checked on 13.01.2022.

EUR-Lex (2021b): Richtlinie. Glossare von Zusammenfassungen. Published by Europäische Union. Glossare von Zusammenfassungen. Available online at https://eur-lex.europa.eu/summary/glossary/directive.html, last checked on 13.01.2022.

EUR-Lex (2021c): Verordnung. Glossare von Zusammenfassungen. Published by Europäische Union. Glossare von Zusammenfassungen. Available online at https://eur-lex.europa.eu/summary/glossary/regulation.html, last updated 13.01.2022.

Europäische Kommission (2018): A sustainable bioeconomy for Europe. Strengthening the connection between economy, society and the environment : updated bioeconomy strategy. Luxembourg: Publications Office of the European Union. Available online at https://doi.org/10.2777/792130.

Europäische Kommission (2019): Europäischer grüner Deal. Published by Europäische Kommission. Available online at https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_de, last updated 11.06.2021, last checked on 25.10.2021.

Europäische Kommission (2020): Sustainable and Smart Mobility Strategy -putting European transport on track for the future. Available online at https://ec.europa.eu/transport/sites/default/files/legislation/com20200789-annex.pdf, last checked on 26.08.2021.

Europäische Kommission (2021): Umsetzung des europäischen Grünen Deals. Available online at https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_de, last updated 14.07.2021, last checked on 23.08.2021.

Europäische Kommission (2022a): Commission Delegated Regulation (EU) supplementing Directive (EU) 2018/2001 of the European Parliament and of the Council by establishing a minimum threshold for greenhouse gas emissions savings of recycled carbon fuels and by specifying a methodology for assessing greenhouse gas emissions savings from renewable liquid and gaseous transport fuels of non-biological origin and from recycled carbon fuels. Document Ares(2022)3836721. Document Ares(2022)3836721. Available online at https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=PI_COM%3AAres%282022%293836721&qid=1653925514357, last checked on 27.09.2022.

Europäische Kommission (2022b): Commission Delegated Regulation (EU) supplementing Directive (EU) 2018/2001 of the European Parliament and of the Council by establishing a Union methodology setting out detailed rules for the production of renewable liquid and gaseous transport fuels of non-biological origin. Document Ares(2022)3836651. Published by Europäische Kommission. Document Ares(2022)3836651. Available online at https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=PI_COM:Ares(2022)3836651, last checked on 27.09.2022.

Europäische Union (2014): Technology readiness levels (TRL). HORIZON 2020 – WORK PROGRAMME 2014-2015. Extract from Part 19 - Commission Decision C(2014)4995. HORIZON 2020 – WORK PROGRAMME 2014-2015. Available online at https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf, last checked on 25.10.2021.

Europäisches Klimagesetz (04.03.2021): Verordnung zur Schaffung des Rahmens für die Verwirklichung der Klimaneutralität. Europäisches Klimagesetz.

Eurostat (2021a): Bestand der Fahrzeuge nach Kategorie und NUTS-2-Regionen. TRAN_R_VEHST. Published by Eurostat. TRAN_R_VEHST. Available online at https://ec.europa.eu/eurostat/databrowser/view/TRAN_R_VEHST__custom_996134/default/table, last checked on 25.10.2021.

Eurostat (2021b): Erstzulassungen von Krafträdern, nach Hubraumklassen. ROAD_EQR_MOTORS. Published by Eurostat. ROAD_EQR_MOTORS. Available online at https://ec.europa.eu/eurostat/databrowser/view/ROAD_EQR_MOTORS/default/table, last checked on 26.10.2021.

Eurostat (2021c): Erstzulassungen von Omnibussen, Kleinbussen und Oberleitungsomnibussen, nach Art der Antriebsenergie. ROAD_EQR_BUSMOT. Published by Eurostat. ROAD_EQR_BUSMOT. Available online at https://ec.europa.eu/eurostat/databrowser/view/road_eqr_busmot/default/table?lang=de, last checked on 26.10.2021.

Eurostat (2021d): Final energy consumption in road transport by type of fuel. Available online at https://ec.europa.eu/eurostat/databrowser/view/ten00127/default/table?lang=en, last updated 12.11.2021, last checked on 12.11.2021.

Eurostat (2021e): Final energy consumption in transport by type of fuel. Available online at https://ec.europa.eu/eurostat/databrowser/view/ten00126/default/table?lang=en, last updated 12.11.2021, last checked on 12.11.2021.

Eurostat (2021f): Gewerbliche Flugzeugflotte nach Flugzeugtypen. AVIA_EQ_ARC_TYP. Published by Eurostat. AVIA_EQ_ARC_TYP. Available online at https://ec.europa.eu/eurostat/databrowser/view/avia_eq_arc_typ/default/table?lang=de, last checked on 26.10.2021.

Eurostat (2021g): Gütermotorschiffe, und Güterschleppkähne, Güterschubleichter und Schub-Güterschleppkähne, nach der Nutzlast. IWW_EQ_LOADCAP. Published by Eurostat. IWW_EQ_LOADCAP. Available online at https://ec.europa.eu/eurostat/databrowser/view/iww_eq_loadcap/default/table?lang=de, last checked on 26.10.2021.

Eurostat (2021h): Komplette Energiebilanzen bis 2020. Available online at https://ec.europa.eu/eurostat/databrowser/view/NRG_BAL_C__custom_1802907/default/table?lang=de, last checked on 21.12.2021.

Eurostat (2021i): Komplette Energiebilanzen. NRG_BAL_C. Published by Eurostat. NRG_BAL_C. Available online at https://ec.europa.eu/eurostat/databrowser/view/NRG_BAL_C__custom_1071932/default/table?lang=de, last checked on 26.10.2021.

Eurostat (2021j): Treibhausgasemissionen nach Quellsektor. ENV_AIR_GGE. Published by Eurostat. ENV_AIR_GGE. Available online at https://ec.europa.eu/eurostat/databrowser/view/ENV_AIR_GGE__custom_1072051/default/table?lang=de, last checked on 26.10.2021.

Eurostat (2021k): Vereinfachte Energiebilanzen. NRG_BAL_S. Published by Eurostat. NRG_BAL_S. Available online at https://ec.europa.eu/eurostat/databrowser/view/NRG_BAL_S__custom_1071520/default/table?lang=de, last checked on 26.10.2021.

ExxonMobil (2017): Proven process. Proven plants. Proven performance. Energy lives here. Energy lives here. Available online at https://www.exxonmobilchemical.com/~/media/chemicals/kl-media-assets/2017/08/24/09/52/mtg_webpage_enpdf.pdf, last updated 24.08.2017, last checked on 26.10.2021.

F.O. Licht (2009): World Ethanol and Biofuels Report. In: *F.O. Licht* 7 (18).

F.O. Licht (2011a): World Ethanol & Biofuels Report. In: *F.O. Licht* 9 (17).

F.O. Licht (2011b): World Ethanol & Biofuels Report. In: *F.O. Licht* 9 (18).

F.O. Licht (2012a): World Ethanol and Biofuels Report. In: *F.O. Licht* 10 (14).

F.O. Licht (2012b): World Ethanol and Biofuels Report. In: *F.O. Licht* 10 (15).

F.O. Licht (2014a): World Ethanol and Biofuels Report. In: *F.O. Licht* 12 (15).

F.O. Licht (2014b): World Ethanol and Biofuels Report. In: *F.O. Licht* 12 (16).

F.O. Licht (2015a): World Ethanol & Biofuels Report. In: *F.O. Licht* 13 (22).

F.O. Licht (2015b): World Ethanol and Biofuels Report. In: *F.O. Licht* 13 (15).

F.O. Licht (2015c): World Ethanol and Biofuels Report. In: *F.O. Licht* 13 (16).

F.O. Licht (2015d): World Ethanol and Biofuels Report. In: *F.O. Licht* 13 (20).

F.O. Licht (2016a): World Ethanol & Biofuels Report. In: *F.O. Licht* 14 (23).

F.O. Licht (2016b): World Ethanol and Biofuels Report. In: *F.O. Licht* 14 (16).

F.O. Licht (2016c): World Ethanol and Biofuels Report. In: *F.O. Licht* 14 (18).

F.O. Licht (2017a): World Ethanol & Biofuels Report. In: *F.O. Licht* 15 (22).

F.O. Licht (2017b): World Ethanol and Biofuels Report. In: *F.O. Licht* 15 (16).

F.O. Licht (2018a): World Ethanol & Biofuels Report. In: *F.O. Licht* 16 (20).

F.O. Licht (2018b): World Ethanol and Biofuels Report. In: *F.O. Licht* 16 (15).

F.O. Licht (2019): World Ethanol and Biofuels Report. In: *F.O. Licht* 17 (17).

FAO (1999): Sugar Beets / White Sugar. Available online at http://www.fao.org/3/ae377e/ae377e.pdf, last updated 10.1999, last checked on 26.10.2021.

FAO (2021): FAOSTAT. Available online at http://www.fao.org/faostat/en/#home, last checked on 26.10.2021.

Faria-Oliveira, Fabio; Puga, Sonia; Ferreir, Celia (2013): Yeast. World's Finest Chef. In: Innocenzo Muzzalupo (Hg.): Food Industry: InTech.

Fasihi, Mahdi; Bogdanov, Dmitrii; Breyer, Christian (2016): Techno-Economic Assessment of Power-to-Liquids (PtL) Fuels Production and Global Trading Based on Hybrid PV-Wind Power Plants. In: *Energy Procedia* 99, p. 243–268. DOI: 10.1016/j.egypro.2016.10.115.

Fernández-Dacosta, Cora; Shen, Li; Schakel, Wouter; Ramirez, Andrea; Kramer, Gert Jan (2019): Potential and challenges of low-carbon energy options. Comparative assessment of alternative fuels for the transport sector. In: *Applied Energy* 236 (9), p. 590–606. DOI: 10.1016/j.apenergy.2018.11.055.

Ferrari, Joseph (2021): Electric utility resource planning. Past, present and future.

finanzen.net (2020a): Ethanolpreis historische Kurse in Euro. Published by finanzen.net GmbH. Available online at https://www.finanzen.net/rohstoffe/ethanolpreis/historisch/euro, last checked on 01.11.2021.

finanzen.net (2020b): Weizenpreis historische Kurse in Euro. Published by finanzen.net GmbH. Available online at https://www.finanzen.net/rohstoffe/weizenpreis/historisch, last checked on 01.11.2021.

Fischedick, Manfred (2007): Geologische CO2-Speicherung als klimapolitische Handlungsoption. Technologien, Konzepte, Perspektiven. Wuppertal: Wuppertal-Inst. für Klima Umwelt Energie (Wuppertal spezial, 35).

Fischedick, Manfred; Görner, Klaus; Thomeczek, Margit (2015): CO2. Abtrennung, Speicherung, Nutzung. Berlin, Heidelberg: Springer Berlin Heidelberg.

FLEDGED (2018): Flexible Dimethyl ether production from biomass gasification with sorption enhanced processes. Available online at https://cordis.europa.eu/project/id/727600/de, last checked on 01.11.2021.

FLEDGED (2021a): FLEDGED Gasifier. Available online at http://www.fledged.eu/biomass-to-dme-process/fledged-gasifier/, last checked on 01.11.2021.

FLEDGED (2021b): Gasification. Available online at http://www.fledged.eu/biomass-to-dme-process/gasification-2/, last checked on 01.11.2021.

FNR (2016): Biofuels. Available online at http://www.fnr.de/fileadmin/allgemein/pdf/broschueren/brosch_biofuels_web.pdf, last checked on 01.11.2021.

FNR (2021): Bioethanol. Available online at https://biokraftstoffe.fnr.de/kraftstoffe/bioethanol, last checked on 01.11.2021.

Foit, Severin R.; Vinke, Izaak C.; Haart, Lambertus G. J. de; Eichel, Rüdiger-A (2017): Power-to-Syngas. An Enabling Technology for the Transition of the Energy System? In: *Angewandte Chemie (International ed. in English)* 56 (20), p. 5402–5411. DOI: 10.1002/anie.201607552.

Formann, Steffi; Hahn, Alena; Janke, Leandro; Stinner, Walter; Sträuber, Heike; Logroño, Washington; Nikolausz, Marcell (2020): Beyond Sugar and Ethanol Production. Value Generation Opportunities Through Sugarcane Residues. In: *Front. Energy Res.* 8, p. 92. DOI: 10.3389/fenrg.2020.579577.

Frankfurt HOLM (2021): Industriepark Höchst wird zum Innovationshub für CO2-neutrale Kraftstoffe – mit dabei: CAPHENIA. Available online at https://frankfurt-holm.de/news/industriepark-h%C3%B6chst-wird-zum-innovationshub-f%C3%BCr-co2-neutrale-kraftstoffe-mit-dabei-caphenia/, last checked on 03.11.2021.

Fraunhofer ISE (2018): Stromgestehungskosten Erneuerbare Energien. With collaboration of Christoph Kost, Shivenes Shammugam, Verena Jülich, Huyen-Tran Nguyen und Thomas Schlegl. Available online at https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/DE2018_ISE_Studie_Stromgestehungskosten_Erneuerbare_Energien.pdf, last checked on 12.01.2022.

Fraunhofer ISE (2021): Nettostromerzeugung in Deutschland 2020: erneuerbare Energien erstmals über 50 Prozent. Available online at https://www.ise.fraunhofer.de/de/presse-und-medien/news/2020/nettostromerzeugung-in-deutschland-2021-erneuerbare-energien-erstmals-ueber-50-prozent.html, last updated 04.01.2021, last checked on 03.11.2021.

Frerking, Margaret A.; Beauchamp, Patricia M. (2014): JPL Technology Readiness Assessment Guideline. Available online at https://trs.jpl.nasa.gov/bitstream/handle/2014/46024/CL%2316-0153.pdf, last checked on 05.08.2021.

FReSMe (2021): From residual steel gases to methanol. Available online at http://www.fresme.eu/, last checked on 03.11.2021.

Friedel, Marcus (2017): DME-regenerativ. Projektsteckbrief. Published by DBI - Gastechnologisches Institut gGmbH Freiberg. Projektsteckbrief. Freiberg. Available online at https://www.dbi-gti.de/files/PDFs/Projekte/83_Projektsteckbrief_DMEregenerativ_MF14007.pdf, last checked on 27.09.2022.

Friedel, Marcus (2018): Direct synthesis of dimethyl ether (DME) from renewable resources. 9th International Freiberg Conference. Berlin (2018). Available online at https://tu-freiberg.de/sites/default/files/media/professur-fuer-energieverfahrenstechnik-und-thermische-rueckstandsbehandlung-16460/publikationen/24-05-180606_direct_synthesis_of_dimethyl_ether_dme_dbifreiberg.pdf, last checked on 05.11.2021.

Frilund, Christian; Tuomi, Sanna; Kurkela, Esa; Simell, Pekka (2021): Small- to medium-scale deep syngas purification. Biomass-to-liquids multi-contaminant removal demonstration. In: *Biomass and Bioenergy* 148, p. 106031. DOI: 10.1016/j.biombioe.2021.106031.

Frøhlke, Ulrik (2021): Haldor Topsoe to build large-scale SOEC electrolyzer manufacturing facility to meet customer needs for green hydrogen production. Available online at https://blog.topsoe.com/haldor-topsoe-to-build-large-scale-soec-electrolyzer-manufacturing-facility-to-meet-customer-needs-for-green-hydrogen-production, last updated 04.03.2021, last checked on 03.11.2021.

FuelEU Maritime (2021): Proposal for a Regulation on the use of renewable and low-carbon fuels in maritime transport. FuelEU Maritime.

Fulcrum Bioenergy (2021): Facilities. Sierra Biofuels Plant. Published by Fulcrum Bioenergy. Sierra Biofuels Plant. Pleasanton. Available online at https://fulcrum-bioenergy.com/facilities/, last checked on 03.11.2021.

futurefuels.blog (2021): Klimaneutral Fliegen mit synthetischem Kerosin. Published by Wirtschaftsverband Fuels und Energie e. V. Available online at https://futurefuels.blog/in-der-praxis/klimaneutral-fliegen-mit-synthetischem-kerosin/, last checked on 16.01.2022.

Gaikwad, Rohit; Villadsen, Sebastian N. B.; Rasmussen, Jan Pihl; Grumsen, Flemming Bjerg; Nielsen, Lars Pleth; Gildert, Gary et al. (2020): Container-Sized CO2 to Methane. Design, Construction and Catalytic Tests Using Raw Biogas to Biomethane. In: *Catalysts* 10 (12), p. 1428. DOI: 10.3390/catal10121428.

Ganesan, Ramya; Manigandan, S.; Samuel, Melvin S.; Shanmuganathan, Rajasree; Brindhadevi, Kathirvel; Lan Chi, Nguyen Thuy et al. (2020): A review on prospective production of biofuel from microalgae. In: *Biotechnology reports (Amsterdam, Netherlands)* 27, e00509. DOI: 10.1016/j.btre.2020.e00509.

Gaurina-Međimurec, Nediljka; Novak-Mavar, Karolina; Majić, Matej (2018): CCS TECHNOLOGY. OVERVIEW OF PROJECTS, TECHNOLOGY AND MONITORING. In: *MGPB* 33 (2), p. 1–14. DOI: 10.17794/rgn.2018.2.1.

Gaya (2021): A unique technological platform in Europe. A platform at the center of Chemical Valley. A platform at the center of Chemical Valley. Available online at https://www.projetgaya.com/en/a-unique-technological-platform-in-europe/, last checked on 03.11.2021.

Ge, Xumeng; Li, Yebo (Publisher) (2016): Advances in bioenergy. Volume one. Volume one. First edition. Cambridge, MA: Academic Press. Available online at http://proquest.tech.safaribooksonline.de/9780128097229.

Geisel, Ernesto (1975): Legislação Informatizada - Decreto nº 76.593, de 14 de Novembro de 1975 - Publicação Original. Available online at https://www2.camara.leg.br/legin/fed/decret/1970-1979/decreto-76593-14-novembro-1975-425253-publicacaooriginal-1-pe.html, last checked on 04.01.2022.

Geleynse, Scott; Brandt, Kristin; Garcia-Perez, Manuel; Wolcott, Michael; Zhang, Xiao (2018): The Alcohol-to-Jet Conversion Pathway for Drop-In Biofuels. Techno-Economic Evaluation. In: *ChemSusChem* 11 (21), p. 3728–3741. DOI: 10.1002/cssc.201801690.

Geupel, Markus; Richter, Simone; Schlesinger, Lisa (2021): Stickstoff – Element mit Wirkung. Ein integrierter Zielwert setzt einen neuen Rahmen. Hintergrund. Published by Umweltbundesamt. Ein integrierter Zielwert setzt einen neuen Rahmen. Dessau-Roßlau. Available online at https://www.umweltbundesamt.de/sites/default/files/medien/5750/publikationen/2021_hgp_stickstoff-element_mit_wirkung_bf.pdf, last checked on 03.11.2021.

GIRADA Energy (2021): Advanced Methanol Amsterdam. Producing advanced methanol for use in fuel blending, to meet the RED II objective. Producing advanced methanol for use in fuel blending, to meet the RED II objective. Available online at https://www.gidara-energy.com/advanced-methanol-amsterdam, last checked on 03.11.2021.

Global CCS Institute (2019): Bioenergy and Carbon Capture and Storage. Available online at https://www.globalccsinstitute.com/wp-content/uploads/2019/03/BECCS-Perspective_FINAL_PDF.pdf, last checked on 03.11.2021.

GML (2021): Trends in Atmospheric Carbon Dioxide. Available online at https://gml.noaa.gov/ccgg/trends/global.html, last checked on 28.10.2021.

Götz, Kristin; Zickmann, Stefan; Fey, Barbara; Bünger, Jürgen; Stapf, Wolfgang; Fan, Zhu (2015): Diesel R33. Abschlussbericht zum Projektvorhaben. Published by Jürgen Krahl, Axel Munack, Peter Eilts und Jürgen Bünger. Abschlussbericht zum Projektvorhaben.

GRAFORCE (2020): Wasserstoff-Produktion. Wasserstoff - Der Stoff, aus dem das Leben ist. Wasserstoff - Der Stoff, aus dem das Leben ist. Available online at https://graforce.com/leistungen/wasserstoff-produktion, last checked on 03.11.2021.

Grand View Research (2021): Electric Scooters Market Size, Share & Trends Analysis Report By Product (Retro, Standing/Self-Balancing, Folding), By Battery (Sealed Lead Acid, NiMH, Li-Ion), By Voltage, By Region, And Segment Forecasts, 2021 - 2028. Published by Grand View Research. Available online at https://www.grandviewresearch.com/industry-analysis/electric-scooters-market, last checked on 03.11.2021.

Grathwohl, Peter; Schmidt, Torsten; Bittens, Martin; Valtchev, Simeon (2005): Herkunft und Bilanzierung des Eintrags des Benzinzusatzes Methyl-tert-butylether (MTBE) und seinen Abbauprodukten in Grundwasser mittels multikompartimenteller Modellierung. Available online at https://pudi.lubw.de/detailseite/-/publication/87207-Herkunft_und_Bilanzierung_des_Eintrags_des_Benzinzusatzes_Methyl-tert-butylether_%28MTBE%29_und_seinen_A.pdf, last checked on 03.11.2021.

Gray, David; Sato, Suzanne; Garcia, Fernando; Eppler, Ross; Cherry, Joel (2014): Amyris, Inc. Integrated Biorefinery Project Summary Final Report - Public Version.

Green Car Congress (2020): ASTM approves 6th pathway for sustainable aviation fuel (SAF): catalytic hydrothermolysis jet fuel (CHJ). Available online at https://www.greencarcongress.com/2020/02/2020-0201-astmchj.html, last updated 01.02.2020, last checked on 03.11.2021.

Greenair (2019): Air BP and Neste supply SAF for Swedish regional aviation 'perfect flight' and business aviation initiative on GreenAir Online. Published by Greenair Communications. Available online at https://www.greenaironline.com/news.php?viewStory=2595, last updated 21.05.2019, last checked on 13.05.2021.

Greenair (2020a): Japan's ANA becomes Neste's first Asian airline customer and starts SAF-fuelled flights from Tokyo on GreenAir Online. Published by Greenair Communications. Available online at https://www.greenaironline.com/news.php?viewStory=2749, last updated 11.11.2020, last checked on 13.05.2021.

Greenair (2020b): Neste supplies San Francisco with first batch of sustainable aviation fuel through existing fuel pipeline on GreenAir Online. Published by Greenair Communications. Available online at https://www.greenaironline.com/news.php?viewStory=2718, last updated 16.07.2020, last checked on 13.05.2021.

Greenea (2015): Glycerine market: lack of interdependence between supply and demand. Available online at https://www.greenea.com/wp-content/uploads/2016/11/11.-Glycerine-Market-Nov-Greenea.pdf, last checked on 22.06.2021.

Greenea (2020): Market analysis for Used Cooking oil. Available online at https://www.greenea.com/en/market-analysis/, last updated 25.07.2021, last checked on 03.11.2021.

Gröngröft, Arne; Hauschild, Stephanie; Grasemann, Elias; Meisel, Kathleen; Meyer, Kirsten (2014): Technical, ecological and economic assessment of biokerosene production. 11th International Conference "Fuels of the Future". Berlin (2014).

Grope, Norbert; Schöder, Olaf; Krahl, Jürgen; Müller-Langer, Franziska; Schröder, Jörg; Mattheß, Eric (2018): Survey on Advanced Fuels for Advanced Engines. Project report. Published by IEA Bioenergy. Project report. Available online at http://task39.sites.olt.ubc.ca/files/2018/10/Survey-on-Advanced-Fuels-for-Advanced-Engines-IEA_Bioenergy_T39_AFAE_DBFZ.pdf, last checked on 07.01.2022.

Guzman, Alexander; Torres, Juan E.; Prada, Laura P.; Nuñez, Manuel L. (2010): Hydroprocessing of crude palm oil at pilot plant scale. In: *Catalysis Today* 156 (1-2), p. 38–43. DOI: 10.1016/j.cattod.2009.11.015.

Guzmán, Hilmar; Salomone, Fabio; Batuecas, Esperanza; Tommasi, Tonia; Russo, Nunzio; Bensaid, Samir; Hernández, Simelys (2020): How to make sustainable CO2 conversion to Methanol. Thermocatalytic versus electrocatalytic technology. In: *Chemical Engineering Journal*, p. 127973. DOI: 10.1016/j.cej.2020.127973.

Hacker, Florian; Blanck, Ruth; Görz, Wolf; Bernecker, Tobias; Speiser, Jonas; Röckle, Felix et al. (2020): StratON. Bewertung und Einführungsstrategien für oberleitungsgebundene schwere Nutzfahrzeuge. Endbericht. Published by Öko-Institut e.V. Bewertung und Einführungsstrategien für oberleitungsgebundene schwere Nutzfahrzeuge. Berlin. Available online at https://www.oeko.de/fileadmin/oekodoc/StratON-O-Lkw-Endbericht.pdf, last checked on 06.10.2021.

Hahn, Markus (2021): Vorstellung Evaluations- und Erfahrungsbericht 2020. BBE/UFOP-Fachseminar "Nachhaltigkeit von Biokraftstoffen" (2021). Available online at https://www.fachseminar-nachhaltigkeit.de/fachseminar-nachhaltigkeit-von-biokraftstoffen/.

Hajjaji, Noureddine; Martinez, Sylvain; Trably, Eric; Steyer, Jean-Philippe; Helias, Arnaud (2016): Life cycle assessment of hydrogen production from biogas reforming. In: *International Journal of Hydrogen Energy* 41 (14), p. 6064–6075. DOI: 10.1016/j.ijhydene.2016.03.006.

Haldor Topsoe (2021): Hydrogen - green energy carrier of the future. Available online at https://info.topsoe.com/green-hydrogen, last checked on 03.11.2021.

Halmenschlager, Cibele Melo; Brar, Maganjot; Apan, Ioan Tudor; Klerk, Arno de (2016): Oligomerization of Fischer–Tropsch Tail Gas over H-ZSM-5. In: *Ind. Eng. Chem. Res.* 55 (51), p. 13020–13031. DOI: 10.1021/acs.iecr.6b03861.

Hamelinck, Carlo; Defillet, Matti; Smeets, Bas; Heuvel, Eric van den (2021): Conversion efficiencies of fuel pathways for Used Cooking Oi. Study commissioned by EWABA and MVaK Final Report. Published by MVAK Ewaba. Study commissioned by EWABA and MVaK Final Report. Available online at https://www.studiogearup.com/wp-content/uploads/2021/01/21_0119_sGU_Hamelinck_FotF_Comparison-of-motor-fuels-from-UCO.pdf.

Hänggi, Severin; Elbert, Philipp; Bütler, Thomas; Cabalzar, Urs; Teske, Sinan; Bach, Christian; Onder, Christopher (2019): A review of synthetic fuels for passenger vehicles. In: *Energy Reports* 5 (7), p. 555–569. DOI: 10.1016/j.egyr.2019.04.007.

