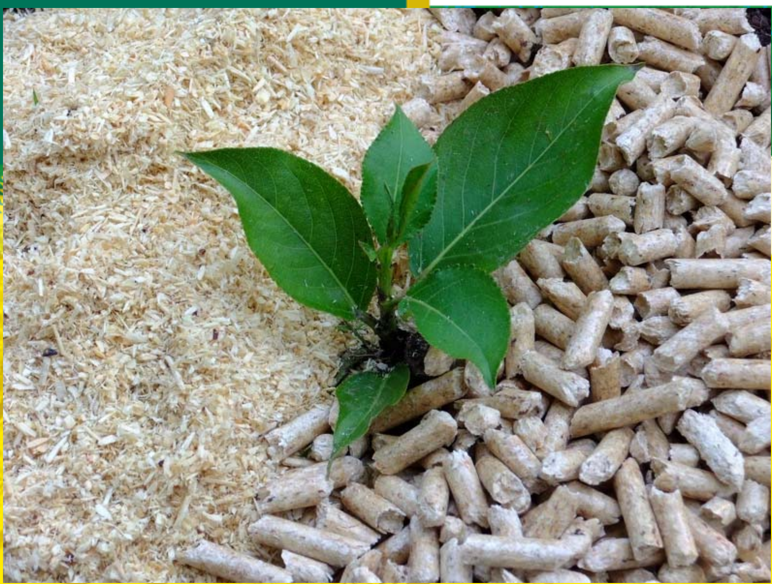
Margin potential for a long-term sustainable wood pellet supply chain



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IEA Bioenergy Task 40: 5/2019

Margin potential for a long-term sustainable wood pellet supply chain

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IEA Bioenergy Task 40

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Published by IEA Bioenergy

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1 Introduction

Uwe R. Fritsche (IINAS) & Patrick Lamers (INL)

The global wood pellet market is one of the most dynamic across all bioenergy commodities evaluated by the IEA Bioenergy Task 40 over the last 15 years[1]. By 2015, global trade had reached 220 PJ (13 million tons = Mt) from 30 PJ (1.7 Mt) in 2004, clearly illustrating the exponential growth of the industry. The expansion of cumulative production capacity and increasing plant sizes are symbols of the maturation of this industry. At the same time, growth, optimization, and increasing competition has also reduced the present margins in wood pellet supply chains:

- Established **industrial** (large-scale) use for co-firing with coal or standalone biopower plants (roughly 40% of current global pellet use), is under price pressure to become competitive to other low-carbon electricity technologies. Furthermore, coal is being phased out increasingly in Europe and North America due to countries' activities to meet their climate change mitigation ambitions under the Paris Agreement.
- The **residential** use markets (presently about 60% of current global pellet use) face increasing competition from alternative heating technologies such as district heating, heat pumps as well as fossil fuels (e.g., natural gas or heating oil) which are still cheap due to the lack of a carbon tax. Furthermore, competing bioenergy options such as biogas and biomethane, as well as – in the longer-term – renewables gases of non-biogenic origin (e.g. power-to-gas) could compete with pellets in residential and commercial heat supply. On the other hand, pellets can play an increasing role in district heating which avoids, compared to pellet stoves, air pollution concerns in cities.

The long-term viability of the wood pellet supply chain and the potential market flexibility (i.e., product fungibility) are key issues to keep operating. Without long-term viability, individual actors may leave the supply chain (e.g., go bankrupt or mothball their production plants). This will reduce the likelihood of wood pellets becoming a long-term supply option for the future bioeconomy (e.g., for biorefineries), and may imply problems also for bioenergy applications which may be needed to achieve net-negative greenhouse gas (GHG) emissions, especially Bioenergy with Carbon Capture and Storage (BECCS), and Bioenergy with Carbon Capture and Use (BECCU).

This would not only mean a loss of rural jobs and economic revenue, it could also have wider consequences, such as a delay in the commercialization of advanced biofuel technologies due to the lack of a commodity-type feedstock, and respective transport and trade infrastructures.

This study[2] evaluates the future market prospects of wood pellets in

- industrial low- and high-temperature heat,
- industrial processes (e.g. steelmaking), and
- BECCS/BECCU.

It presents a cost baseline summarizing the current market outlook for pellets and respective supply chain "hot spots" in Section 2. Section 3 analyzes potential supply cost reductions. Section 4 details the market prospects, and Section 5 summarizes the key findings and conclusions of this study.

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[1] Junginger, Martin et al. (2019) The future of biomass and bioenergy deployment and trade: a synthesis of 15 years IEA Bioenergy Task 40 on sustainable bioenergy trade. Biofuels, Bioproducts and Biorefining 13: 247-266 https://doi.org/10.1002/bbb.1993

[2] An Annex to this report provides background information on the cost data presented in Section 2, and gives details on the innovation potentials (Section 3.1). It is available on the IEA Bioenergy Task 40 website (www.task40.ieabioenergy.com)

2 Baseline and supply chain hotspots

Ric Hoefnagels (UU) & Fabian Schipfer (EEG)

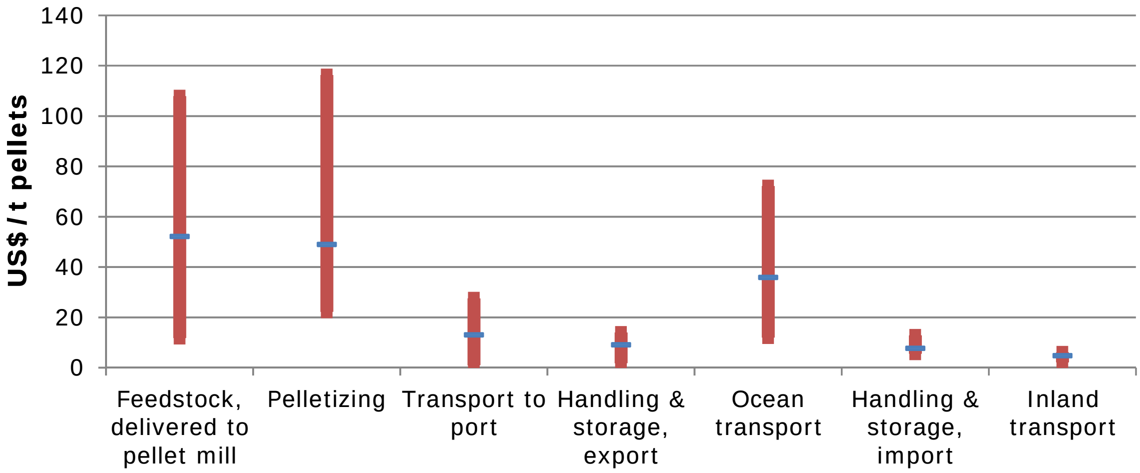
The development of the wood pellet market has enabled economically valuable long distance transport of solid biomass that in its raw form, often lacks the characteristics to be used outside its production area. These include higher bulk density, flowability within high-volume handling infrastructure and storability (Searcy et al. 2014). Prices of wood pellets for industrial and residential markets have proven to be volatile as a result of exchange rate developments, temperatures during heating seasons, fuel prices (e.g. heating oil) and renewable energy support.

European spot prices of pellets delivered to the ARA (Antwerp – Rotterdam - Amsterdam) region have varied between 115 €/t (July 2007) to its peak in April 2014 at 185 €/t (Sikkema et al. 2010, Argus Media 2015). Most industrial pellets are, however, sold under long-term bilateral contracts in local currencies of the exporting country (FutureMetrics 2018), and not on spot markets.

Several studies have estimated the supply chain cost of pellets produced at different locations, at different scales, from a wide variety of feedstock types and for both residential and industrial end users. Feedstock types include pulp-grade roundwood, forest residues, wood processing residues (mainly sawdust and shavings), and agriculture residues (mainly straw).

Visser et al. (2018) showed that if assumed to be delivered to the ARA region, total wood pellet supply chain cost vary between 99 $/t and 248 $/t. The variation in cost at component level of the available studies is largest for feedstock supply, pelletization cost and ocean transport, as depicted in Figure 1.

Figure 1 Ranges per component found in previous studies on pellet production cost estimations



Source: Visser et al. (2019); data given in $$_{2016}$

Insight in wood pellet supply chains and underlying cost structures is of importance to identify cost reduction strategies and possible price risks along the supply chain. Yet, it has proven to be difficult to acquire actual production cost data. Feedstock prices, but also pellet production cost are proprietary confidential information and not disclosed to the public.

Furthermore, the heterogeneity of pellet mills (size, feedstock, infrastructure, design, and location) and the impact of price factors (including feedstock, energy, freight rates, exchange rates and labor cost) add uncertainty to these estimates.

The objective of this chapter is to analyze the supply chain cost structure of existing and potential new pellet supply chains.

Three baseline supply chains are included:

- **USA**: industrial large scale, export to EU (Netherlands, UK). The US Southeast has become the largest exporting region of wood pellets. US pellet exports reached nearly 5 Mt in 2015, representing about 30% of globally traded pellets (Thrän et al. 2019).
- **Germany**: residential heating market. Germany is the second largest consumer of wood pellets for heating purposes in Europe (after Italy). About 2.0 Mt wood pellets were used for heating purposes in 2016, i.e. 15% of the EU28 total (AEBIOM 2017).
- **Brazil**: bagasse pellets, export to EU for industrial uses (Netherlands). The Brazilian pellet market is still immature. Nevertheless, with a production of 174 Mt and an estimated surplus of 17.4 Mt, sugarcane bagasse could potentially become a valuable source of fibers to produce pellets.

The pellet supply chain cost estimates are compared with actual spot market price trends. It should be noted that respective cost of supply chains and potential savings can be easily overshadowed by raw material costs, which can range between 0 and 120 € per dry ton of feedstock. Continuous raw material availability and accessibility are relevant issues. Also, developments in exchange rates and bunker fuel charges can easily outweigh efficiency gains in the supply chain.

2.1 Wood pellet price development

In contrast to the discussed wood pellet supply chain costs actual wood pellet prices include furthermore surcharges of the involved supply chain actors and underlie fluctuations regarding supply and demand.

Figure 2 illustrates wood pellet prices for residential heating markets in Germany, Italy, Austria, Sweden, France and Switzerland as well as prices for the industrial markets for shipping to Western Europe. Residential wood pellet prices are illustrated including value-added tax (VAT). Longest and most comprehensive time series with monthly prices starting in 2001 – 2002 are available for **Austria and Germany**. Nominal prices increased in these countries from an average of 180 €/t between 2001 and 2006 to an average of 240 €/t in the last five years.

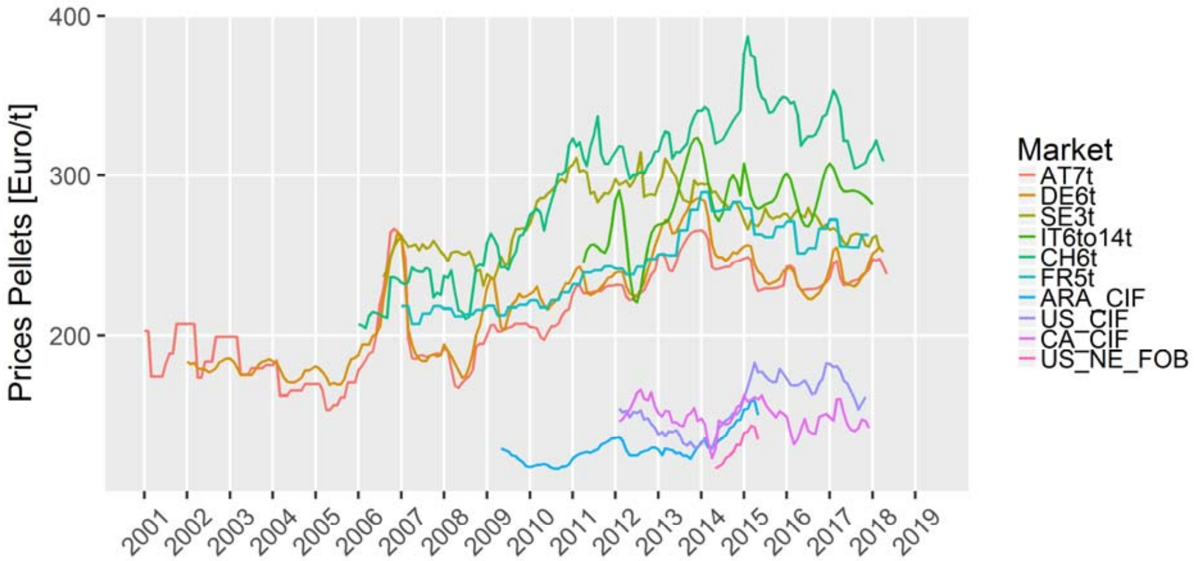
Interesting to notice are the overlapping trends especially in the last three to four years in German and Austrian prices with prices in average 7 €/t higher in Germany than in Austria. **Italian prices** also follow a similar trend, however on a 14 €/t higher price level than in Austria. An Italian-specific price hike is illustrated for the turn of the year 2014 to 2015 where the VAT was increased from 10% to 22%. **French prices** also show similar seasonality's with price maxima in winter and minima in summer. Average French prices are at about 263 €/t (between 2012 and now) with summer lows of 251 €/t and winter highs of 279 €/t in the last three years. **Swedish** and **Swiss prices** are collected in Swedish Krona and Swiss Francs and have to be converted into Euro. For Sweden, converted pellet prices fell from an average of 295 €/t between 2011 and 2014 to an average of 269 €/t in the last years (since 2015) with a continuously decreasing trend and prices in April 2018 as low as in Germany (254 €/t).

Pellet export prices **from Canada** and the **United States** for the North American pellet market and to Western Europe mainly for large scale industrial consumption are collected monthly from Future Metrics and on a weekly basis from Argus Media (without VAT). The monthly time series for the US destination as well as the weekly prices for the ARA ports represent contracted prices including costs, insurances and freight (CIF) until the buyer's port.

For Canadian and US pellets for the North American industrial and residential market, an average of 149 €/t and 156 €/t can be calculated. Prices in the ARA ports are spot and long-term (one and three years) contract prices with an average of 129 €/t for the illustrated time series.

Furthermore, free-on-board (FOB) prices time series are available for different regions in Canada and the US, as illustrated for North-East (US NE) ports of the US. They are assumed to follow the CIF prices for spot and long-term contracts at the ARA ports with price differences according to their respective shipping distances (North-East US to Western Europe with about 6.000 km and North-West US to Western Europe with about 16.000 km for example).

Figure 2 Wood pellet price development for residential (with VAT) and industrial (without VAT) markets



Sources: ProPellets (2018), DEPI (2018), Pelletsforbundet (2018), AIEL (2018), BS-CH (2018), Beyond 20/20 France (2018), Argus Media (2016 + 2018), FutureMetrics (2018), Quandl.com (2018)

2.2 Pellet supply chains

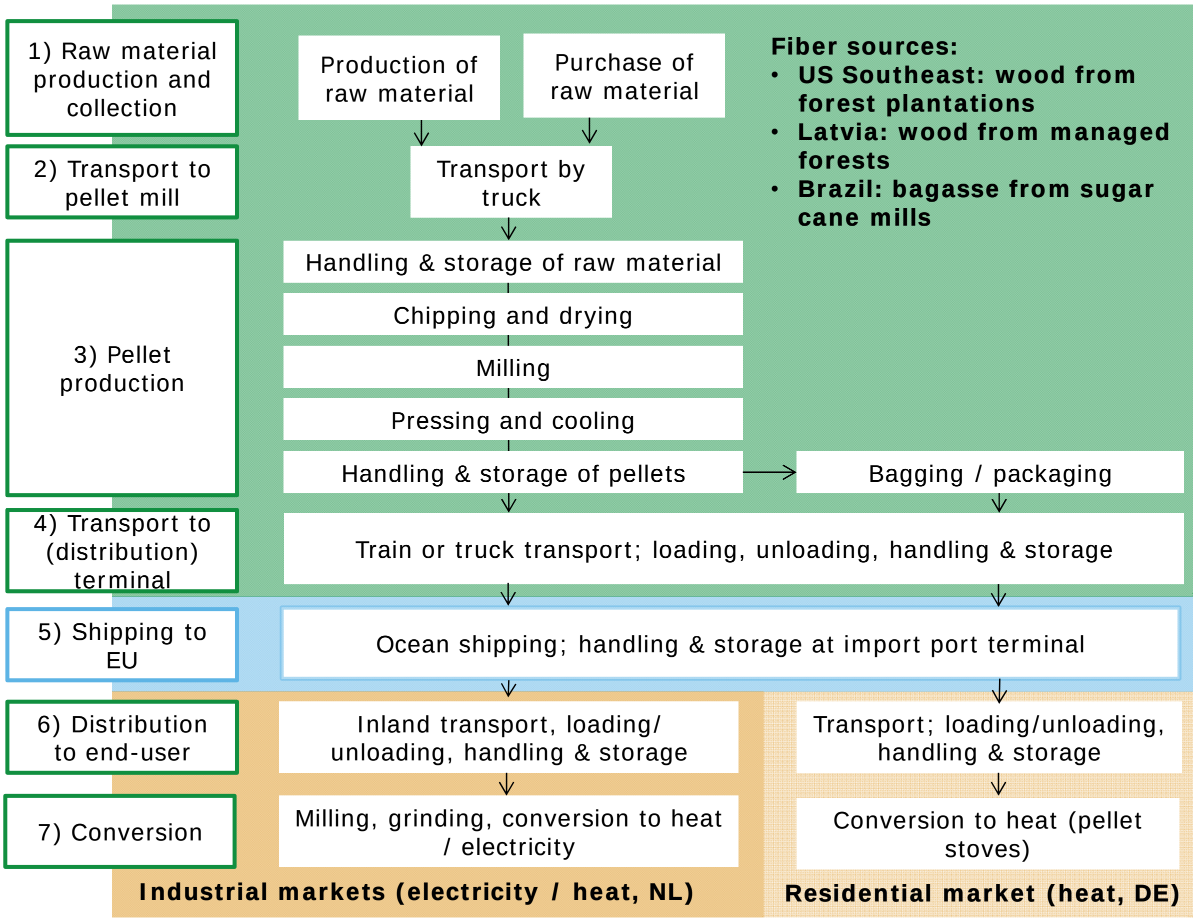
2.2.1 General pellet supply chain outline

The following outlines experience of wood pellet trading via six different supply chains for European end-users. The investigated supply chains can be clustered into supply chains for industrial and for residential end-users and are furthermore differentiated into various sizes of shipping vessels in which wood pellets are transported in a bulk or bagged. Next to the transportation in vessels, also experience with truck and train transport can be included with (shipping) container as additional option and link between the transport modes.

How these chains are built up today and what links the chain is comprised of is illustrated in Figure 3 and further discussed below. More details are provided in the Annex[3].

[3] The Annex to this report is available as a separate document on the IEA Bioenergy Task 40 website: www.task40.ieabioenergy.com

Figure 3 General pellet supply chain outline and case studies



Source: own compilation

2.2.2 Raw material supply and pellet production

Wood pellets can be produced from several types of forestry feedstocks, from industry residues such as sawdust and shavings, from forestry management residues, such as thinnings, or from roundwood products. Large scale pellet production will often we based on a mixture of various feedstocks, depending on local availability and costs. Given new developments in pelletization (see Section 3.1.3), the raw material base for pellets can be extended to low-quality and low-cost biomass (Hoefnagels, Junginger & Faaij 2014) while ensuring quality and sustainability requirements.

For a long time, industry residues were the preferred feedstock for pellet production. These feedstocks are a by-product of secondary wood products, timber, pulp or paper production and are therefore of lower value. This ensured a relative constant availability against low costs. Furthermore, residues such as sawdust and shavings are generally finely ground and relatively dry compared to roundwood, eliminating the need for several pellet processing steps. (Obernberger & Thek 2010).

