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Status and Perspectives of Biomass Use for Industrial Process Heat for Industrialized Countries

Full reduction of greenhouse gas emissions involves transforming the industrial process heat supply. The status and future perspectives of biomass for industrial heat mainly based on the German example are reviewed, and a more differentiated consideration by a newly introduced method is attempted. The article focuses on temperature levels above 200 °C combined with an individual examination of most energy-consuming industrial subsectors according to the feasibility of biomass utilization. Numerous studies conclude that biomass use will shift substantially from residential to industrial heat. Results indicate that biomass could play a bigger role especially for cement and clinker production, but they indicate also a significant need for further research and development to take final conclusions.

Keywords: Bioenergy, Biomass utilization, Heat from biomass, Industrial process heat

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1 Introduction

Within the final energy consumption, heating and cooling is dominating with almost 50 % in the EU [1] and with over 50 % in Germany [2]. Heat is requested by the industry, households as well as trade and commerce at different temperature levels, i.e., space heating with 40–90 °C, domestic hot water supply with 50–70 °C, and process heat with up to more than 1500 °C). In Germany, roughly 43 % is used for households in 2018. The remaining 57 % is utilized either in industry or in trade and commerce (Fig. 1) [3].

In total, industrial fuel consumption worldwide – mainly for heating processes – emitted roughly about 20 % of all the CO_2 emissions in 2010 (5.2 Gt + 0.2 Gt for coke) [7].

The share of renewable energies for process heat supply is about 5.3 % for Germany in 2018 (94.5 PJ; PJ = 10^{15} Joule) [3], mainly in form of bioenergy (in total almost 93 PJ of solid biomass). Including water and space heating within industry and the other sectors with low temperature heat demands, roughly another 310 PJ of solid biomass is used for heating purposes in Germany [4–6].

Industrial processes demand a certain quality and amount of process heat supply over time, and engineers, technicians, and operators must ensure that this heat is provided just in time, with high reliability and at the lowest possible cost. Therefore, many industrial producers utilize coal, heavy oil or natural gas as homogeneous fuels with low prices for industrial consumers, at least up to now. Exceptions only occur, if (i) the use of combustible production residues is cheaper than external disposal plus fuel costs or (ii) customers have a focus on renewable or CO_2-friendly production and producers react to this demand [8].

Currently, renewable process heat is provided mainly by biogenic residues, wastes, and solid biofuels as well as in some cases by concentrating solar thermal heating plants. In some very few cases geothermal heat supply is also available, but as a major source only in countries with high temperature geothermal potentials, like Iceland.

Despite available unused biomass sources, the exclusive use of biomass would not be sufficient to cover the entire heat demand in a renewable way. In addition to its use for energy purposes, biomass also plays a decisive role for food and feed supply and will be increasingly used for material purposes in the future (bioeconomy) [8]. At the same time, biodiversity protection, sustainability, and nature-based carbon capture and storage have to increase significantly (e.g., renaturation of former moorlands) to reach the international sustainability goals (SDG) and climate objectives. Sustainable provision of biomass for energy has to consider all previously mentioned objectives and challenges including the development in the competing food and feed sectors [9].

For all these reasons, biomass is a limited resource. Available biomass for heating purposes gets increasingly scarce on a

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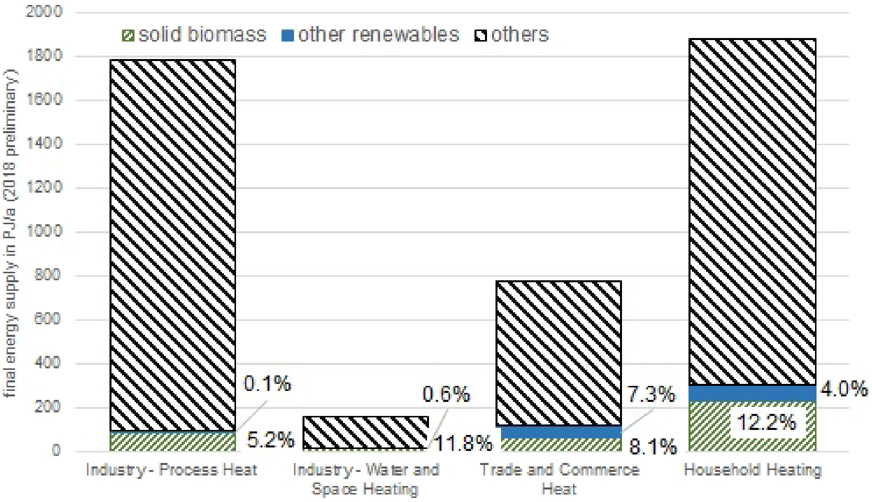