Hao, Botian; Xu, Donghai; Jiang, Guanyu; Sabri, Tanveer Ahmed; Jing, Zefeng; Guo, Yang (2021): Chemical reactions in the hydrothermal liquefaction of biomass and in the catalytic hydrogenation upgrading of biocrude. In: *Green Chem.* 23 (4), p. 1562–1583.

Harndorf, Horst; Buchholz, Bert; Schümann, Ulrike; Wichmann, Volker; Flügge, Evelyn; Sadlowski, Thomas (2019): Betriebsverhalten von Industrie- und Landtechnikmotoren Abgasstufe EU COM IV im Biodieselbetrieb. Rostock. Available online at https://www.fnr-server.de/ftp/pdf/berichte/22012113.pdf, last checked on 03.11.2021.

Härtl, Martin; Seidenspinner, Philipp; Jacob, Eberhard; Wachtmeister, Georg (2015): Oxygenate screening on a heavy-duty diesel engine and emission characteristics of highly oxygenated oxymethylene ether fuel OME1. In: *Fuel* 153 (7), p. 328–335. DOI: 10.1016/j.fuel.2015.03.012.

Härtl, Martin; Stadler, Andreas; Backes, Fabian; Wachtmeister, Georg; Jacob, Eberhard (2017): Potenziell CO2-neutrale Kraftstoffe für saubere Ottomotoren. In: *MTZ Motortech Z* 78 (7-8), p. 80–88. DOI: 10.1007/s35146-017-0056-5.

Hauch, A.; Küngas, R.; Blennow, P.; Hansen, A. B.; Hansen, J. B.; Mathiesen, B. V.; Mogensen, M. B. (2020): Recent advances in solid oxide cell technology for electrolysis. In: *Science (New York, N.Y.)* 370 (6513). DOI: 10.1126/science.aba6118.

Héder, Mihály (2017): From NASA to EU: the evolution of the TRL scale in Public Sector Innovation. Available online at https://www.innovation.cc/discussion-papers/2017_22_2_3_heder_nasa-to-eu-trl-scale.pdf, last checked on 03.11.2021.

Heinz, Markus; Roth, Tobias (2018): Hohes Weizengras ls Biogassubstrat. Available online at https://www.biogas-forum-bayern.de/media/files/0004/hohes-weizengras-als-biogassubstrat.pdf, last checked on 08.11.2021.

Heneka, M.; Köppel, W.; Graf, F. (2020): Vergleichende Bewertung von Power-to-X-Prozessen. zur Bereitstellung von Kraftstoffen aus erneuerbaren Quellen. In: *Energie-, Wasser-Praxis* (3/2020), p. 40–46.

Hengstler, J.; Russ, M.; Stoffregen, A.; Hendrich, A.; Weidner, S.; Held, M.; Briem, A.-K. (2021): Aktualisierung und Bewertung der Ökobilanzen von Windenergie- und Photovoltaikanlagen unter Berücksichtigung aktueller Technologieentwicklungen. Published by Umweltbundesamt. Dessau-Roßlau (CLIMATE CHANGE, 35/2021). Available online at https://www.umweltbundesamt.de/sites/default/files/medien/5750/publikationen/2021-05-06_cc_35-2021_oekobilanzen_windenergie_photovoltaik.pdf, last checked on 03.11.2021.

Henke, Wilfried; Bräutigam, Volker; Planer, Jörg (2018): Zwischen- und Zweitfrüchte im Pflanzenbau. 2. Auflage.

Higman, Christopher; van der Burgt, Maarten (2008): Gasification. 2nd ed. Burlington: Elsevier. Available online at http://search.ebscohost.com/login.aspx?direct=true&scope=site&db=nlebk&db=nlabk&AN=220264.

Hitzler, G.; Bargende, M. (2000): Schadstoffemissionen von Pkw mit reformulierten Kraftstoffen unter realen Fahrbedingungen. Published by Forschungsinstitut für Kraftfahrwesen und Fahrzeugmotoren Stuttgart FKFS. Available online at http://fachdokumente.lubw.baden-wuerttemberg.de/servlet/is/40054/PEF397006SBer.pdf?command=downloadContent&filename=PEF397006SBer.pdf&FIS=203, last checked on 08.05.2019.

Hoefnagels, Ric; Germer, Sonja (2018): Supply potential. suitability and status of lignocellulosic feedstocks for advanced biofuels. D2.1 Report on lignocellulosic feedstock availability, market status and suitability for RESfuels. D2.1 Report on lignocellulosic feedstock availability, market status and suitability for RESfuels. Available online at http://www.advancefuel.eu/contents/reports/d21-report-on-lignocellulosic-feedstock-availability.pdf, last updated 15.11.2018, last checked on 08.11.2021.

Hoefnagels, Ric; Kluts, Ingeborg; Junginger, Martin; Visser, Lotte; Resch, Gustav; Mantau, Udo et al. (2017): Biomass supply potentials for the EU and biomass demand from the material sector by 2030. Annex A. Annex A. Available online at https://ec.europa.eu/energy/sites/default/files/documents/biosustain_annexes_final.pdf, last updated 05.2017, last checked on 08.11.2021.

Höök, Mikael; Fantazzini, Dean; Angelantoni, André; Snowden, Simon (2014): Hydrocarbon liquefaction. Viability as a peak oil mitigation strategy. In: *Philosophical transactions. Series A, Mathematical, physical, and engineering sciences* 372 (2006), p. 20120319. DOI: 10.1098/rsta.2012.0319.

Huber, Georg; Scholz, Alexander; Stöhr, Michael; Düsseldorf, Christian; Flierl, Rudolf; Thuneke, Klaus et al. (2015): Herstellung und Demonstration der Praxistauglichkeit von Traktoren mit Motoren der Abgasstufe IV im Betrieb mit Pflanzenöl. Published by Technologie- und Förderzentrum im Kompetenzzentrum für Nachwachsende Rohstoffe. Straubing (Berichte aus dem TFZ, 44). Available online at https://docplayer.org/73033166-Herstellung-und-demonstration-der-praxistauglichkeit-von-traktoren-mit-motoren-der-abgasstufe-iv-im-betrieb-mit-pflanzenoel.html, last checked on 03.11.2021.

Huber, Georg; Thuneke, Klaus; Emberger, Peter; Remmele, Edgar (2019): Abgasverhalten von Fahrzeugen im realen Betrieb mit alternativen Kraftstoffen. Bestimmung mit einem portablen Emissionsmesssystem (PEMS). Published by Technologie- und Förderzentrum im Kompetenzzentrum für Nachwachsende Rohstoffe. Bestimmung mit einem portablen Emissionsmesssystem (PEMS) (Berichte aus dem TFZ, 62). Available online at http://www.tfz.bayern.de/mam/cms08/biokraftstoffe/dateien/tfz_bericht_62_pems_ges.pdf, last checked on 03.11.2019.

HyFlexFuel (Publisher) (2021): The HyFlexFuel project. Next generation biofuel technologies. Next generation biofuel technologies. Available online at https://www.hyflexfuel.eu/, last checked on 13.01.2022.

IATA (2021a): Dangerous Goods Regulations (DGR). Available online at https://www.iata.org/en/publications/dgr/, last updated 21.05.2021, last checked on 21.05.2021.

IATA (2021b): Offsetting CO2 Emissions with CORSIA. Available online at https://www.iata.org/en/programs/environment/corsia/#tab-1, last updated 20.05.2021, last checked on 08.11.2021.

ICAO (2019): Resolution A40-19: Consolidated statement of continuing ICAO policies and practices related to environmental protection - Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). Available online at https://www.icao.int/environmental-protection/Documents/Assembly/Resolution_A40-19_CORSIA.pdf, last checked on 08.11.2021.

ICAO (2021): Technical Instructions For The Safe Transport of Dangerous Goods by Air (Doc 9284). Available online at https://www.icao.int/safety/DangerousGoods/Pages/Doc9284-Technical-Instructions.aspx, last checked on 08.11.2021.

Icha, P.; Lauf T.; Kuhs, G. (2021): Entwicklung der spezifischen Kohlendioxid-Emissionendes deutschen Strommix in den Jahren 1990 - 2020. Published by Umweltbundesamt. Dessau-Roßlau (CLIMATE CHANGE, 45/2021). Available online at https://www.umweltbundesamt.de/sites/default/files/medien/5750/publikationen/2021-05-26_cc-45-2021_strommix_2021.pdf, last checked on 08.10.2021.

IEA (2019a): Renewables 2019. Market analysis and forecast from 2019 to 2024. Market analysis and forecast from 2019 to 2024. Available online at https://www.iea.org/reports/renewables-2019, last updated 10.2019, last checked on 10.11.2021.

IEA (2019b): The Future of hydrogen. Seizing today's opportunities. Seizing today's opportunities. Available online at https://www.iea.org/reports/the-future-of-hydrogen, last checked on 08.11.2021.

IEA (2020): ETP Clean Energy Technology Guide. Available online at https://www.iea.org/articles/etp-clean-energy-technology-guide, last updated 04.11.2020, last checked on 08.11.2021.

IEA (2021a): Ammonia Technology Roadmap. Towards more sustainable nitrogen fertiliser production. Towards more sustainable nitrogen fertiliser production. Available online at https://iea.blob.core.windows.net/assets/6ee41bb9-8e81-4b64-8701-2acc064ff6e4/AmmoniaTechnologyRoadmap.pdf, last checked on 08.11.2021.

IEA (2021b): Data & Statistics - IEA. Explore energy data by category, indicator, country or region. CO2 emissions, CO2 emissions by sector, World. Published by International Energy Agency. Explore energy data by category, indicator, country or region. Paris. Available online at https://www.iea.org/data-and-statistics/data-browser?country=WORLD&fuel=CO2%20emissions&indicator=CO2BySector, last updated 17.06.2021, last checked on 17.06.2021.

IEA (2021c): Data and statistics. Explore energy data by category, indicator, country or region. Balances, World, 1990. Explore energy data by category, indicator, country or region. Available online at https://www.iea.org/data-and-statistics/data-tables?country=WORLD&energy=Balances&year=1990, last checked on 08.11.2021.

IEA (2021d): Data and statistics. Explore energy data by category, indicator, country or region. Balances, World, 2018. Published by International Energy Agency. Explore energy data by category, indicator, country or region. Available online at https://www.iea.org/data-and-statistics/data-tables?country=WORLD&energy=Balances&year=2018, last checked on 08.11.2021.

IEA (2021e): Data and statistics. Explore energy data by category, indicator, country or region. Balances, World, 2019. Explore energy data by category, indicator, country or region. Available online at https://www.iea.org/data-and-statistics/data-tables?country=WORLD&energy=Balances&year=2019, last checked on 28.10.2021.

IEA (2021f): Data and statistics. Explore energy data by category, indicator, country or region. Electricity, Germany, Europe, World, 2019. Published by IEA. Explore energy data by category, indicator, country or region. Available online at https://www.iea.org/data-and-statistics/data-tables?country=WORLD, last checked on 12.01.2022.

IEA Bioenergy (2013): Black Liquor Gasification. Summary and Conclusions from the IEA Bioenergy ExCo54 Workshop. Summary and Conclusions from the IEA Bioenergy ExCo54 Workshop. Available online at https://www.ieabioenergy.com/wp-content/uploads/2013/10/Black-Liquor-Gasification-summary-and-conclusions3.pdf, last checked on 08.11.2021.

IEA Bioenergy (2020a): Green methanol from biogas in Denmark. a versatile transport fuel. a versatile transport fuel. Available online at https://www.ieabioenergy.com/wp-content/uploads/2020/12/Case-Story-DK_-Green-Methanol_web-1.pdf, last checked on 08.11.2021.

IEA Bioenergy (2020b): The Role of Renewable Transport Fuels in Decarbonizing Road Transport. Summary Report. Published by Advanced Motor Fuels TCP und IEA Bioenergy TCP. Summary Report. Available online at https://www.ieabioenergy.com/wp-content/uploads/2020/11/Summary-Report.pdf, last checked on 08.11.2021.

IEA Bioenergy (2021a): Deployment of bio-CCS: case studies. Available online at https://www.ieabioenergy.com/blog/publications/deployment-of-bio-ccs-case-studies/, last updated 05.2021, last checked on 08.11.2021.

IEA Bioenergy (2021b): Facilities. Global database of biomass conversion facilities, including advanced biofuels, combustion, gasification and pyrolysis plants. Global database of biomass conversion facilities, including advanced biofuels, combustion, gasification and pyrolysis plants. Available online at https://www.ieabioenergy.com/installations/, last checked on 21.06.2021.

IEA Bioenergy (2021c): Upgrading Plant List 2021. Published by IEA Task 37: Energy from Biogas. Available online at http://task37.ieabioenergy.com/plant-list.html, last checked on 08.11.2021.

IGC (2021): Supply & Demand. Available online at https://www.igc.int/en/markets/marketinfo-sd.aspx, last updated 27.05.2021, last checked on 08.11.2021.

IHS Markit (2018-2020): World Ethanol & Biofuels Report. Food & Agricultural Commodities Economics. In: *IHS Markit* 16-19 (Vol. 16 Nr.9-Vol. 19 Nr. 8).

IHS Markit (2020a): World Ethanol & Biofuels Report. Food & Agricultural Commodities Economics. In: *IHS Markit* 18 (22).

IHS Markit (2020b): World Ethanol & Biofuels Report. In: *IHS Markit* 18 (24).

IHS Markit (2020c): World Ethanol and Biofuels Report. Food & Agricultural Commodities Economics. In: *IHS Markit* 18 (19).

IHS Markit (2021a): Plants & Projects. Available online at https://iegvantage.agribusiness.ihsmarkit.com, last checked on 29.11.2021.

IHS Markit (2021b): World Ethanol & Biofuels Report. Food & Agricultural Commodities Economics. In: *IHS Markit* 19 (15).

IHS Markit (2021c): World Ethanol & Biofuels Report. Food & Agricultural Commodities Economics. In: *IHS Markit* 19 (17).

IHS Markit (2021d): World Ethanol & Biofuels Report. Food & Agricultural Commodities Economics. In: *IHS Markit* 19 (18).

IHS Markit (2021e): World Ethanol & Biofuels Report. Food & Agricultural Commodities Economics. In: *IHS Markit* 19 (19).

IHS Markit (2021f): World Ethanol & Biofuels Report. Food & Agricultural Commodities Economics. In: *IHS Markit* 19 (22).

IHS Markit (2021g): World Ethanol & Biofuels Report. Food & Agricultural Commodities Economics. In: *IHS Markit* 20 (1).

IHS Markit (2021h): World Ethanol & Biofuels Report. Food & Agricultural Commodities Economics. In: *IHS Markit* 20 (2).

IHS Markit (2021i): World Ethanol & Biofuels Report. Food & Agricultural Commodities Economics. In: *IHS Markit* 20 (4).

IHS Markit (2021j): World Ethanol and Biofuels Report. Food & Agricultural Commodities Economics. In: *F.O. Licht* 19 (16).

IHS Markit (2021k): World Ethanol and Biofuels Report. Food & Agricultural Commodities Economics. In: *F.O. Licht* 19 (6).

IHS Markit (2021l): World Ethanol and Biofuels Report. Food & Agricultural Commodities Economics. In: *F.O. Licht* 20 (2).

IMDG-Code from 2020 (1974): International Maritime Dangerous Goods Code.

IMO (2018): Note by the International Maritime Organization to the UNFCCC Talanoa Dialogue. Adoption of the initial IMO Strategy on reduction of the GHG emissions from ships and existing IMO activity relatd to reducing GHG emissions in the shipping sector. Adoption of the initial IMO Strategy on reduction of the GHG emissions from ships and existing IMO activity relatd to reducing GHG emissions in the shipping sector. Available online at https://unfccc.int/sites/default/files/resource/250_IMO%20submission_Talanoa%20Dialogue_April%202018.pdf, last checked on 08.11.2021.

IMO (2019): Fuel oil availability and quality – Regulation 18. Published by International Maritime Organization (IMO). Available online at https://www.imo.org/en/OurWork/Environment/Pages/Fuel-oil-quality-%E2%80%93-Regulation-18.aspx, last checked on 17.05.2021.

Imperial College London (2021): Sustainable biomass availability in the EU, to 2050. Ref: RED II Annex IX A/B. Ref: RED II Annex IX A/B. Available online at https://www.concawe.eu/wp-content/uploads/Sustainable-Biomass-Availability-in-the-EU-Part-I-and-II-final-version.pdf, last checked on 14.01.2022.

Indufor (2013): Study on the Wood Raw Material Supply and Demand for the EU Wood-processing Industries. European Commission, Enterprise and Industry Directorate General. A11-04451. Published by Indufor. European Commission, Enterprise and Industry Directorate General. Available online at https://ec.europa.eu/docsroom/documents/10017/attachments/1/translations/en/renditions/native, last checked on 17.01.2022.

INERATEC (2021): Modulare Chemische Anlagen. Die innovative chemische Reaktortechnologie eignet sich aufgrund hoher Lastflexibilität hervorragend für fluktuierende erneuerbare Energieanwendungen. Die innovative chemische Reaktortechnologie eignet sich aufgrund hoher Lastflexibilität hervorragend für fluktuierende erneuerbare Energieanwendungen. Available online at https://ineratec.de/technologien/, last checked on 08.11.2021.

INERATEC (2022): Nachhaltige e-Fuels für die Luftfahrt. Published by INERATEC GmbH. Available online at https://ineratec.de/nachhaltige-e-fuels-fuer-die-luftfahrt/, last checked on 16.01.2022.

International Union of Railways (2021): RAIL Information System and Analyses. uic-statistics-synopsis-2020. Published by International Union of Railways. uic-statistics-synopsis-2020. Available online at https://uic.org/IMG/pdf/uic-statistics-synopsis-2020.pdf, last checked on 10.06.2021.

Ioannis Pappis; Carlos Centurion; Eunice Pereira Ramos; Mark Howells; Silvia Ulloa; Eduardo Ortigoza et al. (2021): Implications to the electricity system of Paraguay of different demand scenarios and export prices to Brazil. In: *Energy Syst*, p. 1–29. DOI: 10.1007/s12667-020-00420-w.

IPCC (2006): 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Available online at https://www.ipcc-nggip.iges.or.jp/public/2006gl/, last checked on 08.11.2021.

IPCC (2007): Climate change 2007. The physical science basis ; contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. 1st published. New York: UNEP. Available online at https://www.ipcc.ch/site/assets/uploads/2018/05/ar4_wg1_full_report-1.pdf, last checked on 08.11.2021.

IPCC (2013): Clima Change 2013. The Physical Science Basis - Anthropogenic and Natural Radiative Forcing. The Physical Science Basis - Anthropogenic and Natural Radiative Forcing. Available online at https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter08_FINAL.pdf, last checked on 08.11.2021.

IPCC (2021): Clima Change 2021. The Physical Science Basis - Summary for Policymakers. The Physical Science Basis - Summary for Policymakers. Available online at https://www.de-ipcc.de/media/content/AR6-WGI-SPM.pdf, last checked on 08.11.2021.

IRENA (2016): Innovation Outlook . Advanced Liquid Biofuels. Available online at https://www.irena.org/publications/2016/Oct/Innovation-Outlook-Advanced-Liquid-Biofuels, last checked on 08.11.2021.

IRENA (2018): Hydrogen from renewable power. Technology outlook for the energy transition. Available online at https://www.irena.org/publications/2018/sep/hydrogen-from-renewable-power, last checked on 08.11.2021.

IRENA (2021a): Data & Statistics. Available online at https://www.irena.org/Statistics, last checked on 08.11.2021.

IRENA (2021b): Technologies. Available online at https://www.irena.org/Statistics/View-Data-by-Topic/Capacity-and-Generation/Technologies, last checked on 08.11.2021.

IRENA; Methanol Institute (2021c): Innovation Outlook. Renewable Methanol. Renewable Methanol. Available online at https://www.irena.org/publications/2021/Jan/Innovation-Outlook-Renewable-Methanol, last checked on 08.11.2021.

ISCC System GmbH (2020a): ISCC CORSIA 202 Sustainability Requirements. Version 1.0. Available online at https://www.iscc-system.org/wp-content/uploads/2020/04/ISCC_CORSIA_202_Sustainability_Requirements_1.0.pdf, last checked on 08.11.2021.

ISCC System GmbH (2020b): ISCC CORSIA 205 Life Cycle Emissions. Version 1.0. Available online at https://www.iscc-system.org/wp-content/uploads/2020/04/ISCC_CORSIA_205_Life_Cycle_Emissions_1.0.pdf, last checked on 08.11.2021.

ISO 16861 (2015): Mineralölerzeugnisse - Kraftstoffe (Klasse F) - Spezifikationen für Dimethylether (DME) (2015).

Jafri, Yawer; Wetterlund, Elisabeth; Anheden, Marie; Kulander, Ida; Håkansson, Åsa; Furusjö, Erik (2019): Multi-aspect evaluation of integrated forest-based biofuel production pathways. Part 2. economics, GHG emissions, technology maturity and production potentials. In: *Energy* 172, p. 1312–1328. DOI: 10.1016/j.energy.2019.02.036.

Jensen, Allan; Ip, Trevor; Percy, Jamie (2012): Methanol purification System. Available online at http://www.ahlundberg.com/wp/wp-content/uploads/2017/05/AHL-Methanol-Purification-System.pdf, last checked on 08.11.2020.

Jochen, Praefke; Armin, Rix; Silvia, Santiago Fernandez; Matthias, Grömping; Frank, Höper; Udo, Peters et al. (2005): Preparing ethyl tertiary butylether from hydrocarbon mixture, useful as fuel additive, comprises reacting isobutene with ethanol, separating the hydrocarbon, reacting separated isobutene with ethanol and separating unconverted hydrocarbon. Registered through Oxeno Olefinchemie GmbH at 28.12.2005. Registration no: DE102005062722A. Publication no: DE102005062722A1. Priority data: 28.12.2007.

Jöhrens, Julius; Rücker, Julius; Kräck, Jan; Allekotte, Michel; Helms, Hinrich; Biemann, Kirsten et al. (2020): Roadmap OH-Lkw: Einführungsszenarien 2020-2030. Optimierung des Infrastrukturaufbaus für O-Lkw und Analyse von Kosten und Umwelteffekten in der Einführungsphase. Published by ifeu - Institut für Energie- und Umweltforschung Heidelberg gGmbH. Optimierung des Infrastrukturaufbaus für O-Lkw und Analyse von Kosten und Umwelteffekten in der Einführungsphase. Heidelberg. Available online at https://www.ifeu.de/fileadmin/uploads/Roadmap-OH-Lkw-Bericht-Einfuehrungsszenarien-web.pdf, last checked on 06.10.2021.

Jong, Sierk de; Hoefnagels, Ric; Faaij, André; Slade, Raphael; Mawhood, Rebecca; Junginger, Martin (2015): The feasibility of short-term production strategies for renewable jet fuels - a comprehensive techno-economic comparison. In: *Biofuels, Bioprod. Bioref.* 9 (6), p. 778–800. DOI: 10.1002/bbb.1613.

Jos, Edmilson; Cantarella, Heitor; Bovi Ambrosano, Glucia Maria; Aparecida, Eliana; Ferreira Dias, Fbio Luis; Rossi, Fabrcio et al. (2013): Crop Rotation Biomass and Effects on Sugarcane Yield in Brazil. In: Miodrag Darko Matovic (Hg.): Biomass Now - Cultivation and Utilization: InTech.

Joseph Jr, Henry (2013): Flex Fuel Vehicles in Brazil. Associação Nacional dos Fabricantes de Veículos Automotores (ANFAVEA). Available online at http://www.globalbioenergy.org/fileadmin/user_upload/gbep/docs/2013_events/GBEP_Bioenergy_Week_Brasilia_18-23_March_2013/4.5_JOSEPH.pdf, last checked on 02.04.2020.

Jungmeier, Gerfried; Pucker, Johanne; Könighofer, Kurt; Ernst, Martin; Haselbacher, Peter; Lesschen, Jan Peter (2016): Improving the Sustainability of Fatty Acid Methyl Esters (FAME-Biodiesel). Tender No. ENER/C2/2013/628. Tender No. ENER/C2/2013/628.

Kalligeros, Stamatis; van den Heuvel, Eric; Waldheim, Lars; Landälv, Ingvar; Maniatis, Kyriakos (2018): Building up the future, cost of biofuel. Sub group on advanced biofuels : sustainable transport forum. Luxembourg: Publications Office.

Kaltschmitt, Martin; Hartmann, Hans; Hofbauer, Hermann (Publisher) (2016): Energie aus Biomasse. Grundlagen, Techniken und Verfahren. Grundlagen, Techniken und Verfahren. 3. Ed. Berlin: Springer. Available online at dx.doi.org/10.1007/978-3-662-47438-9.

Kaltschmitt, Martin; Streicher, Wolfgang; Wiese, Andreas (2020): Erneuerbare Energien. Systemtechnik · Wirtschaftlichkeit · Umweltaspekte. 6., vollst. überarb. Auflage 2020.

Kang, Peng; Morrow, Gary; Zhang, Xiaolei; Wang, Tipeng; Tan, Zhongfu; Agarwai, Jayant (2017): Systematic comparison of hydrogen production from fossil fuels and biomass resources. In: *International Journal of Agricultural and Biological Engineering* 10 (6), p. 192–200. DOI: 10.25165/j.ijabe.20171006.2990.

Kasinath, Archana; Fudala-Ksiazek, Sylwia; Szopinska, Malgorzata; Bylinski, Hubert; Artichowicz, Wojciech; Remiszewska-Skwarek, Anna; Luczkiewicz, Aneta (2021): Biomass in biogas production. Pretreatment and codigestion. In: *Renewable and Sustainable Energy Reviews* 150, p. 111509. DOI: 10.1016/j.rser.2021.111509.

Kaur, Jaspreet; Sarma, Anil Kumar; Jha, Mithilesh Kumar; Gera, Poonam (2020): Valorisation of crude glycerol to value-added products. Perspectives of process technology, economics and environmental issues. In: *Biotechnology reports (Amsterdam, Netherlands)* 27, e00487. DOI: 10.1016/j.btre.2020.e00487.

KBA (2010): Fahrzeugzulassungen (FZ 15). Bestand an Kraftfahrzeugen und Kraftfahrzeuganhängern nach Fahrzeugalter 1. Januar 2010. FZ 15. Published by Kraftfahrt-Bundesamt. Bestand an Kraftfahrzeugen und Kraftfahrzeuganhängern nach Fahrzeugalter 1. Januar 2010. Flensburg. Available online at https://www.kba.de/SharedDocs/Publikationen/DE/Statistik/Fahrzeuge/FZ/2010/fz15_2010_pdf.pdf?__blob=publicationFile&v=7, last checked on 28.05.2021.

