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DBFZ REPORT NR. 41

National Resource Monitoring for Biogenic Residues, By-products and Wastes

Development of a Systematic Data Collection, Management and Assessment for Germany

Dissertationsschrift
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IMPRESSUM

Herausgeber:
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Institutionelle Förderung:
Das Deutsche Biomasseforschungszentrum wird institutionell gefördert durch das Bundesministerium für Ernährung und Landwirtschaft aufgrund eines Beschlusses des Deutschen Bundestages

Gefördert durch:

Bundesministerium
für Ernährung
und Landwirtschaft

aufgrund eines Beschlusses
des Deutschen Bundestages

Geschäftsführung:
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DBFZ Report Nr. 41
National Resource Monitoring for Biogenic Residues, By-products and Wastes – Development of a Systematic Data Collection, Management and Assessment for Germany
Leipzig: DBFZ, 2021
ISSN: 2197-4632 (Online)
ISBN: 978-3-946629-74-0
DOI: 10.48480/p63p-dc92

Autor:
André Brosowski

Bilder:
Sofern nicht am Bild vermerkt: DBFZ, Stefanie Bader (Karte), Roman Ibeschitz / pixelio.de (Titelbild groß), UN.org (Icons)

Datum der Veröffentlichung:
7. Juli 2021

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Die Deutsche Nationalbibliothek verzeichnet diese Publikationen in der Deutschen Nationalbibliografie; detaillierte bibliografische Daten sind im Internet unter der Adresse www.dnb.de abrufbar.

National Resource Monitoring for Biogenic Residues, By-products and Wastes – Development of a Systematic Data Collection, Management and Assessment for Germany

A DISSERTATION

Approved by the Faculty of Economics and Management Science,
Leipzig University,
for Obtaining the Academic Degree

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Dr.-Ing.

Presented by
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Prof. Dr.-Ing. Ralf Bill

Date of conferral 16 June 2021

Bibliographic description

Brosowski, André
National Resource Monitoring for Biogenic Residues, Wastes and By-products –
Development of a Systematic Data Collection, Management and Assessment for Germany

Leipzig University, Dissertation
VIII+112 P., 394 Lit., 26 Fig., 24 Tab.

Abstract: The reduction of greenhouse gases in the atmosphere and the transformation from a fossil-based to a bio-based economy are declared social, political and entrepreneurial goals. The efficient material and energetic use of biogenic residues, by-products and wastes offers numerous means of working towards these goals. However, it is still unclear what raw materials can be understood under these collective terms, what quantities exist across sectors and what additional contribution can be expected from their improved use. In the context of this thesis, an internationally applicable method has been developed which can be used to continuously balance and evaluate the technical biomass potential and current use.

The basis for this is a modular monitoring system that is used to develop a multi-stage biomass categorisation, a regularly updatable network of biomass-specific calculation elements and a procedure for the continuous improvement of data quality. The monitoring system was tested for a consistent reference year using Germany as an example. In addition, the temporal and spatial dynamics of the biomass availability were analysed for the case study of cereal straw using a geo-information system.

With the help of 1,113 calculation elements, the supply and use of 77 biomasses from five sectors were balanced. On this basis, the technical biomass potential for the year 2015 amounts to 86–140 million tonnes of dry matter. Between 65 % and 84 % are already tied up in a material or energetic use. There is a clear focus on only a few raw materials; 20 % of the resources make up more than 80 % of the supply. By further tapping the mobilisable potential of 14–48 million tonnes of dry matter, an annual primary energy contribution of at least 6 % and up to 15 % could be achieved in future, for example. The detailed analysis for the case study also shows that, despite significant fluctuations over time, large parts of the potential are concentrated in only a few regions. The overall broad ranges of results indicate that the data quality is uncertain and, in particular in the areas of soil and water quality, biodiversity and eutrophication of ecosystems, there is a need for research on how the complex interactions can be integrated into future calculations of biomass potentials, using which data sets. The consequent provision of the monitoring results and calculation methodology in an online data repository (http://webapp.dbfz.de) provides the opportunity to reflect on the existing approaches in an open debate and to continue developing them in line with the respective needs.

Using the findings generated by the monitoring system, the focus can be placed on the most important raw materials and regions for the implementation of political and entrepreneurial strategies and for filling gaps in the data. On this basis, the next steps for an optimal and sustainable contribution to a bio-based circular economy can be prioritised and discussed with regional stakeholders and shareholders.

Declaration of academic integrity

I hereby declare that I have composed this dissertation myself and without inadmissible outside help, in particular without the help of a doctoral consultant (*Promotionsberater*). I have used no other sources and aids than those stated. I have indicated all text passages that are incorporated, verbatim or in substance, from published or unpublished writings. I have indicated all data or information that is based on oral communication. All material or services provided by other persons are indicated as such.

Leipzig, 30 September 2020

André Broso

André Brosowski

Dedicated to sustainability

“If you can’t measure it, you can’t improve it”

Peter F. Drucker, 1909–2005

Abstract (EN)

The reduction of greenhouse gases in the atmosphere and the transformation from a fossil-based to a bio-based economy are declared social, political and entrepreneurial goals. The efficient material and energetic use of biogenic residues, by-products and wastes offers numerous means of working towards these goals. However, it is still unclear what raw materials can be understood under these collective terms, what quantities exist across sectors and what additional contribution can be expected from their improved use. In the context of this thesis, an internationally applicable method has been developed which can be used to continuously balance and evaluate the technical biomass potential and current use.

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Keywords: Bioeconomy, biogenic resources, bio-based products, biomass potential assessment, ecological sustainability, GIS

Zusammenfassung (DE)

Die Reduktion von Treibhausgasen in der Atmosphäre und die Transformation von einer fossilbasierten zu einer bio-basierten Wirtschaftsweise sind erklärte gesellschaftliche, politische und unternehmerische Ziele. Die effiziente stoffliche und energetische Nutzung von biogenen Reststoffen, Nebenprodukten und Abfällen bietet zahlreiche Möglichkeiten, diesen Zielen näher zu kommen. Unklar ist bisher jedoch, welche Rohstoffe unter diesen Sammelbegriffen verstanden werden können, welche Mengen sektorenübergreifend existieren und welcher zusätzliche Beitrag aus einer optimierten Nutzung erwartet werden kann. Im Rahmen dieser Arbeit wurde daher eine international anwendbare Methode entwickelt, mit der das technische Biomassepotenzial und die aktuelle Nutzung fortlaufend bilanziert und bewertet werden kann.

Die Grundlage bildet hierfür ein modulares Monitoringsystem, mit dem u. a. eine mehrstufige Biomassekategorisierung, ein regelmäßig aktualisierbares Netzwerk aus biomassespezifischen Berechnungselementen sowie ein Vorgehen zur kontinuierlichen Verbesserung der Datenqualität entwickelt wurde. Das Monitoringsystem wurde am Beispiel von Deutschland und für ein konsistentes Bezugsjahr erprobt. Für das Fallbeispiel Getreidestroh wurde darüber hinaus die zeitliche und räumliche Dynamik der Rohstoffverfügbarkeit mit einem Geo-Informationssystem analysiert.

Mit Hilfe von 1.113 Berechnungselementen wurden das Aufkommen und die Nutzung für 77 Biomassen aus fünf Sektoren bilanziert. Auf dieser Grundlage ergibt sich für das Jahr 2015 ein technisches Biomassepotenzial in Höhe von 86–140 Millionen Tonnen Trockenmasse. Zwischen 65 % und 84 % waren bereits in einer stofflichen oder energetischen Nutzung gebunden. Ein deutlicher Schwerpunkt liegt auf nur wenigen Rohstoffen; 20 % der Rohstoffe repräsentieren über 80 % des Potenzials. Durch die weitere Erschließung der noch mobilisierbaren Potenziale in Höhe von 14–48 Millionen Tonnen Trockenmasse könnte zukünftig z. B. ein jährlicher Primärenergiebeitrag von mindestens 6 % und bis zu 15 % realisiert werden. Die Detailanalyse für das Fallbeispiel zeigt darüber hinaus, dass trotz erheblicher zeitlicher Schwankungen große Teile des Potenzials in nur wenigen Regionen konzentriert sind. Die insgesamt hohen Ergebnisbandbreiten deuten jedoch auf eine unsichere Datenqualität hin und insbesondere bei den Themen Boden- und Wasserqualität, Biodiversität und Eutrophierung von Ökosystemen besteht Forschungsbedarf, wie und mit welchen Datensätzen die komplexen Wirkungsgefüge zukünftig in die Potenzialberechnungen integriert werden können. Durch die konsequente Offenlegung der Monitoringergebnisse und der Berechnungsmethodik in einem Online-Datenrepositorium (http://webapp.dbfz.de) besteht die Möglichkeit, die bisherigen Ansätze in einem offenen Diskurs zu reflektieren und bedarfsgerecht weiterzuentwickeln.

Mit Hilfe der Erkenntnisse aus dem Monitoringsystem kann der Fokus für die Umsetzung von Politik- und Unternehmensstrategien und das Schließen von Datenlücken auf die wichtigsten Rohstoffe und Regionen gelenkt werden. Zusammen mit den regionalen Stake- und Shareholdern können auf dieser Grundlage die nächsten Schritte für einen optimalen und nachhaltigen Beitrag zu einer bio-basierten Kreislaufwirtschaft priorisiert und weiterführend diskutiert werden.

Stichworte: Bioökonomie, biogene Rohstoffe, bio-basierte Produkte, Biomassepotenzialberechnung, ökologische Nachhaltigkeit, GIS

Acknowledgements (EN)

My doctoral thesis would not have been possible without the support I received from many people. I had the good luck to find the right inspiration at the right moments. Mr Bill, during the GeoForum MV in 2014 you recommended me to think about doing a PhD. At the time, I was actually happy working on national and international projects, and a doctoral position in my mid-30s was out of question for various reasons. Stefan, you helped me combine the two. With plenty of ideas up my sleeve, I came across some opportunities on my search for funding, but somehow the money did not come. Our son was born, our home became too cramped, should we stay in Leipzig or not, should I get a new job or not, where should we move, north or south ... Daniela, back then you advised me to be patient. I followed your recommendation, and a few months later all the opportunities suddenly opened up. It kicked off! At the time, of course, I had no real idea of what that meant. From today's perspective, I am hugely grateful for all the highs and lows of the last few years. When I think of the highs, I mainly think with immense gratitude of the incredibly effective collaboration with all my co-authors and project partners from Hamburg (Prof. Udo Mantau, Christian Blanke), Bremen (Prof. Bernd Mahro, Prof. Anja Noke), Witzenhausen (Dr Felix Richter, Thomas Raussen), Jena (Thomas Hering, Roland Bischof, Gerd Reinhold), Rostock (Prof. Ralf Bill) and of course Leipzig (Prof. Daniela Thrän, Prof. Walter Stinner, Dr Georgia Erdmann, Philipp Adler). Special thanks go in particular to Tim Krause and Paul Müller. Over the years, you have been the most intensely involved in the day-to-day details of work on the project. And I will never forget the business trips across Germany and Bosnia-Herzegovina that gave me the chance to put the monitoring system through its paces and bring it into use internationally. Thank you very much to Thomas Mitschke for your trust in what was then an unfinished system. In that context, many thanks also go to Prof. Mersudin Avdibegović, Prof. Hamid Čustović, Dr Melisa Ljuša, Dr Dragan Čomić, Alexander Mrkobrada, Senka Mutabdžija Bećirović, Prof. Mirza Ponjavić, Prof. Almir Karabegović and Nihad Harbas for countless hours spent at extremely productive workshops and many other moments spent as friends in the mountains and towns, or by the sea. During the lows, there were friends by my side. Thank you Konstantin, Bastian, Christoph, Markus, Basti and many others for your strength and motivation and, above all, for being so understanding when I vanished from the scene for so long. I am most grateful, of course, to my family, who celebrated my highs with me and put up with my moods during the lows. Thanks a million to Geli, Gunter, Mauny and Bernhard for helping with Bruno, and many, many thanks too to Frank, Claudi, Judith, Katja, Micha and Dirk for distraction and encouragement. A big, very far-reaching thank you goes to my supervisors. Thanks so much to Daniela and Mr Bill for the great support you offered and the many ways you inspired me, constantly giving me fresh perspectives. But by far the most important and biggest thank you goes to my beloved wife! Steffi, without you and your constant, daily support over years, none of the things related to this work would have been possible.

Danksagung (DE)

Ohne die Unterstützung von vielen Menschen wäre meine Doktorarbeit nicht möglich gewesen. Ich hatte das Glück, in den richtigen Momenten die richtigen Impulse zu bekommen. Herr Bill, Sie haben mir beim 2014er GeoForum MV empfohlen, über eine Dissertation nachzudenken. Zu dieser Zeit war ich mit der Bearbeitung von nationalen und internationalen Projekten eigentlich glücklich und eine Promotionsstelle mit Mitte 30 kam für mich aus verschiedenen Gründen nicht in Frage. Stefan, du hast mich dabei unterstützt, beides miteinander zu verbinden. Mit vielen Ideen im Gepäck und auf der Suche nach Finanzierungen entwickelten sich Möglichkeiten, aber das Geld kam irgendwie nicht. Unser Sohn wurde geboren, die Wohnung wurde zu eng, in Leipzig bleiben ja oder nein, neuer Job ja oder nein, wohin weiterziehen, nach Süden oder Norden … Daniela, du hast mir damals zur Geduld geraten. Ich folgte deiner Empfehlung und wenige Monate danach entfalteten sich auf einmal alle Möglichkeiten. Es ging los! Was das bedeutete, konnte ich damals selbstverständlich nicht überblicken. Aus heutiger Sicht bin ich extrem dankbar für alle Höhen und Tiefen der letzten Jahre. Mit den Höhen und großer Dankbarkeit verbinde ich vor allem die von der ersten Minute unfassbar gute Zusammenarbeit mit allen Projektpartnern und Co-Autoren aus Hamburg (Prof. Udo Mantau, Christian Blanke), Bremen (Prof. Bernd Mahro, Prof. Anja Noke), Witzenhausen (Dr. Felix Richter, Thomas Raussen), Jena (Thomas Hering, Roland Bischof, Gerd Reinhold), Rostock (Prof. Ralf Bill) und natürlich aus Leipzig (Prof. Daniela Thrän, Prof. Walter Stinner, Dr. Georgia Erdmann, Philipp Adler). Ein besonderer Dank gilt vor allem Tim Krause und Paul Müller. Ihr wart über Jahre in die tagtäglichen Details der Projektarbeit am intensivsten involviert. Unvergessen sind auch die Dienstreisen quer durch Deutschland und Bosnien-Herzegovina, wo ich das Monitoringsystem auf Herz und Nieren testen und in die internationale Anwendung bringen konnte. Vielen Dank Thomas Mitschke für dein Vertrauen in das damals noch nicht fertige System. Großer Dank geht in diesem Zusammenhang auch an Prof. Mersudin Avdibegović, Prof. Hamid Čustović, Dr. Melisa Ljuša, Dr. Dragan Čomić, Alexander Mrkobrada, Senka Mutabdžija Bećirović, Prof. Mirza Ponjavić, Prof. Almir Karabegović und Nihad Harbas für die unzähligen Stunden in den äußerst produktiven Workshops und den vielen freundschaftlichen Momenten in den Bergen, den Städten und am Meer. In den Zeiten der Tiefs standen Freunde an meiner Seite. Danke Konstantin, Bastian, Christoph, Markus, Basti und vielen weiteren für eure Kraft und Motivation und vor allem für euer Verständnis, dass ich längere Zeit von der Bildfläche verschwunden war. Der größte Dank gilt natürlich meiner Familie, die meine Höhen mit mir gefeiert und meine Launen während der Tiefs ertragen haben. 1000 Dank an Geli, Gunter, Mauny und Bernhard für die Hilfe mit Bruno und auch vielen Dank an Frank, Claudi, Judith, Katja, Micha und Dirk für Ablenkung und Zuspruch. Ein großes, sehr weitreichendes Dankeschön gilt meiner Betreuung. Liebe Daniela, lieber Herr Bill – vielen Dank für die super Unterstützung und für alle Impulse, die mir immer wieder neue Perspektiven ermöglicht haben. Der mit Abstand wichtigste und größte Dank gilt jedoch meiner geliebten Frau! Steffi, ohne dich und deine unendliche, tagtägliche Unterstützung über mehrere Jahre wäre nichts davon möglich gewesen, was mit dieser Arbeit verbunden ist.

List of publications

This thesis is based on the following appended papers:

I Brosowski, A., Thrän, D., Mantau, U., Mahro, B., Erdmann, G., Adler, P., Stinner, W., Reinhold, G., Hering, T., Blanke, C. (2016): A review of biomass potential and current utilisation – Status quo for 93 biogenic wastes and residues in Germany, *Biomass and Bioenergy*, 95, 257–272. (also published in *Elseviers' Virtual Issue on Earth Day 2017)*

II Brosowski, A., Krause, T., Mantau, U., Mahro, B., Noke, A., Richter, F., Raussen, T., Bischof, R., Hering, T., Blanke, C., Müller, P., Thrän, D. (2019): How to measure the impact of biogenic residues, wastes and by-products: Development of a national resource monitoring based on the example of Germany, *Biomass and Bioenergy*, 127, 105275.

III Brosowski, A., Bill, R., Thrän, D. (2020): Temporal and spatial availability of cereal straw in Germany – Case study: Biomethane for the transport sector, *Energy, Sustainability and Society,* 10:42, 1–21.

Work related to this thesis has also been presented in the following publications:

Thrän, D., Billig, E., **Brosowski, A.**, Klemm, M., Seitz, S. B., Witt, J. (2018): Bioenergy Carriers – From smoothly treated biomass towards solid and gaseous biofuels, *Chemie Ingenieur Technik*, 90, 68–84.

Pfeiffer, A., Krause, T., Horschig, T., Avdibegović, M., Čustović, H., Ljuša, M., Čomić, D., Mrkobrada, A., Mitschke, T., Mutabdžija Bećirović, S., Ponjavić, M., Karabegović, A., **Brosowski, A.** (2019): Report on biomass potential monitoring in Bosnia and Herzegovina, published by *Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH (GIZ) and United Nations Development Programme (UNDP)*.

Bringezu, S., Banse, M., Ahmann, L., Bezama, N. A., Billig, E., Bischof, R., Blanke, C., **Brosowski, A.**, Brüning, A., Borchers, M., Budzinski, M., Cyffka, K.-F., Distelkamp, M., Egenolf, V., Flaute, M., Geng, N., Gieseking, L., Graß, R., Hennenberg, K., Hering, T., Iost, S., Jochem, D., Krause, T., Lutz, C., Machmüller, A., Mahro, B., Majer, S., Mantau, U., Meisel, K., Moesenfechtel, U., Noke, A., Raussen, T., Richter, F., Schaldach, R., Schweinle, J., Thrän, D., Uglik, M., Weimar, H., Wimmer, F., Wydra, S., Zeug, W. (2020): Pilotbericht zum Monitoring der deutschen Bioökonomie, published by *Center for Environmental Systems Research* (CESR), University of Kassel.

List of abbreviations

API	Application Programming Interface
BGR	Federal Institute for Geoscience and Natural Resources
CNG	Compressed Natural Gas
CO_2-eq.	Carbon Dioxide Equivalent
DM	Dry Matter
DWD	German Meteorological Service
EMAS	Eco-Management and Audit Scheme
FAO	Food and Agriculture Organisation
GBEP	Global Bioenergy Partnership
GHG	Greenhouse Gas
GIS	Geo-Information System
ISO	International Organisation for Standardisation
ITOC	Inventory TO Consumer
LNG	Liquefied Natural Gas
NRP	National Reporting Platform
NUTS	Nomenclature of Territorial Units for Statistics
SDG	Sustainable Development Goals
SNG	Synthetic Natural Gas
UBA	Federal Environment Agency
UFZ	Helmholtz Centre for Environmental Research
UNFCCC	United Nations Framework Convention on Climate Change
WDPA	World Database on Protected Areas
WFS	Web Feature Service
WMS	Web Map Service

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Part I:
Annual monitoring of biomass potentials

CHAPTER 1

Background

For the last 28 years, international negotiations have been taking place on how to make our life together as a society sustainable and protect the environment. Based on the United Nations Framework Convention on Climate Change (UNFCCC, [1]), the reduction of greenhouse gases (GHGs) was agreed upon, among other things in the Kyoto Protocol [2] and in the Paris Agreements [3]. In addition to emission reduction, many other fields of life were addressed in the Sustainable Development Goals (SDGs), which are designed to provide international guidance on the path to greater sustainability [4]. In this context, the year 2030 is shaping up to be a crucial milestone, both internationally and nationally. On one hand, the period set for the SDGs will come to an end, and there will be close scrutiny of what has been achieved so far. On the other hand, Germany is the first country in the world to have laid down laws committing to slash greenhouse gas emissions by at least 55 % by that point, compared to 1990. The Federal Climate Protection Act [5] addressing that topic was adopted on 17 December 2019, and an accompanying Climate Action Programme [6] listed numerous measures to achieve those goals and organise institutional responsibilities. At the same time, the national bioeconomy research strategy [7] and the national bioeconomy policy strategy [8] call for a bio-based economy by 2030. These political activities were last brought together on 15 January 2020 in a national bioeconomy strategy developed by the German federal government [9]. The focus is on Germany's climate-neutral development and the cross-generational conversion from a fossil-based to a bio-based, circular economy. In detail, this includes "the production, exploitation and use of biological resources, processes and systems to provide products, processes and services across all economic sectors" [9]. The strategy paper is closely interwoven with the SDGs, giving Germany a current framework for developing solutions for the sustainability agenda.

According to information from the Federal Ministry of Education and Research [10], some innovative initial approaches include bio-based products such as platform chemicals made from lignocellulose, starch-based biopolymers, innovative construction and insulation materials made from renewable materials; packaging or cleaning materials from straw, fashion articles made from wood, coffee grounds or leftover milk, bags or drinking straws made from apple waste, glue made from lignin, fertiliser from cocoa shell, tyres made from dandelions or car parts made from hemp. In addition to the material use of biogenic resources, another important option for the provision of renewable energy is the production of bio-energy carriers in gaseous form (e. g. biomethane, bio CNG/SNG), liquid form (e. g. biodiesel, bioethanol, biokerosene, bio LNG, pyrolysis oil) or solid form (e. g. pellets, biochar) [11]. Considerable potential for development is seen, above all, in combining their material and energetic use in cascades and value-adding networks on as large a scale as possible [12]. One limiting factor, however, is the availability of raw materials, and a question that is central to the entire debate around the bioeconomy of the future is what additional affect can be achieved by improving the use of biogenic resources [13].

1.1 Raw materials for the bioeconomy

The central sources of raw materials in the bioeconomy are agriculture, forestry, fishing and waste management. Biomass from aquatic systems (e. g. algae or bacteria) and carbon from industrial CO_2 emissions are also expected to play an increasingly important role when relevant processes become achievable on a large technological scale. [9]

With regard to agriculture, in 2019 renewable raw materials were cultivated on around 16 % of usable agricultural land, and 89 % of those raw materials are so far used to produce energy [14]. In this context, Thrän et al. [15] point out that the various sustainability requirements applying to their cultivation still cannot be adequately managed. The Federal Government's current Climate Action Programme [6] does not expect this land to be expanded any further. There is also intensive discussion on the ecosystem services of the forest, e. g. by storing carbon and water, regulating the microclimate, providing a habitat for flora and fauna or being used for recreation, nature conservation and biodiversity [16, 17]. The availability of wood in the short, medium and long term is currently subject to significant disruptions due to various calamities (e. g. water stress, infestation by pests, windsnap, forest fires) [17]. The amount of damaged timber between 2018 and 2020 amounts to some 160 million cubic metres [18], higher than the average annual amount felled in the 20 years before [19]. This means that there are considerable quantities on the market in the short term which will, however, be lacking in the long term [17]. The Climate Action Programme [6], the bioeconomy strategy [9] and, for example, the European Renewable Energy Directive [20] emphasise, among other things, the greater use of biogenic residues and waste materials. The efficient use of these raw materials can avoid additional competition for land use [9] and achieve high GHG savings [21–23]. While the European Waste Catalogue [24] clearly defines wastes that are subject to mandatory collection, it is still unclear which biomass types are to be seen as falling under the collective term "residues". In contrast to the detailed statistical reporting on agricultural and forestry production [19, 25] and on waste generation [26], when it comes to related residues or by-products there is neither any regularly published primary data nor any consistent information across the different sectors.

1.2 Increasing demand for biogenic raw materials

The Federal Climate Protection Act [5] sets down binding annual emission budgets for a total of six sectors. The values to be achieved by 2030 and the development so far are summarised in Figure 1.1. A total reduction of around 31 % (as of 2018) has been achieved since 1990. So far, the greatest reductions have been achieved in the energy sector. Almost no change has been seen in the transport sector. Across sectors, another 316 million tonnes of CO_2 equivalents must still be saved by 2030, or 45 % of the actual target. Short-term solutions are therefore necessary, and the measures formulated in the Climate Action Programme [6] indicate, among other things, an increasing demand for biogenic raw materials. In relation to the sectors listed in Figure 1.1, for example, in the energy sector this means solutions for the heating transition (in particular via combined heat and power); in the buildings sector it means constructing with renewable raw materials (e. g. wood); in the transport sector it means providing advanced biofuels and replacing fossil-derived raw materials; and in industry it means increasingly using by-products [6]. In the agriculture and waste sectors, by contrast, the issue is not an additional demand for raw materials, but the more efficient recovery of raw materials in material flows which are established, or are yet to be exploited [9].

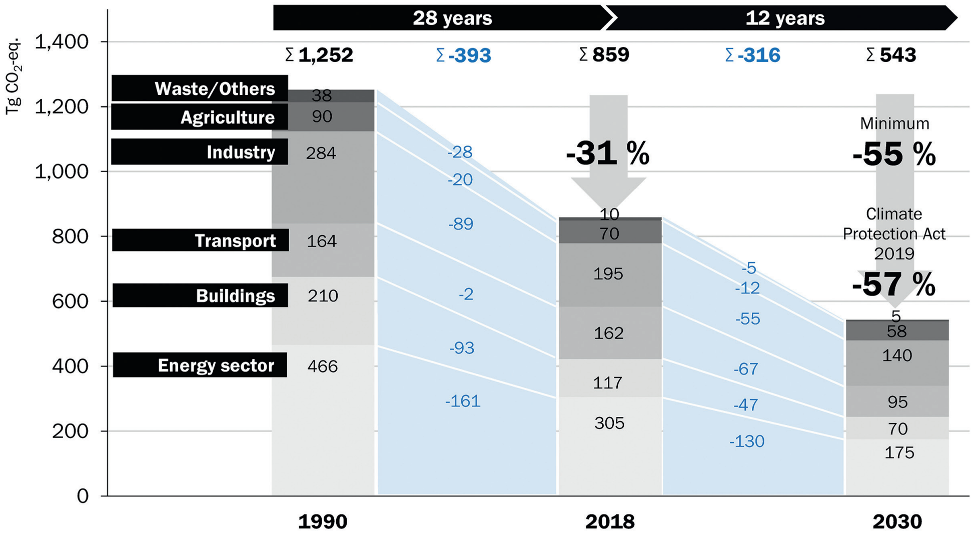


Figure 1.1: Goals and fulfilment of greenhouse gas mitigation in Germany (based on [5, 27])

These political goals and measures are also reflected in entrepreneurial strategies. By 2030, for example, the German chemical industry association “Verband der Chemischen Industrie (VCI)” would like to save up to 27 million tonnes of GHG emissions, among other things by using around 8.5 million tonnes of lignocellulosic biomass [28]. Automotive manufacturers such as VW, BMW or Mercedes increasingly aim to offer customers CO_2-neutral vehicles and employ new, bio-based materials [29–31]. Siemens intends to become climate-neutral by 2030 [33], while Bosch will already achieve that goal by 2020 [34]. In connection with the examples of bio-based products given above, it can be assumed that demand will increase for biogenic raw materials for material and energetic use. Above all, this is also connected to the discussion on the potential purposes of such raw materials and the ideal means of employing them [35, 36]. In this context, the federal government [9] is placing a clear emphasis on the point that any potential must only be tapped within ecological limits.

1.3 Determination of biomass potential

The availability of biomass is assessed by means of potential analysis, on a methodological basis divided into various definitions of potential [37, 38]. In 2009, Kaltschmitt, Hartmann and Hofbauer [38] differentiated between what they called the theoretical, technical, economic and implementation biomass potential. The maximum quantity in one region and one period of time, limited only by physical restrictions, is known as the *theoretical potential*. The other terms relate to different restrictions in terms of content and time which considerably constrain the extent to which that maximum limit is actually reached. The *technical potential* is part of the theoretical potential, and addresses not only technical restrictions but also other constraints, such as legal requirements or ecological and structural limitations [38]. According to Batidzirai, Smeets and Faaij [39], Thrän and Pfeiffer [40] and Faaji [37], these include restrictions relating to competing uses in the production of food, feed and fibre, or other material uses. Thus interpreted, the technical biomass potential describes the possible contribution which biomass from any source can make to the bioeconomy at a specific time and place. The *economic potential*, which is part of the technical potential, comprises further restrictions in connection with the economic feasibility of a project [38]. Numerous, constantly changing background circumstances (e. g. competition with fossil-derived raw materials, the price of oil, the cost of supplying or converting the biomass, the price of CO_2) mean that the economic potential is subject to much higher fluctuations over time than the technical potential [37–40]. Finally, the *implementation potential* describes the part of the economic potential that can actually be achieved in the long term at a specific location, taking into account all the restrictions, and with the involvement of relevant stakeholders [38]. In 2012, Batidzirai, Smeets and Faaij added another term to these definitions: that of the *ecologically sustainable potential*. Insofar as criteria related to ecological sustainability (e. g. soil, water, biodiversity) are taken into account when calculating the potential, this further limits the technical and economic potential [39]. The ecological restrictions already underlined in Kaltschmitt, Hartmann and Hofbauer [38] were thus linked to the concept of sustainability. Figure 1.2 illustrates the levels of potential explained above and how they overlap, also emphasising the content on which this thesis focuses.

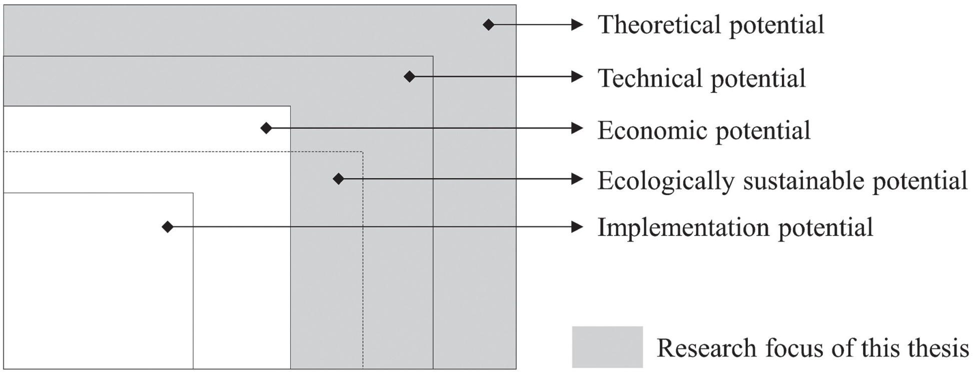


Figure 1.2: Biomass potential terminology, overlaps and illustration of research focus (based on [38, 39])

At present, there are no binding standards or minimum requirements for calculating biomass potential. As a result, there are numerous methodological approaches for calculating the levels of potential explained above, and the findings fall within a broad range for individual or multiple sectors, regions, countries and continents [41–45]. Although the proposals made by Vis et al. [46] for harmonising the different methods go all the way back to 2010, in recent years others such as Batidzirai, Smeets and Faaij [39], Creutzig et al. [47], Kluts et al. [48] and Hänninen et al. [49] have confirmed that the findings of different studies can only be compared to a very limited extent. There are, for example, significant differences in how they take into account and describe individual types of biomass, spatial and temporal contexts, source data and types of potential [37, 46]. So far, calculations of potential have been made in separate studies. The main challenges lie in describing the temporal and spatial developments in the raw material base, including the use of the raw materials, in a methodologically consistent and continuous manner. This is the only way of recognising trends and avoiding overuse. Against this background, Faaij [37] sums up the situation by concluding that, so far, there has been no single, complete calculation of biomass potential.

1.4 Research goal and objectives

Due to the unclear description of biogenic residues and waste materials, and the incomplete primary data (Chapter 1.1), the cross-sectoral volume of these raw materials and their current use can only be assessed incompletely. At the same time, political and entrepreneurial goals are aimed at increased use without exceeding ecological limits (Chapter 1.2). The ongoing lack of sufficient source data is creating an impasse in which it is impossible to quantify or evaluate either the current potential of biogenic residues and waste materials in a bioeconomy, or that which would meet ecological requirements. However, if regularly published basic data (such as statistics) are systematically linked to irregularly published specialist information (e. g. in the literature) then the missing information can be given structure and calculated continuously. This would require the development of a comprehensive information and data processing system which would take the specific features of different biomass types into account, and be capable of painting a consistent, updatable overall picture of the residues and waste materials produced by multiple sectors. The aim of the research is:

> **Development of a systematic method for annually reporting the potential and use of biogenic residues.**

Using the terms for describing potential (Figure 1.2), this method focuses on regularly measuring the theoretical and technical biomass potential with the aim of establishing a continuous improvement process for approaching the ecologically sustainable potential. The main requirements to achieve this goal are:

- High accessibility of data for subsequent use
- High understandability of calculation methods
- Spatial transferability of the monitoring system
- Continuous improvement of data quality to increase the reliability, completeness and timeliness of the monitoring system

The thesis consists of two parts and a total of three publications. Part I contains an introduction to the topic and describes how the publications are related in terms of their content. Part II contains the publications.

The first paper pinpoints which types of biomass are understood under the collective term “residues” and how those raw materials can be described consistently across all the sectors. Building on this, in the second paper a monitoring system is developed in line with the requirements, and tested based on the example of Germany. In the third paper, a case study is used to demonstrate how the monitoring system can be updated, thus improving its quality. Moreover, in the summary, there will also be a description of the implementation process and the methodological approaches used to measure data quality. Against this background, a transparent basis will be created for gradually working towards a calculation of the ecologically sustainable biomass potential. The structure of the thesis is illustrated in Figure 1.3.

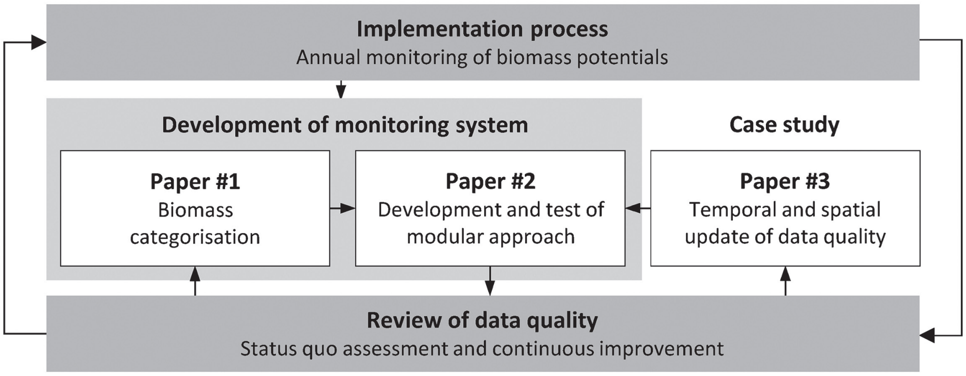


Figure 1.3: Structure of thesis and links between the papers

CHAPTER 2

Methodology

The methodological approach is made up three parts: implementation, developing the monitoring system and reviewing the data quality (Figure 1.3). The implementation (Chapter 2.1) is focused on organising the process required to set up the system and operate it in the long term. The development (Chapter 2.2) involves using a modular approach to collect data for all the sectors, calculate the potential, make the results accessible and ensure that the documentation is clearly understandable. The review of data quality (Chapter 2.3) includes the quantitative assessment of the three quality criteria reliability, completeness and timeliness as well as and the temporal and spatial updating of the monitoring system based on a case study. In the explanations, reference is made to the three appended papers (Part II, p. 43 ff.) which were used to develop and test the methodology.

2.1 Implementation process for the monitoring system

The implementation of the monitoring system is based on the idea of continuous improvement, which dates back to the 1930s and has its origin in quality assurance [50]. A process-oriented attitude is adopted with the goal of achieving evolutionary quality development [51]. Unlike the separate calculations of potential which were previously carried out (Chapter 1.3), this step-by-step, cumulative approach enables the calculation methods to be regularly reviewed and adapted. Calculation steps which pass the review become standards, and uncertainties can be regularly spotted and deliberately minimised. The basis for this procedure is a four-stage process known as Deming-Circle [50, 51], which has become established in numerous management systems and standards (e. g. EMAS [51, 52], ISO 9001 [53], ISO 14001 [54] or ISO 50001 [55]). The four stages are Plan, Do, Check and Act [51]. At the “Plan” stage, goals are defined and their achievement planned. At the “Do” stage, solutions are developed, documented and visualised. At the “Check” stage, the results are reflected upon, and at the “Act” stage, improvements are initiated. [51] This general approach has been adapted to the research goal of this thesis, producing a total of eleven steps for the implementation of the monitoring system, as summarised in Figure 2.1. The various steps lead to defined interim results, which in turn are closely connected to the individual modules of the monitoring system (Figure 2.2).

At *Stage 1* (Plan), the scope of the monitoring activities is defined. **Step 1** involves identifying and categorising the biomass types from the different sectors which are to be taken into account in the monitoring system (Paper # 1). **Step 2** then consists in determining the level of reporting detail. This involves defining key items of information to describe the material flow, and the temporal and spatial resolution of the calculations of the potential. To ensure that the findings are well accepted, **Step 3** brings together an inter-institutional group of experts to work on the relevant topics together, with the aim of setting out clear responsibilities for individual raw materials or sectors.

Figure 2.1: Implementation process for the monitoring system

Once the level of detail and the responsibilities have been established, at *Stage 2* (Do), work starts on putting the measures into practice. **Step 4** involves collecting applicable calculation elements for assessing the biomass potential, and their source data. This is the step at which an inter-institutional exchange of knowledge begins. In **Step 5**, the calculation elements which have been gathered are placed in a mathematical relationship to one other. This creates an automated calculation network (Paper # 2), which is at the core of the potential calculations. To improve the understandability of the calculations which have been carried out, **Step 6** consists in visualising the methodological approach in the form of calculation flowcharts (Paper # 2). To complement this, in **Step 7** the types of biomass potential are contextualised to make it easier to understand their significance in the context of the future use of raw materials (Papers # 1, # 2 and # 3). The main goal at this point is to identify the relevance of individual raw materials or sectors, and determine priorities for further analyses. **Step 8** involves ensuring that access is provided to the results of the calculations for individual subsequent use by e. g. an online data repository. If the results contain a spatial differentiation, it is also possible to integrate an online atlas.

At *Stage 3* (Check), the quality of the data is assessed. **Step 9** consists in measuring the status quo of reliability, completeness and timeliness. The findings are used to identify gaps in the data and determine the need for research.

On this basis, at *Stage 4* (Act), concrete measures can be taken to improve data quality as required. With this in mind, **Step 10** is focused on updating the automatic calculation network by adding, for example, temporal and spatial details (Paper # 3) or other calculation elements, to come closer to the ecologically sustainable biomass potential. This is connected to Steps 2, 3 and 4, which could require

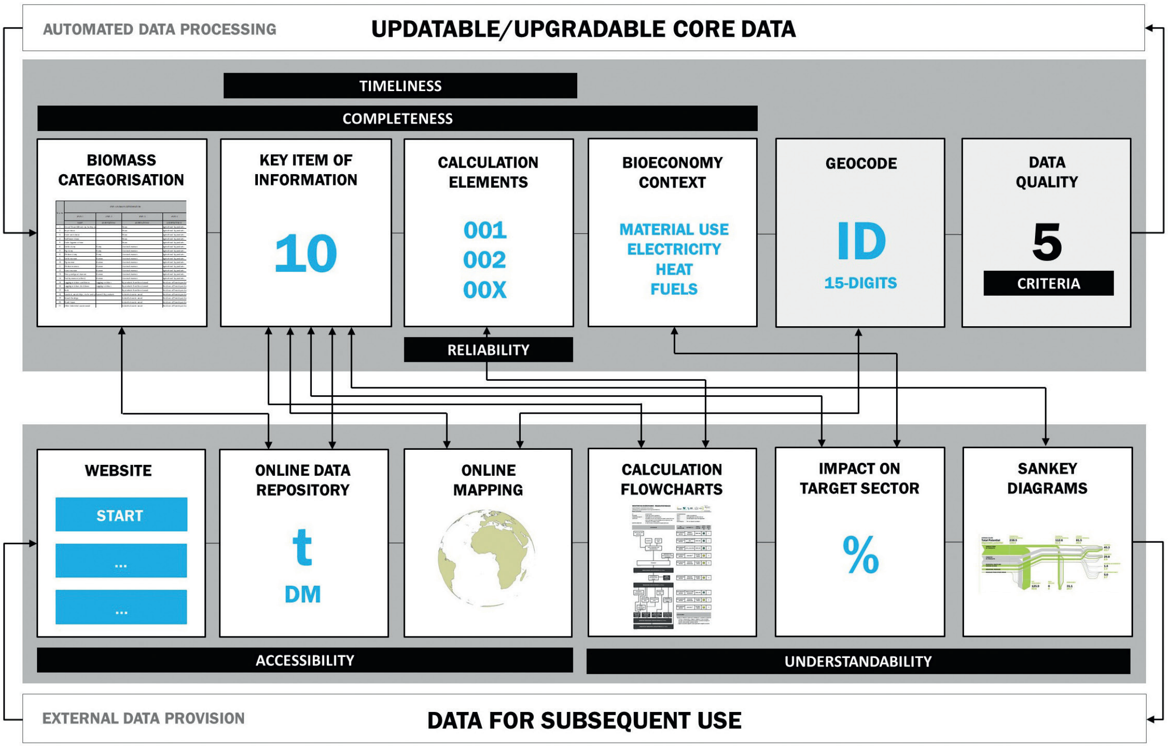


Figure 2.2: Overview of the twelve modules of the monitoring system, the five criteria of data quality and their connection to one other

other experts to be involved. As well as the content being updated, a structural upgrade (**Step 11**) can also be used to integrate new types of biomass or other key items of information to describe the material flow into the system. This creates a direct link to Steps 1 and 2, and rounds off the work plan. At Stage 4, the focus should be on each of the raw materials which were identified as being of high priority in Step 7. This means that the continuous process for improving the calculation methodology and the monitoring system can always be adjusted to suit the most relevant issues.

2.2 Development of the monitoring system

The monitoring system consists of a total of twelve modules, used to organise the automated data processing and external data provision (Figure 2.2). The relationships between the various modules and the link to the implementation steps (Figure 2.1) are described in the following.

Biomass categorisation: So far, there are no binding standards laying down which specific biogenic raw materials can be said to fall under the collective term “residues”. The first step in developing the monitoring system was thus to identify and categorise relevant types of biomass across the different sectors (Paper # 1, Step 1 in Figure 2.1). In this process, the following five sectors were taken into account:

- Agriculture
- Forestry
- Municipal waste and sewage sludge
- Industrial residues
- Residues from other areas

To study the example of Germany, an inter-institutional review of the literature was carried out, analysing a total of 30 studies and numerous terms used to describe biomass. On this basis, a four-stage naming convention was developed which can be used to consistently describe both individual raw materials and groups thereof, enabling findings to be communicated in aggregate. This flexible means of describing raw materials is a central principle behind the monitoring system.

Key items of information: A total of ten key items of information were defined (Step 2 in Figure 2.1) for communicating findings in a targeted, clearly organised manner. On this basis, the entire material flow is consistently described for each individual type of biomass (Figure 2.3), starting out with the theoretical potential then moving on to the technical potential and the details of its uses. The difference between the biomass supply and the biomass utilisation is the mobilisable technical potential; this could also be used for the future production of bio-based products. In combination with the high level of detail from the biomass categorisation, this makes it possible to analyse the results flexibly along the material flow for every type of biomass. Paper #2 contains further information on the functional relationships between the key items of information.