Figure 1. Heat requirement of the sectors and utilization of solid biomass in Germany in 2018.

global point of view, considering quite significant regional differences. Knowing all the restrictions about giving actual data about potentials and costs of biomass resources according to [10] for the year 2015, the technical biomass potential for energy purposes without energy crops might be in the range of almost 160 EJ a^{-1} worldwide (EJ = 10^{18} Joule) and for Europe including Eurasia in the range of about 33 EJ a^{-1}. The global use of bioenergy was roughly about 75 EJ in 2014 [10]. Thus, on average about 10–25 % of all the primary energy demand of almost 630 EJ a^{-1} (2017) [11] can be supplied by biogenic resources, depending, among others, on the state of industrialization and bioproductivity of farmland and forests with quite high regional variations [10, 12, 13]. Additionally, biomass, along with wastes and residues, is often a quite expensive energy source compared to other renewables [13].

Investments are often in the range of other renewables or even higher, but especially fuels with higher quality or at least with a certain homogeneity are frequently not available without fuel costs. Again, prices can vary very much due to strongly different impacts as well as regional conditions and market developments. Just to give one possible idea about prices: Wood collected from forests for energy purposes can be in the price segment of 20–200 €/t of dry matter according to quality and all the impacting factors [14].

Despite the drawback of limited availability and higher costs (e.g., compared to solar or wind with free energy sources), biomass has three main advantages in comparison to other renewable heating options: (i) its storability for at least half a year, being in this way an alternative for its more or less flexible utilization in bioenergy plants [15, 16], and (ii) its ability to generate heat with high temperatures. Another interesting opportunity is (iii) to generate negative emissions from biomass utilization by carbon capture and storage (CCS) from combustion [17]. These three advantages are particularly interesting for a stable, high-temperature heat supply over the year in combination with other renewables such as concentrating solar thermal energy, i.e., for industrial process heat.

Currently, due to economic reasons, biomass is mainly used for low-temperature heat supply in private households as well as in low-temperature industrial applications like cleaning, drying, and cooking in breweries [18], while all the main advantages seem to focus on industrial process heating. As a consequence, a lot of political strategies and scientific outlooks state for the future a switch of biomass heating technologies from small-scale household and heating grids towards (high-temperature) industrial heat supply [19–21]. However, often no detailed information is given about the applied technologies and biomass qualities needed. Therefore, technical challenges and barriers of biomass utilization for heat supply in special industrial processes are seldom considered.

These considerations about the use of biomass for heating purposes have to be seen in the entire context of discussions about the utilization of biomass not only in the heating sector, but also for power production and, very often emphasized, for fuel production, especially for aviation and shipping [22]. Without doubt, these utilization pathways and a growing bioeconomy will have a high impact on future availability of biomass for heating purposes. But nevertheless, a reduction of biomass for heating purposes in total will put increasing pressure on optimized use of the remaining biomass potentials for heating.

2 Scope of Review

Renewable heat supply is a very complex issue. Even focusing on industrial heat means a lot of different temperature levels of heat demand, amounts of heat needed, quality of heat supply, and possible combination with other chemical reactions. So far, two main approaches to consider biomass for industrial heat supply can be found in literature: (i) general consideration of the heat demand for industry or more detailed industrial subsectors [19, 23] compared to available biomass potentials and (ii) technical opportunities to use biomass for the replacement of fossil fuels for certain industrial heat processes [24]. In contrast to this state-of-the-art, this article focuses exclusively on industrial process heat supply above 200 °C, whereas household heating and small-scale industry, trade, and commerce as well as heat demand in industry with temperature levels below 200 °C are not considered. Second specialty is combining technical perspectives of the processes according to the utilization opportunities of biomass in comparison to other renewable solutions together with relevance aspects of these processes according to effectivity of measures. That is to say, for which of the industrial processes biomass is best compared to other renewable options and which of these processes will have a quick and significant impact on reduction of global warming gases.

Overall, this paper gives an overview on today's utilization of biomass for process heat as well as on its future perspectives, wherever possible on a worldwide, European, and German level. A general overview is provided based on relevant studies. If data is available, subsectors with high process heat demand will be presented individually. Furthermore, in the discussion chapter, a short plausibility check of the future perspectives is included under the estimation of fulfilling the goal of a CO_2-neutral energy supply.