KBA (2011): Fahrzeugzulassungen (FZ 25). Bestand an Nutzfahrzeugen und Kraftfahrzeuganhängern nach technischen Daten (Größenklassen, Motorisierung, Fahrzeugklassen und Aufbauarten) 1. Januar 2011. Published by Kraftfahrt-Bundesamt. Bestand an Nutzfahrzeugen und Kraftfahrzeuganhängern nach technischen Daten (Größenklassen, Motorisierung, Fahrzeugklassen und Aufbauarten) 1. Januar 2011. Flensburg. Available online at https://www.kba.de/SharedDocs/Downloads/DE/Statistik/Fahrzeuge/FZ25/fz25_2011_pdf.pdf?__blob=publicationFile&v=1, last checked on 07.01.2022.

KBA (2019): Monatliche Neuzulassungen 2019 (FZ 8). Januar bis Dezember. FZ 8. Published by Kraftfahrt-Bundesamt. Januar bis Dezember. Flensburg. Available online at https://www.kba.de/DE/Statistik/Fahrzeuge/Neuzulassungen/MonatlicheNeuzulassungen/n_monatl_neuzulassungen_inhalt.html?nn=2601598, last updated 28.06.2021, last checked on 28.06.2021.

KBA (2020a): Fahrzeugzulassungen (FZ 13). Bestand an Kraftfahrzeugen nach Umwelt-Merkmalen, 1. Januar 2020. FZ 13. Bestand an Kraftfahrzeugen nach Umwelt-Merkmalen, 1. Januar 2020. Flensburg. Available online at https://www.kba.de/SharedDocs/Publikationen/DE/Statistik/Fahrzeuge/FZ/2020/fz13_2020_pdf.pdf?__blob=publicationFile&v=6, last checked on 31.05.2021.

KBA (2020b): Fahrzeugzulassungen (FZ 15). Bestand an Kraftfahrzeugen und Kraftfahrzeuganhängern nach Fahrzeugalter, 1. Januar 2020. FZ 15. Published by Kraftfahrt-Bundesamt. Bestand an Kraftfahrzeugen und Kraftfahrzeuganhängern nach Fahrzeugalter, 1. Januar 2020. Flensburg. Available online at https://www.kba.de/SharedDocs/Publikationen/DE/Statistik/Fahrzeuge/FZ/2020/fz15_2020_pdf.pdf?__blob=publicationFile&v=6, last checked on 28.05.2021.

KBA (2020c): Fahrzeugzulassungen (FZ 8). Neuzulassungen von Kraftfahrzeugen und Kraftfahrzeuganhängern, Monatsergebnisse, Dezember 2019. FZ 8. Published by Kraftfahrt-Bundesamt. Neuzulassungen von Kraftfahrzeugen und Kraftfahrzeuganhängern, Monatsergebnisse, Dezember 2019. Flensburg. Available online at https://www.kba.de/SharedDocs/Publikationen/DE/Statistik/Fahrzeuge/FZ/2019_monatlich/FZ8/fz8_201912_pdf.pdf?__blob=publicationFile&v=5, last checked on 01.06.2021.

KBA (2021a): Anfrage Statistik Fahrzeugbestand. Flensburg (2021). AZ:321-130/11298-21 to Jörg Schröder.

KBA (2021b): Bestand an Kraftfahrzeugen und Kraftfahrzeuganhängern nach Zulassungsbezirken. Published by Kraftfahrt-Bundesamt. Flensburg. Available online at https://www.kba.de/SharedDocs/Downloads/Statistik/Fahrzeuge/FZ/2021/fz1_2021.xlsx, last checked on 26.05.2021.

KBA (2021c): Der Fahrzeugbestand im Überblick am 1. Januar 2021 gegenüber dem 1. Januar 2020. Published by Kraftfahrt-Bundesamt. Flensburg. Available online at https://www.kba.de/DE/Statistik/Fahrzeuge/Bestand/Jahrebilanz_Bestand/2021/2021_b_ueberblick_pdf.pdf?__blob=publicationFile&v=1, last checked on 16.11.2021.

KBA (2021d): Fahrzeugzulassungen (FZ 1). Bestand an Kraftfahrzeugen und Kraftfahrzeuganhängern nach Zulassungsbezirken 01.01.2021. Published by Kraftfahrt-Bundesamt. Bestand an Kraftfahrzeugen und Kraftfahrzeuganhängern nach Zulassungsbezirken 01.01.2021. Flensburg. Available online at https://www.kba.de/SharedDocs/Downloads/DE/Statistik/Fahrzeuge/FZ1/fz1_2021.xlsx?__blob=publicationFile&v=2, last checked on 07.01.2022.

KBA (2021e): Fahrzeugzulassungen (FZ 13). Bestand an Kraftfahrzeugen nach Umwelt-Merkmalen, 1. Januar 2021. FZ 13. Published by Kraftfahrt-Bundesamt. Bestand an Kraftfahrzeugen nach Umwelt-Merkmalen, 1. Januar 2021. Flensburg. Available online at https://www.kba.de/SharedDocs/Publikationen/DE/Statistik/Fahrzeuge/FZ/2021/fz13_2021.pdf?__blob=publicationFile&v=3, last checked on 09.06.2021.

KBA (2021f): Fahrzeugzulassungen (FZ 15). Bestand an Kraftfahrzeugen und Kraftfahrzeuganhängern nach Fahrzeugalter, 1. Januar 2021. FZ 15. Published by Kraftfahrt-Bundesamt. Bestand an Kraftfahrzeugen und Kraftfahrzeuganhängern nach Fahrzeugalter, 1. Januar 2021. Flensburg. Available online at https://www.kba.de/SharedDocs/Publikationen/DE/Statistik/Fahrzeuge/FZ/2021/fz15_2021_pdf.pdf?__blob=publicationFile&v=6, last checked on 01.06.2021.

KBA (2021g): Fahrzeugzulassungen (FZ 25). Bestand an Nutzfahrzeugen, Kraftfahrzeugen insgesamt und Kraftfahrzeuganhängern nach technischen Daten (Größenklassen, Motorisierung, Fahrzeugklassen und Aufbauarten) 1. Januar 2020. FZ 25. Published by Kraftfahrt-Bundesamt. Bestand an Nutzfahrzeugen, Kraftfahrzeugen insgesamt und Kraftfahrzeuganhängern nach technischen Daten (Größenklassen, Motorisierung, Fahrzeugklassen und Aufbauarten) 1. Januar 2020. Flensburg. Available online at https://www.kba.de/SharedDocs/Publikationen/DE/Statistik/Fahrzeuge/FZ/2020/fz25_2020_pdf.pdf?__blob=publicationFile&v=5, last checked on 01.06.2021.

KBA (2021h): Fahrzeugzulassungen (FZ 27). Bestand an Kraftfahrzeugen und Kraftfahrzeuganhängern nach Bundesländern, Fahrzeugklassen und ausgewählten Merkmalen, 1. Januar 2021. FZ 27. Published by Kraftfahrt-Bundesamt. Bestand an Kraftfahrzeugen und Kraftfahrzeuganhängern nach Bundesländern, Fahrzeugklassen und ausgewählten Merkmalen, 1. Januar 2021. Flensburg. Available online at https://www.kba.de/SharedDocs/Publikationen/DE/Statistik/Fahrzeuge/FZ/2021/fz27_202101.xlsx?__blob=publicationFile&v=5, last checked on 10.06.2021.

KBA (2021i): Fahrzeugzulassungen (FZ). Bestand an Kraftfahrzeugen und Kraftfahrzeuganhängern nach Bundesländern, Fahrzeugklassen und ausgewählten Merkmalen. Bestand am 1. Januar 2021. Bestand an Kraftfahrzeugen und Kraftfahrzeuganhängern nach Bundesländern, Fahrzeugklassen und ausgewählten Merkmalen. Available online at https://www.kba.de/SharedDocs/Downloads/DE/Statistik/Fahrzeuge/FZ27/fz27_202101.xlsx?__blob=publicationFile&v=6, last updated 01.01.2021, last checked on 09.11.2021.

KBA (2021j): Fahrzeugzulassungen (FZ). Bestand an Kraftfahrzeugen und Kraftfahrzeuganhängern nach Bundesländern, Fahrzeugklassen und ausgewählten Merkmalen. Bestand am 1. Juli 2021. Bestand an Kraftfahrzeugen und Kraftfahrzeuganhängern nach Bundesländern, Fahrzeugklassen und ausgewählten Merkmalen. Available online at https://www.kba.de/SharedDocs/Downloads/DE/Statistik/Fahrzeuge/FZ27/fz27_202107.xlsx?__blob=publicationFile&v=3, last updated 01.07.2021, last checked on 09.11.2021.

KBA (2021k): Monatliche Neuzulassungen 2020 (FZ 8). Januar bis Dezember. FZ 8. Published by Kraftfahrt-Bundesamt. Januar bis Dezember. Flensburg. Available online at https://www.kba.de/DE/Statistik/Fahrzeuge/Neuzulassungen/MonatlicheNeuzulassungen/n_monatl_neuzulassungen_inhalt.html?nn=2601598, last checked on 28.06.2021.

KBA (2021l): Monatliche Neuzulassungen 2021 (FZ 8). Januar bis Mai, November. FZ 8. Published by Kraftfahrt-Bundesamt. Januar bis Mai, November. Flensburg. Available online at https://www.kba.de/DE/Statistik/Fahrzeuge/Neuzulassungen/MonatlicheNeuzulassungen/n_monatl_neuzulassungen_inhalt.html?nn=2601598, last checked on 04.01.2022.

KBA (2021m): Verkehr in Zahlen 2020/2021. 49. Jahrgang. Published by Bundesministerium für Verkehr und digitale Infrastruktur (BMVI). Flensburg. Available online at https://www.bmvi.de/SharedDocs/DE/Publikationen/G/verkehr-in-zahlen-2020-pdf.pdf?__blob=publicationFile, last checked on 20.05.2021.

Keeling, C. D.; Chin, J. F. S.; Whorf, T. P. (1996): Increased activity of northern vegetation inferred from atmospheric CO2 measurements. In: *Nature* 382 (6587), p. 146–149. DOI: 10.1038/382146a0.

Keith, David W.; Holmes, Geoffrey; St. Angelo, David; Heidel, Kenton (2018): A Process for Capturing CO2 from the Atmosphere. In: *Joule* 2 (8), p. 1573–1594. DOI: 10.1016/j.joule.2018.05.006.

Kempkens, Wolfgang (2021): Australien wird zur Wasserstoff-Nabelschnur der Welt. Published by Golem. Available online at https://www.golem.de/news/energiewende-australien-wird-zur-wasserstoff-nabelschnur-der-welt-2111-160766.html, last updated 10.11.2021, last checked on 12.11.2021.

Kendziorski, Mario; Göke, Leonard; Kemfert, Claudia; von Hirschhausen, Christian; Zozmann, Elmar (2021): 100% erneuerbare Energie für Deutschland unter besonderer Berücksichtigung von Dezentralität und räumlicher Verbrauchsnähe. Potenziale, Szenarien und Auswirkungen auf Netzinfrastrukturen. Published by Deutsches Institut für Wirtschaftsforschung (DIW). Potenziale, Szenarien und

Auswirkungen auf Netzinfrastrukturen. Berlin (Politikberatung kompakt, 167). Available online at https://www.diw.de/documents/publikationen/73/diw_01.c.816979.de/diwkompakt_2021-167.pdf, last checked on 13.12.2021.

Kenkel, Philipp; Wassermann, Timo; Zondervan, Edwin (2020): Design of a Sustainable Power-to-methanol Process. A Superstructure Approach Integrated with Heat Exchanger Network Optimization. In: Sauro Pierucci, Flavio Manenti, Giulia Luisa Bozzano und Davide Manca (Hg.): Computer Aided Chemical Engineering : 30 European Symposium on Computer Aided Process Engineering, Bd. 48: Elsevier, p. 1411–1416.

KEROSyN (2021): Die Dekarbonisierung des Verkehrssektors. Available online at https://www.kerosyn100.de/, last checked on 08.11.2021.

Kessinger, Susan; Minkos, Andrea; Dauert, Ute; Feigenspan, Stefan (2021): Luftqualität 2020. Vorläufige Auswertung. Hintergrundpapier. Published by Umweltbundesamt. Vorläufige Auswertung. Dessau-Roßlau. Available online at https://www.umweltbundesamt.de/sites/default/files/medien/5750/publikationen/hgp_luftqualitaet_2020_bf.pdf, last checked on 16.10.2021.

Khan, M. A.; Al-Attas, Tareq; Roy, Soumyabrata; Rahman, Muhammad M.; Ghaffour, Noreddine; Thangadurai, Venkataraman et al. (2021): Seawater electrolysis for hydrogen production. A solution looking for a problem? In: *Energy Environ. Sci.* 14 (9), p. 4831–4839. DOI: 10.1039/D1EE00870F.

Kiendl, Isabel (2018): Reaktionstechnische Untersuchungen der Direktsynthese von Dimethylether aus Synthesegas. Dissertation, München. Fakultät für Maschinenwesen. Available online at https://mediatum.ub.tum.de/doc/1437354/1437354.pdf, last checked on 08.11.2021.

Kim, Chul-Hwan; Lee, Ji-Young; Park, See-Han; Moon, Sun-Ok (2019): Global Trends and Prospects of Black Liquor as Bioenergy. In: *JKTAPPI* 51 (5), p. 3–15. DOI: 10.7584/JKTAPPI.2019.10.51.5.3.

Kircher, Manfred; Schwarz, Thomas (2020): CO2 und CO – Nachhaltige Kohlenstoffquellen für die Kreislaufwirtschaft. 1st ed. 2020. Available online at https://doi.org/10.1007/978-3-662-60649-0.

Kirsch, Hannah; Brübach, Lucas; Loewert, Marcel; Riedinger, Michael; Gräfenhahn, Alexander; Böltken, Tim et al. (2020a): CO 2 -neutrale Fischer-Tropsch-Kraftstoffe aus dezentralen modularen Anlagen. Status und Perspektiven. In: *Chemie Ingenieur Technik* 92 (1-2), p. 91–99. DOI: 10.1002/cite.201900120.

Kirsch, Hannah; Lochmahr, Natalie; Staudt, Christiane; Pfeifer, Peter; Dittmeyer, Roland (2020b): Production of CO2-neutral liquid fuels by integrating Fischer-Tropsch synthesis and hydrocracking in a single micro-structured reactor. Performance evaluation of different configurations by factorial design experiments. In: *Chemical Engineering Journal* 393, p. 124553. DOI: 10.1016/j.cej.2020.124553.

KIT (2021): Power-to-Liquid (E-Fuels). Available online at https://www.elab2.kit.edu/power2liquid.php, last updated 22.06.2021, last checked on 08.112021.

Klein-Marcuschamer, Daniel; Blanch, Harvey W. (2013): Survival of the fittest. An economic perspective on the production of novel biofuels. In: *AIChE J.* 59 (12), p. 4454–4460. DOI: 10.1002/aic.14245.

KOM(2001) 547 (2001): Vorschlag für eine Richtlinie des Europäischen Parlaments und des Rates zur Förderung der Verwendung von Biokraftstoffen. KOM(2001) 547 from 07.11.2001.

König, Daniel H.; Baucks, Nadine; Dietrich, Ralph-Uwe; Wörner, Antje (2015): Simulation and evaluation of a process concept for the generation of synthetic fuel from CO2 and H2. In: *Energy* 91, p. 833–841. DOI: 10.1016/j.energy.2015.08.099.

König, Daniel Helmut (2016): Techno-ökonomische Prozessbewertung der Herstellung synthetischen Flugturbinentreibstoffes aus CO2 und H2, Stuttgart. Available online at https://elib.dlr.de/109210/, last checked on 25.05.2021.

KSG (2021): Bundes-Klimaschutzgesetz. KSG from 18.08.2021.

Kugler, Kurt (2015): Electrochemical Nitrogen Reduction for Ammonia Synthesis. Elektrochemische Stickstoffreduktion für die Ammoniaksynthese. Available online at http://publications.rwth-aachen.de/record/572765/files/572765.pdf, last checked on 16.11.2021.

Küppers Engineering (2021): Atex Temperaturklassen. Published by Küppers Engineering. Available online at https://www.druckgeraete-online.de/seiten/atex/atex_produkt/atex_temperaturklassen.htm, last checked on 16.10.2021.

Lael, Manoel Regis Lima Verde; Hernandes, Thayse Aparecida Dourado (2020): SUCRE. Sugarcane Renewable Electricity. Sugarcane Renewable Electricity. Available online at https://lnbr.cnpem.br/wp-content/uploads/2020/07/SUCRE-Project-Final-Report.pdf, last checked on 04.01.2022.

Lal, B.; Rana, K. S.; Rana, D. S.; Shivay, Y. S.; Sharma, D. K.; Meena, B. P.; Gautam, Priyanka (2019): Biomass, yield, quality and moisture use of Brassica carinata as influenced by intercropping with chickpea under semiarid tropics. In: *Journal of the Saudi Society of Agricultural Sciences* 18 (1), p. 61–71. DOI: 10.1016/j.jssas.2017.01.001.

Landälv, Ingvar (2020): Status - Renewable Bio-methanol Production. Lund (Schweden) (2020). Available online at https://www.fastwater.eu/data/11%20Status%20renewable%20bio-methanol%20production%20-%20Ingvar%20Land%C3%A4lv.pdf, last checked on 03.11.2021.

Lane, Jim (2017): Amyris' Sweet-'N-High: Biotech pioneer sells farnesene plant to DSM, focuses on next-gen sweetener. Available online at https://www.biofuelsdigest.com/bdigest/2017/11/20/amyris-sweet-and-high-biotech-pioneer-sells-farnesene-plant-to-dsm-focuses-on-next-gen-sweetener/, last updated 20.11.2017, last checked on 16.11.2021.

Lane, Jim (2021): Dig their Big Rig: Licella commissions world's largest operating hydrothermal liquefaction facility. With collaboration of Jim Lane. Available online at https://www.biofuelsdigest.com/bdigest/2021/09/14/dig-their-big-rig-licella-commissions-worlds-largest-operating-hydrothermal-liquefaction-facility/#:~:text=2021%20%7C%20Jim%20Lane-,Licella%20commissions%20world's%20largest%20operating%20hydrothermal%20liquefaction%20facility,with%20Canadian%20Forest%20Products%20Ltd., last updated 14.09.2021, last checked on 08.11.2021.

Larsson, Anton; Gunnasrsson, Ingemar; Tengberg, Freddy (2019): The GoBiGas Project. Demonstration of the Production of Biomethane from Biomass via Gasification. With collaboration of Freddy Tengberg Ingemar Gunnasrsson. Demonstration of the Production of Biomethane from Biomass via Gasification. Gothenburg, Sweden. Available online at https://www.goteborgenergi.se/Files/Webb20/Kategoriserad%20information/Forskningsprojekt/The%20GoBiGas%20Project%20-%20Demonstration%20of%20the%20Production%20of%20Biomethane%20from%20Biomass%20v%20230507_6_0.pdf?TS=636807191662780982, last checked on 16.11.2021.

Lauf, T.; Memmler, M.; Schneider, S. (2019): Emissionsbilanz erneuerbarer Energieträger. Bestimmung der vermiedenen Emissionen im Jahr 2018. Published by Umweltbundesamt. Dessau-Roßlau. Available online at https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2019-11-07_cc-37-2019_emissionsbilanz-erneuerbarer-energien_2018.pdf, last checked on 16.11.2021.

Lauf, Thomas; Memmler, Michael; Schneider, Sven (2021): Emissionsbilanz erneuerbarer Energieträger. Bestimmung der vermiedenen Emissionen im Jahr 2020. Published by Umweltbundesamt. Bestimmung der vermiedenen Emissionen im Jahr 2020. Dessau-Roßlau. Available online at https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2021-12-13_climate-change_71-2021_emissionsbilanz_erneuerbarer_energien_2020_bf.pdf, last checked on 18.01.2022.

Laurikko, Juhani; Hannula, Ilkka; Nylund, Nils-Olof; Aakko-Saksa, Päivi (2020): The Role of Renewable Transport Fuels in Decarbonizing Road Transport. Scenarios and Contributions in Selected Countries. Published by IEA AMF TCP. Scenarios and Contributions in Selected Countries. Available online at https://www.iea-amf.org/app/webroot/files/file/Annex%20Reports/AMF_Annex_58_Scenarios%20and%20Contributions%20in%20Selected%20Countries.pdf, last checked on 18.11.2021.

LBST (2016): Renewables in Transport 2050. Empowering a sustainable mobility future with zero emission fuels from renewable electricity Kraftstoffstudie II. With collaboration of Patrick Schmidt, Werner Zittel, Werner Weindorf und Tetyana Raksha. Published by Ludwig-Bölkow-Systemtechnik GmbH (LBST). Empowering a sustainable mobility future with zero emission fuels from renewable electricity Kraftstoffstudie II.

Leblanc, Johann (2021): Ethanol. La liste des modèles compatibles E85 sans boîtier en France. Published by L'argus. Available online at https://www.largus.fr/actualite-automobile/ethanol-la-liste-des-modeles-compatibles-e85-sans-boitier-en-france-10731394.html, last updated 28.09.2021, last checked on 18.11.2021.

Lenz, Volker; Naumann, Karin; Denysenko, Velina; Daniel-Gromke, Jaqueline; Rensberg, Nadja; Schröder, Jörg et al. (2021): Erneuerbare Energien. In: *BWK Energie* (73), p. 56–89. Available online at https://www.ingenieur.de/wp-content/uploads/2021/12/BWK_E-Paper-Special_2021_r.pdf, last checked on 13.12.2021.

Lepage, Thibaut; Kammoun, Maroua; Schmetz, Quentin; Richel, Aurore (2021): Biomass-to-hydrogen. A review of main routes production, processes evaluation and techno-economical assessment. In: *Biomass and Bioenergy* 144, p. 105920. DOI: 10.1016/j.biombioe.2020.105920.

Li, Hailong; Tan, Yuting; Ditaranto, Mario; Yan, Jinying; Yu, Zhixin (2017): Capturing CO2 from Biogas Plants. In: *Energy Procedia* 114, p. 6030–6035. DOI: 10.1016/j.egypro.2017.03.1738.

Liebich, Axel; Fröhlich, Thomas; Münther, Daniel; Fehrenbach, Horst; Giegrich, J.; Köppen, Susanne et al. (2020): Systemvergleich speicherbarer Energieträger aus erneuerbaren Energien. Available online at https://www.umweltbundesamt.de/publikationen/systemvergleich-speicherbarer-energietraeger-aus, last checked on 18.11.2021.

Linde (2020): Smaller carbon footprint. Higher process efficiency. Synergized benefits of Linde DRYREF™ and BASF SYNSPIRE™. Synergized benefits of Linde DRYREF™ and BASF SYNSPIRE™. Available online at https://www.engineering.linde.com/dryref, last checked on 18.11.2021.

Linde Gas GmbH (2018): Wasserstoff, verdichtet. Sicherheitsdatenblatt. Published by Linde Gas GmbH. Sicherheitsdatenblatt. Available online at https://produkte.linde-gas.at/sdb_konform/H2_10021694DE.pdf, last checked on 06.10.2021.

Linde Gas GmbH (2021): Methan. Sicherheitsdatenblatt. Published by Linde Gas GmbH. Sicherheitsdatenblatt. Available online at https://produkte.linde-gas.at/sdb_konform/CH4_10021692DE.pdf, last checked on 18.11.2021.

Liu, Yanyong; Sotelo-Boyás, Rogelio; Murata, Kazuhisa; Minowa, Tomoaki; Sakanishi, Kinya (2011): Hydrotreatment of Vegetable Oils to Produce Bio-Hydrogenated Diesel and Liquefied Petroleum Gas Fuel over Catalysts Containing Sulfided Ni–Mo and Solid Acids. In: *Energy Fuels* 25 (10), p. 4675–4685. DOI: 10.1021/ef200889e.

Loewert, Marcel; Hoffmann, Julian; Piermartini, Paolo; Selinsek, Manuel; Dittmeyer, Roland; Pfeifer, Peter (2019): Microstructured Fischer-Tropsch Reactor Scale-up and Opportunities for Decentralized Application. In: *Chem. Eng. Technol.* 42 (10), p. 2202–2214. DOI: 10.1002/ceat.201900136.

Loh, Saw Hong; Chen, Mee Kee; Fauzi, Nur Syazana; Aziz, Ahmad; Cha, Thye San (2021): Enhanced fatty acid methyl esters recovery through a simple and rapid direct transesterification of freshly harvested biomass of Chlorella vulgaris and Messastrum gracile. In: *Scientific reports* 11 (1), p. 2720. DOI: 10.1038/s41598-021-81609-6.

Lorenzi, G.; Mignini, L.; Venezia, B.; Silva, C.; Santarelli, M. (2019): Integration of high-temperature electrolysis in an HVO production process using waste vegetable oil. In: *Energy Procedia* 158, p. 2005–2011. DOI: 10.1016/j.egypro.2019.01.465.

Löschau, Gunter (2019): Ultrafeine Partikel, Ruß und Stickoxide in der Außenluft in Sachsen. 17. FAD-Konferenz, Herausforderung - Abgasnachbehandlung. FAD e.V. Dresden (2019). Available online at https://www.umwelthaus.org/media/5_messungenen_von_ufp_staedten_dr._loeschau.pdf, last checked on 18.11.2021.

Lutz, Martin (2021): Eine Bilanz der verkehrsbedingten Luftbelastung in Städten und was das für EURO 7/VII bedeutet? FAD-Webinar. FAD e.V. (2021).

Mabanaft (2021): FAME (Biodiesel). Sicherheitsdatenblatt. Published by Mabanaft Deutschland GmbH & Co. KG. Sicherheitsdatenblatt. Available online at https://www.mabanaft.com/fileadmin/content/global_content/downloads/mabanaft/SDS_Mabanaft-D_FAME-Biodiesel_de.pdf, last checked on 18.11.2021.

Macrelli, Stefano; Mogensen, Johan; Zacchi, Guido (2012): Techno-economic evaluation of 2nd generation bioethanol production from sugar cane bagasse and leaves integrated with the sugar-based ethanol process. In: *Biotechnol Biofuels* 5 (1), p. 22. DOI: 10.1186/1754-6834-5-22.

Maier, Thomas; Härtl, Martin; Jacob, Eberhard; Wachtmeister, Georg (2019): Dimethyl carbonate (DMC) and Methyl Formate (MeFo). Emission characteristics of novel, clean and potentially CO2 -neutral fuels including PMP and sub-23 nm nanoparticle-emission characteristics on a spark-ignition DI-engine. In: *Fuel* 256 (3), p. 115925. DOI: 10.1016/j.fuel.2019.115925.

Majer, Stefan; Gröngröft, Arne; Drache, Christian; Braune, Maria; Meisel, Kathleen; Müller-Langer, Franziska et al. (2015): Technische und methodische Grundlagen der THG-Bilanzierung von Biodiesel. Version 1.0. Leipzig: DBFZ (Handreichung). Available online at https://www.dbfz.de/fileadmin/user_upload/Referenzen/broschueren/Handreichung_Biodiesel.pdf.

Marlin, Dana S.; Sarron, Emeric; Sigurbjörnsson, Ómar (2018): Process Advantages of Direct CO2 to Methanol Synthesis. In: *Frontiers in chemistry* 6, p. 446. DOI: 10.3389/fchem.2018.00446.

