Renewable and Sustainable Energy Reviews 150 (2021) 111449

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

Biomass flow in bioeconomy: Overview for Germany

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ARTICLE INFO

Keywords:
bioeconomy
Biomass flow
Germany
Sankey diagram

ABSTRACT

The sustainable management of renewable resources is one of the crucial pillars in the encouraged transition from a fossil-based economy towards a sustainable bioeconomy in Germany. In order to support the current strategic actions, endorsed by the National Bioeconomy Strategy (2020), a broad range of information about the bioeconomy must be generated in terms of available biomass sources and their uses. This study presents a contribution towards bioeconomy knowledge, with the calculations and depiction of the biomass flows of production and use in the German bioeconomy. First, the system boundaries for this study were established. The system includes agriculture, forest and biogenic residues and waste as biomass producing and generating sectors, and food, feed, material, and energy as biomass use sectors. Further, the net trade of biomass was considered. An extensive collection and processing of available official data and its harmonisation was carried out and validated with experts. Core of the study was the construction of a biomass flow Sankey diagram for the year 2015. Our results showed, that the most important consumer of the agricultural biomass was the food and feed sector with about 95 million tons of dry matter. The total amount of biomass from biogenic residues and waste summed up to 32 million tons of dry matter, of which 22 million tons of dry matter were used by the energy sector. The forest sector produced around 33 million tons of dry matter of woody biomass, of which around 20 million tons of dry matter forest biomass was used as solid fuel.

1. Introduction

Sustainable development is the overall principle to meet human development goals and to protect the planet at the same time. The United Nations (UN) has developed the Agenda 2030, and formulated the Sustainable Development Goals (SDGs) [1] and targets for a wide range of aspects of sustainability. One important pillar is the sustainable management of resources. The use of fossil resources implies environmental risks and pressure, as well as dependency on limited and imported resources [2]. A transition from a fossil-based towards a fossil-free, resource-efficient economy, based on renewable resources, is therefore an important contribution for a sustainable development. To support the shift towards a renewable, bio-based economy, the Germany Federal Government has established the Bioeconomy Council, launched a German Research Strategy of Bioeconomy in 2010 [3] and a National Policy Strategy on Bioeconomy in 2013 [4]. Furthermore, a new comprehensive bioeconomy strategy for Germany was published in 2020 [5]. For the purpose of this study, bioeconomy is defined as "the production and utilization of biological resources (including knowledge) to provide products, processes and services in all sectors of trade and industry within the framework of a sustainable economy" [5]. According to this definition, bioeconomy includes numerous sectors, among them agriculture, forestry, fishery and aquaculture, as biomass producing sectors and food, feed, bioenergy and materials, as biomass using sectors. Bioeconomy besides includes policy areas in the fields of environment, sustainability, climate, and research and innovation. The development and use of bio-based products and services concerns

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https://doi.org/10.1016/j.rser.2021.111449
Received 19 June 2020; Received in revised form 12 June 2021; Accepted 2 July 2021
Available online 23 July 2021

Abbreviations

BLE	Bundesanstalt für Landwirtschaft und Ernährung (Federal Office for Agriculture and Food)
BMEL	Bundesministerium für Ernährung und Landwirtschaft (Federal Ministry of Food and Agriculture)
CU	cereal unit
dbh	diameter at breast height
DESTATIS	Statistisches Bundesamt (Federal Statistical Office)
DM	dry matter
FNR	Fachagentur Nachwachsende Rohstoffe e. V. (Agency for Renewable Raw Materials)
GWhel	gigawatt hours electric
JFSQ	Joint Forest Sector Questionnaire
JRC	Joint Research Centre
JWEE	Joint Wood Energy Enquiry
MM	million
SDG	Sustainable Development Goal
SRC	short rotation coppice
t(atro)	tons of completely dry wood matter
tDM	tons of dry matter
tFM	tons of fresh mass
UBA	Umweltbundesamt (Federal Environment Agency)

different stakeholders along the value chains, such as research, policy, industry, Non-Governmental Organization (NGO), and the society as a whole. Bioeconomy makes up an important part of the economy in Germany [6]. Its contribution was estimated at a 6% share of the gross value added and a 12% share of the employment in the national economy for 2010 [6]. To ensure that the opportunities associated to a bioeconomy will be exploited and possible risks will be reduced, a sustainable bioeconomy strategy can play an important role. A bioeconomy monitoring system can be a useful tool used for monitoring the bioeconomy in general or the implementation of a strategy. The European Union (EU) as well as Germany are aiming to establish a bioeconomy monitoring system that includes the resource potential, main drivers, economic and environmental figures. For all those, and further decision making in the bioeconomy field, a transparent data set about the biomass flows is a cornerstone. Currently, there is no established manner to represent the biomass flows at a national level in Germany, which depicts the generation of all biomass types and its allocation to different bioeconomy uses sectors. The pioneering work on a representation of biomass flows in bioeconomy on the EU level, as well as on the level of individual member states is described in Gurría et al. (2017) [7] and Camia et al. (2018) [8]. Following the approach taken by the Joint Research Centre (JRC) in the EU biomass flows technical report, this paper aims at providing a representation of the biomass flows in the bioeconomy for Germany, depicting the supply of biomass from agriculture, forestry, and biogenic residues and waste (in the following named "residues/waste"), their use for food, animal feed, material and energy sectors, as well as their net trade.

This paper is structured as follows: In section two, the overarching methodology is detailed, including the design of the Sankey diagram, data collection and management, as well as the delimitation of the system for the calculations. The results are then presented in section three, showing the final Sankey diagram and describing the encountered or calculated biomass flows for each production and use category. The paper then finishes with a discussion and outlook.

2. Methodology

To build up the status quo of biomass flows for Germany, first, the system boundaries are set by applying the bioeconomy definition of the German Bioeconomy Council [9] as overall framework. As next, biomass types are grouped in biomass production/generation and use categories: “agriculture”, “forest” and “residues/waste”. The fisheries and aquaculture sector is excluded of the analysis, as we have focused on the vegetable parts of the biomass in our work (with some exceptions e.g. sums of oils and animal fats - as these cannot be separated in the statistics). In the calculation of the foods used, we included therefore the vegetable fractions. Finally, the residues/waste comprises a broad range of biomass from different sectors, described in 3.4.

The categories and units (tDM) follow other studies in this field (see e.g. Refs. [7,8]). However, since in such detailed reports there are uncertainties of trade data e.g. of living animals or the production and use of feed, we opted for an aggregated presentation of the flow streams (without more detailed categories). Nevertheless, compared to the studies, our results also yielded comparable results. A Sankey diagram structure is built up for the representation of the biomass sectors and flows (unused biomass is not considered). To reach a harmonized data set, relevant data from official statistics, individual reports and surveys are compiled, evaluated, and processed. In order to complete the Sankey diagram of biomass flow within the bioeconomy, extensive cross-sectoral calculations are carried out between the different disciplines. Then, the structured biomass flows are visualised by means of a Sankey diagram. The detailed description of all steps is followed in the next chapters.

2.1. Sankey diagram structure

To summarize and visualize Germany’s biomass flows from raw biomass to each determined use in the bioeconomy sectors, namely materials, energy, food and feed, the tool Sankey diagram was selected and applied, using the software e!Sankey. The three main categories are applied according to the priorisation of the biomass use: first food and feed, then material and finally at the end of the pathway for energy, as applied e.g. in the National Bioeconomy Strategy in Germany.

In the Sankey diagram, flows are represented by arrows, where the width proportionally indicates the magnitude of the flows. The directed flows are always formed at least between two nodes, indicating, aside from quantities, information about the connections of the system [10]. The process of developing the Germany’s bioeconomy Sankey diagram was set up into two steps, with iterative revisions. The first step was to create the structure, including the main biomass generation groups and biomass uses as well as an initial assignment of biomass types within the expected corresponding processes. Existing studies, at EU level such as the JRC technical report [7], at national level (Kalt, G. 2015 [11]), on material flow of selected biomass types (Weimar, H. 2011 [12]) and some with special focus on the energetic or material use of biomass (e.g. Thrän et al., 2018 [13]) were revised. The second step was to identify the actual flows, to adjust the initial structure, to collect and process data and add quantities to the diagram. This included the creation of a systematic overview of available data, including data sources, type and unit as well as year and geographical unit of the availability. In order to integrate the data of different sectors (agriculture, forest and biogenic resources), the physical unit for all biomasses was defined as tons of dry matter (tDM). The harmonisation of units across all sectors required the use of conversion factors.

2.2. Data sources and management

For a comprehensive overview of the material flows of biomass, annually updated publications, official statistics and surveys were reviewed. During the data gathering process, data gaps were identified and discussed with experts. Data from different sources were subject to a cross-check procedure to identify possible inconsistences.