Increasing demand for feedstock for pellet production, combined with the limited availability of low cost residues, has resulted in the use of increasingly more forestry products such as pulp-grade roundwood. Local factors such as the regional availability of certain feedstocks, as well as changing industrial landscapes such as local closures of sawmills or paper mills will determine the costs of the different feedstock types in practice.

Sawdust and wood dust are the most expensive source of wood pellets in the US (Figure 5), but also most suitable raw material for pelletisation due to their low moisture content and particle size that do not need further drying and grinding at the pellet mill. For homogeneity reasons, fine grinding in a hammermill is however applied still (Obernberger & Thek 2010). With debarking and chipping, stemwood requires the most pre-treatment steps before pelletization (Table 1).

Table 1 Pre-treatment requirements for raw materials used in pellet production

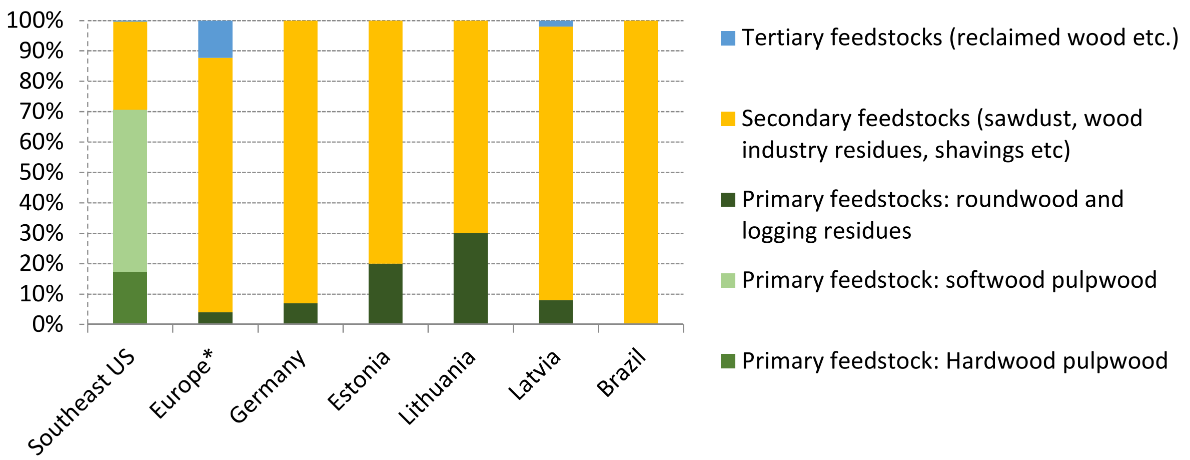
Pre-treatment	Pulpgrade stemwood	Forest wood chips	Industrial Wood chips	Sawdust	Shavings	Wood dust	Bagasse
Chipping/debarking	X						
Course grinding	X	X	X				X
Drying	X	X	X	X			X
Fine grinding	X	X	X	X	X	X	X
Conditioning	X	X	X	X	X	X	X
Pelletization	X	X	X	X	X	X	X

Source: own compilation

Raw material use in pellet production in Europe is still dominated by sawmill residues (84%), while in the US Southeast, pulp-grade roundwood has become the main source of wood pellet production (Figure 4). Production and raw material uses for the US Southeast beyond 2013 are calculated from announced figures while those for the EU are calculated from actual shares of raw material used in pellet production per European country.

In the European Union (EU28), secondary feedstocks such as sawdust from sawmills are still the main raw material for pellet production. Over 83% was produced from wood residues still.

Figure 4 Estimated current raw material shares in wood pellet production in the EU

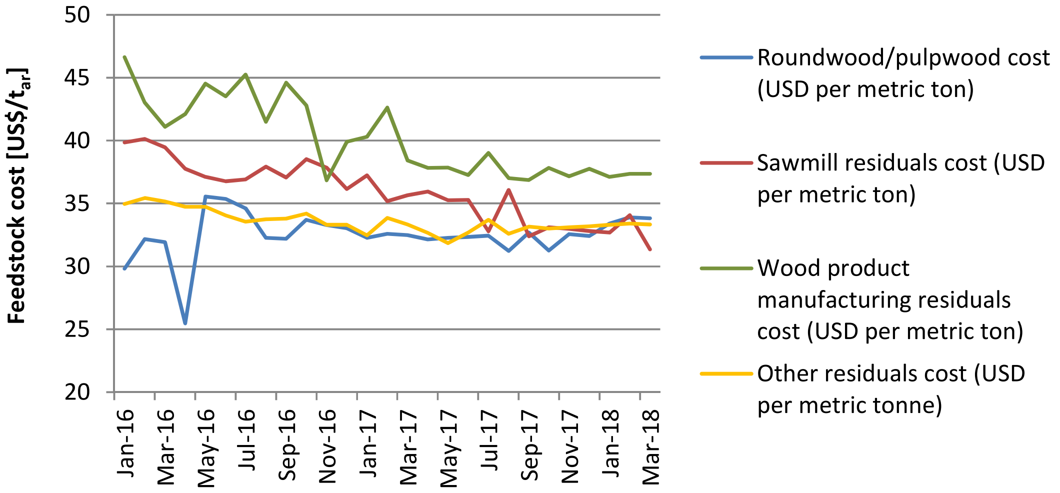


*Source: own calculation based on EPC survey 2017 results (AEBIOM 2017), US Southeast (Abt et al. 2014) and Brazil (Garcia et al. 2016); *) Europe: EU28 + Other Europe.*

Raw material costs can range between 0 and 120 € per dry ton with continuous raw material availability and accessibility being relevant issues. Raw material cost for pellet production are scarce and often considered confidential.

US EIA reports raw material cost on monthly basis since 2016 in their Densified Biomass Fuel Report (EIA 2018). Figure 5 shows the price developments of raw material cost between 2016 and 2017.

Figure 5 Total delivered feedstock cost of pellet production in the US



Source: EIA (2018), including all transportation, commodity costs, taxes, handling, etc.

The cost assumptions for the different pellet mills are provided in Table 1 of the Annex 1 to this report[4]. Investment cost are calculated for a plant size of 120 kt/y output in Latvia and Brazil and a pellet plant size of 400 kt/y in the US Southeast.

The pellet market in Brazil is still in its infancy producing only 49 kt/y and a total production capacity of 192 kt/y, mainly from sawdust (95%) and mostly in small pellet mills (0.5 – 4.0 kt/y) (Garcia et al. 2016). Existing pellet mills and pellet mills under construction are mainly located in the south of Brazil (Parana, Sante Catarina and Rio Grande do Sul and Sao Paolo). One pellet mill in Sao Paolo aims to use sugar cane bagasse as a feedstock, but is currently idled. The relatively high level of idled capacity is the result of the current market immaturity and lack of demand. Key factors include technical issues with equipment that has been designed for animal feed industries and relatively high production cost caused by small-scale production, high cost of electricity and high logistic cost of both feedstock supply and transport of pellets to end consumers or export shipping terminals (Garcia et al. 2016).

2.2.3 Transport of pellets

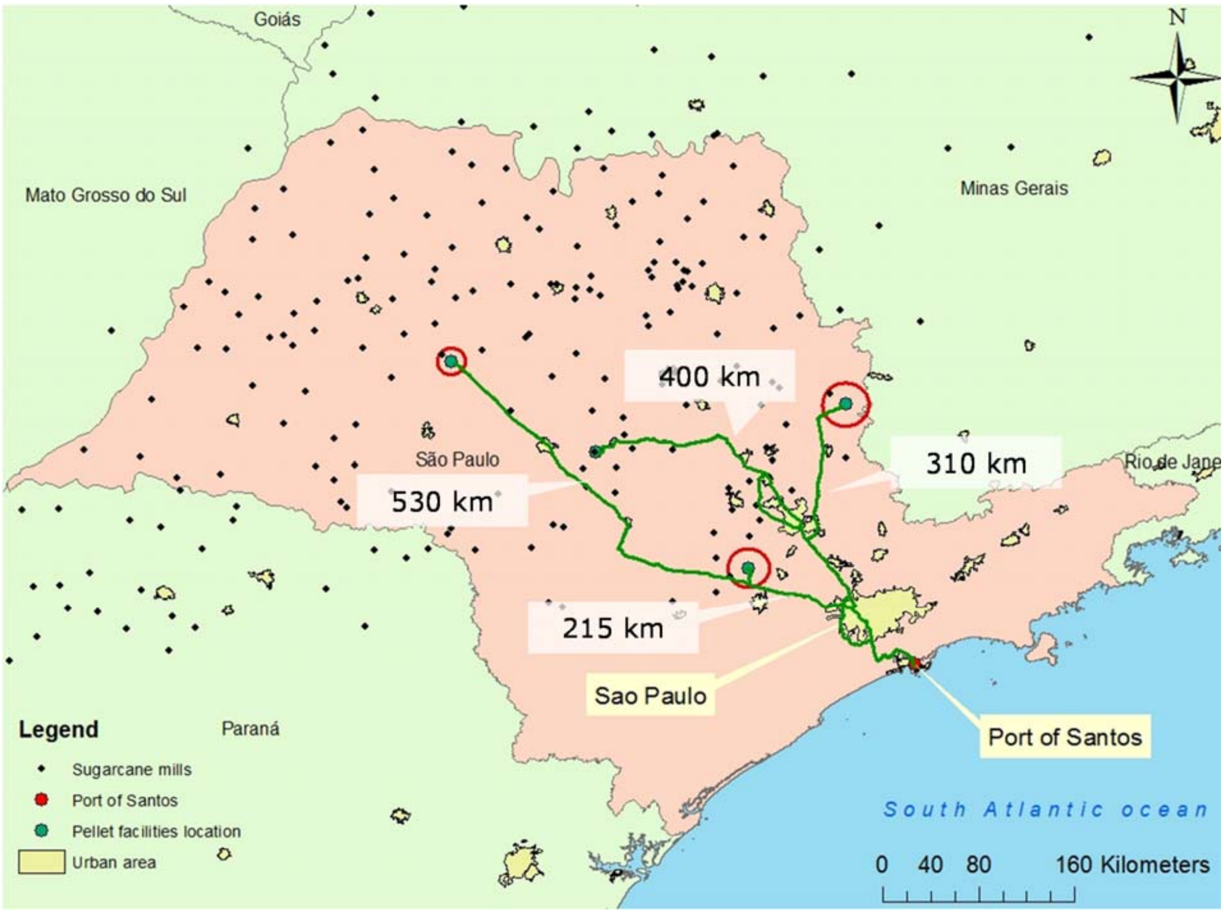
As a rule of thumb inland truck transportation in Central Europe is estimated at 1.2 €/vkm (vehicle – km) with an estimated global range between 0.3 – 2.2 €/vkm. For delivering pellets from producers to the port for shipping, typically 4-13 $/t are payed for larger contracts while 20-40 $/t for container transport have to be estimated.

Based on additional information experts (pers. comm. with Cosan), the planned locations of bagasse pellets were determined. Closest sugar cane facilities were assumed to supply bagasse to the pellet mills. Transport of bagasse to pellet mills are, therefore, small to zero if located at the sugarcane mill.

[4] The Annex to this report is available as a separate document on the IEA Bioenergy Task 40 website: www.task40.ieabioenergy.com

The inland locations of these sugar cane mills do however result in long transport distances of bagasse pellets to an export shipping terminal in the port of Santos (215 – 530 km). The feasibility of rail transport of bagasse pellets between an inland terminal and export shipping terminal will be assessed in the future (Cosan 2018). The available rail infrastructure could potentially be used when demand would increase. Transport of bagasse pellets by truck from the pellet mills to inland intermodal rail terminals will be required because the rail network is not directly linked to sugar cane mill locations.

Figure 6 Existing pellet facilities in Sao Paulo (Brazil) and transport distance to an export terminal in Port of Santos



Source: Vera et al. (2019)

At the port, pellets are stored, their quality and safety is managed and finally loaded into a vessel. While for quality and safety management costs between 0-0.5 $/t occur, the loading can be estimated with 3-10 $/t.

The lower figure where higher loading speeds (10-12000 t/WWD) are achieved and the working hours include Saturdays, Sundays and Holidays (SSHINC).

Figure 7 Left side; Quebec Stevedores, Quebec City, 75 kt. Right side; Westview Pellet Terminal, Prince Rupert BC, 60kt

Source: WPAC

Eventual costs for vessel demurrage and port congestions (-1 to 5 $/t), for documentation and agency fees (0.1-0.5 $/t and 2-6 $/t for bulk and container resp.) are to be considered, too. Privately owned, or from associations co-owned berths could lead to cost reductions. After loading, loaded weight and quality has to be determined leading to additional 0.1-0.3 $/t.

Cost advantages can be highlighted for Panamax ready storages and export terminals. Cost factors that can be minimized at this stage furthermore include loading volume shortage and sloppy stowage reducing the durability index and increasing the fines content.

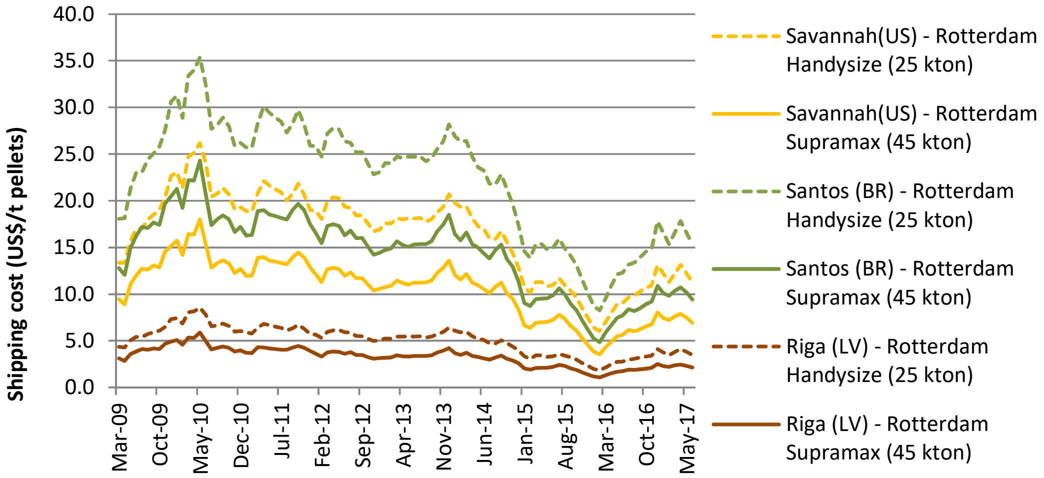
Optimal scheduling and for the latter, training for the stevedores are recommended.

Shipping to the ARA ports results in costs of 10-35 $/t for bulk and 30-50 $/t for container transport. Beside these differences, vessel sizes have obvious impacts on the economies of scale. At the destination ports, again costs for loaded weight and quality determination, unloading resp. container handling, vessel demurrage/port congestion or transloading to final transporter barge (2.5-6 €/t) occur. Additionally, for container transport, inspection and collection or return result in costs of 15-30 €/t. This cost factor can also be outlined as highly negotiable.

Dry bulk carriers are classified according to the total weight they are allowed to carry in deadweight tonnage (DWT). Light weight tonnage (LDT) is the weight of the ship itself excluding cargo, crew, ballast, water. The largest bulk carriers are Capesize (above 150,000 DWT) can only enter a restricted number of ports and cannot navigate through the Panama and Suez canals.

Capesize dry bulk carriers are often used to transport iron and coal and are not used to transport biomass. Also Panamax size ships can access only 27% of the world sea ports (Hoefnagels et al. 2014).

Figure 8 Ocean shipping cost bases on historic daily rates and bunker fuel prices (2009 – 2017).



Source: own calculation

2.2.4 Pellet delivery for industrial end users

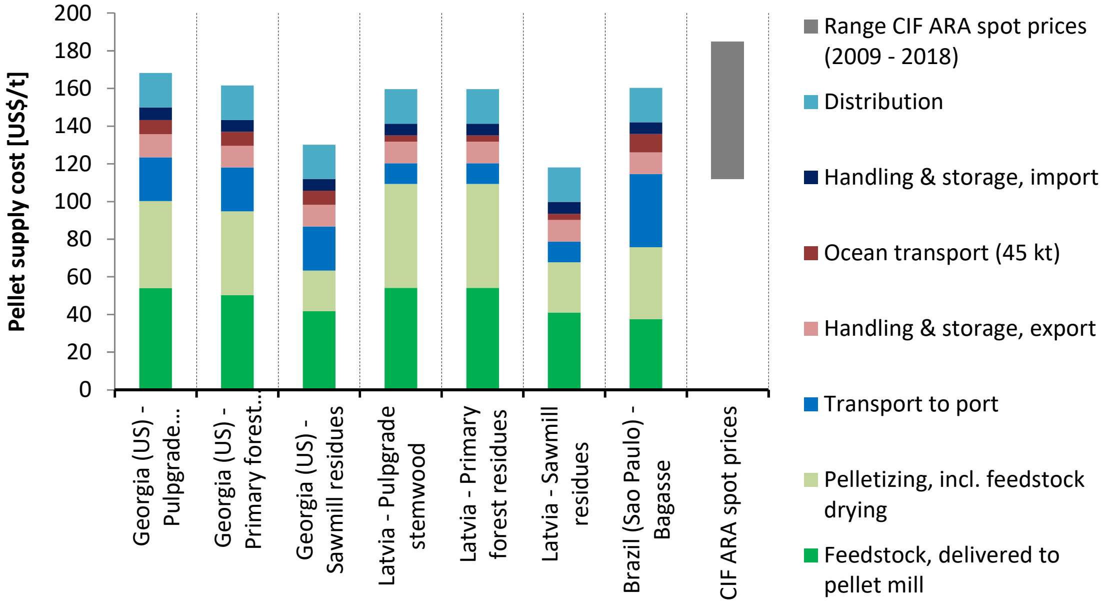
The supply chain cost of wood pellets and bagasse pellets delivered to a port in Western Europe (Rotterdam) are estimated between 99.7 $/t and 149 $/t as shown in Figure 9. In the period 2009 to 2018, CIF ARA spot prices of wood pellets were on average 162 $/t and peaked July 2014 at 185 $/t and were at its lowest in January 2017 at 112 $/t.

The cost comprise raw feedstock cost at roadside (wood chips or bagasse), transport to a pellet mill for, transport of pellets to an export shipping terminal, shipping to the Netherlands and unloading and storage in the Netherlands (port of Rotterdam).

In the case of further barging to a customers' inland port, costs of 4-20 €/t can be expected. Distribution to industrial end users by vessel adds, therefore, on average 18 $/t to the total supply chain cost.

The lower costs apply for waterways in proximity to ocean ports, the higher when barging does go into Central Europe reaching the upper Rhine or the Danube via the Main. Unforeseen cost influencing contingency are low water or ice closure of water locks causing delays. Bulk unloading implies costs of 5-8 €/t. Bulk storage in warehouses at the port or loading station over short periods of time result in about 5 €/t, followed by another 3 €/t for the reloading to trucks for onwards transport of distribution.

Figure 9 Cost structure of pellets supplied to industrial end-users (by vessel), compared to ranges of historic wood pellet spot prices (2009 – 2018, CIF ARA)



Source: own calculation

2.2.5 Pellet delivery for residential end-users

For residential consumers, the distribution via blower truck in combination with 5-6 t built-in storages connected to the pellet boilers is one option to reduce supply chain costs. Costs for this efficient distribution mode can be estimated in the range of 23-33 €/t.

Alternatively, pellets are packed in 15 kg sacks and palleted (10-15 €/t) after screening and manipulation (0-10 €/t) in an interim (seasonal) storage of the regional distributor. Total costs of the seasonal storage in these smaller scale warehouses are estimated with about 15€/t.