MARPOL Annex VI from 20.05.2021 (2021): Internationalen Übereinkommen zur Verhütung der Meeresverschmutzung durch Schiffe - Verhütung der Verschmutzung der Luft durch Seeschiffe.

Marsh, Susan K.; Owen, Kartley; Wright, Bernard S. (1988): Conversion of methanol to gasoline. Registered through ExxonMobil Oil Corp. Registration no: US81543885A. Priority data: 31.12.1985.

Materazzi, Massimiliano; Foscolo, Pier Ugo (2019): Substitute natural gas from waste. Technical assessment and industrial applications of biochemical and thermochemical processes. London: Academic Press.

Matsakas, L.; Rova, U.; Christakopoulos, P. (2016): Strategies for enhanced biogas generation through anaerobic digestion of forest material – An overview. In: *BioResources* (11 (2)), p. 5482–5499. Available online at https://bioresources.cnr.ncsu.edu/issues/vol11-issue2/page/19/, last checked on 23.11.2021.

Matthischke, Steffi; Krüger, Raphael; Rönsch, Stefan; Güttel, Robert (2016): Unsteady-state methanation of carbon dioxide in a fixed-bed recycle reactor — Experimental results for transient flow rate ramps. In: *Fuel Processing Technology* 153, p. 87–93. DOI: 10.1016/j.fuproc.2016.07.021.

Mauerhofer, Anna; Benedikt, Florian; Hammerschmid, Martin; Bartik, Alexander; Veress, Marton (2020): Reallabor zur Herstellung von Holzdiesel und Holzgas aus Biomasse und biogenen Reststoffen für die Land- und Forstwirtschaft.

Mazubert, Alex; Aubin, Joelle; Elgue, Sébastien; Poux, Martine (2014): Intensification of waste cooking oil transformation by transesterification and esterification reactions in oscillatory baffled and microstructured reactors for biodiesel production. In: *Green Processing and Synthesis* 3 (6), p. 1646. DOI: 10.1515/gps-2014-0057.

McPhy (2015): Audi E-Gas. Eine 6 MW Elektrolyse-Lösung für Audi. Eine 6 MW Elektrolyse-Lösung für Audi. Available online at https://mcphy.com/de/industrieller-wasserstoff/audi/?cn-reloaded=1, last updated 21.05.2015, last checked on 23.11.2021.

Meisel, Kathleen (2015): Technische und methodische Grundlagen der THG-Bilanzierung von Bioethanol. Handreichung. Version 1.0. Leipzig: DBFZ.

Mellios, G.; Kastori, M.; Zierock, K-H. (2019): Technical support for the review obligations under Regulation (EU) 2016/1628 (NRMM). Draft Final Report. Published by Europäische Kommission. Draft Final Report. Brüssel. Available online at https://circabc.europa.eu/sd/a/4415ad0e-7946-4fa9-a432-d4c700c6915d/190503_NRMM_final_v3.pdf, last checked on 23.11.2021.

Menezes, Eliana Weber de; Cataluña, Renato (2008): Optimization of the ETBE (ethyl tert-butyl ether) production process. In: *Fuel Processing Technology* 89 (11), p. 1148–1152. DOI: 10.1016/j.fuproc.2008.05.006.

Methanol Institute (2021): Methanol price and supply/demand. Available online at https://www.methanol.org/methanol-price-supply-demand/, last checked on 23.11.2021.

microbEnergy (2020): BiON® – Robust. Flexibel. Umweltfreundlich. Synthetisches Methan aus CO2 und H2. Available online at https://www.microbenergy.de/fileadmin/user_upload/9451834_08-2020_DE.pdf, last checked on 23.11.2021.

Millinger, Markus; Ponitka, Jens; Arendt, Oliver; Thrän, Daniela (2017): Competitiveness of advanced and conventional biofuels. Results from least-cost modelling of biofuel competition in Germany. In: *Energy Policy* (107), p. 394–402. DOI: 10.1016/j.enpol.2017.05.013.

Millinger, Markus; Tafarte, Philip; Jordan, Matthias; Hahn, Alena; Meisel, Kathleen; Thrän, Daniela (2021): Electrofuels from excess renewable electricity at high variable renewable shares. Cost, greenhouse gas abatement, carbon use and competition. In: *Sustainable Energy Fuels* 5 (3), p. 828–843. DOI: 10.1039/d0se01067g.

Mineralölwirtschaftsverband e.V. (2020): Preiszusammensetzung. Zusammensetzung des Verbraucherpreises für Kraftstoffe. Published by Mineralölwirtschaftsverband e.V. Zusammensetzung des Verbraucherpreises für Kraftstoffe. Available online at https://www.mwv.de/statistiken/preiszusammensetzung/, last updated 23.11.2021.

Mineralölwirtschaftsverband e.V. (2021): Rohölpreise | Brent. Available online at https://www.mwv.de/statistiken/rohoelpreise/, last updated 25.05.2021, last checked on 24.11.2021.

Ministério da Agricultura (2015): Cronologia da Mistura Carburante Etanol Anidro - Gasolina no Brasil. Ministério da Agricultura, Pecuária e Abastecimento. Published by Ministério da Agricultura, Pecuária e Abastecimento. Available online at cronologia-da-mistura-carburante-etanol-anidro.pdf, last checked on 04.01.2022.

Ministério de Minas e Energia (2021): Série histórica do levantamento de preços. Available online at https://www.gov.br/anp/pt-br/assuntos/precos-e-defesa-da-concorrencia/precos/precos-revenda-e-de-distribuicao-combustiveis/serie-historica-do-levantamento-de-precos, last updated 06.12.2021, last checked on 04.01.2022.

Minutillo, M.; Perna, A.; Forcina, A.; Di Micco, S.; Jannelli, E. (2020): Analyzing the levelized cost of hydrogen in refueling stations with on-site hydrogen production via water electrolysis in the Italian scenario. In: *International Journal of Hydrogen Energy. DOI:* 10.1016/j.ijhydene.2020.11.110.

Mock, Peter (2021): The European Commission's fitness program for climate protection sluggards | International Council on Clean Transportation. Available online at https://theicct.org/blog/staff/european-commission-fitfor55-jul2021, last updated 15.07.2021, last checked on 03.12.2021.

Mohsenzadeh, Abas; Zamani, Akram; Taherzadeh, Mohammad J. (2017): Bioethylene Production from Ethanol. A Review and Techno-economical Evaluation. In: *ChemBioEng Reviews* 4 (2), p. 75–91. DOI: 10.1002/cben.201600025.

Montoya Sanchez, Natalia; Cordoba, Fernando; Trujllo, Carlos Alexander; Gil, Ivan; Rodriguez, Gerardo (2011): Fusel Oil Separation Process. Available online at https://www.researchgate.net/publication/267309762_Fusel_Oil_Separation_Process, last updated 19.10.2011, last checked on 22.06.2021.

Moretti, Christian; López-Contreras, Ana; Vrije, Truus de; Kraft, Axel; Junginger, Martin; Shen, Li (2021): From agricultural (by-)products to jet fuels. Carbon footprint and economic performance. In: *Science of The Total Environment* 775, p. 145848. DOI: 10.1016/j.scitotenv.2021.145848.

Moshood, Taofeeq D.; Nawanir, Gusman; Mahmud, Fatimah (2021): Microalgae biofuels production. A systematic review on socioeconomic prospects of microalgae biofuels and policy implications. In: *Environmental Challenges* 5 (4), p. 100207. DOI: 10.1016/j.envc.2021.100207.

Motoki, Paulo Toshio (1994): Portarian No 23, de 6 de Junho de 1994. Available online at https://sistemas.mre.gov.br/kitweb/datafiles/Cgpi/pt-br/file/portaria%20dnc%2023_1994.pdf, last checked on 04.01.2022.

Motorcyclesdata (2021): Global Motorcycles Market lost 9 million sales in 2020. In: *MotorCycles Data* (2021). Available online at https://www.motorcyclesdata.com/2021/04/08/world-motorcycles-market/, last checked on 24.11.2021.

Müller, K.; Fleige, M.; Rachow, F.; Schmeißer, D. (2013): Sabatier based CO2-methanation of Flue Gas Emitted by Conventional Power Plants. In: *Energy Procedia* 40, p. 240–248. DOI: 10.1016/j.egypro.2013.08.028.

Müller-Langer, Franziska; Dögnitz, Niels; Marquardt, Christian; Zschocke, Alexander; Schripp, Tobias; Oehmichen, Katja et al. (2020): Multiblend JET A-1 in Practice. Results of an R&D Project on Synthetic Paraffinic Kerosenes. In: *Chem. Eng. Technol.* 43 (8), p. 1514–1521. DOI: 10.1002/ceat.202000024.

Müller-Langer, Franziska; Oehmichen, Katja; Dietrich, Sebastian; Zech, Konstantin M.; Reichmuth, Matthias; Weindorf, Werner (2019): PTG-HEFA Hybrid Refinery as Example of a SynBioPTx Concept—Results of a Feasibility Analysis. In: *Applied Sciences* 9 (19), p. 4047. DOI: 10.3390/app9194047.

Müller-Langer, Franziska; Schneider, Jens; Pohl, Marcel; Majer, Stefan (2016): Innovative erneuerbare Produkte durch Ausschöpfung von ynergien aus Bioenergie und Power-to-X (2016). Available online at https://www.dbfz.de/fileadmin/user_upload/Download/Extern/DBFZ_SynBioPTx_2016-09.pdfhttps://www.dbfz.de/fileadmin/user_upload/Download/Extern/DBFZ_SynBioPTx_2016-09.pdf, last checked on 24.11.2021.

Munich Airport (2021): Weichenstellung für sauberes Fliegen am Flughafen München. Published by Munich Airport. Available online at https://www.munich-airport.de/presse-gruenes-licht-fuer-sustainable-fuels-11029201, last updated 06.05.2021, last checked on 25.11.2021.

NASA (2021): Carbon Dioxide. Available online at https://climate.nasa.gov/vital-signs/carbon-dioxide/, last updated 10.2021, last checked on 2310.2021.

Naumann, Karin; Müller-Langer, Franziska; Meisel, Kathleen; Majer, Stefan; Schröder, Jörg; Schmieder, Uta (2021): Weiterentwicklung der deutschen Treibhausgasminderungsquote. Hintergrundpapier. Published by DBFZ Deutsches Biomasseforschungszentrum gemeinnützige GmbH. Hintergrundpapier. Leipzig. Available online at https://www.dbfz.de/fileadmin//user_upload/Referenzen/Statements/Hintergrundpapier_Weiterentwicklung_THG-Quote.pdf, last checked on 24.06.2021.

Naumann, Karin; Müller-Langer, Franziska; Schröder, Jörg; Meisel, Kathleen; Cyffka, Karl-Friedrich (2022): Hintergrundpapier zur Quote zur Treibhausgasminderung bei Kraftstoffen. Leipzig. Available online at https://www.dbfz.de/fileadmin//user_upload/Referenzen/Statements/Hintergrundpapier_THG-Quote_DE_Nov2022.pdf, last checked on 23.11.2022.

Naumann, Karin; Oehmichen, Katja; Remmele, Edgar; Thuneke, Klaus; Schröder, Jörg; Zeymer, Martin et al. (2016): Monitoring Biokraftstoffsektor. 3. Ed. Leipzig (DBFZ-Report, 11). Available online at https://www.dbfz.de/fileadmin/user_upload/Referenzen/DBFZ_Reports/DBFZ_Report_11_3.pdf.

Naumann, Karin; Oehmichen, Katja; Zeymer, Martin; Meisel, Kathleen (2014): Monitoring Biokraftstoffsektor. 2. Ed. Leipzig: DBFZ (DBFZ-Report, 11).

Naumann, Karin; Oehmichen, Katja; Zeymer, Martin; Müller-Langer, Franziska; Scheftelowitz, Mattes; Adler, Philipp et al. (2012): Monitoring Biokraftstoffsektor. Leipzig: DBFZ (DBFZ-Report, 11).

Naumann, Karin; Schröder, Jörg; Oehmichen, Katja; Etzold, Hendrik; Müller-Langer, Franziska; Remmele, Edgar et al. (2019): Monitoring Biokraftstoffsektor. 4. überarbeitete und erweiterte Auflage. Published by DBFZ Deutsches Biomasseforschungszentrum gemeinnützige GmbH. Leipzig (DBFZ-Report, Nr. 11).

NEP 2035 (2021): Netzentwicklungsplan Strom. Available online at https://www.netzentwicklungsplan.de/de.

Neste (2021): Website - Führende Luftfahrt-Akteure starten erste In-Flight-Emissionsstudie mit 100 Prozent nachhaltigem Flugkraftstoff (SAF). Published by Neste. Available online at https://www.neste.de/releases-and-news/aviation/fuehrende-luftfahrt-akteure-starten-erste-flight-emissionsstudie-mit-100-prozent-nachhaltigem, last updated 18.03.2021, last checked on 03.08.2021.

Neste Oyj (2019): Neste Renewable Diesel; Neste Renewable Diesel 100 %; Neste MY Renewable Diesel. Safety Data Sheet. Published by Neste Oyj. Safety Data Sheet. Available online at https://www.neste.fi/static/ktt/13898_eng.pdf, last checked on 25.11.2021.

Neste Oyj (2020): Aviation Jet Fuel JET A-1 (JETA1). Safety Data Sheet. Published by Neste. Safety Data Sheet. Available online at https://www.neste.fi/static/ktt/10505_eng.pdf, last checked on 25.11.2021.

Neste Oyj (2021): Neste maps. Published by Neste Oyj. Available online at https://www.neste.fi/asemat?orig=&dest=&field_geofield_distance%5Borigin%5D=&field_station_tuotteisto_value_9%5B1%5D=1, last checked on 13.05.2021.

NETL (2021): Gasifipedia. Available online at https://netl.doe.gov/research/Coal/energy-systems/gasification/gasifipedia, last checked on 25.11.2021.

Neuling, Ulf; Kaltschmitt, Martin; Hofbauer, Hermann (2018): Biokerosinherstellung. Dissertation.

Newbery, Charles (2021): COP26: Australia's FFI plans $8.4 billion green hydrogen project in Argentina. Published by S&P Global. Available online at https://www.spglobal.com/platts/en/market-insights/latest-news/energy-transition/110121-cop26-australias-ffi-plans-84-billion-green-hydrogen-project-in-argentina, last updated 01.11.2021, last checked on 25.11.2021.

Norske (2020): Supplying your renewable fuel. Unlimited. The demonstration. Published by Norkse e-Fuel AS. The demonstration. Available online at https://www.norsk-e-fuel.com/en/, last checked on 16.01.2022.

NovaCana (2021): Raüizen fecha com Yara sua primiera venda de biometano a longo prazo. Available online at https://www.novacana.com/n/industria/usinas/raizen-fecha-yara-primeira-venda-biometano-longo-prazo-210921, last updated 21.09.2021, last checked on 29.10.2021.

NPM (2021): Wege für mehr Klimaschutz im Verkehr. AG1 - Bericht. Published by Bundesministerium für Verkehr und digitale Infrastruktur (BMVI). AG1 - Bericht. Berlin. Available online at https://www.plattform-zukunft-mobilitaet.de/wp-content/uploads/2021/07/NPM_AG1_Wege-fuer-mehr-Klimaschutz.pdf, last checked on 07.01.2022.

Nylund, Nils-Olof; Aakko-Saksa, Päivi; Le Feuvre, Pharoah (2018): Air quality implications of transport biofuel consumption. Special Report. Published by IEA AMF TCP. Special Report. Available online at https://iea-amf.org/app/webroot/files/file/other%20publications/Renewables%202018_biofuels%20and%20air%20quality.pdf, last checked on 25.11.2021.

Oberon Fuels (2021): Oberon's Process & Facilities. Available online at https://oberonfuels.com/technology/oberon-process/, last checked on 25.11.2021.

OICA (2021): Global Sales Statistics 2019 – 2020. Published by International Organization of Motor Vehicle Manufacturers (OICA). Available online at https://www.oica.net/wp-content/uploads/Passenger-Cars_Sales-2020.pdf, last checked on 31.05.2021.

Olsson, Olle; Bang, Christian; Borchers, Malgorzata; Hahn, Alena; Karjunen, Hannu; Thrän, Daniela; Tynjälä, Tero (2020a): Deployment of BECCS/U value chains. Technological pathways, policy options and business models. Technological pathways, policy options and business models. [s.l.] (IEA Bioenergy Task 40).

Olsson, Olle; Tynjälä, Tero; Bang, Christian; Thrän, Daniela (2020b): Deployment of BECCS/U – technologies, supply chain setup & Policy options. IEA Bioenergy Task 40 webinar. IEA Bioenergy (2020). Available online at https://www.ieabioenergy.com/wp-content/uploads/2020/06/BECCUS-Webinar-Slide-0020200616-final.pdf, last checked on 13.12.2021.

Omari, Ahmad; Heuser, Benedikt; Pischinger, Stefan (2017): Potential of oxymethylenether-diesel blends for ultra-low emission engines. In: *Fuel* 209 (12), p. 232–237. DOI: 10.1016/j.fuel.2017.07.107.

Onthong, Usa; Juntarachat, Niramol (2017): Evaluation of Biogas Production Potential from Raw and Processed Agricultural Wastes. In: *Energy Procedia* 138, p. 205–210. DOI: 10.1016/j.egypro.2017.10.151.

OrangeGas (2021): Locations - OrangeGas. Published by OrangeGas. Available online at https://orangegas.nl/en/refueling-locations, last checked on 25.11.2021.

Ordóñez, Diego Freire; Guillén-Gosálbez, Gonzalo (2020): Techno-economic and Environmental Assessment of Electrofuels. A Case Study of Gasoline Production using a PEM Electrolyser. In: Sauro Pierucci, Flavio Manenti, Giulia Luisa Bozzano und Davide Manca (Hg.): Computer Aided Chemical Engineering : 30 European Symposium on Computer Aided Process Engineering, Bd. 48: Elsevier, p. 595–600.

Our World in Data (2021): Motor vehicle ownership, per 1000 inhabitants. Published by ourworldindata.org. Available online at https://ourworldindata.org/grapher/motor-vehicle-ownership-per-1000-inhabitants?country=~USA, last checked on 11.06.2021.

Overmaat, Bernd (2019): BioTfueL: Der Biokraftstoff der Zukunft entsteht aus Abfall. Available online at https://engineered.thyssenkrupp.com/biotfuel-der-biokraftstoff-der-zukunft-entsteht-aus-abfall/, last updated 04.06.2019, last checked on 25.11.2021.

Ovsyannikova, Ekaterina; Kruse, Andrea; Becker, Gero C. (2020): Feedstock-dependent phosphate recovery in a pilot-scale hydrothermal liquefaction bio-crude production. In: *Energies* 13 (2), p. 379.

Parapouli, Maria; Vasileiadis, Anastasios; Afendra, Amalia-Sofia; Hatziloukas, Efstathios (2020): Saccharomyces cerevisiae and its industrial applications. In: *AIMS microbiology* 6 (1), p. 1–31. DOI: 10.3934/microbiol.2020001.

Park, Min Bum; Park, Eun Duck; Ahn, Wha-Seung (2019): Recent Progress in Direct Conversion of Methane to Methanol Over Copper-Exchanged Zeolites. In: *Frontiers in chemistry* 7, p. 514. DOI: 10.3389/fchem.2019.00514.

Paula, Eduardo Marostegan; da Silva, Lorrayny Galoro; Brandao, Virginia Lucia Neves; Dai, Xiaoxia; Faciola, Antonio Pinheiro (2019): Feeding Canola, Camelina, and Carinata Meals to Ruminants. In: *Animals : an open access journal from MDPI* 9 (10). DOI: 10.3390/ani9100704.

Pérez, Rena (1997): Feeding pigs in the tropics. Rome (FAO animal production and health paper, 132).

Peters, Dann; Stojcheva, Viktorija (2017): Crude tall oil low ILUC risk assessment. Comparing global supply and demand. Comparing global supply and demand. Available online at https://www.upmbiofuels.com/siteassets/documents/other-publications/ecofys-crude-tall-oil-low-iluc-risk-assessment-report.pdf, last checked on 25.11.2021.

Peters, Ralf (2020): Grünes Methanol – erfolgreiche Kostenkalkulation. Available online at http://www.c3-mobility.de/news/gruenes-methanol-erfolgreiche-kostenkalkulation/, last checked on 24.08.2021.

Pfeifer, Peter; Biffar, Linus; Timm, Friedemann; Böltken, Tim (2020): Influence of Power-to-Fuel Plant Flexibility Towards Power and Plant Utilization and Intermediate Hydrogen Buffer Size. In: *Chemie Ingenieur Technik* 92 (12), p. 1976–1982. DOI: 10.1002/cite.202000084.

Pitt, Fernando D.; Domingos, Anabela M.; Barros, A. ChivangaA. (2019): Purification of residual glycerol recovered from biodiesel production. In: *South African Journal of Chemical Engineering* 29 (3), p. 42–51. DOI: 10.1016/j.sajce.2019.06.001.

POET (2021): Shell Rock, IA. Available online at https://poet.com/shellrock, last checked on 25.11.2021.

Porsche (2020): Porsche und Siemens Energy treiben mit Partnern die Entwicklung klimaneutraler eFuels voran. Available online at https://newsroom.porsche.com/de/2020/unternehmen/porsche-siemens-energy-pilotprojekt-chile-forschung-entwicklung-synthetische-kraftstoffe-efuels-23020.html, last updated 02.12.2020, last checked on 25.11.2021.

Porter, Adam (2020): French gasoline rebound takes ethanol demand to record. Published by Argus Media group. Available online at https://www.argusmedia.com/en/news/2141745-french-gasoline-rebound-takes-ethanol-demand-to-record, last updated 16.09.2020, last checked on 25.11.2021.

Posmanik, Roy; Labatut, Rodrigo A.; Kim, Andrew H.; Usack, Joseph G.; Tester, Jefferson W.; Angenent, Largus T. (2017): Coupling hydrothermal liquefaction and anaerobic digestion for energy valorization from model biomass feedstocks. In: *Bioresour. Technol.* 233, p. 134–143.

Prognos; Öko-Institut; Wuppertal-Institut (2021): Klimaneutrales Deutschland 2045. Wie Deutschland seine Klimaziele schon vor 2050 erreichen kann. Zusammenfassung im Auftrag von Stiftung Klimaneutralität, Agora Energiewende und Agora Verkehrswende. Published by Agora Energiewende, Agora Verkehrswende, Stiftung Klimaneutralität. Wie Deutschland seine Klimaziele schon vor 2050 erreichen kann. Available online at https://static.agora-energiewende.de/fileadmin/Projekte/2021/2021_04_KNDE45/A-EW_231_KNDE2045_Langfassung_DE_WEB_2.pdf, last checked on 25.10.2021.

Proposal 2021/0205 (14.07.2021): Proposal for a Regulation on ensuring a level playing field for sustainable air transport. Proposal 2021/0205 from 14.07.2021.

Proposal EU-ETS (2021): Directive amending Directive 2003/87/EC as regards aviation's contribution to the Union’s economy-wide emission reduction target and appropriately implementing a global market-based measure. Proposal EU-ETS from 14.07.2021.

Prussi, Matteo; Panoutsou, Calliope; Chiaramonti, David (2022): Assessment of the Feedstock Availability for Covering EU Alternative Fuels Demand. In: *Applied Sciences* 12 (2), p. 740. DOI: 10.3390/app12020740.

Purr, Katja; Günther, Jens; Lehmann, Harry; Nuss, Philip (2019): Wege in eine ressourcenschonende Treibhausgasneutralität. RESCUE -Studie. Published by Umweltbundesamt. RESCUE -Studie. Dessau-Roßlau (CLIMATE CHANGE, 36/2019). Available online at https://www.umweltbundesamt.de/sites/default/files/medien/376/publikationen/rescue_studie_cc_36-2019_wege_in_eine_ressourcenschonende_treibhausgasneutralitaet.pdf, last checked on 06.10.2021.

Quartier, Dieter (2019): France and Sweden get Ford Kuga Flexfuel that runs on E85 bioethanol. Published by FleetEurope. Belgien. Available online at https://www.fleeteurope.com/en/new-energies/europe/features/france-and-sweden-get-ford-kuga-flexfuel-runs-e85-bioethanol?a=DQU04&t%5B0%5D=France&t%5B1%5D=Sweden&t%5B2%5D=bioethanol&t%5B3%5D=E85&t%5B4%5D=CNG&curl=1, last updated 21.02.2019, last checked on 01.12.2021.

Queensland University of Technology (2020): Response to ARENA Bioenergy Roadmap Call for Submissions. Published by Queensland University of Technology. Available online at https://cms.qut.edu.au/__data/assets/pdf_file/0005/1004594/10-June-2020-QUT-Response-to-ARENA-Bioenergy-Roadmap-Call-for-Submissions_4A7C-web-sm.pdf, last checked on 13.05.2021.

Quispe, César A.G.; Coronado, Christian J.R.; Carvalho Jr., João A. (2013): Glycerol. Production, consumption, prices, characterization and new trends in combustion. In: *Renewable and Sustainable Energy Reviews* 27 (3), p. 475–493. DOI: 10.1016/j.rser.2013.06.017.

Rajabihamedani, Sara (2018): Life cycle assessment of energy generation from agricultural biomass via innovative energy conversion systems. Available online at https://iris.uniroma1.it/handle/11573/1128492?mode=full.1074.

Ramirez-Cadavid, David A.; Kozyuk, Oleg; Lyle, Parker; Michel, Frederick C. (2016): Effects of hydrodynamic cavitation on dry mill corn ethanol production. In: *Process Biochemistry* 51 (4), p. 500–508. DOI: 10.1016/j.procbio.2016.01.001.

Ramos, Camila Souza; Ribeiro, Ivo (2020): GranBio becomes a technology supplier. Paulo Nigro becomes the company's CEO in this new phase. Paulo Nigro becomes the company's CEO in this new phase. Available online at http://www.granbio.com.br/en/site/noticias/granbio-becomes-a-technology-supplier/, last updated 18.02.2020, last checked on 01.12.2021.

Rashid, Khalid T.; Mansour, Khalid; Abid, Mohammad F.; Ali, Salah M.; Abed, Kadhim N. (2019): Synthesis of dimethyl carbonate for enhancement of gasoline performance. In: *Journal of King Saud University - Engineering Sciences* 31 (2), p. 171–177. DOI: 10.1016/j.jksues.2018.11.006.

Rashid, M. M.; Al Mesfer, M. K.; Naseem, H.; Danish, M. (2015): Hydrogen Production by Water Electrolysis: A Review of Alkaline Water Electrolysis, PEM Water Electrolysis and High Temperature Water Electrolysis. In: *International Journal of Engineering and Advanced Technology 4* (4(3)), p. 80–93. Available online at https://www.researchgate.net/publication/273125977_Hydrogen_Production_by_Water_Electrolysis_A_Review_of_Alkaline_Water_Electrolysis_PEM_Water_Electrolysis_and_High_Temperature_Water_Electrolysis, last checked on 01.12.2021.