For the producing/generating sectors – agriculture, forest and residues/waste – the following primary sources were used for the description of biomass from agriculture for food and feed, energy and material use: the statistical yearbook of the Federal Ministry of Food and Agriculture (BMEL, 2017, 2018) [14,15], data from the Federal Statistical Office (DESTATIS, 2011, 2015a,b) [16–18], graphic and tables from the Agency for renewable raw materials (FNR, 2014, 2017, 2018) [19–21], and Guzmán et al. (2014) [22], the third National Forest Inventory [23] and the Estimation of Wood Removals and Fellings [24], Federal Environment Agency (UBA) [25], DESTATIS [26], Joint Forest Sector Questionnaire (JFSQ) [27] and Joint Wood Energy Enquiry (JWEE) [28]. Regarding woody biomass from agricultural areas, the data for SRC were calculated based on an information sheet from Ref. [29] and own calculations.

Residues/waste encompasses residual and waste materials accumulated during or after harvest, as well as during the processing of biomass. Data under this category include e.g. by-products of cereal cultivation, peel, bran and flour-dust generated by producing cereal flours, also dried spent grains, malt sprouts, brewer's yeast, stillage as well as starch products for potato protein or corn gluten [30]. Additional residues/waste materials accounted for are pomace or ingredients of vinasse. Data collections on recovered paper, post-consumer recovered wood and glycerin are based on officially available statistics which are collected annually ([25–28,31]).

In regard to the biomass use sectors – namely food and feed, material, and energetic use – extensive data surveys were carried out. Individual biomass was grouped into several clusters and then calculated for 2015, the most recent year, in which all required data was available.

Material use of agricultural biomass was calculated based on data from Brosowski 2016 [30], BMEL/FNR [32,33] and FAOSTAT [27,34]. To describe the material flow for biogas production [35,36] the results of the annual survey of biogas plant operators in Germany was used. In this context the utilization of slurry includes both slurry and solid manure. Based on BMEL/FNR data [32] the material flow to biofuels was described, including vegetable oil fuels, rapeseed oil, biodiesel and sugar for bioethanol from cereals and sugar beets, animal fats and used cooking oils for biodiesel. For the data collection on solid fuels specific literature and sources were reviewed [14,27,28,32,37–40]. Solid biofuels for combustion can be Miscanthus, SRC, paludi, straw, landscaping residues, fuelwood from the forest, post-consumer recovered wood, charcoal, pellets, briquettes, saw by-products, black liquor and other industrial wood. For the determination of SRC own cross-sectional calculations were carried out [39]. To obtain data on single biomasses (e.g. bran, beer berry, malt germ, oil cake, molasses and others), own calculations were carried out based on [32]. Finally, to present the sum of agricultural biomass net trade (import-export), statistical data was applied [14]. Data on net-trade of woody biomass are gathered from UBA [25], DESTATIS [26], JFSQ [27] and JWEE [28].

To ensure a transparent and a clear overview, and for future visualisation, the numerous categories of biomasses are assigned to a total of three main categories of biomass production or generation: agriculture, forestry and residues/waste. All quantities are set to MM tDM and conversion factors used when necessary to transform data into this named unit. Respective data are provided in Tableas and Figures and in the Annex I.

Each of the three delimited biomass production categories shown in the Sankey refer to the first processing phase of the biomass (raw biomass). In the following, materials have been associated to raw biomass (e.g. wood fibres stem from forest biomass), with few exceptions, e.g. SRC is associated to agriculture. Another example for associated raw biomass is the residual timber and agricultural accompaniments, which are described in the category residues/waste. Slurry and manure for use in biogas plants also are included in the category residues/waste. Already used biomasses (e.g. in cascades-municipal organic waste) are assigned to residues/waste.

The description of individual categories as well as their data sources and harmonisation is presented in more detail in Annex II.

3. Results

3.1. Biomass flow diagram

First, the structure of the Sankey diagram was created and presented in Fig. 1. At the left-hand side of the figure the three biomass producing/generating sectors can be found, at the right-hand side the use sectors are shown, and the trade is included as well.

1. For the agriculture we consider 17 MM ha, for the forestry 11.4 MM ha. 2. Please note that the green arrows from the box **Energy/Materials** to **Materials** and **Solid fuel** contain amounts of Residues and Waste whose totals are difficult to determine.

The developed bioeconomy Sankey structure represents the biomass flows in Germany in 2015 (the unused, but available biomass is not included). The fisheries and aquaculture sector is excluded of the analysis, as we have only focused on the vegetable parts of the biomass in our work (with some exceptions, e.g. totals of oils and animal fats - as these cannot be separated in the statistics). This representation can be explained through the characterisation of the interrelationships of the different biomass resources (in a first stage), the resulting bio-based streams (after conversion and processing), with the national infrastructures of the different analysed sectors. In order to explain the different interrelationships, please refer to the following sections.

3.2. Biomass from agriculture

3.2.1. Agricultural land use and volumes

In Germany, about 17.0 MM ha (ha) or 47% of the entire land is used for agriculture [14]. In 2016, 11.8 MM ha (71%) of total agricultural used area were used as arable land, 4.7 MM ha (28%) as permanent grassland and permanent crops covered 0.2 MM ha (about 1%).

Table 1 shows the calculation of volume of biomass produced on area used for agriculture, although by harvest volumes only the main output (e.g. grain from cereals) is considered. This calculation indicates a total volume of about 215 million tons of fresh matter. The dry matter (DM) volumes were calculated using the dry matter conversion factors. The total volume of biomass in Germany for 2015 equals 117 million tDM.

Regarding uses two different types of conversion factors could be applied: the cereal unit (CU) mostly used for food and feed (Brankatschek & Finkbeiner, 2014) [42], and the dry matter (DM) usually applied for the energy or material use.

Since the DM is more used internationally, and it allows to sum over biomass types from all sources, it was applied in this paper (see Table 1).

3.2.2. Agricultural biomass uses and trade

In the Sankey diagram the upper arrow "Net Trade" is used to depict the net trade (import – export) of two types of biomass: primary crops (related to category "biomass from agriculture") and processed biomass used as animal feed (related to category residues/waste), which actually restricted to the most important imported product, soya meal. Table III/1 summarises the respective calculation for Germany in 2015. Germany is a net-importer, mainly due to high imports of oilseeds, corn and soya meal. The net import of primary agricultural products is estimated at 5.4 MM tDM. With additional net import of soya meal at 0.95 MM tDM the total net trade amounts to 6.3 MM tDM. The Trade with primary agricultural biomass is presented in Table III/1 in Annex III.

3.2.3. Agricultural biomass use for food and feed

Table 2 shows the calculation of biomass used in Germany in 2015 for animal feed. The total estimated volume is 208 MM tFM or approximately 80 MM tDM. Non-marketable feed such as fresh grass, grass silage, hay and maize silage make together almost 47 MM tDM and therefore more than a half of total biomass. Marketable primary feed is dominated by cereals and makes further 22 MM tDM. Animal feed obtain from processing cover the rest 12 MM tDM; here the oil cakes/meals is the main category.

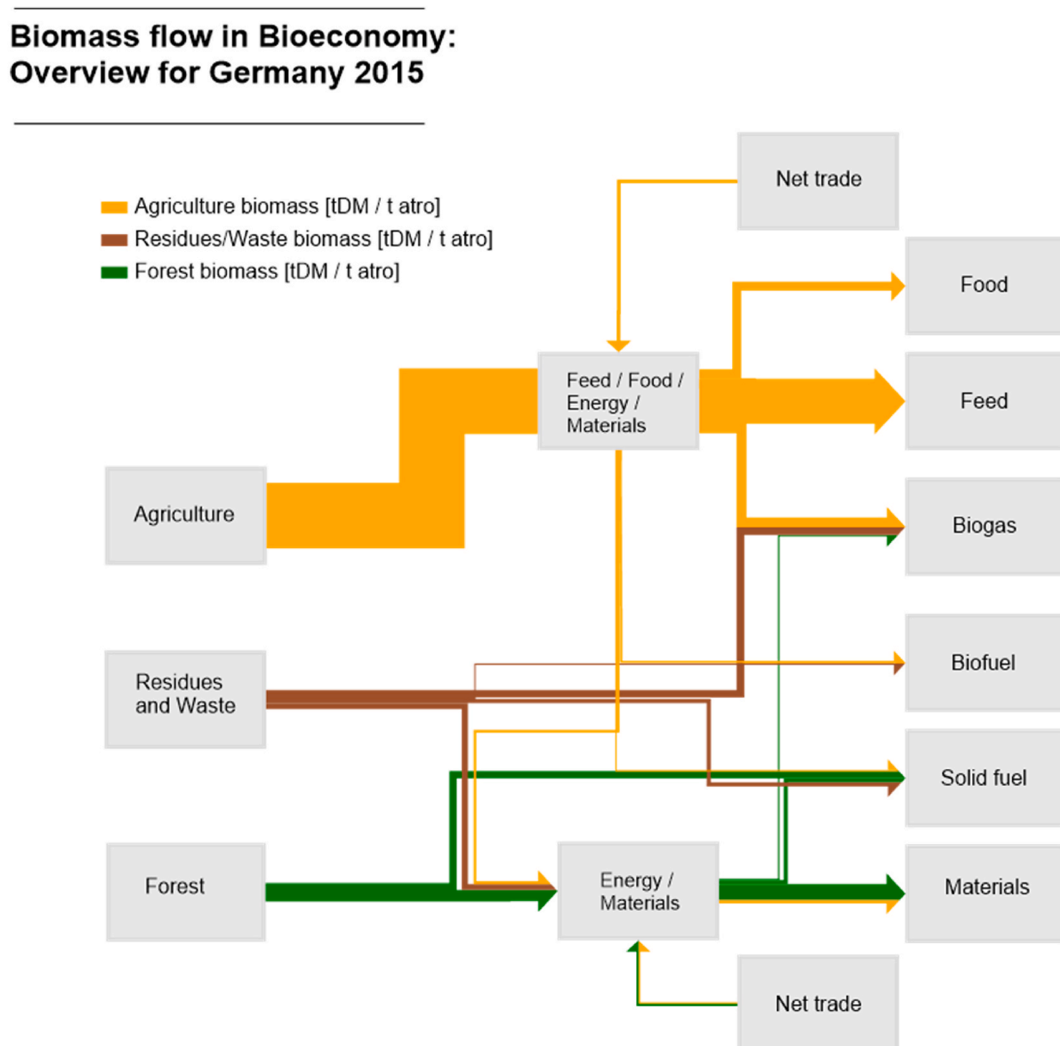

Fig. 1. Biomass flow in Germany (2015) in tDM/tons (t) of completely dry wood matter (t(atro)).