2.1 Focus on Industrial Heat Processes

Heat supply is rather complex because different temperature levels occur as well as different sizes of plants for energy generation due to a wide range of applications. Temperature demands below 200 °C can be supplied by high-temperature heat pumps, geothermal energy, concentrating solar thermal energy, waste heat from high-temperature processes, and combinations together with hot water storage (for temperatures above 100 °C pressurized) [25]. Utilization of biomass heating in this temperature range would be more or less the same as for households and would not profit from the high combustion temperatures of biomass. Therefore, in this review, in contrast to other authors, one clear focus is set on industrial heat demand with temperature levels above 200 °C. Thus, most industrial washing, drying, and even cooking processes are not considered. As indicated in Tab. 1, this means focusing on 60 % of all the industrial heat demand in the case of Germany [26].

In Germany, for 2013 roughly 63 % of all industrial heat demand lies in the temperature level of more than 200 °C. Main subsectors are "chemical and petrochemical", "glass and ceramic", "cement and clinker", "steel production", and "non-iron metals". These higher temperature levels can be summed up to 200–500 °C, mainly supplied by steam, and over 500 °C, mainly supplied by direct firing.

There are only few sources with this depth of detail. More frequently, only data about total process heat consumption, total heat consumption in industry, or even total final energy consumption in industry is available. Therefore, the authors of this paper had to estimate the amount of process heat above 200 °C included in other databases. As an indicator, the relations of Tab. 1 were used. For sure, other countries could have quite different data, and the importance of the subsectors might differ significantly. Even the temperature levels could have differing relevance in other regions of the world. But, most industrial high-temperature processes have only very few totally different production pathways. Therefore, the relation of the temperature levels within a subsector will be more or less comparable at least for industrialized countries.

2.2 Methodology for Assessing the Perspectives on Industrial Process Sectors

Besides collecting data about biomass use for industrial heat supply, this review intends to provide a more differentiated view on the usability of biomass for industrial process heat. Thus, not only availability of appropriate biomass resources

Table 1. Industrial heat demand in Germany according to branches and temperature levels 2013 [26, 27]. Italic numbers indicate decreasing values compared to 2008 and all other numbers stable or increasing values. * denotes absolutely significant changes in $TWh\,a^{-1}$ of final energy demand.

Subsector industry in TWh	< 100 °C	100–200 °C	200–500 °C	500–1000 °C	1000–1500 °C	> 1500 °C	Total
Mining and quarrying	*2.7*	0	0	0	0	0	2.7
Food and tobacco	23.6	16.1	*1*	1.5	0	0	42.2
Pulp and paper	*3.6*	37.1*	1.6	0.7	0	0	43
Chemical and petrochemical	1.7	2.5	24.9*	49*	10.9*	10.1*	99.1
Other chemical industry	12.3*	7.2	0.9	0	0	0	20.4
Rubber and plastic production	*5.3*	*2.5*	*1.5*	0	0	0	9.3
Glass and ceramic	*2*	*2.8*	*0.3*	0.3	*2.6*	*9.8*	17.8
Cement and clinker	*1.1*	*2.2*	*3*	*14*	*21.9*	*2.8*	45
Steel production	*2*	*1.1*	*1.1*	*25.9*	*98.1*	*5.9*	134.1
Non-iron metals	*1.5*	0.1	*3.4*	*11.8**	*8.3**	0	25.1
Metal transforming	*10.9**	*1.4*	0.9	1.3	3.2	0	17.7
Machinery	*10.7**	*0.2*	0.1	0.2	0.5	0	11.7
Vehicles production	*13*	*1.4*	0.9	1.2	3.2	0	19.7
Other manufacturing	*20.5*	*4.8*	3.2	0.9	3.9*	*0*	33.3
Sum in 2013	*110.9*	*79.4*	42.8	106.8	152.6	*28.6*	521.1

and technical feasibility is investigated, but also the need for biomass use according to other renewable heating alternatives.

To verify this, the following scheme is applied for all main industrial process sectors, as basis for decision making:

I) Estimation of the macroeconomic substitution potential

1. Significance of the industrial heat process in the future: How much of the product will be needed in the future?
2. Which is the temperature range of the heat demand for the industrial process? According to supply technologies, the following three ranges can be distinguished: low-temperature heat-up to 200 °C, steam supply with 200 °C to 500/600 °C, and direct firing with temperatures above 500/600 °C.
3. Possibility of a temperature shift to lower ranges, at least partially: Which is the remaining range of heat demand after including all possible temperature level reductions (temperature range, heat demand quantities)?

As result, the amount of heat demand assigned to the temperature range is available for each subsector.