If pellets are imported in containers, they need to be packed and palettized if the container is loaded in bulk. But import does also happen with bagged and palettized pellets in 40 feet containers. Costs in this chain start with TSCTHC costs of 15-30 €/t followed by local port costs for unloading, inspection and eventually necessary re-stacking or re-palleting in port warehouse before onwards delivery. Those costs are estimated at 15 - 20 €/t, in occasional cases up to 40 €/t.

Clever container loading and quality packing/palleting can minimize costs. Any interim storage costs apply as above. Residential consumer bags are then distributed to customer warehouses with additional estimated costs of 5-15 €/t. Quality and safety management has to be considered also at this site, as well as final loading and transport to the end users.

Figure 10 Loading (left) and sealing (right) of bulk transport in normed shipping container

Source: Wild & Partner

Figure 11 Pellet blower truck loading (left) and blowing into the cellar of a residential consumer (right)

Source: Stadlober GmbH

2.2.6 Conclusions

Wood pellets logistics builds upon only a moderate number of innovations addressing the needs for pellets handling and pellets handling alone. Deployed supply chain processes and routines are the same or sometimes slightly adopted versions as for other commodities. Thus, the discussion on potential efficiency gains can be seen in a broader context of logistical improvements and the transport sector in general. For the presented work, these overall improvement potentials are only shortly mentioned, as the focus was to clearly separate the few exceptional wood pellet supply chain specific improvement potentials.

In summary, overall improvement potentials for logistics of any commodity include thorough negotiations for all supply chain steps, transport contracts for higher volumes, optimal utilization of the weight capacity of the different transport means, minimized storage periods, elimination of waiting and stand-still times and general handling improvements and elimination of risks. Wood pellet supply chain specific improvement potentials include increased energy and bulk densities, reduced mechanical stress for pellets along the supply chain and eventually associating co-owned berths with storing and loading facilities for Panamax-vessels and well trained stevedores.

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Visser, Lotte; Hoefnagels, Ric & Junginger, Martin (2019) Wood pellet supply chain costs - A review and cost optimization analysis. Copernicus Institute, Utrecht University (forthcoming)

All sources for continuous pellet price collection are listed below:

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http://developpement-durable.bsocom.fr/Statistiques/ReportFolders/reportFolders.aspx
https://depi.de/de/
http://www.aielenergia.it/
http://pelletsforbundet.se/statistik/
https://www.bfs.admin.ch/bfs/de/home/statistiken/preise/landesindex-konsumentenpreise.html
https://www.futuremetrics.info/
https://www.argusmedia.com/en/bioenergy/argus-biomass-markets

3 Technical advancements & innovation potential for wood pellet supply chains

3.1 Technical Advancement of pellet supply chains[5]

Jaya Shankar Tumuluru, Chenlin Li, J. Richard Hess & Patrick Lamers (INL)

3.1.1 Advantages of Biomass Densification

Low bulk densities in herbaceous and woody biomass create problems in handling and result in high transportation costs. Densification, the compression of loose biomass into a pellet, briquette, cube, or other using mechanical systems, can help overcome density limitations and reduce moisture content and volume, making the biomass more stable and durable for long-term storage and transportation (Tumuluru et al. 2011).

Densification boasts several other advantages, including consistent particle size distribution, improved flowability for feeding and handling, and improved compositional quality for converting biomass into products towards different end-use applications.

Pellet mills, cubers, and briquette presses are common systems used for biomass densification. Pellets, in particular, are the most commonly used densified product for bioenergy production.

3.1.2 Conventional Pellet Production Process

One of the major limitations facing the use of high moisture (above 30%) woody and herbaceous biomass for biofuels production is high preprocessing costs (Searcy et al. 2015).

Preprocessing, which entails size reduction, drying, and densification of the biomass, represents about 33–35% of the total feedstock cost. Research has shown that unit operations performance with regard to energy consumption, throughput, and capital cost plays a major role on the total cost of the pellets produced. Conventional pellet drying takes about 65–70% of the total pelleting energy (Lamers et al. 2015; Tumuluru 2015 & 2016).

In the conventional pellet production process (Figure 12), high-moisture biomass is conveyed, or transferred, through a grinder and is then sent to a high temperature rotary dryer where it is dried to a lower moisture content. Once dried, the biomass is sent to another grinder for further size reduction and to be pelletized using steam.

A significant issue in drying biomass with high-temperature dryers, however, is the emission of volatile organic emissions (VOC), which pose a serious concern for both humans and the environment.

In addition, rotary dryers can take about 70% of total energy, comparing to an energy consumption of 9% for pelleting.

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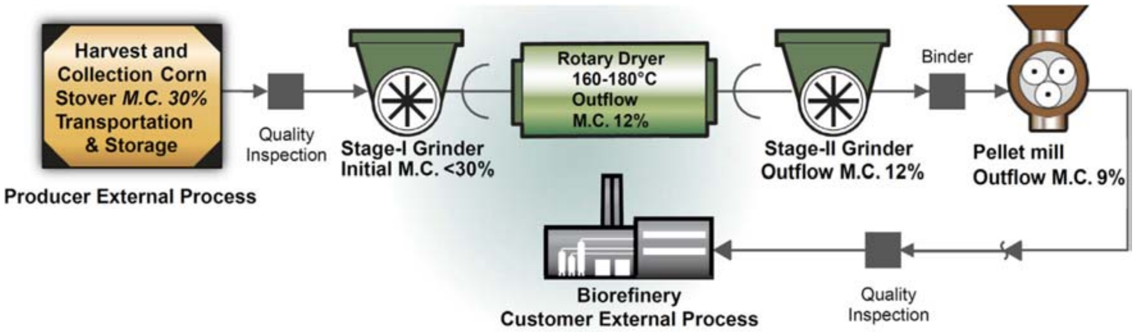
[5] An Annex to this report provides details on the innovation potentials, especially for “wet” pelletization. It is available on the IEA Bioenergy Task 40 website (www.task40.ieabioenergy.com)

Figure 12 Conventional pelleting process



Source: *Lamers et al. (2015)*

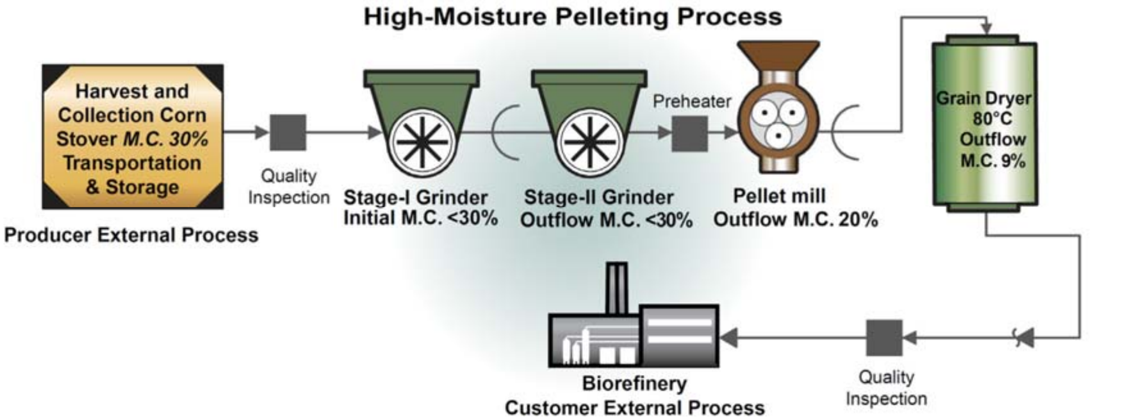
3.1.3 High Moisture Pellet Production

To handle high moisture biomass, advanced preprocessing technology needs to be developed to adapt to a wide range of biomass moisture content with reduced cost, energy consumption and harmful impact to environment.

Idaho National Laboratory, sponsored by U.S. Department of Energy, has developed a high-moisture pelleting process (Figure 13) to reduce grinding and drying energy, make pelleting more cost-effective and convert biomass into a dense and flowable product. High-moisture content (30–35%) biomass is preheated and pelletized instead of dried prior to pelleting as in the conventional pelleting process. Rather than using a rotary dryer, this process uses a grain or belt dryer to lower moisture content.

These grain and belt dryers are less energy and capital-intensive, and the low temperature drying process also eliminates VOCs. In addition, steam conditioning is replaced with a short preheating step, where biomass moisture can be reduced. Preheating can also promote softening of the natural binders in the biomass, increase the throughput of the pellet mill and reduce the energy requirement per kilogram of biomass pellets produced.

Figure 13 High moisture pelleting process



Source: *Lamers et al. (2015)*

3.1.4 Pellet Quality

The quality of the pellets produced plays a major role in handling, storage and transportation properties. Quality is heavily influenced by factors such as preheating temperatures and initial moisture content of the feedstock. With respect to density and durability specifically, pellet quality decreases with high moisture content (Tumuluru et al. 2016). Efficient moisture management, therefore, is critical to reduce the preprocessing costs of biomass.

One measure for product quality during pelleting lies in the binding of the biomass itself, which could be a result of glass transition temperature changes in biomass components such as lignin, waxes, protein, and others (Tumuluru 2014 & 2018). Lignin, an organic polymer found in the cell walls of many plants, is considered a basic binding agent for both woody and herbaceous biomass to form pellets (Tumuluru 2018).

Under glass transition temperature (Tg) - the range of temperatures where a material transitions from a hard to viscous state - lignin acts as a brittle material; however, above Tg, it's viscous. Once the lignin cools, it re-solidifies and strengthens the densified biomass. Pellets produced below the Tg exhibit lower durability.

Pilot scale testing and commercial pellet mill testing of this high-moisture process have produced consistent results. The studies indicate the quality of pellets decreases with increased moisture content (Tumuluru et al. 2017). Tests also signified that drying the high moisture pellets helped improve durability values and that pelleting energy consumption increased with higher moisture content. One major benefit of a high-moisture process is that both woody and herbaceous biomass can be pelleted at high moisture contents.

3.1.5 Techno-economic Analysis of High Moisture Pelleting Process

Conventional biomass production has traditionally been hamstrung by supply chain issues that have limited it to specific areas. Even where corn stover, pulpwood, energy crops or other herbaceous or woody residues can be easily and cheaply procured from local growers, supply uncertainties caused by inclement weather, drought and flood have caused financial analysts to classify biorefining as high risk, limiting broader investment.

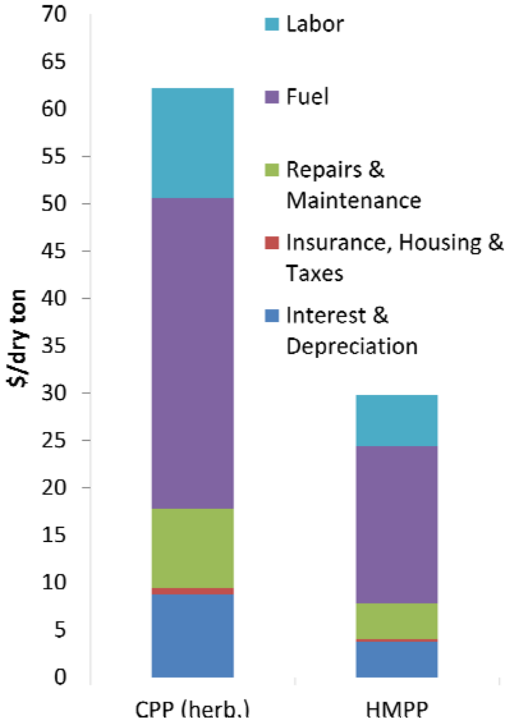
Scaling up the nation's biorefining industry will require more biomass at less cost and without interruption. To reach a 2022 fuel target of gasoline at $3 per gallon, the U.S. Department of Energy's Bioenergy Technologies Office (BETO) has set a biomass production goal of $ 88/t. In *Techno-economic analysis of decentralized biomass processing depots,* published in the journal Bioresource Technology, a team led by Dr. Patrick Lamers of Idaho National Laboratory points toward an advanced system of distributed biomass processing centers as the best way forward. These "depots" can use one or several biomass types to generate uniform feedstock commodities at lower cost and less risk. With the support of depots, biorefineries could be built almost anywhere, including lower yield areas.

At a standard depot, the focus would be on improving feedstock stability, bulk density, flowability, thereby reducing material losses. Any improvement of feedstock quality would be a value-add rather than the operation's primary intent. The process flow includes particle size reduction, moisture mitigation and densification. The most basic standard depot configuration is a conventional pelleting process while the more advanced standard depot can make the process more efficient by implementing high moisture pelleting process.

An analysis based on a scenario in which 10 depots support an annual biorefinery demand of 725,600 metric tons was conducted (Lamers et al. 2015). Variables examined included cost year indices, total capital investment and ownership costs (insurance, housing & taxes, and interest & depreciation), operating costs (repair and maintenance, fuel and labor cost). Economic comparison was conducted for the conventional pelleting and high-moisture pelleting process. This analysis concluded that decentralized depots can process biomass economically with the cost to produce pellets using a high-moisture pelleting process at $ 30.8/t, 37% saving comparing to the conventional pelleting process ($ 47.8/t) used in industry (Figure 14).

Fuel cost is significantly lower for high moisture pelleting process compared to conventional process mainly due replacing rotary dryer with grain or belt dryer. Lower capital costs using high moisture pelleting resulted in lower interest and depreciation. Repairs, maintenance, insurance, housing and taxes are also lower for high moisture pelleting process. The economic uncertainty of each design depends greatly on the energy consumption of the processing equipment involved. By increasing the effective machine throughput, reducing the number of equipment operations necessary to process material, consequently lowering capital costs.

Figure 14 Cost comparison between high moisture pelleting process (HMPP) and conventional pelleting process (CPP)



Source: Lamers et al. (2015)

In summary, high moisture pelleting process has shown many benefits including decreased VOC emissions and harmful impact to environment, reduced risk of fire and explosion, effective management of the biomass moisture, and less capital cost and energy consumption. This technology also has the promise to process various types of feedstocks such as energy crops, other agricultural residues (sugar cane bagasse) and municipal solid wastes with high moisture characteristics, into stable and durable pellet products towards different end-use applications.

3.1.6 References

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3.2 Torrefaction

Michael Wild (Wild & Partner) & Lotte Visser (UU)

Torrefaction, the roasting of biomass in an inert atmosphere with aim to drive off remaining water and a certain percentage of the volatiles in the biomass, is one of today´s more promising technological advancements to improve the efficiency along the whole value chain of biomass for energy.

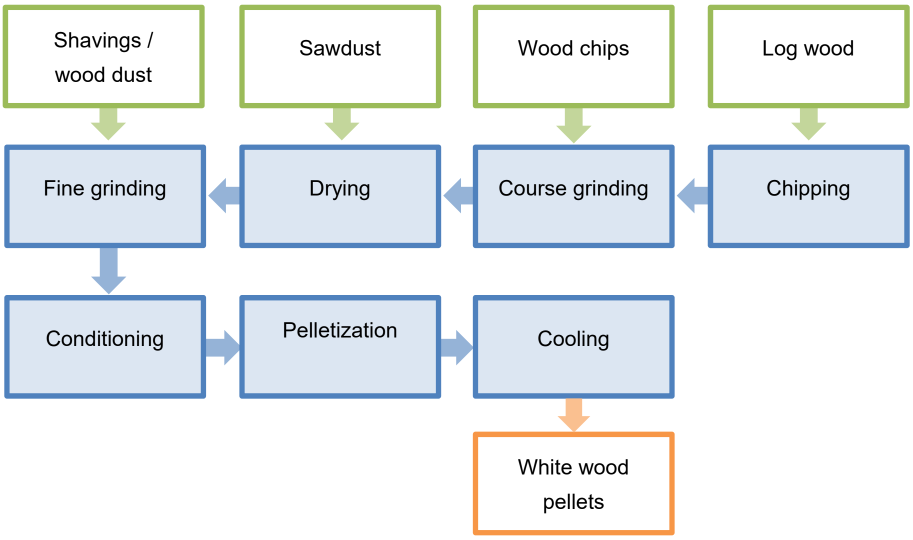
Torrefaction is one of the technologies that made it from R&D status to first industrial installations, resulting in sizable production in. numerous demonstration plants around the globe.

Biomass can be torrefied at every stage of the supply chain, close to the origin, in loading ports or eventually directly at the consuming power plant before entering the milling process. In most of the cases the processing of the biomass as close as possible to the source is the method of choice.

Therefore, and also for direct comparability, it will be assumed in the following paragraphs that the torrefaction is established at the same stage in the supply chain as the White Wood Pellets processing, close to the forests.

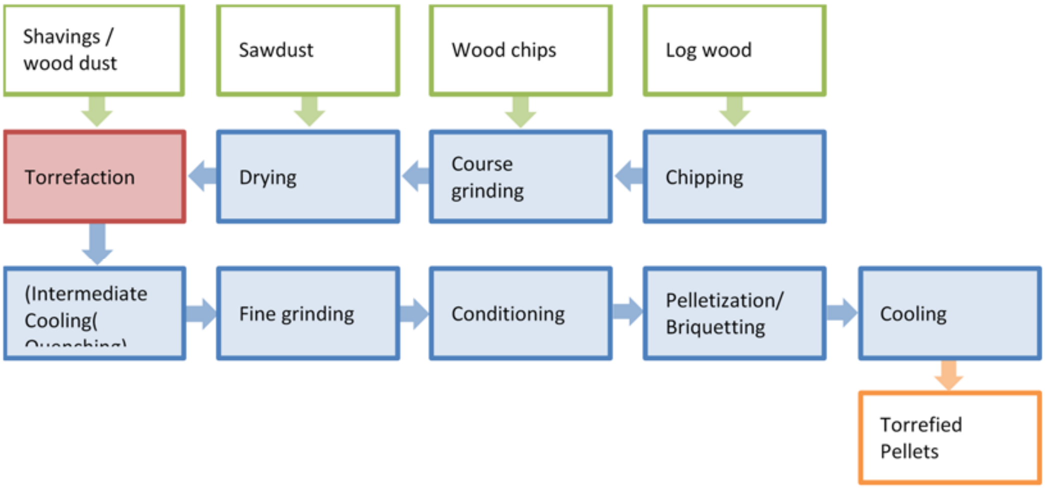
Steps analyzed within the comparison of the White Wood Pellets (WWP) chain with the alternative of Torrefied Wood Pellets (TWP) or Briquettes are depicted in Figure 15 and Figure 16.

Figure 15 White pellets processing steps



Source: Wild & Visser (2019)

Figure 16 Torrefied pellets processing steps



Source: Wild & Visser (2019)

In order to calculate the energy consumption across a specific supply chain, the following assumptions were made:

Biomass in the form of forest residues and thinnings (50% moisture content) is assumed to be the result of harvesting of value timber, and processing of residues. Biomass is assumed to be transported by truck to a pellet plant.

Raw material is chipped in a diesel driven chipper, dried, ground and densified to ISO 17225-2 I2 (ISO 2016) requirements, to create white wood pellets containing 8% moisture, with a bulk density of 650 kg/m3 and a NCV of 17.56 MJ/kg.

Torrefied pellets minimum requirements, also written down in ISO TS 17225-8 (ISO 2016), are currently available at NCVs from 20 to 30 GJ/t, depending very much on the chosen degree of carbonization by the producer. For the comparison in this study, a process is chosen in which all driven of syngases are used for feedstock drying and no excess energy remains available in the form of syngases.

Pellets are assumed to be transported by truck over 15 km one-way to the export port. Rail access is not available in the particular location investigated. In-port logistics consist of the unloading and conveying of pellets into storage and later on conveying from storage onto vessels. Air travel of supervisors and quality surveyors to export ports is included in this stage of the supply chain. Pellets are transported overseas on Handysize vessels, at an average speed of 13 knots/h.