The volume of biomass used for plant-based food is an estimate. Taking into account some identified discrepancy regarding allocation of biomass from agriculture (silage maize, green fodder) it was estimated to be approximately 15.5 MM tDM.

3.2.4. *Agricultural biomass for material and fibre production and use*

Renewable raw materials are used in the economy for a multitude of different products, ranging from natural fibre-based textiles to bio-based chemicals. While the data on the domestic consumption of renewable raw materials is provided in tDM, the domestic supply is given in ha of cultivation areas. In order to derive the domestic supply in tDM, average hectare yields in Germany have been used. Based on data from Brosowski 2016 [30] the material supply of straw was calculated at 4.1 MM tDM for 2015.

As a result, Table 3 shows the domestic supply, consumption and import demand for renewable agricultural raw materials for material uses. Approximately 5 MM tDM agricultural biomass can be provided for the production of materials or bedding for animals.

3.2.5. *Agricultural biomass for energetic conversion and use*

The total biomass quantity for energy supply from all three categories (agriculture, forest, residual/waste) in Germany in 2015 amounts to approximately 64 MM tDM according to our calculations. Agriculture with renewables and residues/waste with high share of liquid manure and waste wood account for 34% of the energetic use of biomass. The forest has a slightly smaller fraction of 31%. If the waste wood and wood used for landscape conservation were to be counted as forest and the waste fats etc. as agriculture and residues/waste were completely excluded, the distribution would still be 57% in favour of agriculture compared to 43% for forest. The largest share of agricultural raw materials for conversion into electricity in biogas plants is occupied by maize, maize silage and whole plant silage (see Table 4). Maize continues to play the dominant role, both through domestic cultivation and imports. Bioethanol and biodiesel crops such as rapeseed and cereals are in second place with approximately 3.8 MM tDM (see Table 4) and are applied in the transport sector. Straw, SRC and Miscanthus as solid fuels support energy production with a total of 168.375 tDM (shown in Table 4).

According to a study by the DBFZ [36] in 2015, energy crops are the main consumption with 51% in biogas plants. At the same time, maize silage accounts for the highest share of the mass-based substrate quantity at 73%. This is due to the high efficiency of the energy supply, as 51% of renewable energies in biogas plants supply 73% of the energy [36].

At the end of 2015, Germany had approximately 8,900 biogas plants with an installed electrical energy of 4,410 MW (MW) and a possible electricity generation of 27.9 terrawatt hours (TWh). In addition, at least 2.2 TWh of electrical energy was generated by biomethane [44]. Electricity generation from biogas (including biomethane) reached around 32,370 GW h electric (GWh_{el}) in 2016 [45]. This corresponds to 17.2%

Table 1
Biomass harvested from agricultural used area (economic production) in Germany in 2015*.

Crop	Cultivated area, 1000 ha	Crop yield, t/ha	Harvest volume, 1000 t	DM conver-sion factor	DM volume tDM/ha	DM volume 1000 tDM
Cereals (grain production)	6,529	7.49	48,884	0.860	6.44	42,040
Wheat	3,283	8.09	26,550	0.860	6.95	22,833
Barley	1,622	7.17	11,630	0.860	6.17	10,002
Rye (incl. other winter cereals)	616	5.66	3,488	0.860	4.87	3,000
Oat	126	4.49	566	0.860	3.86	487
Other spring cereals	14	4.43	62	0.860	3.81	53
Triticale	402	6.46	2,598	0.860	5.56	2,234
Maiz	455	8.73	3,973	0.860	7.51	3,417
Others	11	1.50	17	0.860	1.29	14
Pulses	**160**	**3.05**	**488**	**0.860**	**2.62**	**419**
Peas	79	3.51	277	0.860	3.02	238
Field beans	38	3.50	133	0.860	3.01	114
Sweet fodder lupins	30	1.27	38	0.860	1.09	33
Others	13	3.05	40	0.860	2.62	34
Root crops	**554**	**59.89**	**33,182**	**0.243**	**14.54**	**8,055**
Potatoes	237	43.76	10,370	0.227	9.93	2,354
Sugar beet	313	72.12	22,572	0.250	18.03	5,643
Others	4	59.89	240	0.243	14.55	58
Oil fruit for grain	**1,332**	**3.83**	**5,103**	**0.910**	**3.49**	**4,644**
Winter rape	1,282	3.91	5,008	0.910	3.55	4,557
Spring rape, bird rape	4	2.25	9	0.910	2.05	8
Sunflowers	18	1.94	35	0.910	1.77	32
Others	28	1.80	51	0.910	1.64	46
Other industrial crops	**42**	**6.40**	**267**	**0.583**	**3.73**	**156**
Hops	18	1.54	28	0.200	0.31	6
Culinary plants	4	20.00	82	0.200	4.00	16
Aromatic and medicinal plants	8	1.34	11	0.900	1.21	10
Miscanthus	5	15.00	68	0.850	12.75	57
Other energy crops	7	12.00	78	0.850	10.20	66
Plants harvested green	**2,746**	**34.19**	**93,886**	**0.350**	**11.97**	**32,860**
Silage maize	2,100	41.53	87,219	0.350	14.54	30,527
Others	646	10.32	6,667	0.350	3.61	2,334
Vegetables	**137**	**27.91**	**3,824**	**0.098**	**2.74**	**375**
Brassicas	19	44.06	824	0.097	4.26	80
Leafy and stalked vegetable	46	13.71	632	0.080	1.09	50
Root, tuber & bulb vegetables	29	45.42	1,333	0.120	5.45	160
Vegetables cultivat. For fruit	9	35.89	328	0.044	1.57	14
Fresh pulses	11	6.93	78	0.121	0.84	9
Other veget. (incl.under glass)	23	27.91	629	0.098	2.74	62
Fruits	**66**	**19.98**	**1,308**	**0.164**	**3.28**	**215**
Apples	31	30.99	973	0.175	5.42	170
Pears	2	22.68	43	0.166	3.77	7
Stone fruits	12	8.69	100	0.175	1.52	17
Strawberries	14	11.46	161	0.102	1.17	16
Other berries	7	4.76	32	0.102	0.49	3
Permanent grassland	**4,495**	**6.29**	**28,262**	**1.000**	**6.29**	**28,262**
Meadows and pastures	4,495	6.29	28,262	1.000	6.29	28,262
TOTAL	**16,054**	13.03	**215,125**	0.544	7.29	**117,026**

Source: Own calculation based on data from BMEL (2018, 2017) [15], [14], [41], DESTATIS (2011, 2015a,b) [16–18], FNR (2014, 2017, 2018) [19–21], Guzmán et al. (2014) [22], LfL (2017a, b) [55,56], Schmitz & Pforte (2014) [57], Vetter & Biertümpfel (2001) [58].

of gross electricity generation from renewable energies. Electricity generation from biomass continued to increase. Biogas and biomethane accounted for around 5% of gross electricity generation in Germany [45]. According to calculations, in 2015 the substrates to biogas and biomethane for electricity production were covered with renewable raw materials, animal excrement as well as waste from residual materials with approximately 31.3 MM tDM. This corresponds to an estimate by Lenz et al. [44] for the year 2015, whose article refers to about 32 MM t (atro). A further upward trend can be achieved in the coming years, above all by increasing the capacity of existing plants through flexibilisation and a more active use of waste food from agricultural production.

Bioethanol and biodiesel crops such as rapeseed and cereals are in second place with 18% (approximately 3.8 MM tDM) and used in the transport sector. Further biofuels or biogenic raw materials for fuel production are imported to a considerable extent to meet the demand of the petroleum industry for biofuels for blending with diesel fuel or petrol under quota obligations [46]. Biodiesel as a fuel is now almost exclusively added to fossil fuel (B7: diesel with a maximum of 7% biodiesel (vol.)). In 2015, around 1.9 MM t were consumed (provisional estimate based on Federal Office of Economics and Export Control (BAFA): Amtliche Mineralöldaten, March 2015 [44]). Only 0.2% are marketed as pure fuel (approximately 3400 t) [44]. Germany continues to be the largest ethanol market in the EU and has saved around 1 billion litres of petrol by 2016 [47].