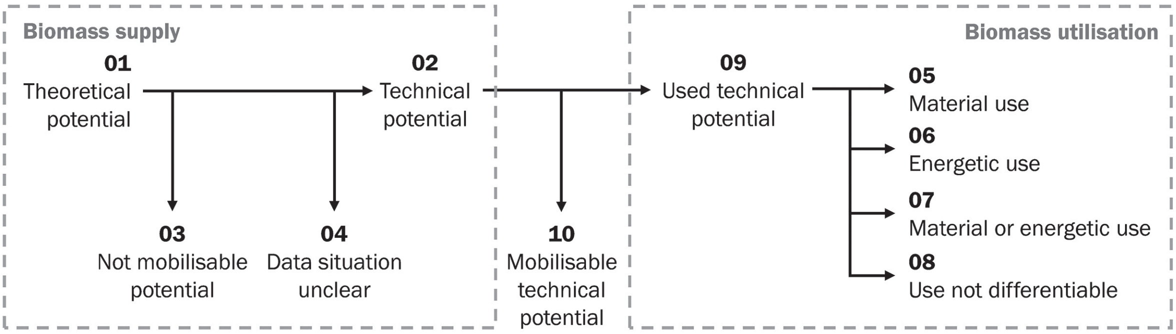


Figure 2.3: Overview of key items of information used to describe the material flow within the monitoring system

Calculation elements: To calculate the potential in a manner that can be regularly updated and is temporally and methodologically consistent, detailed information is required on the calculation elements which are used. For the year 2015 and for the purpose of national reporting (Step 2 in Figure 2.1), another 122 sources were analysed across the different institutions, and biomass-specific calculations were brought together (Steps 3 and 4 in Figure 2.1) and linked to each other mathematically (Step 5 in Figure 2.1). By this means, an updatable calculation network was set up which enables key items of information to be calculated automatically (Paper #2). To be able to take ranges of results into account, the minimum and maximum values were recorded in each case.

Calculation flowcharts: To improve the understandability of the biomass potential calculations, the relationships between the calculation elements and the key items of information for every type of biomass considered were each visualised as a calculation flowchart on a single A4 page (Paper #2; Step 6 in Figure 2.1). For each calculation element, the document also contains meta-information about the source of the data, their dynamics, their updatability and their reliability.

Bioeconomy context, impact on target sector: The interpretation of the results is made possible by contextualising the key items of information. If relevant basic data are integrated (e.g. the characteristics of raw materials, conversion factors, water content, etc.), a biomass potential can automatically be converted into an amount of bio-based target product. Combined with further information about the needs of a target market, this allows the relevance of a potential future use to be calculated and priorities identified for individual raw materials (Step 7 in Figure 2.1). As part of the testing of the monitoring system, different contexts were presented in Papers #1, #2 and #3, building upon one another. Paper #1 addresses the topic of the contribution to the primary energy consumption expected from biogenic residues, by-products and wastes. Paper #2 focuses on the bio-based target product of biomethane, for the target sector of transport. This choice was based on the fact that very little progress has been made so far in reducing the level of GHGs in the transport sector (Figure 1.1), meaning that there is considerable pressure to take action if the 2030 goals are to be achieved. Paper #3 extends the contextualisation to include the case study of biomethane derived from cereal straw, used in the transport sector, as this raw material is extremely relevant in terms of quantity. As well as its potential for replacing fossil-derived fuels, the absolute amounts of GHGs which could potentially be reduced in this connection were also estimated. In light of the climate targets named in Chapter 1.2, these figures can be used to work out the strategic significance of the case in question. The methodological background and the calculation parameters which were used are described in detail in the respective papers.

Sankey diagrams: The quantitative relationships in the material flow can be visualised in a clearly understandable manner using Sankey diagrams. As the key items of information are structured in a manner which is valid for the entire system, corresponding diagrams can be created for multiple biomass types or sectors. In the overall view, it is also possible to distinguish visually between types of biomass with specific raw material properties (e. g. digestibility). An example of this is included in Paper #2.

Website, online data repository: So that the data can be used subsequently (Step 8 in Figure 2.1), a freely accessible website has been set up at http://webapp.dbfz.de with an online data repository offering access to biomass-specific key items of information and their contextualisation (Paper #2).

Geocoding, online mapping: To enable the monitoring system to be transferred geographically, the data structure is based on 15-digit geocodes which unambiguously describe countries, regions, all biomass types, sectors, key items of information and biomass-specific calculation elements, both temporally and spatially. Thanks to the mapping module, geographically subdivided results can thus be provided in online atlas systems. A full description of the coding is included in Paper #2.

Data quality: The data quality has a decisive influence on how informative and well accepted the findings on potential are. With regard to the requirements posed for the monitoring system, as set out in Chapter 1.4, and on the basis of quality criteria such as those defined by Wang and Strong [56] and Spruit and van der Linden [57] in 1996 and 2019, the five criteria of accessibility, understandability, reliability, completeness and timeliness are taken into account. Table 2.1 contains a description of these in the context of the research objective, and their links to the various modules of the monitoring system are shown in Figure 2.2. While the two criteria of accessibility and understandability are determined structurally, the three other criteria are evaluated quantitatively as part of the continuous improvement process. Each of the methodological approaches is explained in the next chapter.

Table 2.1: Criteria used to determine data quality and their description in the context of the research objective (based on [56, 57])

Data quality criteria		Description in the context of the research objective
1	Accessibility	The findings are provided for subsequent use.
2	Understandability	The biomass potential calculation and the findings are clearly comprehensible and transparent.
3	Reliability	The data source for the calculation elements is evaluated.
4	Completeness	The required information is contained in the monitoring system.
5	Timeliness	The findings are up to date.

2.3 Review of data quality

The continuous improvement of the data quality enables the monitoring system to be updated and extended step by step. To enable corresponding adjustments to be made in a targeted, needs-based manner, the status quo of data quality must be known. To test out the related Steps 9–11 (Figure 2.1) exemplarily, five methodological approaches were developed and tested for the three quality criteria reliability, completeness and timeliness. Table 2.2 presents an overview.

Table 2.2: Approaches for assessing the status quo and testing the continuous improvement of data quality

Steps towards improvement	Data quality criteria		
	Reliability	Completeness	Timeliness
Status quo assessment (Step 9)	a) Points-based evaluation of calculation elements	b) Consideration of ecological sustainability indicators	c) Dynamics of data sources
Updating and upgrading the monitoring system (Steps 10 and 11)	–	d) Temporal and spatial details of important biomass	–
	–	e) Integration of further content	–

2.3.1 Status quo assessment

a) Points-based evaluation of calculation elements: The calculations of potential include biomass-specific calculation elements based on various sources. For this purpose, Paper #2 distinguishes between six types of source – statistics, models, primary data, databases, the literature and expert judgements – and assesses them using a three-level system. In this context, it was assumed, for example, that regularly published official statistics are highly reliable, whereas an expert judgement is linked to uncertainties. Following this understanding, all of the calculation elements for each individual biomass were evaluated. Averaging the evaluation points produces a value for the reliability of the source data, described as “reliable”, “uncertain” or “not reliable”. Paper #2 contains a detailed explanation of the methodological procedure. In this context, a distinction was also made between the findings for individual sectors and key items of information, enabling corresponding differences along the material flows to be pinpointed.

b) Consideration of ecological sustainability indicators: The aim is to mobilise the biomass potential within ecological limits (Chapter 1.2). So far, there are no firmly established criteria to determine whether or not that goal can be achieved. As a means of initially ascertaining and evaluating the status quo regarding ecologically sustainable potential, relevant sustainability indicators were selected, and reviews carried out to check whether they were taken into account when the potential was calculated. The following three sources were used as the basis for selecting the indicators:

- **Global Bioenergy Partnership (GBEP):** In December 2011, the GBEP named a total of 24 sustainability indicators for bioenergy [58]. A working paper [59] operationalised these indicators and named numerous data sets which were required.
- **Sustainable Development Goals:** The SDGs came into force in January 2016 [4]. The operationalisation of the goals is an ongoing process which is coordinated in Germany by the Federal Statistical Office and documented by the National Reporting Platform (NRP) [60]. As of July 2020, 247 indicators in all were named, of which 146 are connected to a measurable national data set.
- **German Federal Government Sustainable Development Strategy:** This strategy paper goes back as far as 2002 and was most recently adapted to the structure of the SDGs in 2018 [61]. At present, it names 66 indicators which are to be used to measure the progress made towards achieving various sustainability goals by 2030.

Fritsche et al. [62] linked the GBEP indicators to the SDGs in 2018, while Zeug et al. [63] identified the SDGs relevant to the bioeconomy in 2019. On the basis of these connections, the above sources were analysed with regard to the ecological sustainability indicators and their operationalisation. The indicators thus identified were then compared with the calculation elements for the 15 types of biomass described as the most important in terms of their technical potential, using one of three statements:

1. The indicator was taken into account.
2. The indicator was not taken into account.
3. The indicator is not relevant.

This shows the current completeness of the sustainability indicators in the potential calculations, used as the basis for gradually coming closer to the ecologically sustainable biomass potential in future.

c) Dynamics of data sources: The timeliness of the monitoring findings depends on whether the calculation elements can be updated, and the intervals at which the corresponding data bases are updated. In the monitoring system, a difference was thus made between dynamic and non-dynamic calculation elements. The first step involved ascribing each of the source types named in (a) to one of these distinguishing features. The second step was to analyse, on this basis, the sources of all the calculation elements contained in the system. Further explanations of this can be found in Paper # 2. Similarly to (a), during the summing up, the analyses were expanded to include individual sectors and key items of information.

2.3.2 Updating and upgrading the monitoring system

d) Temporal and spatial details of important biomass: The monitoring system is tested at the national level and for a single reference year, producing a single data point which is initially only a snapshot of the situation. However, biogenic raw materials are distributed spatially differently, and may also be subject to fluctuations over time. Paper # 3 thus demonstrates how the monitoring system can be updated. For the example of cereal straw, the completeness of the data was increased in terms of the temporal and spatial details, and the calculation network was consistently updated for the years 2010–2018, on the level of the district. At the same time, the opportunity was taken to test whether the system could be transferred geographically, from a national to a regional level. For the raw material which was selected, the calculation elements in the monitoring system were connected to another 30 regionalised data sets in all. Because of the structure of statistical data collection, a complete set of data is not available for all calculation elements on the regional level. Missing data were therefore temporally interpolated, spatially weighted or collected. The data preparation described in detail in Paper #3 was used to calculate the key items of information named in Figure 2.3 for every year and every district in Germany. The findings were then linked to high-resolution official geodata on cropland, enabling the spatial distribution of the real reference area within the analysed districts to be taken into account. Using a geo-information system (GIS), the interregional context of the raw material assessment was analysed over time. On that basis, key regions were identified where raw materials could potentially be tapped in future. A full description of the steps in the analysis is included in Paper #3.

e) Integration of further content: The biomass types initially included in the monitoring system, the calculation elements and the key items of information describing the material flow all build upon the reviews in Papers #1 and #2. The status achieved by that means can be continuously improved by updating the content or upgrading the structure of the monitoring system. From a technical perspective, the available data is highly heterogeneous. It may include individual tables, publications, research reports, calculation models, internal databases or other formats. So far, the data structures have been incompatible. To combine the inter-institutional knowledge within the monitoring system, a central structure has thus been developed for data processing which maximises the potential interoperability with minimal technical requirements. The Excel-based structure is shown in Table 2.3 and contains the information on all twelve monitoring modules for all the biomass types considered (Chapter 2.2).

Table 2.3: Technical structure for inter-institutional data processing

1	*2*	*3–6*	*7*	*8*	*9*	*10*	*[…]*
Geocode 15 digits	**Biomass Level 1**	**Meta infor-mation**	**Key items of information and calculation elements**	**Unit**	**2015 MIN**	**2015 MAX**	**[…]**
DE000ABCST01000	Cereal straw	Source, dynamics, updatability, reliability	**Theoretical potential**	t dm	Automated calculation		
DE000ABCST01001	Cereal straw		Wheat production	t fm	Collected values		
DE000ABCST01002	Cereal straw		Dry matter content	%			
DE000ABCST01003	Cereal straw		[…]	[…]			
DE000ABCST02000	Cereal straw		**Technical potential**	t dm	Automated calculation		
DE000ABCST02001	Cereal straw		Technical recovery ratio	%	Collected values		
DE000ABCST02002	Cereal straw		[…]	[…]			
DE000…	*[…]*		*[…]*	*[…]*			

In Column 1 (geocode), the spatial level of the calculation, the biomass categorisation, each key item of information and each calculation element can be clearly identified and addressed for further analysis (Paper #2). Adding to this, Column 2 contains the name of the biomass based on the multi-level biomass categorisation (Paper #1). Columns 3–6 contain relevant meta-information on the calculation elements for documentation in the flowcharts (Paper #2). This is followed, in Column 7, by the designations of the individual key items of information and the calculation elements, with the associated unit of measurement noted in Column 8. Columns 9 and 10 contain the minimum and maximum values of the calculation elements and the automated calculations of the key items of information, using tonnes of dry matter (t dm) as the measurement unit for the entire system. Here, "automated" means that the formulae for the biomass-specific key items of information are the same for every year of the calculation. The temporal differentiation results from the various changing values for the individual calculation elements. If required, the minimum and maximum values can be used to automatically derive further statistical key figures (e. g. mean values). Where there are several data points, this also includes regression analysis, which can be used to analyse and extrapolate trends. The described structure is used to organise the balancing for all biomass types and for all relevant time and space references. If the content of the system is updated (Step 10, Figure 2.1), new columns can hold additional reference periods (e. g. years), while new rows can hold additional spatial levels or new calculation elements specific to certain biomass types. If the system is to be structurally upgraded (Step 11, Figure 2.1), further types of biomass or new key items of information can be included by adding new rows. To ensure that the system-wide calculation network and the communication of findings remain consistent, additional calculation elements must be depicted in the same way in the table for all the years included, and new key items of information must be depicted in the same way for all the biomass types. This means that findings can be adapted retroactively if the calculations are updated or changed. In any case, the system as a whole remains internally consistent.

CHAPTER 3

Results and discussion

The monitoring system was tested based on the example of Germany, and covers a total of 77 biogenic residues, by-products and waste from five sectors. As a result, the system contains an automated network of 1,113 calculation elements. Using these, along with ten key items of information, each type of biomass considered can be assessed and analysed in detail in terms of the supply and use of raw materials. Chapter 3.1 focuses on the findings on potential along the material flow and the associated priorities and levels of relevance (Step 7, Figure 2.1). Chapter 3.2 describes the transferability of the system, and Chapter 3.3 sums up the status quo of data quality for the five criteria considered. Finally, Chapter 3.4 discusses different options available for the further, continuous improvement of data quality. The explanations always include the relationship to the respective appended Papers # 1 to # 3 (Part II, p. 43 ff.).

3.1 Biomass potential monitoring

3.1.1 Identification of priorities

Using the four-stage biomass categorisation process (Paper # 1) and the ten key items of information (Paper # 2), the findings on potential for all 77 types of biomass (Paper # 2) can be analysed consistently and individually at different levels of detail. As the minimum and maximum values are taken into account consequently for all the calculation elements and key items of information, the range of the findings is broad for many raw materials from almost every sector. Despite these uncertainties, when summing up, it is possible to identify clear focal points in terms of how the quantities are distributed over the material flow, and clear priorities for individual raw materials within the overall system.

Building on the findings discussed in Paper # 2, Figure 3.1 shows the sector-specific material flows as a range of minimum and maximum values, set out in respect to the key items of information for the reference year, 2015. So that the relative proportions can be assessed quantitatively, corresponding values are given for each key item of information. The theoretical biomass potential is the starting point, at 100 % (black numbers) and a volume of 199–278 Tg dm (blue numbers). For the reference year for which tests were carried out, it can be said that roughly half of this (43–50 %) is technically usable, roughly one third (33–36 %) is in use and up to one sixth (7–17 %) can still be mobilised. The percentages change depending on the starting point used for these observations, even if the absolute quantities of raw materials remain the same. With regard to the technical potential (100 %, dark grey value), 65–84 % is already in use and up to just over a third (16–35 %) can still be mobilised. In terms of the potential used (100 %, light grey values), more than half (54–58 %) is put to material use, while more than a third (37 %) is used to produce energy. For 5–9 % in all, it is not possible to clearly identify or narrow down the use. Concrete indications as to which raw materials are particularly relevant, and corresponding priorities, can only be distinguished on a detailed level for individual raw materials.

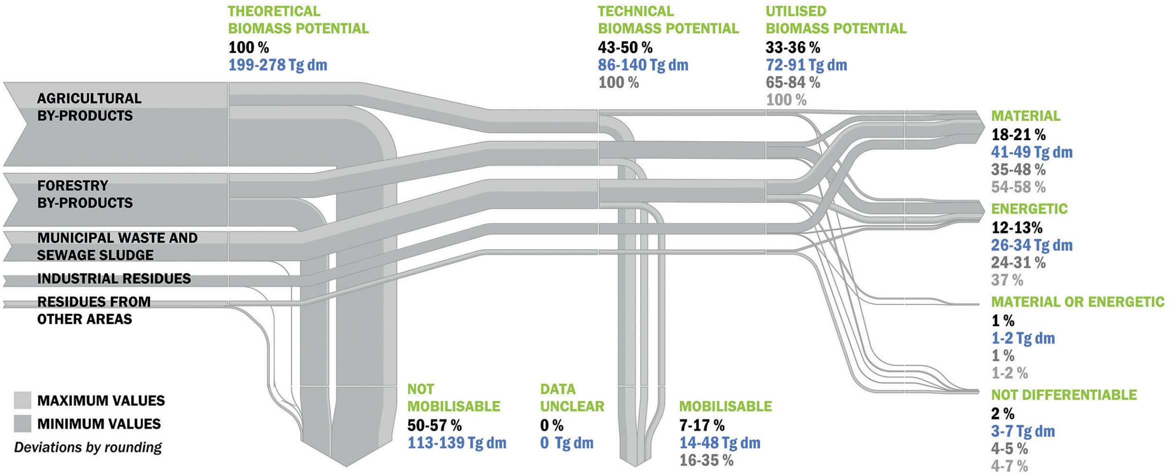
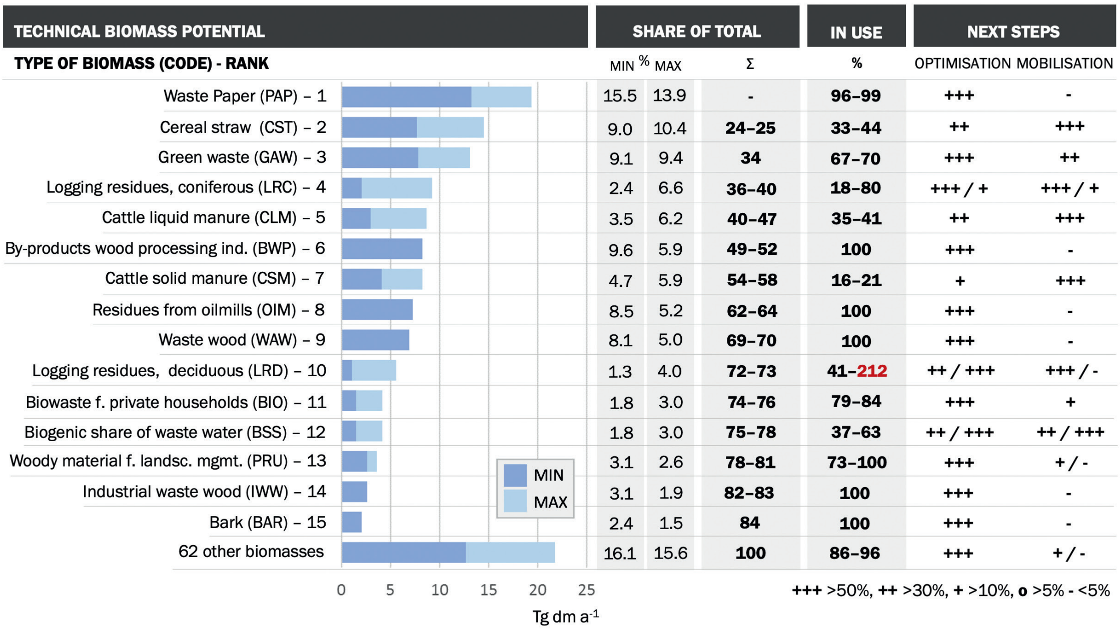


Figure 3.1: Minimum and maximum values of sectoral biomass potential and use for 77 biogenic residues, 2015

Due to the level of detail in the source data the individual raw materials can be ranked for each key item of information (Paper #2). By this means, for example, the most important raw materials in terms of volume can be prioritised across all sectors, and recommendations made for further steps (e.g. optimisation and mobilisation strategies). One example is summarised in Figure 3.2 for the key item of information "Technical biomass potential", showing the 15 most important types of biomass sorted by the maximum values in tonnes of dry matter per year. The "Share of total" columns show the minimum and maximum values as percentages of the total technical potential. What are sometimes broad ranges (e.g. logging residues, liquid cattle manure, biowaste) are reduced to very similar scales in relation to the totals at each respective time. The most important 3 out of the 77 types of biomass make up one third; the most important 6 make up one half, the most important 10 almost three quarters, and all 15 of the biomasses depicted make up 84 % of all the types of biomass in the overall monitoring system. The remaining 62 types are distributed over the remaining 16 %.

The extent to which optimisation or mobilisation strategies might be the next step towards improved use can be derived from the way the raw materials are used. The "In Use" column shows the percentage of the technical potential that is currently put to use. This information is based on the key item of information "Utilised biomass potential" and is also shown as a range. A qualitative recommendation is indicated in the "Next Steps" column on this quantitative basis. If almost all the volumes of raw materials are in use (e.g. waste paper, by-products of wood processing industries, residues from oil mills etc.), the priority is given to optimising the existing use, e.g. through cascading use or more efficient production or recycling processes. By contrast, where large proportions are not yet used as part of the bioeconomy (e.g. cereal straw, cattle liquid manure, cattle solid manure), priority is given to mobilising these volumes of raw materials. These two strategic approaches involve taking different measures, with different stakeholders. In the case of some raw materials (e.g. coniferous/deciduous logging residues), the range of results is so broad that no clear conclusion can be drawn. In the case of deciduous logging residues, when the background circumstances are extremely restrictive, more than twice the existing volume of raw materials is used. In this case, the monitoring system detects a significant overuse of the raw material in question.

This raw material ranking can be used to make decisions about which are the most relevant biomasses to focus on when carrying out future activities designed to implement strategies or improve the source



TECHNICAL BIOMASS POTENTIAL TYPE OF BIOMASS (CODE) - RANK	SHARE OF TOTAL MIN %	 MAX %	 Σ	IN USE %	NEXT STEPS OPTIMISATION	 MOBILISATION
Waste Paper (PAP) – 1	15.5	13.9	-	96–99	+++	-
Cereal straw (CST) – 2	9.0	10.4	24–25	33–44	++	+++
Green waste (GAW) – 3	9.1	9.4	34	67–70	+++	++
Logging residues, coniferous (LRC) – 4	2.4	6.6	36–40	18–80	+++ / +	+++ / +
Cattle liquid manure (CLM) – 5	3.5	6.2	40–47	35–41	++	+++
By-products wood processing ind. (BWP) – 6	9.6	5.9	49–52	100	+++	-
Cattle solid manure (CSM) – 7	4.7	5.9	54–58	16–21	+	+++
Residues from oilmills (OIM) – 8	8.5	5.2	62–64	100	+++	-
Waste wood (WAW) – 9	8.1	5.0	69–70	100	+++	-
Logging residues, deciduous (LRD) – 10	1.3	4.0	72–73	41–212	++ / +++	+++ / -
Biowaste f. private households (BIO) – 11	1.8	3.0	74–76	79–84	+++	+
Biogenic share of waste water (BSS) – 12	1.8	3.0	75–78	37–63	++ / +++	++ / +++
Woody material f. landsc. mgmt. (PRU) – 13	3.1	2.6	78–81	73–100	+++	+ / -
Industrial waste wood (IWW) – 14	3.1	1.9	82–83	100	+++	-
Bark (BAR) – 15	2.4	1.5	84	100	+++	-
62 other biomasses	16.1	15.6	100	86–96	+++	+ / -

+++ >50%, ++ >30%, + >10%, **o** >5% - <5%

Figure 3.2: 15 most important biomass types ranked in order of maximum technical biomass potential, the biomass specific shares and cumulative totals, current use and evaluation of next steps, 2015

data (Step 7, Figure 2.1). If corresponding measures are adopted, this can also be expected to have the greatest impact on the bioeconomic system as a whole (e. g. GHG reduction, Chapter 1.2).

To maintain high data quality, the process of continuously improving the calculation methods is an important constituent of the monitoring system. Paper # 3 thus describes a case example demonstrating how an improvement of this kind can be carried out. Based on the rankings in Figure 3.2, cereal straw was chosen as the biomass for this purpose. Out of the entire monitoring system, this is the most relevant biomass in terms of the volume that can still be mobilised. The findings from the temporal and spatial analysis for 2010 to 2018 and at district level exhibit considerable fluctuations in the yield in a range extending regionally beyond + 20 % to – 40 %. In this context, the reference year for the national monitoring, 2015, is a relatively strong year. By contrast, the detailed analysis reveals extreme values for the years 2014 and 2018, in particular, with the highest values since records began appearing in 2014, while 2018 saw the lowest production volume since 1994. The strongly fluctuating volume of raw materials is in stark contrast with the relative lack of dynamism in terms of use, limited to certain clearly defined geographical focal points. Despite the fluctuations, the assessment of the regional volumes of raw materials and their use reveals clear key regions where considerable portions of the national cereal straw potential are concentrated. For example, one third of the entire mobilisable potential is found in at most 30 out of 401 districts. GIS analysis was used to go beyond individual districts and identify key regions which had an especially high technical potential in terms of cereal straw. By far the most important regions in Germany are found in the north (Mecklenburg-Western Pomerania, eastern Schleswig-Holstein) and in a band reaching from Central Saxony, southern Saxony-Anhalt and the south of Lower Saxony to western North Rhine-Westphalia. These are mainly classic fertile *Börde* lowlands with particularly high levels of high-yield grain cultivation. Further detailed information on the temporal and spatial context are described in Paper # 3.

3.1.2 Quantification of relevance

The role that biogenic residues can play in the future bioeconomy depends crucially on the potential target products and the demand for them on a target market. To make the relevance of the identified raw material priorities (Chapter 3.1.1) easier to understand, the monitoring system contains the modules “Bioeconomy context” and “Impact on target sector”, thus enabling the findings to be contextualised. Concrete examples of this are presented in Papers #1 (primary energy contribution), #2 (biomethane in the transport sector) and #3 (biomethane from cereal straw for the transport sector), as summarised below.

In relation to the current energetic use (26–34 Tg dm, Figure 3.1) and subject to the general assumption that the raw materials have an energy content between 15 and 18 MJ (kg dm)$^{-1}$ [11], their approximate contribution to primary energy is 390–612 PJ. In connection with the German primary energy demand in 2015 (13,262 PJ [64]), this corresponds to a contribution of between three and almost five percent. If the mobilisable potential (14–48 Tg dm) was also used to generate energy after material utilisation, another 210–864 PJ could be provided. This would thus raise the contribution to primary energy consumption (600 to 1,476 PJ in all) to a total of five to eleven per cent. If the primary energy consumption were to be reduced to 10,066 PJ, in line with the political targets for 2030 [65], the calculated proportion would rise to between almost 6 and 15 %. This could mean at least a doubling of the current contribution. However, this would require the volume of resources to remain at a similar level, while all of the potential yet to be mobilised was tapped in full. Furthermore, the general range of energy contents is only of limited significance, as there are countless options for using and reusing raw materials. However, this calculation offers rough evidence that, even taking the lowest values, this potential application can be of relevance, for example in the energy system, and, for instance, generate at least nine times the primary energy produced by hydropower (68 PJ in 2015 [64]).

Papers #2 and #3 substantiate these rough estimates step by step. Selecting biomethane as a target product and examining 2015 as a reference year, Paper #2 demonstrates that fermenting the remaining mobilisable potential could generate between 108 and 136 PJ of biomethane. This could mean, for example, that all the energy required by certain modes of transport (e. g. buses, ships), or some of that required by others (e. g. heavy goods vehicles, cars) was provided by a low-emission fuel – at least from the point of view of resource availability. The details of how this could happen and the percentages provided per mode of transport are described in detail in Paper #2.

Paper #3 adds to this analysis in relation to cereal straw, as a particularly relevant raw material (Chapter 3.1.1). If the mobilisable potential from cereal straw were used e. g. in the form of biomethane in the transport sector, with the additional feature of the digestate being returned to the harvesting site, then, despite the yield fluctuations, between 57 and 145 PJ of renewable energy could be provided by just one biomass. This could then cover between 80 % and > 100 % of the energy required by vessels, 8–21 % of that of trucks, or 4–10 % of that of cars. If a possible range relating to emissions reduction is also taken into account (Paper #3), this would result in GHG mitigation of 3–12 Tg CO_2-eq. With regard to Figure 1.1, a further 67 Tg CO_2-eq. would have to be saved in the transport sector by 2030. Up to a sixth of that target could be achieved via the efficient use of cereal straw, but it is unrealistic to imagine that the full mobilisable potential can be tapped. Paper #3 thus investigates further graduations, revealing, for example, that if a lower proportion (10 %) is tapped, between 6 and 15 PJ can be provided, cutting back on up to a million tonnes of CO_2 equivalent. Although this would still cover 8–15 % of the demand in the shipping sector, it would represent less than 1–2 % of that for heavy goods vehicles, or less than 1 % for the automotive sector. The strategic relevance of a potential contribution to meeting the GHG mitigation targets in the transport sector then drops to between not even one percent and a maximum of two percent.

3.1.3 Summary

The presentation of the findings outlines one way in which the monitoring system can be used to identify priorities and describe levels of relevance on a target market. In addition to the quantitative description of the material flow based on the key items of information, the rankings can be used to identify specific raw materials which are particularly relevant across all sectors. This reveals that 15 out of 77 raw materials already cover 84 % of the entire technical potential. Taking the current use into account also produces signs that logging residues (deciduous) are overused, and recommendations for further analyses which could be carried out regarding strategies for optimisation or mobilisation. Building on this, the case example of cereal straw offers a detailed insight into the temporal and spatial dynamics of biomass availability. The results show that, despite considerable regional fluctuations, large parts of the national potential are concentrated in only a few key regions. In the example context of cereal-straw-derived biomethane for the transport sector, it was also shown that tapping the mobilisable potential would have significant potential to mitigate GHGs in this sector. However, the volumes which could actually be tapped in future depend above all on the decisions made by regional stakeholders and shareholders. The monitoring system can be used to name specific regions where one fruitful next step could be further discussions on mobilisation measures. In this context, the system acts as a tool to support decision-making on the measures which can be implemented to achieve the goals of the bioeconomy strategy.

3.2 Transferability to other countries or regions

The 15-digit geocode (Paper #2) can be used to transfer the monitoring system to other countries, or regions within countries. To this end, the code contains an international country code (ISO 31662, [66]) which can be used to identify all components of the system as relating to a specific country, so that the data can be processed individually. Other geospatial tiers beneath the national level (e. g. federal states, government regions, districts) are described using at least three further combinations of letters and numbers (e. g. NUTS codes for Europe, [67]). This means that they are fully interoperable with any other country-specific code systems which may have more than three digits. By this means, every component of the monitoring system can be consistently mapped on any geospatial level, and can always be addressed unambiguously. To illustrate these possibilities, five geospatially diverse examples for the calculation element "wheat production" are shown in Table 3.1.

Table 3.1: Examples of the monitoring system's international and regional transferability

#	Geocode, 15 digits	National level	Regional level	Description
1	**DE000**ABCST01001	DE: Germany	000: National level	A: Agriculture, B: By-product, CST: Cereal straw, 01: Theoretical potential 001: Wheat production
2	**DE40I**ABCST01001	DE: Germany	40I: District of Uckermark	
3	**CASK0**ABCST01001	CA: Canada	SK0: Prov. of Saskatchewan	
4	**CNSD0**ABCST01001	CN: China	SD0: Shandong Province	
5	**BA060**ABCST01001	BA: Bosnia and Herzegovina	060: Canton of Central Bosnia	

The regional transferability of the monitoring system was tested as part of the case example in Paper #3. Its international transferability was successfully demonstrated as part of an external project carried out in Bosnia-Herzegovina [68] which led, among other things, to an online atlas. This structured transferability to multiple countries and regions consequently means that findings can be consistently compared from one country or region to another.

3.3 Status quo of data quality

3.3.1 Accessibility of data for subsequent use

Access to the monitoring results is guaranteed via the three modules "Website", "Online data repository" and "Online mapping". The monitoring system currently depicts ten key items of information on 77 types of biomass, showing three types of result (minimum, maximum, automatically generated mean value). On a national level, with 2015 as the reference year, this generates 2,310 individual data sets. The case example of cereal straw, with nine reference years and 401 districts, results in 108,270 data sets. Full access to these findings is provided thanks to a public online data repository which is free of charge and has been established in the long term. This can be found at *http://webapp.dbfz.de*, is continually being expanded and thus always presents the latest developments in the work on biomass potential assessment (Step 8, Figure 2.1). The data repository features various intuitive selection menus enabling the findings to be assessed individually. As well as a data search, the findings, basic data and documentation can also be downloaded, and contact information is provided for users to ask any unanswered questions directly. The data can also be directly integrated into external computer systems via an application programming interface (API) (Paper #2). This interface also offers the option of connecting to web-based atlas systems to produce cartographic illustrations of geospatially explicit results.

3.3.2 Understandability of biomass potential calculations and findings

The modules "Calculation flowcharts", "Impact on target sector" and "Sankey diagrams" were developed to make the potential calculations and their results easier to understand. In connection with the access options (Chapter 3.3.1), they mean that an understanding can gradually be gained of details on the methodology and content of the calculation, with a different amount of information provided at every level (Figure 3.3).

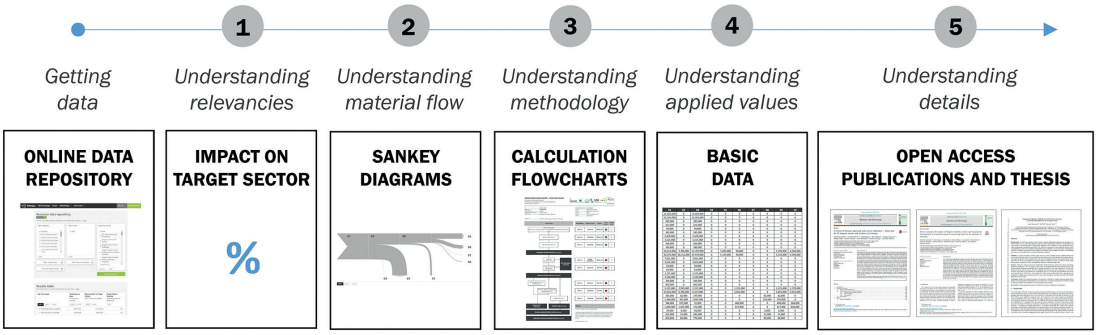


Figure 3.3: Levels of information for a step-by-step understanding of the biomass potential calculations and monitoring outcomes

The entry point is the online data repository, where users can search for findings on key items of information. At the first level, they can follow the logic of how a certain biomass potential may be relevant for a potential target market. The impact module, which is available online, initially includes the target product of biomethane and the target sector of transport, with four subsectors (road, rail, air, shipping) and numerous modes of transport. As the available data sets can be freely combined, and cover various types of biomass, the findings can be individually interpreted in countless possible ways. This offers a flexible means of understanding the priorities given to individual or multiple biomass types for a particular future purpose. At the second level, users can learn how the volumes are connected at different points in the material flow by means of a dynamic sankey diagram. At the third level, they can understand the methodological relationships between the key items of information and the biomass-specific calculation elements. With the help of the online available calculation flowcharts, the situation for each biomass is visualised, and documented using relevant meta-information. This provides a rapid overview of which aspects are taken into account in the calculation methodology, as well as which sources are used for this purpose, with which properties. At the same time, the flowcharts provide a compact basis for discussion aimed at continuously improving the potential calculations. At the fourth level of the information, users can view data on the basic values used (e. g. the water content, methane yield, etc.), and at the fifth and final level, they can follow all the remaining details on the monitoring modules and potential calculations in the three open-access publications and the thesis.

3.3.3 Reliability of calculation elements

The monitoring system contains 1,113 calculation elements; the figures on these come from different sources. The reliability of the sources used was quantified using a points-based assessment system. The sector-specific findings are summarised in Figure 3.4.

In terms of the overall results, shown in (A), for the entire system the reliability of all 1,113 calculation elements scores 1.21 points, putting it in the "uncertain" range, but close to the transition to "reliable" (Paper #2). The results are more fine-grained when it comes to the key items of information. Almost three quarters of the calculation elements (n = 809) relate to the theoretical potential (B). Especially as numerous statistics are used, the reliability is above the average for the entire system, at 1.31 points, but still falls just within the "uncertain" range. The technical potential (C) contains 97 calculation elements, and their overall reliability scores 0.67 points, putting them at a position between uncertain and not reliable. The 207 calculation elements for the used potential (D) have 1.32 points; a result similar to that for the theoretical potential. Within the sectors, further differences can be identified, some of which are significant.

The calculations for *Agricultural by-products* cover 467 calculation elements in all and thus make up the largest part of the monitoring system. Whereas values which correspond with the average are achieved for (A) and (B), in the case of the technical potential (C), only 0.36 points are achieved: the second-lowest and most unreliable value in the entire system. At 0.69 points, the calculation elements used to describe usage (D) also have the lowest value compared to all other sectors.

The 75 calculation elements for *Forestry by-products* bring in the strongest results in the system. One key reason for this is that a system has long been in place for monitoring wood as a raw material (Paper #2), and offers a particularly detailed view of usage. The overall view (A) contains the highest

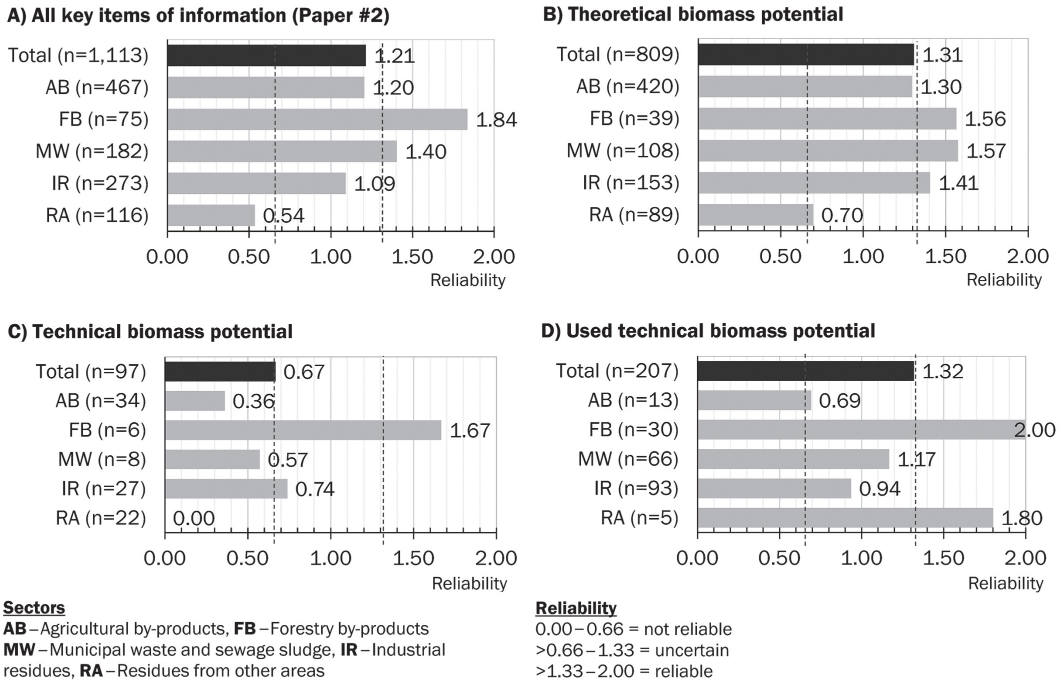


Figure 3.4: Sector-specific reliability of calculation elements for selected key items of information

value in the system; 1.84 points. At 1.57 and 1.67 points, respectively, the reliability of the theoretical potential (B) and the technical potential (C) is somewhat lower, but both values are still within the "reliable" range. Usage (D) has the highest value at 2.00.

At 1.40 points, the sector *Municipal waste/sewage sludge*, which is also statistically well documented, brings in the second-highest value in the system (A) for 182 calculation elements. In terms of the theoretical potential (B), the highest value is even reached: 1.57 points, whereas the technical potential (C) produces a very low value at 0.57 points. The usage (D) is slightly below average at 1.17 points.

A similar picture emerges for *Industrial residues*, whose potential is determined using 273 calculation elements. With a below-average 1.09 points, the overall result (A) can be described as uncertain. However, at 1.41 points, the theoretical potential (B) achieves an above-average, reliable value. With regard to the technical potential (C) and usage (D), the findings fall within the "uncertain" range.

In the case of *Residues from other areas*, the lowest values are found both in the overall view (A) and in the theoretical and technical potential (B, C). By contrast, a particularly high value, 1.80 points, is found for the usage (D). The source data for this is the above-mentioned monitoring of wood as a raw material, which produces detailed, reliable findings for, among other things, wooden landscape management materials, which fall within this sector.

3.3.4 Completeness of sustainability criteria

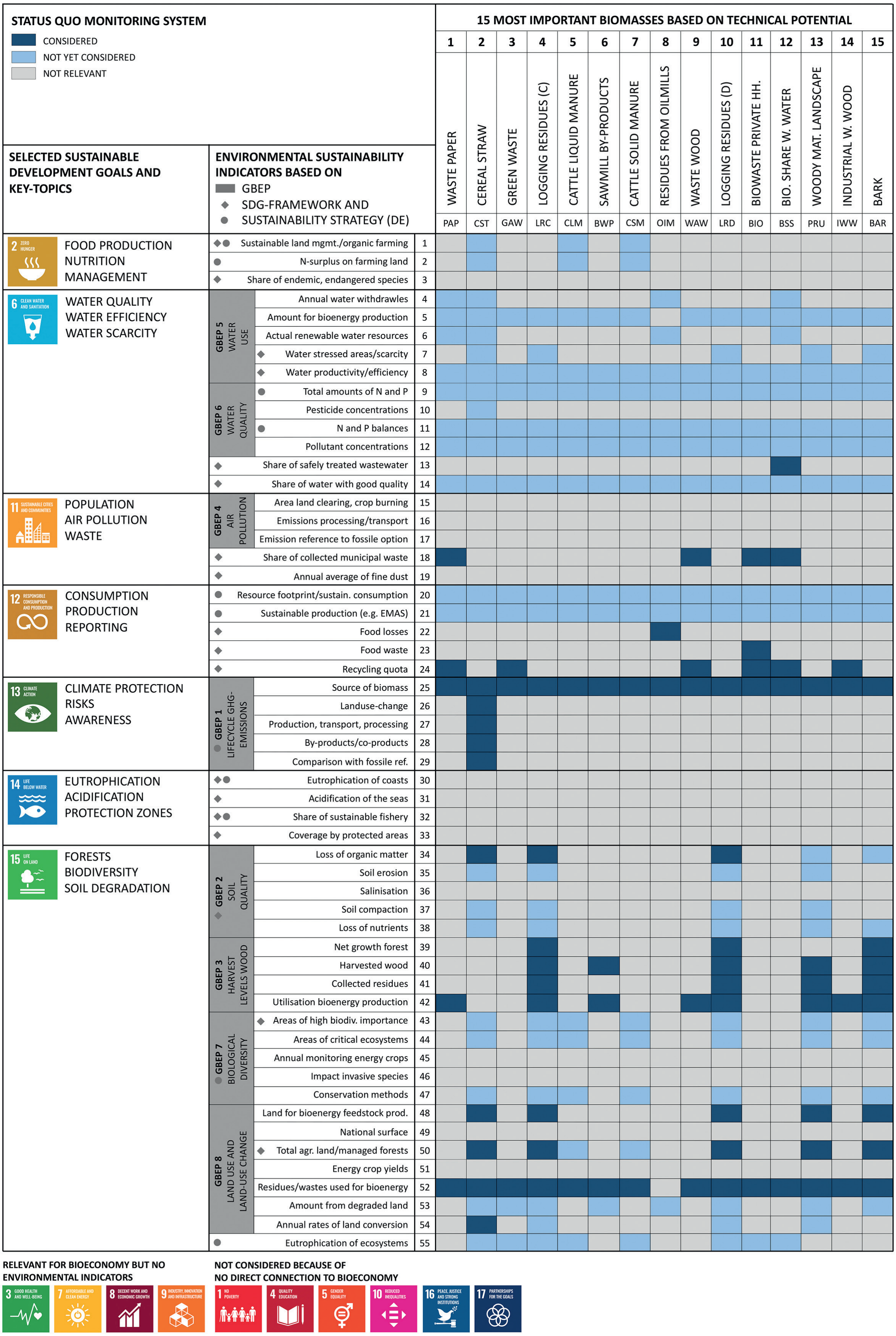
As well as evaluating the reliability of the calculation elements already contained in the system, this chapter presents findings on the completeness of the sustainability criteria which have been taken into account so far in the calculation methods. The three sources which are analysed unite a total of 55 ecological sustainability indicators. In Figure 3.5, the findings are presented in a matrix. The left half of the illustration sets out the identified findings sorted according to the corresponding eight GBEP indicators and seven SDGs. Some sustainability indicators can be found in all three of the analysed sources. Overlaps are indicated with a symbol. On the right-hand side of the illustration is the findings matrix for the 15 types of biomass that are the most important in the entire monitoring system, as identified in Figure 3.2 (Chapter 3.1.1). A distinction is made between whether the respective indicator is included in the calculation method used in the monitoring system, is not yet included in it, or is not relevant.