At the import port, pellets are unloaded and conveyed to storage and later transferred onto trucks, to be transported for 50 km one-way to the end consumer. In this final supply chain stage only the energy of unloading and conveying pellets to the consumer stockpile is included.

3.2.1 Processing

The lineup of machinery in a Torrefaction plant is not dramatically different to a White Wood pellet plant. An additional “superdrying-roasting” element is introduced between pre-drier and hammer mill. In this roasting process, independent of employed technology, a certain percentage of the volatile matter is driven off in the form of syngas. This syngas drive off causes an energy defect and an over proportional mass defect resulting in a product with higher energy density per product mass. The energy in the syngas is not wasted but reinjected as fuel in the pre-drying unit reducing the need for woody or non-woody fuel at this stage.

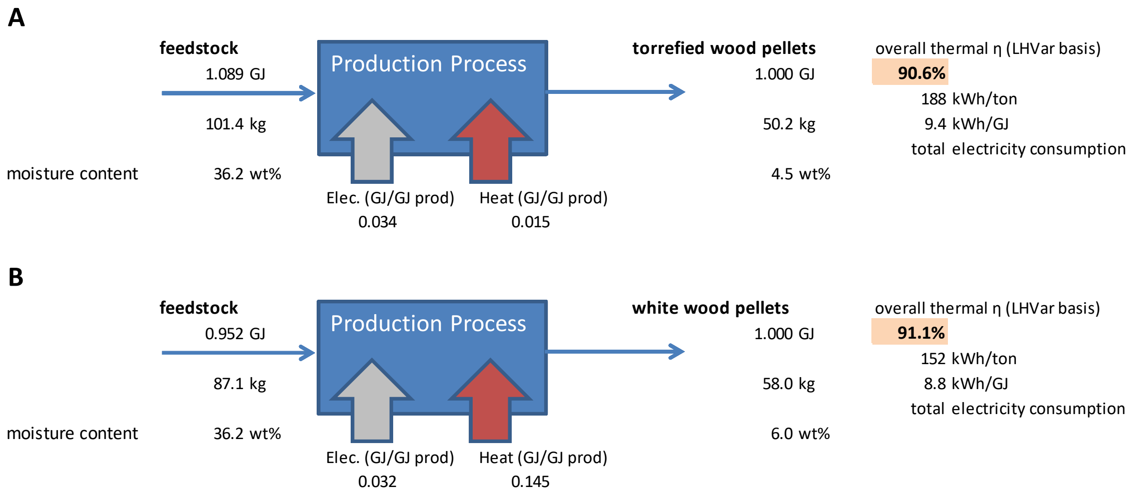
IBTC (2018) analyzed the aggregated data for mass and energy throughput of existing and producing torrefaction plants and compared results with the respective mass and energy throughput of white wood pellet plants from literature.

The mass and energy balances were calculated in a black box approach as shown in the figure below, using an identical energy output basis. The results illustrate that drying is the major thermal energy sink in any pellet production plant.

Moreover, the average electricity consumption of torrefaction plants is higher than for white wood pellet plants (excluding debarking) in kWh/t pellet. This difference is in line with current experience at pellet press suppliers. Expressed in energy output basis, this difference is smaller as a result of the higher energy content of torrefied wood pellets.

The average energy efficiency for both torrefied and white wood pellet plants are comparable when a conventional drying technology is assumed. The latter is the result of using the heat from combustion of the torrefaction gases (syngases) for feedstock pre-drying and further temperature increase up to torrefaction conditions. Therefore, lower supplementary heat input is required during torrefaction in comparison with white wood pellets. However, during white wood pellet production this is compensated by the lower mass input in terms of feedstock.

Figure 17 Comparison of (A) torrefaction vs. (B) white wood pellet production



Source: Nanou et al. (2017)

This data on thermal and electrical consumption and efficiency were fed into a full logistics chain analyzes to understand the advantage of one over the other fuel at the consumers stock yard.

This analysis as such has not considered some of the major benefits of Torrefied Wood Pellets over White Wood Pellets like better grindability, lower off-gassing of carbon monoxide and considerably better water resistance as only the last one could have an influence on the efficiency in logistics and storage but no firm data on this is available currently. Also the reduction in chlorine during the torrefaction and the advantages resulting by opening up the fuel window for chlorine rich agro by-products (Keipi et al. 2014) are not analyzed here.

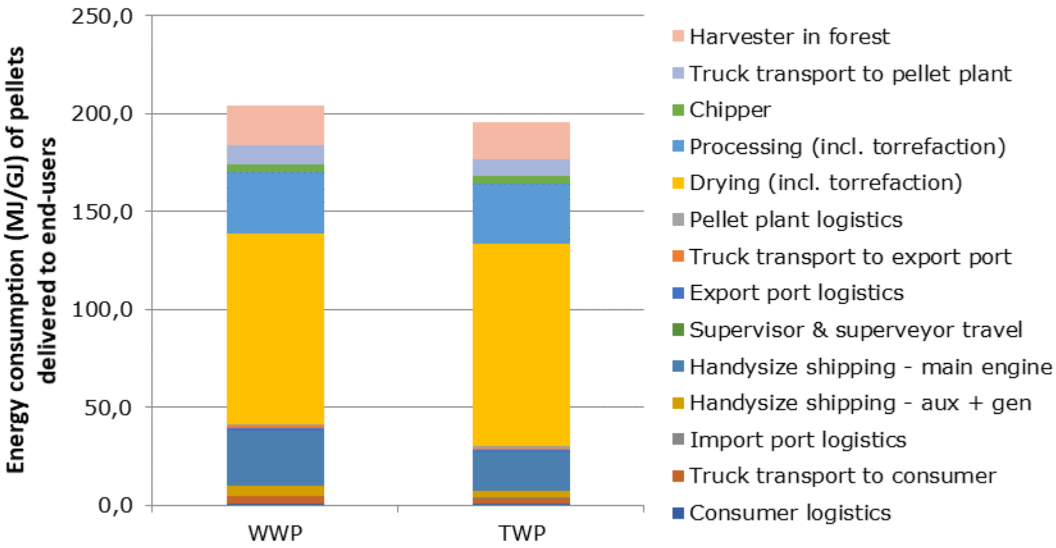
3.2.2 Energy comparison across the chain

When analyzing the entire pellet supply chains, it becomes obvious that it is preferable to establish additional pre-treatment and densification as early in the chain as possible. The improved handling characteristics and increased energy density of torrefied pellets result in lowered energy consumption during transport from processing plant to customer. By including torrefaction at the pellet plant, the subsequent handling, truck transport and shipping of pellets becomes more energy and cost efficient, and the characteristics of the produced biofuel are more suitable for handling within existing coal chain premises and installations in the import and export port and at the end consumer.

As shown in previous section, by reference to final products the overall thermal efficiency of WWP processing and Torrefied Pellets processing is almost identical. The pelleting of torrefied wood does consume slightly more electricity than pelleting of wood only (IBTC 2018).

Whether torrefied pellets save energy across the supply chain depends on the balance between marginally increased processing energy consumption and decreased transport energy consumption. Figure 18 shows that for this particular supply chain, from Indonesia to Japan, overall energy savings of 6.7% can be reached by shifting from WWP to TWP.

Figure 18 Comparison the energy consumption of white wood pellets (WWP) and torrefied wood pellets (TWP) supplied to the end consumer



Source: Wild & Visser (2019)

On final product energy basis, upstream harvesting and transport is 8.2% less energy intensive for TWP than for WWP. The production of TWP requires the same amount of process heat as WWP. Differences are within up to +0.5 % for TWP compared to WWP. Processing of torrefied wood pellets requires more electricity per ton, 188 kWh/t compared to 152 kWh/t for white wood (IBTC 2018).

This is, however, largely offset by the larger energy density of TWP, resulting in only slightly higher electricity consumption per unit of delivered energy, 8.5 kWh/GJ for TWP versus 8.8 kWh/GJ for WWP.

Table 2 Full chain calculation comparison results in MJ per GJ delivered energy

	Device/Machine/Installation	Normalised WWP	Normalised TP	Energy consumed TP/WWP
		MJ/GJ	MJ/GJ	%
NCV of product		17,56	22,20	
Raw material				
	Harvesting smaller machines			
	Harvester in forest	20,73	19,02	91,77%
	Loader to truck			
	Truck to plant	9,30	8,53	91,77%
	Chipper	4,25	3,90	91,77%
Processing (pretreatment)	black box data from processors	31,16	30,49	104,18%
	thermal and electric energy incl drying	97,69	103,75	
	Source IBTC study			
Downstream				
to port	Wheel loader 300kW	0,49	0,38	79,10%
	Truck	1,09	0,86	79,10%
	Train			
	(Un)Loader or crane 300kW	0,49	0,38	79,10%
in port	Conveyor	0,05	0,04	79,10%
	Loader	0,49	0,38	79,10%
	Conveyor	0,05	0,04	79,10%
	Crane 400kW Diesel	0,31	0,25	79,10%
	Auxiliary			
	Vessel berth engin			
	Surveyor&Superviser travel	0,06	0,05	79,10%
pellets shipping				
main engine	Handysize	49,55	35,39	71,41%
	Handymax	38,85	27,74	71,41%
	Panmax	32,02	22,87	71,41%
aux+gen	Handysize	6,66	4,76	71,41%
	Handymax	5,18	3,70	71,41%
	Panmax	4,38	3,13	71,41%
unloading	cranes	0,05	0,04	79,10%
	elevators			
	conveyors	0,01	0,01	79,10%
tertiary transport	shifters			
	loaders to truck/train/barge	0,49	0,38	79,10%
	train			
	truck	3,64	2,88	79,10%
	barge			
	loaders from truck/train/barge	0,49	0,38	79,10%
Consumers stockpile	Loaders	0,17	0,14	79,10%
	4 Conveyors	0,05	0,04	79,10%
	full chain of pellets			
	Handysize	227,27	212,10	93,33%
	Handymax	215,07	203,40	94,57%
	Panmax	207,44	197,95	95,42%
	downstream logistics only			
	Handysize	68,38	50,31	73,57%
	Handymax	56,19	41,60	74,03%
	Panmax	48,56	36,15	74,45%
	full chain on WWP and torrefied briquettes			
	Handysize	227,27	203,86	89,70%
	Handymax	215,07	195,16	90,74%
	Panmax	207,44	189,71	91,45%

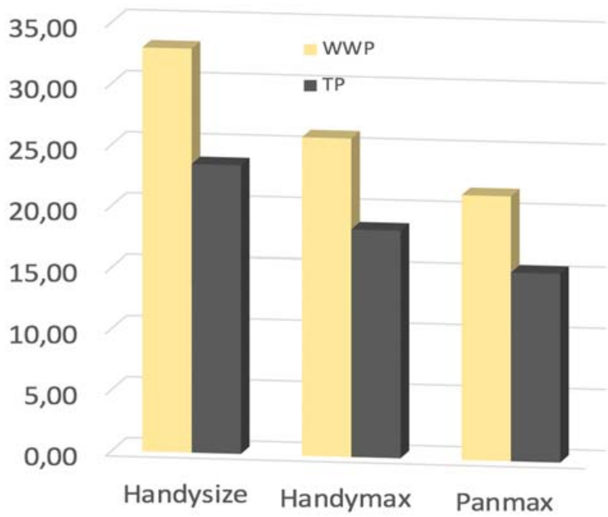
Source: own calculation

The energy consumption reduction across the TWP supply chain, at 22 MJ/kg (NCV basis), largely stems from a reduction in downstream logistics of 26.4% if based on transport in a Handysize vessel.

The longer the distance the supply chain is bridging, the larger the energy savings as a result of the transport energy consumption having a larger share across the supply chain (i.e. from Brazil to China).

The downstream energy reduction across the chain is the largest for transport in Handysize ships (26.4 %) and slightly lower for transport in Handymax (26.0%) or Panamax ships (25.6%). The energy reduction is larger for the shipping component than for the other logistics stages, which is why the Handysize chain, in which the share of shipping is larger, results in a larger energy saving. The reduction in downstream energy requirements confirms the advantage to establish additional pre-treatment as early in the chain as possible.

Figure 19 WWP versus TP: Energy consumed in shipping



Source: IBTC & Wild (2018); data in MJ/GJ shipped

In terms of energy carriers consumed and again referenced to MJ energy supplied to customer, a 16% increase in bioenergy, used for drying and torrefaction, is needed in the processing of torrefied wood pellets. The consumption of fossil fuels is however reduced, with a 20.9% reduction of liquid fuels consumption (Diesel, MDO and IFO) and a 2.3% reduction of electricity consumption. The picture of a very relevant overall energy reduction across the supply chain of 6.7% is completed by an even more considerable reduction in fossil fuels.

3.2.3 Sensitivity

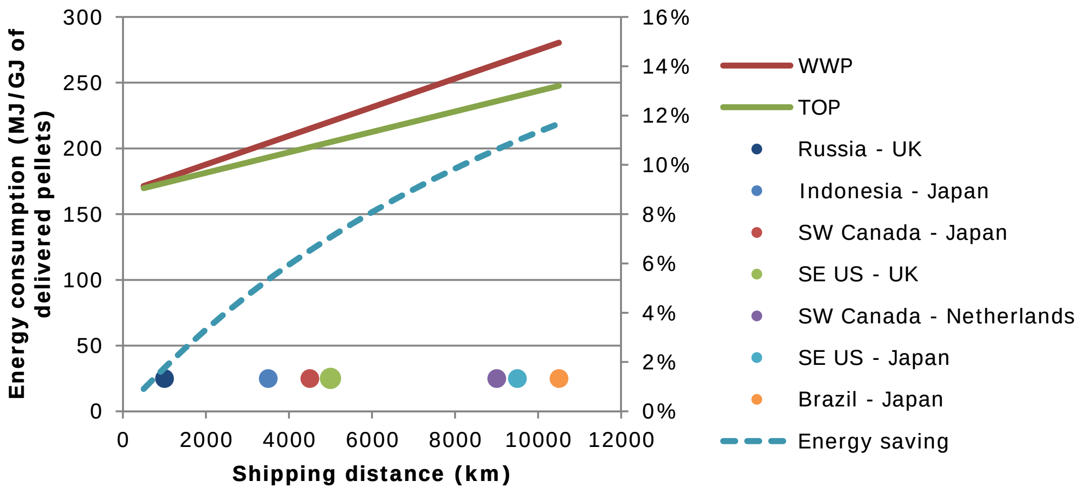
3.2.3.1 Shipping distance

The impact of logistics on supply chain energy consumption and GHG emissions is large. With shipping in this case study accounting for 31% of the non-renewable energy consumption across the supply chain. Therefor the comparative sensitivity of the overall GHG balance to shipping distance for the two supply chains is worth analyzing.

Since a considerable energy consumption and GHG emissions reduction can be realized for downstream logistics for torrefied pellets compared to white wood pellets, the longer the shipping distance, the larger the expected savings are. Figure 6 shows the respective energy consumption for different shipping distances.

For intra-continental transport distances, for instance from Russia to the UK, the supply chain savings are 1.8%. For the supply chain analyzed in this paper, from Indonesia to Japan, the energy savings have increased to 5.3%. In the current situation, a significant share of the worldwide pellet trade is between the southeast of the United States (SE US) and the UK/ARA, for this supply chain, potential energy savings increase to 7.1%. Longer transport distances are possible, for instance from southwest (SW) Canada to the Netherlands (10.6% savings), SE US to Japan (11.0% savings) and Brazil to Japan (11.7% savings).

Figure 20 Impact of shipping distance on supply chain energy consumption for Torrefied Pellets (TWP) and White Wood Pellets (WWP)

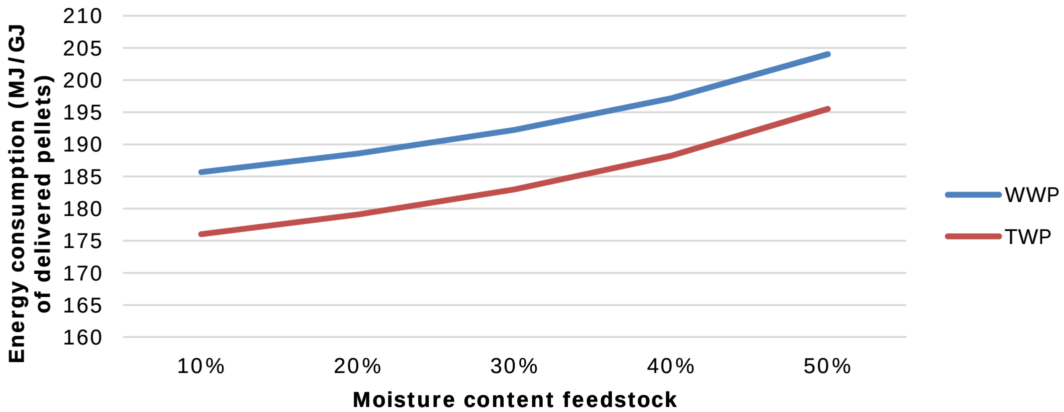


Source: Wild & Visser (2019)

3.2.3.2 Moisture Content

Feedstock drying, evaporating and removing the water content from feedstock represents the dominant energy consumer in the overall chain. The thermal efficiency of producing torrefied pellets, including the energy required for torrefaction, is marginally lower for TWP than for WWP, as a result of which, the potential energy savings are slightly reduced for increased feedstock moisture content. If pre-dried feedstock is supplied, at 10% moisture, TWP result in an energy saving of 5.2% compared to WWP. For moisture content of 50%, this is reduced to 4.2%, as can be seen in Figure 21.

Figure 21 Impact of moisture content on supply chain energy consumption for Torrefied Pellets (TWP) and White Wood Pellets (WWP)



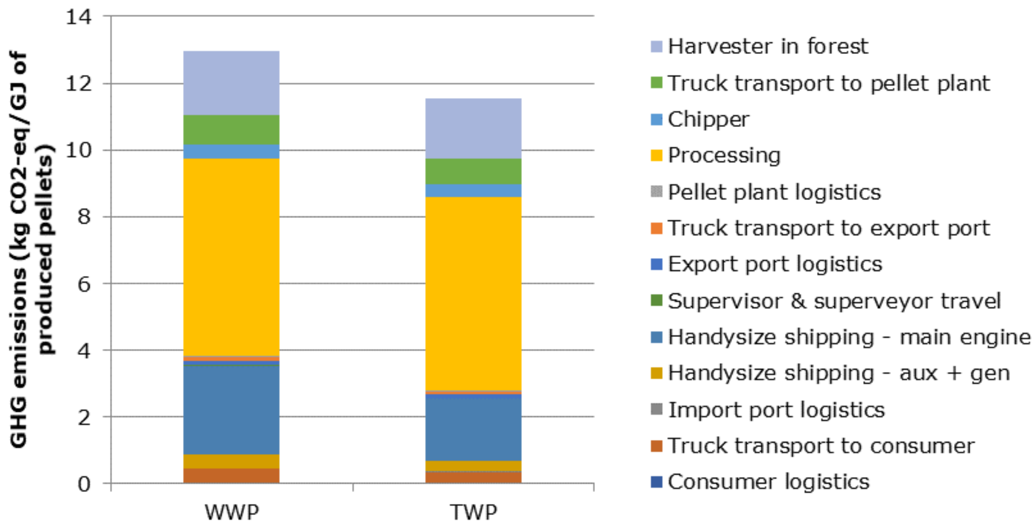
Source: Wild & Visser (2019)

3.2.4 GHG comparison along the chain

Biomass used to provide the thermal energy in the pellet production process is considered carbon neutral under EU legislation, based on the assumption that CO_2 emissions during combustion will be re-absorbed during the subsequent tree growth[6]. In order to compare the GHG emissions across the chain, the GHG emissions resulting from biomass combustion are not included in the overall calculation.