In the transport sector, biomethane plays a subordinate role among renewable fuels with 1.1% [48]. For the use of pure vegetable oil, rapeseed oil for biodiesel, sugar for bioethanol from cereals, sugar for bioethanol from sugar beet for the transport sector, a total of 3.8 MM tDM were calculated.

The heat supply from biogas and biomethane reached around 16.9 TWhth in 2016. This corresponds to about 1.4% of the final energy consumption for heat or 10.4% of the heat supply from renewable energies [45]. In 2015, agriculture potentially produced about 1.71% heat from vegetable oil and biodiesel [44].

Own calculations based on the Statistical Yearbook [14], BMEL/FNR

Table 2
Biomass used for animal feeding in Germany (2015).

	Volume 1000 tFM	DM conversion factor	Volume 1000 tDM
Cereals	24,897	0.86	21,411
Pulse	298	0.90	268
Oil seeds	87	0.91	79
Dry green fodder	282	0.86	242
Sum primary feeding stuff	**25,563**	**-**	**22,001**
Oil cakes/meal	8,957	0.88	7,882
Other	4,016	–	3,558
Sum feeding stuffs obtain from processing	**12,973**	**-**	**11,441**
Grass, fresh	34,732	0.18	4,689
Grass, silage	65,060	0.35	17,078
Grass, hay	8,016	0.86	5,170
Silage maize	56,692	0.35	19,842
Potatoes	607	0.23	138
Intermediate crops, straw etc.	4,265	–	–
Sum non-marketable feedstuff*	**169,372**	**-**	**46,917**
TOTAL	**207,908**	–	**80,359**

*DM excl. Intermediate crops, straw etc. Source: German statistic on feed resources (BLE, 2017 [43]).

Table 3
Domestic consumption, supply and demand of renewable agricultural raw materials for material uses (in tDM, 2015).

Raw material	Domestic consumption for material uses (tDM)	Domestic supply (tDM)	Import demand (tDM)
Starch	870,000	668,250	201,750
Sugar	144,000	155,228	−11,228
Fats and oils	1,145,000	203,351	941,649
Proteins	114,000	0	114,000
Natural fibres	136,000	2,682	133,318
Others*	596,000	9,889	586,111
Straw	-	4,173,928	–
Total	**3,005,000**	**5,213,328**	**1,965,600**

* The category "Others" contains also resources from the agricultural sector (rubber and cork).
Source: Own calculation based on data from: Brosowski, 2016 [30], FNR, 2017 [20], BMEL/FNR, 2018 [32].

[32], DBFZ database and various sources (e.g. for SRC and Miscanthus) were used for the modelling of solid fuels from agricultural land [39]. There was a slight upward trend in the use of straw, grass and SRC as solid fuels up to 2015, as well as for energy crops. Since 2015, the cultivated areas have remained constant at 1000 ha and the volumes at 166,000 tDM, as a study from BMEL/FNR [32] shows. These data show sums similar to the calculations of the present modelling, according to which approximately 144,375 tDM of biomass will be used as solid fuel in 2015. SRC is mainly used domestically and is based on agricultural subsidies with a consumption of 20,000 tDM. An extension of the SRC subsidies and the extension of the SRC cultivation to possible urban uses could bring about a sustained upward trend in the future. Since 2012, the energy consumption of grain straw has increased significantly from 20,000 tDM to DM 90,000 tDM [32]. This is partly due to the fact that the first straw-fired combined heat and power plant in Germany with a yearly consumption of 62,000 tDM and a thermal output of 49.8 MW was built in recent years. An overall slight increase or the development of the cultivation of energy crops for biogas plants in Germany can be recorded [32]. The cultivation of alternative energy crops, such as silphia, is particularly striking. In northern Germany, a biomass combustion plant with paludi substrate was commissioned for the first time in 2014 [38].

Table 4
Agricultural biomass in descending sums and use for energy purposes.

Energetic Use	Agricultural biomass	Year	Sum [tDM]
Biogas	Sum renewables for biogas		17,564,807
Biogas	Maize silage	2015	13,082,850
Biogas	Gras silage and cereal whole crop silage	2015	3,676,757
Biogas	Sugarbeat	2015	333,000
Biogas	Catch crops	2015	233,100
Biogas	Other	2015	233,100
Biogas	Cup plant	2015	6,000
Biofuel	Sum of Bioethanol-biodiesel biomass (without Net Trade) Sum of bioethanol-biodiesel biomass with Import of Soya and Palm oel		**3,868,580** **4,059,580**
Biofuel	Rapseed oil for biodiesel	2015	2,230,000
Biofuel	Sugar for bioethanol from cereal	2015	1,148,400
Biofuel	Sugar for bioethanol from sugarbeat	2015	488,180
Biofuel	Palm oil for biodiesel - Import	2015	121,000
Biofuel	Soya oil for biodiesel - Import	2015	70,000
Biofuel	Pure plant oil (PPO)	2015	2,000
Solid fuel	Sum biomass for solid fuels	**168,375**	
Solid fuel	Straw	2015	90,000
Solid fuel	Miscanthus	2015	57,375
Solid fuel	SRC	2015	2,000
Solid fuel	Paludi	2014	1,000

Source: Own calculation based on data from: Dahms 2015 [38], Daniel-Gromke et al., 2017 [35,36], BMEL/FNR 2018 [32], AFC Consulting 2016 [41], Energy Crops [39], DBFZ 2018 [40], DLG 2012 [29], FNR 2017 [33].

3.3. *Woody biomass from forest*

The data on forest area and forest biomass used for the present study are obtained from the Third National Forest Inventory [23], the Estimation of Wood Removals and Fellings [24] and the reports in the JFSQ [27]. This data gives important information on forest development, timber harvesting potentials and wood removals in Germany. All figures are subject to conversion and rounding. The total volumes are calculated as weighted mean of coniferous and non-coniferous shares of wood biomass. The conversion factors are given in a Table I/1, see Annex I. In 2012, the German forests occupied approximately 11.4 MM ha [23]. In the same year, German growing stocks per hectare amount to round about 159 tDM and thus, belongs to the largest in Europe 3. The mean annual timber volume increment from 2002 to 2012 was about 5 tDM per hectare and year[1] while the average annual amount of wood removals was around 4 tDM per hectare and year. The total growing stock increased about 7%.

In 2015, total wood removals in form of forest biomass (incl. Bark) approximated 32.9 MM tDM. The domestic supply of industrial roundwood for material use diameter at breast high (dbh) > 7 (course wood) was 19.6 MM tDM and thus, about 5 MM tDM above the level of 2000. Before 2008, Germany was a net-exporter of industrial roundwood but became a net importer of - mainly coniferous – round wood in 2009. In 2015, net imports exceeded 2.5 MM tDM. The available amount of bark per year depends on the amount of felling and is calculated as the proportion of reported fellings in a given year. Based on the findings of the Third National Forest Inventory [23] and Brosowski et al. [49], it is assumed that 45% of the available bark remains in the forest while the other 55% are used. For the year 2015, we calculated the amount of bark extracted from the forest at 2.0 MM tDM.

From 2000 to 2005, the woody biomass demand leaped up more than 10 MM tDM and since then varied between 36 MM tDM and 42 MM tDM per year. Between 2002 and 2012, around 78% of the wood used was coniferous. The use of non-coniferous wood hardly varies and was

[1] Harvestable volume under bark of trees dbh>7 cm in m^3/a of used stand. In the following the unit m^3 indicates the harvestable volume under bark of trees dbh>7 cm in m^3/a of used stand, unless indicated otherwise.

determined by fuelwood production. Between 2000 and 2015 the portion of fuelwood from forests in the total wood supply has grown from 15% to 34%. By 2015, around 70% of the non-coniferous wood removals was used as fuelwood (Jochem et al. [24]).

3.3.1. Forest biomass in material fibre processing

Forest biomass is the raw-material for and input to material fibre processing. In 2015, 19.6 MM tDM of domestically harvested wood plus 0.4 MM tDM of bark entered into material fibre processing. Another 4.1 MM tDM of wood was imported at the same time as 1.8 MM tDM was exported. In addition, around 1.0 MM tDM of post-consumer recovered wood and 10.6 MM tDM of waste paper were used as raw materials in wood-based panel (post-consumer recovered wood) and the paper industries (recovered paper). Spin-off products from wood processing are transformed to energy products (e.g. briquettes, pellets) or directly used as solid fuel (e.g. sawing by-products).