With regard to SDG 2 (Zero Hunger), organic farming and the nitrogen surplus are identified as indicators for the three biomass types generated by agriculture. However, these aspects have not been taken into account in previous potential calculations. Organic farming is indirectly represented, e. g. by cereal yields, but so far no further, more finely subdivided calculation elements have been named with regard to the use of by-products. There are also significant gaps for all biomass types in connection with SDG 6 (Clean Water). With the sole exception of wastewater treatment, none of the listed indicators for the use and quality of water, its efficiency and nutrient/pollutant content have been included in previous potential calculations. One point that deserves special emphasis in this context is water stress, which has not been taken into account so far and can have a major impact on the availability of raw materials, especially those which are site-specific (e. g. cereal straw, forest waste wood, woody materials from landscape management, bark). The yield figures indirectly represent corresponding effects (Paper # 3), but as yet no preventive measures have been taken, such as introducing regional harvesting rates.

With regard to SDG 11 (Sustainable Cities), the analysed biomass types overlap to some extent in the case of municipal waste (waste paper, waste wood, biowaste, waste water) whose contribution to the collected volume is already included in the potential calculations. This link is also reflected in SDG 12 (Responsible Consumption) in relation to recycling rates or food losses and wastes. For SDG 13 (Climate Action), the monitoring provides detailed volume-based information on the supply and use of raw materials. These data can also be used as input to further quantify, for example, absolute GHG mitigation volumes. A concrete example for cereal straw was presented in Paper # 3. The 15 biomass types examined show no signs of being connected to SDG 14 (Life Below Water).

However, there are extensive links to SDG 15 (Life On Land) and 40 % of the 55 indicators are covered in this thematic field. So far, most overlaps occur in relation to wood harvesting and use, which is partly because there is a system for monitoring the use of wood as a raw material (Chapter 3.3.3). As a result, that field is comparatively well documented. Another topic which is also well documented and depicted in full in the monitoring system is the use of residues to produce bioenergy. Apart from residues from oil mills, all the biomass types taken into account are also used to generate energy, among other things. However, there are numerous indicators which are not taken into account for almost all the biomass types, e. g. those related to soil erosion, soil compaction, loss of nutrients, biodiversity and ecosystem eutrophication. By contrast, the ITOC model (Paper # 2) covers the loss of organic material in the case of logging resiudues, while this loss is covered in the case of cereal straw by the literature (Paper # 2) and an example of circular processing (Paper # 3).

Figure 3.6 contains an evaluation of the findings matrix. On the left is a summary of the number of sustainability indicators which have or have not been taken into account so far. Depending on the biomass, this number varies between 12 (residues from oil mills, industrial waste wood) and 32 (cereal straw). The generally highest number is found for biomass from agriculture and forestry.



STATUS QUO MONITORING SYSTEM
■ CONSIDERED
▨ NOT YET CONSIDERED
□ NOT RELEVANT

15 MOST IMPORTANT BIOMASSES BASED ON TECHNICAL POTENTIAL

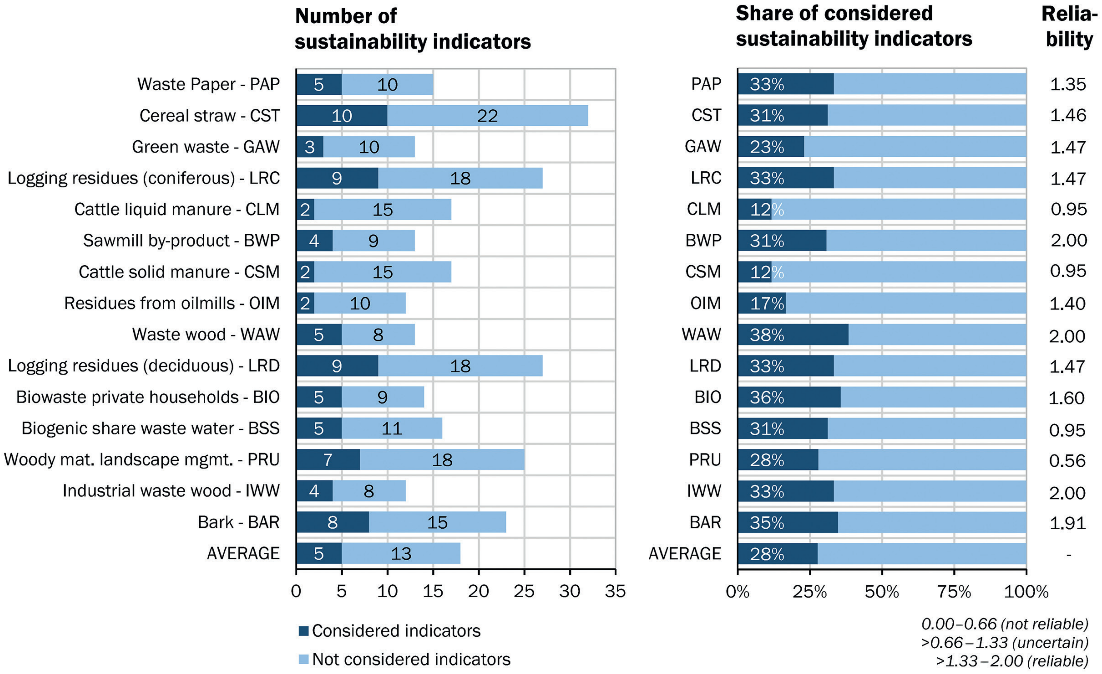
ENVIRONMENTAL SUSTAINABILITY INDICATORS BASED ON
▬ GBEP
◆ SDG-FRAMEWORK AND
● SUSTAINABILITY STRATEGY (DE)

SELECTED SUSTAINABLE DEVELOPMENT GOALS AND KEY-TOPICS	ENVIRONMENTAL SUSTAINABILITY INDICATORS BASED ON			1 WASTE PAPER PAP	2 CEREAL STRAW CST	3 GREEN WASTE GAW	4 LOGGING RESIDUES (C) LRC	5 CATTLE LIQUID MANURE CLM	6 SAWMILL BY-PRODUCTS BWP	7 CATTLE SOLID MANURE CSM	8 RESIDUES FROM OILMILLS OIM	9 WASTE WOOD WAW	10 LOGGING RESIDUES (D) LRD	11 BIOWASTE PRIVATE HH. BIO	12 BIO. SHARE W. WATER BSS	13 WOODY MAT. LANDSCAPE PRU	14 INDUSTRIAL W. WOOD IWW	15 BARK BAR
2 ZERO HUNGER FOOD PRODUCTION NUTRITION MANAGEMENT		◆● Sustainable land mgmt./organic farming	1	□	▨	□	□	▨	□	▨	□	□	□	□	□	□	□	□
		● N-surplus on farming land	2	□	▨	□	□	▨	□	▨	□	□	□	□	□	□	□	□
		◆ Share of endemic, endangered species	3	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
6 CLEAN WATER AND SANITATION WATER QUALITY WATER EFFICIENCY WATER SCARCITY	GBEP 5 WATER USE	Annual water withdrawles	4	▨	▨	□	□	□	□	□	▨	□	□	□	▨	□	□	□
		Amount for bioenergy production	5	▨	▨	▨	▨	▨	▨	▨	□	▨	▨	▨	▨	▨	▨	▨
		Actual renewable water resources	6	▨	▨	□	□	□	□	□	▨	□	□	□	▨	□	□	□
		◆ Water stressed areas/scarcity	7	□	▨	□	▨	□	□	□	□	□	▨	□	□	▨	□	▨
		◆ Water productivity/efficiency	8	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	GBEP 6 WATER QUALITY	● Total amounts of N and P	9	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
		Pesticide concentrations	10	□	▨	□	□	□	□	□	□	□	□	□	□	□	□	□
		● N and P balances	11	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
		Pollutant concentrations	12	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
		◆ Share of safely treated wastewater	13	□	□	□	□	□	□	□	□	□	□	□	■	□	□	□
		◆ Share of water with good quality	14	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
11 SUSTAINABLE CITIES AND COMMUNITIES POPULATION AIR POLLUTION WASTE	GBEP 4 AIR POLLUTION	Area land clearing, crop burning	15	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
		Emissions processing/transport	16	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
		Emission reference to fossile option	17	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
		◆ Share of collected municipal waste	18	■	□	□	□	□	□	□	□	■	□	■	■	□	□	□
		◆ Annual average of fine dust	19	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
12 RESPONSIBLE CONSUMPTION AND PRODUCTION CONSUMPTION PRODUCTION REPORTING		● Resource footprint/sustain. consumption	20	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
		● Sustainable production (e.g. EMAS)	21	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
		◆ Food losses	22	□	□	□	□	□	□	□	■	□	□	□	□	□	□	□
		◆ Food waste	23	□	□	□	□	□	□	□	□	□	□	■	□	□	□	□
		◆ Recycling quota	24	■	□	■	□	□	□	□	□	■	□	■	■	□	■	□
13 CLIMATE ACTION CLIMATE PROTECTION RISKS AWARENESS	● GBEP 1 LIFECYCLE GHG-EMISSIONS	Source of biomass	25	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
		Landuse-change	26	□	■	□	□	□	□	□	□	□	□	□	□	□	□	□
		Production, transport, processing	27	□	■	□	□	□	□	□	□	□	□	□	□	□	□	□
		By-products/co-products	28	□	■	□	□	□	□	□	□	□	□	□	□	□	□	□
		Comparison with fossile ref.	29	□	■	□	□	□	□	□	□	□	□	□	□	□	□	□
14 LIFE BELOW WATER EUTROPHICATION ACIDIFICATION PROTECTION ZONES		◆● Eutrophication of coasts	30	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
		◆ Acidification of the seas	31	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
		◆● Share of sustainable fishery	32	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
		◆ Coverage by protected areas	33	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
15 LIFE ON LAND FORESTS BIODIVERSITY SOIL DEGRADATION	◆ GBEP 2 SOIL QUALITY	Loss of organic matter	34	□	■	□	■	□	□	□	□	□	■	□	□	▨	□	▨
		Soil erosion	35	□	▨	□	▨	□	□	□	□	□	▨	□	□	▨	□	□
		Salinisation	36	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
		Soil compaction	37	□	▨	□	▨	□	□	□	□	□	▨	□	□	▨	□	□
		Loss of nutrients	38	□	▨	□	▨	□	□	□	□	□	▨	□	□	▨	□	▨
	GBEP 3 HARVEST LEVELS WOOD	Net growth forest	39	□	□	□	■	□	□	□	□	□	■	□	□	□	□	■
		Harvested wood	40	□	□	□	■	□	■	□	□	□	■	□	□	■	□	■
		Collected residues	41	□	□	□	■	□	□	□	□	□	■	□	□	■	□	■
		Utilisation bioenergy production	42	■	□	□	■	□	■	□	□	■	■	□	□	■	■	■
	● GBEP 7 BIOLOGICAL DIVERSITY	◆ Areas of high biodiv. importance	43	□	▨	□	▨	▨	□	▨	□	□	▨	□	□	▨	□	▨
		Areas of critical ecosystems	44	□	▨	□	▨	▨	□	▨	□	□	▨	□	□	▨	□	▨
		Annual monitoring energy crops	45	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
		Impact invasive species	46	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
		Conservation methods	47	□	▨	□	▨	▨	□	▨	□	□	▨	□	□	▨	□	▨
	GBEP 8 LAND USE AND LAND-USE CHANGE	Land for bioenergy feedstock prod.	48	□	■	□	■	□	□	□	□	□	■	□	□	■	□	■
		National surface	49	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
		◆ Total agr. land/managed forests	50	□	■	□	■	▨	□	▨	□	□	■	□	□	■	□	■
		Energy crop yields	51	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
		Residues/wastes used for bioenergy	52	■	■	■	■	■	■	■	□	■	■	■	■	■	■	■
		Amount from degraded land	53	□	▨	▨	▨	□	▨	□	▨	□	▨	□	□	▨	□	▨
		Annual rates of land conversion	54	□	■	□	▨	□	□	□	□	□	▨	□	□	▨	□	□
		● Eutrophication of ecosystems	55	□	▨	▨	▨	▨	□	▨	□	□	▨	▨	▨	□	□	□

RELEVANT FOR BIOECONOMY BUT NO ENVIRONMENTAL INDICATORS
3 GOOD HEALTH AND WELL-BEING
7 AFFORDABLE AND CLEAN ENERGY
8 DECENT WORK AND ECONOMIC GROWTH
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE

NOT CONSIDERED BECAUSE OF NO DIRECT CONNECTION TO BIOECONOMY
1 NO POVERTY
4 QUALITY EDUCATION
5 GENDER EQUALITY
10 REDUCED INEQUALITIES
16 PEACE, JUSTICE AND STRONG INSTITUTIONS
17 PARTNERSHIPS FOR THE GOALS

Figure 3.5: Sustainability indicators which are currently taken into account, not taken into account or not relevant to current biomass potential calculations, focusing on the 15 most important biomass types in the monitoring system (based on [4, 59, 61–63])



Biomass type	Considered indicators	Not considered indicators	Share of considered	Reliability
Waste Paper - PAP	5	10	33%	1.35
Cereal straw - CST	10	22	31%	1.46
Green waste - GAW	3	10	23%	1.47
Logging residues (coniferous) - LRC	9	18	33%	1.47
Cattle liquid manure - CLM	2	15	12%	0.95
Sawmill by-product - BWP	4	9	31%	2.00
Cattle solid manure - CSM	2	15	12%	0.95
Residues from oilmills - OIM	2	10	17%	1.40
Waste wood - WAW	5	8	38%	2.00
Logging residues (deciduous) - LRD	9	18	33%	1.47
Biowaste private households - BIO	5	9	36%	1.60
Biogenic share waste water - BSS	5	11	31%	0.95
Woody mat. landscape mgmt. - PRU	7	18	28%	0.56
Industrial waste wood - IWW	4	8	33%	2.00
Bark - BAR	8	15	35%	1.91
AVERAGE	5	13	28%	-

Figure 3.6: Summary of sustainability indicators which are taken into account, or which are relevant but not taken into account in current biomass potential calculations, and biomass-specific reliability, focusing on the 15 most important biomass types in the monitoring system

The right-hand side of the figure depicts the percentages for the indicators so far considered in the calculations, in relation to the sum determined. The results range from 12 % (manure) to 38 % (waste wood). On average, a good quarter (28 %) of the sustainability indicators identified as relevant to the analysed biomass types are already included in the calculations.

Figure 3.6 also contains the biomass-specific findings on the reliability of the calculation elements used (Chapter 3.3.3). Taking stock of the sustainability indicators so far taken into account, these findings are now expanded to include an examination of the calculation methodology from the point of view of content. It is thus shown, for example, that reliable sources have been used on the whole to calculate the potential of cereal straw. Nonetheless, only 31 % of the sustainability indicators identified as relevant to this biomass have been taken into account in the calculations so far. For cattle liquid and solid manure, among other things, a particular combination of findings is produced. Especially low values are found both for the reliability of the basis for the calculation and for the percentages of sustainability indicators taken into account.

3.3.5 Timeliness of the monitoring system

Paper #2 shows that out of a total of 1,113 calculation elements, 27 % (= 302) are based on dynamic source data and 73 % (= 811) on non-dynamic source data. This means that so far, roughly a quarter of the calculation elements can be regularly updated. Further, sector-specific differences are depicted in Figure 3.7.

The overall view (A) paints a relatively uniform picture despite the widely differing number of calculation elements within the sectors. With one exception, the share of dynamic elements is

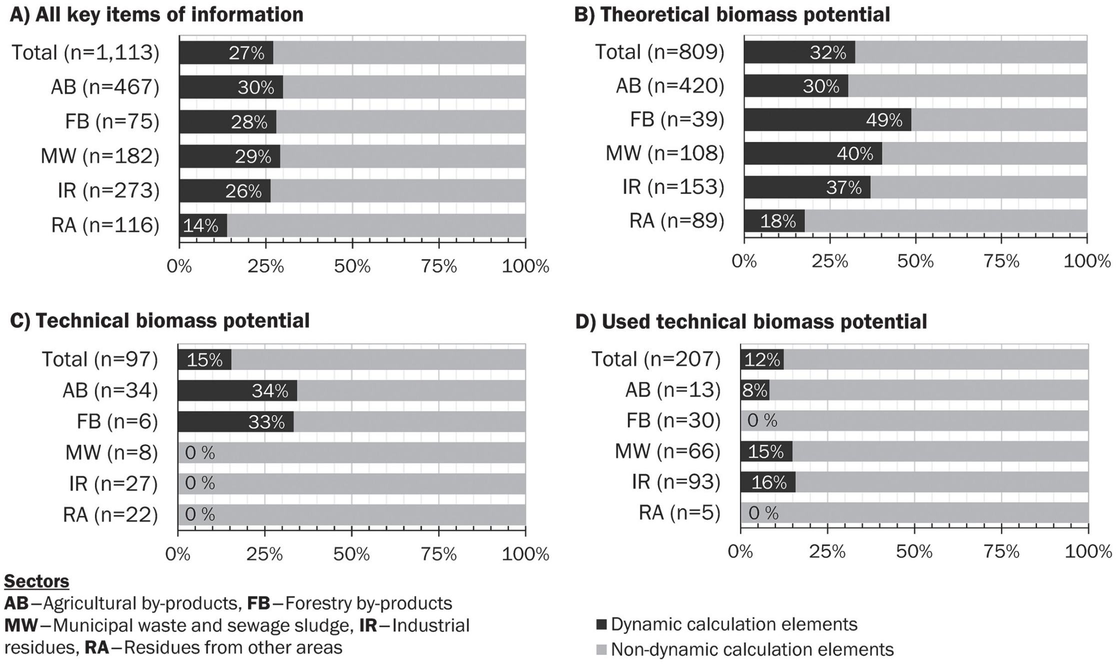


Figure 3.7: Sector-specific share of dynamic and non-dynamic calculation elements in biomass potential calculations for selected key items of information

between 26 % and 30 %. The highest percentage and also the highest number of calculation is found in the case of agricultural by-products; the lowest percentage is 14 %, for residues from other areas. Clear differences can be seen when examining selected key items of information.

The findings on the theoretical potential (B) are mostly well above average. Across all sectors, roughly a third (32 %) of the calculation elements for the theoretical potential are linked to dynamic source data. For forestry by-products, for example, half of the calculation elements are dynamic. With regard to the technical potential (C), the percentage for the agriculture and forestry sectors are above average, whereas the other three sectors are described only using non-dynamic calculation elements. In respect to usage (D), the highest values are found for municipal waste/sewage sludge and industrial residues, although the absolute percentages are at a low level, at 15–16 %. At 8 %, the percentage for agricultural by-products is very low compared to the findings for the other key items of information. In the forestry sector, usage is described entirely by non-dynamic calculation elements. However, as these are literature-based, irregularly recurring findings generated by monitoring wood as a raw material, it has not yet been possible to clearly distinguish the dynamics.

The regularly published source data are updated at different intervals. Table 3.2 contains a summary for the national level. Apart from a small number of exceptions, the dynamic source data are published annually. Usually, statistical data are available in the second half of the following year at the latest. Information on various animal populations (e. g. poultry) is published every three years, and information on husbandry only roughly every ten years. Information on the many fields in which wood is used is published at various, unspecified intervals, but is usually related to individual reference years.

The monitoring system was tested for 2015 as the reference year, meaning that this year, 2020, the data are five years old. However, the overview in Table 3.2 shows that, in principle, it is possible to update the dynamic calculation elements at the national level on an annual basis. In the second half of 2020, significant parts of the monitoring system could be updated to reflect the year 2019 and previous years. In Paper # 3, a temporal and spatial update of the monitoring system was tested. Gaps in the data were filled using further calculations and interpolations; overall, consistent data were generated for the years 2010 to 2018.

Table 3.2: Sectoral timeliness of selected dynamic data sources on a national level

Regular updating	**Sectors**				
	Agricultural by-products	**Forestry by-products**	**Municipal waste/ sewage sludge**	**Industrial residues**	**Residues from other areas**
Annually	Cultivation area, harvest quantities, livestock (cattle, pigs, chickens)	Harvest quantities	Disposal quantities, utilisation	Production quantities, import, export	Transport network (road, rail, water) cultivation area, maintenance area
Other regularity	3 years: Other livestock 10 years: husbandry	Utilisation	–	–	–

3.3.6 Summary

Until now, the monitoring system has distinguished between five criteria to describe data quality. While the two criteria of accessibility and understandability are determined structurally, using various modules, the three criteria of reliability, completeness and timeliness are measured. In terms of reliability, the calculation elements used in the monitoring system must generally be described as "uncertain". There are clear differences from one sector to the next, and also with regard to various key items of information. The calculation elements leading to the technical potential exhibit the weakest results overall. In addition to this, when the completeness of the sustainability indicators in the potential calculations for the 15 most important biomass types are analysed, it is revealed that only a good quarter of all the indicators identified as relevant are already taken into account in current calculations. In particular, the topics of soil and water quality, biodiversity and ecosystem eutrophication are almost completely lacking in the calculations of potential to date. By combining the findings on the reliability of the calculation elements and the completeness of the sustainability indicators, priorities can be set for further research. The weakest results for both quality criteria are found for liquid and solid cattle manure. However, it is found that as yet, the political target for the ecologically sustainable potential (Chapter 1) has not been met with regard to any of the other biomass types examined. Moreover, only roughly a quarter of the calculation elements are connected to regularly updated source data. Nonetheless, the status quo of data quality, as recorded here, acts as the starting point for a process of continuous improvement which can update the monitoring system step by step and raise the quality of its findings as required.

3.4 Discussion on continuous improvement of data quality

Accessibility to the findings generated so far, and their understandability, are important prerequisites for being able to reflect on the quality of the calculations of biomass potential across different institutions, and continuously improve them in future. The online data repository which has been established makes it possible to easily access both data and the data documentation. The flowcharts, in particular, provide a fast means of initial access to the calculation methodology. Among other things, they reveal the reliability of the individual calculation elements, allowing users to assess the sources which have been used to date. However, this does not take into account the evaluation of the content-related quality of the calculation method. The analysis of the completeness of the biomass-specific sustainability indicators provides an additional basis for this kind of evaluation, revealing how far there is to go to achieve the ecologically sustainable potential. Meanwhile, the source data used to cover a sustainability indicator (e. g. expert judgements or complex modelling) determine the reliability of the calculation element. The interplay between the calculation elements used and the sustainability indicators which need to be taken into account should therefore be continuously reflected upon by different specialist disciplines, and optimised by expanding the calculation methods, or adding new ones.

Challenges are posed not only by the professional aspiration to take all the sustainability indicators into account, but also, above all, by the technological availability and usability of corresponding data sets. The interaction of many sustainability indicators is both complex and temporally and geospatially dynamic. As described in Paper # 2, more than ten thousand peer-reviewed articles on the assessment of biomass potential are published every year without the findings and calculation methods becoming any more comparable. To overcome the nature of such self-contained studies and to ensure that the calculation of information on biogenic raw material is dynamic and consistent, technological data interfaces are urgently required. This means structured, well-documented, publicly accessible APIs or web services which can take the existing specialist data, and new data which are continuously generated, and directly integrate them into further calculation systems which employ databases. This would mean that data did not have to be obtained separately (e. g. downloaded), and new calculations could be carried out regularly with considerably less effort. In the case of large volumes of data, especially (e. g. regional data), extreme events (such as crop failure, flooding, storm damage) could be mapped and interpreted much faster when assessing levels of biomass potential.

So far, however, the data services required are few and far between, the extent of the data provided is limited, or they are still being set up. Functioning APIs are already available, for example, for national or international statistics websites such as Destatis [70] or FAOStat [71], and research institutions also increasingly offer digital data interfaces. The Thünen Institute [72], for instance, provides an atlas system with regional, specialist data on land use, the soil carbon content and water balances. Via a Web Feature Service (WFS), users can feed data directly into their own geo-information and database systems, and process them. However, it has not yet been possible to use these interfaces, as they do not yet include enough of the required data sets. In addition to these specialist data, the Federal Institute for Geosciences and Natural Resources (BGR, [73]), among others, provides large volumes of basic data on the topics of soil, geology and groundwater – but so far only as a Web Map Service (WMS). This service enables users to integrate data directly into their own computer systems, but only for the purpose of visualisation; the data cannot be processed. Processable data have to be downloaded separately.

Consistent specialist data of high geospatial quality, gathered over time, are particularly interesting in the case of monitoring systems. The Federal Environment Agency (UBA), for example, has collected nationwide figures on air pollution [74] and nitrogen balances [75] over the course of many years, and makes the data available via a website [76]. The Helmholtz Centre for Environmental Research (UFZ) operates a drought monitor [77] which is updated daily and can be used, for example, to identify regional water stress. The same site provides a web GIS showing the locations and installed capacity of bioenergy plants [78] on a year-by-year basis. Germany's National Meteorological Service, the Deutscher Wetterdienst (DWD), provides a climate atlas which is updated monthly and covers local weather data from 1881 to the forecast for 2100 [79]. The World Database on Protected Areas (WDPA, [80]) offers data on the status of terrestrial and marine protected areas, updated on a monthly basis. The listed of publicly available data is long, but so far the data sets described can only be downloaded separately, on request or even just as an illustrated report. At best, the data can thus only be integrated into further calculations manually and with great effort.

As well as the mere availability of basic and specialist data, another aspect of particular importance is research findings on the interplay between, for example, climate change, biodiversity and anthropogenic influences. One example of this is a recent work by Bowler et al. [81] analysing and globally mapping interactions between a large number of ecological sustainability indicators. These data can also be downloaded, but the measurement data used refer to different periods of time, and the geographical resolution of the results is 100 km². One central issue affecting the continuous improvement of methods for calculating biomass potential is thus the extent to which existing specialist knowledge can be technologically combined with data sets which are ideally dynamic, and the result continually expanded with every new work that is published. This type of knowledge transfer could not take place without the inter-institutional management of knowledge and data, and professional operation of the necessary IT infrastructures. Among other things, this would facilitate targeted reactions to gaps in the data, and allow attention to be drawn to the most urgent research requirements. If knowledge is simply published, and data sets can only be downloaded separately, then the continuous improvement process will continue to advance only with considerable effort.

In this context, the findings on the quality criterion of timeliness show that, so far, only 27 % of the 1,113 calculation elements are linked to dynamic source data. To continuously increase this percentage, one solution could be to disaggregate the calculation elements and link them to other data sets, which could be more detailed. One example of this is the water content of raw materials from agriculture and forestry. At present, this is derived in a non-dynamic manner from the literature, but a calculation element of this kind could, for example, also be built upon results derived from the UFZ drought monitor [77]. The spatio-temporal analyses in Paper #3 show that the yield fluctuates regionally to a considerable extent. Under the same conditions, the water content of a biomass can also be assumed to fluctuate. Until now, influences of this kind have only been represented in the calculations by non-dynamic ranges. Although this may even suffice for the strategic analysis of these findings, in future, there should be more detailed deliberation on when this kind of general assessment no longer suffices – especially for regional analysis. In the future, machine-readable data interfaces to relevant specialist data could greatly simplify the processing of complex data sets and the methodological expansion of calculations of biomass potential. This could significantly increase the reliability, completeness and timeliness of the monitoring system.

CHAPTER 4

Conclusion

4.1 Measurement of the raw material base

In view of the increasing demand for biogenic raw materials and their limited supply, the efficient use of raw materials is becoming increasingly important. Easily accessible, understandable, reliable, complete, timely data on the raw material base can form a possible starting point for evaluating their future use. The monitoring system which has been developed, implemented and tested is a versatile measuring instrument which can be used to quantify the volume and use of biogenic residues, by-products and waste across different sectors in a detailed, regular manner. The goal of the thesis – to develop a systematic method for annually reporting on the potential and use of biogenic residues – was thus achieved in full.

Among other things, the tool that is made available can be used to describe the relevance of individual or multiple biomass types along the material flow, and to identify the research required to continuously improve the quality of data. On that basis, the opportunities and risks related to biomass availability can be assessed, and priorities set for further measures. The findings show that a small number of biomass types make up large parts of the technical biomass potential. In the case of cereal straw, it was also shown that a considerable percentage of the potential is concentrated in only a few regions. To achieve the highest possible absolute level of GHG mitigation, the focus should initially be on the raw materials and regions with a particularly high volume. Firstly, so that solutions can be developed for optimising the future use of biogenic raw materials, extending their expected lifecycle and the value chain as much as possible, and secondly so that the basis for the calculations in the monitoring system can be continuously improved in that regard.

The online data repository which has been set up offers potential users numerous degrees of freedom for individually analysing the findings, and a multi-level documentation of the calculation methods. Making the data and methods public in such a comprehensive manner provides a low-threshold opportunity for public debate on the specifics of how the calculation methods should be improved. The findings from the analysis of the data quality describe, among other things, the current uncertainties in the calculation elements and reveal that, so far, only a quarter of the sustainability indicators identified as relevant have already been included in the methods for calculating the analysed biomass types. Equally, only a quarter of the calculation elements are linked to a regularly published data set. Improving the data quality must therefore be understood as a long-term process through which the goal set in terms of the ecologically sustainable potential can only be achieved if it is iterated repeatedly. The monitoring system offers a suitable technical and organisational framework for this.

Both the raw material assessment and the evaluation of the data quality can be transferred to other countries or regions within countries. A code system enables the monitoring modules and the calculation methods to be applied in a geographically flexible manner, and its use can generate consistent, internationally comparable calculation results. In connection with time series and geospatially subdivided findings on potential, in particular, this can be used as the basis, for example, to recognise and evaluate national and international trends, synergies, competing uses, overuses or the effects of material flow adjustments, extreme weather events or climate change at an early stage in their development. Appropriate measures could be discussed and introduced in a timely manner. Continuous monitoring activities are an important prerequisite for this.

As we move towards a bio-based, circular economy, the monitoring system offers extensive support in making decisions on the focuses to choose when implementing political and entrepreneurial strategies. However, the analyses it facilitates are related only to the aspect of biomass availability. The extent to which the identified types of potential can be mobilised for a future purpose depends on numerous other factors. To make a sustainable, substantial contribution to the bioeconomy, this includes, for example, creating the conditions for infrastructural, legal and economic feasibility, as well as numerous aspects relating to the topics of the biomass supply, regional added value or technical innovation, types of certification and their acceptance. The monitoring system provides central information on the raw material base and can be used to identify specific regions where raw material availability is particularly stable. By this means, it acts as a bridge where scientific knowledge on the resource base meets corresponding stakeholder-related issues in the relevant regions. It is only by involving regional stakeholders from the fields of politics, business, science and society that a productive discourse can be conducted on the sustainable mobilisation of biogenic raw materials and the future production of bio-based products.

4.2 Contribution to Sustainable Development Goals

As an instrument for measuring the volume and use of biogenic raw materials, the monitoring system which has been developed can help work towards various Sustainable Development Goals. It is particularly closely connected to sub-goals 7.2, 12.2 and 13.3:

SDG 7.2: “By 2030, increase substantially the share of renewable energy in the global energy mix” [82]. The monitoring system provides detailed information on the availability of biogenic residues, by-products and wastes for use as raw materials, and thus offers source data for evaluating the relevance of their potential contribution to the energy system. On the basis of the findings, it has been shown that, from the point of view of resource availability, up to 15 % of the annual demand for primary energy could be covered by the raw materials analysed. The current contribution is three to five percent.

SDG 12.2: “By 2030, achieve the sustainable management and efficient use of natural resources” [83]. In this regard, the monitoring system provides transparent, publicly available baseline data, and also provides information as to whether there is any potential to mobilise further raw materials, or whether any individual raw materials are already being over-used. The question of what purpose the different raw materials should be used for can be supported quantitatively by the findings.

SDG 13.3: "Improve education, awareness-raising and human and institutional capacity on climate change mitigation, adaptation, impact reduction and early warning" [84]. The monitoring system can be used to assess at an early stage how relevant a planned measure or procedure could be from the point of view of resource availability. In addition, risks can be identified in certain time periods and geographies regarding the availability of raw materials and regional competition for their use. By this means, stakeholders and shareholders can be made scientifically aware of which raw materials enable the longest possible value chains and a long line of cascading uses, or play an important role in the system in terms of the bioeconomy strategy.

4.3 Future research

The potential of monitoring is only unlocked when it involves a large amount of consistent data over a period of time. Testing the system within Germany produces one data point for each of the 77 biomass types, for the reference year 2015. For the years 2010 to 2018 and all districts in Germany, there are nine data points for cereal straw as a raw material. The main focus of future work is thus on providing various time series on different geospatial levels for at least the most important raw materials on the system, and ideally for all of them. On that basis, it would be possible to evaluate the developments which have taken place so far and also make statements about the future availability of raw materials.

As well as regularly updating the existing system, another focus is on continually improving the calculation methods it uses. Due to a lack of standards, analyses of biomass potential currently take the form of self-contained snapshots. The outcome is countless calculation methods, producing findings which cannot be compared. This situation is extremely unsatisfactory when it comes to assessing the possible actions that can be taken. In this scientific discipline, structural progress can thus be achieved by finding a means of building upon knowledge that has already been acquired. If the various institutions could collectively work on one (single) calculation method, reflect on it from the point of view of different disciplines and continuously develop it with the goal of fully taking into account the sustainability indicators, then the objectives pursued in terms of the ecologically sustainable biomass potential could gradually be translated into measurable data with reliable calculation elements. It would not appear productive, by contrast, to engage in a discourse on who has not taken into account which aspects in their calculation method and has thus produced inadequate results. However justified this type of criticism might be, it does not contribute to any progress on the matter in hand.

Adding further biomass types could, firstly, fill in the gaps to paint a consistent picture of the resource base. Taking the example of Germany, for example, this would include primary agricultural and forestry products (e. g. renewable raw materials, round timber), aquatic biomass (e. g. algae, bacteria) or, in principle, carbon dioxide from industrial applications. At the same time, the key items of information used to describe the material flow could be further subdivided, e. g. more detailed key items of information could be added on international trade (imports/exports), the raw materials put to material or energetic use (e. g. percentage of food and feed, various energy sources) or cascading use (e. g. in the case of biowaste). It would also be possible to show the percentages of, for instance, certified raw materials, as a quantitative record of the progress made towards sustainable production. It would also make sense to separately note any lack of knowledge about individual key items of information, revealing any gaps in the data. The pilot report on the monitoring of the German bioeconomy which came out in June 2020 [85] already provides extensive basic data on these topics, along with numerous points of reference.

So that the findings can be interpreted appropriately for each target group, another promising addition to the system would be to include additional target products and target markets in the online data repository. This would make it possible to interpret the relevance of bio-based products and associated processes flexibly, in the context of the actual needs of each target market. In terms of judging whether political and corporate goals can be implemented, in particular, this function could be a very useful means of choosing which steps to prioritise in strategies for optimisation and mobilisation.

Additional key items of information, target products and target markets should be described and documented using reliable and, ideally, regularly updatable calculation elements. However, extending and updating the calculation network will continually increase the complexity of the interconnected calculation system. Considering the many ways in which biogenic raw materials can be used in process engineering, the additional cascading uses and the mutually dependent material flows, at some point the static tools used for documentation will no longer be able to describe the calculation elements which are taken into account with sufficient transparency. The development and provision of digital knowledge models offer attractive approaches to solving this important set of challenges. To this end, the logical relationships between the calculation elements and key items of information could be mapped in ontologies, and the ways they affect one another described in full. This would create a system enabling users to reflect on a subject from any one point of view without losing track of how it relates to all the other elements in the system. The findings could be provided in the shape of user-friendly, web-based 3 D models. This could form the basis for inter-institutional discourse on which sustainability indicator could be integrated into the system at which point, using which data set. In this context, a digital knowledge model also serves as a template for digital data systems in which real data can be stored in a structured manner, and ideally made available for further analysis via digital interfaces. With regard to the technology, this is also where connections can be made to other topics relating to the steps in the use of biogenic raw materials (biomass supply, processing, production and conversion techniques, certification, costs, GHG mitigation, recycling, disposal, etc.). Another advantage of such knowledge models is the consistent reporting of basic data (e. g. water contents, energy contents, conversion factors, emission factors, etc.). Even when identical calculation methods are followed, the sometimes inconsistent use of such data can lead to considerable discrepancies in the interpretation of results. This can result in counter-productive lines of argument, especially when estimating the potential impact of a future use of raw materials. To create a high degree of transparency and consistency in this regard, the data used should be freely accessible for all stakeholders to reflect upon together. Providing a comprehensive knowledge model could encourage the first steps to be taken towards filling the gaps in our understanding, and coming closer to calculating an ecologically sustainable biomass potential.

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Contribution to appended papers

The authors' contributions to the work reported in the appended papers were as follows:

I Brosowski, A., Thrän, D., Mantau, U., Mahro, B., Erdmann, G., Adler, P., Stinner, W., Reinhold, G., Hering, T., Blanke, C. (2016): A review of biomass potential and current utilisation – Status quo for 93 biogenic wastes and residues in Germany, *Biomass and Bioenergy*, 95, 257–272, and *Elsevier's Virtual Issue on Earth Day 2017.*

Brosowski had the idea, developed the review, collected data on agriculture, municipal waste and residues from other areas, carried out the harmonisation and analysis of cross-sectoral data and wrote the manuscript, **Thrän** supervised the research and provided feedback on the review and manuscript, **Mantau** provided data on forestry sector, its categories and feedback on the review and manuscript, **Mahro** provided data on industrial residues, its categories and feedback on the review and manuscript, **Erdmann** provided data on animal manure/slurry and feedback on the manuscript, **Adler** supported the description/translation of biomasses and provided feedback on the manuscript, **Stinner** provided feedback on animal manure/slurry and the manuscript, **Reinhold** provided feedback on the categorisation of agricultural biomasses, **Hering** provided feedback on agricultural sector, the review and manuscript, **Blanke** provided data on forestry, its categories and feedback on the review and manuscript. The authors read and approved the final manuscript.

II Brosowski, A., Krause, T., Mantau, U., Mahro, B., Noke, A., Richter, F., Raussen, T., Bischof, R., Hering, T., Blanke, C., Müller, P., Thrän, D. (2019): How to measure the impact of biogenic residues, wastes and by-products: Development of a national resource monitoring based on the example of Germany, *Biomass and Bioenergy*, 127, 105275.

Brosowski had the idea, developed the twelve modules of the monitoring system, collected data on sector residues from other areas, carried out the cross-sectoral data analysis and wrote the manuscript, **Krause** supported the data consolidation and provided feedback on the manuscript, **Mantau** applied the monitoring system, provided data on forestry and feedback on the manuscript, **Mahro** and **Noke** applied the monitoring system, provided data on industrial residues and feedback on the manuscript, **Richter** and **Raussen** applied the monitoring system, provided data on municipal waste and feedback on the manuscript, **Bischof** and **Hering** applied the monitoring system, provided data on agriculture and feedback on the manuscript, **Blanke** applied the monitoring system, provided data on forestry and feedback on the manuscript, **Müller** programmed the online database and provided feedback on the section databases, **Thrän** supervised the research and provided feedback on the manuscript. The authors read and approved the final manuscript.

III Brosowski, A., Bill, R., Thrän, D. (in review): Temporal and spatial availability of cereal straw in Germany – Case study: Biomethane for the transport sector, *Energy, Sustainability and Society.*

Brosowski had the idea, developed the analysis, carried out all the modelling and calculations and wrote the manuscript, **Bill** and **Thrän** supervised the research, supplemented parts of the manuscript and provided feedback on the analysis and manuscript. The authors read and approved the final manuscript.

Part II:
Appended papers

#1

A review of biomass potential and current utilisation – Status quo for 93 biogenic wastes and residues in Germany

Brosowski, A., Thrän, D., Mantau, U., Mahro, B., Erdmann, G., Adler, P., Stinner, W.,
Reinhold, G., Hering, T., Blanke, C.

Biomass and Bioenergy (2016), 95, 257–272 and *Elseviers' Virtual Issue on Earth Day 2017*

17 P., 63 Lit., 1 Fig., 7 Tab.

Biomass and Bioenergy 95 (2016) 257–272

Contents lists available at ScienceDirect

Biomass and Bioenergy

journal homepage: http://www.elsevier.com/locate/biombioe

Review

A review of biomass potential and current utilisation — Status quo for 93 biogenic wastes and residues in Germany

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ARTICLE INFO

Article history:
Received 24 March 2016
Received in revised form
30 September 2016
Accepted 31 October 2016

Keywords:
Biomass categorization
Utilization
Comparability
Availability
Bio-economy

ABSTRACT

The efficient use of biogenic by-products, residues and waste offers an extensive range of advantages. As well as fulfilling requirements of public services, intelligent “cascading” can tap alternative sources of carbon and play a key part in a system using renewable sources of energy. However, a comprehensive overview of existing resources and their current use is required as a sufficient basis for decision-making. Accordingly, this article studies the development and application of a four-stage categorisation of relevant biomasses and a consistent comparison of existing findings in form of a literature review. Taking the case example of Germany, 30 studies were evaluated with regard to their information on the theoretical and technical potential of biomass and its current use as a material and source of energy. The compiled results offer a detailed, consistent overview of the status quo in Germany for a total of 93 individual biomass types. The findings show a technical biomass potential between 92.7 and 122.1 million Mg (DM) that means up to 1,500 kg per capita. A share of 62.7—71.2 million Mg (DM) is already in established use. 26.9—46.9 million Mg (DM) are still unused. Currently, however, there is no guaranteed, unified reference year for cross-sectoral reporting on the potential and use of biomass. Also, the handling of sustainability criteria is regulated insufficiently. Thus, long-term monitoring is required to manage the efficient, sustainable use of resources in a future-proof manner. Looking forward, up to 7% of Germany's current primary energy consumption, and at least 13% of the target consumption, could be met using residual matter and waste.

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http://dx.doi.org/10.1016/j.biombioe.2016.10.017

1. Introduction

Biogenic residual matter and waste accumulate in many fields of business and society. The spectrum extends from agriculture and forestry to industrial manufacturing and municipal waste. Bioeconomy opens up some interesting options to elevate the efficiency of already established utilisations and for the use of material that hitherto has been regarded as waste. These include, for example, the production of basic chemicals [1,2] and the generation of sustainable energy with the potential to save large amounts of greenhouse gases [3]. The far-reaching use of residual matter and waste to support a circular economy is receiving increasing levels of international funding [4–8] and support [9,10].

In this context, a biomass potential is defined as a resource which is generally being tapped and sometimes unused [11,12]. There is, however, no comprehensive quantitative estimate of the potential of biomass as a raw material and a source of energy. Reviews such as those by Searle & Malins [13], Bentsen & Felby [14], Batidzirai et al. [15], Smeets et al. [16], Stecher et al. [17] and Berndes et al. [18] show that results cover a wide range both nationally and internationally. There are currently no quality specifications or minimum requirements for calculating biomass potential [11,14,15,19,20]. Numerous authors [11,13–15,19,21] have suggested that methods should be harmonised, but these recommendations have yet to be applied consistently. Two of the most important factors affecting biomass potential are land availability (e.g. potential energy crops) and population distribution (residual materials). These are closely related to production- and process-related contexts [22]. To estimate potential, various assumptions have to be made which strongly affect the results. Kaltschmitt et al. [12] distinguish between theoretical, technical, economic and realisable potential. Thrän & Pfeiffer [11] also describe a sustainable potential. The restrictions involved in each case affect the degree of biomass potential in different ways. Among others, Hennig et al. [4], Thrän & Pfeiffer [11], Stecher et al. [17], Brosowski & Majer [20], Offermann et al. [22], Brosowski & Adler [23] and Vis et al. [19] point to the large number of basic parameters in studies on biomass potential. The lack of standards leads to uncertainties caused by differing definitions and interpretations of the contexts taken into consideration. This includes, for example, biomasses being allocated to higher-order groups. Table 1 shows an example of the range of different definitions and categorisations.