Red Rock Fuels (2021): Lakeview site. Available online at https://www.redrockbio.com/lakeview-site/, last checked on 25.06.2021.

Reeve, Jennifer Sarah (2020): Modelling advanced reforming of bio-compounds for hydrogen production. Doktorarbeit. School of Chemical and Process Engineering.

Refhyne (2019): REFHYNE - Clean Refinery Hydrogen For Europe. Available online at https://refhyne.eu/de/shell-rheinland-raffinerie-baubeginn-der-weltweit-grosten-wasserstoff-elektrolyse-2/, last updated 28.06.2019, last checked on 03.11.2021.

Reichel, Johannes (2018): Volkswagen. R33 BlueDiesel senkt CO2-Emissionen. Published by HUSS-VERLAG GmbH. R33 BlueDiesel senkt CO2-Emissionen. Available online at https://www.vision-mobility.de/de/news/volkswagen-r33-bluediesel-senkt-co2-emissionen-2475.html, last updated 08.05.2019.

Renewable Energy Group Inc. (2021): Website - Geismar Biorefinery. Available online at https://www.regi.com/find-fuel/production-facilities/geismar, last updated 2021, last checked on 01.12.2021.

REPOTEC (2018): Firmenseite. Available online at http://www.repotec.at/index.php/ws-biomassekraftwerk-guessing.html, last checked on 01.12.2021.

Rezaei, Ebrahim; Dzuryk, Stephen (2019): Techno-economic comparison of reverse water gas shift reaction to steam and dry methane reforming reactions for syngas production. In: *Chemical Engineering Research and Design* 144 (70), p. 354–369. DOI: 10.1016/j.cherd.2019.02.005.

Rezende Pinho, Andrea de; Almeida, Marlon Brando Bezerra de; Mendes, Fabio Leal; Ximenes, Vitor Loureiro (2014): Production of lignocellulosic gasoline using fast pyrolysis of biomass and a conventional refining scheme. In: *Pure and Applied Chemistry* 86 (5), p. 859–865. DOI: 10.1515/pac-2013-0914.

Ricardo Energy & Environment (2016): The role of natural gas and biomethane in the transport sector.

Richtlinie (EU) 2015/1513: Richtlinie (EU) 2015/1513 des Europäischen Parlaments und des Rates vom 9. September 2015 zur Änderung der Richtlinie 98/70/EG über die Qualität von Otto- und Dieselkraftstoffen und zur Änderung der Richtlinie 2009/28/EG zur Förderung der Nutzung von Energie aus erneuerbaren Quellen. Richtlinie (EU) 2015/1513. In: *Amtsblatt der Europäischen Union* (L 239), p. 1.

Richtlinie (EU) 2018/2001 (2018): Richtlinie (EU) 2018/2001 des Europäischen Parlaments und des Rates vom 11. Dezember 2018 zur Förderung der Nutzung von Energie aus erneuerbaren Quellen (Neufassung). Richtlinie (EU) 2018/2001 from 21.12.2018. In: *Amtsblatt der Europäischen Union* 61 (L 328), p. 82–209.

Richtlinie (EU) 2019/1161 (2019): Richtlinie (EU) 2019/1161 des Europäischen Parlaments und des Rates vom 20. Juni 2019 zur Änderung der Richtlinie 2009/33/EG über die Förderung sauberer und energieeffizienter Straßenfahrzeuge. Richtlinie (EU) 2019/1161 from 20.06.2019. In: *Amtsblatt der Europäischen Union* (L188), p. 116–130.

Richtlinie 2003/30/EG (2003): Richtlinie 2003/30/EG des Europäischen Parlaments und des Rates vom 8. Mai 2003 zur Förderung der Verwendung von Biokraftstoffen oder anderen erneuerbaren Kraftstoffen im Verkehrssektor. Richtlinie 2003/30/EG from 08.05.2003. In: *Amtsblatt der Europäischen Union* (L 123), p. 42.

Richtlinie 2009/28/EG (2009): Richtlinie 2009/28/EG des Europäischen Parlaments und des Rates vom 23. April 2009 zur Förderung der Nutzung von Energie aus erneuerbaren Quellen und zur Änderung und anschließenden Aufhebung der Richtlinien 2001/77/EG und 2003/30/EG. Richtlinie 2009/28/EG from 23.04.2009. In: *Amtsblatt der Europäischen Union* (L 140), p. 16.

Richtlinie 2009/29/EG (23.04.2009): Richtlinie 2009/29/EG des Europäischen Parlaments und des Rates vom 23. April 2009 zur Änderung der Richtlinie 2003/87/EG zwecks Verbesserung und Ausweitung des Gemeinschaftssystems für den Handel mit Treibhausgasemissionszertifikaten (Text von Bedeutung für den EWR). Richtlinie 2009/29/EG from 05.06.2009. In: *Amtsblatt der Europäischen Union* 52 (L140), p. 3–27.

Richtlinie 2014/94/EU (22.10.2014): Richtlinie 2014/94/EU des Europäischen Parlaments und des Rates vom 22. Oktober 2014 über den Aufbau der Infrastruktur für alternative Kraftstoffe Text von Bedeutung für den EWR. Richtlinie 2014/94/EU from 12.11.2021. In: *Amtsblatt der Europäischen Union* (L307), p. 1–20.

Richtlinie 98/70/EG (13.10.1998): Richtlinie 98/70/EG des Europäischen Parlaments und des Rates vom 13. Oktober 1998 über die Qualität von Otto- und Dieselkraftstoffen und zur Änderung der Richtlinie 93/12/EWG des Rates. Richtlinie 98/70/EG.

RID (2021): Ordnung für die internationale Eisenbahnbeförderung gefährlicher Güter. RID.

Rogers, Nick (2008): Trends in Motorcycles Fleet Worldwide. Lillehammer (2008). Available online at https://www.itf-oecd.org/sites/default/files/docs/lillehammer08rogers.pdf, last checked on 13.07.2021.

Rönsch, Stefan; Schneider, Jens; Matthischke, Steffi; Schlüter, Michael; Götz, Manuel; Lefebvre, Jonathan et al. (2016): Review on methanation – From fundamentals to current projects. In: *Fuel* 166, p. 276–296. DOI: 10.1016/j.fuel.2015.10.111.

Royal Society and Royal Academy of Engineering (2018): Greenhouse gas removal. Published by Royal Society and Royal Academy of Engineering. Available online at https://royalsociety.org/-/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf, last checked on 21.12.2021.

Rutz, Dominik; Janssen, Rainer; Reumerman, Patrick; Spekreijse, Jurjen; Matschegg, Doris; Bacovsky, Dina et al. (2020): Technical Options for Retrofitting Industries with Bioenergy. München: WIP Renewable Energies. Available online at https://www.biofit-h2020.eu/publications-reports/BioFitHandbook-2020-03-18.pdf.

Ryan, Chris (2021): An overview of Gevo´s biobased isobutanol production process. Gevo ferments residual starches and sugars to make Isobutanol, a useful building block to make energy-dense liquid hydrocarbons and renewable chemicals, and our process is a scalable, adaptive pathway to a variety of markets. Gevo ferments residual starches and sugars to make Isobutanol, a useful building block to make energy-dense liquid hydrocarbons and renewable chemicals, and our process is a scalable, adaptive pathway to a variety of markets. Available online at https://gevo.com/wp-content/uploads/2021/05/Gevo-Whitepaper-%E2%80%93-Isobutanol-Production-Process.pdf, last checked on 03.11.2021.

Sacchi, Romain; Bauer, Christian; Cox, Brian L. (2021a): Does Size Matter? The Influence of Size, Load Factor, Range Autonomy, and Application Type on the Life Cycle Assessment of Current and Future Medium- and Heavy-Duty Vehicles. In: *Environmental science & technology* 55 (8), p. 5224–5235. DOI: 10.1021/acs.est.0c07773.

Sacchi, Romain; Bauer, Christian; Cox, Brian; Mutel, Chris (2021b): carculator: an open-source tool for prospective environmental and economic life cycle assessment of vehicles. When, Where and How can battery-electric vehicles help reduce greenhouse gas emissions?

submitted. In: *Submitted to Renewable and Sustainable Energy Reviews*. Available online at https://www.psi.ch/en/media/57994/download, last checked on 02.12.2021.

Salkuyeh, Yaser; Adams, Thomas (2015): Co-Production of Olefins, Fuels, and Electricity from Conventional Pipeline Gas and Shale Gas with Near-Zero CO2 Emissions. Part I. Process Development and Technical Performance. In: *Energies* 8 (5), p. 3739–3761. DOI: 10.3390/en8053739.

Salomonsson, Per (2013): BioDME - Final report of the European BioDME Project. Ann Arbor (2013). Available online at http://www.biodme.eu/wp/wp-content/uploads/DME5_BioDME_Salomonsson.pdf, last checked on 02.12.2021.

Sánchez-Bastardo, Nuria; Schlögl, Robert; Ruland, Holger (2020): Methane Pyrolysis for CO 2 -Free H 2 Production. A Green Process to Overcome Renewable Energies Unsteadiness. In: *Chemie Ingenieur Technik* 92 (10), p. 1596–1609. DOI: 10.1002/cite.202000029.

Santos, Catarina I.; Silva, Constança C.; Mussatto, Solange I.; Osseweijer, Patricia; van der Wielen, Luuk A.M.; Posada, John A. (2018): Integrated 1st and 2nd generation sugarcane bio-refinery for jet fuel production in Brazil. Techno-economic and greenhouse gas emissions assessment. In: *Renewable Energy* 129 (6), p. 733–747. DOI: 10.1016/j.renene.2017.05.011.

Sarno, Maria; Iuliano, Mariagrazia (2019): Biodiesel production from waste cooking oil. In: *Green Processing and Synthesis* 8 (1), p. 828–836. DOI: 10.1515/gps-2019-0053.

SaubFahrzeugBeschG (2021): Gesetz über die Beschaffung sauberer Straßenfahrzeuge. SaubFahrzeugBeschG from 09.06.2021.

SaubFahrzeugBeschG (2021): Gesetzentwurf über die Beschaffung sauberer Straßenfahrzeuge (Umsetzung der Clean Vehicles Directive). SaubFahrzeugBeschG from 21.01.2021.

Schäfer, Dominik; Janßen, Tomke; Fang, Qingping; Merten, Frank; Blum, Ludger (2021): System-Supporting Operation of Solid-Oxide Electrolysis Stacks. In: *Energies* 14 (3), p. 544. DOI: 10.3390/en14030544.

Scheuermann, Armin (2021): Shell beauftragt Worley mit dem Bau einer Wasserstoff-Elektrolyse. 200-MW-Projekt in den Niederlanden. Published by Chemietechnik. 200-MW-Projekt in den Niederlanden. Available online at https://www.chemietechnik.de/anlagenbau/shell-beauftragt-worley-mit-dem-bau-einer-wasserstoff-elektrolyse-338.html, last updated 08.01.2021, last checked on 02.12.2021.

Schlagermann, Pascal; Göttlicher, Gerold; Dillschneider, Robert; Rosello-Sastre, Rosa; Posten, Clemens (2012): Composition of Algal Oil and Its Potential as Biofuel. In: *Journal of Combustion* 2012 (4571), p. 1–14. DOI: 10.1155/2012/285185.

Schlüter, Michael (2018): Die Niedertemperatursynthese von Methan in Thermoöl-temperierten Plattenreaktoren. Dissertation. [online]. Leipzig: DBFZ (DBFZ-Report, 31). Available online at https://www.dbfz.de/fileadmin/user_upload/Referenzen/DBFZ_Reports/DBFZ_Report_31.pdf.

Schmidt, Patrick; Weindorf, Werner; Roth, Arne; Batteiger, Valentin; Riegel, Florian (2016): Power-to-Liquids: Potentials and Perspectives. Published by German Environment Agency. Available online at https://www.umweltbundesamt.de/en/publikationen/power-to-liquids-potentials-perspectives-for-the, last checked on 03.11.2021.

Schmieder, Lisa; Scheer, Dirk (2021): Regenerative Kraftstoffe im System betrachtet. Zur Rolle von reFuels in Energiesystemanalysen. Published by reFuels. Zur Rolle von reFuels in Energiesystemanalysen. Available online at https://www.researchgate.net/profile/Dirk-Scheer/publication/349139467_reFuels_-Kraftstoffe_neu_denken_wwwrefuelsde_Regenerative_Kraftstoffe_im_System_betrachtet_Zur_Rolle_von_reFuels_in_Energiesystemanalysen_Kontakt/links/602259c8458515893990733e/reFuels-Kraftstoffe-neu-denken-wwwrefuelsde-Regenerative-Kraftstoffe-im-System-betrachtet-Zur-Rolle-von-reFuels-in-Energiesystemanalysen-Kontakt.pdf?_sg%5B0%5D=iBEZQ-h4Js9IiHgmIKWJS5goK6HoPoro4iurZBLzGAzyt230VWDIlvKYW5erNobBpqnqvEHKjl6JzjPQ_zodnw.jM3Sov0uGofAHODJdJw4jcKaDsUNS8GnrsoHXQ0TxWWaRmTyNAI071v3WyTtZIrWYTM1JGWfuF8ezlEulHCehQ&_sg%5B1%5D=EBkCzmHput5wCwjZBPTra2YDTxRYUwzX1pouK0t69VAEMIhiodyl-F1RkO7YuYjNuU9IDj77U4ESsPEoNsja2wBkzik7QJvvTi3gxI2nzqrB.jM3Sov0uGofAHODJdJw4jcKaDsUNS8GnrsoHXQ0TxWWaRmTyNAI071v3WyTtZIrWYTM1JGWfuF8ezlEulHCehQ&_iepl=, last checked on 13.01.2022.

Schmitz, Niklas; Homberg, Fabian; Berje, Jürgen; Burger, Jakob; Hasse, Hans (2015): Chemical Equilibrium of the Synthesis of Poly(oxymethylene) Dimethyl Ethers from Formaldehyde and Methanol in Aqueous Solutions. In: *Ind. Eng. Chem. Res.* 54 (25), p. 6409–6417. DOI: 10.1021/acs.iecr.5b01148.

Schönebein, Michael; Hochhaus, Karl-Heinz (2021): Abwracken. Hochhaus-Schiffsbetriebs. Hochhaus-Schiffsbetriebs. Available online at https://hochhaus-schiffsbetrieb.jimdo.com/abwracken/, last checked on 02.12.2021.

Schröder, Jörg; Dietrich, Maren; Winkler, Markus; Wicht, Richard (2019): Element Contents in Biodiesel. In: *MTZ Worldw* 80 (10), p. 64–68. DOI: 10.1007/s38313-019-0099-8.

Schröder, Jörg; Görsch, Kati (2020a): Storage Stability and Material Compatibility of Poly(oxymethylene) Dimethyl Ether Diesel Fuel. In: *Energy Fuels* 34 (1), p. 450–459. DOI: 10.1021/acs.energyfuels.9b03101.

Schröder, Jörg; Hartmann, Franziska; Eschrich, Robert; Worch, Denis; Böhm, Jürgen; Gläser, Roger; Müller-Langer, Franziska (2017): Accelerated performance and durability test of the exhaust aftertreatment system by contaminated biodiesel. In: *International Journal of Engine Research* 18 (10), p. 1067–1076. DOI: 10.1177/1468087417700762.

Schröder, Jörg; Müller-Langer, Franziska; Aakko-Saksa, Päivi; Winther, Kim; Baumgarten, Wibke; Lindgren, Magnus (2020b): Methanol as Motor Fuel. Summary Report. Summary Report. Available online at https://iea-amf.org/content/publications/project_reports, last updated 08.2020, last checked on 06.07.2021.

Schröder, P.; Beckers, B.; Daniels, S.; Gnädinger, F.; Maestri, E.; Marmiroli, N. et al. (2018): Intensify production, transform biomass to energy and novel goods and protect soils in Europe-A vision how to mobilize marginal lands. In: *The Science of the total environment* 616-617, p. 1101–1123. DOI: 10.1016/j.scitotenv.2017.10.209.

SeaH2Land (2021): SeaH2Land Summary. Published by SeaH2Land. Available online at https://seah2land.nl/en/summary, last checked on 02.12.2021.

Sekab (2021): Biorefinery Demo Plant. Advanced research and development. Advanced research and development. Available online at https://www.sekab.com/en/this-is-how-it-works/biorefinery-demo-plant/, last checked on 27.09.2022.

Shahbaz, Muhammad; AlNouss, Ahmed; Ghiat, Ikhlas; McKay, Gordon; Mackey, Hamish; Elkhalifa, Samar; Al-Ansari, Tareq (2021): A comprehensive review of biomass based thermochemical conversion technologies integrated with CO2 capture and utilisation within BECCS networks. In: *Resources, Conservation and Recycling* 173 (3), p. 105734. DOI: 10.1016/j.resconrec.2021.105734.

Sharafi, Yousef; Majidi, Mohammad Mahdi; Goli, Sayed Amir Hossein; Rashidi, Fatemeh (2014): Oil Content and Fatty Acids Composition in Brassica Species. In: *International Journal of Food Properties* 18 (10), p. 2145–2154. DOI: 10.1080/10942912.2014.968284.

Shell (2016): Shell LNG 3. Safety Data Sheet. Published by Shell. Safety Data Sheet. Available online at https://www.shell.de/business-customers/shell-commercial-fuels/supplier-and-contacts/_jcr_content/par/tabbedcontent_ceef/tab_b10c/textimage_9921.stream/1519807638613/a03492ab2dbc767ef99aaa715df074f098423d8e/lng-gasnor-de-en-180416.pdf, last checked on 06.10.2021.

Shell (2021a): GTL products. Available online at https://www.shell.com.qa/en_qa/energy-and-innovation/gtl-products.html#vanity-aHR0cHM6Ly93d3cuc2hlbGwuY29tLnFhL2VuL3Byb2R1Y3RzLXNlcnZpY2VzL3BlYXJsLmh0bWw, last checked on 02.12.2021.

Shell (2021b): Pearl GTL - Overview. Key facts. Key facts. Available online at https://www.shell.com/about-us/major-projects/pearl-gtl/pearl-gtl-an-overview.html, last checked on 02.12.2021.

Shell (2021c): Shell pledges financial supporte to bio-crude project in Norway. Available online at https://www.shell.com/energy-and-innovation/new-energies/new-energies-media-releases/shell-pledges-financial-support-to-bio-crude-pilot-project-in-norway.html, last updated 25.06.2021, last checked on 02.12.2021.

Sherrard, Alan (2017): HVO100, a biofuel hit for Swedish motorists and hauliers. Published by Bioenergy International. Available online at https://bioenergyinternational.com/markets-finance/hvo100-biofuel-hit-swedish-motorists-hauliers, last updated 2017, last checked on 13.05.2021.

Siemens (2021): A new hydrogen reality: Fuel from wind and water. The next step towards decarbonizing the global transport sector begins in a windy region in the south of Chile. Explore the Haru Oni project. The next step towards decarbonizing the global transport sector begins in a windy region in the south of Chile. Explore the Haru Oni project. Available online at https://www.siemens-energy.com/global/en/offerings/renewable-energy/hydrogen-solutions/haru-oni.html, last checked on 22.06.2021.

Siemens Energy (2021): Haru Oni: A new age of discovery. Published by Siemens Energy. Available online at https://www.siemens-energy.com/global/en/news/magazine/2021/haru-oni.html, last checked on 02.12.2021.

Silva Green Fuel (2017): Demoanlegget. Available online at https://www.silvagreenfuel.no/demoanlegget/, last checked on 22.06.2021.

Silva, Mauro; Rezende Pinho, Andrea de; Huziwara, Wilson Kenzo; Neto, Amîlcar Pereira da Silva; Khalil, Carolos Nagib; Cabral, Júlio Amîlcar Ramos et al. (2020): Catalytic cracking process for production of diesel from seeds of oleaginous plants. Registered through Petroleo Brasileiro SA Petrobras. Registration no: BRPI0702541-6A. Priority data: 21.06.2007.

Smith, Lawrence A.; Arganbright, Robert P. (1990): Process for the production of MTBE. Registered through Chemical Research and Licensing Co at 07.11.1990. Registration no: US60975590A.

Sotelo-Boyás, Rogelio; Liu, Yanyong; Minowa, Tomoaki (2011): Renewable Diesel Production from the Hydrotreating of Rapeseed Oil with Pt/Zeolite and NiMo/Al 2 O 3 Catalysts. In: *Ind. Eng. Chem. Res.* 50 (5), p. 2791–2799. DOI: 10.1021/ie100824d.

Spath, P.; Aden, A.; Eggeman, T.; Ringer, M.; Wallace, B.; Jechura, J. (2005): Biomass to Hydrogen Production Detailed Design and Economics Utilizing the Battelle Columbus Laboratory Indirectly,. Published by NREL. Available online at https://www.nrel.gov/docs/fy05osti/37408.pdf, last checked on 25.11.2021.

Stadt Hamburg (2021): Wasserstoffprojekt Hamburg-Moorburg. Vier Partner unterzeichnen Absichtserklärung über 100 Megawatt Elektrolyse. Published by Stadt Hamburg. Vier Partner unterzeichnen Absichtserklärung über 100 Megawatt Elektrolyse. Available online at https://www.hamburg.de/pressearchiv-fhh/14847126/2021-01-21-bukea-wasserstoffprojekt-am-standort-moorburg/, last updated 22.01.2021, last checked on 03.12.2021.

Starck, Laurie; Pidol, Ludivine; Jeuland, Nicolas; Chapus, Thierry; Bogers, Paul; Bauldreay, Joanna (2016): Production of Hydroprocessed Esters and Fatty Acids (HEFA) – Optimisation of Process Yield. In: *Oil Gas Sci. Technol. – Rev. IFP Energies nouvelles* 71 (1), p. 10. DOI: 10.2516/ogst/2014007.

Steeper Energy (2017): Steeper Energy announces EUR 50,6 M (DKK 377 M) advanced biofuel project with norwegian-swedish joint venture silva green fuel in licensing deal. Available online at https://steeperenergy.com/2017/12/15/steeper-energy-announces-eur-50-6-m-dkk-377-m-advanced-biofuel-project-with-norwegian-swedish-joint-venture-silva-green-fuel-in-licensing-deal/, last updated 15.12.2017, last checked on 03.12.2021.

Stoffels, Felix (2020): Die ältesten Flieger der Lufthansa-Gruppe | aeroTELEGRAPH. Available online at https://www.aerotelegraph.com/das-sind-die-aeltesten-flieger-der-lufthansa-gruppe, last updated 09.04.2020, last checked on 28.05.2021.

Stora Enso (2020): Sunila Mill. Key Facts. Key Facts. Available online at https://www.storaenso.com/en/about-stora-enso/stora-enso-locations/sunila-mill, last checked on 03.12.2021.

SuM4All (2017): Global Mobility Report 2017. Tracking Sector Performance. Published by Sustainable Mobility for All. Tracking Sector Performance. Available online at https://openknowledge.worldbank.org/bitstream/handle/10986/28542/120500.pdf?sequence=6, last checked on 15.06.2021.

Sun, Qiming; Xie, Zaiku; Yu, Jihong (2018): The state-of-the-art synthetic strategies for SAPO-34 zeolite catalysts in methanol-to-olefin conversion. In: *National Science Review* 5 (4), p. 542–558. DOI: 10.1093/nsr/nwx103.

Sunde, Kathrin; Brekke, Andreas; Solberg, Birger (2011): Environmental Impacts and Costs of Hydrotreated Vegetable Oils, Transesterified Lipids and Woody BTL—A Review. In: *Energies* 4 (6), p. 845–877. DOI: 10.3390/en4060845.

sunfire (2020): GrInHy2.0: Sunfire liefert weltweit größten Hochtemperatur-Elektrolyseur an Salzgitter Flachstahl. Available online at https://www.sunfire.de/de/news/detail/sunfire-liefert-weltweit-groessten-hochtemperatur-elektrolyseur-an-salzgitter-flachstahl, last updated 25.08.2020, last checked on 03.12.2021.

Surgenor, Christopher (2021): apan Airlines and ANA operate SAF flights with fuels made from wood chips and microalgae. Available online at https://www.greenairnews.com/?p=1239, last updated 22.06.2021, last checked on 03.11.2021.

Swedish Energy Agency (2008): Swedish Pulp Mill BIorefineries. A vision of future possibilities. A vision of future possibilities. Available online at https://www.osti.gov/etdeweb/servlets/purl/951488, last checked on 03.12.2021.

Taghipour, Alireza; Ramirez, Jerome A.; Brown, Richard J.; Rainey, Thomas J. (2019): A review of fractional distillation to improve hydrothermal liquefaction biocrude characteristics; future outlook and prospects. In: *Renew. Sust. Energ. Rev.* 115, p. 109355.

Terry Marker (2005): Opportunities for Biorenewables in Oil Refineries. Final Technical Report. With collaboration of John Petri, Tom Kalnes, Mike McCall, Dave Mackowiak, Bob Jerosky, Bill Reagan, Lazlo Nemeth, Mark Krawczyk, Stefan Czernik, Doug Elliott, David Shonnard. Published by UOP. Final Technical Report. Illinois/USA. Available online at https://www.osti.gov/servlets/purl/861458, last checked on 03.12.2021.

TFZ (2021): Riesenweizengras (Agropyron elongatum). Available online at https://www.tfz.bayern.de/rohstoffpflanzen/mehrjaehrigekulturen/086025/index.php, last checked on 03.12.2021.

The Maritime Executive (2017): The Global Fleet Revealed. In: *The Maritime Executive* (2017). Available online at https://www.maritime-executive.com/article/the-global-fleet-revealed, last checked on 09.06.2021.

The World Bank (2021): Population. Available online at https://data.worldbank.org/indicator/SP.POP.TOTL, last checked on 06.07.2021.

Thema, M.; Bauer, F.; Sterner, M. (2019): Power-to-Gas. Electrolysis and methanation status review. In: *Renewable and Sustainable Energy Reviews* 112 (7), p. 775–787. DOI: 10.1016/j.rser.2019.06.030.

THGMQWG (2021): Gesetz zur Weiterentwicklung der Treibhausgasminderungs-Quote. THGMQWG from 24.09.2021. In: *BGBl* (Teil I Nr. 69), p. 4458.

ThyssenKrupp (2021): Erstes Projekt für grünen Wasserstoff wird Realität: thyssenkrupp installiert 88 Megawatt-Wasserelektrolyse für Hydro-Québec in Kanada. Available online at https://www.thyssenkrupp.com/de/newsroom/pressemeldungen/pressedetailseite/erstes-projekt-fur-grunen-wasserstoff-wird-realitat--thyssenkrupp-installiert-88-megawatt-wasserelektrolyse-fur-hydro-quebec-in-kanada-93776, last updated 18.01.2021, last checked on 03.12.2021.