3.3.2. Wood fibres in material use

Fibres are processed to semi-finished products which enter into material use. In total, 34.0 MM tDM of raw woody fibres was used to produce 10.0 MM tDM sawnwood, 5.1 MM tDM wood-based materials, 2.1 MM tDM wood pulps, and 15.9 MM tDM of paper products. All these semi-finished goods are also subject to international trade. Trade activities resulted in an accumulated net import quota for wood pulp equal to 2.9 MM tDM and an accumulated net export quota for sawnwood, wood-based panels, and paper products equal to 1.0 MM tDM, 0.2 MM tDM and 1.5 MM tDM respectively. In sum, 33.3 MM tDM semi-finished wood-based material products are used in various industries including the construction sector and furniture industries and - to a minor extent – e.g. the textile or chemical industry.

3.3.3. Forest biomass for energetic use as solid fuels

Forest biomass is used as solid fuel for heat and power generation. The major share of woody biomass in solid fuels comes directly from the forest. Solid fuels from the forests comprise: fuelwood dbh> 7 cm (cm) at the thinner end (course wood), forest wood residuals dbh <7 cm at the thicker end (uncoarsed wood), and bark. In sum, 9.5 MM tDM of fuelwood, 2.0 MM tDM of forest wood residuals, and 1.5 MM tDM of bark were used as solid fuels for energy production. Fuelwood is only traded to a minor extent and the trade flow of fuelwood is included into the trade flows to and from energy/materials and passed together with wood fibre energy products to solid fuels.

3.3.4. Wood fibres in solid fuels

In addition to forest fuelwood, landscaping residuals, and post-consumer recovered wood, processed fibres or spin-off products from fibre processing (energy/materials) are used as solid fuels for heat and power generation. Wood-based spin-off products either are processed into energy products (here: charcoal, briquettes and pellets) or used directly after processing (here sawmill by-products, black liquor, post-consumer recovered wood from recycling and industrial wood residues). For the year 2015, this study recorded total net exports of briquettes and pellets of 0.6 MM tDM and net imports of charcoal equal to 0.2 MM tDM and of recovered wood equal to 1.0 MM tDM. In sum, 1.8 MM tDM briquettes and pellets, 0.2 MM tDM charcoal, 0.9 MM tDM sawing by-products, 2.0 MM tDM black liquor, 2.2 MM tDM industrial wood residues, and 5.3 MM tDM post-consumer recovered were used as solid fuels for energy and head production.

3.3.5. Wood gasification

Wood gasification plays only a very minor role in Germany. Wood pellets and wood chips are used primarily. According to our own calculations using data from the DBFZ database and the adjusted database of the Federal Network Agency 2016, these flows are 65,700 tDM.

3.4. Biogenic residues and waste

3.4.1. Biogenic residues and waste status quo and volumes

Biogenic residues and waste (residues/waste) comprises diverse residual materials, such as post-consumer recovered wood, landscaping residues, rests of starch and sugar productions and animal slurry (pig, chicken, and cattle). Likewise, residuals from settlements are considered in this category, including recovered paper from recycling, food and kitchen waste from households, restaurants caterers and residues from food processing plants.

The total amount of residues/waste either available for material or energy use sums up to 32 MM tDM. The main potential is hold by post-consumer recovered wood and waste paper with 16 MM tDM, followed by animal by-products 7.6 MM tDM and, in third position, settlement waste/industrial and agriculture waste which accounts for 6 MM tDM. Data sources for each one of the flows from residues/waste are shown in Annex IV.

The information from animal sludge, biogenic waste for biogas and biomethane and the residual materials (trade, industry, agriculture) for 2015 results from the annual surveys of bioplant operators in Germany, which are reported as fresh mass ([35,36]) and further converted, as explained in the next section. Although, the surveys provide a rough indication of the distribution of substrates used for biogas, information is limited since the response rate to the survey was around 10%.

The development and availability of postconsumer recovered wood in the waste disposal market from 2001 to 2015 are presented by Döring et al., 2018 [31]. The domestic availability of post-consumer recovered wood increased in this period from 4.5 MM tDM to 5.3 MM tDM. The material use of post-consumer recovered wood varied slightly between 0.8 MM tDM and 1.4 MM tDM over the reporting period. In contrast, the amount of post-consumer recovered wood used for energy production grew from 2.3 MM tDM to 3.6 MM tDM during the same period. Data on trade volumes of post-consumer recovered wood are obtained from DESTATIS [26] and UBA [25].

In Germany, paper for recycling is gathered in a separate high-quality collection system by municipalities and commercial collectors and recycled in paper mills. From 2001 to 2015, the domestic recovery of paper for recycling increased from 7.3 MM tDM to 9.9 MM tDM. That signifies an increase of the recycling ration of nearly 75%.

While landscaping residues are entirely used for energy generation, recovered paper from recycling is entirely used for material processing. Post-consumer recovered wood is either used as solid fuel for energy or material production. Hence, after sorting 5.3 MM tDM of post-consumer recovered wood flows from residues/waste to solid fuels (together with other wood energy products, see chapter 3.2.1.) while 1.00 MM tDM is used for material production.

Other material use results as waste from industrially produced or used agricultural resources, such as bran & flour dust, which is generated in the production of cereal flour, the manufacture of starch products: potato protein, corn gluten or residues from distilleries and other lipids, minerals, proteins and phenolic components. These flows are not very well documented and therefore the quantities are not very large, which is why they mostly originate from the assumed calculation by Brosowski et al. [30]. Also a very small amount was calculated for bioethanol production. We used data from the FNR 2018 [32] and determined the dry stillage from sugar for bioethanol from grain and dried stillage and molasses from sugar for bioethanol from sugar beet.

3.4.2. Biogenic residues and waste for energetic production and use

Compared to the other two sectors (agriculture and forestry), residues/waste has the biggest share in energy production from biomass. This may be due to the fact that it was impossible to clearly classify some biomasses to other uses such as feed use or material production. The determination of a substrate as waste or by-product remains a difficult discussion. Waste materials contribute to energy generation mainly as input for biogas production for electricity, biodiesel and as solid fuel for heat generation. After energy crops (51%), animal slurry and manure (41.4%) is the most used substrate on biogas plants [36], followed by municipal biogenic waste and other residuals (industry, trade and agriculture), which represent 4.4% and 3.1% of the total substrate respectively. Finally, a small fraction of landscaping residues material also contributes to electricity generation as substrate to biogas, while its majority is used as solid material for the heat sector [36].

In Germany, about 9.6 MM t of biogenic waste from separated collection were accumulated in 2015 and mostly recycled as compost [50]. When calculating electricity flows, we base our data on the publications of the DBFZ [35,36]. Total biomass contributing to biogas plants in form of biogenic waste, residual products and manure is 13.7 MM tDM. The conversion from solid to DM is a major problem here. Since industrial and other residual materials could not be categorised in more detail, a coarse uniform conversion factor had to be used for these "mixed materials" based on the study [51]. Animal excrements such as manure and solid manure are also calculated with a roughly uniform conversion factor (for the same reasons), with a total mass flow of 7.6 MM tDM for the production of biogas 2015 in Germany.

According to the JWEE reporting[2] the energy use of post-consumer recovered wood peaked at 5.8 MM tDM in 2015. Further the JWEE reporting states that the use of biogenic waste in form landscaping residuals as solid fuels for energy production amounted to 2.1 MM tDM.

Additionally, animal fats and used cooking fats are suitable for biodiesel and -ethanol production. The FNR [32] published data for the shares of raw materials for biodiesel production in Germany in 2015, according to which used cooking fats accounted for 22% and animal fats and fatty acids for 3% of the total biodiesel production of around 3 MM t. Taking into account the approximate conversion factor from oils or fats to biodiesel of 0.94, around 700,000 t of used cooking oils and 100,000 t of animal fats and fatty acids were used for biodiesel in 2015 (see Table 5).

Table 5
Use of residual materials for the electricity, heat and transport sector.

Flow	Description	Biomass/Products	Total	Unit
Biogenic residues and waste to biogas	Total settlement residuals to biogas production	Settlements biogenic waste for biogas	3,343.118	tDM
		Settlements biogenic waste for Biomethane	0.27	tDM
		Residuals (trade, industry, agriculture) (biogas)	2,355.379	tDM
		Landscaping residues material for biogas	399,000	tDM
	Total manure to Biogas production	Solid manure, liquid manure (biogas)	7,650.000	tDM
		Solid manure, Liquid manure (Biomethane) in fresh mass-conversion factor not available	0.71	tFM
Biogenic residues and waste to biofuel	Bioethanol & Biodiesel	Animal fats for biodiesel	100,000	tDM
		Used cooking oils for biodiesel	700,000	tDM
Biogenic residues and waste to solid fuel	Material to combustion of solids	Landscaping residues material	2,082,063	t (atro)

Source: Own calculation based on data from: Daniel-Gromke 2017 [35,36], Landwirtschaftskammer Salzburg 2009 [37], BMEL/FNR 2018 [32], JWEE 2018 [28].