Table 1
Example descriptions of biomass.

Reference	Biomass categorisation for residues
Berndes et al. [18]	Primary residues (agricultural crop harvest residues, forest residues), secondary residues (food processing residues, wood and other processing residues, animal dung), tertiary residues (e.g. non-food organic wastes) and others
Smeets et al. [16]	Harvest residues, process residues, waste
Haberl et al. [24]	Residues on cropland
Yamamoto et al. [25]	Woody biomass residues, food biomass residues
Fischer and Schrattenholzer [26]	Crop residues, wood from forests, forest residues, animal waste, municipal waste
Thrän et al. [27]	Residual materials (straw, logging residues, excrement from livestock, municipal waste, production specific residuals)

It is not clear what individual forms of biomass are actually meant by, for example, “residues on cropland”, “woody biomass residues”, “excrements from livestock” or “animal waste”. As well as such heterogeneous descriptions, different source data (e.g. statistics, geodata, expert opinions), temporal references (e.g. present, future), spatial references (e.g. rural district, federal state, nation, continent) and physical units (e.g. Mg (FM), Mg (DM), GWh, PJ etc.) lead to considerable structural differences in the way that findings are presented [20]. Ultimately, the combination of all these parameters means that findings on biomass potential from different studies cannot be compared [4,17,20]. This situation is not satisfactory.

Biogenic by-products, residual matter and waste occur at different points along the production and processing chains. Until now, most higher-level summaries of different forms of biomass have been made in a legal context. The European Waste Catalogue, for example, defines individual types of waste using a six-figure number [29]. These waste types are collected, recycled or disposed of as public services [30]. However, bioeconomic use includes other resources which do not have to be collected. As yet, there is no binding regulation requiring these biomasses to be categorised on a large scale. In view of the highly uncertain data, on one hand, and the increasing importance of biogenic residual matter and waste for the transition to renewable energy, on the other, it is becoming increasingly important to be able to describe the availability and use of these material flows in a comprehensive, transparent and reproducible manner.

In Europe, Germany plays a key role in the use of biomass as an energy source. In 2015, 8.0% of total primary energy consumption (TPEC) in Germany was covered by bioenergy [31], making the absolute sum higher than in any other European country [32]. For this reason, the aim was to compile a large-scale review of the occurrence and use of biogenic residual matter and waste for the case example of Germany. This requires data to be classified and structured for the wide range of material fractions and a comprehensive point-in-time analysis to be carried out for the different types of biomass, which also need to be merged in a summary.

2. Methods and materials

The methodical approach contains three parts. The first part (Chapter 2.1) describes the development of a scheme for biomass categorisation. The second part is focused on characteristics for a consistent database (Chapter 2.2) and the third part outlines the proceeding for data collection (Chapter 2.3).

2.1. Biomass residue categorisation

It was necessary to describe the different biomasses with sufficient precision based on their origin. The aim was to bring together these different types of biomass transparently to form an extensive overall picture of existing resources. In the authors' opinion, this requires a schematic with at least four levels (Table 2).

The first level describes the individual biomasses. As well as the name, they can also be identified accurately using a free-text definition. For their further categorisation, two aggregation levels (Levels 2 and 3) allow individual biomasses to be integrated into groups based on content. At Level 4 they are categorised in higher-order groups by origin. The following groups were established for this purpose:

- Agricultural by-products
- Residues of forestry and wood industries
- Municipal waste
- Industrial residues
- Residues from other areas

2.2. Specifying demands for a consistent data base

The data availability differs depending on where each biomass comes from. In order to keep the data on potential comparable, the review took into account a total of three characteristics for each biomass, comparing the type and range of biomass potential (Chapter 2.2.1), the current biomass use (Chapter 2.2.2) and the time referred to in the sources (Chapter 2.2.3). The following paragraphs describe how the selected characteristics for comparison were dealt with.

2.2.1. Type and range of biomass potentials

The review is focused on the theoretical and technical biomass potential. According to Thrän & Pfeiffer [11] and Batidzirai et al. [15] the theoretical biomass potential quantifies the maximum productivity of biomass under optimal management. The technical biomass potential includes biomass-specific restrictions which could limit its use as a raw material or source of energy. These include, for example, technical limits on biomass collection or conversion as well as competing uses and legal regulations. In the case of some types of waste and residual materials, the theoretical and technical biomass potential can be considered as identical if the potential is directly linked to the production process for the primary product (e.g. molasses in sugar production).

As highlighted in the introduction, the absence of binding methodical standards in the field of biomass potentials makes it challenging to compare relevant findings. For instance, it is not clear which restrictions exactly define a technical potential. Also, the handling of sustainability criteria is regulated insufficiently. Batidzirai et al. [15] describe an ecologically sustainable potential as part of a technical potential. Weiser et al. [3] present a sustainable potential. However, it remains open which and how many sustainability criteria have to be taken into account. In literature the definitions and its combinations are not consistent [15].

In order to compile a status quo for theoretical and technical biomass potentials, the review was focused on a data collection. The first step was to examine the studies considered to find information about the theoretical potential for each biomass. Next, the information provided on the technical biomass potential was collected. In some cases the presentation of findings covers a wide range because of differences in the calculation or estimation of the biomass potentials. For this reason, the minimum and maximum values were recorded. For the further quantitative analysis of the findings both values were processed. To compare the findings consistently, “metric tons of dry matter” [Mg (DM)] was selected as a reference unit in the review.

2.2.2. Current utilisation

Another part of the review involved recording the current utilisation of each biomass and comparing it with the technical biomass potential (Chapter 2.2.1). When the studies investigated contained relevant information, overall utilisation was divided into use as a raw material and use as a fuel. The difference between the technical biomass potential and actual use produces the unused biomass potential. The information collected was also recorded as Mg (DM).

2.2.3. Time reference

One important quality factor is that the resource information is up to date. In this context, however, the year in which a study was published does not offer any information about the recency of the source data used. For this reason, both pieces of information were recorded for evaluation in this review. To do so, the literature and data sources in the studies investigated were checked and the year of the source data determined.

2.3. Data collection

In all, 30 studies were evaluated for the case example of Germany. The references used are listed in Table 3 according to the origin of the biomass (Chapter 2.1).

The biomass-specific findings were combined in a data table that can be found in Appendix A–D. Appendix A contains the Level 4 categorisation of all 93 biomasses. Remarks on consideration and data for the theoretical and technical potential are part of Appendix B. Appendix C includes data of current utilisation. Appendix D contains the unused potential, time reference and biomass specific references for information on potentials and utilisation. To make the findings clearer, the merged biomass-specific individual results were summarised in Level 4 categories and also summed up across all the categories.

Table 2
Scheme for categorisation.

Level	Description	Remarks	Example
1.	Name	Description of each biomass	Molasses
	Definition	Free description of each biomass to identify it uniquely	Molasses, by-product of sugar production
2.	Aggregation level I	Multi-level summary of each biomass by content. Not relevant for every type of biomass	Beet sugar production
3.	Aggregation level II		Residues from food industry
4.	Aggregation level III	Higher-order area of origin, by content	Industrial residues

Table 3
Overview of considered references for potentials and utilisation.

Biomass level 4 category	References for potentials	References for utilisation
Agricultural by-products	[3]; [27]; [33]; [34]; [35]; [36]	[37]; [38]
Residues of forestry and wood industries	[35]; [39]; [40]; [41]; [42]; [43]; [44]	[41]; [42]; [43]; [44]
Municipal waste	[23]; [35]; [45]; [46]; [47]; [48]; [49]	[47]; [48]; [50]
Industrial residues	[51]; [52]	[53]
Residues from other areas	[35]; [40]; [46]; [54]; [55]; [56]; [57]; [58]; [59]	[41]

3. Results

3.1. Biomass categorisation

For the review, a total of 93 biomasses were identified and included in the data collection. The biomasses studied are listed in Table 4.

The Level 4 schematic was used to structure and summarise the biomasses (Table 5). The 93 individual biomasses (Level 1) were sorted into 67 biomasses/categories at the first stage of aggregation (Level 2). At the second stage of aggregation (Level 3), 24 labels were established. At the third and last stage of aggregation (Level 4), the five categories of origin were determined. The full set of biomass categories (Levels 1 to 4) are found in Appendix A.

3.2. Consistent database

Using the three comparators (Chapter 2.2), relevant findings were consistently combined for a total of 77 out of 93 individual biomasses. For these biomasses information on theoretical biomass potential is available, while for 70 biomasses also data on the technical potential were found. 49 data records contain information on current utilisation. Details in the literature are available for 23 biomasses while 26 data records are based on assumptions. Relating biomasses (industrial residues and biogenic fraction of household waste) are subject to German disposal and recycling requirements [30]. Althougt no information on current utilisation was found in the literature and statistics, it must be assumed that 100% are in use.

Table 5
Number of categorised biomasses in the 4-level schematic.

Level 1	Level 2	Level 3	Level 4	
18	11	3	1	Agricultural by-products
8	7	3	1	Residues of forestry and wood industries
17	13	3	1	Municipal waste
21	18	5	1	Industrial waste
29	18	10	1	Residues from other areas
$\sum$93	$\sum$67	$\sum$24	$\sum$5	

With regard to the time reference, information for all consistent data records is available. Table 6 summarises the explanations and the appendix contains corresponding information on each individual biomass.

Merging the 77 consistent datasets leads to the results shown in Table 7. For the case example of Germany, a theoretical biomass residual material potential of 151.0–152.7 million Mg (DM) was summarised based on this data. Due to restrictions, 30.6 to 58.3 million Mg (DM) of the theoretical potential cannot be used. This is mainly residual matter from the wood industry and forestry, or agricultural by-products. One key driving force behind this is maintaining soil function. The data situation is unclear for at least another 9.8 million Mg (DM), which includes biomasses such as used cooking oils, wooden landscape management materials and sewage sludge.

The identifiable technical biomass potential is thus between 92.7 and 122.1 million Mg (DM) in all. It stands for up to 1500 kg per capita. The vast majority (68–75%) of this potential comes from residual matter from the wood industry and forestry and from agricultural by-products. 11–15% is from industrial residual matter, almost 10–12% from municipal waste and a good 5–6% from

Table 4
Overview of biomasses studied by 4-level categorisation.

Level 4 category	Level 1 category
Agricultural by-products (n = 18)	1: Winter catch crop; 2: Summer catch crop (spring grain); 3: Residues from vegetable gardening, esp. field vegetable residues; 4: Beet leaves; 5: Cereal straw (wheat, rye, barley, oats, triticale); 6: Rape straw; 7: Grain corn straw; 8: Sunflower straw; 9: Grain legumes straw; 10: Cattle slurry; 11: Pig slurry; 12: Chicken slurry; 13: Cattle manure; 14: Pig manure; 15: Chicken manure; 16: Horse manure; 17: Sheep and goat manure; 18: Poultry manure (others)
Residues of forestry and wood industries (n = 8)	19: Logging residues (coniferous); 20: Logging residues (deciduous); 21: Bark; 22: Sawmill By-products (sawdust, wood chips, slabs and splinters); 23: Wood shavings; 24: Black liquor; 25: Other industrial waste wood; 26: Waste wood,
Municipal waste (n = 17)	27: Biowaste; 28: Biogenic fraction of household waste; 29: Green waste; 30: Waste fabrics; 31: Mixed packaging/recyclable and reusable material; 32: Biodegradable waste from kitchens and canteens; 33: Waste from weekly markets; 34:, Commercial food waste (not waste management); 35: Used cooking oil from municipal waste; 36: Oils from separators in waste and water treatment; 37: Faecal sludge; 38: Waste from sewage cleaning; 39: Sewage sludge from food industry; 40: Sewage sludge from pulp/paper/cardboard/paperboard; 41: Sewage sludge from others (leather and fur industry, from organic chemical processes, from thermal processes); 42. Sewage sludge from public wastewater treatment plants; 43: Sewage sludge from public water treatment plants
Industrial residues (n = 29)	44: Epizootic animals, fallen animals, blood, heart, lungs; Bristles, skin, hooves, heads, horns, bones, stomach, intestines; 45: By-catch; 46: Fruit remnants, pomace; 47: Vegetable remnants; 48: Potato peelings; 49: Peel, press cake, extraction meal; 50: Milk processing; 51: Bran & flour-dust; 52: Adhesive proteins; 53: Returned bread; 54: Spent grains/yeast residues from breweries; 55: Malt culms, sorting grain from malting; 56: Residues from distilleries; 57: Residues from winemaking, 58: Molasses; 59: Molasses pulp; 60: Pressed pulp; 61: Dried pulp; 62: Wet pulp; 63: Pre production cleaning residues; 64: Residues of confectionery production; 65: Production of ready-made meals, condiment & sauces; 66: Coffee and tea production; 67: Nutshells; 68: Production of compound feed; 69: Tobacco residues; 70: Vinasse, cell residues; 71: Vinasse, brewer grains; 72: Glycerol from biodiesel production
Residues from other areas (n = 21)	Stalks/woody biomass from 73/74: Biomass from communal green areas; 75/76: Cemeteries; 77/78: Heath areas; 79/80: Orchards; 81/82: Vineyards; 83/84: Peatland; 85/86: Roadside greenery; 87/88: Greenery along waterways; 89/90: Greenery along railways; 91: Driftwood; 92: Aquatic plants; 93: Wooden landscape management materials

Table 6
Overview about datasets.

Number of data record	Remark	Comparator
93	**Biomasses were taken into account**	
16 of 93	Biomasses with no data	
77 of 93	**Biomasses were consistently combined with information on theoretical biomass potential at least**	Biomass potential
70 of 77	Biomasses with information on technical biomass potential	
49 of 77	Biomasses with information on current utilisation	Current utilization
23 of 49	Biomasses with information on current utilisation based on literature	
26 of 49	Biomasses with information on current utilisation based on assumptions	
77 of 77	Biomasses with information on time reference	Time reference

Table 7
Biomass potential of residual matter and waste and their current use – status quo in Germany in million Mg (DM) and Level-4-categories (deviations because of rounding).

	Agricultural by-products	Residues of forestry and wood industries	Municipal waste	Industrial residues	Residues from other areas	Total
Theoretical biomass potential	44.6	65.5–66.8	18.5–18.8	13.5	8.8	151.0–152.7
Technical biomass potential	24.7–29.3	37.9–61.8	11.0–11.7	13.5	5.6–5.8	92.7–122.1
Utilisation	8.8	28.4–36.9	9.5	13.5	2.5	62.7–71.2
Material use	*4.2*	*8.3–9.1*	*8.5*	*8.6*	*No data*	*29.6–30.4*
Energetic use	*4.6*	*17.7–25.2*	*1.0*	*0.1*	*2.5*	*25.8–33.4*
Material or energetic use	*0.0*	*2.4–2.6*	*0.0*	*4.9*	*No data*	*7.3–7.5*
Use unclear	0.0	0.0	1.2–1.9	0.0	1.9–2.1	3.1–4.0
Not used	15.9–20.5	9.5–24.9	0.3	0.0	1.2	26.9–46.9

biomass from other areas. Altogether, 62.7–71.2 million Mg (DM) of the technical potential is being used. Due to disposal and recycling requirements [30], use is almost 100% in the case of municipal waste and industrial residual matter. Use is also high (up to 75%) in the case of residual matter from the wood industry and forestry. By contrast, as of now only one third of agricultural by-products are used. Across the entire range, it can be said that 29.6–30.4 million Mg (DM) of biomass are used as a raw material. 25.8–33.4 million Mg (DM) are used as a fuel. Another 7.3–7.5 million Mg (DM) have been identified as being used, though without any information on whether this is as a raw material or as a fuel. Proof of use is uncertain for at least 3.1–4.0 million Mg (DM).

Altogether, 26.9–46.9 million Mg (DM) of the identified technical potential is not used or not known to be used. Up to 97% of the unused potential is determined to come from the three biomasses of logging residues (about 9.5–24.9 million Mg (DM)), animal excrement (9.1 million Mg (DM)) and cereal straw (6.8–11.4 million Mg (DM)). Another 1.2 million Mg (DM) are from wooden landscape management materials.

The appendix contains a complete overview of biomass-specific findings.

With regard to the recency of the evaluated and finally considered biomasses, a wide range was found for the year of publication and the time which the source data for potentials and utilisation are from. In the case of publication, the range extended from 2006 to 2016. The source data used for biomass potentials goes from 2000 to 2013. Fig. 1 shows an evaluation of the findings.

For 2016 the evaluation shows that more than 70% of the sources from the literature are no more than three years old. Only one percent of the biomass potentials evaluated are based on source data from the last three years. Almost half the source data used are more than four years old. Another 18% are more than five years old, and roughly a third of the source data are six years old, or older. For a total of 23 biomasses (Table 6) data on utilisation is available in the literature. In 15 cases information on potentials and its use refer to the same year. For the other biomasses information on utilisation is between two and eight years newer than the corresponding information on biomass potential. To summarise, it can be said that across all the data evaluated, it is not possible to find one standard reference year either for the year of publication or for the year of the source data employed.

4. Discussion

For the case example of Germany, this review presents an extensive, transparent collection of data on the potential of residual biomass and its use. Using a four level schematic it was possible to structure the 93 biomasses studied by content and to consistently merge the findings for 77 biomass types. With up to 1,500 kg per capita the amount of biogenic residues and wastes is remarkable in Germany.

With regard to data consistency, the information basis for agricultural by-products, forest residues of forest and wood industries and industrial residues is well defined, while for municipal waste and biomass from other areas some overlapping and inconsistencies can be noticed. Municipal waste such as green waste (e.g. from public green) is collected as a public service, but only the total quantity removed is recorded in the statistics. It is well known that these materials are only collected particularly and an unknown share is left behind in situ to save costs. However, estimations for theoretical and technical biomass potential can be found in some studies [23,45–47,54,55] evaluated. It is not yet possible to distinguish clearly between the amount already in the municipal disposal system and the amount which remains unused in situ. In the case of materials from landscape management (e.g. Refs. [40,56,59]), it is also not possible to identify beyond all doubt which reference areas and which yields are included in the calculations. As the parameters used for calculation (e.g. the yield, water content, recovery rate, etc.) are very sensitive, this field is subject to a relatively high level of uncertainty. Compared with the total quantities of all biomass, however, the resulting influence is low, meaning that analysing local material flows could lead to an improvement in the regional circular economy.

Merging the data allows the status quo to be presented in detail, though it is not yet possible to compare the quality of the potential findings recorded. Though the data on the technical potential

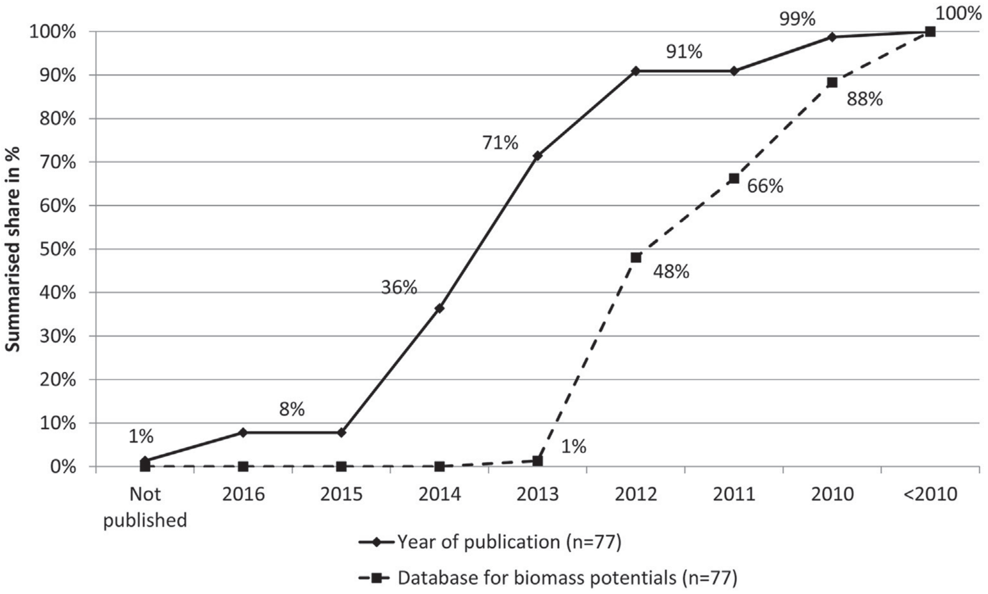

Fig. 1. Age of the presented data in relation to the year of data generation or publication.

include biomass-specific restrictions, the calculations do not have to meet the same quality standards. Initial evaluations of the recency of publications and source data reveal a wide range of figures. Currently, it is not possible to present findings with a single reference year. Furthermore, the findings present a large bandwidth especially for the technical potentials of agricultural by-products and residues of forestry and wood industries. At the same time the related individual biomasses (especially logging residues and straw) stand for the most important unused biomasses. To achieve the target of sustainability, in the next step the findings need to be evaluated using sustainability criteria, such as the 24 sustainability indicators proposed by the Global Biomass Partnership (GBEP) in 2011 [60]. Among other things, this would address the topics of lifecycle green house gas emissions, soil quality, biodiversity, employment in the bioenergy sector and the efficiency of technological processes. This could be used firstly to judge how informative published results were, and secondly to improve the data in a calculated manner if it did not meet the targets required by research. It would elevate the transparency in the field of biomass potentials and could be a basis to identify priorities for further research.

The future use of previously unused biomasses as a raw material or fuel, and the adjustment of current material flows, are subject to economic and legal conditions. To mobilise unused biomasses regional and competitive biomass supply concepts are required. In case of straw, for example, steady prices for raw material are an essential precondition to establish regional value chains. Established material flows like waste streams and industrial residues are subject to legal frameworks. Biowaste, for instance, is well integrated into German public disposal system and detailed data is available from public statistics. In contrast, a detailed utilisation of industrial residues remains unclear. These biomasses are part of private companies and it can merely be assumed that 100% are in use. There are no public statistics available. The question to be considered is where and in which extent smart cascades can increase efficiency of these material flows.

Towards 2020 and 2030 it can be assumed that the annual amount of residues and wastes will remain at a similar level in Germany. However, consumer behaviour and production methods are interrelated to the amount of wastes and residues. Decreasing meat consumption for example affects the animal population and finally the amount of excrements. Breeding methods can increase or decrease the proportion of straw in the crop production and higher standards in biodiversity can limit the use of logging residues and materials from landscape management.

Currently, residual materials and waste used as a fuel make up 541 PJ of the German energy system [61]. If the currently unused potential for energy production were added this would provide another 390–680 PJ. In relation to the German total primary energy consumption of 13,306 PJ in 2015 [62], at least 7% could be covered by the identified technical biomass potential of residues and wastes. This share could be raised significantly if the federal government's targets for reduction 7190 PJ in 2050 [63] were achieved. Assuming that the amount of residual material and waste remained at the same level, according to this calculation the future percentage could be at least 13%. In other words, the efficient use of residual materials and waste as a raw material and a fuel could play an important role in lastingly reducing Germany's dependency on imported energy.

5. Conclusion

In the case example of Germany, the findings offer an initial, extensive overall view of current known resources and their use. As studies on biomass potential are generally individual projects, the merged results do not share a reference year. Biomass use is comparatively well recorded thanks to constant market observation. However, there have only been occasional comparisons with national biomass potential including flows of imports and exports, and the results are very incomplete, especially in the field of biogenic residual materials. It is currently possible to evaluate the temporal development of individual biomasses and their use in occasional cases, but no overview is possible. In view of the fact that there is increasing demand for residual materials to be used and for cascading recycling systems, information on the potential of residual material is gaining in importance.

With a potential share of up to 13% of the future primary energy consumption in Germany, the identified potential is significant for the energy transition and needs specific consideration. For regular statements to be made on biomass potential and current use, continuous and more precise reporting is required. On this point, corresponding national and international requirements need to be discussed, bindingly established and constantly applied. At present, there is a lack of suitable organisational systems and data structures for this purpose, or of clear responsibilities among the institutions providing and receiving the data. In the long term, monitoring biogenic resources will allow resources to be evaluated with data of sufficient quality and over time. A database of this kind could be used to support decision-making as policy on the bioeconomy is further adapted.

Acknowledgements

These findings were established as part of the project “Biomass potential of residual matter and waste – status quo in Germany”. The project was funded by the Federal Ministry of Food and Agriculture [FKZ 22020114] under its funding programme for “Renewable Resources”. Special thanks go to the FNR (Fachagentur Nachwachsende Rohstoffe e.V.) for their intensive support throughout the project.

Appendix A. Biomass categorisation

Seq. no.	Level-4-Biomass-Categorisation				
	Level 1		Level 2	Level 3	Level 4
	Name	Definition	Aggregation I	Aggregation II	Aggregation III
1	Catch crop, winter	Additional biomass from catch crops	–	Catch crops	Agricultural by-products
2	Catch crop, summer (spring grain)	Additional biomass from catch crops	–	Catch crops	Agricultural by-products
3	Residues from vegetable gardening, esp. field vegetable residues	Residues from olericulture	–	–	Agricultural by-products
4	Beet leaves	By-products from beet harvesting	–	–	Agricultural by-products
5	Cereal Straw (Wheat, rye, barley, oats, triticale)	By-products of cereal cultivation	–	Straw	Agricultural by-products
6	Rape straw	By-products of rape cultivation	–	Straw	Agricultural by-products
7	Grain corn straw	By-products of grain corn cultivation	–	Straw	Agricultural by-products
8	Sunflower straw	By-products of sunflower cultivation	–	Straw	Agricultural by-products
9	Grain legumes straw	By-products of grain legume cultivation	–	Straw	Agricultural by-products
10	Cattle slurry	Liquid manure from cattle farming	Slurry	Livestock manure	Agricultural by-products
11	Pig slurry	Liquid manure from pig farming	Slurry	Livestock manure	Agricultural by-products
12	Chicken slurry	Liquid manure from chicken farming	Slurry	Livestock manure	Agricultural by-products
13	Cattle manure	Manure (solid) from cattle farming	Manure	Livestock manure	Agricultural by-products
14	Pig manure	Manure (solid) from pig farming	Manure	Livestock manure	Agricultural by-products
15	Chicken manure	Manure (solid) from chicken farming	Manure	Livestock manure	Agricultural by-products
16	Horse manure	Manure (solid) from horse keeping	Manure	Livestock manure	Agricultural by-products
17	Sheep and goat manure	Manure (solid) from sheep and goat farming	Manure	Livestock manure	Agricultural by-products
18	Poultry manure (others)	Manure (solid) from poultry farming (ducks, geese, etc.)	Manure	Livestock manure	Agricultural by-products
19	Logging residues coniferous	Logging residues combine wood < 7 cm in diameter and merchantable wood that remains in stock. It thus consists of stem wood including bark, branches and twigs, crop residues, roots and rhizomes and possibly adhering needles and leaves.	Logging residues	By-products from forest wood	Residues of forestry and wood industries
20	Logging residues deciduous	Logging residues combine wood < 7 cm in diameter and merchantable wood that remains in stock. It thus consists of stem wood including bark, branches and twigs, crop residues, roots and rhizomes and possibly adhering needles and leaves.	Logging residues	By-products from forest wood	Residues of forestry and wood industries
21	Bark	All trunk and branch portions outside of the cambium (cell-forming layer). Bark consists of the inner bark (bast) and the outer bark	–	By-products from forest wood	Residues of forestry and wood industries
22	Sawdust, wood chips, slabs and splinters	Sawdust: Co-product of wood cutting, flat cuboid and pin-like shape. Chips: by-product of the chopping process in lumber production. Solid wood parts cut diagonal to the	Sawmill By-products	Industrial waste wood	Residues of forestry and wood industries

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(*continued*)

Seq. no.	Level-4-Biomass-Categorisation				
	Level 1		Level 2	Level 3	Level 4
	Name	Definition	Aggregation I	Aggregation II	Aggregation III
		fiber direction. Slabs & splinters: co-products of the trimming of logwood (slabs) and board (splinters)			
23	Wood shavings	Wood chips (thin and flat chips) are a co-product of wood processing in sawmills or affiliated value-added processes (carpenters, wood moldings manufacturer)	–	Industrial waste wood	Residues of forestry and wood industries
24	Black liquor	Black liquor is a byproduct of pulp production. It results in the separation of lignin and cellulose, and is a mixture of lignin, water and the chemicals that are used for the extraction.	–	Industrial waste wood	Residues of forestry and wood industries
25	Other industrial waste wood	Other industrial waste wood accumulates during the processing of wood products. It does not include sawmill By-products and wood shavings.	–	Industrial waste wood	Residues of forestry and wood industries
26	Waste wood	Industrial waste wood and used wood, if these are wastes in the meaning of §3 para. 1 of the current German recycling and waste legislation. Waste Wood Ordinance, §2, section 1 (2007).	–	Recycling materials	Residues of forestry and wood industries
27	Biowaste	Biogenic share in household waste, collected and reported separately.	–	Collected by municipal waste management	Municipal waste
28	Biogenic fraction of household waste	Biogenic share in household waste, not collected and reported separately.	–	Collected by municipal waste management	Municipal waste
29	Green waste	Green waste, collected and reported by municipal waste management	–	Collected by municipal waste management	Municipal waste
30	Biodegradable waste from kitchens and canteens	Biodegradable kitchen and canteen waste, collected and reported by municipal waste management	–	Collected by municipal waste management	Municipal waste
31	Waste from weekly markets	Waste from weekly markets, collected and reported by municipal waste management	–	Collected by municipal waste management	Municipal waste
32	Oils from separators in waste and water treatment	Oils from separators, collected and reported by municipal waste management	–	Collected by municipal waste management	Municipal waste
33	Waste fabrics	Waste fabrics, collected and reported by municipal waste management	–	Collected by municipal waste management	Municipal waste
34	Mixed packaging/recyclable and reusable material	Mixed packaging/recyclable and reusable material, collected and reported by municipal waste management	–	Collected by municipal waste management	Municipal waste
35	Commercial food waste, not waste management	Commercial food waste, not collected and reported by municipal waste management	–	Not collected by municipal waste management	Municipal waste
36	Used cooking oil	Used cooking oil, not collected and reported by municipal waste management	–	Not collected by municipal waste management	Municipal waste
37	Faecal sludge	Faecal sludge, reported by official waste statistics	Sewage sludge from municipal waste	Sewage sludge	Municipal waste
38	Waste from sewage cleaning	Waste from sewage cleaning, reported by official waste statistics	Sewage sludge from municipal waste	Sewage sludge	Municipal waste
39	Sewage sludge from food industry	Sewage sludge from in-house waste water treatment, reported by official waste statistics	Sewage sludge from in-house waste water treatment	Sewage sludge	Municipal waste
40	Sewage sludge from pulp/paper/cardboard/paperboard	Sewage sludge from in-house waste water treatment of pulp, paper, cardboard, paperboard industry, reported by official waste statistics	Sewage sludge from in-house waste water treatment	Sewage sludge	Municipal waste
41	Sewage sludge from other industries (leather and fur industry, from organic chemical processes, from thermal processes)	Sewage sludge from in-house waste water treatment of leather and fur industry, reported by official waste statistics	Sewage sludge from in-house waste water treatment	Sewage sludge	Municipal waste
42	Sewage sludge from public wastewater treatment plants	Sewage sludge from public wastewater treatment plants, reported by official waste statistics	Sewage sludge from waste water treatment and drinking water treatment	Sewage sludge	Municipal waste
43	Sewage sludge from public water treatment plants	Sewage sludge from water treatment plants, reported by official waste statistics	Sewage sludge from waste water treatment and drinking water treatment	Sewage sludge	Municipal waste

(*continued*)

Seq. no.	Level-4-Biomass-Categorisation				
	Level 1		Level 2	Level 3	Level 4
	Name	Definition	Aggregation I	Aggregation II	Aggregation III
44	Epizootic animals, fallen animals, blood, heart, lungs; Bristles, skin, hooves, heads, horns, bones, stomach, intestines	Residues from slaughter, not meat processing. Different Categories for By-products from slaughter. (Cat.1: Epizootic animals. Cat.2: fallen animals. Cat. 3 (usable for human alimentation: blood, heart, lung) In addition: bristles, skin, hooves, heads, horns, bones, stomach, intestines	Offal & meat processing	Food industry	Industrial residues
45	By-catch (possibly overboard), fish remains (bones heads, tails, entrails)	Only disembarked fish residues are recorded; nor recorded are fish residues and bycatch processed directly on board	Fish processing	Food industry	Industrial residues
46	Fruit remnants, pomace	Rejected fruits & vegetables, peels, pits, press cake, pomace	Fruit- & vegetable processing	Food industry	Industrial residues
47	Vegetable remnants	Rejected vegetables stalks, shells, seeds	Fruit- & vegetable processing	Food industry	Industrial residues
48	Potato peelings	Residues generated by producing products such as potato chips, frozen products and other potato products	Fruit- & vegetable processing	Food industry	Industrial residues
49	Peel, press cake, extraction meal	Peel, press cake, extraction meal	Production of vegetable & animal oils & fats	Food industry	Industrial residues
50	TS, primarily whey	Whey is a quantitatively relevant by-product; in addition small amounts of rinsing milk used for washing pprocessing units	Milk processing	Food industry	Industrial residues
51	Bran & flour-dust	Bran & flour-dust generated by producing cereal flours	Hulling & grinding mills, production of starch & starch products	Food industry	Industrial residues
52	Adhesive proteins	Production of starch products: potato protein, corn gluten, etc.	Hulling & grinding mills, production of starch & starch products	Food industry	Industrial residues
53	Returned bread	Returned bread and offcuts	Production of bakery and farinaceous products	Food industry	Industrial residues
54	Spent grains/yeast residues from breweries	Largest proportion: spent grains (ca. 75%); in addition: malt dust, hot and cold trub (10%), yeast residues (10%) and diatomaceous earth	Production of beverages	Food industry	Industrial residues
55	Malt culms, sorting grain from malting	In the production of malt from cereals different percentages (DM) of the collected grain is turned into residues (depending on the quality): 0.8% sorting grain (DM: 85%) and 5% Malt culms (DM: 92%) (interview data)	Production of beverages	Food industry	Industrial residues
56	Residues from distilleries	Pomace, ingredients of vinasse, "Vorlauf", (lipids, minerals, proteins and phenolic components)	Production of beverages	Food industry	Industrial residues
57	Residues from winemaking	Not considered here: Green cuttings (see agricultural waste)	Production of beverages	Food industry	Industrial residues
58	Molasses	Molasses, by-product of sugar production	Beet sugar production	Food industry	Industrial residues
59	Molasses pulp	Molasses pulp, which arise as residue/by-product of sugar production	Beet sugar production	Food industry	Industrial residues
60	Pressed pulp	Pressed pulp, by-product of sugar production	Beet sugar production	Food industry	Industrial residues
61	Dried pulp	Dried pulp, by-product of sugar production	Beet sugar production	Food industry	Industrial residues
62	Wet pulp	Wet pulp, by-product of sugar production	Beet sugar production	Food industry	Industrial residues
63	Pre production cleaning residues	Residues produced by cleaning beets before processing, by-product of sugar production	Beet sugar production	Food industry	Industrial residues
64	Residues of confectionery production	The quantitatively largest waste streams are produced by manufacturing chocolate products and raw products: Cocoa shells, skin of almond and other nuts, fat fractions, additives for filled chocolates	–	Food industry	Industrial residues
65	Residues of production of ready-made meals, condiment & sauces	For "convenience products" (egg) shells, seeds, offcuts, faulty batches. Condiment production: pomace of spice plants	–	Food industry	Industrial residues
66	Residues of coffee and tee production	Largest proportion: Coffee grounds (production of coffee extract); Coffee skins (from roasting); Dusts, faulty batches, run-up batches	–	Food industry	Industrial residues
67	Nutshells	Nutshells (Walnut, peanut, hazelnut; cashew nut, pistachio, almond, chestnut, macadamia), not generated in the confectionery production	–	Food industry	Industrial residues
68	Residues of production of compound feed	When receiving grain from agricultural production: husks (mass fraction), "Schmachtgetreide", straw, weed seeds, faulty raw materials, faulty and cleaning batches	–	Feed production for livestock & pets	Industrial residues
69	Tobacco residues	Tobacco residues from the tobacco industry	–	Cigarette- & tobacco industry	Industrial residues

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(*continued*)

Seq. no.	Level-4-Biomass-Categorisation				
	Level 1		Level 2	Level 3	Level 4
	Name	Definition	Aggregation I	Aggregation II	Aggregation III
70	Vinasse, cell residues	Mainly fermentation residues, especially molasses residues (=vinasse) and cell residues. In addition: Faulty batches (e.g. drugs)	Chemical-, pharmaceutical-, yeast industry	Biotech industries	Industrial residues
71	Vinasse, brewer grains	Mainly fermentation residues, especially from the fermentation of molasses or starch	Bioethanol production	Biotech industries	Industrial residues
72	Glycerin from biodiesel production	Glycerin, which is generated during the production of biodiesel	–	–	Industrial residues
73	Stalks from public green area	Stalks from parks, zoos, amusement parks, recreational areas, allotments etc.)	–	Biomass from public green area	Residues from other areas
74	Woody biomass from public green area	Ligneous content of biomass from parks, zoos, amusement parks, recreational areas, allotments etc.)	–	Biomass from public green area	Residues from other areas
75	Stalks from cementries	Stalks from cemeteries	–	Biomass from cemeteries	Residues from other areas
76	Woody biomass from cementries	Ligneous content of biomass from cemeteries	–	Biomass from cemeteries	Residues from other areas
77	Stalks from heath areas	Stalks from heath areas	–	Biomass from heath areas	Residues from other areas
78	Woody biomass from heath areas	Ligneous content of biomass from heath areas	–	Biomass from heath areas	Residues from other areas
79	Stalks from orchards	Stalks from orchards	–	Biomass from orchards	Residues from other areas
80	Woody biomass from orchards	Ligneous content of biomass from orchards	–	Biomass from orchards	Residues from other areas
81	Stalks from vineyards	Stalks from vineyards	–	Biomass from vineyards	Residues from other areas
82	Woody biomass from vineyards	Ligneous content of biomass from vineyards	–	Biomass from vineyards	Residues from other areas
83	Stalks from peatland	Stalks from peatland	–	Biomass from peatland	Residues from other areas
84	Woody biomass from peatland	Ligneous content of biomass from peatland	–	Biomass from peatland	Residues from other areas
85	Stalks from roadside greenery	Herbaceous content of biomass cut alongside roads	Roadside greenery	Biomass from traffic areas	Residues from other areas
86	Woody biomass from roadside greenary	Ligneous content of biomass cut alongside roads	Roadside greenery	Biomass from traffic areas	Residues from other areas
87	Stalks along waterways	Herbaceous content of biomass cut alongside waterways	Greenery along waterways	Biomass from traffic areas	Residues from other areas
88	Woody biomass along waterways	Ligneous content of biomass cut alongside waterways	Greenery along waterways	Biomass from traffic areas	Residues from other areas
89	Stalks along railways	Herbaceous content of biomass cut alongside railways	Greenery along railways	Biomass from traffic areas	Residues from other areas
90	Woody biomass aloong railways	Ligneous content of biomass cut alongside railways	Greenery along railways	Biomass from traffic areas	Residues from other areas
91	Driftwood	Fluvial transported woody debris	–	–	Residues from other areas
92	Aquatic plants	Biomass from waters	–	–	Residues from other areas
93	Wooden landscape management materials	Resulting from actions that predominantly serve objectives of nature and landscape conservation and are not cultivated specifically. Accordingly waste from gardens and parks is excluded	–	–	Residues from other areas

Appendix B. Remarks on consideration and theoretical/technical biomass potential

Seq. no.	Consideration of dataset		Comparator 1			
			Theoretical biomass potential		Technical biomass potential	
			Min	Max	Min	Max
	yes/no	Remark	Mg (DM)	Mg (DM)	Mg (DM)	Mg (DM)
1	No	Insufficient data	No data	No data	No data	No data
2	No	Insufficient data	No data	No data	No data	No data
3	No	Insufficient data	No data	No data	No data	No data
4	No	Part of humus balance for straw potential. Not available as additional potential.	2,300,000	2,300,000	575,000	1,150,000
5	Yes	Full dataset	25,655,520	25,655,520	11,024,340	15,568,580
6	No	Part of humus balance for straw potential. Not available as additional potential.	7,637,000	7,637,000	1,527,400	1,527,400

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Seq. no.	Consideration of dataset		Comparator 1			
			Theoretical biomass potential		Technical biomass potential	
			Min	Max	Min	Max
	yes/no	Remark	Mg (DM)	Mg (DM)	Mg (DM)	Mg (DM)
7	No	Part of humus balance for straw potential. Not available as additional potential.	3,440,000	3,440,000	No data	No data
8	No	Insufficient data	No data	No data	No data	No data
9	No	Insufficient data	No data	No data	No data	No data
10	Yes	Full dataset	7,458,391	7,458,391	4,930,440	4,930,440
11	Yes	Full dataset	2,907,900	2,907,900	2,590,479	2,590,479
12	No	Insufficient data	No data	No data	No data	No data
13	Yes	Full dataset	5,594,538	5,594,538	3,570,426	3,570,426
14	Yes	Full dataset	2,424,258	2,424,258	2,052,557	2,052,557
15	Yes	Full dataset	582,148	582,148	562,876	562,876
16	No	Insufficient data	No data	No data	No data	No data
17	No	Insufficient data	No data	No data	No data	No data
18	No	Insufficient data	No data	No data	No data	No data
19	Yes	Full dataset	20,119,000	20,119,000	7,002,000	18,424,000
20	Yes	Full dataset	18,936,000	18,936,000	6,605,000	17,377,000
21	Yes	Full dataset	6,843,000	6,843,000	4,708,000	5,074,000
22	Yes	Full dataset	6,774,000	7,050,000	6,774,000	7,050,000
23	Yes	Full dataset	1,570,000	1,570,000	1,570,000	1,570,000
24	Yes	Full dataset	1,757,000	1,757,000	1,757,000	1,757,000
25	Yes	Full dataset	2,718,000	2,718,000	2,718,000	2,718,000
26	Yes	Full dataset	6,751,000	7,849,000	6,751,000	7,849,000
27	Yes	Full dataset	1,779,600	1,779,600	1,632,000	1,632,000
28	Yes	Information on potentials but no information on utilisation.	1,960,000	1,960,000	400,000	800,000
29	Yes	Full dataset	2,337,000	2,337,000	2,290,500	2,290,500
30	Yes	Full dataset	275,200	275,200	275,200	275,200
31	Yes	Full dataset	28,000	28,000	28,000	28,000
32	Yes	Information on potentials but no information on utilisation.	1235	1235	1235	1235
33	Yes	Full dataset	100,000	100,000	100,000	100,000
34	Yes	Full dataset	5,462,000	5,462,000	5,462,000	5,462,000
35	Yes	Information on potentials but no information on utilisation.	728,800	728,800	721,600	721,600
36	Yes	Information on technical potentials but no information on utilisation or theoretical potential.	41,705	380,000	41,705	380,000
37	Yes	Information on theoretical potential only.	16,300	16,300	No data	No data
38	Yes	Information on theoretical potential only.	54,700	54,700	No data	No data
39	Yes	Information on theoretical potential only.	720,900	720,900	No data	No data
40	Yes	Information on theoretical potential only.	120,300	120,300	No data	No data
41	Yes	Information on theoretical potential only.	14,600	14,600	No data	No data
42	Yes	Information on theoretical potential only.	4,703,700	4,703,700	No data	No data
43	Yes	Information on theoretical potential only.	158,200	158,200	No data	No data
44	Yes	Information on potentials and total utilisation.	390,000	390,000	390,000	390,000
45	Yes	Full dataset	25,000	25,000	25,000	25,000
46	Yes	Information on potentials and total utilisation.	45,000	45,000	45,000	45,000
47	Yes	Information on potentials and total utilisation.	37,000	37,000	37,000	37,000
48	Yes	Information on potentials and total utilisation.	48,000	48,000	48,000	48,000
49	Yes	Full dataset	6,100,000	6,100,000	6,100,000	6,100,000
50	Yes	Full dataset	780,000	780,000	780,000	780,000
51	Yes	Full dataset	1,430,000	1,430,000	1,430,000	1,430,000
52	Yes	Full dataset	312,000	312,000	312,000	312,000
53	Yes	Information on potentials and total utilisation.	470,000	470,000	470,000	470,000
54	Yes	Information on potentials and total utilisation.	360,000	360,000	360,000	360,000
55	Yes	Information on potentials and total utilisation.	105,000	105,000	105,000	105,000
56	Yes	Full dataset	15,000	15,000	15,000	15,000
57	Yes	Information on potentials and total utilisation.	113,000	113,000	113,000	113,000
58	Yes	Information on potentials and total utilisation.	586,000	586,000	586,000	586,000
59	Yes	Information on potentials and total utilisation.	1,310,000	1,310,000	1,310,000	1,310,000
60	Yes	Information on potentials and total utilisation.	330,000	330,000	330,000	330,000
61	Yes	Information on potentials and total utilisation.	25,000	25,000	25,000	25,000
62	Yes	Information on potentials and total utilisation.	4400	4400	4400	4400
63	Yes	Information on potentials and total utilisation.	28,000	28,000	28,000	28,000
64	Yes	Information on potentials and total utilisation.	48,000	48,000	48,000	48,000
65	Yes	Information on potentials and total utilisation.	113,000	113,000	113,000	113,000
66	Yes	Information on potentials and total utilisation.	14,500	14,500	14,500	14,500
67	No	Insufficient data.	No data	No data	No data	No data
68	Yes	Information on potentials and total utilisation.	53,000	53,000	53,000	53,000
69	Yes	Information on potentials and total utilisation.	6600	6600	6600	6600
70	Yes	Information on potentials and total utilisation.	81,000	81,000	81,000	81,000
71	Yes	Information on potentials and total utilisation.	522,000	522,000	522,000	522,000
72	Yes	Information on potentials and total utilisation.	180,400	180,400	180,400	180,400
73	Yes	Information on potentials but no information on utilisation.	831,00	831,000	415,500	415,500
74	Yes	Information on potentials but no information on utilisation.	327,600	327,600	163,800	163,800