Timmerberg, Sebastian; Bullerdiek, Nils; Kaltschmitt, Martin; Gnann, Till; Neumann, Fabian; Wietschel, Martin (2019): Teilstudie „Import von Stromkraftstoffen für den Verkehr – Lkw, Binnen-/Seeschiffe, Flugzeuge. Wissenschaftliche Beratung des BMVI zur Mobilitäts- und Kraftstoffstrategie. Wissenschaftliche Beratung des BMVI zur Mobilitäts- und Kraftstoffstrategie. Hamburg.

Toch, K.; Thybaut, J. W.; Arribas, M. A.; Martínez, A.; Marin, G. B. (2017): Steering linear 1-alkene, propene or gasoline yields in ethene oligomerization via the interplay between nickel and acid sites. In: *Chemical Engineering Science* 173, p. 49–59. DOI: 10.1016/j.ces.2017.07.025.

Tommaso, Giovana; Chen, Wan-Ting; Li, Peng; Schideman, Lance; Zhang, Yuanhui (2015): Chemical characterization and anaerobic biodegradability of hydrothermal liquefaction aqueous products from mixed-culture wastewater algae. In: *Bioresour. Technol.* 178, p. 139–146.

TotalEnergies (2019): Website - Total Starts Up the La Mède Biorefinery. News. News. Available online at https://totalenergies.com/media/news/press-releases/total-starts-la-mede-biorefinery, last updated 03.07.2019, last checked on 03.12.2021.

TotalEnergies (2020): Dieselkraftstoff. Sicherheitsdatenblatt. Published by TotalEnergies. Sicherheitsdatenblatt. Available online at https://services.totalenergies.de/sites/g/files/wompnd2336/f/atoms/files/sicherheitsdatenblatt_dieselkraftstoff_0.pdf, last checked on 16.10.2021.

Tremel, Alexander; Wasserscheid, Peter; Baldauf, Manfred; Hammer, Thomas (2015): Techno-economic analysis for the synthesis of liquid and gaseous fuels based on hydrogen production via electrolysis. In: *International Journal of Hydrogen Energy* 40 (35), p. 11457–11464. DOI: 10.1016/j.ijhydene.2015.01.097.

Tretbar, Maik; Witzel, Thomsen; Hauffe, Anika; Junghans, Ulrike; Bulc, Aleš; Pufky-Heinrich, Daniela (2018): Feasibility Study on the Etherification of Fermentative-Produced Isobutylene to Fully Renewable Ethyl Tert-Butyl Ether (ETBE). In: *Catalysts* 8 (11), p. 514. DOI: 10.3390/catal8110514.

Tschöke, Helmut; Marohn, Ralf (Publisher) (2019): 11. Tagung Einspritzung und Kraftstoffe 2018. Diesel · Benzin · Gas · Alternative Kraftstoffe · Medien für SCR · Wasser. Diesel · Benzin · Gas · Alternative Kraftstoffe · Medien für SCR · Wasser. Wiesbaden: Springer Fachmedien Wiesbaden (Proceedings). Available online at https://doi.org/10.1007/978-3-658-23181-1.

U.S. Department of Agriculture (2019): Corn, sweet, yellow, raw. Available online at https://fdc.nal.usda.gov/fdc-app.html#/food-details/169998/nutrients, last updated 01.04.2019, last checked on 22.06.2021.

UBA (2016): Power-to-Liquids. Potentials and Perspectives for the Future Supply of Renewable Aviation Fuel. With collaboration of Patrick Schmidt, Werner Weindorf und Arne Roth. Published by Umweltbundesamt. Potentials and Perspectives for the Future Supply of Renewable Aviation Fuel. Available online at https://www.umweltbundesamt.de/sites/default/files/medien/377/publikationen/161005_uba_hintergrund_ptl_barrierrefrei.pdf, last checked on 05.01.2022.

UBA (2020): Weltweiter Autobestand. Published by Umweltbundesamt. Available online at https://www.umweltbundesamt.de/bild/weltweiter-autobestand, last updated 31.05.2021, last checked on 31.05.2021.

UBA (2021a): Berichterstattung unter der Klimarahmenkonvention der Vereinten Nationen und dem Kyoto-Protokoll 2021. Nationaler Inventarbericht zum Deutschen Treibhausgasinventar 1990 – 2019. Umweltbundesamt – UNFCCC-Submission. Published by Umweltbundesamt. Nationaler Inventarbericht zum Deutschen Treibhausgasinventar 1990 – 2019. Dessau-Roßlau. Available online at https://www.umweltbundesamt.de/sites/default/files/medien/5750/publikationen/2021-05-19_cc_43-2021_nir_2021_1.pdf, last checked on 03.12.2021.

UBA (2021b): Emissionsübersichten in den Sektoren des Bundesklimaschutzgesetzes. Published by Umweltbundesamt. Available online at https://www.umweltbundesamt.de/dokument/emissionsuebersichten-in-den-sektoren-des, last updated 15.10.2021, last checked on 15.10.2021.

UBA (2021c): EU-Emissionshandel im Luftverkehr. Published by Umweltbundesamt. Available online at https://www.dehst.de/DE/Europaeischer-Emissionshandel/Luftfahrzeugbetreiber/Emissionshandel/emissionshandel-im-luftverkehr_node.html, last updated 31.05.2021, last checked on 03.12.2021.

UBA (2021d): Renewable energies in figures. Published by Umwelt Bundesamt. Available online at https://www.umweltbundesamt.de/en/topics/climate-energy/renewable-energies/renewable-energies-in-figures, last updated 04.03.2021, last checked on 03.12.2021.

Uddin, Md Mosleh; Simson, Amanda; Wright, Mark Mba (2020): Techno-economic and greenhouse gas emission analysis of dimethyl ether production via the bi-reforming pathway for transportation fuel. In: *Energy* 211, p. 119031. DOI: 10.1016/j.energy.2020.119031.

UERV (2018): Verordnung zur Anrechnung von Upstream-Emissionsminderungen auf die Treibhausgasquote. UERV from 22.01.2018. In: *BGBl* (Heft I Nr. 5), p. 169.

UFOP (2006): Bericht 2005/2006. Published by Union zur Förderung von Oel- und Proteinpflanzen e.V. Berlin. Available online at https://www.ufop.de/files/5013/3935/7008/UFOP_Bericht_06.pdf, last checked on 03.12.2021.

UFOP (2009): Bericht 2008/2009. Published by Union zur Förderung von Oel- und Proteinpflanzen e.V. Berlin. Available online at https://www.ufop.de/files/1213/3935/7068/UFOP_GB_2008_09_WEB.pdf, last checked on 03.12.2021.

UFOP (2018): Biodiesel 2017/2018. Assessment report and outlook – Excerpt from the UFOP annual report. Published by Union zur Förderung von Oel- und Proteinpflanzen e.V. Assessment report and outlook – Excerpt from the UFOP annual report. Available online at https://www.ufop.de/files/5315/3994/5756/WEB_UFOP_1605_Biodieselauszug_EN_191018.pdf, last checked on 03.12.2021.

UFOP (2021): Biodiesel & Co. 2020/2021. Sachstandsbericht und Perspektive – Auaszug aus dem UFOP-Jahresbericht. Published by Union zur Förderung von Oel- und Proteinpflanzen e.V. Sachstandsbericht und Perspektive – Auaszug aus dem UFOP-Jahresbericht. Berlin. Available online at https://www.ufop.de/files/4016/3394/3275/DE_UFOP_1795_GB_Biodieselauszug_2021_111021.pdf, last checked on 13.10.2021.

Ulfah, M.; Firdaus; Octavia, S.; Suherman, H.; Subagjo (2019): Biodiesel Production Through Waste Cooking Oil (WCO) Esterification Using Sulfated Alumina as Catalyst. In: *IOP Conf. Ser.: Mater. Sci. Eng.* 543, p. 12007. DOI: 10.1088/1757-899X/543/1/012007.

UNECE (2021): European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterways. ADN. ADN. Available online at https://unece.org/about-adn, last updated 20.05.2021, last checked on 03.12.2021.

UNFCCC (2021a): The Paris Agreement. Available online at https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement, last updated 20.05.2021, last checked on 03.12.2021.

UNFCCC (2021b): United Nations Framework Convention on Climate Change. Available online at https://unfccc.int/process-and-meetings/the-convention/what-is-the-united-nations-framework-convention-on-climate-change, last updated 20.05.2021, last checked on 03.12.2021.

UNICA (2020): Licenciamento anual de autoveículos novos no Brasil (ciclo Otto) por tipo de combustível. União da Indústria de Cana-de-Açúcar. União da Indústria de Cana-de-Açúcar. Available online at https://www.unicadata.com.br/listagem.php?idMn=54, last checked on 29.10.2021.

United Nations (2016): 7. d Paris Agreement. Available online at https://treaties.un.org/Pages/ViewDetails.aspx?src=IND&mtdsg_no=XXVII-7-d&chapter=27&clang=_en, last updated 20.05.2021, last checked on 03.12.2021.

UPEI (2021): Compatibility of retail station infrastructure with higher biofuel blends. UPEI Guidance document. Published by UPEI. UPEI Guidance document. Available online at https://www.upei.org/library/download/1361/1066/17?method=view, last checked on 07.01.2022.

UPM (2021): Producing advanced biofuels. Available online at https://www.upmbiofuels.com/about-upm-biofuels/production/, last checked on 28.10.2021.

UPM Biofuels (2022): UPM Lappeenranta Biorefinery. Available online at https://www.upmbiofuels.com/about-upm-biofuels/production/upm-lappeenranta-biorefinery/, last updated 2022, last checked on 13.01.2022.

USDA (2013): Biofuels Annual: EU Biofuels Annual 2013. With collaboration of Bob Flach, Karin Bendz, Roswitha Krautgartner und Sabine Lieberz. Published by USDA Foreign Agricultural Service (GAIN Report, NL3034). Available online at https://apps.fas.usda.gov/newgainapi/api/report/downloadreportbyfilename?filename=Biofuels%20Annual_The%20Hague_EU-27_8-13-2013.pdf, last checked on 04.08.2021.

USDA (2016): Biofuels Annual: EU Biofuels Annual 2016. With collaboration of Bob Flach, Sabine Lieberz, Marcela Rondon, Barry Williams und Candice Wilson. Published by USDA Foreign Agricultural Service (GAIN Report, NL6021). Available online at https://apps.fas.usda.gov/newgainapi/api/report/downloadreportbyfilename?filename=Biofuels%20Annual_The%20Hague_EU-28_6-29-2016.pdf, last checked on 04.08.2021.

USDA (2018): Biofuels Annual: EU Biofuels Annual 2018. With collaboration of Bob Flach, Sabine Lieberz, Jennifer Lappin und Sophie Bolla. Published by USDA Foreign Agricultural Service (GAIN Report). Available online at https://apps.fas.usda.gov/newgainapi/api/report/downloadreportbyfilename?filename=Biofuels%20Annual_The%20Hague_EU-28_7-3-2018.pdf, last checked on 04.08.2021.

USDA (2020): Biofuels Annual: EU Biofuels Annual 2020. With collaboration of Bob Flach, Sabine Lieberz und Sophie Bolla. Published by USDA Foreign Agricultural Service (GAIN Report). Available online at https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=Biofuels%20Annual_The%20Hague_European%20Union_06-29-2020, last checked on 04.08.2021.

USDA (2021): Oilseeds: World Markets and Trade. India Implements Further Cuts to Palm Oil Duties. India Implements Further Cuts to Palm Oil Duties. Available online at https://apps.fas.usda.gov/psdonline/circulars/oilseeds.pdf, last checked on 03.12.2021.

USDA Foreign Agricultural Service (2011): 2nd Generation Biofuel Company Declares Insolvency. Available online at https://apps.fas.usda.gov/newgainapi/api/report/downloadreportbyfilename?filename=2nd%20Generation%20Biofuel%20Company%20Declares%20Insolvency_Berlin_Germany_07-13-2011.pdf, last checked on 25.06.2021.

USDA Foreign Agricultural Service; GAIN (2021): Biofuel Mandates in theEU by Member State and United Kingdom -2021. With collaboration of Sabine Lieberz und Kirsten Luxebacher. Berlin. Available online at https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=Biofuel%20Mandates%20in%20the%20EU%20by%20Member%20State%20and%20United%20Kingdom%20-%202021_Berlin_European%20Union_06-06-2021.pdf, last checked on 03.12.2021.

Uslu, Samet; Celik, M. Bahattin (2020): Combustion and emission characteristics of isoamyl alcohol-gasoline blends in spark ignition engine. In: *Fuel* 262 (5), p. 116496. DOI: 10.1016/j.fuel.2019.116496.

Vakkilainen, Esa; Välimäki, Erkki (2009): Effect of Lignin Separation to Black Liquor and Recovery Boiler Operation.

Valente, Antonio; Iribarren, Diego; Gálvez-Martos, José-Luis; Dufour, Javier (2019): Robust eco-efficiency assessment of hydrogen from biomass gasification as an alternative to conventional hydrogen. A life-cycle study with and without external costs. In: *The Science of the total environment* 650 (Pt 1), p. 1465–1475. DOI: 10.1016/j.scitotenv.2018.09.089.

Valmet (2020): First LignoBoost plants producing large volumes of kraft lignin to the market place. Available online at https://www.valmet.com/media/articles/up-and-running/new-technology/PEERS1stLignoBoostPlants/, last checked on 03.12.2021.

van der Drift, A.; Boerrigter, H. (2006): Synthesis Gas from Biomass for fuels and chemicals. Available online at http://www.ieatask33.org/app/webroot/files/file/publications/syngasFromBiomassvanderDrift.pdf, last checked on 03.12.2021.

van Dyk, Susan; Saddler, Jack (2021): Progress in Commercialization of Biojet/Sustainable Aviation Fuels (SAF). Technologies, potential and challenges. Published by IEA Bioenergy: Task 39. Technologies, potential and challenges. Available online at http://task39.sites.olt.ubc.ca/files/2021/08/Task-39-Progress-in-the-commercialisation-of-biojet-fuels-FINAL-August-2021.pdf, last checked on 27.10.2021.

van Dyk, Susan; Su, Jianping; Mcmillan, James D.; Saddler, Jack (2018): Potential synergies of drop-in biofuel production with further co-processing at oil refineries. In: *Biofuels, Bioprod. Bioref.* 13 (3), p. 760–775. DOI: 10.1002/bbb.1974.

van Dyk, Susan; Su, Jianping; Mcmillan, James D.; Saddler, Jack N. (2019): 'DROP-IN' BIOFUELS: The key role that co-processing will play in its production. Available online at https://www.ieabioenergy.com/wp-content/uploads/2019/09/Task-39-Drop-in-Biofuels-Full-Report-January-2019.pdf, last updated 01.2019, last checked on 03.12.2021.

Varone, Alberto; Ferrari, Michele (2015): Power to liquid and power to gas. An option for the German Energiewende. In: *Renewable and Sustainable Energy Reviews* 45, p. 207–218. DOI: 10.1016/j.rser.2015.01.049.

VCI Online (2021): REACH-Revision. Available online at https://www.vci.de/themen/chemikaliensicherheit/reach/vci-position-zur-reach-revision.jsp, last updated 26.08.2021, last checked on 26.08.2021.

Veipa, Agate; Kirsanovs, Vladimirs; Barisa, Aiga (2020): Techno-Economic Analysis of Biofuel Production Plants Producing Biofuels Using Fisher Tropsch Synthesis. In: *Environmental and Climate Technologies* 24 (2), p. 373–387. DOI: 10.2478/rtuect-2020-0080.

Velocys (2021a): Altalto. Available online at https://www.velocys.com/projects/altalto/, last checked on 03.12.2021.

Velocys (2021b): Bayou Fuels. Available online at https://www.velocys.com/projects/bayou-fuels/, last checked on 03.12.2021.

VERBIO Schwedt GmbH (2021): VERBIO Bioethanol-Standort. Available online at https://www.verbio.de/unternehmen/konzernstruktur/verbio-schwedt-gmbh/, last updated 15.10.2021, last checked on 03.12.2021.

Verordnung (EG) Nr. 1907/2006 (01.10.2021): Konsolidierter Text: Verordnung (EG) Nr. 1907/2006 des Europäischen Parlaments und des Rates vom 18. Dezember 2006 zur Registrierung, Bewertung, Zulassung und Beschränkung chemischer Stoffe (REACH), zur Schaffung einer Europäischen Chemikalienagentur, zur Änderung der Richtlinie 1999/45/EG und zur Aufhebung der Verordnung (EWG) Nr. 793/93 des Rates, der Verordnung (EG) Nr. 1488/94 der Kommission, der Richtlinie 76/769/EWG des Rates sowie der Richtlinien 91/155/EWG, 93/67/EWG, 93/105/EG und 2000/21/EG der Kommission. Verordnung (EG) Nr. 1907/2006.

Verordnung (EU) 167/2013 (05.02.2013): Verordnung (EU) Nr. 167/2013 des Europäischen Parlaments und des Rates vom 5. Februar 2013 über die Genehmigung und Marktüberwachung von land- und forstwirtschaftlichen Fahrzeugen Text von Bedeutung für den EWR. Verordnung (EU) 167/2013 from 18.04.2019. In: *Amtsblatt der Europäischen Union* 56 (L 60), p. 1–51.

Verordnung (EU) 168/2013 (15.01.2013): Verordnung (EU) Nr. 168/2013 des Europäischen Parlaments und des Rates vom 15. Januar 2013 über die Genehmigung und Marktüberwachung von zwei- oder dreirädrigen und vierrädrigen Fahrzeugen Text von Bedeutung für den EWR. Verordnung (EU) 168/2013 from 14.11.2020. In: *Amtsblatt der Europäischen Union* 56 (L60), p. 52–128.

Verordnung (EU) 2016/1628 (14.09.2014): Verordung (EU) 2016/162 über die Anforderungen in Bezug auf die Emissionsgrenzwerte für gasförmige Schadstoffe und luftverunreinigende Partikel und die Typgenehmigung für Verbrennungsmotoren für nicht für den Straßenverkehr bestimmte mobile Maschinen und Geräte, zur Änderung der Verordnungen (EU) Nr. 1024/2012 und (EU) Nr. 167/2013 und zur Änderung und Aufhebung der Richtlinie 97/68/EG. Verordnung (EU) 2016/1628 from 30.06.2021. In: *Amtsblatt der Europäischen Union* 59 (L 252), p. 53–117.

Verordnung (EU) 2016/1718 (2016): Verordnung (EU) 2016/1718 zur Änderung der Verordnung (EU) Nr. 582/2011 hinsichtlich der Emissionen von schweren Nutzfahrzeugen in Bezug auf die Bestimmungen über Prüfungen mit portablen Emissionsmesssystemen (PEMS) und das Verfahren zur Prüfung der Dauerhaltbarkeit von emissionsmindernden Einrichtungen für den Austausch (Text von Bedeutung für den EWR). Verordnung (EU) 2016/1718 from 20.09.2016. In: *Amtsblatt der Europäischen Union* 59 (L 259), p. 1–41.

Verordnung (EU) 2017/655 (19.12.2016): Delegierte Verordnung (EU) 2017/655 zur Ergänzung der Verordnung (EU) 2016/1628 des Europäischen Parlaments und des Rates im Hinblick auf die Überwachung der Emissionen gasförmiger Schadstoffe von in Betrieb befindlichen Verbrennungsmotoren in nicht für den Straßenverkehr bestimmten mobilen Maschinen und Geräten. Verordnung (EU) 2017/655 from 07.08.2018. In: *Amtsblatt der Europäischen Union* 60 (L 102), p. 334–363.

Verordnung (EU) 2018/842 (19.06.2018): Verordnung (EU) 2018/842 des Europäischen Parlaments und des Rates vom 30. Mai 2018 zur Festlegung verbindlicher nationaler Jahresziele für die Reduzierung der Treibhausgasemissionen im Zeitraum 2021 bis 2030 als Beitrag zu Klimaschutzmaßnahmen zwecks Erfüllung der Verpflichtungen aus dem Übereinkommen von Paris sowie zur Änderung der Verordnung (EU) Nr. 525/2013. Verordnung (EU) 2018/842 from 19.06.2018. In: *Amtsblatt der Europäischen Union* 61 (L 156), p. 26–42.

Verordnung (EU) 2018/842 (30.05.2018): Verordnung (EU) 2018/842 des Europäischen Parlaments und des Rates vom 30. Mai 2018 zur Festlegung verbindlicher nationaler Jahresziele für die Reduzierung der Treibhausgasemissionen im Zeitraum 2021 bis 2030 als Beitrag zu Klimaschutzmaßnahmen zwecks Erfüllung der Verpflichtungen aus dem Übereinkommen von Paris sowie zur Änderung der Verordnung (EU) Nr. 525/2013 (Text von Bedeutung für den EWR). Verordnung (EU) 2018/842 from 19.06.2018. In: *Amtsblatt der Europäischen Union* 61 (L156), p. 26–42.

Verordnung (EU) 2018/858 (30.05.2018): Verordnung (EU) 2018/858 des Europäischen Parlaments und des Rates vom 30. Mai 2018 über die Genehmigung und die Marktüberwachung von Kraftfahrzeugen und Kraftfahrzeuganhängern sowie von Systemen, Bauteilen und selbstständigen technischen Einheiten für diese Fahrzeuge, zur Änderung der Verordnungen (EG) Nr. 715/2007 und (EG) Nr. 595/2009 und zur Aufhebung der Richtlinie 2007/46/EG (Text von Bedeutung für den EWR.). Verordnung (EU) 2018/858 from 26.09.2021. In: *Amtsblatt der Europäischen Union* 61 (L151), p. 1–218.

Verordnung (EU) 490/2013 (2013): Verordnung (EU) Nr. 490/2013 der Kommission vom 27. Mai 2013 zur Einführung eines vorläufigen Antidumpingzolls auf die Einfuhren von Biodiesel mit Ursprung in Argentinien und Indonesien. Verordnung (EU) 490/2013. In: *Amtsblatt der Europäischen Union* (L 141), p. 6.

Verordnung (EU) 64/2012 (23.01.2012): Verordnung (EU) Nr. 64/2012 der Kommission vom 23. Januar 2012 zur Änderung der Verordnung (EU) Nr. 582/2011 zur Durchführung und Änderung der Verordnung (EG) Nr. 595/2009 des Europäischen Parlaments und des Rates hinsichtlich der Emissionen von schweren Nutzfahrzeugen (Euro VI). Verordnung (EU) 64/2012 from 31.01.2012. In: *Amtsblatt der Europäischen Union* 55 (L 28), p. 1–23.

Verordnung (EU) Nr. 582/2011 (25.05.2011): Verordnung (EU) Nr. 582/2011 der Kommission vom 25. Mai 2011 zur Durchführung und Änderung der Verordnung (EG) Nr. 595/2009 des Europäischen Parlaments und des Rates hinsichtlich der Emissionen von schweren Nutzfahrzeugen (Euro VI) und zur Änderung der Anhänge I und III der Richtlinie 2007/46/EG des Europäischen Parlaments und des Rates. Verordnung (EU) Nr. 582/2011 from 01.01.2021.

Viebahn, P.; Horst, J.; Scholz, A.M Zelt, O. (2018): Technologiebericht 4.4 Verfahren der CO2-Abtrennung aus Faulgasen und Umgebungsluft. Technologien für die Energiewende. Teilbericht 2 an das Bundesministerium für Wirtschaft und Energie (BMWi). Teilbericht 2 an das Bundesministerium für Wirtschaft und Energie (BMWi). Available online at https://epub.wupperinst.org/frontdoor/deliver/index/docId/7062/file/7062_CO2-Abtrennung.pdf, last checked on 03.12.2021.

Viebahn, Peter; Scholz, Alexander; Zelt, Ole (2019): The Potential Role of Direct Air Capture in the German Energy Research Program—Results of a Multi-Dimensional Analysis. In: *Energies* 12 (18), p. 3443. DOI: 10.3390/en12183443.

Walker, Graeme; Stewart, Graham (2016): Saccharomyces cerevisiae in the Production of Fermented Beverages. In: *Beverages* 2 (4), p. 30. DOI: 10.3390/beverages2040030.

Wan Isahak, Wan Nor Roslam; Che Ramli, Zatil Amali; Ismail, Manal; Mohd Jahim, Jamaliah; Yarmo, Mohd Ambar (2014): Recovery and Purification of Crude Glycerol from Vegetable Oil Transesterification. In: *Separation & Purification Reviews* 44 (3), p. 250–267. DOI: 10.1080/15422119.2013.851696.

Wang, Lei; Quiceno, Raul; Price, Catherine; Malpas, Rick; Woods, Jeremy (2014): Economic and GHG emissions analyses for sugarcane ethanol in Brazil. Looking forward. In: *Renewable and Sustainable Energy Reviews* 40, p. 571–582. DOI: 10.1016/j.rser.2014.07.212.

Wang, Wei-Cheng; Tao, Ling; Markham, Jennifer; Zhang, Yanan; Tan, Eric; Batan, Liaw et al. (2016): Review of Biojet Fuel Conversion Technologies. Published by NREL. Available online at https://www.nrel.gov/docs/fy16osti/66291.pdf, last checked on 25.11.2021.

Warnqvist, Jan; Släger, Johan Olsson; Eliasson, Anders (2015): Process for removal of sulphur from raw methanol. Publication no: US10160706B2. Priority data: 11.10.2013.

Wassermann, Timo; Schnuelle, Christian; Kenkel, Philipp; Zondervan, Edwin (2020): Power-to-Methanol at Refineries as a Precursor to Green Jet Fuel Production. A Simulation and Assessment Study 48, p. 1453–1458. DOI: 10.1016/B978-0-12-823377-1.50243-3.

Ways2H (2020): Website. Our process and products. Our process and products. Available online at https://ways2h.com/about-us/, last checked on 03.12.2021.

WEF (2021): Guidelines for a Sustainable Aviation Fuel Blending Mandate in Europe. Insight report. Published by World Economic Forum. Insight report. Available online at https://www3.weforum.org/docs/WEF_CST_EU_Policy_2021.pdf, last checked on 16.01.2022.

Wernet, Gregor; Bauer, Christian; Steubing, Bernhard; Reinhard, Jürgen; Moreno-Ruiz, Emilia; Weidema, Bo (2016): The ecoinvent database version 3 (part I). Overview and methodology. In: *Int J Life Cycle Assess* 21 (9), p. 1218–1230. DOI: 10.1007/s11367-016-1087-8.

Wess, Johannes; Brinek, Martin; Boles, Eckhard (2019): Improving isobutanol production with the yeast Saccharomyces cerevisiae by successively blocking competing metabolic pathways as well as ethanol and glycerol formation. In: *Biotechnol Biofuels* 12, p. 173. DOI: 10.1186/s13068-019-1486-8.

WHG from 18.08.2021 (2021): Gesetz zur Ordnung des Wasserhaushalts (Wasserhaushaltsgesetz - WHG). In: *Bundesgesetzblatt* 2020.