3.4.3. *Biogenic residues and waste for material production and use*

Biogenic residues and waste also provide raw-material input in the flow to energy/materials. In sum there were 6.3 MM tDM post-consumer recovered wood available for subsequent use. Since 5.8 MM tDM were utilized as solid fuel, the material use of recovered wood in fibre processing was about 1.0 MM tDM in 2015. This amount is in line with the development drawn by Döring et al. [31]. For the year 2015, data on trade of post-consumer recovered wood sum up to 1.7 MM tDM imports and 0.7 MM tDM exports. Here, the resulting net import of approximately 1 MM tDM is captured as trade flow towards biomass fiber processing. In 2015, recovered paper is the most important raw-material input for the production of paper products in terms of volume. Between 1995 and 2015, the domestic consumption of recovered paper as raw-material input nearly doubled to 10.7 MM tDM while the production of paper products only increased by round about 50% to 14.4 MM tDM. This leads to an overall increase in the average utilization rate of recovered paper from 58% to 74% between 1995 and 2015. After the turn of the millennium until 2015, both import and export volumes substantially rose from 4.6 MM tDM and 3.9 MM tDM to 7.5 MM tDM and 8.8 MM tDM, respectively. In combination with increasing recovered paper consumption this turns Germany from a net-exporter to a net-importer country.

4. Discussion and conclusion

4.1. *Agricultural biomass availability and use*

The total quantity of biomass from agricultural used area produced for economic purpose was estimated in Germany in 2015 at 117 MM tDM. The most important crop category is cereals (42 MM tDM), followed by roots (8 MM tDM) and oil crops (4.6 MM tDM); pulses, fruit, vegetables and industrial crops make together 1.2 MM tDM. Plants harvested green account for 33 MM tDM and permanent grassland makes further 28 MM tDM. The total net import of primary agricultural biomass and feedstuff (mainly oil cakes) is calculated at 6.5 MM tDM, which results in total supply of more than 123 MM tDM. On the demand side the most important use category is the use of biomass as feed for animal husbandry (80 MM tDM). This biomass however includes besides the primary biomass from agriculture (69 MM tDM) also biomass that arises as by-products or residue during the production of plant-based food (11.4 MM tDM). To the category energy use was allocated approximately 22 MM tDM and to the category material use further 5 MM tDM of biomass from agriculture.

A closer look at the allocation of some types of agricultural biomass to different use categories makes clear that there are some inconsistencies between individual data sources. The most illustrative examples are allocation of silage maize and plants harvested green to animal feed [52] and energy use categories. The total use calculated using the use-side statistic exceed considerably the total supply calculated using the supply-side statistic: A biomass deficit of approximately 15 MM tDM is estimated. There are no reasonable grounds to prefer one or another kind of statistical information. A further work to bring different statistics in line with each other is required.

The quantity of agricultural biomass used directly for the production of plant-based food is an estimate, which is calculated based on information about the production and use of biomass for other purposes. Given the uncertainties surrounding flows used for this calculation, it has to be admitted, that the quantity of biomass used for production of plant-based food is associated with high uncertainties.

The Sankey diagram gives a good overall picture about the supply and use of biomass from agriculture in Germany. However, it is important to note, that we look only in the first stage of allocation of

[2] The UNECE/FAO Forestry and Timber Section, in collaboration with the Joint ECE/FAO Working Party on Forest Statistics, the International Energy Agency (IEA), the Food and Agriculture Organization (FAO) and the European Commission (EC) conduct "Joint Wood Energy Enquiry" (JWEE).

biomass to different types of use and especially the trade with processed products and the food sector including the analysis of marine and live animals as well as all 2nd hand produced products, can possibly change the picture to some extent.

4.2. Forest biomass availability and use

In sum, 33 MM tDM of forest biomass from German areas were available for either material or energetic use in 2015. Roughly one third of the primary forest biomass (13 MM tDM) was used for solid fuel. However, woody biomass flows from residues/waste or energy/materials (fibre processing) spin-offs summed up to 14 MM tDM and thus, exceeded the amount of forest biomass for solid fuel. One main input for material fibre processing was recycled fibres in form of recovered paper from residues/waste flows which is predominately used for the production of paper and paper products. Demand and import of wood increased during the last decade. On the other hand, forest inventory stocks in Germany are increasing. This does not necessarily mean, however, that the de facto potential of exploitable woody biomass demanded by various manufacturer also grew since: The highest growing timber volumes stock in privately owned forests. Private forest account for nearly half of the forested area in Germany and around 50% of these forests are owned by small holders. Wood resources mobilization in privately owned forest is less intensive than in forests of other sizes and ownership. In addition, timber stock increments were predominately realised by non-coniferous tree species. Except the fuelwood sector, the market demand for non-coniferous wood is constantly low and additional biomass potentials did not stimulate customers' interests in the past. The German forest-based value chain is highly specialised on coniferous timber as raw material. Spruce is both the most important commercial tree species and the only tree species with decreasing timber stocks.

The technological properties of coniferous and non-coniferous tree species are different in nature. Due to their specific material and processing properties, coniferous and non-coniferous tree species are no perfect substitutes in their major fields of use. This means, that for traditional uses of wood products not the total amount, but the wood species available for use, is critical for further processing and manufacturing. Decreasing supply of coniferous wood from domestic forests may affect the wood-based industries, whereas direction and magnitude of impacts might be manifold and possibly spread-out along the value chain (Schier et al., 2018 [52]).

Finally, the major share of timber stock increments is realised by old-grown trees. In fact, the overall stock of younger trees with dbh<30 cm decreased between 2003 and 2012. Albeit the increasing supply potential of old-growth timber, the utilization of strong timber persists to be problematic and the market demand remains low.

However, current trends in forest age, diameter, and species composition structure together with forest management goals (target diameter and harvesting age) limits the exploitability of available wood biomass resources. Future challenges for resources mobilization include the forest ownership structure, the growing stocks in non-coniferous tree species, decreasing stock of the most important coniferous species spruce, and major stocks in the strong (non-coniferous) timber compartment. Another problem is that heavy storm events (e.g. storm event Lothar in 2000 and storm event Kyrill in 2007) are not projectable but strongly influence biomass supply. Thus, an effective use of domestic forest resources requires technological leap together with a re-thinking of management strategies in terms of resource mobilization and changes in tree-species composition.

4.3. Biogenic residues and waste availability and use

According to our calculations, material from residues/waste is the third most abundant biomass in Germany in 2015 with 32 MM tDM. The largest share is used for energy recovery in biogas plants (13.6 tDM) and for the incineration of postconsumer wood as solid fuels with an amount of 7.2 MM tDM. With a total of 9.7 MM tDM waste paper for material use is the second largest share.

Smaller amounts of material are used in industrial processes, e.g. from by-products or residues of starchy substrates, grain or brewery waste, but also from dried slurries of sugar and molasses for bioethanol production. The data for agricultural by-products, industrial residues are well defined, even although perhaps not entirely. For example, there is still room for discussion on whether straw should be counted as residue/waste rather than as a material used from agriculture. Further inconsistencies arise in the case of agricultural by-products, which are counted again as residue/waste by food processing or enter the biogas plant as inductor residues and are therefore recorded twice.

A very difficult task is the calculation of waste masses, as these are often used in mixed ratios. To use consistent conversation factors is very important for e.g. a monitoring or future modelling of a comparative Sankey diagram.

Also difficult to represent are cycles such as oil cake, which is generated in biodiesel production or other materials produced in industrial processes, which are either used as animal feed or go into material use.

Furthermore, an additional factor, not only in the waste sector but also in considering the different sectors, is the comparison of dry and wet materials. In this respect, reference should be made to the mass of manure, which generates various problems not only in calculation, but also in handling and storage. In contrast to this the dry pellets or tree trunks in the forest.

The presented paper provides an overview of the interaction of the different biomass sources and their uses in Germany within the main sectors of the bioeconomy (food/feed, material and energy) for the first time at this level of complexity. The results include definition of terms, data sources and data quality at one particular assessment year, in 2015. Such systematic representation of the biomass flows can contribute towards a better understanding of the national biomass availability, as well as of the different value chains and their associated sectors. The diagram can be used to identify relevant biomass use sectors, main biomass sources, import or export potentials, as well as the main limits and boundaries of the bioeconomy development in Germany. These results can therefore support the bioeconomy monitoring activities, which is a crucial basis for decision making in the bioeconomy field, particularly to determine which further data should be gathered or assessed for the sectors of interest.

The biomass production and use is undergoing continuous and dynamic changes and therefore the figures related to the individual sectors might need adjustments from year to year. This means that the presented picture in 2015 may not fully represent the same status of the bioeconomy in the year 2021. Nonetheless, this work represents a big step forward in understanding the overall bioeconomy system, and it is demonstrated that it can be used to analyse the current databases, once they are completely updated. In order to be able to follow such sectorial changes, a regular update of such a flow diagram could be useful to observe their relevance in the context of the overall system. A crucial factor for establishing a regular update as proposed will be the improvement of the data availability at different and points in time. For the time being, whilst the database for the years 2016–2020 are established, it is recommended to take the results presented in this work as reference points. The analysis of the current situation should be carried out by complementing the provided information and putting them in the context of the current available data from single sectors.