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Seq. no.	Consideration of dataset		Comparator 1			
			Theoretical biomass potential		Technical biomass potential	
			Min	Max	Min	Max
	yes/no	Remark	Mg (DM)	Mg (DM)	Mg (DM)	Mg (DM)
75	Yes	Information on potentials but no information on utilisation.	200,250	200,250	100,500	100,500
76	Yes	Information on potentials but no information on utilisation.	26,650	26,650	13,325	13,325
77	Yes	Information on potentials but no information on utilisation.	231,000	231,000	115,500	115,500
78	Yes	Information on potentials but no information on utilisation.	200,200	200,200	100,100	100,100
79	Yes	Information on potentials but no information on utilisation.	381,000	381,000	190,500	190,500
80	Yes	Information on potentials but no information on utilisation.	165,100	165,100	165,100	165,100
81	Yes	Information on potentials but no information on utilisation.	89,250	89,250	45,000	45,000
82	Yes	Information on potentials but no information on utilisation.	232,700	232,700	232,700	232,700
83	Yes	Information on potentials but no information on utilisation.	600,000	600,000	59,400	59,400
84	Yes	Information on potentials but no information on utilisation.	232,050	232,050	46,150	46,150
85	Yes	Information on potentials but no information on utilisation.	545,500	545,500	50,000	75,000
86	Yes	Information on potentials but no information on utilisation.	575,250	575,250	162,500	357,500
87	No	Insufficient data	No data	No data	No data	No data
88	Yes	Information on potentials but no information on utilisation.	10,000	10,000	10,000	10,000
89	No	Insufficient data	No data	No data	No data	No data
90	Yes	Information on potentials but no information on utilisation.	500,000	500,000	25,000	40,000
91	Yes	Information on potentials but no information on utilisation.	20,000	20,000	10,000	10,000
92	No	Insufficient data	No data	No data	No data	No data
93	Yes	Information on technical potential and utilisation but no theoretical potential.	3,670,000	3,670,000	3,670,000	3,670,000

Appendix C. Use of biomass

Seq. no.	Comparator 2									
	Utilisation									
	Total		Material		Energetic		Material or energetic		Use unclear	
	Min	Max	M	Max	Min	Max	Min	Max	Min	Max
	Mg (DM)	Mg (DM)	Mg (DM)	Mg (DM)	Mg (DM)	Mg (DM)	Mg (DM)	Mg (DM)	Mg (DM)	Mg (DM)
1	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data
2	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data
3	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data
4	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data
5	4,208,928	4,208,928	4,173,928	4,173,928	35000	35000	–	–	–	–
6	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data
7	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data
8	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data
9	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data
10	2,958,264	2,958,264	0	0	2,958,264	2,958,264	–	–	–	–
11	466,286	466,286	0	0	466,286	466,286	–	–	–	–
12	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data
13	785,494	785,494	0	0	785,494	785,494	–	–	–	–
14	20,526	20,526	0	0	20,526	20,526	–	–	–	–
15	371,498	371,498	0	0	371,498	371,498	–	–	–	–
16	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data
17	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data
18	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data
19	1,435,410	3,776,920	119,139	313,484	1,316,271	3,463,436	–	–	–	–
20	2,694,840	7,089,816	26,948	70,898	2,667,892	7,018,918	–	–	–	–
21	4,708,000	5,074,000	832,271	896,972	1,752,421	1,888,654	2,123,308	2,288,374	–	–
22	6,774,000	7,050,000	5,446,296	5,668,200	1,327,704	1,381,800	–	–	–	–
23	1,570,000	1,570,000	593,460	593,460	976,540	976,540	–	–	–	–
24	1,757,000	1,757,000	0	0	1,757,000	1,757,000	–	–	–	–
25	2,718,000	2,718,000	40,770	40,770	2,677,230	2,677,230	–	–	–	–
26	6,751,000	7,849,000	1,268,945	1,475,329	5,205,264	6,051,862	276,791	321,809	–	–
27	1,632,000	1,632,000	1,615,680	1,615,680	16,320	16,320	–	–	–	–
28	No data	No data	No data	No data	No data	No data	No data	No data	400,000	800,000
29	2,274,467	2,274,467	2,160,743	2,160,743	113,723	113,723	–	–	–	–
30	272,448	272,448	248,473	248,473	23,975	23,975	–	–	–	–
31	23,800	23,800	23,015	23,015	785	785	–	–	–	–
32	No data	No data	No data	No data	No data	No data	No data	No data	1235	1235
33	99,500	99,500	99,003	99,003	497	497	–	–	–	–

(*continued*)

Seq. no.	Comparator 2									
	Utilisation									
	Total		Material		Energetic		Material or energetic		Use unclear	
	Min	Max	M	Max	Min	Max	Min	Max	Min	Max
	Mg (DM)	Mg (DM)	Mg (DM)	Mg (DM)	Mg (DM)	Mg (DM)	Mg (DM)	Mg (DM)	Mg (DM)	Mg (DM)
34	5,188,900	5,188,900	4,394,998	4,394,998	793,902	793,902	–	–	–	–
35	No data	No data	No data	No data	No data	No data	No data	No data	721,600	721,600
36	No data	No data	No data	No data	No data	No data	No data	No data	41,705	380,000
37	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data
38	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data
39	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data
40	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data
41	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data
42	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data
43	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data
44	390,000	390,000	No data	No data	No data	No data	390,000	390000	–	–
45	25,000	25,000	25,000	25,000	0	0	–	–	–	–
46	45,000	45,000	No data	No data	No data	No data	45,000	45,000	–	–
47	37,000	37,000	No data	No data	No data	No data	37,000	37,000	–	–
48	48,000	48,000	No data	No data	No data	No data	48,000	48,000	–	–
49	6,100,000	6,100,000	6,100,000	6,100,000	0	0	–	–	–	–
50	780000	780000	780000	780000	0	0	–	–	–	–
51	1,430,000	1,430,000	1,349,920	1,349,920	80,080	80,080	–	–	–	–
52	312,000	312,000	312000	312000	0	0	–	–	–	–
53	470,000	470,000	No data	No data	No data	No data	470,000	470,000	–	–
54	360,000	360,000	No data	No data	No data	No data	360,000	360,000	–	–
55	105,000	105,000	No data	No data	No data	No data	105,000	105,000	–	–
56	15,000	15,000	13500	13500	1500	1500	–	–	–	–
57	113,000	113,000	No data	No data	No data	No data	113000	113000	–	–
58	586,000	586,000	No data	No data	No data	No data	586000	586000	–	–
59	1,310,000	1,310,000	No data	No data	No data	No data	1,310,000	1,310,000	–	–
60	330,000	330,000	No data	No data	No data	No data	330,000	330,000	–	–
61	25,000	25,000	No data	No data	No data	No data	25,000	25,000	–	–
62	4400	4400	No data	No data	No data	No data	4400	4400	–	–
63	28,000	28,000	No data	No data	No data	No data	28,000	28,000	–	–
64	48,000	48,000	No data	No data	No data	No data	48,000	48,000	–	–
65	113,000	113,000	No data	No data	No data	No data	113,000	113,000	–	–
66	14,500	14,500	No data	No data	No data	No data	14,500	14,500	–	–
67	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data
68	53,000	53,000	No data	No data	No data	No data	53,000	53,000	–	–
69	6600	6600	No data	No data	No data	No data	6600	6600	–	–
70	81,000	81,000	No data	No data	No data	No data	81,000	81,000	–	–
71	522,000	522,000	No data	No data	No data	No data	522,000	522,000	–	–
72	180,400	180,400	No data	No data	No data	No data	180,400	180,400	–	–
73	No data	No data	No data	No data	No data	No data	No data	No data	415,500	415,500
74	No data	No data	No data	No data	No data	No data	No data	No data	163,800	163,800
75	No data	No data	No data	No data	No data	No data	No data	No data	100,500	100,500
76	No data	No data	No data	No data	No data	No data	No data	No data	13,325	13,325
77	No data	No data	No data	No data	No data	No data	No data	No data	115,500	115,500
78	No data	No data	No data	No data	No data	No data	No data	No data	100,100	100,100
79	No data	No data	No data	No data	No data	No data	No data	No data	190,500	190,500
80	No data	No data	No data	No data	No data	No data	No data	No data	165,100	165,100
81	No data	No data	No data	No data	No data	No data	No data	No data	45,000	45,000
82	No data	No data	No data	No data	No data	No data	No data	No data	232,700	232,700
83	No data	No data	No data	No data	No data	No data	No data	No data	59,400	59,400
84	No data	No data	No data	No data	No data	No data	No data	No data	46,150	46,150
85	No data	No data	No data	No data	No data	No data	No data	No data	50,000	75,000
86	No data	No data	No data	No data	No data	No data	No data	No data	162,500	357,500
87	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data
88	No data	No data	No data	No data	No data	No data	No data	No data	10,000	10,000
89	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data
90	No data	No data	No data	No data	No data	No data	No data	No data	25,000	40,000
91	No data	No data	No data	No data	No data	No data	No data	No data	10,000	10,000
92	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data
93	2,495,600	2,495,600	0	0	2,495,600	2,495,600	–	–	–	–

Appendix D. Unused biomasses, time reference, biomass specific references

Seq. no.	Comparator 2		Comparator 3			Biomass specific references	
	Unused		Time reference			Biomass potentials	Utilisation
	Min	Max	Publication	Data			
	Mg (DM)	Mg (DM)		Potentials	Utilisation		
1	No data	No data	No data	No data	No data	No data	No data
2	No data	No data	No data	No data	No data	No data	No data
3	No data	No data	No data	No data	No data	No data	No data
4	No data	No data	2003	2000	No data	[33]	No data
5	6,815,412	11,359,652	2012	2007	2015	[3,34,35]	[37]
6	No data	No data	2010	2007	No data	[27]	No data
7	No data	No data	2011	2007	No data	[34]	No data
8	No data	No data	No data	No data	No data	No data	No data
9	No data	No data	No data	No data	No data	No data	No data
10	1,972,176	1,972,176	2016	2010	2013	[35,36]	[38]
11	2,124,193	2,124,193	2016	2010	2013	[35,36]	[38]
12	No data	No data	No data	No data	No data	No data	No data
13	2,784,932	2,784,932	2016	2010	2013	[35,36]	[38]
14	2,032,032	2,032,032	2016	2010	2013	[35,36]	[38]
15	191378	191378	2016	2010	2013	[35,36]	[38]
16	No data	No data	No data	No data	No data	No data	No data
17	No data	No data	No data	No data	No data	No data	No data
18	No data	No data	No data	No data	No data	No data	No data
19	5,566,590	14,647,080	2014	2012	2012	[35,39,40]	[41]
20	3,910,160	10,287,184	2014	2012	2012	[35,39,40]	[41]
21	0	0	2014	2012	2012	[35,41]	[41]
22	0	0	2012	2010	2010	[35,42]	[42]
23	0	0	2006	2006	2006	[43]	[43]
24	0	0	2012	2012	2012	[41]	[41]
25	0	0	2012	2012	2012	[41]	[41]
26	0	0	2012	2010	2010	[35,44]	[44]
27	0	0	2014	2011	2011	[23,35,45]	[50]
28	No data	No data	2012	2008	No data	[46]	No data
29	16034	16034	2014	2011	2011	[23,35,45]	[50]
30	2752	2752	2014	2012	2012	[47]	[47]
31	4200	4200	2014	2012	2012	[47]	[47]
32	No data	No data	2012	2010	No data	[48]	No data
33	500	500	2014	2012	2012	[47]	[47]
34	273100	273100	2014	2012	2012	[47]	[47]
35	No data	No data	2014	2000	No data	[46]	No Data
36	No data	No data	2012	2010	No Data	[48,49]	No Data
37	No data	No data	2012	2010	No Data	[48]	No Data
38	No data	No data	2012	2010	No Data	[48]	No Data
39	No data	No data	2012	2010	No Data	[48]	No Data
40	No data	No data	2012	2010	No Data	[48]	No Data
41	No data	No data	2012	2010	No Data	[48]	No Data
42	No data	No data	2012	2010	No Data	[48]	No Data
43	No data	No data	2012	2010	No Data	[48]	No Data
44	0	0	2013	2012	No Data	[51]	Assumption
45	0	0	2013	2012	No Data	[51]	Assumption
46	0	0	2013	2012	No Data	[51]	Assumption
47	0	0	2013	2012	No Data	[51]	Assumption
48	0	0	2013	2012	No Data	[51]	Assumption
49	0	0	2013	2012	No Data	[51]	Assumption
50	0	0	2013	2012	No Data	[51]	Assumption
51	0	0	2013	2012	No Data	[51]	Assumption
52	0	0	2013	2012	No Data	[51]	Assumption
53	0	0	2013	2012	No Data	[51]	Assumption
54	0	0	2013	2012	No Data	[51]	Assumption
55	0	0	2013	2012	No Data	[51]	Assumption
56	0	0	2013	2012	2014	[51]	[53]
57	0	0	2013	2012	No Data	[51]	Assumption
58	0	0	2013	2012	No Data	[51]	Assumption
59	0	0	2013	2012	No Data	[51]	Assumption
60	0	0	2013	2012	No Data	[51]	Assumption
61	0	0	2013	2012	No Data	[51]	Assumption
62	0	0	2013	2012	No Data	[51]	Assumption
63	0	0	2013	2012	No Data	[51]	Assumption
64	0	0	2013	2012	No Data	[51]	Assumption
65	0	0	2013	2012	No Data	[51]	Assumption

(*continued*)

Seq. no.	Comparator 2		Comparator 3			Biomass specific references	
	Unused		Time reference			Biomass potentials	Utilisation
	Min	Max	Publication	Data			
	Mg (DM)	Mg (DM)		Potentials	Utilisation		
66	0	0	2013	2012	No Data	[51]	Assumption
67	No data	No data	No data	No data	No Data	No data	No data
68	0	0	2013	2012	No Data	[51]	Assumption
69	0	0	2013	2012	No Data	[51]	Assumption
70	0	0	2013	2012	No Data	[51]	Assumption
71	0	0	2013	2012	2014	[51]	[53]
72	0	0	not published	2013	No data	[52]	Assumption
73	No data	No data	2014	2011	No Data	[54]	No data
74	No data	No data	2014	2011	No Data	[54]	No data
75	No data	No data	2014	2011	No Data	[55]	No data
76	No data	No data	2014	2011	No Data	[55]	No data
77	No data	No data	2014	2011	No Data	[56]	No data
78	No data	No data	2014	2011	No Data	[56]	No data
79	No data	No data	2014	2011	No Data	[57]	No data
80	No data	No data	2014	2011	No Data	[57]	No data
81	No data	No data	2014	2011	No Data	[35,58]	No data
82	No data	No data	2014	2011	No Data	[35,58]	No data
83	No data	No data	2014	2011	No Data	[59]	No data
84	No data	No data	2014	2011	No Data	[59]	No data
85	No data	No data	2010	2007	No Data	[46]	No data
86	No data	No data	2010	2007	No Data	[46]	No data
87	No data	No data	2010	2008	No Data	[46]	No data
88	No data	No data	2010	2008	No Data	[46]	No data
89	No data	No data	2010	2008	No Data	No data	No data
90	No data	No data	2010	2008	No Data	[46]	No data
91	No data	No data	2010	2008	No Data	[46]	No data
92	No data	No data	No data	No data	No Data	No data	No data
93	1,174,400	1,174,400	2010	2010	2010	[35,40]	[41]

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#2

How to measure the impact of biogenic residues, wastes and by-products: Development of a national resource monitoring based on the example of Germany

Brosowski, A., Krause, T., Mantau, U., Mahro, B., Noke, A., Richter, F., Raussen, T., Bischof, R., Hering, T., Blanke, C., Müller, P., Thrän, D.

Biomass and Bioenergy (2019), 127, 105275

20 P., 170 Lit., 5 Fig., 8 Tab.

Biomass and Bioenergy 127 (2019) 105275

Contents lists available at ScienceDirect

Biomass and Bioenergy

journal homepage: www.elsevier.com/locate/biombioe

Research paper

How to measure the impact of biogenic residues, wastes and by-products: Development of a national resource monitoring based on the example of Germany

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ARTICLE INFO

Keywords:
Biomass potential assessment
Transport sector
Biomethane
SDGs
Bioeconomy
Method harmonisation

ABSTRACT

The United Nations' Sustainable Development Goals call for affordable, clean energy. The efficient use of biogenic residues offers various means of promoting that goal. Key questions, however, are which biomasses are available to what extent, and what additional contribution can be expected from improved use. Answering these questions require cross-sectoral, regular and consistent information on the available resources. A comprehensive, continuously applicable measuring instrument for this task does not yet exist. To fill this gap, a monitoring system was developed which is able to quantify the resource base annually, is easy to update and can be used internationally. Using Germany as a case study, a review was carried out for 77 biomasses from five different sectors. The result is a network of 1,113 calculation elements, which forms the basis for an automatic data processing. Based on that, Germany's supply of technically usable biogenic residues was determined to 86–140 million Mg (DM) in 2015. Between 66% and 84% of this amount already has an established use, while the potential which can still be mobilised is in the range of 14–48 million Mg (DM). If this amount were provided as e.g. biomethane, the amount of final energy coming from renewable sources in Germany could thus be increased by up to 18%. Just four biomasses bear the main responsibility for this figure. The monitoring system is able to prioritise areas for action and can provide crucial support in the development of policy and business strategies for the future use of residues.

1. Introduction

On 1 January 2016, the United Nations brought the Sustainable Development Goals (SDGs) into force: global targets for a global society [1]. According to Fritsche et al. [2] and Müller et al. [3], of the total of 17 targets, seven are directly related to the use of biomass, and eight others indirectly. Special focus is placed on the material and energetic use of biogenic residues, by-products and waste from multiple sectors such as agriculture and forestry, municipal waste and sewage sludge, industrial residues or residues from other areas [4]. This does not create additional competition for land: above all, this instead optimises its existing use [5,6]. The range of possible applications is broad – extending, for example, from the recovery of nutrients [7–9] or the substitution of fossil-derived raw materials in the chemicals, pharmaceutical and packaging industries [10–13] to the production of sustainable sources of energy with great potential to reduce greenhouse gases [14–16].

In order to determine the impact of biogenic residues on corresponding target markets and to evaluate the options for future optimisation, the supply and in particular the current use of biogenic residues must be known in detail. The description of the raw material basis through biomass potential studies has a long tradition. On 26 May 2019, a total of 93,347 results are shown on www.sciencedirect.com from a search for "biomass potential assessment". Fig. 1 shows the

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https://doi.org/10.1016/j.biombioe.2019.105275
Received 18 December 2018; Received in revised form 28 May 2019; Accepted 7 June 2019

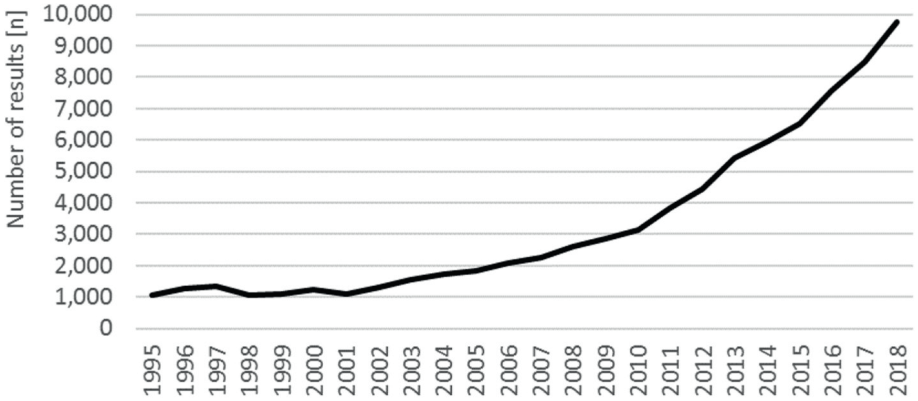


Fig. 1. Search results for "biomass potential assessment" at www.sciencedirect.com on 26 May 2019.

findings over time from 1995 to 2018. In the last ten years, the annual number of scientific articles on the topic has quadrupled, reaching almost 10,000 in the year 2018.

The available works have a different character. For example, there are calculations for individual sectors and countries [17–19] or cross-sectoral studies for countries, transnational regions or continents [20–26]. Due to the lack of standards in the calculation of biomass potentials, the range of calculation methods and results is high [4]. Recommendations for harmonisation approaches, e.g. by Vis and van den Berg [27], go back to the year 2010. So far, no rules have been set down, and it is not easy even to update or compare extensive, internally consistent studies for an entire continent (e.g. Scarlat et al. [22], Hamelin et al. [24], or Lindner et al. [25] for Europe).

The diversity of the results so far provides a heterogeneous picture of the resource availability. In addition to quantifying the amount of raw materials, a central challenge is determining the current use of residues. The regular balancing of supply and use of residues is, however, the key to evaluating raw material use in the future. Only in this way it can be avoided that calculated biomass potentials are not planned more than once. For a better provision of corresponding results in the future, the options of digitisation have to be taken more into account: a well structured and regularly updated public database is required. The results on the availability of resources must be consistent across multiple sectors and the calculation methodology must be easy to understand. In this way, the strengths and weaknesses, e.g. with regard to the data sources used, can be clearly identified and data gaps can be closed more efficient in the future.

The inconsistencies in the existing studies already begin with the naming of the biomasses. What are biogenic residues? Which individual biomass belongs to animal excrements? Does the term straw mean all straw types or only cereal straw? Which industries are considered in industrial residues and what does municipal waste actually include? With this in mind, Brosowski et al. [4] propose a multi-level means of describing 93 residues from the sectors of agriculture and forestry, municipal waste and sewage sludge, industrial residues and residues from other areas. At the same time and based on available studies, their work shows that it was not possible to quantify the raw material potential across all sectors for a single reference year.

Reliable and up-to-date data on the availability of biogenic residues is a crucial prerequisite for evaluating the fulfilment of strategic goals such as SDGs. To meet this requirement, this article presents an internationally utilisable, modular monitoring system to automatically measure the occurrence and in particular, the current use of biogenic residues for a common reference year. The system is also able to contextualise the information on the raw material so as to quantify its impact on a potential application in terms of resource availability. SDG 7.2 ("By 2030, increase substantially the share of renewable energy in the global energy mix" [1]) was chosen as an example to put the application options of the monitoring system into context. The findings can be used to assess the relevance of individual raw materials or groups thereof and to quantify their influence on the achievement of the objectives of the selected SDG. On that basis, priorities can be derived for measures to optimise the existing use of biomasses or to exploit those yet to be mobilised. The monitoring system which was developed was tested on the case example of Germany. Germany was selected because of its political commitment to optimising the use of biogenic residues. Among other things, the federal government's climate protection plan [28] and its strategy for bioeconomic research [29] and policy [30] stress that residues must be seen as an important part of achieving various sustainability goals.

2. Methodology for systematically collecting and updating data

The monitoring system consists in twelve modules as a means of organising the data processing in a manner that is systematic, consistent and updatable. The modules are mutually interdependent in various ways. Fig. 2 summarises the system.

Calculation elements (Section 2.2) are used to determine the biomass potential of the biomasses included in the monitoring (Section 2.1). In this context, calculation elements are understood as values of various origins and dynamics that are used to calculate the potential of a biomass. For better communication of results, the calculations of the potential are reduced to ten key items of information (Section 2.3). These key items of information are to be understood as various terms for potential (e.g. "theoretical potential") which quantitatively describe the resources available and how the resources are used. In order to ensure transparent documentation of all calculations, biomass specific calculation flowcharts (Section 2.3) were developed, which illustrate the calculation methodology for an individual biomass on only one A4 page. To judge how robust the findings are, the quality of the data produced by the calculation elements (Section 2.4) is evaluated quantitatively. Contextualisation (Section 2.5) creates a link between the key items of information and potential use so as to calculate the possible impact (Section 2.5) in terms of resource availability. Sankey diagrams (Section 2.5) are used to document the biomass quantities with relevant substrate characteristics.

The automatic data processing is based on the modules geocoding, database, website and mapping (Section 2.6). Geocoding can be used to describe the spatial assignment of all aspects of the monitoring unambiguously, anywhere in the world. All the key items of biomass-specific information were transferred to a database which is publicly accessible on a website and can be connected to mapping systems in future. With the help of these modules, the external data provision of the monitoring can be clearly described in terms of time and space. This is an important requirement for the international transferability of the entire system. The following chapters contain a detailed description of the modules presented.

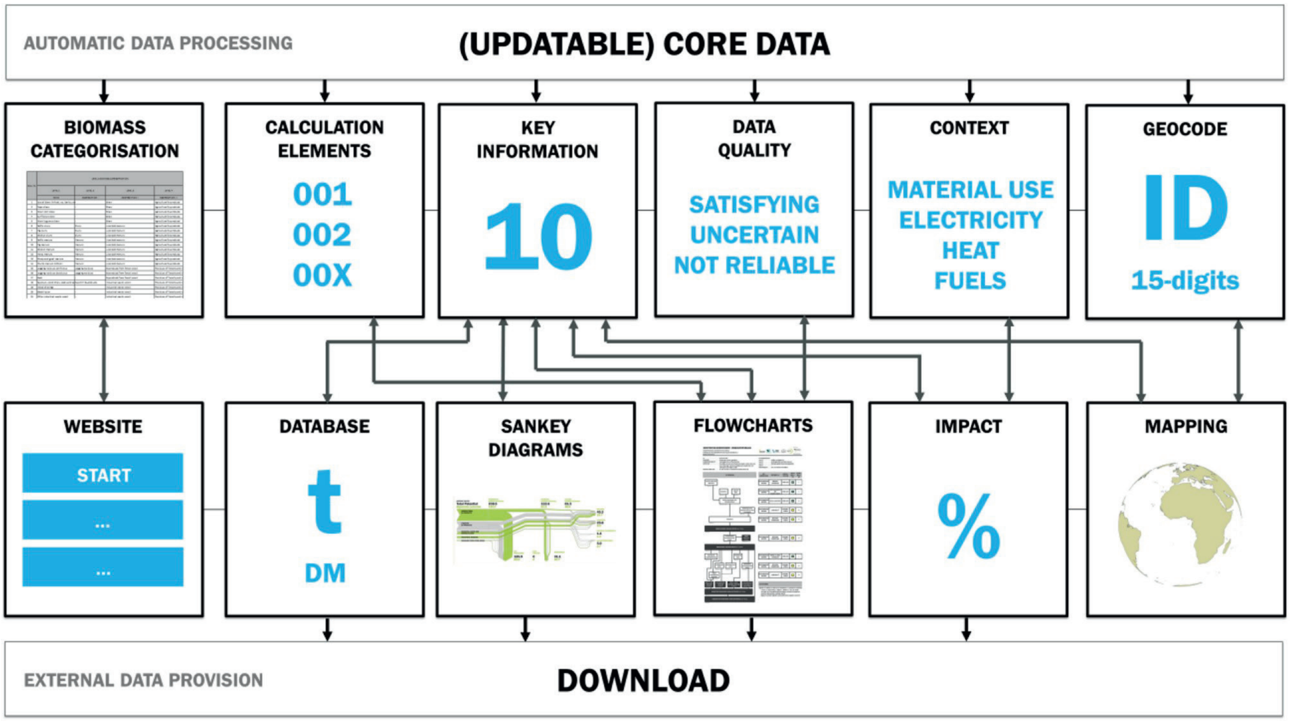


Fig. 2. Illustration of the 12 modules of monitoring system and their connection to each other.

2.1. Biomass categorisation

The unambiguous identification of the individual biomass types considered is an essential prerequisite for the cross-sector description of the raw material basis. Brosowski et al. [4] present a four-level system for categorising a total of 93 individual types of biomass from the sectors of agriculture and forestry, municipal waste and sewage sludge, industrial residues and residues from other areas. Using this system, all the individual biomasses therein were integrated and the review described in Section 2.2 was employed to group them by points or add further biomasses.

2.2. Calculation elements for biomass potential determination

A biomass potential is determined by combining various calculation elements [27] with different origins and dynamics. The first aim of an extensive review was to collect relevant elements for calculating biomass potentials and the minimum and maximum numerical values for 2015, the reference year. The collected data were then interlinked using basic arithmetic operations. The aim was to form an extensive network for the automatic calculation of biomass potentials. A second important objective was to evaluate the origin and dynamics of the calculation elements. Their dynamics have a particularly decisive influence on whether they, and thus the monitoring system as a whole, can be regularly updated. To make their documentation transparent, the sources used were divided into six clusters and characterised as dynamic or non-dynamic.

2.2.1. Dynamic sources

(1) *Statistics:* Official statistics including those published by associations are provided regularly by third parties and this input can be used to dynamically (e.g. annually) update a calculation element. An example of this is the wheat production [31], which has an influence on the availability of cereal straw.
(2) *Modelling:* This includes models that are able to process basic statistical data as well as other data (e.g. environmental protection requirements, process-relevant data). An example of this is the ITOC-Model [32] to calculate the biomass potential of logging residues. As soon as a data input is changed, new data can be made available on a regular basis.
(3) *Primary data assessment:* Continuous surveys or analyses of material flows can provide dynamic input for biomass potential calculation. In waste management, for example, regular investigations are carried out to measure the share of impurities [33]. Such information is, for example, an important element for calculating the utilisable amount of bio-waste from private households.
(4) *Internal database:* This refers to continuous electronic databases, which are not publicly accessible, but contain valuable information for the calculation of biomass potential or its use. An example of this is an internal plant database for the fermentation of waste [34].

2.2.2. Non-dynamic sources

(5) *Literature:* This means books, articles or websites which are published irregularly or on a one-off basis and can only be updated with considerable effort. An example for this are results for the calculation of the humus balance [35], which has a direct and comprehensive influence on agricultural by-products.
(6) *Expert assessment:* Irregular interviews, assumptions or plausibility checks provide insights based on the experience of experts. Up-to-date information on this cannot yet be covered by other sources. This includes, for example, technical recovery rates or transport losses [36].

In an extensive review of a total of 122 sources, relevant calculation elements were collected and evaluated according to this approach. Table 1 summarises the sources used for each sector. A detailed allocation of the sources for each calculation element is part of the calculation flowcharts, which are explained in Section 2.3.

2.3. Key items of information and calculation flowcharts

The calculation elements (Section 2.2) form an extensive network

Table 1
Sector-specific sources of data collection.

Sector	References
Agricultural by-products	[31,35,37–53]
Forestry by-products	[32,54–61]
Municipal waste and sewage sludge	[33,34,55,62–85]
Industrial residues	[36,86–96],[97-115],[116-144]
Residues from other areas	[55,145–151]
All sectors	122

Table 2
Description of the key items of information and its basis for the calculation of biomass potentials.

ID	Key items of information	Based on
1	Theoretical biomass potential	Individual calculation elements
2	Technical biomass potential	Individual calculation elements
3	Not mobilisable	Functional dependence (03 = 01 - 02 - 04)
4	Data situation unclear	Individual calculation elements
5	Material use	Individual calculation elements
6	Energetic use	Individual calculation elements
7	Material or energetic use	Individual calculation elements
8	Use not differentiable	Individual calculation elements
9	Technical biomass potential used	Functional dependence (09 = 05 + 06 + 07 + 08)
10	Mobilisable technical biomass potential	Functional dependence (10 = 02 - 09)

for an automatic calculation of biomass potentials. For a better communication of results, the output of the monitoring system is reduced to meaningful key items of information. Brosowski et al. [4] presented ten of these key items of information which can be used to describe the supply and the use of raw materials in all sectors (Table 2). According to this structure, seven of the ten key items of information in the monitoring system are based on mathematically linking individual, biomass-specific calculation elements (Section 2.2). The remaining three are functionally interdependent on other key items of information.

With this system, all the calculation elements collected were allocated to the key items of information and the corresponding min./max. values were calculated. In addition to these two values, a third value was generated which allows statistical evaluations (e.g. regressions) to be carried out over several reference years. As data was only gathered for a single reference year, this function was initially applied as an arithmetic mean of the min./max. values.

In order to provide a compact record of the methodological approach for a specific biomass, calculation flowcharts were prepared for each biomass type. One A4 sheet per biomass visualises the link between individual calculation elements and the key item of information in question. Annex A contains a further explanation and an example, taking cereal straw as the biomass.

2.4. Data quality of calculation elements

Another module in the monitoring system is the calculation elements' data quality. As an initial, general assessment, all calculation elements were evaluated based on three quality levels and a score system (Table 3). By this means, each calculation element is given an expert evaluation documented by a traffic light system in the calculation flowcharts (Section 2.3, Annex A). For quantitative evaluation, each traffic light color stands for a score. The total number of scores for an individual biomass type divided by its number of calculation elements form the basis for an initial evaluation of the data quality. The result of this calculation is within one of the ranges shown in Table 3. For better understanding, the range of quality levels is associated with the terms 'satisfying', 'uncertain' and 'not reliable'. Due to the inhomogeneity of calculation elements, clusters mentioned in Section 2.2 can reach different types of quality levels. An overview of feasible options is given in Table 3. In detail, this means that official statistics are always connected with satisfying data quality. A literature value, on the other hand, can provide satisfying (e.g. corn-crop-ratios), uncertain (e.g. dry matter content) or not reliable information (e.g. humus balance).

2.5. Contextualisation, sankey diagrams and impact of biomass potential

To strategically evaluate the relevance of a biomass potential, a specific context is required in which the raw material can potentially be used. Among other things, these include options for material use (e.g. platform chemicals for the chemical and pharmaceutical industries, construction materials, packaging), energetic use in the production of fuels, heat and electricity, or a smart combination of material and energetic use of one or more biomasses [6]. For the calculation of an expected impact the following information must be known:

(a) Raw material characteristics for technology selection
(b) Technology parameters to quantify a potential market supply
(c) Demand of the target market

With the help of this information, the potential substitution share of e.g. fossil raw materials to biogenic raw materials can be estimated, at least from the point of view of resource availability. In order to test the monitoring system, an example was selected for which all three information were available from publicly accessible sources. The example selected was that of the production of biomethane in transport sector, as this energy source can be used very flexibly and has great potential to reduce greenhouse gases, while its digestate also remains available for material use as a fertiliser [152].

(a) First, the fermentable biomasses were identified with the help of literature [5,153–155]. Only the fermentability was considered. Further criteria (e.g. legal and economic framework, infrastructural requirements) were not taken into account. Applying this monitoring filter generates the digestible amounts of substrate for each key item of information. A Sankey diagram was used to capture the quantitative and sectoral relationships between digestible and non-digestible biomasses.

(b) The next step was to gather information on the specific biogas yields and methane contents for all the relevant individual biomass types, provided by the Bavarian State Office for Agriculture (LfL) [153], the Association for Technology and Structures in Agriculture (KTBL) [154] and Archea [155]. Minimum and maximum values were gathered from the literature sources in order to take into account the entire range of different substrate characteristics. A methane slip of 1–2% was also taken into consideration [156]. No further losses (e.g. from pipes or feeder points) were taken into account. Finally, biomethane's potential final energy output in petajoules was calculated in conjunction with the lower heating value of biomethane (35.89 MJ/m^3, [5]) and the tonnages of biomass-specific key items of information (Section 2.3).

(c) The findings were then related to a field of application to produce a quantitative interpretation of the relevance of this information. The example selected was that of the transport sector: the pressure to take action is especially high in that field considering the globally rising greenhouse gas emissions [157,158]. Publicly available statistics produced by the Federal Ministry of Transport and Digital Infrastructure (BMVI) [159] show the final energy demand in petajoules, not only for the entire sector, but also separated into different modes of transport (car, freight, rail, air, sea). The combination of the biomethane potential (= supply) and the energy demand in the transport sector (= demand) produces the potential impact from the point of view of resource availability. As the minimum and maximum values were consistently taken into account throughout the calculations, the impact was also formulated as a range.

Table 3
Framework of data quality evaluation.

Traffic light colour included in calculation flowcharts	Score for each calculation element	Range of results for overall evaluation per biomass	Term to describe data quality	Feasible options for evaluating the clusters					
				Statistics	Modelling	Primary data assessment	Internal database	Literature	Expert assessment
Green	2	1.33–2.00	Satisfying	✓	✓	✓	✓	✓	-
Yellow	1	0.66–1.33	Uncertain	-	✓	✓	✓	✓	✓
Red	0	0.00–0.66	Not reliable	-	-	-	-	✓	✓

2.6. Geocoding, website, database and mapping

In order to ensure reproducible and spatially unambiguous data processing of the biomass potential calculation, each part of the monitoring system is described with a unique geocode. In this way, the monitoring system can be used not only for different countries, but also for different regional levels within a country. In application, this means that the production quantity of e.g. wheat in France is different than in Germany. The thematically identical calculation element (= wheat production) therefore requires the possibility of taking different values. The spatial assignment is feasible via a code consisting of a total of 15 letters and numbers (Table 4).

Characters 1–5 describe the spatial level, with a unique address for any country, any administrative unit and any geographical location. The basis is the international reference system ISO-3166/2 [160] and UN/LOCODE [161], as well as other regional nomenclatures such as NUTS [162] for Europe. Characters 6–10 define the sector and the individual biomass types (Section 2.1). In this way, individual biomass and its affiliation in the sense of Brosowski et al. [4] can be clearly described and compared with each other across studies. Characters 11–15 cover the key item of information as well as the consecutive biomass-specific calculation elements, thus mapping all the components of the biomass potential calculations (Sections 2.2 and 2.3). The example code shown in Table 4 thus describes a calculation element (here 001, wheat production) for calculating the theoretical biomass potential (01) of cereal straw (CST) as an agricultural by-product (AB) at national level (000) in Germany (DE). An overview of the complete coding of the example can be found in Annex A. The coding for all the other biomass types is included in Annex B.

To make the data accessible in a practical manner over the long term, a user-friendly website was set up and a document-oriented database developed. In addition to the code system shown in Table 4, the database contains additional attributes for the time reference of the results, the min./max. and average values recorded in the review (Section 2.2) and the physical unit of the results. In the totality of these structures, all key items of information for each biomass can be clearly described spatially and temporally. At the same time, the system offers the possibility of being linked to online mapping systems in the future. In this way, both multinational and regional findings can be automatically processed and mapped.

3. Results and discussion

3.1. Biomass categorisation

For the common reference year of 2015, a full set of consistent data was collected for a total of 77 individual biomass types. Table 5 lists all biomasses considered for each sector. The highest number of different biomasses can be found for industrial residues (23). Numerous branches of food production as well as fodder and biofuel production were taken into account. For the agricultural sector (22), a distinction was made between numerous types of straw and animal excrements as well as by-products from fermentation and horticulture. In the area of municipal waste (14), a variety of dutiable biological wastes and sewage sludges were distinguished. The category of residues from other areas (11) includes biomasses from a non-municipal context such as material from landscape management or areas accompanying roads, tracks or waterways. In the forestry sector (7), the by-products of forest management and residual materials from various processing operations were taken into account.

3.2. Calculation elements for biomass potential determination

For the 77 biomass types across the different sectors, 1,113 calculation elements were brought together. On this basis, an extensive network for the automatic calculation of biomass potentials was implemented in Germany. A total of 302 elements are dynamic and 811 are non-dynamic (Fig. 3). Half of all the calculation elements are based on information from the literature and, together with the expert assessments, 73% of the elements are non-dynamic in origin. The dynamic elements are dominated by statistics and account for nearly 24% of the total monitoring. By contrast, models, primary data collection and internal databases account for a comparatively small proportion; approx. 3%. It is striking that so far it has only been possible to integrate one internal database. In summary, it can be said that roughly 97% of the calculation elements depend on three types of sources: statistics, sources from the literature and expert assessments.

The system will only be able to fulfil its actual function of continuous monitoring when further time references are used. In order to extend the calculation network to past or future reference years, the 302 dynamic data sources must be updated for the corresponding years. The 811 non-dynamic calculation elements can be transferred directly. They can be used for some years to come, but without more research, the system will become less informative over the long term if non-dynamic calculation elements continue to be used (e.g. humus balance figures from the literature). With support of geocoding (Section 2.6) the system is able to include further calculation elements or to replace non-dynamic calculation elements (e.g. dry matter content) by dynamic data (e.g. climate data). Thanks to this flexibility, the calculation methodology can be improved continuously and selectively.

Updating the system requires significantly less effort than recalculation and can guarantee a consistent calculation methodology

Table 4
Coding system for spatially unique identification of each component of the monitoring system.

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*
Spatial level					**Biomass categorisation**					**Biomass potential calculation**				
Country		Administrative unit			Sector		Biomass			Key information		Calculation element		
D	E	0	0	0	A	B	C	S	T	0	1	0	0	1

Table 5
Overview of biomasses contained in the monitoring system per sector.

Sector	Biomasses	
Agricultural by-products	Digestate; By-products from vegetable gardening; Corn cobs; Beet leaves; Potatoe leaves; Cereal Straw; Rapeseed straw; Sunflower straw; Grain corn straw; Grain legumes straw; Cattle liquid manure; Cattle slurry; Pig liquid manure; Pig slurry; Chicken liquid manure; Cattle solid manure; Pig solid manure; Chicken solid manure; Horse manure; Sheep manure; Goat manure; Poultry manure	22
Forestry by-products	Logging residues (coniferous); Logging residues (deciduous); Bark; By products of wood processing industries and wood shavings; Black liquor; Other industrial waste wood; Waste wood	7
Municipal waste and sewage sludge	Bio waste from private households; Green waste; Biogenic share of old textiles; Waste paper; Cooking oil and fats from private households; Commercial food waste; Kitchen and canteen wastes; Leaves; Biogenic share of road sweepings; Biogenic share of sewer sludge, grit slurry and grit chambers; Sewage sludge from food processing industries; Sludges from pulp, leather and textile industries; Sewage sludge from public wastewater treatment plants; Biogenic share of waste water	14
Industrial residues	Residues from Meat processing; Fish processing; Fruits processing; Vegetable processing; Potatoe processing; Oil mills; Milk processing; Cereal processing; Starch production; Bread and bakery production; Breweries; Malting; Distilleries; Winemaking; Sugar production; Cacao produktion; Production of ready-made meals; Coffee production; Fodder industry; Tobacco processing; Yeast production; Bioethanol production; Biodiesel production	23
Residues from other areas	Stalks from landscape management; Wooden materials from landscape management; Stalks from roadside greenery; Woody biomass from roadside greenery; Railway lineside stalks; Railway lineside wood; Stalks from orchards; Woody biomass from orchards; Stalks from vineyards; Woody biomass from vineyards; Driftwood	11
Total		**77**

over several years. In this way, information on the availability and use of resources can be provided on a regular basis.

3.3. Key items of information

The ten key items of information are available as minimum, maximum and average values for each of the 77 individual biomass types. This results in 2,310 individual values, found grouped by sector in Table 6. The complete data set for individual evaluation is found in Annex C.