WHO (2021): WHO global air quality guidelines. Particulate matter (PM2.5 and PM10), oone, nitrogen dioxide, sulfur dioxide and carbon monoxide. Published by World Health Organization (WHO). Particulate matter (PM2.5 and PM10), oone, nitrogen dioxide, sulfur dioxide and carbon monoxide. Available online at https://apps.who.int/iris/bitstream/handle/10665/345329/9789240034228-eng.pdf, last checked on 03.12.2021.

Wijeyekoon, Suren; Torr, Kirk; Corkran, Hilary; Bennett, Paul (2020): Commercial status of direct thermochemical liquefaction technologies. Published by IEA Bioenergy. Available online at https://www.ieabioenergy.com/wp-content/uploads/2020/09/Direct-Thermochemical-Liquefaction_Commercialization_Overview.pdf, last checked on 19.10.2021.

Williams (2021): Raizen will provide biomethane for yara ammonia production. Available online at http://williams.com.br/raizen-will-provide-biomethane-for-yara-ammonia-production/, last checked on 03.12.2021.

Wissenschaftliche Dienste Deutscher Bundestag (2020): Energiespeicher der Elektromobilität. Entwicklung der Energiedichten. Published by Deutscher Bundestag. Entwicklung der Energiedichten (Sachstand, WD 8 - 3000 - 090/20). Available online at https://www.bundestag.de/resource/blob/819220/31128d3d32638f43627fa8a99bd3cb83/WD-8-090-20-pdf-data.pdf, last checked on 22.09.2021.

Witte, Julika (Publisher) (2019): Biomasse im Spannungsfeld zwischen Energie- und Klimapolitik. Strategien für eine nachhaltige Bioenergienutzung. Strategien für eine nachhaltige Bioenergienutzung. München, Halle (Saale), Mainz: acatech - Deutsche Akademie der Technikwissenschaften; Deutsche Akademie der Naturforscher Leopoldina e.V. - Nationale Akademie der Wissenschaften; Union der Deutschen Akademien der Wissenschaften e.V (Stellungnahme). Available online at http://nbn-resolving.org/urn:nbn:de:gbv:3:2-105631.

WKO (2021): Tankstellendichte in Europa. Dichtes Versorgungsnetz für Mobilität. Published by Wirtschaftskammer Österreich. Dichtes Versorgungsnetz für Mobilität. Available online at https://newsletter.wko.at/WKO%20FV%20Mineraloelindustrie/Tankstellendichte-in-Europa-Dichtes-Versorgungsnetz-fuer-Mobilitaet-.aspx?sub=2356bed7-f175-4779-9e21-29079f264586&cmp=3dcc2c59-0927-412f-a9d2-2ccdbf2f57fb&chk=a33992f3-c33c-4fa1-a3f5-5e26aeba7117&clt=ea6ba666-2863-4be8-97f7-98c4b85172d6&tid=0-fiswK-2jxVIM, last updated 22.06.2021, last checked on 03.12.2021.

Wolf, Andreas; Jess, Andreas; Kern, Christoph (2016): Syngas Production via Reverse Water-Gas Shift Reaction over a Ni-Al 2 O 3 Catalyst. Catalyst Stability, Reaction Kinetics, and Modeling. In: *Chem. Eng. Technol.* 39 (6), p. 1040–1048. DOI: 10.1002/ceat.201500548.

Wright, Madison (2020): Examples of ground transport biofuel mandates around the world. Fact Sheet 6. Published by IATA. Fact Sheet 6. Available online at https://www.iata.org/contentassets/d13875e9ed784f75bac90f000760e998/biofuel-mandates_fact-sheet6-biofuel.pdf, last checked on 13.05.2021.

Wulf, Christina; Zapp, Petra; Schreiber, Andrea (2020): Review of Power-to-X Demonstration Projects in Europe. In: *Front. Energy Res.* 8, p. 227. DOI: 10.3389/fenrg.2020.00191.

Yan, Yongliang; Manovic, Vasilije; Anthony, Edward J.; Clough, Peter T. (2020): Techno-economic analysis of low-carbon hydrogen production by sorption enhanced steam methane reforming (SE-SMR) processes. In: *Energy Conversion and Management* 226, p. 113530. DOI: 10.1016/j.enconman.2020.113530.

Yao, Jingang; Kraussler, Michael; Benedikt, Florian; Hofbauer, Hermann (2017): Techno-economic assessment of hydrogen production based on dual fluidized bed biomass steam gasification, biogas steam reforming, and alkaline water electrolysis processes. In: *Energy Conversion and Management* 145 (Supplement 1), p. 278–292. DOI: 10.1016/j.enconman.2017.04.084.

Yao, Pin; You, Shengping; Qi, Wei; Su, Rongxin; He, Zhimin (2020): Investigation of fermentation conditions of biodiesel by-products for high production of β-farnesene by an engineered Escherichia coli. In: *Environmental science and pollution research international* 27 (18), p. 22758–22769. DOI: 10.1007/s11356-020-08893-z.

Yara (2021): Yara anuncia aquisição de biometano e dá primeiro passo para a produção de amônia verde no Brasil. Available online at https://www.yarabrasil.com.br/noticias-e-eventos/press-releases/biometano/, last updated 21.09.2021, last checked on 03.12.2021.

Yates, Jonathon; Daiyan, Rahman; Patterson, Robert; Egan, Renate; Amal, Rose; Ho-Baille, Anita; Chang, Nathan L. (2020): Techno-economic Analysis of Hydrogen Electrolysis from Off-Grid Stand-Alone Photovoltaics Incorporating Uncertainty Analysis. In: *Cell Reports Physical Science* 1 (10), p. 100209. DOI: 10.1016/j.xcrp.2020.100209.

Zech, Konstantin M.; Meisel, Kathleen; Brosowski, André; Toft, Lars Villadsgaard; Müller-Langer, Franziska (2016): Environmental and economic assessment of the Inbicon lignocellulosic ethanol technology. In: *Applied Energy* 171, p. 347–356. DOI: 10.1016/j.apenergy.2016.03.057.

Zech, Konstantin M.; Schneider, Uwe A. (2019): Technical biofuel production and GHG mitigation potentials through healthy diets in the EU. In: *Agricultural Systems* 168 (5), p. 27–35. DOI: 10.1016/j.agsy.2018.10.004.

Zech, Konstantin; Oehmichen, Katja; Grasemann, Elias; Michaelis, Julia; Funke, Simon; Seiffert, Michael (2015): Technical, economic and environmental assessment of technologies for the production of biohydrogen and its distribution. In: *International Journal of Hydrogen Energy* 40 (15), p. 5487–5495. DOI: 10.1016/j.ijhydene.2015.01.177.

Zhang, Peng; Su, Xin; Yi, Chengshan; Chen, Hao; Xu, Hongming; Geng, Limin (2020): Spray, atomization and combustion characteristics of oxygenated fuels in a constant volume bomb. A review. In: *Journal of Traffic and Transportation Engineering (English Edition)* 7 (3), p. 282–297. DOI: 10.1016/j.jtte.2020.05.001.

Zhao, Xianhui; Joseph, Babu; Kuhn, John; Ozcan, Soydan (2020): Biogas Reforming to Syngas. A Review. In: *iScience* 23 (5), p. 101082. DOI: 10.1016/j.isci.2020.101082.

Zheng, Lei; Chen, Jingang; Zhao, Mingyue; Cheng, Shikun; Wang, Li-Pang; Mang, Heinz-Peter; Li, Zifu (2020): What Could China Give to and Take from Other Countries in Terms of the Development of the Biogas Industry? In: *Sustainability* 12 (4), p. 1490. DOI: 10.3390/su12041490.

Zheng, Yun; Wang, Jianchen; Yu, Bo; Zhang, Wenqiang; Chen, Jing; Qiao, Jinli; Zhang, Jiujun (2017): A review of high temperature co-electrolysis of H2O and CO2 to produce sustainable fuels using solid oxide electrolysis cells (SOECs). Advanced materials and technology. In: *Chemical Society reviews* 46 (5), p. 1427–1463. DOI: 10.1039/c6cs00403b.

Zhou, Chen; Wang, Nanyi; Qian, Yanan; Liu, Xiaoxing; Caro, Jürgen; Huang, Aisheng (2016): Effiziente Synthese von Dimethylether aus Methanol in einem Membranreaktor mit bifunktioneller Membran. In: *Angew. Chem.* 128 (41), p. 12869–12873. DOI: 10.1002/ange.201604753.

Zitscher, Tjerk; Neuling, Ulf; Habersetzer, Antoine; Kaltschmitt, Martin (2020): Analysis of the German Industry to Determine the Resource Potential of CO2 Emissions for PtX Applications in 2017 and 2050. In: *Resources* 9 (12), p. 149. DOI: 10.3390/resources9120149.

Zoll (2020): Vorläufige Statistische Angaben über die Erfüllung der Treibhausgasquote - Quotenjahr 2019. Published by Generalzolldirektion. Available online at https://www.zoll.de/SharedDocs/Downloads/DE/Links-fuer-Inhaltseiten/Fachthemen/Verbrauchsteuern/quotenerfuellung_2019.pdf, last updated 01.11.2020, last checked on 20.01.2021.

Zoll (2021): Vorläufige Statistische Angaben über die Erfüllung der fortschrittlichen Quote - Quotenjahr 2020*. Published by Generalzolldirektion, last checked on 13.01.2021.

ZVEI (2013): Spannungsklassen in der Elektromobilität. Published by ZVEI - Zentralverband Elektrotechnikund Elektronikindustrie e.V. Available online at https://www.zvei.org/fileadmin/user_upload/Presse_und_Medien/Publikationen/2014/januar/Spannungsklassen_in_der_Elektromobilitaet/Spannungsklassen-Elektromobilitaet.pdf, last checked on 14.07.2021.

Appendix

GABRIEL COSTA DE PAIVA, KARIN NAUMANN, JÖRG SCHRÖDER AND NIELS DÖGNITZ

The following appendix contains supplementary data and explanations on individual aspects from the previous sections.

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A-1: Conversion table for energy units

Table A-1 Conversion table for energy units

Energy unit	Megajoule (MJ)	Kilowatt hour (kWh)	Petajoule (PJ)	Megaton of oil equivalent (Mtoe)
Megajoule (MJ)	1	0.2778	0.000000001	2.39E-11
Kilowatt hour (kWh)	3.6	1	0.0000000036	8.6E-11
Petajoule (TJ)	1,000,000,000	277,777,778	1	0.0239
Megaton of oil equivalent (Mtoe)	41,868,000,000	11,630,000,000	41.868	1

A-2: Conversion table for lower heating values of selected energy carriers

Table A-2 Conversion table for lower heating values of selected energy carriers

Type of fuel	BImSchG [DV THG-Quote (2016)]	RED II [Richtlinie (EU) 2018/2001 (2018)]
Ethanol	21 MJ/l	21 MJ/l or 27 MJ/kg
Ethyl tert-butyl ether	27 MJ/l	27 MJ/l or 36 MJ/kg
Methanol	16 MJ/l	16 MJ/l or 20 MJ/kg
Methyl tert-butyl ether	26 MJ/l	26 MJ/l or 35 MJ/kg
Dimethyl ether	19 MJ/l	19 MJ/l or 28 MJ/kg
tert-Amyl ethyl ether	29 MJ/l	29 MJ/l or 38 MJ/kg
Butanol	27 MJ/l	27 MJ/l or 33 MJ/kg
Fatty acid methyl ester	33 MJ/l	33 MJ/l or 37 MJ/kg
Fischer-Tropsch diesel	34 MJ/l	34 MJ/l or 44 MJ/kg
Fischer-Tropsch naphtha		33 MJ/l or 44 MJ/kg
Fischer-Tropsch kerosene		33 MJ/l or 44 MJ/kg
HVO diesel	34 MJ/l	34 MJ/l or 44 MJ/kg
HVO naphtha		30 MJ/l or 45 MJ/kg
HEFA-SPK		34 MJ/l or 44 MJ/kg
Vegetable oil	34 MJ/l	34 MJ/l or 37 MJ/kg
Biomethane	50 MJ/kg	50 MJ/kg
Liquified petroleum gas (LPG)		24 MJ/l or 46 MJ/kg
Fossil gasoline	32 MJ/l	32 MJ/l or 43 MJ/kg
Fossil diesel	36 MJ/kg	36 MJ/l or 43 MJ/kg
Hydrogen		120 MJ/kg

A-3: Global production of selected forms of biomass

The selection of crops suitable for cultivation depends on numerous factors and therefore varies greatly from region to region. Figure A-1 shows the distribution (by mass and continent) of the primary crops. Soy bean is mainly produced in the Americas (87 %; 57 % of which is produced in South America and 43 % in North America). Corn is mainly produced in America (49 %) and Asia (32 %). Europe leads in the production of sugar beets (67 %) and rape seed (34 %). Sugar cane and oil seed crops are mainly produced in the Americas (53 % and 37 %, respectively) and Asia (41 % and 48 %, respectively). Oceania and Africa produce less than 10 % of all the crops mentioned. [FAO (2021)]

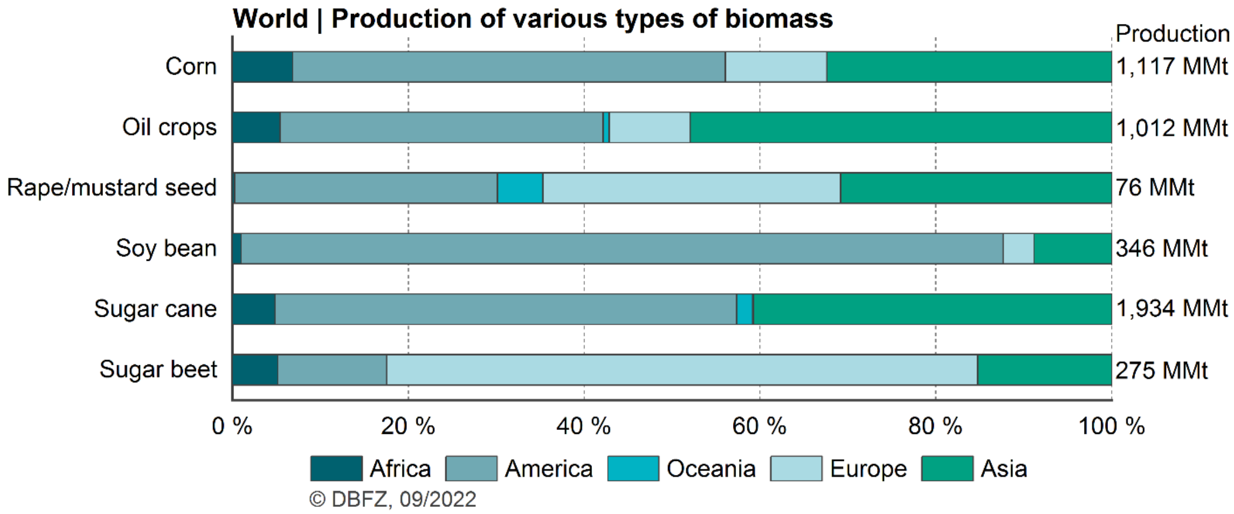

Figure A-1 Percentage of the production of various types of biomass, broken down by continent. Data based on [FAO (2021)]

A-4: Origin of the feedstocks for the biofuels used in Germany

Figure A-2 illustrates the origin of the biomass (energy-related) used to produce the biofuels that were used in Germany in 2020. Most of the biomass came from Europe (46.8 %), 14.4 % of which was produced in Germany. Other types of biomass were almost entirely imported from other continents, which is the case for soy bean (96.4 % from South America), sugar cane (66.7 % from South America and 33.4 % from Central America), and palm oil (90.9 % from Asia and 8.3 % from Central America). Three types of biomass were mainly produced in Germany: sugar beets (91.9 %), barley (85.5 %) and silage corn (100 %). [BLE (2021b)]

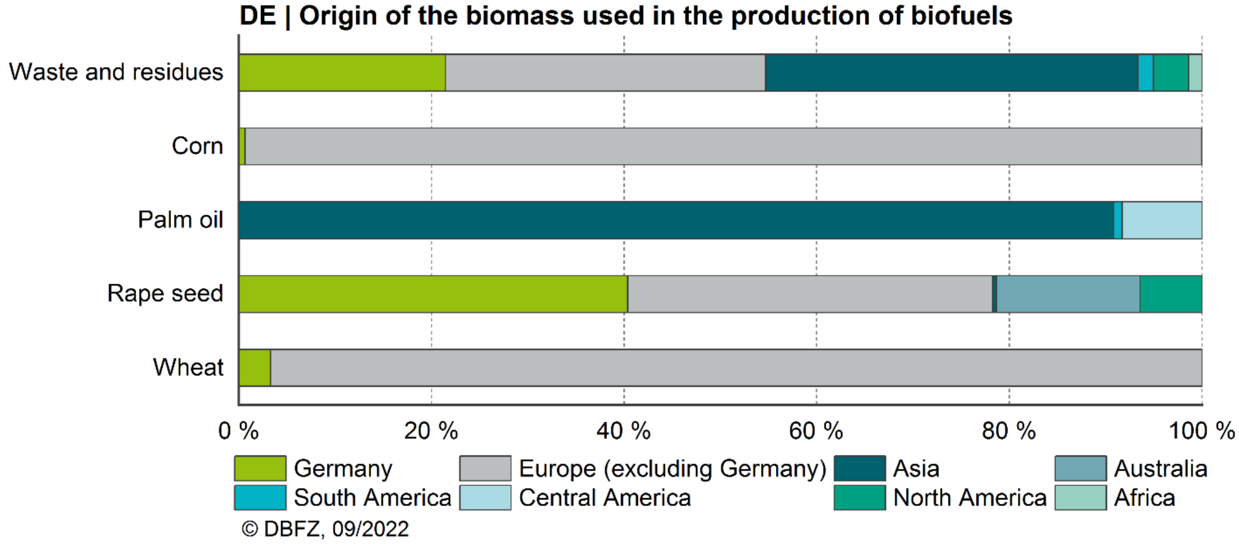

Figure A-2 Origin of the biomass used in the production of biofuels in Germany in 2020. Note: energy-related distribution; data based on [BLE (2021b)]

A-5: FEEDSTOCKS FOR THE PRODUCTION OF FAME AND HVO DIESEL USED IN GERMANY

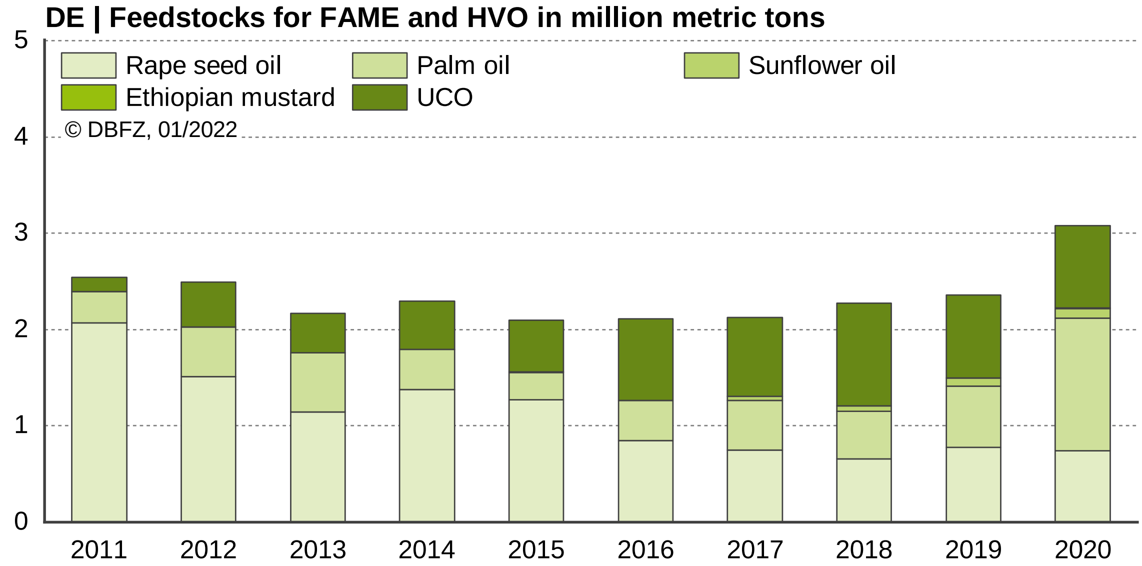

Figure A-3 Feedstocks for the production of the fuels FAME and HVO used in Germany. Data based on [BLE (2012), (2013), (2014), (2015), (2016), (2017), (2018), (2019), (2020), (2021b)]

A-6: FEEDSTOCKS FOR THE PRODUCTION OF BIOETHANOL USED AS FUEL IN GERMANY

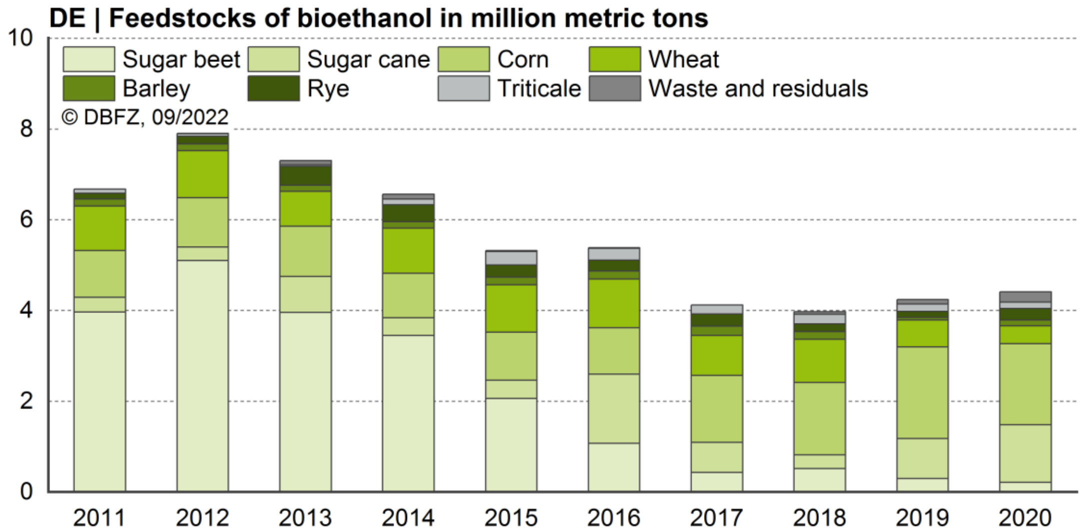

Figure A-4 Feedstocks for the production of bioethanol used as fuel in Germany. Data based on [BLE (2012), (2013), (2014), (2015), (2016), (2017), (2018), (2019), (2020), (2021b)]

A-7: Feedstocks for the production of the biomethane produced in Germany

As shown in Figure A-5, the share of biomethane from waste and residuals increased from about 71 % in 2011 to 100 % by 2017. The share of biomethane from waste and residuals decreased to 94 % in 2018 and to 73 % in 2020. The amount of corn silage used to produce biomethane was 71.9 thousand metric tons in 2011, which increased to 114.2 thousand metric tons and 112.7 thousand metric tons in 2012 and 2013, respectively. In 2014, only 24.5 thousand tons of corn silage was used to produce biomethane, followed by three years (2015 to 2017) in which corn silage was not used at all as a feedstock for biomethane. Corn silage production volumes increased significantly to 59.3 thousand metric tons in 2018, 364.1 thousand metric tons in 2019, and 476.8 thousand metric tons in 2020. In 2020, the share of biomethane from fodder beets, grain, grass and sugar beets totaled 1.9 %. [BLE (2012), (2013), (2014), (2015), (2016), (2017), (2018), (2019), (2020), (2021b)]

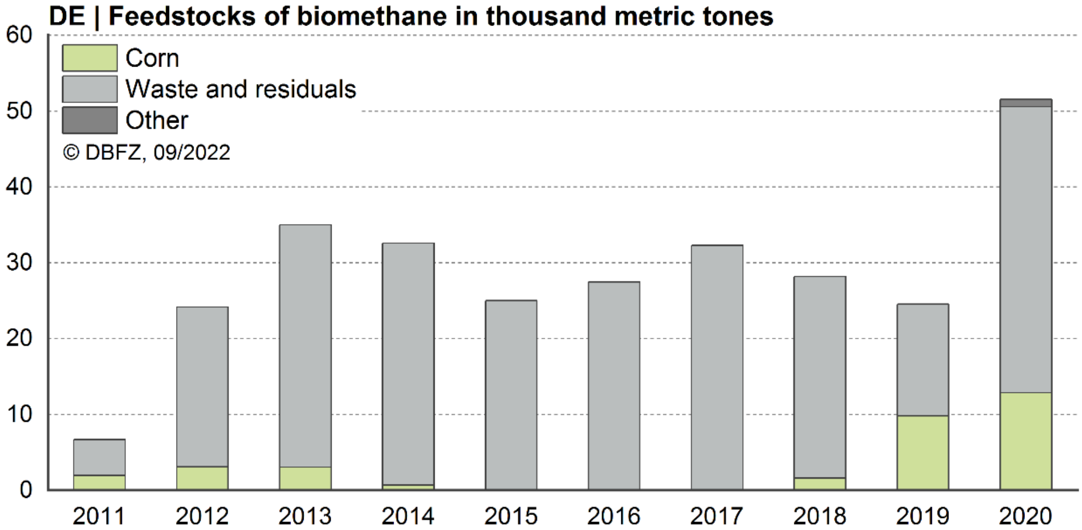

Figure A-5 Feedstocks of the biomethane produced in Germany. Data based on [BLE (2012), (2013), (2014), (2015), (2016), (2017), (2018), (2019), (2020), (2021b)]

A-8: Feedstocks for the production of the FAME and HVO diesel used in the EU

Figure A-6 shows the development of the feedstocks used to produce FAME and HVO diesel in Europe since 2006. FAME was largely produced from rape seed oil in Europe until 2010, followed by soy bean and palm oil. The absolute annual amount of FAME produced in the EU has remained almost constant since 2016, ranging from 12.9 to 13.9 million metric tons and requiring 13.7 to 14.7 million metric tons of vegetable oil or UCO. The amount of FAME produced from UCO has been increasing continuously since 2008 and rose to over 3.5 million metric tons in 2020, which corresponds to 3.9 million metric tons of feedstock. The theoretical amount of rape seed and soy bean meal used as protein feed is calculated at around 13.4 million t/a based on the current FAME production volumes within the EU. [USDA (2013), (2016), (2018), (2020)]