Main challenges for further development and use of the diagram are the data availability and quality and the reconciliation of the different sources (economic, trade, etc.). The diagram and its dataset can be enhanced in many ways, as soon as new data becomes available. For example, the material use of biomass is becoming more relevant and it is to be expected that more data will be available in the subsequent years. In some cases there are different data sources for one biomass type, and the decision on using the most robust/reliable data source might lead to inconsistency. If the data sources will be more harmonized in the future, a more robust database will be available.

The material flow can be calculated in further years, thus can support the monitoring of the bioeconomy. Besides, being a simple and transparent tool, based on nationally available data, other countries can use it to create their own bioeconomy flows. These analyses could be synthesised later on, to identify the cross-country flow, to create an understanding of the interrelationships and thus future steps of bioeconomic solution strategies at EU level.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The content of this publication was prepared during the BEPASO project (Bioökonomie 2050: Potentiale, Zielkonflikte, Lösungsstrategien), financed by the Federal Ministry of Education and Research (BMBF) (Grant Number: 031B0232D). We also thank two anonymous reviewers for their helpful and constructive comments and recommendations.

Annex I: Conversion Factors

Table I/1
Conversion factors m^3 and t to tDM – Wood biomass

		Org. Unit	Factor tDM
Primary solid biomass	Woody biomass from forests		
	coniferous wood	m^3	0.41
	non-coniferous wood	m^3	0.57
	Woody biomass from outside forests		
	landscaping residues	m^3	0.42
Wood based Industry	Sawnwood	m^3	0.47
	Veneer	m^3	0.47
	Plywood	m^3	0.44
	Particle board	m^3	0.42
	Fiberboard	m^3	0.43
	Wood pulp		
	mechanical	t	0.90
	sulphate/sulphite bleached	t	0.77
	dissolving grades	t	0.77
	recovered	t	0.58
	Recovered paper	t	0.64
	Paper and paperboards	t	
	Graphic papers	T	
	newsprint	T	0.73
	uncoated mechanical	T	0.61
	uncoated wood free	T	0.65
	coated papers	T	0.54
	Sanitary and household papers	T	0.84
	Packaging materials	T	
	case materials	T	0.76
	cartonboard	T	0.75
	wrapping papers	T	0.77
	other papers for packaging	T	0.73
	Other papers and paperboards	T	0.64
	Solid fuels from fibers		
	Wood chips, particles, residues	m^3	
	Bark	m^3	
	Black liquor	T	0.80
	Post-consumer recovered wood	T	0.80
	Processed solid fuels		
	Wood charcoal	T	0.92
	Wood pellets and briquettes	T	0.92

ANNEX II. Data sources and harmonisation in details.

Notice: categories “biomass from agriculture” and “biomass from forestry” cover new biomass produced on land in respective year. Category “biogenic residues and waste” on the contrary does not produce “new” biomass but collect biomass, which was generated in the same year or in previous years (for example waste paper).

1. Data on biomass producing/generating sectors

Biomass from agriculture

This category includes crop biomass harvested from agricultural used area. More exactly it covers the biomass grown for economic reason (e.g. it covers corn but not straw by grains). The statistical yearbook from BMEL [14], is the main source of information. Production volumes are expressed mainly in fresh matter volumes. The only exception is the biomass from permanent grassland, which is reported in DM volumes. For volumes reported in fresh matter conversion factors were applied to calculate volumes in tDM.

Biomass from forests

This category refers to woody biomass which originates from forests or other wooded land. Beside the main products, bark is included to this category. The amount of bark is calculated as portion of the reported wood removals in a given year and thus basically depends on fellings and removals. This category accounts for raw material provision, production of wood fibre-based semi-finished goods and their outflow to material use. Thus, and in addition to the forestry sector, the following wood biomass fibre processing sectors are considered: sawmill industry, wood-based material industry including veneer- and plywood and wood-based panels, pulp manufactures and paper industries. Woody plants growing on agricultural area (SRC and Miscanthus) are included in the section "Biomass from agriculture".

Based on Jochem et al. [24] it is assumed that only coarse wood (wood with dbh>7 cm at the thinner end) and a minor portion of bark is used in material fibre processing. In addition, forest biomass is used as solid fuel for heat and power generation. In this study, solid fuels from the forest sector comprise fuelwood (course wood), forest wood residuals dbh < 7 cm at the thicker end (uncoarsed wood), and bark that is not dedicated to material use.

In addition to forest fuelwood, landscaping residues, post-consumer recovered wood, and spin-off products from fibre processing are utilized for energy generation too. Spin-off products from wood processing are transformed to energy products (here: charcoal, briquettes, and pellets) or directly used after processing (here: sawing by-products, black liquor, and industrial wood residues). More information on the use sectors is provided in 3.2.1.

Biomass from biogenic residues and waste

Within the framework of biomass conversion, significant quantities of by-products are generated, which are normally used as animal feed (press cake) or fertilizer (fermentation residues from biogas production). By-products include all materials that are used for further material purposes. Bioenergy sources from residual and waste materials are important in different applications for the provision of biogas, sewage gas and landfill gas as well as for liquid or solid biofuels for electricity and heat production. Biogenic residues and waste materials are generated in various production and utilization areas. Significant residual material potential is seen in the agricultural sector (e.g. liquid manure, straw), in the forestry sector (forest residues) and in the municipal and commercial sector (e.g. biowaste, green waste). The use of liquid manure and solid manure in biogas plants makes it possible to usefully recycle these residues. Only small amounts of straw (as harvest residues) are used. For the use in biogas plants (or biofuel plants) digestion processes are necessary. In addition, there are further potentials of agricultural residues (e.g. beet leaf, flap) which should be used for energetic use in biogas plants.

Brosowski et al. [30] counted 90 different biomasses as waste and residues. A large majority of these materials (44 single materials) are without any data for utilization and therefore cannot be shown in a material flow. In this study sources with datasets are used where biomasses are combined (e.g. Refs. [35,]). At least 20 biogenic residual and waste materials (landscaping residues, post-consumer recovered wood, slurry (different animals), manure (different animals), municipal biowaste, animal fats, used cooking oils, glycerine, post-consumer recovered wood, waste paper, rest of starch and sugar production, kitchen waste, residual feed, potato peelings, fruit pulp, brewer's grains, sugar beet pressed pulp, vegetables, vegetable by-products) are used in the Sankey flow.

2. Data on biomass use sectors

The available biomass from agriculture, forestry and residues/waste is used for food and animal feed, to produce materials, to generate energy or is traded internationally.

Biomass for food and feed (plant-based food and animal feed)

A great share of biomass, especially biomass from agriculture, is used for food production. Biomass from agriculture can be used directly as a plant-based food or it can be feed to animals for the production of animal-based food. To illustrate this fact the Sankey diagram has two boxes - plant-based food and animal feed – within the box food and feed. The flow to the box plant-based food depicts the quantity of biomass (primary crops) produced in Germany or abroad for the production of the plant-based-food. The flow to the box animal feed reflects the quantity of biomass generated in Germany or abroad used for animal feed and comprises biomass from agriculture like primary crops, green fodder and biomass from residues/waste which covers feedstuff generated by food processing like oil cakes, brewing or distilling dregs and waste etc. The source of data about quantity of biomass used for animal feed is the BLE, (2017 [54]). The quantity of biomass used directly for food is an estimate: Only biomass from agriculture produced in Germany or abroad can be used for production of plant-based food; the total supply of this biomass is calculated as domestic production plus net import; the total supply minus use of this biomass for material and energy use as well as agricultural biomass for feed use results in quantity of biomass for plant-based food.

Biomass for material Use

In the bioeconomy, biomass is used in a variety of ways, primarily as food and animal feed, but increasingly also as a supplier of materials and energy for industry. Within the bioeconomy, approaches are being pursued to make the cultivation and use of plants resource-efficient and sustainable. The aim is to achieve the best possible coexistence of conventional agriculture and organic farming and to take account of new opportunities for plants as renewable raw materials outside the food, feed and food industry. Cereals, rapeseed, sugar beet and other crops also play an important role in the production of renewable energies (see energetic use) and as raw materials for industry (e.g. chemicals).

Woody biomass from forests is traditionally input for various materials including products from the construction and housing sectors, paper and packaging industries as well as the chemical and textile industries.

Biomass for energetic use (solid fuel, biofuel, biogas)

Among the renewable energies, biomass (i.e. plants as well as plant and animal residues and waste) is regarded as an all-rounder. It can be used to generate heat, electricity and fuels.

Typical of solid bioenergy sources are wood fuels such as wood chips or wood pellets. Liquid bioenergy sources include biofuels such as vegetable oil, biodiesel or bioethanol. Biogas and biomethane make up the gaseous energy sources [3]. For the energetic use of all 3 categories, agriculture and forestry as well as residues/waste biomasses are used in different quantities. These biomasses are required for the generation of electricity (e.g. biogas plants), heat (incineration plants) and in the transport sector. In biogas plants renewable raw materials such as maize, grass and cereals as well as residues such as landscaping residues, biogenic waste, manure and solid manure are implemented. Materials such as straw, SRC, Miscanthus from agriculture as well as wood pellets, charcoal, raw wood, bark, sawmill by-products, post-consumer recovered wood and landscaping residues can be used as solid fuels. The biomasses rapeseed, sugar beet, cereals, vegetable oils, animal fats and used cooking oils are used for the production of biodiesel.