For the theoretical potential (01), a range of 198.9–278.1 million Mg (DM) can be determined. About half of that (43–50%) can be identified as technical potential (02). The other half cannot be mobilised (03), because it fulfils important roles, such as safeguarding various soil functions. Almost 99% of the non-mobilisable potential falls under agriculture and forestry. The remaining one percent is largely losses due, for example, to recovery and transport. Thanks to the extensive data review, it was possible to generate complete data sets. For this reason, the key information item “data situation unclear” (04) has no value. At 71.7–91.4 million Mg (DM), 66–84% of the technical potential is already tied to a use (09). The material use (05) accounts for the largest share with 54–58%. Another 37% goes to energetic uses (06), while the precise use cannot be determined for roughly 5–9% (07, 08). All in all, there is a potential which can still be mobilised (10) of 13.9–48.2 million Mg (DM), corresponding to 16–35% of the technical potential (2) and roughly 7–17% of the theoretical potential (01). One thing which should be underlined is that the minimum mobilisable potential for forestry by-products is negative. This is due to one biomass type, “logging residues (deciduous)”, which is currently used to a greater extent than the calculated supply available in a scenario featuring nature conservation. Another fact is related to industrial residues and its mobilisable potential. It remains zero because of legal framework (e.g. Ref. [163]) which demand a full utilisation.

Table 7 summarises the ten most important individual biomasses in terms of average values and for four selected key items of information. It can be seen that even within the minimum and maximum values, this ranking changes in terms of its order, but the statement it makes remains largely the same. The bottom line of the table shows the proportion of the overall findings taken up by these ten biomass types. For each of the key items of information presented, they make up more than 70%, while the mobilisable potential is almost fully described by the ten most important biomasses. It should be noted that the five most important biomasses already comprise 81% of the mobilisable potential. The 77 biomasses included in the monitoring produce a clear focus on these few biomass types. On this basis, optimisation strategies (e.g. cascading use, which means a combined energetic and material use, closed-loop recycling, etc.) or mobilisation strategies (e.g. identifying priority regions, stakeholder analysis, feasibility studies) can be discussed for putting these biomass types to more effective use.

The ten key items of information can be used to fully map the material flow of residues in Germany. However, the transnational use of the system may require more key items of information presented here (e.g. import, export). Thanks to geocoding (Section 2.6) the system can be adapted easily.

3.4. Data quality of calculation elements

Across all sectors, the data quality of the calculation elements can be described as uncertain to satisfactory (Fig. 4). With a value of 1.21, the average falls within the “uncertain” range. However, if the individual biomass types are weighted, for example according to the relevance of their theoretical potential, the overall result is 1.35, which falls just within the “satisfactory” range. This means that for biomass with a high potential, the data quality of the calculation elements comes out

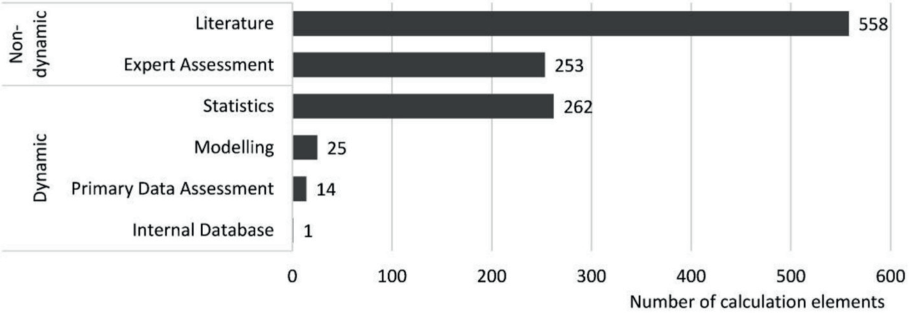


Fig. 3. Number of dynamic and non-dynamic calculation elements per cluster.

Table 6
Results of sectoral key items of information in million Mg (DM), 2015 (deviations by rounding).

Sector	Bandwidth	Key items of information									
		01	02	03	04	05	06	07	08	09	10
		Theoretical potential	Technical potential	Not mobilisable	Data situation unclear	Material use	Energetic use	Material or energetic use	Use not differentiable	Used technical potential	Mobilisable technical pot.
Agricultural by-products	Min	88.2	16.5	71.7	0.0	3.3	1.9	0.0	0.2	5.4	11.1
	Max	126.9	34.9	92.0	0.0	5.1	3.1	0.0	0.5	8.7	26.2
Forestry by-products	Min	64.9	24.9	40.0	0.0	7.4	16.6	0.0	1.6	25.7	−0.8
	Max	79.9	36.6	43.3	0.0	7.4	16.6	0.0	1.6	25.7	10.9
Municipal waste/ sewage sludge	Min	26.4	26.0	0.4	0.0	17.4	3.9	0.7	0.5	22.4	3.6
	Max	44.8	44.6	0.2	0.0	22.7	9.8	1.6	0.4	34.5	10.1
Industrial residues	Min	15.3	15.1	0.2	0.0	13.3	1.0	0.2	0.6	15.1	0.0
	Max	16.2	16.1	0.2	0.0	13.9	1.2	0.3	0.7	16.1	0.0
Residues from other areas	Min	4.1	3.1	1.0	0.0	0.0	2.8	0.0	0.3	3.1	0.0
	Max	10.3	7.4	2.9	0.0	0.0	2.8	0.0	3.6	6.4	1.0
TOTAL	**Min**	**198.9**	**85.6**	**113.3**	**0.0**	**41.4**	**26.2**	**0.9**	**3.2**	**71.7**	**13.9**
	Average	**238.5**	**112.6**	**125.9**	**0.0**	**45.3**	**29.8**	**1.4**	**5.0**	**81.5**	**31.1**
	Max	**278.1**	**139.6**	**138.5**	**0.0**	**49.2**	**33.5**	**1.9**	**6.8**	**91.4**	**48.2**

Table 7
Ranking of the ten most important residues in Germany related to its biomass potential in 2015 and using the example of four selected key items of information.

No.	Theoretical potential (01)	Technical potential (02)	Potential used (09)	Mobilisable potential (10)
1	Logging residues (c)	Waste paper	Waste paper	Cereal straw
2	Cereal straw	Cereal straw	Sawmill by-products/wood shavings	Cattle liquid manure
3	Cattle solid manure	Green waste	Oilmill residues	Cattle solid manure
4	Logging residues (d)	Sawmill by-products/wood shavings	Green waste	Logging residues (c)
5	Waste paper	Oilmill residues	Waste wood	Green waste
6	Digestate	Waste wood	Cereal straw	Biogenic share of waste water for anaerobic treatment
7	Green waste	Cattle solid manure	Woody biomass from landscape management	Logging residues (d)
8	Cattle liquid manure	Cattle liquid manure	Industrial waste wood	Biowaste from private households
9	Sawmill by-products/wood shavings	Logging residues (c)	Biowaste from private households	Pig liquid manure
10	Rapeseed straw	Logging residues (d)	Logging residues (d)	Waste paper
Share	**72.3%**	**72.5%**	**73.0%**	**95.0%**

slightly higher altogether. This is strongly influenced by the comparatively high quality of the data on the use of wood; this has been continuously collected for many years [54–60]. For this reason, the data quality for the forestry sector is found to be the highest, at 1.84. Within the other sectors, however, the quality of data differs significantly. In the case of residues from other areas, especially, the data quality is not reliable (0.54) due to the numerous expert assessments. For industrial residues, the combination of statistics, sources from the literature and various expert assessments results in a data quality that is slightly below average (1.09). The calculation elements for agricultural by-products are average, at 1.20. In the sector of municipal waste and sewage sludge, which is strongly legally regulated (e.g. by the Act for Promoting Closed Substance Cycle Waste Management, KrWG [163]), the many statistical datasets on their occurrence and use mean the data quality is satisfactory and above average (1.40). The findings for all the individual biomasses are found in Annex B.

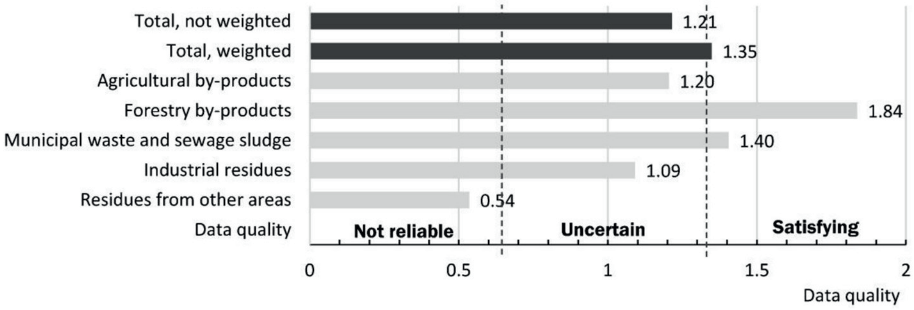


Fig. 4. Scores for evaluation of data quality of calculation elements (total, weighted by biomass quantity and per sector).

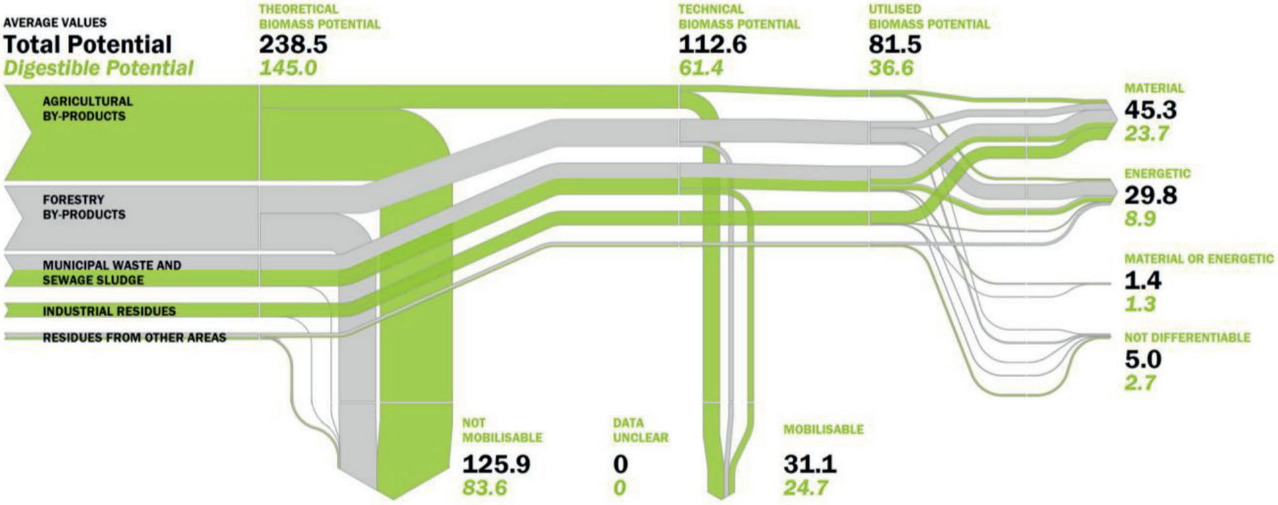


Fig. 5. Sankey diagram of key information as average values incl. visualisation of the amount of digestible biomass in million Mg (DM), 2015.

In addition to the sector-specific evaluations, the biomass-specific results allow a more precise picture. In Table 7, cereal straw was identified as the most important resource that can still be mobilised. According to Annex B, the data quality is an above-average 1.50. Looking at the calculation flowchart in Annex A, it becomes clear that this result is based on the high number of statistics. The calculation element humus balance, which is highly relevant in terms of biomass potential calculation and resource availability, is evaluated with the lowest data quality. The evaluation system used so far is not able to reflect such relevance. To gain a nuanced, objective idea of the situation, additional research is needed, including an assessment of the calculation method. As yet, for example, there has been no assessment of which sustainability goals are involved in the calculations, or which goals can even be depicted. One example of a suitable frame of reference might be the 24 sustainability indicators presented by the Global Bioenergy Partnership (GBEP) [164].

3.5. Contextualisation, sankey diagrams and impact of biomass potential

Fig. 5 shows the entire material flow as a Sankey diagram. The diagram includes all 77 individual biomass types, subdivided into the five sectors, plus the averages of the key items of information (cf. Table 6). For the context of biomethane, for instance, it was found that 59 out of 77 individual biomass types can be digested to biomethane. As the monitoring system relates to individual biomass types, the amounts of substrate with this characteristic can be represented as a whole. In the diagram, the digestible quantities are emphasised.

In terms of technical potential, this corresponds to a share of 61.4 million Mg (DM). Almost 60% or 36.6 million Mg (DM) are already in use. The material use is highest, making up two thirds in all. In this diagram, the mobilisable, digestible potential amounts to 24.7 million Mg (DM), with the share of agricultural by-products the highest, at 76%. The remaining 24% comes from the municipal waste and sewage sludge sector. The biomasses which dominate by far are cereal straw, cattle liquid manure, cattle solid manure and green waste. If all the mobilisable, digestible biomass were used in biogas plants and processed into biomethane, its potential final energy output would be approx. 172 PJ from the point of view of resource availability. When the available min./max. values are included, this results in a range between 108 and 236 PJ.

If the calculated final energy output is compared with the demand in the transport sector, this leads to the impact shown in Table 8. In terms of resource availability, biomethane from mobilisable residues would have an impact of 4–9% on the transport sector as a whole. Though these values are comparatively low, individual sub-sectors are in stark contrast, reaching values > 100%. Through compression (bio CNG) or liquefaction (bio LNG) [5], for example, biomethane from residues can have a considerable substitution potential of fossil fuels e.g. in public road transport (buses), rail transport, inland waterway transport or maritime bunkering for seagoing ships.

What do these results mean for the renewable energy system and the SDG 7.2 in Germany (Section 1)? In 2015, Germany's total final energy demand was 8,898 PJ [165], while the percentage of renewable energy sources was 15.0% [166]. In the example contextualisation of “biomethane in the transport sector”, the share of renewable energies could have been increased in absolute terms by 1.2–2.6% and relatively by 8.0–17.7%. The actual share of biomethane in the transport sector in 2015 was 1.2 PJ [166]. The mobilisable potential for this potential application purpose has therefore only been utilised to less than one percent.

Whether or not such uses are worthwhile depends on the goal to be achieved. These quantitative analyses can be used to identify priority spheres of action in which barriers can deliberately be reduced. However, this analysis is based only on a comparison of the final energy supply and demand. Whether or not options of this kind can be successfully implemented depends on various other conditions that were not taken into account in this work. In particular, these include technological, legal, ecological and economic restrictions, as well as political and social target requirements for their use. However, the example shows how the monitoring system can be used to measure a potential impact of biogenic residues, by-products and wastes. In order to be able to better compare the numerous possible uses of residual materials, further contexts and requirements of the relevant target markets will have to be investigated in the future.

3.6. Geocoding, website, database and mapping

The findings are publicly available in digital form at http://webapp.dbfz.de/resources and consistently follow the systematology of the monitoring. This offers users various degrees of freedom for putting the findings together individually while always allowing them to be compared. The core component of the web-based application is the open-source, freely available MongoDB Community Server [167], which, conforming to the Representational State Transfer (REST) paradigm [168], enables reliable, high-performance communication between computer systems. This means that information from the database can be directly integrated into any external computer or mapping system, without being downloaded separately. The data are thus fully

Table 8
Potential impact of mobilisable biomethane potential in transport sector, 2015 (based on [159]).

(Sub-)Sector	Total final consumption in PJ	Possible impact of mobilisable biomethane potential in %
Transport, total	2.621	4–9
Road transport, total	2.191	5–11
Road transport, passenger, total	1.525	7–15
Road transport, passenger, cars	*1.490*	*7–16*
Road transport, passenger, public transport	*35*	*310–675*
Road transport, goods, total	681	16–35
Rail transport, total	54	201–437
Aviation, total	362	30–65
Coast and inland waterways, total	13	834–1,817
Maritime bunkering for seagoing ships	101	107–234

accessible, open and can be used under Creative Common Licence CC BY 2.0 [169] ubiquitously.

4. Conclusion

With its twelve modules, the monitoring system represents an internationally applicable and regulary updatable measuring instrument for calculating the supply and use of a large number of biogenic residues, by-products and wastes across multiple sectors. The system not only identifies the most relevant resources, but also quantifies the impact of a potential use.

For the case example of Germany, it was shown that the share of renewable sources of energy can be increased by up to 18%, depending significantly on four biomass types: cereal straw, cattle liquid manure, cattle solid manure and green waste. If these raw materials were made available as biomethane, bio-CNG or bio-LNG in the transport sector, for example, considerable quantities of fossil fuels could be substituted for buses, locomotives, inland waterway or sea-going vessels. At least from resource perspective, the possible proportions are in all cases far above 100%. In the future, further examples with other application contexts will have to be provided to moderate the discussion on the allocation of raw materials in a more convenient way. Based on that, mobilisation strategies can be developed as a matter of priority.

At the same time, the monitoring system, e.g. for logging residues (deciduous), shows that under certain conditions the use of the resource is higher than the supply. The monitoring system functions as a transparent tool to record the status quo for a consistent time reference. On the one hand, the use of raw materials can be better controlled on this basis. On the other hand, research activities can be focused on e.g. uncertain calculation elements. Thus the data quality for the most relevant resources can be substantially increased. The sustainable use of biogenic resources can be observed more precisely, which represents a decisive support for political or entrepreneurial strategy development.

To make the calculation of biomass potential internationally more comparable, conditions must be defined in terms of content and technology. These include, for example, minimum requirements for the calculation methodology and a uniform coding system for the provision and use of findings across various studies. For further discussion, the presented geocode and calculation flowcharts offer compact options to clearly describe biomasses and to document their calculation methods. This basic working structure can be used to carry out further inter-institutional work on developing the calculation method, possibly leading to a single international standard (e.g. an ISO standard). Without binding standards such as that used for life-cycle assessment (ISO 14064, [170]), future calculations of biomass potentials will remain inconsistent from one study to the next, making it extremely complicated to factually assess whether goals, such as certain SDGs, can be achieved. Introducing a global standard would thus be an important next step towards improving the assessment of possible actions aimed at the sustainable use of biogenic residues, by-products and wastes.

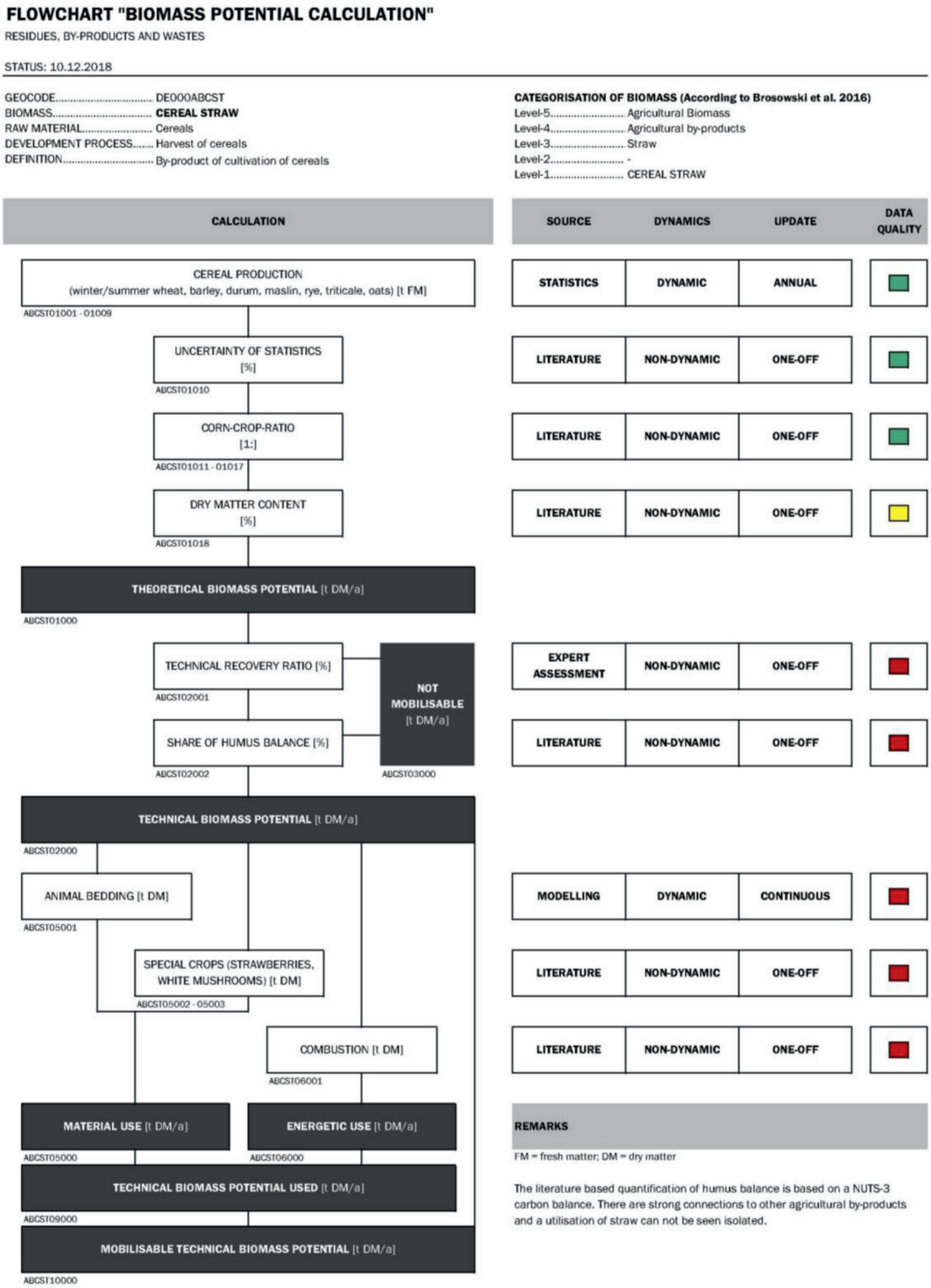
Among other things, binding standards also enable institutional knowledge to be continuously consolidated. When digital, sufficiently documented data interfaces are provided, it is, for example, possible for computer systems to communicate, allowing fundamental information to be provided automatically on a regular basis. Taking the example of Germany, the work presented here shows that these technological possibilities are not yet of significance. However, if digital interfaces are consolidated (such as statistics, research data, basic data), important questions on the resource basis can be answered in a structured manner using the latest data available. One question which remains unanswered here is the theme and the concept an international project of this kind would take up, and the technical standards it would involve. This work proposes a specific answer to that question based on the example of Germany, and suggests numerous ways in which it could be linked to international use or further development.

Acknowledgements

These findings were established as part of the project “Working Group Biomass Potential of Residues in Germany” [FKZ 22019215]. The project was funded by the Federal Ministry of Food and Agriculture under its funding programme “Renewable Resources”. Special thanks go to the Fachagentur Nachwachsende Rohstoffe e.V. (FNR) for their intensive support throughout the project.

Annex_A. Calculation flowchart for cereal straw

At the top there is general information to clearly describe the biomass. On the left side, the methodical link between the calculation elements (Section 2.2) and the key items of information (Section 2.3) is shown graphically. The respective geocode and the units of measurement are also included (Section 2.6). On the right side there is information on the clusters of data sources and their dynamics (Section 2.2) as well as on data quality (Section 2.4). The remaining 76 flowcharts are online available at http://webapp.dbfz.de/resources.



FLOWCHART "BIOMASS POTENTIAL CALCULATION"
RESIDUES, BY-PRODUCTS AND WASTES

STATUS: 10.12.2018

GEOCODE.................................. DE000ABCST
BIOMASS.................................. **CEREAL STRAW**
RAW MATERIAL........................ Cereals
DEVELOPMENT PROCESS....... Harvest of cereals
DEFINITION.............................. By-product of cultivation of cereals

CATEGORISATION OF BIOMASS (According to Brosowski et al. 2016)
Level-5.......................... Agricultural Biomass
Level-4.......................... Agricultural by-products
Level-3.......................... Straw
Level-2.......................... -
Level-1.......................... CEREAL STRAW

REMARKS

FM = fresh matter; DM = dry matter

The literature based quantification of humus balance is based on a NUTS-3 carbon balance. There are strong connections to other agricultural by-products and a utilisation of straw can not be seen isolated.

Annex_B. Data table 1/2 (geocode, biomass, time reference, data quality)

No.	Geocode	Biomass categorisation (based on Brosowski et al. [4])		Reference	Data quality
		Level-1	Level-4	Time	
1	DE000ABDIG	Digestate	Agricultural by-products	2015	1.0

2	DE000ABVEG	By-products from vegetable gardening	Agricultural by-products	2015	1.3
3	DE000ABCOC	Corn cobs	Agricultural by-products	2015	1.2
4	DE000ABSBL	Beet leaves	Agricultural by-products	2015	1.4
5	DE000ABPOL	Potatoe leaves	Agricultural by-products	2015	1.4
6	DE000ABCST	Cereal Straw	Agricultural by-products	2015	1.5
7	DE000ABRST	Rapeseed straw	Agricultural by-products	2015	1.5
8	DE000ABSST	Sunflower straw	Agricultural by-products	2015	1.4
9	DE000ABMST	Grain corn straw	Agricultural by-products	2015	1.4
10	DE000ABLST	Grain legumes straw	Agricultural by-products	2015	1.6
11	DE000ABCLM	Cattle liquid manure	Agricultural by-products	2015	1.0
12	DE000ABCAS	Cattle slurry	Agricultural by-products	2015	1.0
13	DE000ABPLM	Pig liquid manure	Agricultural by-products	2015	1.1
14	DE000ABPIS	Pig slurry	Agricultural by-products	2015	1.2
15	DE000ABCHL	Chicken liquid manure	Agricultural by-products	2015	1.2
16	DE000ABCSM	Cattle solid manure	Agricultural by-products	2015	0.9
17	DE000ABPSM	Pig solid manure	Agricultural by-products	2015	1.2
18	DE000ABCHM	Chicken solid manure	Agricultural by-products	2015	1.1
19	DE000ABHOM	Horse manure	Agricultural by-products	2015	1.1
20	DE000ABSHM	Sheep manure	Agricultural by-products	2015	1.0
21	DE000ABGOM	Goat manure	Agricultural by-products	2015	1.0
22	DE000ABPOM	Poultry manure (others)	Agricultural by-products	2015	1.1
23	DE000FRLRC	Logging residues (coniferous)	Forestry by-products	2015	1.5
24	DE000FRLRD	Logging residues (deciduous)	Forestry by-products	2015	1.5
25	DE000FRBAR	Bark	Forestry by-products	2015	1.9
26	DE000FRBWP	By products of wood processing industries and wood shavings	Forestry by-products	2015	2.0
27	DE000FRBLL	Black liquor	Forestry by-products	2015	2.0
28	DE000FRIWW	Other industrial waste wood	Forestry by-products	2015	2.0
29	DE000FRWAW	Waste wood	Forestry by-products	2015	2.0
30	DE000WMBIO	Bio waste from private households	Municipal waste and sewage sludge	2015	1.6
31	DE000WMGAW	Green waste	Municipal waste and sewage sludge	2015	1.5
32	DE000WMTEX	Biogenic share of old textiles	Municipal waste and sewage sludge	2015	1.9
33	DE000WMPAP	Waste paper	Municipal waste and sewage sludge	2015	1.3
34	DE000WMPCO	Cooking oil and fats from private households	Municipal waste and sewage sludge	2015	1.6
35	DE000WMCFW	Commercial food waste	Municipal waste and sewage sludge	2015	1.3
36	DE000WMKCW	Kitchen and canteen wastes	Municipal waste and sewage sludge	2015	1.4
37	DE000WMLEA	Leaves	Municipal waste and sewage sludge	2015	0.9
38	DE000WMSTR	Biogenic share of road sweepings	Municipal waste and sewage sludge	2015	0.6
39	DE000WMCHA	Biogenic share of sewer sludge, grit slurry and grit chambers	Municipal waste and sewage sludge	2015	1.3
40	DE000WMSSF	Sewage sludge from food processing industries	Municipal waste and sewage sludge	2015	1.6
41	DE000WMSSP	Sludges from pulp, leather and textile industries	Municipal waste and sewage sludge	2015	1.7
42	DE000WMSSM	Sewage sludge from public wastewater treatment plants	Municipal waste and sewage sludge	2015	2.0
43	DE000WMBSS	Biogenic share of waste water of anaerobic treatment	Municipal waste and sewage sludge	2015	1.0
44	DE000WIMEA	Residues from meat processing	Industrial residues	2015	1.1
45	DE000WIFIS	Resiudes from fish processing	Industrial residues	2015	1.4
46	DE000WIFRU	Residues from fruits processing	Industrial residues	2015	0.4
47	DE000WIVEP	Residues from vegetable processing	Industrial residues	2015	0.4
48	DE000WIPOP	Residues from potatoe processing	Industrial residues	2015	1.3
49	DE000WIOIM	Residues from oil mills	Industrial residues	2015	1.4
50	DE000WIMIL	Residues from milk processing	Industrial residues	2015	1.5
51	DE000WICER	Residues from cereal processing	Industrial residues	2015	1.6
52	DE000WISTA	Residues from starch production	Industrial residues	2015	1.7
53	DE000WIBRE	Residues from bread and bakery production	Industrial residues	2015	0.8
54	DE000WIBRW	Residues from breweries	Industrial residues	2015	1.2
55	DE000WIMAL	Residues from malting	Industrial residues	2015	1.3
56	DE000WIDIS	Residues from distilleries	Industrial residues	2015	0.6
57	DE000WIWIN	Residues from winemaking	Industrial residues	2015	1.1
58	DE000WISUG	Residues from sugar production	Industrial residues	2015	1.9
59	DE000WICAC	Residues from cacao produktion	Industrial residues	2015	1.0
60	DE000WIREM	Residues from production of ready-made meals	Industrial residues	2015	0.3
61	DE000WICOF	Residues from coffee production	Industrial residues	2015	1.2
62	DE000WIFOD	Residues from fodder industry	Industrial residues	2015	0.8
63	DE000WITOB	Residues from tobacco processing	Industrial residues	2015	1.1
64	DE000WIYEA	Residues from yeast production	Industrial residues	2015	0.6
65	DE000WIETH	Residues from bioethanol production	Industrial residues	2015	1.0
66	DE000WIGLY	Glycerol from biodiesel production	Industrial residues	2015	1.4
67	DE000WASLM	Stalks from landscape management	Residues from other areas	2015	0.4
68	DE000WAPRU	Wooden materials from landscape management	Residues from other areas	2015	0.6
69	DE000WASRS	Stalks from roadside greenery	Residues from other areas	2015	0.9
70	DE000WAPRS	Woody biomass from roadside greenary	Residues from other areas	2015	0.7
71	DE000WASRR	Railway lineside stalks	Residues from other areas	2015	0.7
72	DE000WAPRR	Railway lineside wood	Residues from other areas	2015	0.7
73	DE000WASOR	Stalks from orchards	Residues from other areas	2015	0.5
74	DE000WAPRO	Woody biomass from orchards	Residues from other areas	2015	0.5
75	DE000WASVI	Stalks from vineyards	Residues from other areas	2015	0.5
76	DE000WAPRV	Woody biomass from vineyards	Residues from other areas	2015	0.5
77	DE000WAWAT	Driftwood	Residues from other areas	2015	0.0

Annex_C. Data table 2/2 (min./max., unit, key items of information)

No.	Reference		Key item of information									
	Min./Max.	Unit	01	02	03	04	05	06	07	08	09	10
1	MIN	t_DM	13,502,253	0	13,502,253	0	0	0	0	0	0	0
1	MIN	PJ_BM_T	9	0	9	0	0	0	0	0	0	0
1	MAX	t_DM	13,502,253	0	13,502,253	0	0	0	0	0	0	0
1	MAX	PJ_BM_T	18	0	18	0	0	0	0	0	0	0
2	MIN	t_DM	285,184	0	285,184	0	0	0	0	0	0	0
2	MIN	PJ_BM_T	6	0	6	0	0	0	0	0	0	0
2	MAX	t_DM	412,118	0	412,118	0	0	0	0	0	0	0
2	MAX	PJ_BM_T	3	0	3	0	0	0	0	0	0	0
3	MIN	t_DM	99,285	0	99,285	0	0	0	0	0	0	0
3	MIN	PJ_BM_T	0	0	0	0	0	0	0	0	0	0
3	MAX	t_DM	245,174	0	245,174	0	0	0	0	0	0	0
3	MAX	PJ_BM_T	1	0	1	0	0	0	0	0	0	0
4	MIN	t_DM	2,477,503	0	2,477,503	0	0	0	0	0	0	0
4	MIN	PJ_BM_T	25	0	25	0	0	0	0	0	0	0
4	MAX	t_DM	3,223,282	0	3,223,282	0	0	0	0	0	0	0
4	MAX	PJ_BM_T	26	0	26	0	0	0	0	0	0	0
5	MIN	t_DM	264,233	0	264,233	0	0	0	0	0	0	0
5	MIN	PJ_BM_T	2	0	2	0	0	0	0	0	0	0
5	MAX	t_DM	359,639	0	359,639	0	0	0	0	0	0	0
5	MAX	PJ_BM_T	2	0	2	0	0	0	0	0	0	0
6	MIN	t_DM	29,413,381	7,706,306	21,707,075	0	3,308,611	90,000	0	0	3,398,611	4,307,694
6	MIN	PJ_BM_T	154	40	114	0	17	0	0	0	18	23
6	MAX	t_DM	32,071,733	14,512,459	17,559,274	0	5,128,916	90,000	0	0	5,218,916	9,293,543
6	MAX	PJ_BM_T	233	105	128	0	37	1	0	0	38	68
7	MIN	t_DM	7,020,711	0	7,020,711	0	0	0	0	0	0	0
7	MIN	PJ_BM_T	29	0	29	0	0	0	0	0	0	0
7	MAX	t_DM	7,655,235	0	7,655,235	0	0	0	0	0	0	0
7	MAX	PJ_BM_T	30	0	30	0	0	0	0	0	0	0
8	MIN	t_DM	58,118	0	58,118	0	0	0	0	0	0	0
8	MIN	PJ_BM_T	0	0	0	0	0	0	0	0	0	0
8	MAX	t_DM	63,371	0	63,371	0	0	0	0	0	0	0
8	MAX	PJ_BM_T	0	0	0	0	0	0	0	0	0	0
9	MIN	t_DM	3,270,574	0	3,270,574	0	0	0	0	0	0	0
9	MIN	PJ_BM_T	17	0	17	0	0	0	0	0	0	0
9	MAX	t_DM	3,566,165	0	3,566,165	0	0	0	0	0	0	0
9	MAX	PJ_BM_T	26	0	26	0	0	0	0	0	0	0
10	MIN	t_DM	369,041	0	369,041	0	0	0	0	0	0	0
10	MIN	PJ_BM_T	2	0	2	0	0	0	0	0	0	0
10	MAX	t_DM	402,394	0	402,394	0	0	0	0	0	0	0
10	MAX	PJ_BM_T	3	0	3	0	0	0	0	0	0	0
11	MIN	t_DM	5,221,012	2,998,732	2,222,280	0	0	139,153	0	0	139,153	2,859,580
11	MIN	PJ_BM_T	51	29	22	0	0	1	0	0	1	28
11	MAX	t_DM	15,061,069	8,704,271	6,356,798	0	0	347,882	0	0	347,882	8,356,389
11	MAX	PJ_BM_T	100	58	42	0	0	2	0	0	2	56
12	MIN	t_DM	359,562	82,285	277,277	0	0	0	0	82,285	82,285	0
12	MIN	PJ_BM_T	14	3	11	0	0	0	0	3	3	0
12	MAX	t_DM	1,383,962	302,998	1,080,964	0	0	0	0	302,998	302,998	0
12	MAX	PJ_BM_T	31	7	24	0	0	0	0	7	7	0
13	MIN	t_DM	744,256	672,659	71,597	0	0	408,336	0	0	408,336	264,322
13	MIN	PJ_BM_T	8	7	1	0	0	4	0	0	4	3
13	MAX	t_DM	1,826,096	1,654,902	171,194	0	0	816,673	0	0	816,673	838,229
13	MAX	PJ_BM_T	10	9	1	0	0	4	0	0	4	5
14	MIN	t_DM	69,905	6,224	63,681	0	0	0	0	6,224	6,224	0
14	MIN	PJ_BM_T	3	0	3	0	0	0	0	0	0	0
14	MAX	t_DM	265,037	23,279	241,758	0	0	0	0	23,279	23,279	0
14	MAX	PJ_BM_T	4	0	4	0	0	0	0	0	0	0
15	MIN	t_DM	858,785	85,879	772,907	0	0	0	0	85,879	85,879	0
15	MIN	PJ_BM_T	2	0	2	0	0	0	0	0	0	0
15	MAX	t_DM	1,340,756	134,076	1,206,681	0	0	0	0	134,076	134,076	0
15	MAX	PJ_BM_T	2	0	2	0	0	0	0	0	0	0
16	MIN	t_DM	18,231,275	4,065,399	14,165,875	0	0	862,568	0	0	862,568	3,202,831
16	MIN	PJ_BM_T	159	35	123	0	0	8	0	0	8	28
16	MAX	t_DM	35,699,056	8,224,026	27,475,031	0	0	1,293,852	0	0	1,293,852	6,930,174
16	MAX	PJ_BM_T	209	48	161	0	0	8	0	0	8	41
17	MIN	t_DM	3,015,449	296,155	2,719,295	0	0	28,349	0	0	28,349	267,806
17	MIN	PJ_BM_T	24	2	21	0	0	0	0	0	0	2
17	MAX	t_DM	5,677,925	538,519	5,139,406	0	0	42,523	0	0	42,523	495,996
17	MAX	PJ_BM_T	30	3	27	0	0	0	0	0	0	3
18	MIN	t_DM	591,408	507,049	84,360	0	0	292,041	0	0	292,041	215,008
18	MIN	PJ_BM_T	1	1	0	0	0	1	0	0	1	0
18	MAX	t_DM	782,170	670,236	111,934	0	0	350,449	0	0	350,449	319,787
18	MAX	PJ_BM_T	1	1	0	0	0	1	0	0	1	1
19	MIN	t_DM	1,975,437	67,347	1,908,090	0	0	67,347	0	0	67,347	0

19	MIN	PJ_BM_T	14	0	13	0	0	0	0	0	0	0
19	MAX	t_DM	2,785,961	94,286	2,691,675	0	0	94,286	0	0	94,286	0
19	MAX	PJ_BM_T	14	0	14	0	0	0	0	0	0	0
20	MIN	t_DM	236,958	27,709	209,249	0	0	27,709	0	0	27,709	0
20	MIN	PJ_BM_T	2	0	2	0	0	0	0	0	0	0
20	MAX	t_DM	345,282	38,868	306,413	0	0	38,868	0	0	38,868	0
20	MAX	PJ_BM_T	2	0	2	0	0	0	0	0	0	0
21	MIN	t_DM	15,486	2,125	13,361	0	0	2,125	0	0	2,125	0
21	MIN	PJ_BM_T	0	0	0	0	0	0	0	0	0	0
21	MAX	t_DM	22,843	2,899	19,944	0	0	2,899	0	0	2,899	0
21	MAX	PJ_BM_T	0	0	0	0	0	0	0	0	0	0
22	MIN	t_DM	112,509	15,376	97,133	0	0	0	0	15,376	15,376	0
22	MIN	PJ_BM_T	1	0	1	0	0	0	0	0	0	0
22	MAX	t_DM	231,694	31,665	200,029	0	0	0	0	31,665	31,665	0
22	MAX	PJ_BM_T	1	0	1	0	0	0	0	0	0	0
23	MIN	t_DM	28,012,665	2,051,367	25,961,297	0	85,772	1,547,557	0	0	1,633,329	418,038
23	MIN	PJ_BM_T	N	N	N	N	N	N	N	N	N	N
23	MAX	t_DM	35,702,452	9,243,365	26,459,087	0	85,772	1,547,557	0	0	1,633,329	7,610,036
23	MAX	PJ_BM_T	N	N	N	N	N	N	N	N	N	N
24	MIN	t_DM	13,525,115	1,070,378	12,454,738	0	21,966	2,248,377	0	0	2,270,343	−1,199,965
24	MIN	PJ_BM_T	N	N	N	N	N	N	N	N	N	N
24	MAX	t_DM	19,610,236	5,580,681	14,029,555	0	21,966	2,248,377	0	0	2,270,343	3,310,338
24	MAX	PJ_BM_T	N	N	N	N	N	N	N	N	N	N
25	MIN	t_DM	3,661,920	2,076,480	1,585,440	0	1,514,880	561,600	0	0	2,076,480	0
25	MIN	PJ_BM_T	N	N	N	N	N	N	N	N	N	N
25	MAX	t_DM	4,851,360	2,076,480	2,774,880	0	1,514,880	561,600	0	0	2,076,480	0
25	MAX	PJ_BM_T	N	N	N	N	N	N	N	N	N	N
26	MIN	t_DM	8,236,800	8,236,800	0	0	4,820,160	3,416,640	0	0	8,236,800	0
26	MIN	PJ_BM_T	N	N	N	N	N	N	N	N	N	N
26	MAX	t_DM	8,236,800	8,236,800	0	0	4,820,160	3,416,640	0	0	8,236,800	0
26	MAX	PJ_BM_T	N	N	N	N	N	N	N	N	N	N
27	MIN	t_DM	1,897,000	1,897,000	0	0	0	1,897,000	0	0	1,897,000	0
27	MIN	PJ_BM_T	N	N	N	N	N	N	N	N	N	N
27	MAX	t_DM	1,897,000	1,897,000	0	0	0	1,897,000	0	0	1,897,000	0
27	MAX	PJ_BM_T	N	N	N	N	N	N	N	N	N	N
28	MIN	t_DM	2,635,412	2,635,412	0	0	144,671	1,114,840	0	1,375,901	2,635,412	0
28	MIN	PJ_BM_T	N	N	N	N	N	N	N	N	N	N
28	MAX	t_DM	2,635,412	2,635,412	0	0	144,671	1,114,840	0	1,375,901	2,635,412	0
28	MAX	PJ_BM_T	N	N	N	N	N	N	N	N	N	N
29	MIN	t_DM	6,923,000	6,923,000	0	0	855,000	5,836,000	0	232,000	6,923,000	0
29	MIN	PJ_BM_T	N	N	N	N	N	N	N	N	N	N
29	MAX	t_DM	6,923,000	6,923,000	0	0	855,000	5,836,000	0	232,000	6,923,000	0
29	MAX	PJ_BM_T	N	N	N	N	N	N	N	N	N	N
30	MIN	t_DM	1,557,284	1,530,718	26,566	0	524,136	636,604	109,103	23,614	1,293,456	237,262
30	MIN	PJ_BM_T	13	12	0	0	4	5	1	0	10	2
30	MAX	t_DM	4,213,801	4,204,945	8,855	0	1,001,412	1,989,167	271,258	70,842	3,332,679	872,266
30	MAX	PJ_BM_T	25	25	0	0	6	12	2	0	20	5
31	MIN	t_DM	7,927,879	7,808,425	119,453	0	3,638,620	1,408,032	402,717	39,818	5,489,188	2,319,238
31	MIN	PJ_BM_T	33	32	0	0	15	6	2	0	23	10
31	MAX	t_DM	13,143,588	13,103,771	39,818	0	5,775,693	2,115,827	783,862	119,453	8,794,835	4,308,935
31	MAX	PJ_BM_T	48	48	0	0	21	8	3	0	32	16
32	MIN	t_DM	314,087	314,087	0	0	284,613	24,749	0	0	309,362	4,724
32	MIN	PJ_BM_T	N	N	N	N	N	N	N	N	N	N
32	MAX	t_DM	843,195	843,195	0	0	318,097	27,661	0	0	345,758	497,437
32	MAX	PJ_BM_T	N	N	N	N	N	N	N	N	N	N
33	MIN	t_DM	13,253,484	13,253,484	0	0	12,580,292	117,928	2,285	452,527	13,153,032	100,452
33	MIN	PJ_BM_T	N	N	N	N	N	N	N	N	N	N
33	MAX	t_DM	19,387,136	19,387,136	0	0	15,044,249	3,156,753	223,896	72,252	18,497,150	889,986
33	MAX	PJ_BM_T	N	N	N	N	N	N	N	N	N	N
34	MIN	t_DM	245,524	245,524	0	0	0	62	0	11	73	245,451
34	MIN	PJ_BM_T	4	4	0	0	0	0	0	0	0	4
34	MAX	t_DM	409,158	409,158	0	0	0	69	0	4	73	409,085
34	MAX	PJ_BM_T	12	12	0	0	0	0	0	0	0	12
35	MIN	t_DM	55,020	50,068	4,952	0	18,500	10,673	17,225	1,001	47,400	2,668
35	MIN	PJ_BM_T	1	1	0	0	0	0	0	0	1	0
35	MAX	t_DM	110,040	108,389	1,651	0	37,000	24,349	34,450	6,503	102,302	6,087
35	MAX	PJ_BM_T	9	9	0	0	3	2	3	1	8	0
36	MIN	t_DM	375,500	349,848	25,652	0	1,749	173,920	139,939	6,997	322,605	27,242
36	MIN	PJ_BM_T	3	2	0	0	0	1	1	0	2	0
36	MAX	t_DM	802,400	793,849	8,551	0	3,969	177,472	317,540	47,631	546,612	247,237
36	MAX	PJ_BM_T	32	32	0	0	0	7	13	2	22	10
37	MIN	t_DM	128,648	110,694	17,954	0	27,197	9,315	0	4,428	40,940	69,754
37	MIN	PJ_BM_T	0	0	0	0	0	0	0	0	0	0
37	MAX	t_DM	358,508	352,524	5,985	0	69,333	29,239	0	42,303	140,875	211,649
37	MAX	PJ_BM_T	0	0	0	0	0	0	0	0	0	0
38	MIN	t_DM	15,180	12,903	2,277	0	6,742	5,516	0	645	12,903	0
38	MIN	PJ_BM_T	0	0	0	0	0	0	0	0	0	0
38	MAX	t_DM	88,550	87,791	759	0	41,042	33,580	0	13,169	87,791	0
38	MAX	PJ_BM_T	0	0	0	0	0	0	0	0	0	0
39	MIN	t_DM	8,421	5,843	2,578	0	1,753	2,156	0	865	4,774	1,069