The GHG calculation along the chain, using BioGrace emission factors, results in an increased advantage of the torrefied wood pellets (Figure 22). Importing torrefied wood pellets instead of white wood pellets can reduce 11% of the CO_2 emissions across the analyzed chain. This reduction is larger than the relative energy reduction since GHG emissions from bioenergy consumption covering the thermal needs were assumed to be carbon neutral.

Figure 22 Comparison of the GHG emissions of white wood pellets (WWP) and torrefied wood pellets (TWP) supplied to the end consumer



Source: Wild & Visser (2019)

3.2.5 Additional advantages to be gained

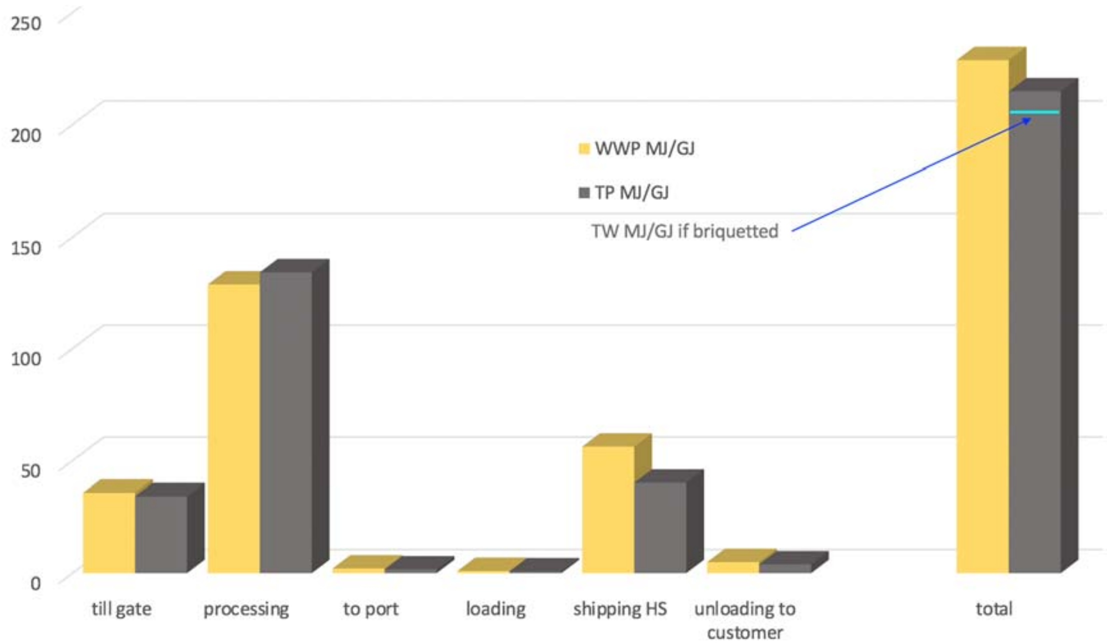
The analyses so far compares products of the same form factor. However, the brittle characteristic of densified torrefied biomass would allow densification into larger pieces such as briquettes or cubes, as this would still be acceptable feed material for coal mills. 50mm max in each dimension seems currently to be the maximum size acceptable by standard coal plants.

Recent tests at coal power plants like the one at PGE plant in Bordman, Oregon are carried out with both pellets and briquettes/cubes of torrefied biomass (pers. comm. with AIREX and HEETWAY).

Briquetting reduces electricity consumption in densification by almost 50% in respect to pelleting (pers. comm. with Wolfgang Stelte). In this case, the energy consumption advantage of the torrefaction chain versus the WWP chain almost doubles to 10.3%.

[6] This assumption ignores some potential sources of CO_2 emissions, such as (indirect) land use change, and ignores the time lag between the moment of harvest and the re-absorption of carbon. Taking these aspects into account is beyond the scope of this research.

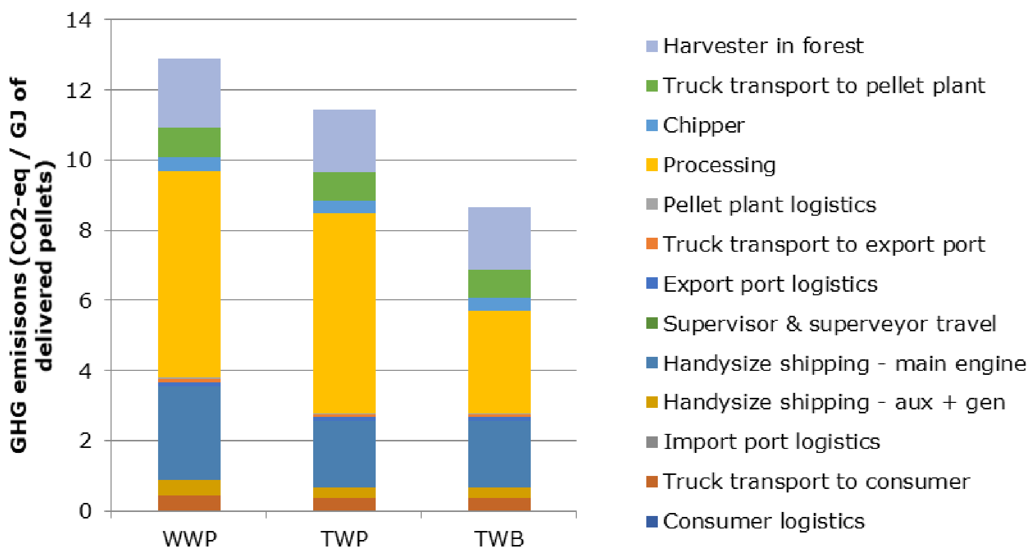
Figure 23 Comparison the energy consumption of white wood pellets (WWP) and torrefied wood pellets (TWP) supplied to the end consumer



Source: IBTC & Wild (2018); Wood torrefied to ca. 22 MJ/kg

The GHG advantage increases accordingly, to a 33% reduction of torrefied wood briquettes (TWB) compared to WWP, as can be seen in Figure 24.

Figure 24 Comparison of the GHG emissions of white wood pellets (WWP), torrefied wood pellets (TWP) and Torrefied wood briquettes (TWB) supplied to the end consumer

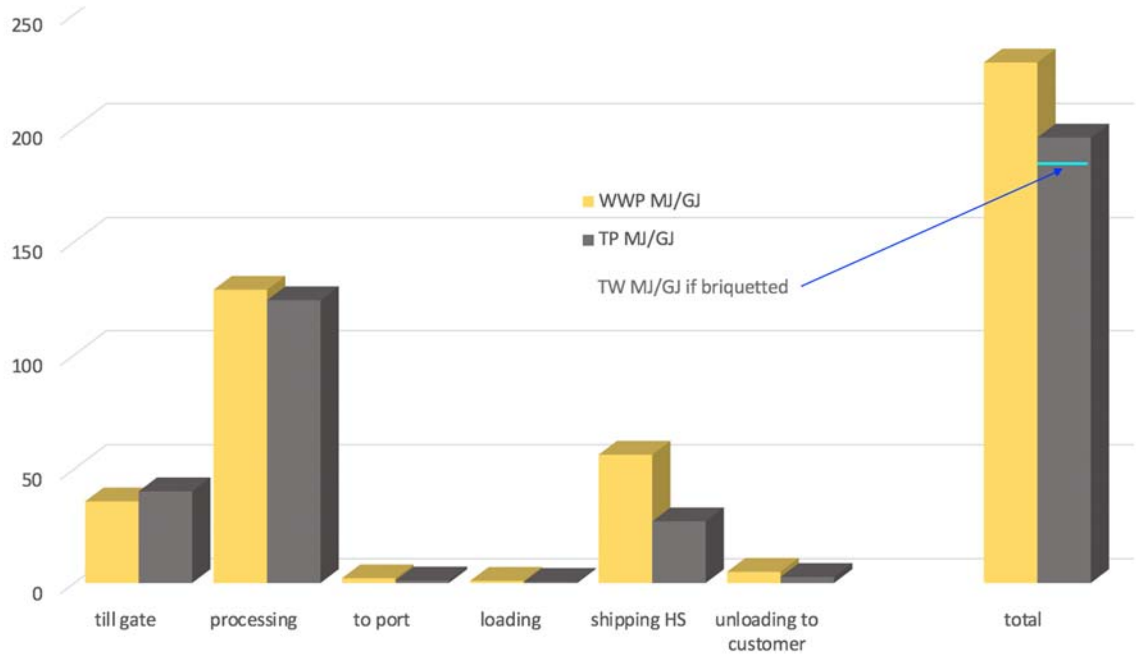


Source: Wild & Visser (2019)

If biomass is torrefied to a higher degree, i.e. carbonized as contemplated and practiced by some of producers, the specific energy uptake in densification is also reduced, especially as for such material some binders will be added reducing the friction in the compression channel. Advantages in logistics increase further and can become as high as 12%, in case of briquetting 17%.

Such very high degree of torrefaction will find its justification only when economical use of the syngases can be achieved at the individual processing site, and the calorific value is driven up to 30MJ/kg.

Figure 25 Comparison the energy consumption of white wood pellets (WWP) and torrefied wood pellets (TWP) supplied to the end consumer



Source: IBTC & Wild (2018); Wood torrefied to ca. 30 MJ/kg

The above energy savings do not yet include the potential savings in the stages of pre-conditioning for combustion and combustion itself as a result of the increased brittleness of torrefied biomass. Torrefaction prior to densification can highly reduce the energy needed for grinding. Ghiasi et al. (2014b) have shown that the energy required to grind torrefied chips was reduced from 292 kJ/kg for untreated wood chips to 39 kJ/kg for torrefied wood chips.

Similar reductions were also found by Phanphanich & Mani (2011), whose research found a factor 10 energy reduction for pine chips and a factor 6 reduction for logging residues. Repellin et al. (2010) have also found grinding energy reductions up to 90% for material torrefied at 280 °C. These results are based on lab-scale tests but are considered indicative for potential reductions on industrial scale.

3.2.6 Reflections on cost impacts

In trade the reduction of the carbon footprint is a desired factor but not the main driver of activity. Costs are the final ruling factor. How do the presented savings in energy consumption and effort in handling and transport of the higher energy density material reflect in costs?

The moving target character of prices and the regional character of some of the cost factors will result in a blurred picture on price effects only. For instance, while a truck consumes almost the same amount of diesel per ton and kilometer independent if operated in Europe, the Americas or an Asian country, the costs of stevedores in the various ports are very different for equal services due to regional or only local reasons. A volatile shipping market and diesel/bunker fuel prices constantly on the move are doing the rest to prove any cost analyses wrong the moment it is presented.

However, independent of the absolute costs the costs share in total supply chain costs itself will always be sensitive to density in bulk handling, in our case the energy density per ton or cubic meter. This does result in a clear advantage of the higher dense torrefied product. Further cost advantages for TP can or do result from significantly increased water resistance, i.e. port storage does not need to be covered, no loading/unloading interruptions due to rain.

Own calculations along the full logistical chain, including upstream handling and logistics to bring the feedstock from forest to mill, and all the downstream steps from loading at mill to final customer stockyard, show costs of 6.44 €/GJ for White wood pellets versus 5.09 €/GJ for torrefied pellets at 22.2 GJ/t. This costs could go as low as 3.77 €/GJ for material torrefied to 30 GJ/t. A cost differential ranging from 1.35 to 2.77 €/GJ for the chain.

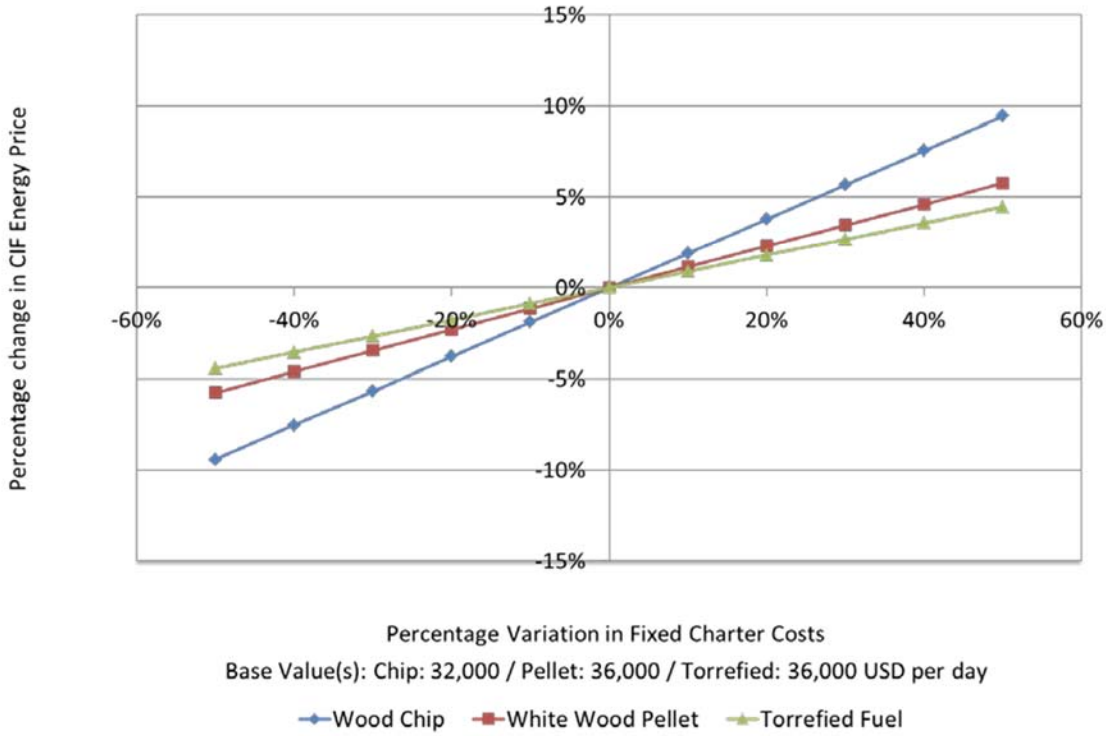
This is a significant amount, both in absolute numbers and relative to full costs which actually would be above stated costs plus stumpage or forest road sale price. That on its own should be a clear driver as the savings opportunity along the logistical chain is outnumbering each and every efficiency investments in raw material processing of combustion efficiency.

The own calculations presented are very much in line with calculations found in literature. Bingham (2012) calculates for the route from British Columbia to Europe costs of 8.24 €/GJ for WWP compared to 7.06 €/GJ for torrefied product of 21.25 GJ/t (Bingham 2012). This numbers include raw fiber costs of 1.4 and 1.5 €/GJ, respectively. The quoted study analyses other routes as well with fairly similar results in percental comparison.

Futuremetrics found that the supply chain segment “loading port to customer” presents an advantage of 0.453 $/GJ for torrefied pellets over white wood pellets on the Northern trans-atlantic route (Strauss 2014).

Hawkins Wright does point out further the decreased sensitivity in the change of individual cost factors along the logistics chain. A factor sometimes crucial for the continued performance of especially longer term supply agreements.

Figure 26 Sensitivity of CIF energy cost to vessel costs (Canada BC - Europe)



Source: Bingham (2012)

Given volatility of 300+% in daily vessel rates witnessed over the past 20 years the reduced sensitivity towards these changes - as depicted in Figure 26 - can have a significant impact on mitigation of impact of changing market conditions like vessel rates but same can be proven for fuel costs or labor rates which are probably not that volatile.

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4 Market & demand side case studies

4.1 Introduction

Fabian Schipfer (EEG) & Uwe R. Fritsche (IINAS)

In addition to the discussed technical innovations, the wood pellet industry might follow various strategies to increase its competitiveness and margin potential. Diversification of their end-use markets regarding supply regions but also regarding supplied end-user types could impact positively, although differently on the producing companies.

Commoditization: As previously highlighted by Lamers et al. (2016), fungibility (interchange-ability) is a central property for the definition of a commodity. It minimizes consumer uncer-tainty, increases market transparency, and eventually facilitates market liquidity.

Internationally recognized standards such as the ISO 17225-2 or the EN 14961-2 determine narrow ranges for parameters that could be important for the users to know before purchase or deployment in their boilers and stoves. Certification schemes including ENplus or CANplus can ensure the compliance with internal quality control and screening regarding these and additional sustainability parameters. The EN standard was created led by Sweden, Austria and Germany after often incompatible national standards resulted in unintended barriers for international trade (Thrän et al. 2017).

However, limited information or perception of existing fungibility can also contribute to inefficient markets, especially for residential wood pellet markets consisting of a high variety of end-users. In these cases, data availability and quality has to be improved to increase transparency and public perception with respect to fungibility of same-quality pellets indepen-dent of pellet color or supply-chain affiliation, e.g. whether regionally or internationally traded.

By facilitating this commoditization process on the one hand, competitive pellet producer can extend their spatial consumer portfolio resulting in lower risks of not being able to sell their products, increasing capacity utilization rates and thus also increased profitability. In the following years and for the consumer point of view, a relatively low and stable pellet price would emerge. This price would be the same in different regions apart of distance costs, variable taxes and seasonal fluctuations. Improved storage possibilities for the main supply chain routes could further stabilize prices and markets. (Schipfer et al. 2017)

On the other hand, in this scenario with more reliable conditions for the demand and the supply side, we would naturally observe lower marginal profits through the increased transparency and thus striving medium- and large scale producers that are able to reduce their unit production costs through scaling. Furthermore, the willingness to pay for sustainable sourcing and processing of the feedstock face the risk of fading. A standardized procedure of pricing-in such “soft” aspects would be necessary to counteract this development.

As discussed previously in this report, pellet price co-integration can be already observed for Germany and Austria. Further integration with prices in France and Italy in the upcoming decade can be expected if commoditization progresses in these markets.

Furthermore, overproduction for the district heating market in Sweden and Denmark in past years has already led to spill-overs into the residential heating market, which is – in contrast to the industrial segment - characterized by smaller and more distributed producers (mainly across Europe), i.e. convergence of residential and industrial wood pellet markets.

Spill-overs into industrial markets from residential markets may be even more likely, since the substitution of low-grade pellets with high-grade pellets will not pose any technical issues (Thrän et al. 2017). This convergence could lead to further spatial market integration between the central European pellet market and markets that use the ARA ports import route namely the US and Canada, as well as the large producers in the Baltic region.

Further impacts on the UK, the main pellets consumer for plain electricity production or on other large importers (South Korea, Japan) and exporters (Russia, Vietnam, China) are more difficult to assess.

Specialization: In addition to increasing fungibility and accessing multiple markets in established segments (heating, CHP, and electricity production), another option is to explore alternative markets either with modified pellets or with the very same pellet qualities. This could lead to higher-value pellet products and better margins for producers. In general, densified commodities containing large shares of biogenic carbon (also derived from lower quality - e.g. herbaceous - biomass) can be discussed as indispensable for at least three types of economic activities in addition to heat & power as current key markets for wood pellets:

(1) Activities providing carbon containing products, e.g. transport fuels, petro- and chemical industry, iron and steel industry)

(2) Activities using process temperatures too high for the provision based on renewable electricity (e.g. processing of non-metallic minerals like glass, ceramic, cement) and

(3) Activities designed for reaching net-negative emissions (biobased carbon capture and storage/BECCS).