Biomass net trade

Some biomasses are produced in Germany, but not used domestically. Similarly, some materials are largely imported from abroad, e.g. net imports for starch[3] or feed (e.g. grain maize and soy [14]). It is therefore important to include trade in the biomass flows.

To illustrate trade in the Sankey model we use 2 arrows (one above at Agrar, one below at Forest), which represent the total net-trade, where import and export are calculated versus each other. Both arrows indicate that in Germany 2015 the import of raw materials predominates.

The top arrow shows the trade with agricultural biomass (primary crops) and animal feed (assigned to the category residues/waste like oil cakes, brewing or distilling dregs and waste etc.

A second arrow (from the bottom) is separated into two colours representing the trade with wood and wood products, such as briquettes, pellets and waste paper, as well as agricultural raw materials for material use such as paper starch, chemical starch, sugar, chemical pulp, natural fibers, proteins, other fats and oils.

3. Data harmonisation and uncertainties

As presented, several steps have been applied to harmonise data in terms of unit, aggregation, disaggregation, etc.

Available data on biomass differ noticeably according to the respective statistics and sources. In some cases, information about single biomasses aggregates are available (e.g. residues/waste), whilst other data sources use categories or subcategories. For instance, the agricultural statistics survey collected data on farm areas of agricultural enterprises, areas used for agriculture, other areas, and production areas, among others for edible mushrooms. Subcategories are arable land, permanent crops, permanent grassland and kitchen gardens. Further subdivisions of individual agricultural biomass are for example cereals for grain production, plants for green harvest, root crops, legumes for grain production, industrial crops, vegetables, strawberries and other garden crops.

To represent the biomass use sectors in a flow diagram, individual biomasses were grouped into clusters. Less data about the material use are available, therefore they were discussed and validated with experts. Some data, not being available, were calculated, e.g. the harvest amounts of short rotation plants. The net trade of agriculture and forestry sector is available in some aggregation. For the separation of them into single biomasses, also own calculations were made.

The use of different data sources is inevitably associated with inconsistencies. If possible the choice of preferred data source is argued. If it is not the case, the reason of inconsistencies is described.

Estimated flows such as quantity of biomass for production of plant-based food are associated with particular uncertainties.

Considering that not all data are available at single biomass level, the described steps to get the required level of detail, including aggregation, separation, own calculation, contain some level of uncertainties. Not for all biomass types are data available (e.g. reports on bark, industry waste and residues) or they have been counted twice. As an example: the raw material for a sandwich is represented by the sum in the agricultural sector, but then repeated by the kitchen products in the residues/waste sector. Another example is, that it is not possible to distinguish, which oil cake is produced inland and which is imported. Here, only an estimation is possible, since it is a by-product of the biodiesel production. Regarding bioethanol production, no import data are available, so the import of bioethanol was not included in the diagram. Some biomass products, even of probably a minor influence, cannot be included in the present study: so far, for example, the material use of bark mulch cannot be considered. This biomass can serve in potting soil or as a covering on planted vegetation areas, but the amount used is currently not statistically detectable.

CRediT author statement

Nora Szarka: Conceptualization, Methodology, Validation, Writing, Reviewing, Supervision, Henryk Haufe: Data curation, Nora Lange: Methodology, Software, Formal analysis, Writing, Data curation, Franziska Schier: Writing, Data curation, Validation Holger Weimar: Writing, Data curation, Validation Martin Banse: Supervisionf Viktoriya Sturm: Writing, Data curation, Validation Lara Dammer: Writing, Data curation, Validation Stephan Piotrowski: Writing, Data curation, Validation Daniela Thrän: Funding acquisition, Supervision.

ANNEX III. Figures on the agriculture sector

[3] FNR/BMEL(2016): Stoffliche Einsatzmengen nachwachsender Rohstoffe in Deutschland 2015.

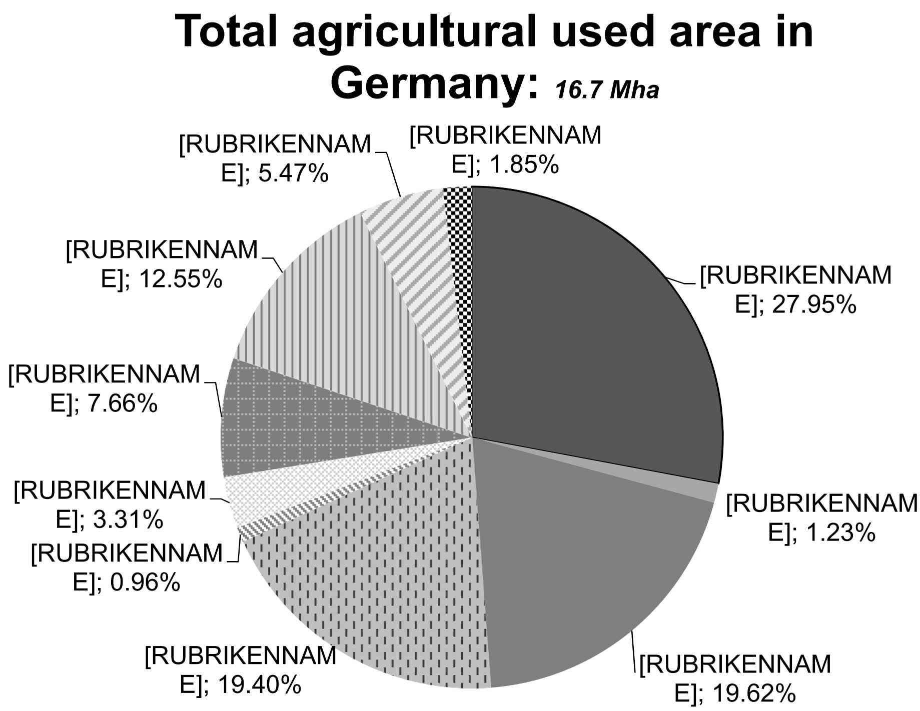

Fig. III/1. Total agricultural used area in Germany by main types of uses in 2015; Source: Own presentation based on data from BMEL, published 2017 [14].

Table III/1
Trade with primary agricultural biomass (Germany, 2015).

	Import 1000 tFM	Export 1000 tFM	Net import (import - export) 1000 tFM	DM conversion factor	Net import (import - export) 1000 tDM
Wheat	4,580.5	10,836.1	−6,255.6	0.86	−5,379.8
Rye	425.6	207.9	217.6	0.86	187.2
Barley	1,433.9	2,784.5	−1,350.6	0.86	−1,161.5
Oat	446.3	41.6	404.7	0.86	348.1
Corn	2,506.8	478.3	2,028.5	0.86	1,744.5
Other cereals	478.2	111.5	366.7	0.86	315.3
Rice (husked)	442.5	129.6	312.9	0.86	269.1
Potatoes	524.8	1,714.6	−1,189.7	0.23	−270.1
Fresh fruit	2,354.4	242.2	2,112.2	0.16	346.3
Citrus fruit	1,123.6	98.9	1,024.7	0.16	168.0
Other tropical fruit	1,806.7	436.8	1,369.9	0.16	224.6
Fresh vegetables	3,315.6	494.1	2,821.4	0.10	276.9
Oil seeds	9,403.2	314.6	9,088.5	0.91	8,270.6
Sum (prim. Agr.)	**28,841.9**	**17,890.7**	**10,951.3**		**5,339.3**
Soy meal	2,939.5	1,869.3	1,070.2	0.89	952.5
Total	**31,781.4**	**19,759.9**	**12,021.5**		**6,291.7**

Source: BMEL (2017) [15].

ANNEX IV Biogenic residues and waste flows description and data sources

Utilization and application	Biomass/Product	Data sources
Biomass for energy/ materials (fibre processing)	Recovered wood	Self calculation based on Statistisches Bundesamt – DESTATIS [26] und UBA [25]
	Recycled paper	JFSQ, 2015 [27]
	Dry stillage from sugar for bioethanol from grain/dried stillage and molasses from sugar for bioethanol from sugar beet	FNR, 2018 [32]
	Bran & flour-dust generated by producing cereal flours, production of starch products: potato protein, corn gluten, residues from distilleries: pomace, ingredients of vinasse, (lipids, minerals, proteins and phenolic components)	Brosowski et al., 2016 [49]
Biogas	Animal slurry	Daniel-Gromke et al., 2017 [35]
	Biogenic-waste from settlements	Daniel-Gromke et al., 2017 [36] at 10. Innovationskongress. Osnabrück
	Landscaping residues	
	Residuals from industry, agriculture and trade	Landwirtschaftskammer Salzburg 2009 [37] (conversion factor for Biogenic waste and Landscaping residues)

(continued on next page)

(*continued*)

Utilization and application	Biomass/Product	Data sources
Biofuel	Animal fats	FNR, 2018 [32]
	Used cooking oils	Modified calculation according to FNR, 2018 [32]
Solid fuel	Landscaping residues	JWEE 2018 [28]

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