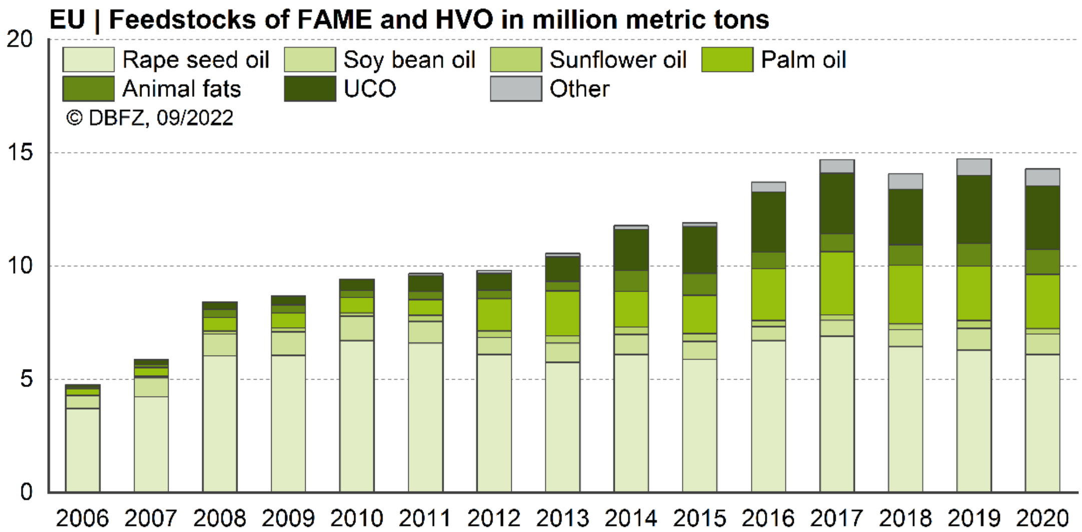

Figure A-6 Feedstocks of the fuels FAME and HVO used in the EU. Data based on [USDA (2013), (2016), (2018), (2020)]

A-9: FEEDSTOCKS FOR THE PRODUCTION OF THE BIOETHANOL USED AS A FUEL IN THE EU

Grain, sugar beets and corn are the main feedstocks used to produce the bioethanol that is used as a fuel in the European Union. Whereas most of the feedstock was grain-based in 2006, by 2008 the focus had shifted significantly toward sugar beets and corn. By 2017, the absolute amount of grain-based bioethanol in the EU increased to about 1.9 million metric tons, which corresponds to a grain volume of 6.8 million metric tons. By 2020, the absolute amount of bioethanol had decreased to about 1.1 million metric tons (made from 4.2 million metric tons of grain). The amount of bioethanol based on sugar beets was 0.9 million metric tons in 2020. In 2020, bioethanol was almost exclusively made from corn (6.4 million metric tons of corn for 1.97 million metric tons of bioethanol). The highest production volume of bioethanol to date was achieved in 2017, when 4.7 million metric tons of bioethanol were produced from 20.6 million metric tons of feedstock. Co-products can be generated during the production of ethanol depending on the feedstock. These are mainly used as animal feed (e.g., dried distillers grains with solubles - DDGS), but can also undergo a second conversion step of anaerobic fermentation to produce biogas, a further energy carrier. Theoretically, the current production of bioethanol for fuel use in the EU (2020) generates approx. 3.2 million t/a of DDGS. [USDA (2013), (2016), (2018), (2020)]

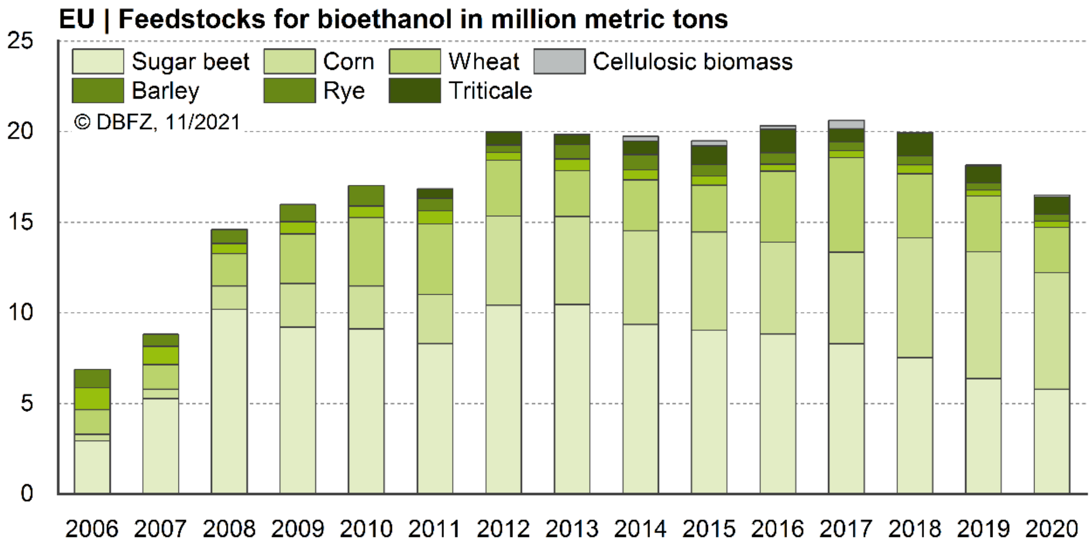

Figure A-7 Feedstocks for the bioethanol used in the EU as a fuel. Data based on [USDA (2013), (2016), (2018), (2020)]

A-10: Feedstocks for globally produced FAME and HVO diesel

As shown in Figure A-8, there has been a comparatively strong change in feedstocks for the global production of FAME and HVO diesel: In 2006, rape seed oil was the dominant feedstock with a share of 60 %. The absolute amount of rape seed oil-based FAME had almost doubled by 2011 and has remained roughly constant since then at 6.9 million metric tons in 2020, corresponding to 6.7 million metric tons of rape seed oil (product quantity slightly higher due to its reaction with methanol). In contrast, the percentage of FAME from soy bean and palm oil as well as UCO has risen sharply. In 2013, there was an almost even distribution among the feedstocks rape seed oil, soy bean oil, palm oil and UCO. In recent years, the absolute and relative share of rape seed oil decreased in favor of UCO. The feedstocks used in 2020 can be broken down into 31 % palm oil, 25 % soy bean oil, 21 % UCO, 16 % rape seed oil, and 7 % other oils. [F.O. Licht (2011a), (2011b), (2015a), (2016a), (2017a), (2018a); IHS Markit (2018)-(2020), (2020b)]

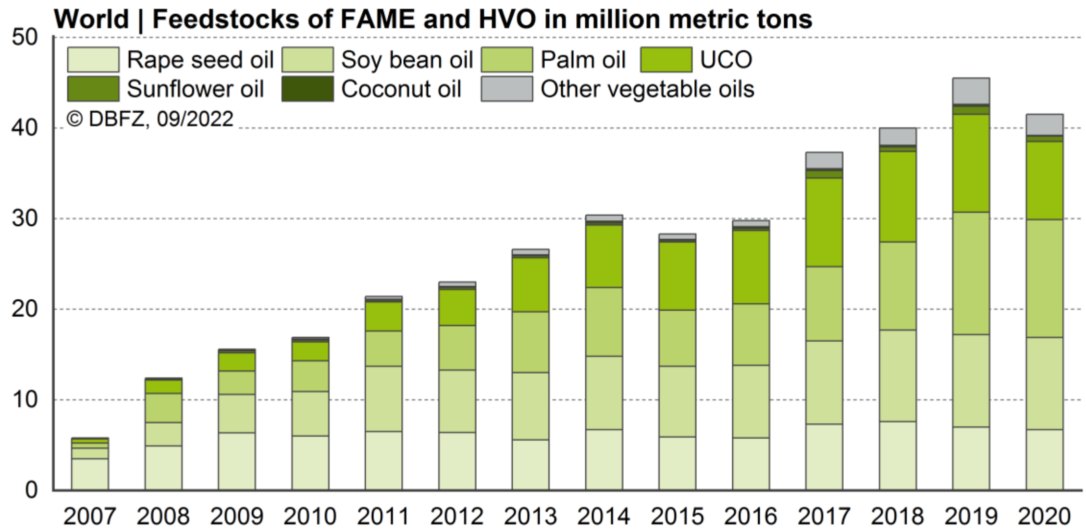

Figure A-8 Feedstocks for the global production of FAME and HVO. Data based on [F.O. Licht (2011a), (2011b), (2015a), (2016a), (2017a), (2018a); IHS Markit (2018)-(2020), (2020b)]

A-11: Feedstocks for the global production of bioethanol

While bioethanol is produced from corn starch in the U.S., sugar cane is the main feedstock used in Brazil, although the share of bioethanol produced from corn has increased there in recent years. As shown in Figure A-9, around 94 % of the bioethanol feedstocks used worldwide in 2006 were processed in production plants in the U.S. and Brazil; this figure had fallen to around 85 % by 2020. The remaining 15 % in 2020 was mainly comprised of 5 % corn from other countries, 3 % sugar cane from other countries, 5 % molasses, 1 % sugar beets and 1 % cassava. The use of cassava has been increasing in recent years, especially in Asia, albeit the quantity is still not very significant. [F.O. Licht (2011a), (2011b), (2015a), (2016a), (2017a), (2018a); IHS Markit (2018)-(2020), (2020b)]

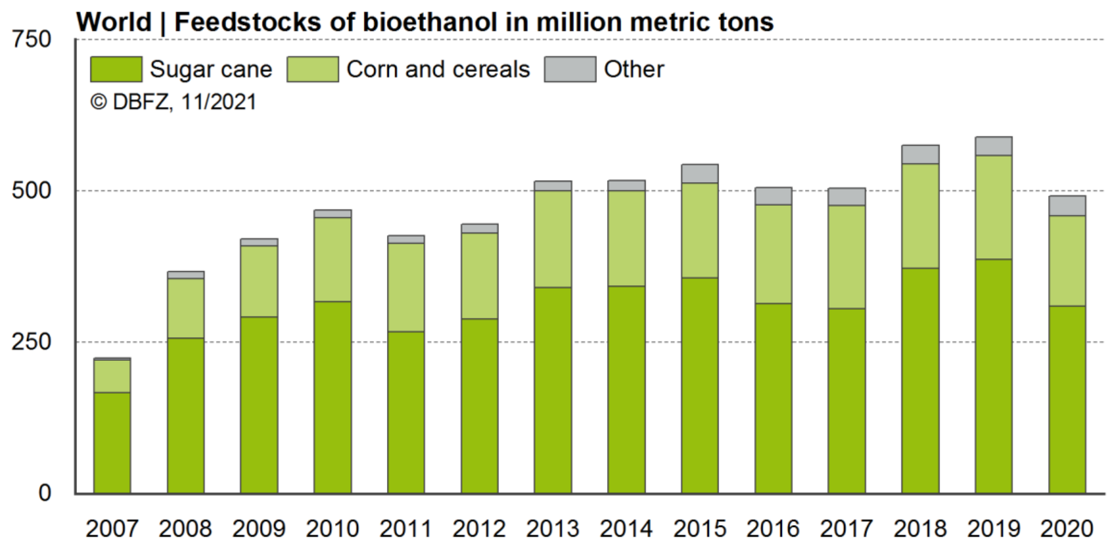

Figure A-9 Feedstocks of globally produced bioethanol. Data based on [F.O. Licht (2011a), (2011b), (2015a), (2016a), (2017a), (2018a); IHS Markit (2018)-(2020), (2020b)]

A-12: Global demand for methanol

The breakdown of methanol production and usage from 2016 to 2021 (for 2021 as a forecast) are shown in Figure A-10. Methanol production increased overall by 29 % (5.8 % annual increase). The largest increase was in the use of methanol to produce olefins, which increased by 79 % over this period, followed by its use in the production of biodiesel (77 %). The use of methanol in the production of DME decreased by 20 % during this period. [IRENA (2021c); Methanol Institute (2021)]

The current global methanol production capacity from renewable sources is approximately 1.71 million t/a, which is divided among various technological production pathways. Renewable methanol capacities under construction or projected amount to approximately 4.0 million t/a, which would result in a total capacity of 5.6 million t/a if fully realized. Even if these projects are completed, this would represent only 3.7 % of actual production capacities, which were estimated at 153.1 million t/a in 2020, as shown in Figure A-10 [IRENA (2021c); Schröder (2020b)].

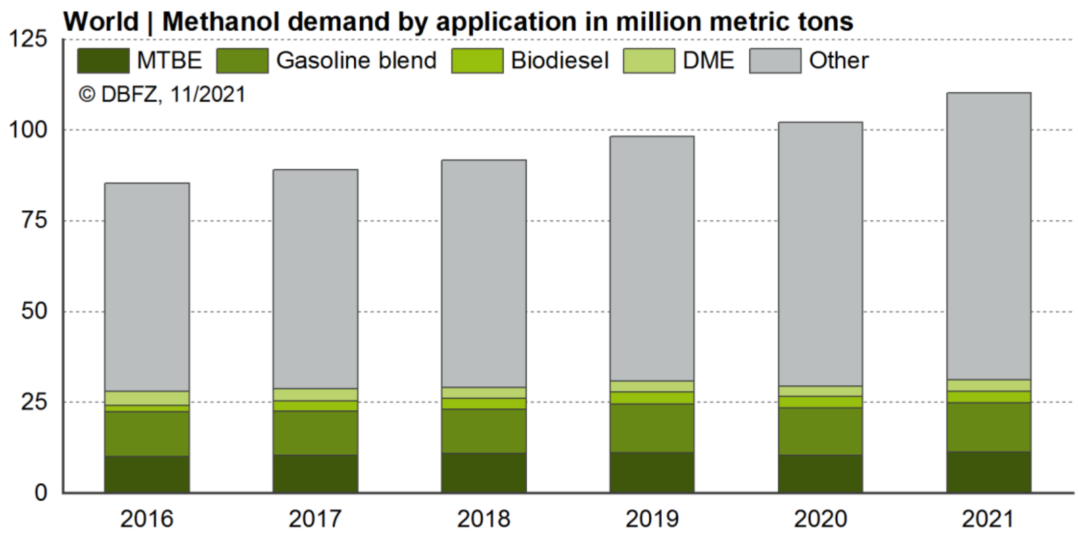

Figure A-10 Global demand for methanol. Data based on [Methanol Institute (2021)]

A-13: GLOBAL CORN PRODUCTION AND ITS AREAS OF UTILIZATION

Figure A-11 shows the global consumption of corn from 2012 to 2021, broken down by area of utilization. Total corn production increased from 901 million metric tons in 2012 to 1,192 million metric tons in 2021, a 32 % increase. In 2012, corn consumption was split into 55 % for feed use, 12 % for food use, 13 % for bioethanol production, and 19 % for other uses. In 2021, the breakdown was 60 % feed use, 11% food use, 12 % bioethanol production, and 17 % other uses. Consumption as animal feed increased the most from 495 million metric tons in 2012 to 717 million metric tons in 2021, an increase of 45 %. Corn consumption for bioethanol production increased from 120 million metric tons to 140 million metric tons, representing a 17 % increase. [IGC (2021)]

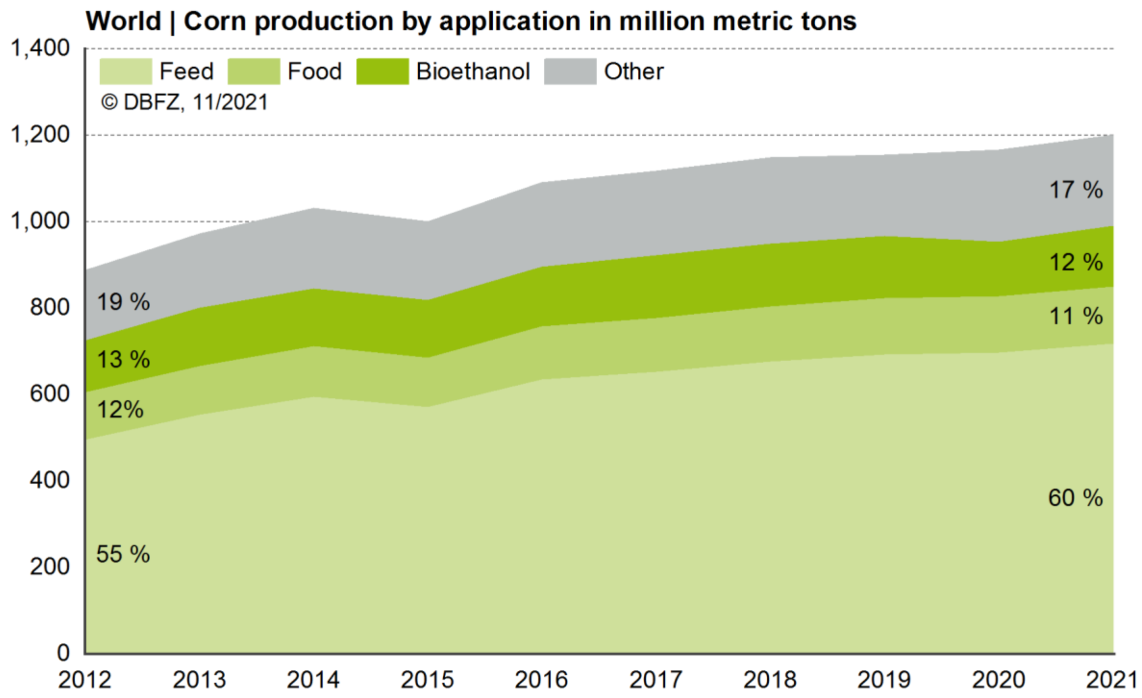

Figure A-11 Global corn production and its areas of utilization. Data based on [IGC (2021)]

A-14: GLOBAL PALM OIL PRODUCTION AND ITS AREAS OF UTILIZATION

Palm kernel is another crop whose production rose sharply. Its oil is used to produce biodiesel. Global production of palm oil increased from 41.5 million metric tons in 2008 to 75.1 million metric tons in 2020, a 69 % increase. In 2008, the breakdown of palm oil use was 72 % food use, 11 % biodiesel production, and 16 % other uses. In 2020, 67 % of the palm oil produced was for food use, 18 % for biodiesel production, and 14 % for other industrial uses. The largest increase was in the use of palm oil for biodiesel production, which was 5.1 million metric tons in 2008 and 13.5 million metric tons in 2020, an increase of 165 %. [FNR (2016); USDA (2021)]

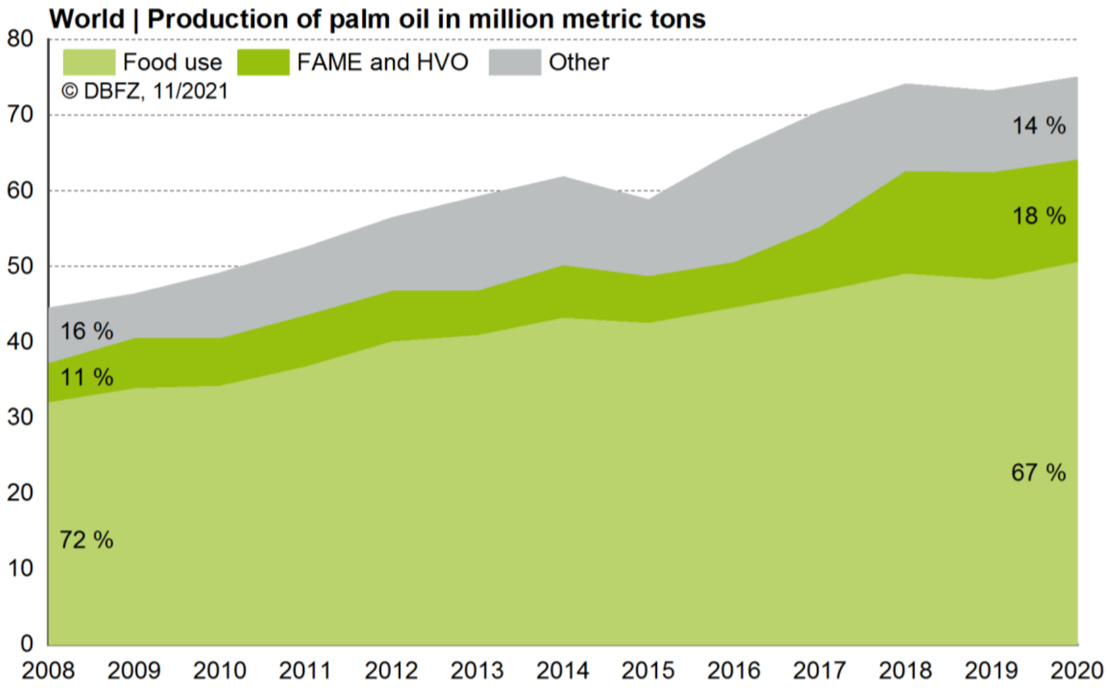

Figure A-12 Global production of palm oil and its areas of utilization. Data based on [USDA (2021)]

A-15: Global production of black liquor

The energy content of black liquor, as a by-product of cellulose production, can vary slightly within the production process. Based on the lower heating value of 12 MJ/kg (DM) [Swedish Energy Agency (2008)], an estimate of the global theoretical energy content of black liquor was 2.74 EJ for 2019. Although there are some examples of extraction of lignin from black liquor [Andritz (2020); Stora Enso (2020); Valmet (2020)], there is no significant use of black liquor beyond energy production and it can be assumed that all energy content is used to generate power and steam. In addition, there is a limited amount of black liquor that could be used in an alternative process to produce biofuels. According to Vakkilainen, up to 20 % of black liquor can be removed without this significantly impacting the cellulose production process; however, when around 30 % black liquor is removed, the process starts to become problematic. Taking this into account, around 0.55 EJ (2019) is most likely the maximum technical potential of black liquor based on current industrial capacities [Vakkilainen (2009)].

Considering that around 7.3 to 15 kg of methanol per metric ton of pulp is produced as a by-product of the kraft process, the potential of methanol recovery is estimated to have a mean value of 36.87 PJ in 2019 [Jensen (2012)].

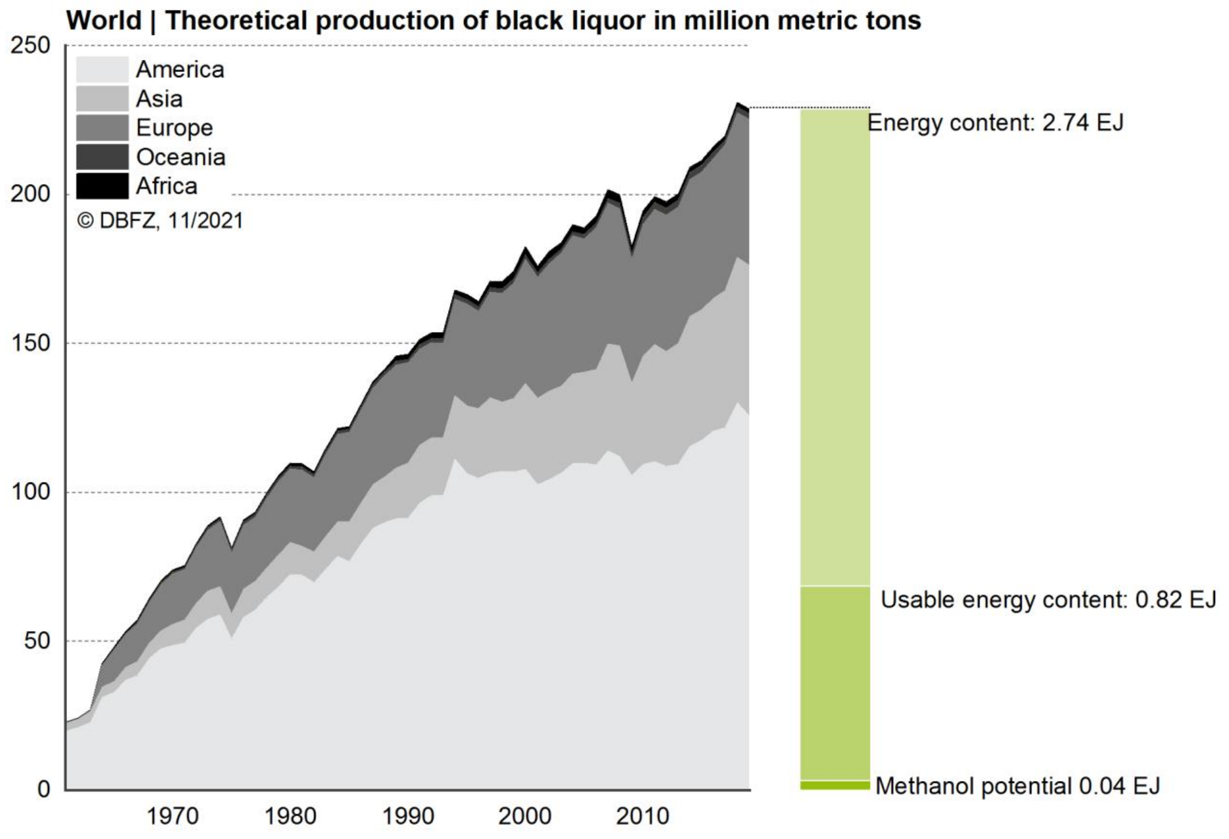

Figure A-13 Estimation of the worldwide production of black liquor broken down by energy content and the quantity that can be used to produce biofuels as well as estimation of the methanol produced in the kraft process. Note: own calculation based on [FAO (2021); Kim (2019); Swedish Energy Agency (2008); Vakkilainen (2009)]

A-16: Production of electricity from renewable sources

Table A-3 Use of electricity from renewable sources broken down by energy source for 2019. Data based on [IEA (2021f)]

	World	Europe	Germany
Bioenergy	543 TWh	180 TWh	44 TWh
Geothermal	91 TWh	22 TWh	0.2 TWh
Tidal power plants	1 TWh	0.5 TWh	0 TWh
Photovoltaics	681 TWh	151 TWh	46 TWh
Solar power	13 TWh	6 TWh	0 TWh
Incineration plants	37 TWh	6 TWh	6 TWh
Hydropower stations	4,329 TWh	656 TWh	26 TWh
Wind (onshore and offshore)	1,427 TWh	463 TWh	126 TWh
Total	7,159 TWh (25,772 PJ)	1,485 TWh (5,344 PJ)	248 TWh (894 PJ)

A-17: Feedstock-related manufacturing costs for commercially available renewable energy carriers

Table A-4 Overview of the manufacturing costs, broken down by process and feedstock and normalized to 2020

	Feedstock	Manufacturing costs	Source
Bioethanol	Sugar beets	23.3 EUR_{2020}/GJ	[Millinger (2017)]
Bioethanol	Sugar cane	12.8 EUR_{2020}/GJ	[Wang (2014)]
Bioethanol	Lignocellulose	24.8 – 43.0 EUR_{2020}/GJ	[IEA Bioenergy (2020b); Kalligeros (2018); Macrelli (2012); Millinger (2017)]
Biodiesel (FAME)	Rape seed	17.0 – 23.3 EUR_{2020}/GJ	[Jungmeier (2016); Millinger (2017)]
Biodiesel (FAME)	Soy bean	13.9 – 21.4 EUR_{2020}/GJ	[Jungmeier (2016)]
Biodiesel (FAME)	Palm	7.9 – 21.6 EUR_{2020}/GJ	[Jungmeier (2016); Sunde (2011)]
Biodiesel (FAME)	Used cooking oil	17.9 – 30.5 EUR_{2020}/GJ	[Jungmeier (2016); Kalligeros (2018)]
Vegetable oil	Rape seed	20.4 – 24.8 EUR_{2020}/GJ	[Dressler (2016)]
Methane	Electricity	32 – 62 EUR_{2020}/GJ	[Liebich (2020)]

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