- Challenges in the substitution of combustible energy carriers that are lightweight and storable for aviation, shipping but also space flight with propulsion technologies based on renewable electricity will require us to consider biofuels produced via gasification pathways based on non-edible cellulosic biomass. Janek & Zeier (2016) discuss current lithium-ion battery densities of about 1 MJ/kg, while liquid fuels (e.g. kerosene but also petroleum) have densities around 42 MJ/kg rendering at least long-distance electrified commercial aviation improbable in the upcoming decades. Centralized large scale gasification of lignocellulosic biomass and conversion to liquid or compressed gaseous biofuels could provide means to substitute 110 EJ of fossil based transport fuels worldwide (2015 values, based on IEA 2018).
- Main products in terms of weight from the chemical industry are in the following order polyethylene and polypropylene, bitumen, lubricants, solvents and surfactants. The higher added values of biochemical compared to bioenergy in general, novel functionalities like biodegradability for polymers and lower VOCs in solvents as well as carbon capturing options especially for lignin as a bitumen alternative should be seen as complimentary to the emission reduction gains in the bioenergy sector. (Schipfer et al. 2017). About 20 EJ (in 2010) primary energy input is estimated for this sector globally (Daioglou et al. 2014).
- Carbon-based fuels and reactants are necessary in steel production yielding a carbon-containing product. (Wild et al. 2016) estimate global primary energy consumption of 20 EJ in the iron and steel industry for 2013.
- High process temperatures are used in the processing of non-metallic minerals, especially for the production of cement but also processing of glass and ceramics. (Wild et al. 2016) estimate global primary energy consumption of 16 EJ in this industry for 2013.
- The IEA GHG R&D program discusses an annual global potential for BECCS of up to 10.4 Gt CO_{2eq} – for comparison, global energy-related emission in 2010 where at 30.6 Gt CO_{2eq}. Limitations are rather seen in sustainable biomass potentials than in storage sites. For this technical potential 59 EJ of bio-electricity and 47 EJ of biofuels are considered per year. Economic potentials are calculated to be at about 3.5 Gt CO_{2eq} assuming a price of 50 €/t CO_2 (Koornneef et al. 2012). The IEA Bioenergy Roadmap assumes in its 2 °C scenario (2DS) that BECCS would remove about 1.5 Gt CO_{2eq} by 2050, and the more ambitious "below 2DS" would require BECCS-based removals of nearly 5 Gt CO_{2eq} by 2050 (IEA 2017).

A possible relevant sectoral diversification, next to spatial diversification could result in increased resilience of the market, relaxed conditions for producers and thus ultimately also lower prices for wood pellets as an energy carrier.

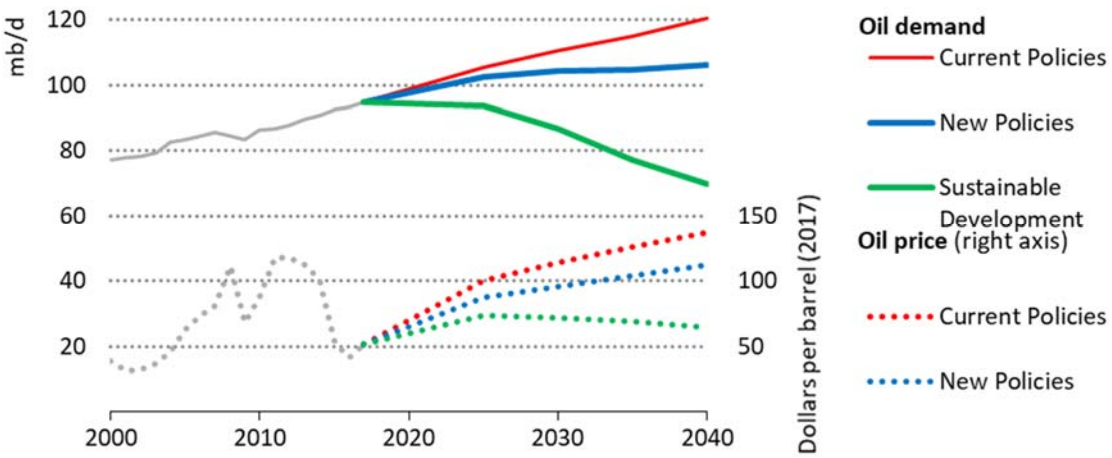
However, lower prices are equal to lower marginal profits which would force smaller and economically less efficient producers from the market place if they cannot compete with the internationally formed pellet price.

While the development of a wood pellet market for energy purposes alone would be facilitated by increasing standardization, untapping niche markets would ask for higher specialization, at least for a certain fraction of the pelletization capacities.

4.1.1 Fossil fuel price dynamics in the IEA World Energy Outlook scenarios

The World Energy Model (WEM) is used to calculate energy scenarios for the IEA World Energy Outlook and is based on energy price trajectories that are levelled for each scenario to bring "*the long-term projections for demand and supply into balance, avoiding either surfeits or shortfalls in investment*" (IEA 2018). The following figure show the range of most recent IEA oil price projections.

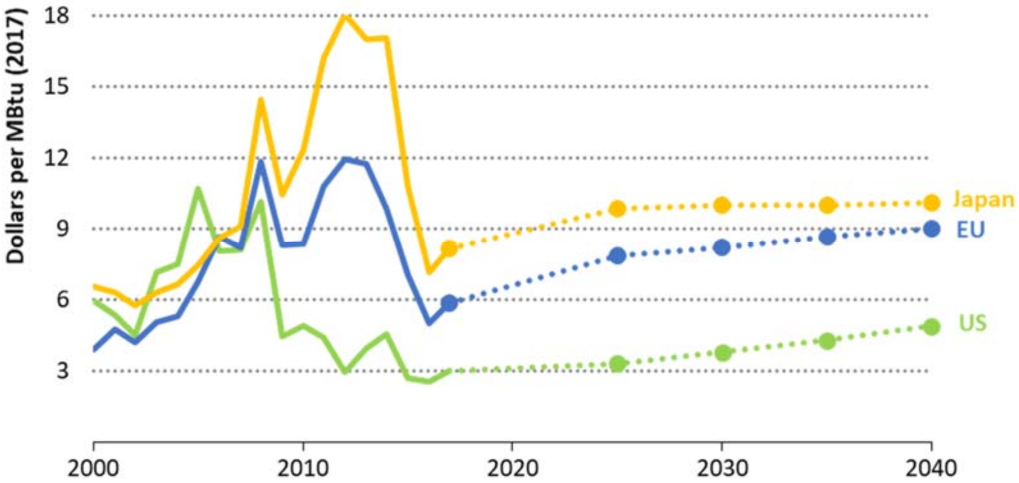
Figure 27 Global oil demand and prices by IEA scenario



Source: IEA (2018)

To provide a baseline for the economic feasibility discussion of the case studies we extract the model price developments for steam coal and natural gas of the New Policy Scenario which can be seen as a middle way of the scenario family in terms of price developments (see Table 3). Based on IEA conversion rates from the same report, prices of 2.3 $€_{2016}$/GJ and 3.0 $€_{2016}$/GJ for steam coal are assumed for US and EU markets, respectively, in 2030. This would equal a price increase of about 30% compared to 2016 values. For natural gas, price increments of about 73% are assumed to 3.2 $€_{2016}$/GJ and 7.0 $€_{2016}$/GJ for US and EU markets, respectively. The following figure show the range of IEA gas price projections in the New Policies Scenario for different world regions.

Figure 28 Natural gas prices by key regions in the IEA New Policies Scenario



Source: *IEA (2018)*

Furthermore, in this scenario the world oil-price is to increase by about 135% until 2030, compared to the 2016 value. A CO_2 price of 100 \$/t equals additional 8.5 $€_{2016}$/GJ for steam coal and 5.1 $€_{2016}$/GJ for natural gas according to the respective carbon contents and the stoichiometric ratio for the CO_2 molecule (IPCC cited in IEA 2018).

Table 3 IEA fossil fuel prices by scenario

Real terms ($2017)	2000	2010	2017	New Policies 2025	New Policies 2030	New Policies 2035	New Policies 2040	Sustainable Development 2025	Sustainable Development 2040
IEA crude oil ($/barrel)	39	88	52	88	96	105	112	74	64
Natural gas ($/MBtu)									
United States	6.0	4.9	3.0	3.3	3.8	4.3	4.9	3.3	3.6
European Union	3.9	8.4	5.8	7.8	8.2	8.6	9.0	7.5	7.7
China	3.6	7.5	6.5	9.2	9.4	9.5	9.8	8.3	8.5
Japan	6.6	12.4	8.2	9.8	10.0	10.0	10.1	9.0	8.8
Steam coal ($/tonne)									
United States	38	64	60	63	63	64	64	58	56
European Union	47	103	85	80	83	84	85	69	66
Japan	45	120	95	85	88	89	90	74	70
Coastal China	35	130	102	91	93	94	94	81	79

Source: *IEA (2018); MBtu = million British thermal units. Crude oil price is a weighted average import price among IEA member countries. Natural gas prices are weighted averages expressed on a gross calorific-value basis. The US natural gas price reflects the wholesale price prevailing on the domestic market. The EU and China gas prices reflect a balance of pipeline and LNG imports, while the Japan gas price is solely LNG imports; LNG prices used are those at the customs border, prior to regasification. Steam coal prices are weighted averages adjusted to 6 000 kCal/kg. The US steam coal price reflects mine-mouth prices (primarily in the Powder River Basin, Illinois Basin, Northern Appalachia and Central Appalachia markets) plus transport and handling cost. Coastal China steam coal price reflects a balance of imports and domestic sales, while the EU and Japanese steam coal price is solely for imports*

4.1.2 Impact of fossil fuel prices on wood pellet prices

ARA CIF prices for wood pellets on an average are at about 7.2 $€_{2016}$/GJ for the first half of 2016 considering a conversion factor of 17 GJ/t (see Section 2.1). The connection between fossil fuel prices and wood pellet prices is discussed controversially in literature. Prices for pellets and their main feedstock sawdust are shown to be more volatile than roundwood prices, with lower volatilities than crude oil and oil products in the most cases, however (Kristöfel et al. 2014; Bürger 2015). For Austrian pellet prices, no significant integration with natural gas prices could be found, while integration with oil prices and GDP are proven (Hruby 2015). Swedish wood fuel prices seem not to be strongly linked to oil prices. However, a long-run connection is not excluded in the discussion of the econometric analysis from (Olsson 2012).

In summary, oil price developments have a rather low impact on pellet production and deployment costs but influence their overall demand and - thus - price trends. Furthermore, no significant correlation with coal prices is expect so far since generally, coal is not used for the production or transport of pellets, and only competes with pellets in a few countries.

4.1.3 CO_2 prices to achieve wood pellet price parity to fossil fuels

About 60 $/t CO_2 would have been necessary to establish a price parity between pellets and coal and natural gas in 2016 (for 2.3 €$_{2016}$/GJ for coal and 4.2 €$_{2016}$/GJ for natural gas in the EU market).

While both fossil energy carriers are discussed to have un-correlated price developments for wood pellets for now, pellet prices could increase, too, due to increasing demand, GDP and oil prices as well as partly due to an extension of the natural-gas-fueled vehicle fleet, and possibly also - to a smaller extent - due to competition with coal-fired applications.

For respective price scenarios, the development of pellet price margins and the willingness to pay of a diversified set of costumers would have to be taken into account as well.

However, the long-term slope for the wood pellet price development until 2030 would have to decouple strongly from the discussed oil price development (135%) to not exceed the natural gas (73%) or even the coal price development (30%) or alternatively, CO_2 price mechanisms would have to provide compensation.

It should also be noted that the fossil price dynamics are much slower in the IEA Sustainable Development Scenario (see Figure 27 and Table 3), which implies a higher CO_2 price to achieve pellet price parity than in the IEA New Policies Scenario.

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4.2 High temperature process heat in the EU: Potential for wood pellets?

Christiane Hennig, Henryk Haufe (DBFZ) & Daniela Thrän (DBFZ/UFZ)

4.2.1 Background

The energy-intensive primary industry (steel and iron production, chemicals, paper, cement, glass, and ceramics) is responsible for around three quarters of the overall energy consumption in the industrial sector.

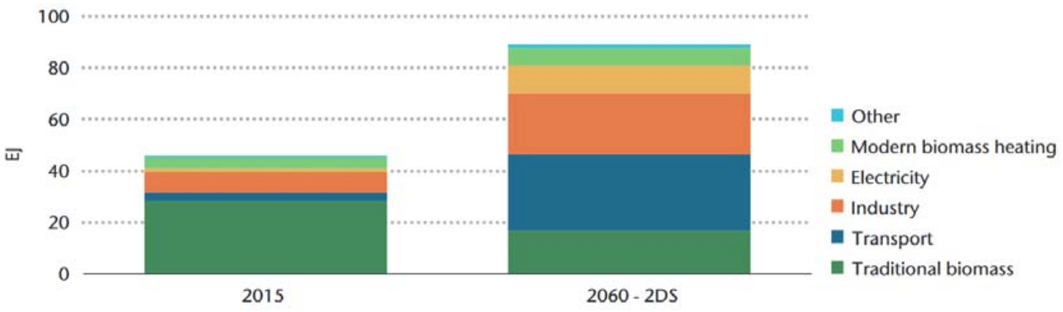
Within the EU (EU28) the industrial sector amounts to 25% of the total final energy consumption and represents - next to energy supply and mobility - one of the major energy consumers, and thus contributing a significant share to energy-related emissions.[7]

The EU goal is to reduce domestic GHG emissions by 80 % by 2050 compared to 1990 levels. This target requires all sectors to be included in this target. In the industrial sector, about 20% of the energy-related CO_2 emissions among all sectors[8] are emitted, corresponding to an annual output of 849 million tons of CO_2 (2016)[9]. By 2030 a GHG emissions reduction of 34-40% compared to 1990 levels and by 2050 of 83-87% compared to 1990 levels have to be achieved within the industrial sector[10].

Within the industrial sector mainly fossil fuels are used for process engineering. A reduction of CO_2 emissions in the industrial sector can be achieved by increasing efficiency that is minimizing process energy required, by the use of renewable energy sources and integrating CCU/CCS. For increasing the share of renewables biogenic resources play a major role for substituting coal and gas for the provision of industrial low-, medium- and high-temperature heat generation.

The IEA Technology Roadmap shows a significant increase in the use of bioenergy within the industrial sector by 2060 - with a transition from currently rather traditional to modern bioenergy applications.

Figure 29 Contribution of bioenergy to final energy demand in 2015 and in the IEA 2DS scenario for 2060



Source: IEA (2017)

[7] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Archive:Consumption_of_energy

[8] Sectoral breakdown: energy supply, industry, transport, residential and commercial, agriculture, waste, international aviation and shipping

[9] https://www.eea.europa.eu/data-and-maps/daviz/ghg-emissions-by-sector-in#tab-chart_2

[10] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52011DC0112&from=EN

4.2.2 Wood pellets for industrial heat

When considering woody biomass - especially wood pellets - for substituting fossil fuels for the provision of high temperature heat in industrial processes the following aspects are - from a current perspective - vital for a successful deployment:

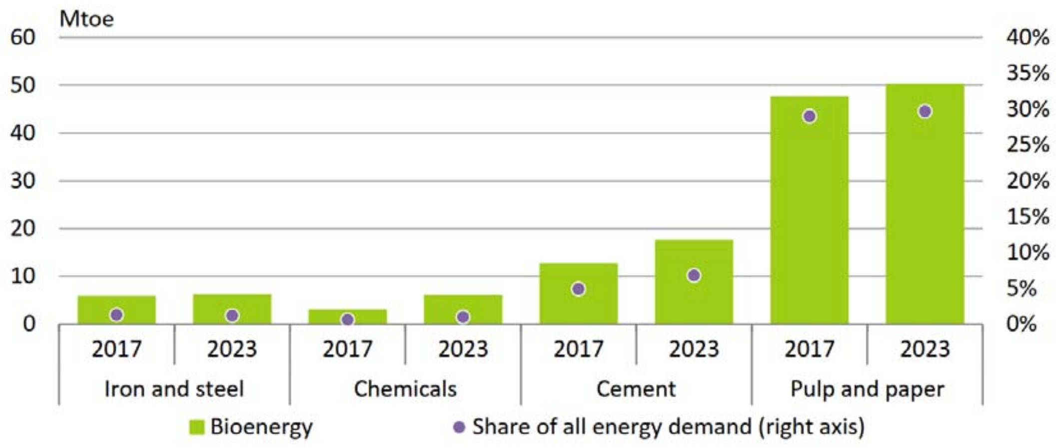
1. Is the utilization possible from a technological point, that is from a process perspective?
2. Are there other renewable energy sources that can be used as fossil fuel substitutes?
3. Is the utilization economically feasible in comparison to other fossil and renewable energy sources?
4. Is there sufficient sustainable feedstock available?

The use of biogenic resources for supplying electricity as well as mid to high temperature heat in the industry already finds worldwide application, see Figure 30 (IEA 2018; Vakkilainen et al. 2013). A very prominent example is the pulp and paper industry with already a significant share of bioenergy for providing steam and electricity by using the organic share contained in the black liquor and wood processing residues as bark. A quarter of the global pulp and paper production takes place in Europe.

Also the application of biomass in the cement, glass and steel and ore industry is increasing. Here, mainly for the provision of mid- to high-temperature heat. Within the cement industry predominantly waste wood and organic fractions from industrial and municipal solid waste are used. Charcoal applications may be found in the steel and ore industry.

Overall, it can be noted that an application of biogenic fuels within industrial process is more likely if the fuels already accrue as wastes and residues on-site of production facilities as e.g. the developments within the pulp and paper industry of the past 20 years have shown.

Figure 30 Global use of bioenergy in industry by subsector in 2017 and by 2023



Source: IEA (2018)

For triggering a wide spread use in the cement and glass industry and also in the iron and steel industry further research and development is required. One of the main challenges are the chemical requirements of the fuel needed to reach the high temperature levels of 1,000 °C and more. By using biogenic resources, pre-treatment as torrefaction, hydrothermal carbonization, pyrolysis and gasification, depending on the type of biomass, is needed to increase the energy-density, to produce a biogenic fuel with favored (fossil fuel-like) properties and thus to run the existing process smoothly.(compare: IEA Bioenergy (2011))

Therefore, much of the current literature is dedicated to the analysis of the options and potential use of biomass to generate high temperature heat levels especially required within the steel and iron industry. Various publications are reflecting on the experiences made with biomass as an appropriate fossil substitute (Mandova et al. 2018; Jha & Soren 2017; Mousa et al. 2016; Wang et al. 2015; Fick et al. 2014; Suopajävri & Fabritius 2013; Norgate et al. 2012).A detailed descriptions of each of the process steps is given in Mousa et al. (2016).

The iron ore reduction process in blast furnaces relies entirely on the fixed carbon. Currently, this mainly comes from coal and coke. Biomass is considered to be the renewable energy source that offers this carbon and thus allows for the possibility for fossil fuel substitution in the iron ore reduction (Mandova et al. 2018).

As for the type of biomass used, pre-treated charcoal possesses equivalent properties for substituting coal (Mousa et al. 2016; Fick et al. 2014; Norgate et al. 2012). Mousa et al. (2016) provide a detailed overview on the properties of wood-based fuels in comparison to coal (Figure 31). This shows that especially with respect to calorific value, volatility and level of fixed carbon content, charcoal provides superior characteristics among the biogenic fuels.

When comparing wood pellets and torrefied wood pellets with coal it turns out that this pre-treatment allows for a similar calorific value and a higher, however not comparable, fixed carbon content and a still high volatility.