39	MIN	PJ_BM_T	N	N	N	N	N	N	N	N	N	N
39	MAX	t_DM	155,553	154,694	859	0	46,408	57,082	0	22,895	126,385	28,309
39	MAX	PJ_BM_T	N	N	N	N	N	N	N	N	N	N
40	MIN	t_DM	8,404	8,404	0	0	3,026	5,379	0	0	8,404	0
40	MIN	PJ_BM_T	0	0	0	0	0	0	0	0	0	0
40	MAX	t_DM	20,544	20,544	0	0	7,396	13,148	0	0	20,544	0
40	MAX	PJ_BM_T	0	0	0	0	0	0	0	0	0	0
41	MIN	t_DM	514	514	0	0	0	514	0	0	514	0
41	MIN	PJ_BM_T	0	0	0	0	0	0	0	0	0	0
41	MAX	t_DM	1,256	1,256	0	0	0	1,256	0	0	1,256	0
41	MAX	PJ_BM_T	0	0	0	0	0	0	0	0	0	0
42	MIN	t_DM	811,389	811,389	0	0	293,135	518,255	0	0	811,389	0
42	MIN	PJ_BM_T	13	13	0	0	5	8	0	0	13	0
42	MAX	t_DM	991,698	991,698	0	0	358,276	633,422	0	0	991,698	0
42	MAX	PJ_BM_T	8	8	0	0	3	5	0	0	8	0
43	MIN	t_DM	1,723,861	1,503,542	220,318	0	0	943,715	0	0	943,715	559,828
43	MIN	PJ_BM_T	27	24	3	0	0	15	0	0	15	9
43	MAX	t_DM	4,283,611	4,136,733	146,879	0	0	1,516,685	0	0	1,516,685	2,620,048
43	MAX	PJ_BM_T	34	33	1	0	0	12	0	0	12	21
44	MIN	t_DM	1,255,738	1,243,181	12,557	0	786,216	453,182	0	3,783	1,243,181	0
44	MIN	PJ_BM_T	4	4	0	0	2	1	0	0	4	0
44	MAX	t_DM	1,255,738	1,243,181	12,557	0	786,216	453,182	0	3,783	1,243,181	0
44	MAX	PJ_BM_T	4	4	0	0	2	1	0	0	4	0
45	MIN	t_DM	78,648	62,918	15,730	0	62,918	0	0	0	62,918	0
45	MIN	PJ_BM_T	1	1	0	0	1	0	0	0	1	0
45	MAX	t_DM	163,784	162,146	1,638	0	76,592	0	0	85,554	162,146	0
45	MAX	PJ_BM_T	1	1	0	0	1	0	0	1	1	0
46	MIN	t_DM	20,806	20,390	416	0	12,234	8,156	0	0	20,390	0
46	MIN	PJ_BM_T	0	0	0	0	0	0	0	0	0	0
46	MAX	t_DM	20,806	20,390	416	0	12,234	8,156	0	0	20,390	0
46	MAX	PJ_BM_T	0	0	0	0	0	0	0	0	0	0
47	MIN	t_DM	37,901	37,143	758	0	27,857	9,286	0	0	37,143	0
47	MIN	PJ_BM_T	0	0	0	0	0	0	0	0	0	0
47	MAX	t_DM	37,901	37,143	758	0	27,857	9,286	0	0	37,143	0
47	MAX	PJ_BM_T	1	1	0	0	1	0	0	0	1	0
48	MIN	t_DM	87,741	85,986	1,755	0	64,489	21,496	0	0	85,986	0
48	MIN	PJ_BM_T	0	0	0	0	0	0	0	0	0	0
48	MAX	t_DM	87,741	85,986	1,755	0	64,489	21,496	0	0	85,986	0
48	MAX	PJ_BM_T	0	0	0	0	0	0	0	0	0	0
49	MIN	t_DM	7,252,080	7,252,080	0	0	7,252,080	0	0	0	7,252,080	0
49	MIN	PJ_BM_T	80	80	0	0	80	0	0	0	80	0
49	MAX	t_DM	7,252,080	7,252,080	0	0	7,252,080	0	0	0	7,252,080	0
49	MAX	PJ_BM_T	107	107	0	0	107	0	0	0	107	0
50	MIN	t_DM	558,800	547,624	11,176	0	512,106	0	0	35,518	547,624	0
50	MIN	PJ_BM_T	0	0	0	0	0	0	0	0	0	0
50	MAX	t_DM	558,800	547,624	11,176	0	512,106	0	0	35,518	547,624	0
50	MAX	PJ_BM_T	11	11	0	0	10	0	0	1	11	0
51	MIN	t_DM	1,439,659	1,410,866	28,793	0	1,297,182	78,264	0	35,421	1,410,866	0
51	MIN	PJ_BM_T	13	13	0	0	12	1	0	0	13	0
51	MAX	t_DM	1,439,659	1,410,866	28,793	0	1,297,182	78,264	0	35,421	1,410,866	0
51	MAX	PJ_BM_T	15	15	0	0	14	1	0	0	15	0
52	MIN	t_DM	382,317	374,670	7,646	0	313,750	0	0	60,920	374,670	0
52	MIN	PJ_BM_T	1	1	0	0	0	0	0	0	1	0
52	MAX	t_DM	382,317	374,670	7,646	0	313,750	0	0	60,920	374,670	0
52	MAX	PJ_BM_T	1	1	0	0	0	0	0	0	1	0
53	MIN	t_DM	163,488	155,313	8,174	0	119,591	26,403	0	9,319	155,313	0
53	MIN	PJ_BM_T	3	3	0	0	3	1	0	0	3	0
53	MAX	t_DM	761,063	761,063	0	0	586,018	129,381	0	45,664	761,063	0
53	MAX	PJ_BM_T	10	10	0	0	8	2	0	1	10	0
54	MIN	t_DM	468,027	463,347	4,680	0	242,000	92,631	0	128,715	463,347	0
54	MIN	PJ_BM_T	5	5	0	0	3	1	0	1	5	0
54	MAX	t_DM	468,027	463,347	4,680	0	242,000	92,631	0	128,715	463,347	0
54	MAX	PJ_BM_T	1	1	0	0	1	0	0	0	1	0
55	MIN	t_DM	87,541	86,666	875	0	66,012	5,444	0	15,210	86,666	0
55	MIN	PJ_BM_T	1	1	0	0	1	0	0	0	1	0
55	MAX	t_DM	87,541	86,666	875	0	66,012	5,444	0	15,210	86,666	0
55	MAX	PJ_BM_T	1	1	0	0	1	0	0	0	1	0
56	MIN	t_DM	28,297	27,731	566	0	19,411	8,319	0	0	27,731	0
56	MIN	PJ_BM_T	0	0	0	0	0	0	0	0	0	0
56	MAX	t_DM	28,297	27,731	566	0	19,411	8,319	0	0	27,731	0
56	MAX	PJ_BM_T	1	1	0	0	1	0	0	0	1	0
57	MIN	t_DM	111,095	108,874	2,222	0	108,874	0	0	0	108,874	0
57	MIN	PJ_BM_T	1	1	0	0	1	0	0	0	1	0
57	MAX	t_DM	111,095	108,874	2,222	0	108,874	0	0	0	108,874	0
57	MAX	PJ_BM_T	4	4	0	0	4	0	0	0	4	0
58	MIN	t_DM	1,844,521	1,844,521	0	0	1,825,096	0	0	19,426	1,844,521	0
58	MIN	PJ_BM_T	17	17	0	0	17	0	0	0	17	0
58	MAX	t_DM	1,844,521	1,844,521	0	0	1,825,096	0	0	19,426	1,844,521	0
58	MAX	PJ_BM_T	22	22	0	0	21	0	0	0	22	0
59	MIN	t_DM	33,868	32,174	1,693	0	0	32,174	0	0	32,174	0

59	MIN	PJ_BM_T	0	0	0	0	0	0	0	0	0	0
59	MAX	t_DM	57,111	57,111	0	0	11,422	45,689	0	0	57,111	0
59	MAX	PJ_BM_T	1	1	0	0	0	0	0	0	1	0
60	MIN	t_DM	4,977	4,927	50	0	0	0	0	4,927	4,927	0
60	MIN	PJ_BM_T	0	0	0	0	0	0	0	0	0	0
60	MAX	t_DM	14,931	14,782	149	0	0	0	0	14,782	14,782	0
60	MAX	PJ_BM_T	0	0	0	0	0	0	0	0	0	0
61	MIN	t_DM	42,013	41,173	840	0	0	41,173	0	0	41,173	0
61	MIN	PJ_BM_T	0	0	0	0	0	0	0	0	0	0
61	MAX	t_DM	42,013	41,173	840	0	0	41,173	0	0	41,173	0
61	MAX	PJ_BM_T	0	0	0	0	0	0	0	0	0	0
62	MIN	t_DM	98	97	1	0	49	49	0	0	97	0
62	MIN	PJ_BM_T	0	0	0	0	0	0	0	0	0	0
62	MAX	t_DM	98,008	97,027	980	0	48,514	48,514	0	0	97,027	0
62	MAX	PJ_BM_T	1	1	0	0	0	0	0	0	1	0
63	MIN	t_DM	5,416	5,416	0	0	0	0	0	5,416	5,416	0
63	MIN	PJ_BM_T	N	N	N	N	N	N	N	N	N	N
63	MAX	t_DM	5,416	5,416	0	0	0	0	0	5,416	5,416	0
63	MAX	PJ_BM_T	N	N	N	N	N	N	N	N	N	N
64	MIN	t_DM	254,178	252,908	1,271	0	75,872	25,291	0	151,745	252,908	0
64	MIN	PJ_BM_T	0	0	0	0	0	0	0	0	0	0
64	MAX	t_DM	254,178	249,095	5,084	0	74,728	24,909	0	149,457	249,095	0
64	MAX	PJ_BM_T	3	3	0	0	1	0	0	2	3	0
65	MIN	t_DM	825,197	808,693	16,504	0	525,650	202,173	0	80,869	808,693	0
65	MIN	PJ_BM_T	6	6	0	0	4	2	0	1	6	0
65	MAX	t_DM	887,785	883,346	4,439	0	574,175	220,837	0	88,335	883,346	0
65	MAX	PJ_BM_T	33	33	0	0	22	8	0	3	33	0
66	MIN	t_DM	297,386	237,941	59,446	0	0	0	237,941	0	237,941	0
66	MIN	PJ_BM_T	5	4	1	0	0	0	4	0	4	0
66	MAX	t_DM	378,833	303,107	75,726	0	0	0	303,107	0	303,107	0
66	MAX	PJ_BM_T	6	5	1	0	0	0	5	0	5	0
67	MIN	t_DM	493,263	147,979	345,284	0	0	122,963	0	25,016	147,979	0
67	MIN	PJ_BM_T	5	1	3	0	0	1	0	0	1	0
67	MAX	t_DM	2,404,226	1,923,381	480,845	0	0	191,111	0	1,732,270	1,923,381	0
67	MAX	PJ_BM_T	17	14	3	0	0	1	0	13	14	0
68	MIN	t_DM	2,654,280	2,654,280	0	0	0	2,654,280	0	0	2,654,280	0
68	MIN	PJ_BM_T	N	N	N	N	N	N	N	N	N	N
68	MAX	t_DM	4,551,390	3,641,112	910,278	0	0	2,654,280	0	0	2,654,280	986,832
68	MAX	PJ_BM_T	N	N	N	N	N	N	N	N	N	N
69	MIN	t_DM	586,339	167,095	419,244	0	0	0	0	167,095	167,095	0
69	MIN	PJ_BM_T	2	1	1	0	0	0	0	1	1	0
69	MAX	t_DM	1,905,602	950,843	954,760	0	0	0	0	950,843	950,843	0
69	MAX	PJ_BM_T	9	5	5	0	0	0	0	5	5	0
70	MIN	t_DM	26,296	5,259	21,037	0	0	0	0	5,259	5,259	0
70	MIN	PJ_BM_T	N	N	N	N	N	N	N	N	N	N
70	MAX	t_DM	157,017	125,614	31,403	0	0	0	0	125,614	125,614	0
70	MAX	PJ_BM_T	N	N	N	N	N	N	N	N	N	N
71	MIN	t_DM	10,666	1,067	9,600	0	0	0	0	1,067	1,067	0
71	MIN	PJ_BM_T	0	0	0	0	0	0	0	0	0	0
71	MAX	t_DM	194,992	58,498	136,495	0	0	0	0	58,498	58,498	0
71	MAX	PJ_BM_T	1	0	1	0	0	0	0	0	0	0
72	MIN	t_DM	3,200	320	2,880	0	0	0	0	320	320	0
72	MIN	PJ_BM_T	N	N	N	N	N	N	N	N	N	N
72	MAX	t_DM	34,999	10,500	24,499	0	0	0	0	10,500	10,500	0
72	MAX	PJ_BM_T	N	N	N	N	N	N	N	N	N	N
73	MIN	t_DM	76,800	15,360	61,440	0	0	0	0	15,360	15,360	0
73	MIN	PJ_BM_T	1	0	1	0	0	0	0	0	0	0
73	MAX	t_DM	320,000	160,000	160,000	0	0	0	0	160,000	160,000	0
73	MAX	PJ_BM_T	2	1	1	0	0	0	0	1	1	0
74	MIN	t_DM	64,000	12,800	51,200	0	0	0	0	12,800	12,800	0
74	MIN	PJ_BM_T	N	N	N	N	N	N	N	N	N	N
74	MAX	t_DM	224,000	112,000	112,000	0	0	0	0	112,000	112,000	0
74	MAX	PJ_BM_T	N	N	N	N	N	N	N	N	N	N
75	MIN	t_DM	51,291	10,258	41,032	0	0	0	0	10,258	10,258	0
75	MIN	PJ_BM_T	0	0	0	0	0	0	0	0	0	0
75	MAX	t_DM	164,130	82,065	82,065	0	0	0	0	82,065	82,065	0
75	MAX	PJ_BM_T	1	0	0	0	0	0	0	0	0	0
76	MIN	t_DM	102,581	51,291	51,291	0	0	0	0	51,291	51,291	0
76	MIN	PJ_BM_T	N	N	N	N	N	N	N	N	N	N
76	MAX	t_DM	328,259	328,259	0	0	0	0	0	328,259	328,259	0
76	MAX	PJ_BM_T	N	N	N	N	N	N	N	N	N	N
77	MIN	t_DM	20,000	4,000	16,000	0	0	0	0	4,000	4,000	0
77	MIN	PJ_BM_T	N	N	N	N	N	N	N	N	N	N
77	MAX	t_DM	20,000	16,000	4,000	0	0	0	0	16,000	16,000	0
77	MAX	PJ_BM_T	N	N	N	N	N	N	N	N	N	N

t_DM = Mg of dry matter; PJ_BM_T = Petajoule biomethane transport sector; N = not digestable

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#3

Temporal and spatial availability of cereal straw in Germany – Case study: Biomethane for the transport sector

Brosowski, A., Bill, R., Thrän, D.

Energy, Sustainability and Society (2020), 10:42, 1–21

21 P., 76 Lit., 7 Fig., 4 Tab.

Brosowski *et al. Energ Sustain Soc (2020) 10:42*
https://doi.org/10.1186/s13705-020-00274-1

Energy, Sustainability
and Society

ORIGINAL ARTICLE **Open Access**

Temporal and spatial availability of cereal straw in Germany—Case study: Biomethane for the transport sector

André Brosowski[1,2*], Ralf Bill[3] and Daniela Thrän[1,2,4]

Abstract

Background: By 2030, the German transport sector needs to achieve additional greenhouse gas savings of 67 million tonnes CO_2-eq. and further progress requires swiftly implementable solutions. The fermentation of cereal straw is a promising option. Returning the digestate to the farmland can close agricultural cycles while simultaneously producing biomethane. The world's first large-scale, mono-digestion plant for straw is operational since 2014. The temporal and spatial biomass availability is a key issue when replicating this concept. No detailed calculations on this subject are available, and the strategic relevance of biomethane from straw in the transport sector cannot be sufficiently evaluated.

Methods: To assess the balance of straw supply and use, a total of 30 data sets are combined, taking into account the cultivation of the five most important cereal types and the straw required for ten animal species, two special crops and 12 industrial uses. The data are managed at district level and presented for the years 2010 to 2018. In combination with high-resolution geodata, the results are linked to actual arable fields, and the availability of straw throughout the country is evaluated using a GIS.

Results: During the analysis period and based on the assumption that in case of fermentation up to 70% of the straw can be utilised, the mobilisable technical biomass potential for future biomethane production is between 13.9–21.5 Tg fm a^{-1}. The annual potential fluctuates considerably due to weather anomalies. The all-time maximum in 2014 and the minimum for the last 26 years in 2018 are separated by just 4 years and a difference of 7.6 Tg fm. However, large parts of the potential are concentrated only in a few regions and biomethane from straw could provide 57–145 PJ of a low-emission fuel, saving 3–12 Tg CO_2-eq. in case of full exploitation.

Conclusion: Despite the strong fluctuations and high uncertainties, the potential is sufficient to supply numerous plants and to produce relevant quantities of biomethane even in weak years. To unlock the potential, the outcomes should be evaluated and discussed further with stakeholders in the identified priority regions.

Keywords: Biomass potential assessment, Biofuels, Bioeconomy, Substitution, GIS analysis

Background

On 12 December 2019, the European Commission announced that Europe is to become the first climate-neutral continent by 2050 [1]. Since 1990, the international base year, greenhouse gas (GHG) emissions in Germany have been reduced by 30.8% (as of 2018) [2, 3]. However, this level must be at least 55% by 2030. While

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some significant reductions have been achieved in the source groups of households, commerce/trade/the service sector, industry and energy management, the current energy-related emissions in the transport sector are at the same level as in 1990 [2]. The German Climate Protection Act [4], which was introduced on 17 December 2019, thus calls for a GHG reduction of at least 67 Tg CO_2-eq. in this sector [5]. The National Platform on the Future of Mobility [6], a steering group convened by the Federal Ministry of Transport and Digital Infrastructure, is currently discussing three fields with regard to technology: electromobility, hydrogen/fuel cells and alternative fuels for internal combustion engines. The latter include e-fuels and biomass-based fuels, which are capable of reducing GHG emissions even in the existing fleet by 2030. Beyond 2030, there is particularly great potential for use in areas which are difficult to electrify, such as maritime shipping and heavy goods vehicle (HGV) traffic [6]. When it comes to the use of biomass in the transport sector, biomethane, among other things, is proving a promising option for replacing fossil fuels and for significantly reducing GHGs [7–9]. In that context, however, the use of energy crops is viewed critically [6], as so far it is not possible to manage sustainability requirements sufficiently [10]. The latest European and German strategy papers (e.g. the EU Renewable Energy Directive [11], the National Climate Action Plan [3] or the National Bioeconomy Strategy [12]) thus focus clearly on biogenic by-products, residues and wastes.

The difference that can be made in the transport sector depends, inter alia, on the raw materials which are available and how they are specifically used. In mid-2019, Brosowski et al. [13] established a cross-sectoral monitoring system for 77 biogenic by-products, residues and wastes in Germany. This instrument can be employed at national level to assess the balance of raw material supply and use and contextualise the findings. If, for example, all the mobilisable technical biomass potential were used in the transport sector in the form of biomethane, large quantities of fossil fuels could be replaced for individual modes of transport—from the point of view of resources, at least [14]. These include, for example, passenger cars, HGVs or vessels previously powered with gasoline, diesel or heavy oil. Independently of the numerous techno-economic challenges for the use of biomethane (e.g. infrastructure, distribution, engine technology, methane slip, costs, etc. [15–17]), the paper explores the question of which limitations arise from the temporal and spatial biomass availability. The focus was put on cereal straw. Based on residue monitoring, this biomass is considered as the most important biogenic resources that are yet to be mobilised for the future production of biomethane [13]. So far, however, the monitoring system has only published findings for the reference year 2015, and only on national level. However, the annual production of cereal straw is linked to cereal production, and the agricultural production system is subject to temporal and spatial fluctuations. Figure 1 shows how cereal production, acreage and yield have developed over time since 1961. The illustration covers five cereal types—wheat, barley, rye, oats and triticale—which account for around 91% of all cereals (including maize) cultivated in Germany [18].

From 1961 to 2018, a reduction in acreage (− 11%) was offset by a significant increase in yield (+ 149%). During that period, the production volume more than doubled (+ 123%). In the last 20 years, however, considerable annual fluctuations in production of several million

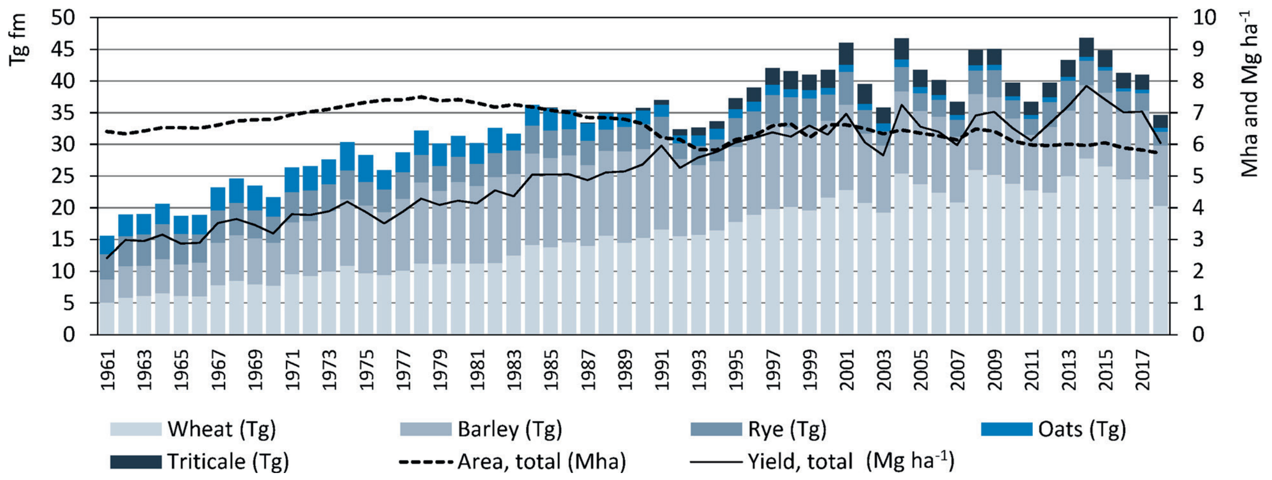

Fig. 1 Development of cereal production in Germany from 1961–2018 (based on [18, 19])

tonnes can be seen. The biggest slumps since 1961 took place in 2002 and 2018. Compared to previous years, the amount harvested dropped by around seven million tonnes. At the same time, these weak years are followed by very strong years. The highest level, almost 11 million tonnes, was in 2004. The second highest, at more than eight million tonnes, was four years later in 2008. These fluctuations are caused, among other things, by weather anomalies. The extremely weak years saw very high rainfall in 2002 [20] followed by a drought with the hottest summer since weather records began in 2003 [21], drought in the spring of 2007 [22], low levels of rain and late frosts in the spring, then heavy rain during the harvest season in 2011 [23], and the second hottest summer with numerous extreme regional values in 2018 [24, 25].

To date, there has not been any sufficient description of how the dynamic interplay of time and space might affect the future use of cereal straw. As a result, the associated risks, especially in connection with its existing use, cannot be adequately assessed. The aim of this article is thus to add a temporal dimension to the monitoring system established by Brosowski et al. [13] and at the same time depict the supply and use of resources with high spatial quality. The subject of how to assess the biomass potential of straw is controversial. Examining multiple studies (e.g. Weiser et al. [26], Scarlat et al. [27], Lindner et al. [28]), it can be seen that the calculation of theoretical potential is methodologically consistent. Cereal production figures are multiplied by grain–straw ratios from the literature. There are differences, among other things, in the number of cereal species considered, the times studied or the source data. The methodological differences are significant, however, when it comes to calculating the technical potential of straw. Key questions in this context include: how much is it technically feasible to harvest? Does straw required for bedding count as a restriction on the amount that can be used [26] or does it count as material use [13]? What is the amount required to maintain the humus content? The latter question in particular polarises the discussion about the future increased industrial use of cereal straw. Weiser et al. [26], for example, assume that industrial use requires straw to be removed, causing a loss. This argument treats various possible uses in material flow management (e.g. incineration, ethanol production, fermentation, etc.) as equal. However, the fermentation of cereal straw offers interesting opportunities for reproducing humus and improving the nutrient balance by returning digestate to the farmland, while simultaneously producing biomethane as an energy source [29–31].

In relation to the debate about the technical biomass potential of straw, this means that with this type of use, significantly higher amounts of straw would be available than indicated by Weiser et al. [26]. This article takes up the idea of this type of use and quantifies the role that biomethane produced from straw could potentially play in the transport sector. As well as the high relevance of this raw material and the intense pressure to take action in the transport sector, this focus is also based on the fact that the world's first large-scale industrial TRL-9 plant with straw mono-digestion is already being operated successfully in Germany [32]. This offers the opportunity to multiply an already proven plant concept and provide a short-term contribution to reduce GHG emissions in the transport sector.

Methodology

Against this background, the methodological approach addresses two key aspects. Firstly, the residue monitoring calculation method developed by Brosowski et al. [13] is consistently transferred from national to regional level and analysed for the years 2010 to 2018. Secondly, the processing of the temporal and spatial data is tested based exclusively on the example of the production of biomethane, including digestate return. Chapter 2.1 describes the steps required to prepare the data. Chapter 2.2 explains how the data generated were analysed with the help of a Geo-Information System (GIS) [33] to identify particularly relevant regions for the future mobilisation of raw materials, using the European NUTS system to describe the territorial levels [34].

Calculation and contextualisation of cereal straw potentials

Consistently transferring the calculation methodology from the present national level (NUTS-0) to Germany's current 401 districts (NUTS-3) [35] requires extensive data preparation. Table 1 summarises the 30 sets of source data used and their availability. The "National Monitoring" column refers to the national calculation methodology developed by Brosowski et al. in 2019 [13] and the "Regional Monitoring" and "Data Set" columns describe the data sets used for consistent calculation at regional level. The table also shows the spatial and temporal qualities of the data sets and their unit of measurement. The respective sources are summarised beneath the overview. At this level of detail, a distinction between conventional and organic farming is not yet possible. However, at least in the statistical databases the respective shares are indirectly included as the sum of both systems.

Table 1 Overview of the data used to calculate the regional supply and use of cereal straw in Germany

#	National monitoring	Regional monitoring	Dataset	Available spatial level	Unit	2010	2011	2012	2013	2014	2015	2016	2017	2018
1	Cereal production	Yield	Wheat, rye, barley, triticale, oats	NUTS-3	dt fm/ha	✓	✓	✓	✓	✓	✓	✓	✓	✓
2		Acreage			ha	✓	LI					✓	LI	
3	Grain-straw ratio			NUTS-0	1:	✓	✓	✓	✓	✓	✓	✓	✓	✓
Theoretical biomass potential				**NUTS-3**	**t fm**	**✓**	**(✓)**	**(✓)**	**(✓)**	**(✓)**	**(✓)**	**(✓)**	**(✓)**	**(✓)**
4	Collection ratio		Wheat, rye, barley, triticale, oats	NUTS-0	%	✓	✓	✓	✓	✓	✓	✓	✓	✓
5	Humus balance	Recovery for bio-CH4			%	✓	✓	✓	✓	✓	✓	✓	✓	✓
Technical biomass potential				**NUTS-3**	**t fm**	**✓**	**(✓)**	**(✓)**	**(✓)**	**(✓)**	**(✓)**	**(✓)**	**(✓)**	**(✓)**
6	Animal bedding	Livestock	Dairy cows	NUTS-3	Heads	✓	✓	✓	✓	✓	✓	✓	✓	✓
7			Other Cattle			✓	✓	✓	✓	✓	✓	✓	✓	✓
8			Pigs			✓	LI					✓	LI	
9			Sheep											
10			Chicken	NUTS-1		✓	LI		✓	LI		✓	LI	
11			Geese											
12			Ducks											
13			Turkeys											
14			Goats											
15			Horses			based on 2015					✓	based on 2015		
16		Type of husbandry	Cattle		Animal places	✓	based on 2010							
17			Pigs											
18			Sheep											
19			Chicken											
20		Bedding requirem.	All types of animals	NUTS-0	t fm	✓	✓	✓	✓	✓	✓	✓	✓	✓
21	Not considered	Fodder	Horses	NUTS-0	t fm	✓	✓	✓	✓	✓	✓	✓	✓	✓
22	Special crops		Strawberries (open field)	NUTS-1	ha	✓	✓	✓	✓	✓	✓	✓	✓	✓
23			Strawberries (under foil)			✓	✓	✓	✓	✓	✓	✓	✓	✓
24			Demand for strawberries	NUTS-0	t/ha	✓	✓	✓	✓	✓	✓	✓	✓	✓
25			White mushrooms		ha	LI		✓	✓	✓	✓	✓	✓	✓
26			Demand for mushrooms		t/ha	✓	✓	✓	✓	✓	✓	✓	✓	✓
27	Industrial use		Packaging	Site specific	t fm	✓	✓	✓	✓	✓	✓	✓	✓	✓
28			Combustion		t fm	✓	✓	✓	✓	✓	✓	✓	✓	✓
29			Biomethane production		t fm	✓	✓	✓	✓	✓	✓	✓	✓	✓
30			Ethanol production		t fm	✓	✓	✓	✓	✓	✓	✓	✓	✓
Used technical biomass potential				**NUTS-3**	**t fm**	**(✓)**	**(✓)**	**(✓)**	**(✓)**	**(✓)**	**(✓)**	**(✓)**	**(✓)**	**(✓)**

LI: linear interpolation, : data set available, (): data set contains interpolations. **Sources:** #1: [36]; #2: [37]; #3: [38]; #4–5: calculated based on Table 2; #6–7: [39]; #8–9: [40]; #9–14: [41]; #15: [41, 42]; #16–19: [43]; #20: [38]; #21: [44]; #22: [45]; #23: [46]; #24: [47]; #25: [48]; #26: [49]; #27: [50]; #28: [51]; #29: [52]; #30: [53]

Altogether, the availability of the data that is required is very heterogeneous, and four different approaches are taken to data preparation:

- Direct data transfer: the data can be taken directly from the statistics with the required spatial and temporal qualities (NUTS-3 and annual).
- Interpolation of missing years: due to the structure used to collect the statistical data, only certain years are available. Here, missing years were linearly interpolated based on the available data points.
- Spatial data weighting: data are available for certain years, but not at NUTS-3 level. Here, the finding in question was weighted and transferred from the available level to the corresponding NUTS-3 level.
- Generation of new data: as yet unavailable data sets on current industrial use were collected by gathering primary data.

There are tonnages for cereal production at national level in Germany, but none at NUTS-3 level. To calculate the required data, the yields of the five available cereals (#1) were thus multiplied by the acreage (#2). However, the acreage is not available for every year, but only for the years 2010 and 2016. The missing years were linearly interpolated based on these two data points. In combination with the grain–straw ratio (#3, Table 2), it was possible to fully calculate the theoretical cereal straw potential at NUTS-3 level. The amount which can be used to produce biomethane was based on the findings gathered by Reinhold [31] and the results of the Germany-wide very first field trials by Knebl et al. [29]. The results show that returning the digestate to the farmland can have positive effects on the humus and nutrient balance. Hence, a large quantity of the straw remains in the agricultural cycle, which is not possible with other industrial uses than fermentation. The technically feasible recovery of straw by combine harvesters is only carried out up to a certain stubble

Table 2 Basic data on calculation of total straw recovery (based on [38, 54–56])

Data set	Grain–straw ratio	Stubble height	Growth height	Feasible collection ratio	Recovery for biomethane production	Total recovery		
	1:	m	m	%	%	%	Average	
Wheat	0.8	0.10	0.50–1.50	80–93	80	64–74	69	71
Rye	0.9		1.50–2.00	93–95		74–76	75	
Barley	0.7		0.70–1.20	86–92		69–74	72	
Triticale	0.9		0.50–1.25	80–92		64–74	69	
Oats	1.1		0.60–1.50	83–93		66–74	70	

height. To stop the mower from being clogged, the minimum height is 10 cm [54]. Along with the growth heights of the cereal types shown in Table 2, this results in a technically feasible collection rate (#4) of between 80 and 95%. If an assumed 80% of this is made available for biomethane production, the average removal rate is around 70% in all (#5). This means that 30% of the straw remains untouched on the field and after fermentation of the removed quantities, the digestate is returned to the farmland. This type of application is associated with numerous open questions which are further elaborated in the discussion (Chapter 4). However, this assumption enables the estimation of a technical potential for further temporal and spatial analyses and to evaluate the strategic significance of straw-based biomethane in the transport sector.

Some of the technical potential of straw is already being used for various purposes. The regional calculation over time takes into account (a) bedding for ten animal species, (b) feed requirements for horses, (c) requirements for special crops and (d) requirements for industrial use.

(a) *Bedding* Calculating the amount of straw used for bedding requires data on the animal population, husbandry and animal-specific bedding requirements. The stock of dairy cows (#6) and other cattle (#7) can be taken directly from the official statistics with the required quality. Data on pigs (#8) and sheep (#9) are available at NUTS-3 level, but only for 2010 and 2016. Data for poultry (#9–13) and goats (#14) are also available for 2013, but in total only at NUTS-1 level. Missing years were linearly interpolated. The database on horses (#15) is particularly incomplete. Official statistics only record numbers in agricultural farms [57]. The number of commercial or recreational horses is not included and is only recorded by the federal states' livestock disease funding associations. For data protection reasons, these data are not publicly available. Taking the reference year 2015, Uhl [42] published a telephone comparison survey at NUTS-1 level. The number of horses reported was almost twice that in the statistics. Uhl [42] points out that not all horses are registered with the disease funding associations and that the actual number could be significantly higher. For this reason, only the figures provided by Uhl [42] are taken, as a consistent database for all the years under consideration. The animal population was then linked to the type of husbandry (#16–19) and the animal-specific bedding quantities (#20). Data on husbandry are only available to the public for the year 2010 and for NUTS-1 level. Time series interpolation is not possible. Literature-based, animal-specific bedding quantities are also constant and only available at NUTS-0 level. On this basis, no different requirements for organic husbandry can be considered so far. The calculation of the bedding quantities follows the methodology proposed by Weiser et al. [26] and can be summed up in the following formula. The calculation values are found in Annex A.

$$Si = \sum (An - (An \times Gp \times Gd)) \times Hsm \times Ba$$

S_i: straw used as bedding (Tg fm a^{-1}); A_n: number of animals; G_p: share of grazing (%); G_d: duration of grazing period per year (%); H_{sm}: share of animals in straw-based housing systems (%); B_a: Bedding requirements (Mg a^{-1}) for every livestock subcategory.

As the numbers of poultry, goats and horses are only available at NUTS-1 level, the data were then weighted spatially. First, the resulting bedding quantities were calculated at NUTS-1 level. Relating this to the technical potential of straw at NUTS-1 level comes up with a percentage for the animal-specific bedding quantities. This weighting was then transferred to each NUTS-3 region. Taking one example, this means that in a NUTS-1 region with ten NUTS-3 units, there is a technical straw potential of 1000 Mg fm, and 250 Mg fm was calculated as the bedding requirement, producing a weighting percentage of 25%. That value was then multiplied by the individual technical potential in each of the ten NUTS-3 units.

b) Horse feed requirements In addition to bedding, straw can also be used as a food supplement or for chewing to prevent boredom. Depending on the breed, an average feed requirement (#21) of 0.42 Mg fm per animal and year is indicated in the literature [44]. That value was applied to the animal numbers in question (#15) and weighted regionally as described.

c) Special crops The cultivation of strawberries and mushrooms also requires straw. Growing data on strawberries (#22–23) are available annually at NUTS-1 level, while those on mushrooms (#25) are only at NUTS-0 level and only from 2012. The two missing years were linearly interpolated. Requirements were calculated in combination with literature-based straw requirements (#24, #26) [47, 49], weighted and applied to NUTS-3 level.

d) Industrial use As yet, there are no public data sets on this type of straw use. Therefore, primary data were collected for the four fields of packaging (#27), incineration (#28), fermentation (#29) and ethanol production (#30). A review of various sources (see Table 1) was used to determine the exact plant locations, straw requirements and start of production.

The overall outcome of the data processing was that the technical potential used for all 401 NUTS-3 units and for the years 2010 to 2018 was consistently compiled and calculated. The difference between the technical potential and the utilisation is known as the mobilisable potential [13]: the proportion which could be used for the future production of biomethane. The basic data in Table 3 were used to further contextualise the mobilisable potential.

On this basis, the substitution potential for fossil fuels and the associated GHG reduction potential were estimated for the selected transport modes passenger cars, heavy goods transport and maritime shipping. This leads primarily to an initial indicative statement and not to a detailed life cycle assessment (LCA). For this reason, general bandwidths were used for the calculations in order to cover the numerous uncertainties as best as possible. In addition to the basic data on biomethane production (e.g. methane yield), an overall efficiency between 70 and 85% was assumed according to Scholwin et al. [15]. This bandwidth includes, for example, transport losses in biomass supply, methane losses and the energy requirements of biogas purification, grid feed-in, gas distribution, etc., in a very general manner. In this way, other forms of supply such as compressed (CNG) or liquefied (LNG) biomethane are also covered. A bandwidth was also assumed with regard to the GHG mitigation potential. The extensive, straw-specific calculations conducted by Majer et al. [62] and the estimates of Scholwin et al. [15] result in a range between 60 and 85%. On this basis, the numerous influencing parameters caused by transport, conversion and distribution were also covered from a very general perspective. The contextualisation is based on the idea of replicating the concept of the world's first successfully operated, large-scale industrial TRL-9 plant for straw mono-digestion. The annual straw requirement is about 40,000 Mg.

Hotspot assessment

When the use of raw materials within a NUTS-3 region grows higher than the supply of raw materials, the additional demand must be balanced out by other regions. Weiser et al. [26] describe all regions with a deficit as

Table 3 Basic data to contextualise the mobilisable straw potential

Baseline data	Min	Max	Unit	Source
Biomethane production				
Methane yield	210	260	L kg_{vs}^{-1}	[58, 59]
Content of organic dry matter	90	92	%	[58, 60]
Dry matter content	86	92	%	[58, 59]
Methane content in biogas	50.8	52.0	%	[58, 60]
Biogas yield	320.0	423.2	L kg_{fm}^{-1}	Calculated
Lower heating value	35.89		MJ $(m^3_{CH4})^{-1}$	[61]
Overall efficiency biogas as fuel	70	85	%	[15]
Emissions				
Overall GHG mitigation potential	60	85	%	[15, 62]
Fossil fuel comparator (RED)	94.0		gCO_2-eq. MJ^{-1}	[11]
TRL-9 plant for cereal straw mono-digestion				
Straw demand	40,000		Mg fm a^{-1}	[52]
Energy demand in target markets 2014/2018				
Passenger cars	1477/1481		PJ	[63]
Heavy goods traffic	675/675			
Bunkering seagoing vessels	96/71			

having zero potential, which does not yet take into account whether they are balanced out by other regions. In the case of high raw material requirements, especially (e.g. in industrial hotspots), this can lead to considerable inaccuracies in assessing the national balance of supply and use. Moreover, assessments at the level of the administrative unit also neglect the spatial context of arable land distribution. To take these special features into account, the findings from Chapter 2.1 were transferred to a GIS. Connecting the data gathered on potential with a suitable geodata set enables a spatial analysis that is independent of administrative units.

The Federal Agency for Cartography and Geodesy (BKG) provides various nationwide geodata sets for this purpose [64]. The digital landscape models (DLMs) in the Authoritative Topographic-Cartographic Information System (ATKIS), e.g. Basis-DLM [65], DLM250 [66] or DLM1000 [67], include arable land under the "AX_Landwirtschaft" feature type, but are not freely available. In ALKIS [68], the Authoritative Real Estate Cadastre Information System, the "arable land" utilisation type is also available under "AX_TatsaechlicheNutzung", though it is only publicly available in a few federal states. CORINE Land Cover [69], by contrast, is a publicly available data set which is based on satellite data and covers arable land throughout Europe for the reference years 1990, 2000, 2006, 2012 and 2018. However, land use is generalised to 25 ha. A data set with 10 ha is available for 2018 [70], but the non-public ATKIS Basis-DLM data set [65] was nonetheless used for the analysis instead. With an area coverage from one hectare and an accuracy of one metre, this annually published geodata set offers the highest level of temporal and spatial detail. It does not, however, cover actual agricultural production. Under the law, this information is not in fact available in Germany [71]. The spatial analysis therefore follows the assumption that each polygon of arable land represents the statistical context of the associated NUTS-3 region. The steps set out in Fig. 2 were required to project the data onto the polygons of arable land.

The starting point is statistical data [37] on the acreage of all crops (A). This information was used to derive the percentages of the five cereal types in question (B). In connection with the polygons from the geodata set (C), this generates the modelled cereal straw production area (D) for each polygon in a NUTS-3 region. In combination with the yield figures (E) from the calculations of potential (Chapter 2.1), the area-related cereal straw potential is then derived for each polygon (F). For further data processing, the findings were converted into point data (G); it was only at that juncture that they were linked to the location-specific information on industrial use (H). The resulting data set (I) contains a full set of information on the mobilisable potential for the future production of biomethane in the form of a 1 × 1 km raster. The spatial context was then evaluated by means of a neighbourhood analysis, distinguishing between catchment areas with radii of 20 and 50 km and adding the total amounts of raw material in each of the resulting areas to another raster data set (J, K). Finally, hotspot regions were identified by classifying the raw material requirements of the potential conversion plant.