This fact impedes a one-on-one substitution of coal by torrefied wood pellets; only a share of coal used throughout iron and steel production process may be substituted (co-firing).[11]

Figure 31 Properties of wood-based fuels in comparison to coal

Property, unit	Wood	Wood Pellets	Torrefaction Pellets	Charcoal	Coal
Moisture content, wt%^{db}	30–45	7–10	1–5	1–5	10–15
Calorific Value, MJ/kg	9–12	15–16	20–24	30–32	23–38
Volatile, wt%^{db}	70–75	70–75	55–65	10–12	15–30
Fixed carbon, wt%^{db}	20–25	20–25	28–35	85–87	50–55
Bulk Density, kg/l	0.2–0.25	0.55–0.75	0.75–0.85	0.2~	0.8–85
Volumetric Energy Density, GJ/m^3	2–3	7.5–10.4	15–18.7	6–6.4	18.4–23.8
Dust	Average	Limited	Limited	High	Limited
Hydroscopic properties	Hydrophilic	Hydrophilic	Hydrophobic	Hydrophobic	Hydrophobic
Biological Degradation	Yes	Yes	No	No	No
Milling Requirements	Special	Special	Classic	Classic	Classic
Handling Properties	Special	Easy	Easy	Easy	Easy
Product Consistency	Limited	High	High	High	High
Transport Cost	High	Average	Low	Average	Low

Source: Mousa et al. (2016)

Mandova et al. (2018) describe that outside of Europe there are plants that use charcoal as sole feedstock. However, in Europe, the furnaces tend to be greater in size and the combustion process requires feedstock properties that charcoal alone could not provide. Thus, especially co-firing takes place.

Concerning the economics of biogenic resources current price estimates both of charcoal (255-386 $/t) (Suopajävri & Fabritius 2013) and torrefied wood pellets (175-265 €/t, i.e. 195-290 $/t) (Carbo et al. 2015) show that they are more expensive than the fossil coal product. For further and a detailed description of the torrefied wood pellet economics see Section 3.2.

The application of a CO_2 tax as an effective policy instrument is vital for biogenic resources to become competitive.

[11] Considering the current iron and steel production routes in place.

Table 4 Overview on the challenges and opportunities for a potential use of wood pellets for providing mid- to high-temperature heat within the EU

Opportunities/Strengths	**Threats/Weaknesses**
Heavy use of coal in iron and steel industry for high temperature process heat provision >> potential for substitution to achieve 83-87% CO_2 emission reduction target within the industrial sector by 2050 compared to 1990 levels	Sustainable supply of wood pellets
Biomass is considered to be the only renewable energy source providing the fixed carbon required for the iron and steel production (except renewable H_2 in case of new plants)	Application for high-temperature heat provision technically difficult: Wood pellets have to have similar qualities as fossil-based fuel (chemical composition, mechanical strength, reactivity and calorific value). differences in qualities allow only a partial substitution of coal (co-firing)
Globally low availability of charcoal and thus potentially other biogenic fuels as wood pellets are of relevance	Charcoal has coal-like properties (wood pellets do not possess this quality)
Available pre-treatment processes such as pyrolysis, torrefaction, hydrothermal carbonization and pyrolysis	Pre-treatment of wood pellets is required
Introduction of a CO_2 tax supporting competitiveness of wood pellets	Wood pellets are currently more expensive than coal
Substitution of natural gas for low/medium temperature heat is comparatively easy	Biomethane may be a more economic substitute
Opportunity of BECCS and BECCU utilization	BECCS and BECCU concepts and corresponding infrastructure needs to be established

Source: own compilation

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4.3 Prospects for new pellet markets: the case of steel

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4.3.1 The role of steel in meeting global climate change mitigation objectives

Recent years have seen important developments in terms of impressive cost reductions and market uptake of key technologies for renewable energy systems, especially solar PV, wind turbines and battery electric vehicles. Although there still are plenty of challenges pertaining to upscaling and mass deployment of these technologies, this has led to growing optimism pertaining to long-term decarbonization of electricity generation and land transport. However, even if these two sectors could be fully decarbonized, more than half of global GHG emissions would still remain unmitigated.

A significant portion of the remaining 50% is made up by emissions from heavy industry like cement production, oil refineries, petrochemicals, and steel, with the steel industry alone being responsible for around 7% of total global GHG emissions. While it is feasible that some of steel used in society could be replaced by other materials (e.g., wood), global steel consumption is likely to grow further in coming decades to fulfil material needs of an expanding global population. Combining increased global steel production with the Paris agreement ambitions of zero global emissions by 2060-2070 is a fundamental challenge indeed.

4.3.2 Decarbonization strategies for the steel industry and the role of biomass

Global steel production can be categorized according to three different technological setups. The first and most common with 70% of global production is the blast furnace-blast oxygen furnace (BF-BOF) route. This uses iron ore as raw material and is for this reason commonly referred to as “primary” steel production to distinguish it from “secondary” steel production based on scrap as raw material which makes up about 25% of global production and is produced in electric arc furnaces (EAFs). These use electricity to melt scrap for manufacturing of new products. The remaining 5% of global steel production uses a technology called Direct Reduction of Iron (DRI) which commonly uses a mixture of iron ore and scrap as raw material and where the reducing agent is based on methane, in contrast to coke in the BF-BOF route[12].

In terms of GHG emissions from steel industry, it is crucial to note that a substantial part of the emissions are a result not simply of combustion of fossil fuels for energy purposes, but of actual industrial processes. The central chemical process in blast furnaces is arguably iron reduction where iron ore reacts with coke to remove oxygen from iron ore to produce pig iron, for further processing into steel. Here, CO_2 is an inherent by-product which makes decarbonization a substantial challenge.

Bataille et al. (2018) identify two main pathways when it comes to deep decarbonization (i.e., 80-100% GHG emission reductions) of heavy industry in general as well as steel industry in particular. The first is to largely keep existing processes, do relatively small process changes and add carbon capture and storage (CCS). The second is to radically change existing processes, primarily by use of (renewable) electrification, either directly or via hydrogen from electrolysis.

As for the “keep existing processes” route, it is important to note that CCS alone will not suffice to achieve zero GHG emissions from steel industry, as certain inherent factors limit CCS emission reductions to about 50-80% (Fischedick et al. 2014).

Biomass in the form of charcoal played the role of the reduction agent for the major part of

[12] Note here that the process used by the Swedish steel powder producer Höganäs uses a DRI process but with coke as the reducing agent.

steel production history and up until the 19th century, but it is highly unlikely that anything close to historical levels of deployment will be feasible. This is largely because fully replacing coke with charcoal in modern blast furnaces is generally ruled out. Charcoal does not have the crushing strength needed to support the tall column composed of coke, iron ore and additives in the blast furnace where the reduction process takes place (Norgate & Langberg 2009). Having said this, there are various other applications of biomass that could play important roles in terms of reducing the industry's GHG emission footprint.

4.3.3 Swedish steel industry: fossil-free by 2045

The Swedish steel industry has an old history, with some firms tracing their ancestry back several centuries. Structural crises during the 1970s forced a radical restructuring of the industry with many industries being shut down. Those who survived redirected their business models towards different kinds of niche markets in order to become competitive on a global market. The industry is now among the most important in Sweden in terms of export value but is also among the largest sources of GHG emissions in the country.

The industry's emissions footprint is made especially clear by the fact that one steel manufacturer, SSAB, alone makes up 10% of all Swedish GHG emissions. These emissions primarily originate from the three blast furnaces that SSAB operates in Sweden, two in Oxelösund close to Stockholm and one in Luleå in the northernmost part of the country. With these blast furnaces, SSAB is one out of two steel companies in Sweden that uses iron ore as raw material. Other than SSAB and Höganäs, which uses a direct reduction process based on fine coke powder, all Swedish steel companies produce secondary steel based on scrap iron.

Sweden has set a national goal to reach national net zero emissions for 2045, and while the country has good preconditions in terms of almost no fossil fuels in electricity or heating, challenges remain in transportation and industry. In 2017, the Swedish government launched an initiative where it encouraged Swedish business sectors to produce roadmaps for how each individual sector is to reach zero emissions by 2045. In spring 2018, nine sectors, including heavy industry sectors like cement, pulp & paper and steel, presented their roadmaps.

The single most important component in the steel industry plan is called HYBRIT. It is a groundbreaking long-term project to completely shift SSABs operations from being based on blast furnaces to using direct reduction. But whereas direct reduction commonly is based on natural gas, HYBRIT will use hydrogen produced by electrolysis of water. This means that the co-product of the reduction process would not be CO_2, but instead H_2O, with corresponding drastic GHG emission reductions as SSABs emissions would be close to zero by 2035 when it planned to be fully implemented. However, a key enable for it to be realized in this is good availability of renewable electricity, as this 10% emission reduction for Sweden also entails a 10% increase in electricity demand as the HYBRIT process alone would demand about 15 TWh to produce the same steel volumes that are currently produced in SSABs three blast furnaces.

However, the shift to hydrogen-based iron reduction is only part of the puzzle to decarbonize Swedish steel, albeit the biggest and most revolutionary and the steel industry's "Zero emissions by 2045" plan is also highly reliant on biomass.

4.3.4 The role of woody biomass and pellets for decarbonization of Swedish steel

In the following, the focus will be on production of primary steel, but just to briefly mention secondary steel, demand for biomass here will primarily be for production of process heat in cases where electrification will not suffice. As much of the fuel demand is currently met by gaseous fuels, (some from biobased gas, e.g., biomethane or biopropane) this is the solution that is currently being seen as the solution here. However, while this is a relatively simple transition from a purely technological perspective, there are substantial obstacles in the lack of sufficient volumes of biogas and associated infrastructure.

As for the potential role of biomass in the production of primary steel, options have been identified in both the BF route operated by SSAB and the DRI process operated by Höganäs.

4.3.5 The Höganäs process from natural gas and coke to syngas and biocoal

Beginning with the latter, Höganäs is exploring the use of an innovative biomass gasification process called WoodRoll (developed by Cortus Energy) to produce syngas to replace its current use of natural gas for process heat, as well as biocoal to replace Höganäs current use of coke for reduction. A 6 MW pilot facility is currently (May 2018) under construction at the Höganäs production facility in Southern Sweden. Thorough tests have to be carried out to see if it is possible to maintain product quality use this non-fossil production route.

In terms of being a possible new market for wood pellets, this particular application may not be the most promising. A key selling point of the Wood Roll process is that it is very flexible in terms of raw material quality and is said to work with a diverse set of fuel, including residues from forestry and agriculture (Lasheras & Baldesca 2012). This makes it less likely that a high quality woody biomass fuel such as wood pellets would be economically competitive, although this obviously depends on availability of local biomass resources as well as how fuel supply systems in general, pertaining to handling etc. are set up.

4.3.6 The role of biomass in the BF-BOF supply chain

As was noted before, the long-term plan for Swedish blast furnaces operated by SSAB is to completely shift to the HYBRIT process based on hydrogen produced by renewables-based electrolysis (Jernkontoret 2018). However, according to the HYBRIT time plan, commercial operations will not be fully in place until 2035 (SSAB et al. 2018) and biomass can play important roles in reducing emissions in the shorter term, before the full conversion to HYBRIT is complete (Jernkontoret 2018).

Starting from the very beginning, before iron ore can be inserted into the reduction process to produce pure iron, the ore itself is processed into an agglomerated spherical product, herein called an *ore pellet* to avoid confusion with wood pellets. Processing of the raw iron ore into ore pellets now uses fossil fuels, especially coke but also some heating oil. The use of biomass in the iron ore sintering process has been evaluated in several studies.

Tests have been conducted using both relatively unprocessed fuels such as regular wood pellets, but also wood that has been pyrolized to different extents. Results from these studies indicate that 25-40% of the coal can be replaced with biomass while maintaining product quality (Mousa et al. 2016; Suopajärvi et al. 2018). It remains uncertain whether higher shares can be accommodated as well.

In the actual blast furnace, biomass has been tested in several different applications. Firstly, full substitution of coke for biocoal is unfeasible, largely because of the poor crushing strength of the latter - however, partial replacement is possible: Studies showed that 5% charcoal can be blended with coal in the coking process without negative effects on quality (Suopajärvi et al. 2017). There are also indications that raw biomass could be feasible, albeit at lower percentages (Wei et al. 2017). Several studies (Larsson et al. 2015; Mousa et al. 2016; Suopajärvi et al. 2017 & 2018) highlight opportunities from using wood-based charcoal injection into blast furnaces. This is to replace coal in a process called pulverized coal injection (PCI), which entails the blowing of pulverized coal into the blast furnace from the bottom. PCI is used to provide supplemental fuel and source of carbon so as to reduce the use of coke, which is a significantly more expensive fuel. Here, it appears feasible to replace 100% of the coal with charcoal, which would then entail that up to 44% of the reduction agent in the blast furnace is bio-based (Suopajärvi et al. 2018).

4.3.7 Conclusions: what is the role of wood pellets in steel industry applications?

The Swedish steel industry has ambitious goals to make the entire industry fossil-free by 2045. The largest contribution to this will be a shift from BOF processes fueled by coke to direct reduction processes based on H_2 produced from renewable electricity and water.

Biomass is still expected to play important roles. Firstly, the non-blast furnace based industries in Sweden expect to use biomass in various forms to reach their individual objectives. However, in both the case of Höganäs (which produces primary steel by use of direct reduction) and the secondary steel producers (based on scrap), biomass will likely be utilized in a gaseous form. It is possible that wood pellets could here act as the raw material for the gasification process depending on process setups and local fuel supply.

Secondly, the HYBRIT process will rely on biomass to play smaller but central roles in the process, especially in the processing of raw iron ore to ore pellets. Thirdly, before the HYBRIT conversion process is complete, utilization of biomass can enable shorter-term emissions reductions in the current blast furnace-based process. Here, using charcoal for pulverized coal injection (PCI) seems to be the most promising application.

In terms of market opportunities for wood pellets, raw biomass is in general not very suitable for metallurgical processes, because of its radical different chemical properties compared to the coal and coke used in current setups (Mousa et al. 2016; Suopajärvi et al. 2017). For this reason, it is highly likely that pre-processing based on some form of pyrolysis process will be necessary to make wood and wood pellets an attractive fuel in the steel industry, at least from a technical point of view. However, in addition to the technical challenges, the wood-based fuels that could come into question are currently not cost-competitive without a significantly higher price on carbon emissions or some other form of policy incentive – but this is true also for alternative low-C options such as direct reduction with H_2.

While the technical challenges associated with biomass use in the steel industry are fairly well mapped and likely to be overcome to a certain extent, the policy obstacle may be more difficult.

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4.4 BECCS/U and NETs: A new market for wood pellets?

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4.4.1 Setting the scene: Energy systems compatible with "well-below 2 °C" emission trajectories

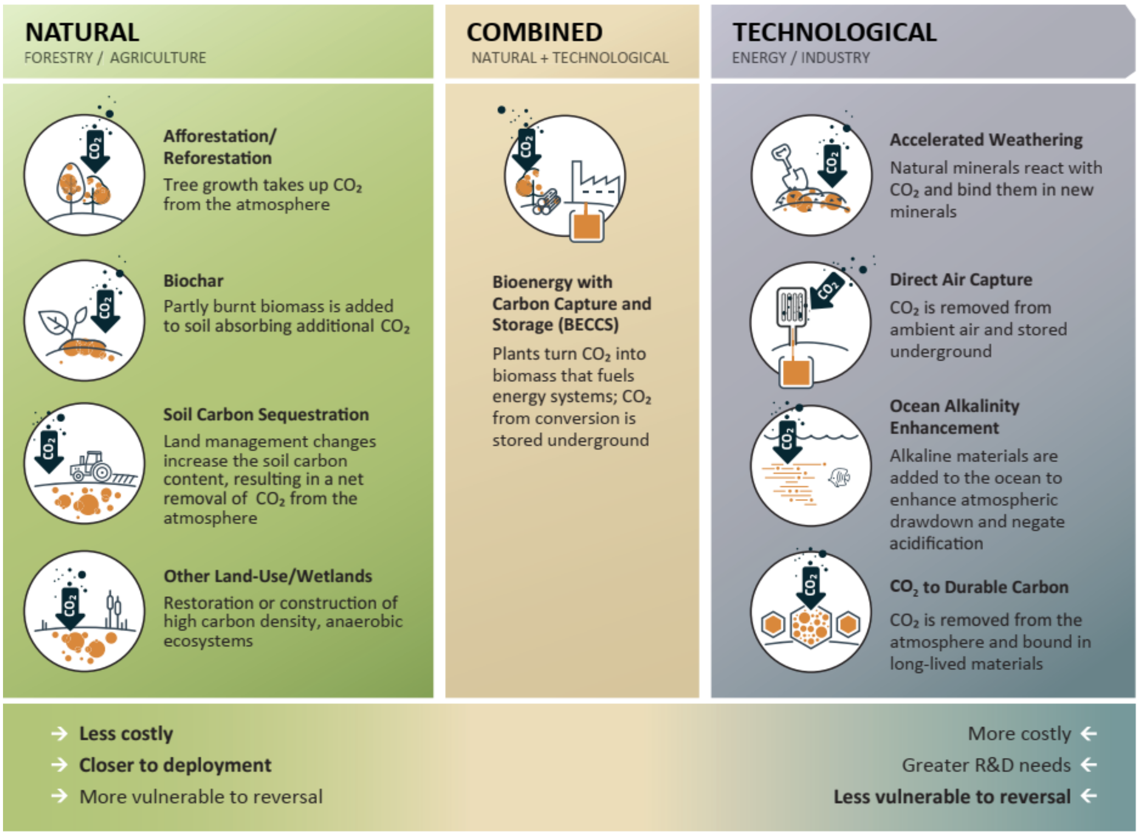
Current national and international policies to achieve the Paris Agreement – i.e. to stay well below 2 °C global temperature increase by the end of this century – are not sufficient, as the United Nations Environment Programme recently showed (UNEP 2018). The gap is significant, implying that global GHG emissions may "overshoot" the emission pathways (trajectories) needed to achieve a 1.5 or at least a well below 2 °C target. Furthermore, there will be "residual" GHG emissions from e.g. agriculture, cement production etc.

With that, the need to compensate excessive emissions by taking CO_2 out of the atmosphere ("negative emissions") could arise by 2050 at the latest (IPCC 2018).

This means that it would not be enough to decarbonize the global energy system, i.e. become carbon neutral, but to deploy "negative emission technologies" (NETs).

There is a variety of such NETs under increasing scientific and technological discussion (EASAC 2018; Fuss 2018; Fuss et al. 2018; Minx et al. 2018). Figure 32 depicts the principal approaches to achieve negative emissions.

Figure 32 Major strategies for negative emission technologies



Source: UNEP (2017), based on Minx et al. (2017)

If bioenergy combustion is combined with carbon capture and storage (CCS), it becomes bioenergy with CCS (BECCS), which could result in **negative** GHG emissions, as cultivation of energy crops removes CO_2 from the atmosphere. The biomass is then converted to energy (e.g., biofuels, electricity, heat), and the CO_2 released during biomass combustion is captured and stored – or used in materials: then it is bioenergy with carbon capture and use (BECCU).

Both BECCS and BECCU are technically feasible (Onarheim & Arasto 2018).

BECCS/U are hybrids of nature-based and technology-based NETs, using photosynthesis to "capture" CO_2 from the atmosphere, and technology to capture CO_2 from combustion exhaust (or the effluent CO_2 from fermentation-based biofuel production) and to store or use it.

4.4.2 BECCS and BECCU: Game changers?

With BECCS/U**,** bioenergy would have a unique advantage over other renewable energies in terms of GHG reduction if feedstock supply could be managed with low GHG emissions (Haszeldine et al. 2018) – for most biomass from forests residues and organic wastes, this is the case (IEA Bio 2018). Muri (2018) provides similar findings for biomass grown on marginal and degraded land, yet with restricted potential.

BECCS is central to the majority of scenarios achieving a below 2 °C, requiring substantive negative carbon emissions by the end of the 21st century (Bauer et al. 2018; IPCC 2018)[13].

BECCU could help achieving carbon-neutral – and for very long-lived products even carbon negative – production of various chemicals, construction materials etc. (see Figure 36) while avoiding the acceptance issue of carbon storage, and respective infrastructure. In that regard it may be seen as a frontrunner to future BECCS deployment.

4.4.3 Biomass supply for BECCS/U

For large-scale BECCS/U plants, feedstock supply is critical. The existing wood pellet value chains – and even more so future improvements (see Section 3) - allow for such supply (Thrän et al. 2019). For many years, the global supply chains for pellets have been analyzed (Junginger et al. 2019), and significant - and sustainable – potential for global trade from e.g. the US Southeast exists (Fingerman et al. 2019).

On the other hand, BECCS/U plants could also be fed by pipelines transporting biomethane, or bio-SNG (synthetic natural gas from e.g. woody biomass gasification, see e.g. Batidzirai et al. 2019; GTI 2019). The existing international natural gas transmission systems in Europe and Northern America allow supplying large-scale combined-cycle powerplants which can be operated with CCS, and sustainable biomethane and bio-SNG potentials are also significant.

Wood pellets could, therefore, also benefit from the market introduction of bio-SNG as a feedstock for large-scale BECCS/U.

The key questions regarding the "real" potential of BECCS/U being a new market for wood pellets is the one on the economics.

4.4.4 The economics of BECCS/U

Should the development of future climate mitigation prove the need for deploying NETs (see Section 4.4.5), the issues of relative costs and overall scale of potential carbon removal will arise.

This "cost-supply" function is shown for the key NETs in the following Figure 33.

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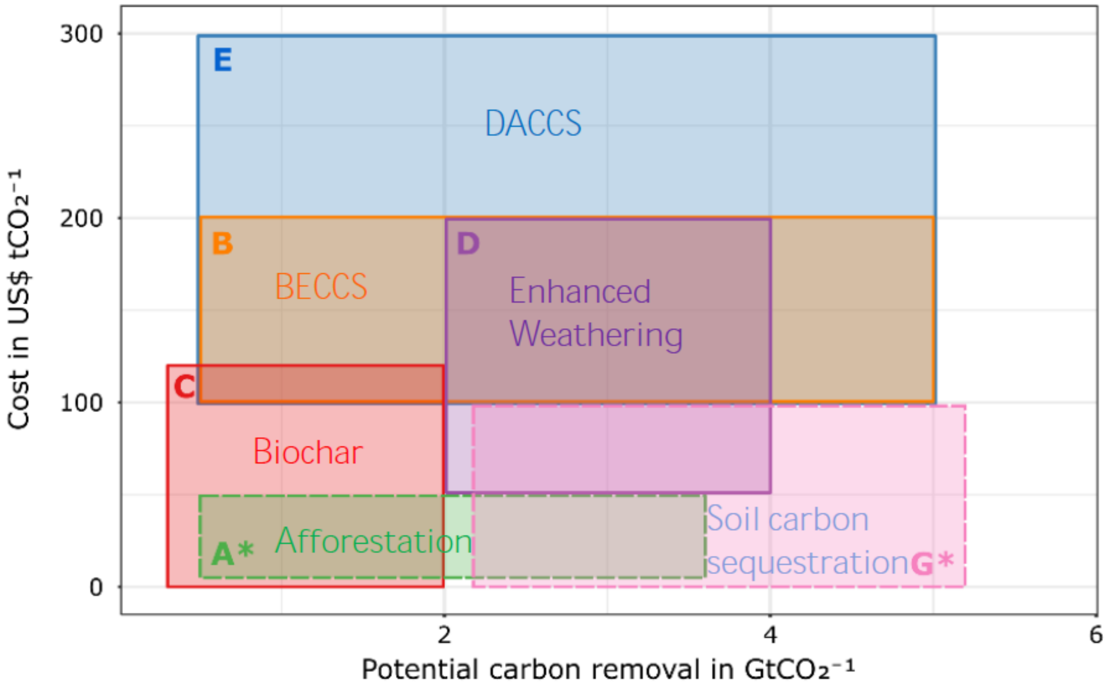
[13] Deploying large-scale BECCS requires careful consideration its land-use implications, as BECCS/U may induce large-scale land-use changes that could cancel much of the assumed CO_2 sequestration and have significant requirements for water and nutrients (EASAC 2018; Gough 2018; Heck et al. 2018; NASEM 2018; Noothout et al. 2019; Stoy et al. 2018) so that feasibility and efficiency of large-scale low-GHG biomass supply is questioned (Creutzig 2016; IPCC 2019).
Furthermore, there are alternatives to BECCS/U for reaching a well-below 2 °C target (Grubler et al. 2018; Kaya, Yamaguchi & Geden 2019; van Vuuren et al. 2018), including more decentral (Schmidt et al. 2019) and "nature-based" options (see left column in Figure 32) which may well be more acceptable, restricting the actual deployment of large-scale BECCS/U and – thus – the potential for woody pellet feedstock use.

Figure 33 Relative competitiveness of NETs: Cost vs. amount of C removed



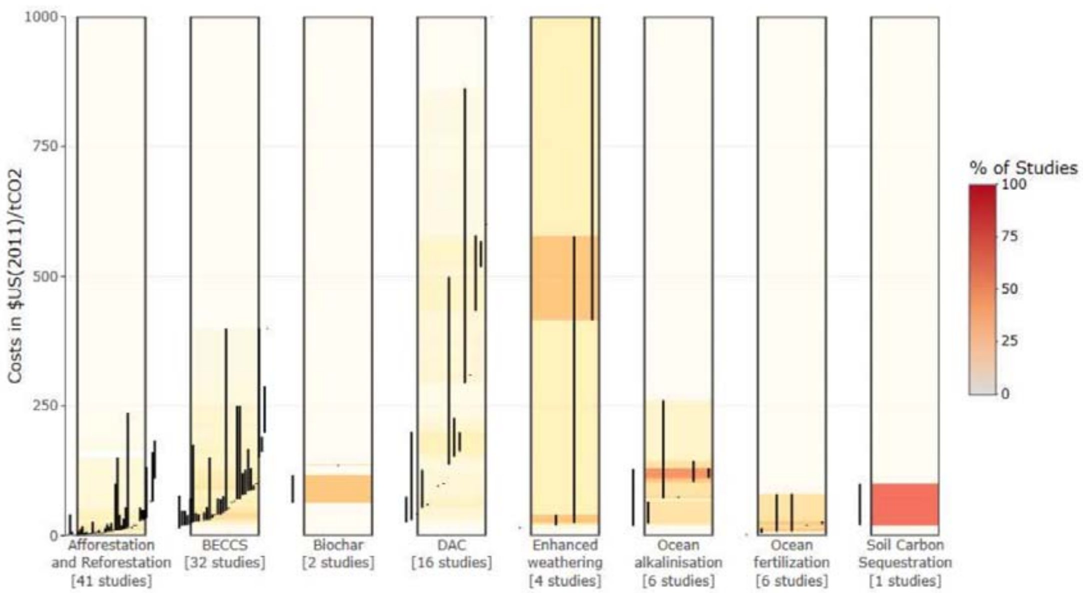
Source: Fuss (2018) based on Haszeldine et al. (2018)

BECCS would have the same magnitude of potential carbon removal as the combination of the nature-based options biochar and afforestation, yet likely at higher cost.

Direct air capture (DAC) – often seen as the "silver bullet" of NETs (Wilcox 2018) – could remove similar amounts of C, but at significantly higher cost.

The indicative data behind the cost-supply potentials of removed carbon shown in the figure above should be seen in the context of the cost ranges of NETs which can cover more than one magnitude, e.g. for DAC (see Figure 34).

Figure 34 Cost ranges for NETs



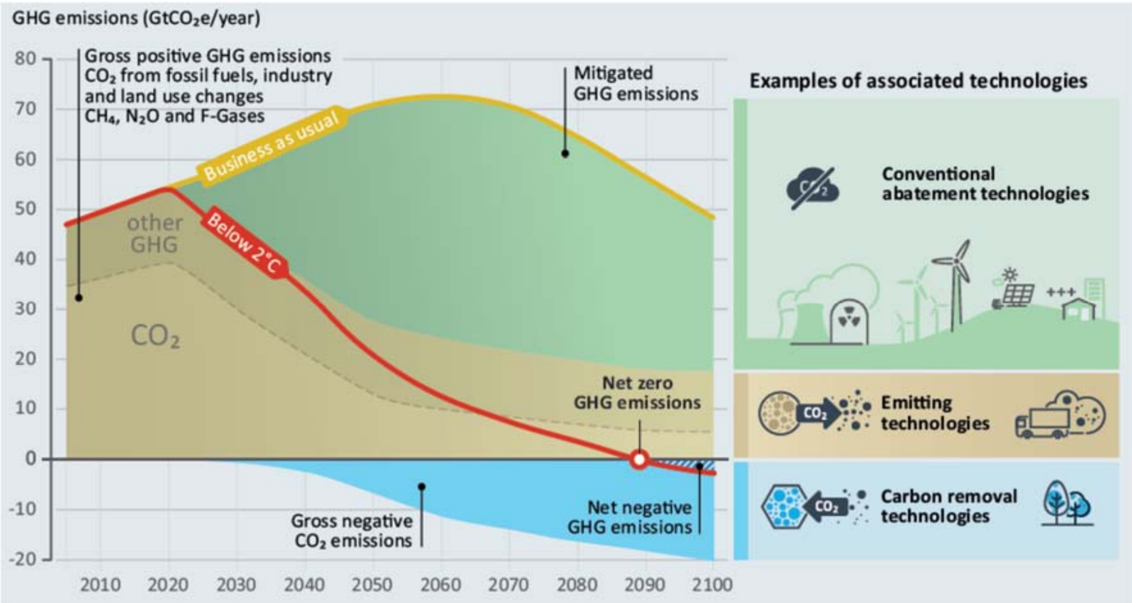
Source: Fuss (2018) based on Fuss et al. (2018)

4.4.5 BECCS/U deployment: when and where?

Given that – for CO_2 prices in the order of 100 $/t or more – BECCS/U could become competitive to other NETs, and subject to agreeing on the need of NET deployment and resolving open sustainability issues, the next questions are: when and where would BECCS/U be deployed?

The logic of "overshoot" determines the time: the later net zero emissions are achieved, the earlier – and more massively – NETs are needed. This illustrates Figure 35: a "below 2 °C" pathway will require NET deployment already starting by 2030.

Figure 35 The dynamic role of NETs in climate change mitigation



Source: UNEP (2017)

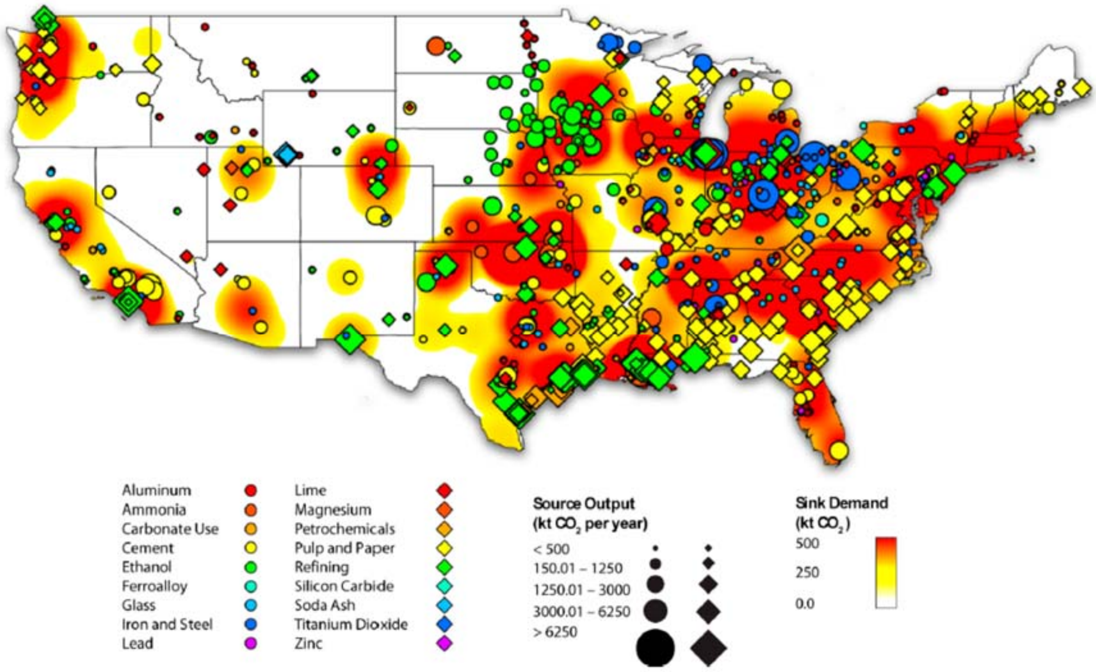
This implies that the discussion around BECCS/U, its sustainability governance and its technological development needs to be resolved in the next years to allow for deployment – if needed – to start by 2030. Just "wait and see" is not compatible with a climate mitigation point of view.

If BECCS/U would be needed, where would deployment start? Turner et al. (2018) studied the global distribution of potential biomass supply for BECCS, and the location of respective CO_2 storage basins. There is a reasonable match, but global trade may prefer certain supply options, and infrastructure constraints (e.g. pipelines for captured CO_2) may imply near-term hot spots such as Scandinavia with its offshore gas reservoirs (once depleted), Belgium and the Netherlands with their international ports and close-by chemical clusters, and the US.

For the latter, Baik et al. (2018) deepened the analysis and showed that the continental US offers plenty opportunities.

For BECCU, though, deployment follows a different logic: Instead of targeting depleted gas and oil reservoirs or deep saline aquifers, CO_2 utilization requires "uptake" in industries, and those must be of a certain size to minimize logistical efforts. Wilcox (2018) showed results of respective analysis based on findings from Psarras et al. (2017) for the continental US. As can be seen in Figure 36, there are "hot spots" in the North-Eastern and South-Eastern US.

Figure 36 Distribution of potential CCU industrial processes in the US



Source: Wilcox (2018) based on Psarras et al. (2017); data given for 90% CO_2 capture rate

The distribution of potential CCU deployment clusters in Europe and the US matches well with the opportunities to either use local biomass resources, or to import pellets.

4.4.6 Conclusions and perspectives

This brief analysis has shown that if large-scale BECCS/U is deployed to achieve the Paris agreement, then woody biomass – and especially pellets – would be a suitable supply option, and in many cases be subject to international trade.

The economic potential of wood pellets (or torrefied material) for BECCS/U is attractive for CO_2 prices > 100 $/t, though sustainability aspects of BECC/U and its social acceptance are yet to be discussed.

Thus, a new market for (torrefied) wood pellets could arise over the next decade and grow significantly further until 2050 and beyond, assuming that the scientific and societal discussions lead to agreeing on BECC/U deployment beyond the R&D stage.

With that, current infrastructure for large-scale international pellet trade could become a necessary asset, and further R&D work on improving pellet production and logistics (see Section 3) makes sense from a NETs deployment perspective.

Yet, establishing BECCS and BECCU concepts and the corresponding infrastructure has to face the **social acceptance** of bioenergy with CCS as a challenge. First studies addressing this aspect constituted that acceptance might be a possible barrier to the use of BECCS (Klepper & Thrän 2019), especially regarding CO_2 storage. The attitude towards BECCS is also influenced by previous debates on CCS for coal powerplants. There are countries such as the Netherlands and Sweden that might have a rather positive view on CCS, while in Germany, CCS is seen rather critical – a national law prohibits CCS deployment.

Given current uncertainties around regulatory policies on and overall governance of sustainable biomass, additional work on a broader, cross-sector and cross-border **sustainability governance of the bioeconomy** is required (see Section 5.4).

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5 Summary and perspectives

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5.1 Beyond the baseline: Improved pellets

This report has shown in Section 2 that wood pellets are a well-established supply chain for residential heat and large-scale industrial (power) markets, and that existing supply "hot spots" can deliver wood pellets at reasonable prices.

Section 3 indicated that further technology development can **reduce wood pellet costs** along (international) supply chains significantly, and can **broaden the feedstock base to low-cost material** such as bagasse, other herbaceous biomass, and wood wastes – subject to adequate sustainability requirements.

Torrefaction could, compared to traditional white pellets, improve energy, GHG and cost performance of long-distance supply, and allows for additional and widespread applications due to its favorable fuel properties.

Yet, given the competition with other renewable energy sources (solar, wind) and energy efficiency in the longer-term (buildings), current wood pellet markets are under price pressure, and actually could shrink in the near future, especially for co-firing in the electricity sector.

5.2 New markets

This report researched **opportunities for new markets** for wood pellets which may arise along transformational pathways of the energy, industry, agricultural and waste systems towards achieving the Paris Agreement, especially when assuming a CO_2 price adder to GHG emissions from fossil fuel uses, industrial processes, and other activities.

5.2.1 High temperature industrial heat

The case study looking into potential markets in industrial high-temperature heat (cement, ceramics, chemicals etc.) found little options for wood pellets as a renewable fuel substitute, mainly due to competition with biomethane (or bio-SNG) – yet, bio-based renewable gases could be derived from wood pellets as well so that this competition may become irrelevant.

There may be some specific cases where pellets could have advantages over renewable gases. For those, creating properties of wood pellets similar to coal (via pre-treatment) to blend into existing industrial processes smoothly is yet a challenge, but torrefaction seems an interesting opportunity.

5.2.2 Steelmaking

The case study on steelmaking also identified some potential for wood pellets, but in the longer-term, process changes towards direct reduction by (renewable) hydrogen may be superior. For many existing iron and steel plants especially in China and India, wood pellets may well be a suitable option, though.

5.2.3 BECCS/U

The brief analysis in Section 4.4 showed that if large-scale BECCS/U is deployed, then wood pellets (or torrefied material) would be a suitable supply option, with attractive economic potential for CO_2 prices above 100 $/t.

With that, current infrastructure for large-scale international pellet trade could become a necessary asset, and (traded) high-density solid biomass as well as biomethane and bio-SNG should be seen key enablers of a new bioenergy role in the longer-term future.

5.3 The critical issue: sustainability governance

Recent results from global modeling underlined that bioenergy plays a crucial role in achieving the Paris Agreement, both in terms of direct use for energy, and through BECCS/U.

International trade of wood pellets and biomethane/bio-SNG could help in fulfilling that role - but only if sustainability concerns of biomass supply – and for BECCS/U: its social acceptance - are sufficiently addressed.

Various research from IEA Bioenergy and others has indicated that to achieve not only the Paris Agreement, but the overarching Sustainable Development Goals (SDGs) as well, bioenergy **can contribute positively**.

Yet to do so, a broader, cross-sector and cross-border **sustainability governance of the bioeconomy** is required, as currently, there are uncertainties around regulatory policies on and overall governance of sustainable biomass, including wood pellets.

5.4 Future work

IEA Bioenergy, in collaboration with international organizations such as IEA, IRENA, Biofuture Platform, FAO, and GBEP, among others, responded to the sustainability challenge by initiating a new specific workstream on the issue[14].

Furthermore, IEA Bioenergy is emphasizing the deployment perspective of bio-based value chains in one of its activities[15].

IEA Bioenergy started carrying out further work to take on the issues raised briefly in the case studies presented here, especially in several intertask projects[16] on

- bioenergy for high-temperature industrial heat;
- renewable gases (biomethane and bio-SNG from biomass, but also Power-to-Gas from CO_2 and hydrogen derived from renewable electricity);
- the potential BECCS/U deployment, and
- the future role of bioenergy in a “well-below 2 °C/SDG” world.

The results of this study will be used in this work.

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[14] IEA Bioenergy Task 45: Climate and sustainability effects of bioenergy within the broader bioeconomy http://task45.ieabioenergy.com/

[15] IEA Bioenergy Task 40: Deployment of bio-based value chains http://task40.ieabioenergy.com

[16] For details see https://www.ieabioenergy.com/task/inter-task-projects/

Further Information

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