Results

Temporal and spatial availability of cereal straw and biomethane

On national level (Fig. 3), in the years in question the theoretical and the technical potential of straw fluctuate

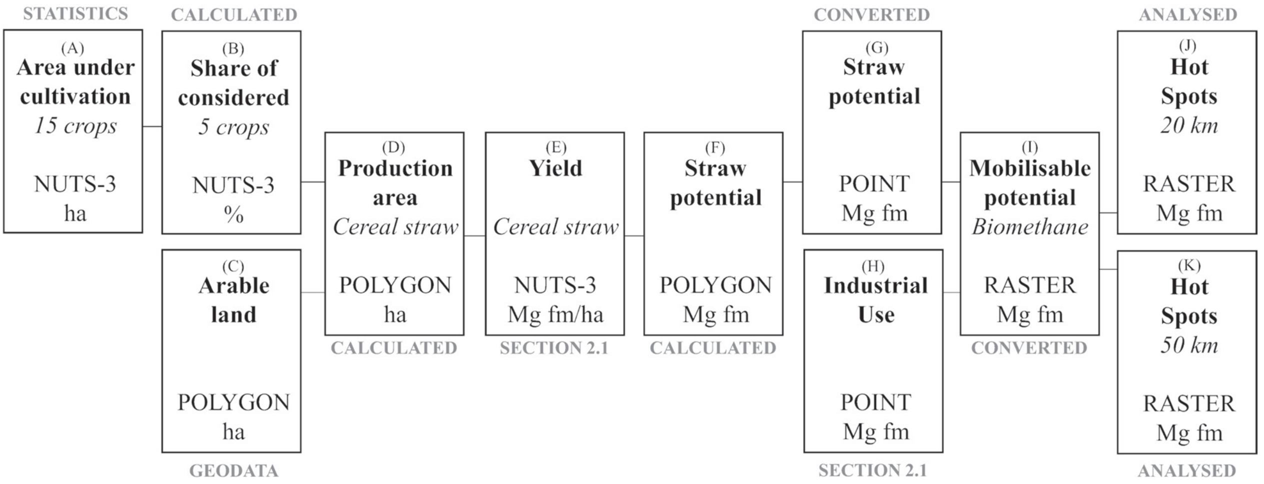

Fig. 2 Methodological approach to assess regional hotspots for future biomethane production based on cereal straw

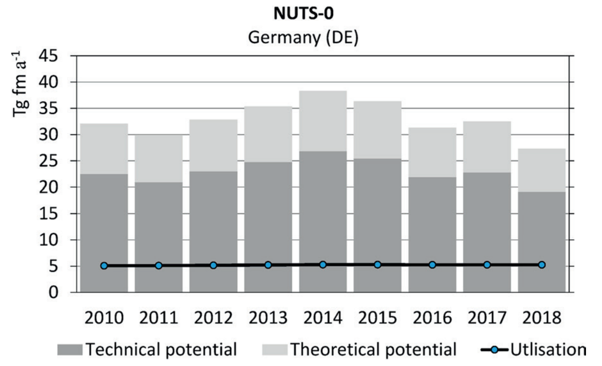

Fig. 3 Profile of biomass potentials and utilisation of cereal straw at national level, 2010–2018

between 27.3 and 38.3 Tg fm a^{-1} and between 19.1 and 26.8 Tg fm a^{-1}, respectively. The maximum in 2014 and the minimum in 2018 are separated by just four years, but also a difference of up to 11 Tg fm a^{-1}, or 40%. The use of cereal straw, however, exhibits no significant fluctuations. From 2010 to 2014 there is an increase (+ 4.1%) followed by a slight decrease (− 0.9%). In 2018, the level was 5.3 Tg fm a^{-1}, i.e. 3.2% above that of 2010. Due to the relatively constant level of use and the fluctuating supply of raw material, the share of the technical straw potential used ranges between a fifth (2014) and more than a quarter (2018).

The use is dominated by the amounts required for bedding and feed. The highest demand arises in 2018 for the husbandry of horses (41%), pigs (24%) and cattle (22%). The remaining animals account for 8%. Apart from livestock farming, the amounts required for special crops (2%) and industrial use (2%) take up a comparatively small share. One point that should be emphasised, however, is that industrial use increased 35 times from 2010 to around 114,000 Mg a^{-1} in 2018. This is mainly made up of incineration (59%) and fermentation (35%). The remaining 6% are other industrial uses. It should be taken into account that the primary data collection on industrial use is not claimed to be complete. In total, detailed information was collected on 12 plants. According to FNR [51], there are several decentralised, smaller plants in the incineration business on which no further information is publicly available. The number is expected to be in the double digits. Neither is there any information on the quantities or locations of straw used as a building material. Despite these uncertainties, on the national level it can be said that the amount of resources used was never higher than the amount supplied. This produces a range between 13.9 and 21.5 Tg fm a^{-1} for the mobilisable straw potential. Compared to Weiser et al. [26] (see Chapter 1), this potential is at least 62% above the level discussed previously, as long as the straw is used in biogas plants including returning the digestate.

The regional availability of raw materials is influenced, among other things, by acreage, yield levels, and existing use. The maps in Fig. 4 show the spatial distribution of the technical potential (= raw material supply) including the trend compared to the previous year, raw material utilisation and the mobilisable potential (= availability). The years 2014 and 2018 were selected to illustrate the spatial range of the findings. Although these years are very close together, they are the all-time maximum (2014) and the minimum (2018) since 1994 (see Fig. 1).

The technical potential falls by almost eight million tonnes between 2014 and 2018. Nevertheless, in both years there are clear hotspots in the north (Schleswig-Holstein, Mecklenburg-West Pomerania) and the east (parts of Brandenburg, Saxony, Saxony-Anhalt), along with certain regions in the west (on the border between Lower Saxony and North Rhine-Westphalia) and a few regions in southern Germany. A comparison of the two years shows a relatively high level of change in the regions in the far east (Brandenburg, eastern Saxony) and the far northwest (northern Lower Saxony). The 2017/2018 trend reveals significant losses ranging between over 20% and, sometimes, over 40% for these and numerous other areas. In contrast, the extreme west and south show some significant increases. The situation is contradictory for 2013/2014, with production significantly higher in 2014 than the previous year, 2013. Significant increases extend from the south across the east to the north. The level remained stable in the other regions. In contrast with this considerable dynamism, regional utilisation hardly shows any sign of change in the observation period. Consistently high utilisation rates can be seen for the northwest (western Lower Saxony, northern North Rhine-Westphalia), and utilisation is also comparatively high in the north (e.g. Mecklenburg-Western Pomerania, Prignitz, Uckermark) and certain regions in the south. On the one hand, this is due to the need for straw for livestock farming. On the other hand, especially in western Lower Saxony and Uckermark, there are industrial uses with a high straw requirement.

The mobilisable potential is the difference between the technical potential and utilisation. Compared with the technical potential, the situation is similar, but more nuanced. For example, the high utilisation rate in the northwest significantly reduces the potential that can still be mobilised there. In the weak year, 2018, the situation is similar for northern Lower Saxony, western Brandenburg and eastern Saxony-Anhalt. With regard to the mobilisable potential, the findings have a clear regional focus in eastern Schleswig-Holstein, throughout

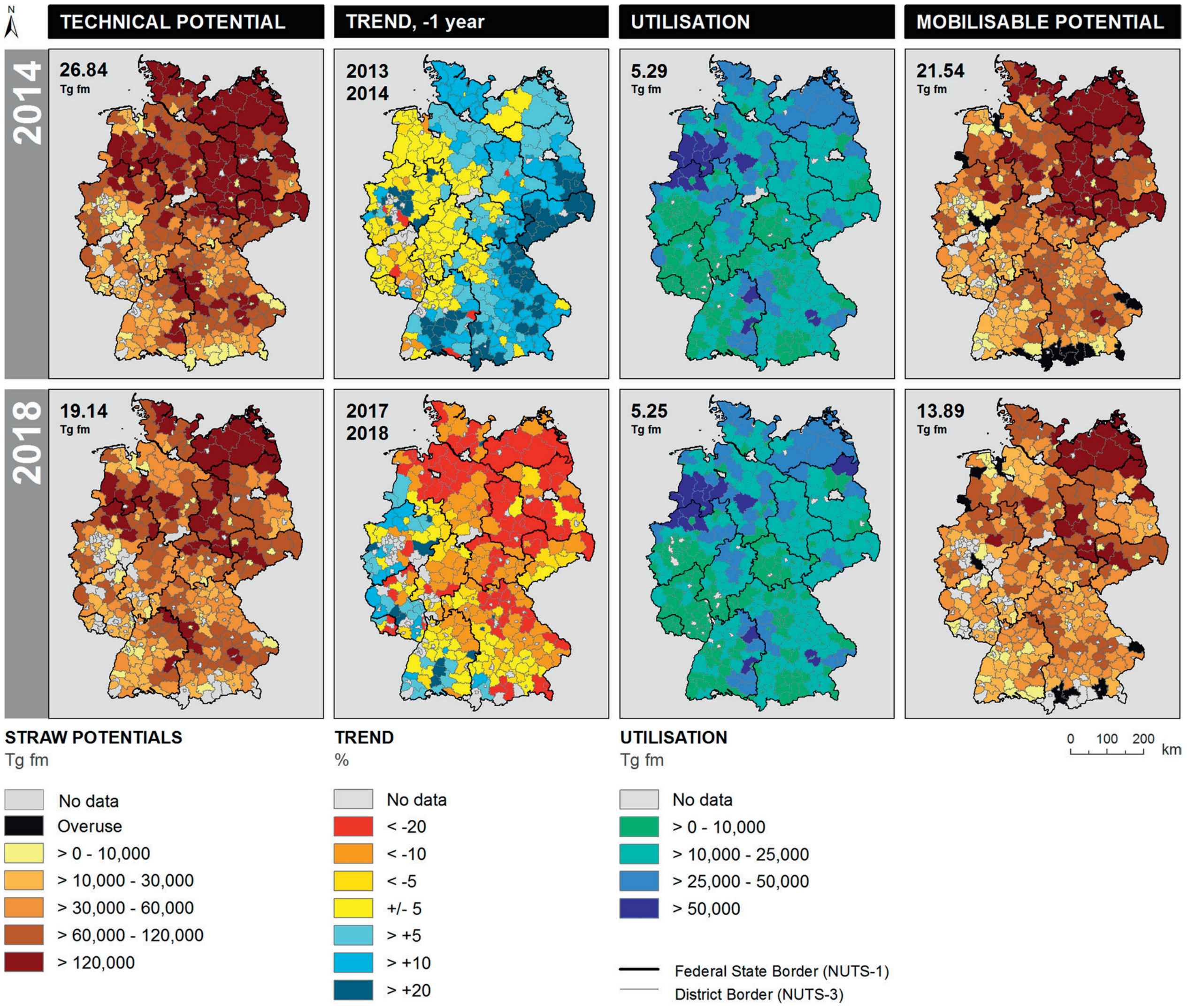

Fig. 4 Spatial distribution of technical straw potential, trend, utilisation and mobilisable straw potential at NUTS-3 level, 2014 and 2018

Mecklenburg-Western Pomerania, in Uckermark, central Saxony, western Saxony-Anhalt and southern Lower Saxony. Despite the higher use of raw materials and the strongly negative trend in 2018, these regions have a large mobilisable potential. In some regions, meanwhile, the amount used is higher than the supply, especially in the Alpine Foreland and a small number of regions in the northwest. The supra-regional situation is evaluated in Chapter 3.2. For some regions, it was not possible to generate any consistent data sets. For 2018, in particular there are a comparatively high number of gaps in the data, e.g. for the metropolitan regions in North Rhine-Westphalia.

To complement the maps, Fig. 5 summarises the quantitative distribution of the mobilisable potential for all NUTS-3 regions. The primary axis shows the potential for each NUTS-3 region sorted in descending order. The secondary axis shows the cumulative potential as a biomass supply curve. In some hotspot regions, especially in Mecklenburg-Western Pomerania, the mobilisable potential is over 500,000 Mg fm a^{-1} (2014) or over 300,000 Mg fm a^{-1} (2018), respectively. This presentation of the findings shows that, of a total of 401 regions, a third of the total potential is concentrated in 27 (2014) and 30 (2018) regions. Two thirds of the potential are located in 88 (2014) and 92 (2018) regions.

Table 4 adds context to what these findings mean for the transport sector. It shows the number of possible plants of the selected plant concept (Chapter 2.1, Table 3), the potential amount of biomethane as fuel and

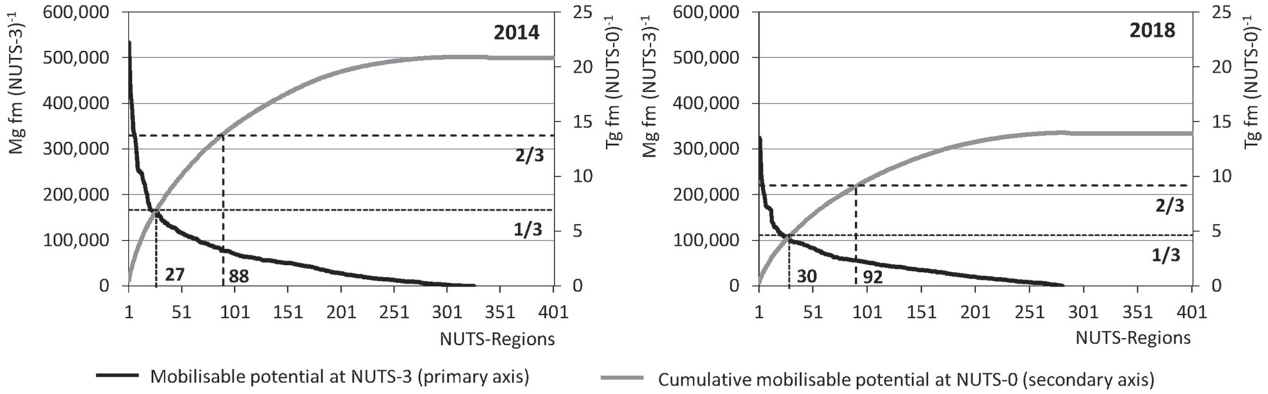

Fig. 5 Mobilisable potential for each NUTS-3 region sorted in descending order (primary axis) and cumulative mobilisable potential (secondary axis) in Germany, 2014 and 2018

two key figures for the selected transport modes passenger cars, heavy goods vehicles and maritime shipping. These relate to the possible GHG mitigation and the substitution of energy requirements in the target market when replacing fossil fuels. As it is unlikely that all the mobilisable potential will be fully tapped, a distinction is also made between the three levels of 66%, 33% and 10%, which can be understood as farmers' willingness to supply straw. At the same time, this differentiation can also be interpreted as a reduction of the recovery rate from 70 to 46%, 23% and 7%.

The differences in production levels for 2014 and 2018 show clear effects on the strategic relevance of biomethane in the transport sector. If the potential is fully tapped, from the point of view of resource availability, well over 300 plants could still be built even in weak years, and up to 7 Tg CO_2-eq. avoided—in good years even up to 12 Tg CO_2-eq. With regard to achieving the climate target in the transport sector by 2030 (Chapter 1), this means making possible progress of up to 11–17% through the effective use of straw alone. However, if the minimum values are adopted, the share is more than halved to 5–8%. In both considerations, the different straw availabilities during extreme years reduce the potential GHG mitigation by more than one third. Taking into account a reduced farmers' willingness to supply straw, the strategic relevance in terms of emissions reduction changes significantly. If only a third of the potential were tapped, well over 100 plants could still be built and in the best case 3–4 Tg CO_2-eq. could be avoided. If, by contrast, only one in ten farmers made their straw available for future biomethane production, 35 plants could still be supplied. However, the use of straw could save not more than one million tonnes of CO_2 equivalents, which is well below 2% of the sector's target. However, this level is higher than the GHG savings achieved in the entire transport sector since 1990. Especially in the case of a higher utilisation rate of cereal straw, there are promising opportunities to realise a significant contribution to GHG mitigation.

With regard to the substitution potential for fossil fuels, considerable differences can be identified for the respective modes of transport. Due to the different energy requirements and taking into account the optimum case, the demand for bunkering seagoing vessels could be met in full. Up to a fifth could be substituted for HGVs and up to a tenth of passenger cars could be supplied with a low-emission fuel. If only a third of the mobilisable straw potential was provided as biomethane in the transport sector, the shares would decrease to 7% and 3%, respectively. The shipping sector would still achieve around half. If only 10% of the potential would be utilised, the share for HGVs and passenger cars is in almost all cases well below one percent and between 13 and 15% for the shipping sector.

Hotspots for future biomethane production

In some regions, meanwhile, the amount of raw materials used is higher than the supply. Figure 6 shows the findings for two selected examples as a graph. In the first region, "Grafschaft Bentheim" (western Lower Saxony), Germany's first plant designed for the industrial use of cereal straw entered operation in 2014. As a result, the use of straw has tripled to over 90,000 Mg a^{-1} and will significantly exceed the local raw material supply this year. Meanwhile, in the second example "Rosenheim, Landkreis" (Alpine Foreland), straw use is entirely related to livestock farming. The high demand has to be balanced out by other regions, which cannot be assessed at the level of the administrative unit (Fig. 4).

The spatial links between the supply of resources and their use were therefore analysed using a GIS. The results

Table 4 Results on contextualisation of mobilisable straw potential, 2014 and 2018

Engagement	Corresponding recovery rate	Mobilisable potential		Number of plants		Biomethane as fuel			Emissions				Potential substitution of fossil fuels					
									GHG mitigation potential		Share of sectors' goal by 2030		Passen-ger cars		Heavy goods vehicles		Bunkering seagoing vessels	
%		2014	2018	2014	2018	Band-width	2014	2018	2014	2018	2014	2018	2014	2018	2014	2018	2014	2018
		Tg fm		n			PJ		Tg CO_2-eq		%		%					
100	70	21.5	13.9	539	347	Min	88	57	5	3	8	5	6	4	13	8	92	80
						Max	145	93	12	7	17	11	10	6	21	14	151	131
66	46	14.2	9.2	355	229	Min	58	37	3	2	5	3	4	3	9	6	60	53
						Max	95	61	8	5	11	7	7	4	14	9	99	87
33	23	7.1	4.6	178	115	Min	29	19	2	1	2	2	2	1	4	3	30	27
						Max	48	31	4	3	6	4	3	2	7	5	50	44
10	7	2.2	1.4	54	35	Min	9	6	< 1	< 1	< 1	< 1	< 1	< 1	1	< 1	9	8
						Max	15	9	1		2	1	1		2	1	15	13

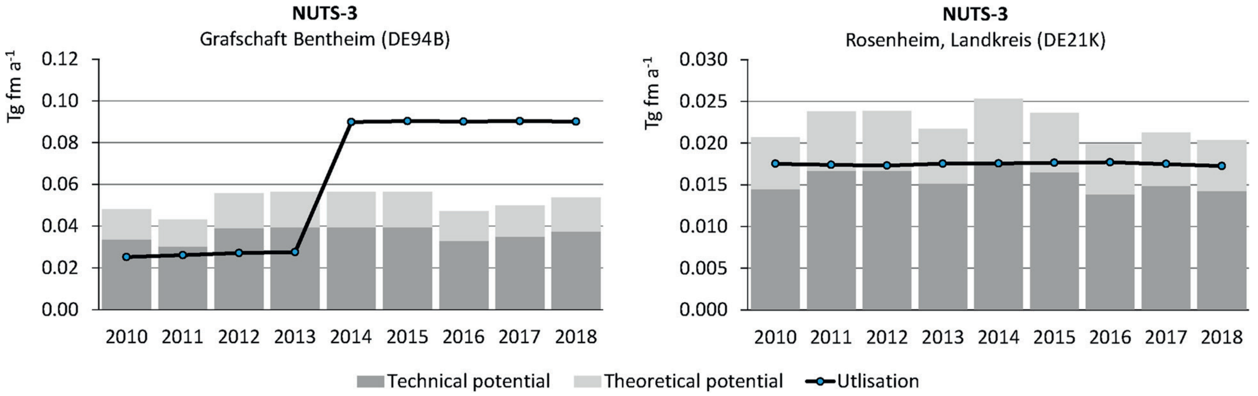

Fig. 6 Exemplary profiles of biomass potentials and use of cereal straw at NUTS-3 level, 2010–2018

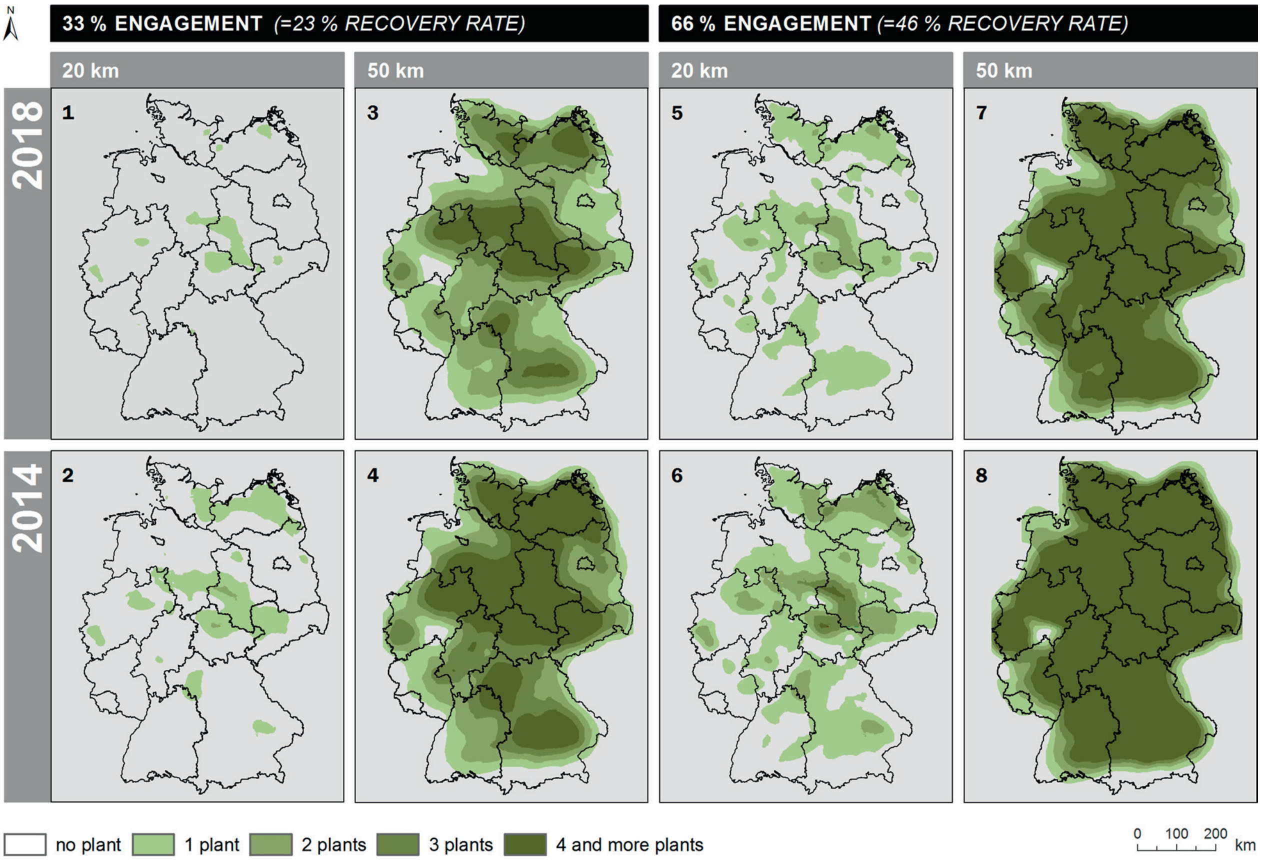

Fig. 7 Hotspot regions with mobilisable potential > 40,000 Mg fm incl. 33% and 66% engagement or 23% and 46% recovery rate and catchment area radii of 20 and 50 km, 2014 and 2018

generated take into account both cross-regional compensation for deficits and the regional importance of multiple small neighbouring regions that can be viewed as a network. On this basis, options for the future use of raw materials can be evaluated on a plant-specific basis. In combination with the catchment areas with radii of 20 and 50 km, Fig. 7 shows the areas in which a plant requirement of 40,000 Mg a^{-1} (Chapter 2.1, Table 3) can be met either fully or multiple times. In line with Table 4, the spatial context is also shown in the case of a willingness to supply straw of 33% and 66% or a recovery rate of 23% and 46%, respectively.

A low willingness to supply straw (33%) and a low transport distance (20 km) set high requirements and generate clearly delineated hotspot regions. In the weak year of 2018 (Map 1), the hotspots run through the fertile Börde lowlands from west to east, from the Jülich-Zülpich Börde west of Cologne, via the Warburg Börde north of Kassel to the Hildesheim Börde south of Hanover, the Magdeburg Börde and the Thuringian Basin. In the strong year of 2014 (Map 2), these regions expand, forming a ribbon extending from west Saxony to North Rhine-Westphalia. In the east of Schleswig-Holstein, the north of Mecklenburg-Western Pomerania, parts of Brandenburg (Uckermark, Oderbruch), around Würzburg and south of Regensburg, there are also very good conditions for a supply of raw material. As these are classic wheat-growing areas with fertile soils, out of all regions they pose the lowest risk of a lack of raw materials. At the same time, the digestate would not have to be transported long distances for spreading. If it is transported over longer distances, the raw material can be supplied almost anywhere. With a catchment area radius of up to 50 km (Maps 3 and 4), plants could be built all over Germany, at least from the point of view of resource availability. The only exceptions are the north and west of Lower Saxony, the Black Forest and the Alpine Foreland, as use in these areas is already relatively high and there is little or no cereal cultivation in those areas. The area in the south of North Rhine-Westphalia is not a gap in the data, but a densely forested mountainous region (the Taunus range). If there is greater willingness to supply straw (66%), the hotspots expand accordingly. Above all, large parts of Bavaria and Hesse also emerge as priority areas (Maps 5 and 6). With a larger catchment area radius, sufficient amounts of raw material can be tapped across the country to operate more or larger plants (Maps 7 and 8). In summary, it can be said that the spatial precision of the findings in Chapter 3.1 can be improved using GIS analysis. This considerably adds to the range of possible interpretations regarding the replication of the plant concept under consideration.

Discussion

Previous studies assume that the future increased industrial use of straw would result in a removal rate that has a negative impact on the humus content. However, the humus and nutrient balance can be positively influenced by biochemical conversion, including returning the digestate to the farmland. Initial field tests show interesting results, though these are not enough for a long-term evaluation. Moreover, as the soil characteristics, soil management and weather are subject to wide regional variation, the results of individual tests cannot be generalised or easily transferred to the country as a whole. Furthermore, the humus and nutrient balance is not the only important parameter for the evaluation of ecological sustainability. The use of straw may also influence numerous other functions such as water balance, weed suppression or feed for soil animals. The impacts on the overall soil quality and biodiversity have not yet been sufficiently considered in any study available. For this reason, the calculations presented are based on the central assumption of a limited straw recovery, resulting in a total of 70% going into potential circular economy. This approach can be discussed as controversial, because there are considerable uncertainties in determining sustainable recovery rates. To describe the effects of a reduced recovery, different mobilisation and corresponding recovery rates down to 7% were evaluated to cover a wide range of conceivable options. However, the aim of the analyses was to examine the possible strategic relevance in the transport sector of biomethane produced from straw under these conditions. It is thus more a question of whether it is worth looking into the topic in further detail. The answer is a clear “yes”. The straw potential calculated is in the best case 65% above the previously known level for this field of application, published by Weiser et al. [26] in 2014. However, the two approaches cannot be compared methodologically. The authors’ extensive assessment of the carbon balance was geared towards the removal of straw, and did not take into account the possibility of digestate being returned to the farmland. The result of 8.0 to 13.3 Tg fm a^{-1} also was based on the average values for 1999, 2003 and 2007. Extreme values in individual years (see Figs. 1, 3) differ significantly from the average and have a significant impact on the amounts that can be mobilised each year. There are thus not enough existing source data to be able to adequately assess the options for biomethane produced from straw, so way in which the specifics of the material flow relate to the straw potential must be assessed individually for each type of use.

Using the new findings, it will be possible to develop a better description of the risks jeopardising resource availability across different times and regions, making it possible to scale up the selected technology. In this context, the results can also be used for evaluating other plant sizes or applications (e.g. heat generation, material use of gases). Particularly suitable regions can be identified for the future mobilisation of raw materials. On this basis, the focus can be placed on the further analysis of regional stakeholder and shareholder relationships. According to Pfeiffer et al. [72], farmers’ willingness to supply straw is the key prerequisite for its successful mobilisation as a raw material. It would thus be an important next step to discuss the results of the calculations with farmers in hotspot regions and compare theory with practice. Further aspects that have not yet been taken into account (e.g. further competitive uses) could be jointly identified and included in future evaluations. A major challenge, for example, is also the return of the digestate that must be brought back to exactly the same area from which the straw was taken. In practice, this is not possible. One thinkable option could be the introduction of certified quality standards, which would make it easier to manage regional differences. Until now, it has only been possible to make a rough estimate of the actual mobilisable potential of straw, as it depends upon decisions made by individuals. However, the findings show that even a low take-up of just 10% could generate significant amounts of low-emission fuels. If it is possible to create a favourable situation with respect to all the stakeholders in the hotspot regions, a promising step on the path to sustainable mobility could be taken well before 2030.

The calculations presented here are based on numerous data sources of heterogeneous temporal and spatial quality. The weighted distribution of some livestock figures from NUTS-1 to NUTS-3 level is associated with a high level of uncertainty. Horses, for example, make up the highest share of straw use at 41%, but official statistics are incomplete; the large number of horses is based on one literature source for a single year. The straw requirement for ducks, geese, turkeys and goats is also weighted, and is comparatively low at less than 8%. By contrast, there is plenty of data on cattle and pigs (together approx. 46%). Regional peculiarities and competing uses can nonetheless only be mapped in general, in part due to the data on husbandry. This information is only available for 2010 and only at NUTS-1 level. As some data is unavailable, structural changes over time or regional hotspots where several animal species are housed on straw can only be reflected to a limited extent in the analysis. Thus, due to insufficient databases, it is not yet possible to differentiate between conventional and organic farming, neither for animal husbandry nor the calculation of straw potentials. The statistical source data will not be updated until the agricultural census in 2020 [73].

Another subject in the discussion on data quality is differences in the regional levels used in official statistics. The sum of the NUTS-3 regions does not necessarily equal the value of the higher level. Missing or inconsistent data sets create gaps in the data. This may lead to incomplete statements, especially with GIS-based analyses. The assumption that each individual polygon of arable land reflects the statistical situation of the associated NUTS-3 region is also a means of linking in with the spatial distribution of arable land, but cannot model actual cultivation. Information on actual annual cultivation is not available for reasons of data protection. Generalising the spatial information to a km^2 raster makes it sufficiently non-specific while still allowing hotspot regions to be identified.

The focus of this work was exclusively on Germany. However, the regional availability of resources does not end at national borders. Considerable regional synergies can be expected, especially in the regions bordering Poland (e.g. south of Szczecin). Transnational analyses (e.g. [27, 28]) offer evidence of this, but the resources have not yet been evaluated in detail over the course of time. With regard to extreme weather events, temporally and spatially detailed information on the availability of resources is becoming increasingly relevant as a better means of evaluating the considerable fluctuations and their possible effects. On this basis, it is possible to quantify the chances of scaling a technology until it becomes strategically relevant for society's goals (e.g. GHG mitigation in the transport sector, level of substitution in target markets). One important prerequisite for an assessment of this kind is that the basic data are consistent from one study to the next. Differences and sensitivities in basic calculation values can lead to considerable deviations in results even if the actual calculation method used is the same. These include, for example, grain–straw ratios, the amount of organic dry matter, the water content or animal-specific bedding requirements. Methane yields and emission factors have a particularly great influence on the strategic relevance of biomethane, for example. Under laboratory conditions, up to 70% higher methane yields are achieved (e.g. [74, 75]) than those published in the general, basic literature (e.g. [58]). In practice, higher methane yields lead to higher levels of substitution in the target markets and also to higher GHG savings. In this work, GHG emissions were only roughly estimated by relatively high bandwidths. However, it is still possible to determine the level of a potential contribution to the transport sector. Detailed, plant-specific LCAs can be used in future to find out at which end of the bandwidth an actual contribution can be expected. For fruitful discussion on these subjects, the basic data need to be constantly reviewed and information urgently needs to be shared among all the stakeholders involved. This, in turn, relies upon a high degree of transparency.

Conclusion

The present work complements Germany's national residue monitoring and offers a detailed insight into the temporal and spatial dynamics of straw availability from 2010 to 2018. Despite the marked fluctuations and the extreme years of 2014 and 2018, an efficient cascade use of straw could achieve relevant shares of the GHG reduction target in the transport sector. However, the strategic contribution depends very much on the mobilisation rate of cereal straw. Taking various scenarios into account, the results show a high bandwidth of less than one and up to 17% of the sector's target. With regard to the substitution of fossil fuels, there are advantages in the context of maritime shipping. It has much greater potential as an alternative means of providing the energy required to bunker seagoing vessels than for heavy goods vehicle or passenger car traffic. In ideal conditions, the energy requirement could be covered completely, and even under restricted conditions, including a mobilisation rate of one third, up to 50% could still be achieved. In heavy goods vehicle and passenger car traffic, only seven and three percent, respectively, can be replaced in the same context. However, the overall contribution to the sector remains the same and in which modes of transport biomethane could be used and would make sense depends on numerous factors. This includes, for example, details of existing or future fuel distribution and filling infrastructures. Major challenges exist especially in engine technology in connection with the methane slip [16]. Leaking methane would have a significant negative impact on the GHG balance. To successfully replicate the plant concept under consideration, numerous additional background circumstances must be taken into account. This involves, among other things, the infrastructure for grid injection and transmission, demand in the target market, legal framework and, in particular, the corresponding economic efficiency. Yet the central prerequisite for successful mobilising straw as a raw material is for an understanding to be reached between regional stakeholders in the fields of agriculture, business, politics, science and society. Without a broad consensus, the importance and impact of biomethane in the transport sector is likely to remain low. Exchanging and disclosing basic data could support discussion among these groups and encourage them to prioritise the next steps to be taken. This could be a means of overcoming reservations and pinpointing commonalities. There is also a particular need for research in connection with sustainable recovery rates and the associated effects on soil quality. One important element in this process is providing open access to the data generated so that the calculations can be individually assessed and continuously improved towards more ecological sustainability. For this reason, the findings will be transferred in full to the DBFZ resource database, which was set up at http://webapp.dbfz.de as part of the national residue monitoring system and can be accessed free of charge in the long term. At the same time, information on the methodological approaches, the background knowledge and the contextualisation used to calculate the potential will be conveyed in e-learning units [76]. This will include practical examples to extend university education of how to deal with open-access data.

An important subsequent step would be regular temporal and spatial assessments of the balance between the supply and use of other important digestible biomass types. In rural contexts, this affects not only straw from the field, but also solid manure as part of straw use and slurry. In urban contexts, the focus is on sewage sludge and organic and green waste. One aspect which could be of particular importance might be identifying regional synergies between different material flows and existing plant capacities. This could be a means of providing an additional, significant amount of biomethane. At the end of 2019, the second large-scale industrial plant for straw mono-digestion went into operation. With the potential presented and the hotspots identified, clear recommendations emerge where future resource mobilisation could be promising.

Appendix

See Table 5.

Table 5 Basic data on animal grazing, husbandry and bedding requirements

	Dairy cattle	Other cattle	Pigs	Sheep	Chicken	Goats	Horses	Turkeys	Ducks	Geese
G_p—share of grazing										
Schleswig-Holstein	77%	58%	0%	82%	0%	100%	100%	0%	0%	0%
Hamburg	100%	73%	0%	95%	0%	100%	100%	0%	0%	0%
Lower Saxony	69%	38%	0%	92%	0%	100%	100%	0%	0%	0%
Bremen	0%	77%	0%	50%	0%	100%	100%	0%	0%	0%
North Rhine-Westphalia	82%	35%	0%	87%	0%	100%	100%	0%	0%	0%
Hesse	48%	51%	0%	86%	0%	100%	100%	0%	0%	0%
Rhineland-Palatinate	62%	52%	0%	90%	0%	100%	100%	0%	0%	0%
Baden-Wuerttemberg	28%	27%	0%	89%	0%	100%	100%	0%	0%	0%
Bavaria	16%	13%	0%	81%	0%	100%	100%	0%	0%	0%
Saarland	67%	57%	0%	93%	0%	100%	100%	0%	0%	0%
Berlin	0%	75%	0%	25%	0%	100%	100%	0%	0%	0%
Brandenburg	15%	53%	0%	83%	0%	100%	100%	0%	0%	0%
Mecklenburg-Western Pomerania	34%	52%	0%	81%	0%	100%	100%	0%	0%	0%
Saxony	15%	40%	0%	78%	0%	100%	100%	0%	0%	0%
Saxony-Anhalt	17%	39%	0%	79%	0%	100%	100%	0%	0%	0%
Thuringia	13%	44%	0%	82%	0%	100%	100%	0%	0%	0%
Germany	42%	35%	0%	84%	0%	100%	100%	0%	0%	0%
G_d—duration of grazing period per year										
Schleswig-Holstein	46%	54%	0%	87%	0%	90%	0%	0%	0%	0%
Hamburg	52%	62%	0%	77%	0%	90%	0%	0%	0%	0%
Lower Saxony	46%	52%	0%	75%	0%	90%	0%	0%	0%	0%
Bremen	48%	54%	0%	73%	0%	90%	0%	0%	0%	0%
North Rhine-Westphalia	50%	52%	0%	79%	0%	90%	0%	0%	0%	0%
Hesse	46%	54%	0%	73%	0%	90%	0%	0%	0%	0%
Rhineland-Palatinate	46%	54%	0%	81%	0%	90%	0%	0%	0%	0%
Baden-Wuerttemberg	44%	50%	0%	73%	0%	90%	0%	0%	0%	0%
Bavaria	40%	46%	0%	67%	0%	90%	0%	0%	0%	0%
Saarland	50%	56%	0%	79%	0%	90%	0%	0%	0%	0%
Berlin	0%	0%	0%	0%	0%	90%	0%	0%	0%	0%
Brandenburg	50%	75%	0%	81%	0%	90%	0%	0%	0%	0%
Mecklenburg-Western Pomerania	48%	65%	0%	83%	0%	90%	0%	0%	0%	0%
Saxony	46%	56%	0%	65%	0%	90%	0%	0%	0%	0%
Saxony-Anhalt	48%	63%	0%	77%	0%	90%	0%	0%	0%	0%

Table 5 (continued)

	Dairy cattle	Other cattle	Pigs	Sheep	Chicken	Goats	Horses	Turkeys	Ducks	Geese
Thuringia	48%	60%	0%	65%	0%	90%	0%	0%	0%	0%
Germany	46%	54%	0%	73%	0%	90%	0%	0%	0%	0%
H_{sm}—straw-based housing										
Schleswig-Holstein	12%	40%	3%	100%	93%	100%	100%	100%	100%	100%
Hamburg	17%	30%	12%	100%	42%	100%	100%	100%	100%	100%
Lower Saxony	14%	34%	4%	100%	89%	100%	100%	100%	100%	100%
Bremen	10%	0%	0%	100%	0%	100%	100%	100%	100%	100%
North Rhine-Westphalia	23%	41%	6%	100%	87%	100%	100%	100%	100%	100%
Hesse	30%	0%	23%	100%	82%	100%	100%	100%	100%	100%
Rhineland-Palatinate	22%	60%	21%	100%	94%	100%	100%	100%	100%	100%
Baden-Wuerttemberg	19%	50%	16%	100%	94%	100%	100%	100%	100%	100%
Bavaria	14%	32%	13%	100%	85%	100%	100%	100%	100%	100%
Saarland	28%	65%	32%	100%	76%	100%	100%	100%	100%	100%
Berlin	0%	0%	100%	100%	100%	100%	100%	100%	100%	100%
Brandenburg	36%	81%	9%	100%	93%	100%	100%	100%	100%	100%
Mecklenburg-Western Pomerania	24%	74%	7%	100%	100%	100%	100%	100%	100%	100%
Saxony	23%	69%	8%	100%	97%	100%	100%	100%	100%	100%
Saxony-Anhalt	31%	80%	6%	100%	83%	100%	100%	100%	100%	100%
Thuringia	27%	69%	8%	100%	99%	100%	100%	100%	100%	100%
Germany	19%	41%	8%	100%	94%	100%	100%	100%	100%	100%
B_a—bedding requirement										
Base data from literature										
Maximum per animal	6	1	1.50	0.6	1220	0.6	6	7	2	11.2
Unit	kg fm (AP d)$^{-1}$	kg fm (AP d)$^{-1}$	kg fm (AP d)$^{-1}$	kg fm (AP d)$^{-1}$	kg fm (1,000 AP a) $^{-1}$	kg fm (A d)$^{-1}$	kg fm (A d)$^{-1}$	kg fm (A cy)$^{-1}$	kg fm (A a)$^{-1}$	kg fm (A a)$^{-1}$
Remarks	fm: fresh matter; AP: animal place; d: day, a: year; A: animal, cy: cycle									
Stable days										
Schleswig-Holstein	197	168	365	49	365	37	365	365	365	365
Hamburg	175	140	365	84	365	37	365	365	365	365
Lower Saxony	197	175	365	91	365	37	365	365	365	365
Bremen	190	168	365	98	365	37	365	365	365	365
North Rhine-Westphalia	183	175	365	77	365	37	365	365	365	365
Hesse	197	168	365	98	365	37	365	365	365	365
Rhineland-Palatinate	197	168	365	70	365	37	365	365	365	365

Table 5 (continued)

	Dairy cattle	Other cattle	Pigs	Sheep	Chicken	Goats	Horses	Turkeys	Ducks	Geese
Baden-Wuerttemberg	204	183	365	98	365	37	365	365	365	365
Bavaria	218	197	365	119	365	37	365	365	365	365
Saarland	183	161	365	77	365	37	365	365	365	365
Berlin	365	365	365	365	365	37	365	365	365	365
Brandenburg	183	91	365	70	365	37	365	365	365	365
Mecklenburg-Western Pomerania	190	126	365	63	365	37	365	365	365	365
Saxony	197	161	365	126	365	37	365	365	365	365
Saxony-Anhalt	190	133	365	84	365	37	365	365	365	365
Thuringia	190	147	365	126	365	37	365	365	365	365
Germany	197	168	365	98	365	37	365	365	365	365
Mg fm a^{-1} (including stable days)										
Schleswig-Holstein	1.182	0.168	0.548	0.029	0.001	0.022	2.190	0.017	0.002	0.011
Hamburg	1.050	0.140	0.548	0.050	0.001	0.022	2.190	0.017	0.002	0.011
Lower Saxony	1.182	0.175	0.548	0.055	0.001	0.022	2.190	0.017	0.002	0.011
Bremen	1.140	0.168	0.548	0.059	0.001	0.022	2.190	0.017	0.002	0.011
North Rhine-Westphalia	1.098	0.175	0.548	0.046	0.001	0.022	2.190	0.017	0.002	0.011
Hesse	1.182	0.168	0.548	0.059	0.001	0.022	2.190	0.017	0.002	0.011
Rhineland-Palatinate	1.182	0.168	0.548	0.042	0.001	0.022	2.190	0.017	0.002	0.011
Baden-Wuerttemberg	1.224	0.183	0.548	0.059	0.001	0.022	2.190	0.017	0.002	0.011
Bavaria	1.308	0.197	0.548	0.071	0.001	0.022	2.190	0.017	0.002	0.011
Saarland	1.098	0.161	0.548	0.046	0.001	0.022	2.190	0.017	0.002	0.011
Berlin	2.190	0.365	0.548	0.219	0.001	0.022	2.190	0.017	0.002	0.011
Brandenburg	1.098	0.091	0.548	0.042	0.001	0.022	2.190	0.017	0.002	0.011
Mecklenburg-Western Pomerania	1.140	0.126	0.548	0.038	0.001	0.022	2.190	0.017	0.002	0.011
Saxony	1.182	0.161	0.548	0.076	0.001	0.022	2.190	0.017	0.002	0.011
Saxony-Anhalt	1.140	0.133	0.548	0.050	0.001	0.022	2.190	0.017	0.002	0.011
Thuringia	1.140	0.147	0.548	0.076	0.001	0.022	2.190	0.017	0.002	0.011
Germany	1.182	0.168	0.548	0.059	0.001	0.022	2.190	0.017	0.002	0.011

Abbreviations

CNG: Compressed natural gas; DLM: Digital Landscape Model; FM: Fresh matter; GHG: Greenhouse gas; GIS: Geo-Information System; HGV: Heavy goods vehicle; LCA: Lifecycle assessment; LNG: Liquefied natural gas; NUTS: Nomenclature des unités territoriales statistiques; RED: Renewable Energy Directive; TRL: Technology readiness level; UN: United Nations; VS: Volatile solids.

Acknowledgements

The authors thank the Federal Agency for Cartography and Geodesy (BKG) for providing the geodata, and Vereinigte Bioenergie GmbH (VERBIO) and Stefan Majer (DBFZ) for the friendly sharing of knowledge.

Authors' contributions

AB designed the analysis, collected the literature, processed the data and wrote the manuscript. RB and DT supervised the research and supplemented parts of the manuscript. All authors read and approved the final manuscript.

Funding

Open Access funding enabled and organized by Projekt DEAL. These findings were gathered as part of the "Pilot plant for synthetic biogas (Pilot SBG)" project, commissioned by the Federal Ministry of Transport and Digital Infrastructure (BMVI). The authors would also like to thank the BMVI for funding the "OpenGeoEdu" project, part of the mFUND programme (Funding no./FZK: 19F2007A).

Availability of data and materials

The compiled data will be publicly available at DBFZ Resource Database following http://webapp.dbfz.de.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Received: 25 February 2020 Accepted: 24 November 2020

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