II) Assessment of the sector-specific management options

4. Can biomass demand be reduced? Heat below 200 °C should be covered by waste heat, deep geothermal energy, and solar thermal energy in combination with ambient heat pumps, as much as possible. Biomass can be used to cover supply gaps in winter, peak loads, and temperature demand peaks.

Heat in the range of 200–500/600 °C can be made available for peak demand via concentrated solar thermal energy in combination with biomass or deep geothermal energy in combination with high-temperature heat pumps and, if necessary, biomass, depending on the availability of space. Low-cost surplus electricity could be included at fluctuating rates with priority compared to biomass utilization.

In the case of direct firing above 500/600 °C, at first flexible electrical heating or partial heating (based on the supply of renewable electricity) should be used. For the remaining residual demand, it must be clarified whether the utilization of biomass is technically possible or whether, e.g., green hydrogen should be given priority. Only the remaining demand should be covered by biomass-based fuels.

The aim is to minimize the biomass demand through intelligent (smart) integration of biomass use. Higher temperature ranges and heat demands that cannot be covered by alternative renewable energies should have priority over purely economic considerations.

5. Needed biomass quality: What is the minimum quality of the fuels for the industrial processes? In comparison with regionally available residual and waste materials (incl. byproducts that cannot be recycled), the biomass supply and treatment must be clarified and secured.
6. Bioenergy with carbon capture and storage (BECCS). Is a technical option for carbon capture available and could it be integrated economically feasible? Finally, it should be examined whether, in the context of industrial heat supply from biomass, it is possible to collect as pure CO_2 as possible with little additional effort and at little extra cost, thus offering an additional economic benefit.

As a result, information about the feasibility of using biomass to supply at least a part of the process heat demand in a certain process is collected and can be applied for further considerations.

2.3 Germany as an Example of an Industrialized Country

While general data is given on a worldwide and European level, detailed information about temperature levels in the observed subsectors of industrial heat demand were found mainly for Germany. Therefore, the focus of the detailed analysis of temperature levels, biomass use according to these levels, and technical restrictions were based on the German perspective. However, Germany with a strong industry for machinery, automotive, and chemical products could be a quite representative example for a highly developed industrial country. As very detailed information is needed, some of the references are only available in German.

2.4 Time Frame

Data about industrial heating processes is difficult to gain. Therefore, full comprehensive data is not available for one single year. Therefore, data for the current status is from the years 2010–2019. Studies on the perspectives often have a time line until 2030, sometimes 2035 and/or 2050.

3 Current Status of Biomass Use for Industrial Heat Processes

3.1 Basic Data on Industrial Heat Demand and Biomass Use

Worldwide, the primary energy supply of biomass is 56.5 EJ (share of total: 9.5 %) in 2016: 2056 PJ for electricity, 1054 PJ for derived heat, 40 600 PJ in direct heat, 3430 PJ in transport (biofuels), and further 9360 PJ is not specified. Most important biomass fuels are solid biomass fuels (49 100 PJ), liquid biofuels (3590 PJ), and municipal waste (1430 PJ) [28]. Heat production from biomass is mainly used for cooking and space heating applications with low efficiencies. The demand for process heat above 200 °C is roughly about 50 EJ a^{-1}, from which only very few is supplied by biomass [29].

The European biomass consumption in the heat sector reaches more than 3.7 EJ and a share of almost 16.9 % in 2017 [20]. Germany, followed by France and Sweden have the highest total use. Besides, countries with the highest share of biomass for heat generation are Sweden, Latvia, and Finland, with about 50–60 % [20].

Industries represented (excluding electricity consumption) 16 % of the final energy consumption in the 28 member states of the European Union (EU28) in 2017, and only 13 % of this industrial energy consumption was from renewables, 99 % of which was bioenergy. The European statistical report states "…it is substantial to put some efforts to decarbonize this energy and hence to promote bioenergy as it is one of the best solutions regarding industrial requirements." Biomass in the European industry is mainly based on solid biomass (94.4 %) followed by renewable municipal waste (3 %) and biogas 2.2 %, while liquid biofuels account for less than 0.4 % [20].

The paper, pulp, print as well as the wood and wood product industries employed a total of 81 % of all biomass used for industrial energy supply in 2017. The main heat demand is below 200 °C in this subsector and own production residues are also utilized in combined heat and power (CHP) plants. The subsector non-metallic minerals including glass, ceramic, cement, and other building material industries uses 8 % of the biomass for energy within the industrial sector [20]. This is the subsector with the highest biomass utilization without own biomass residues. The typical heat demand is above 500 °C.

In Germany, the total primary energy use of biomass is 1087 PJ (2018) [3], including solid and gaseous biomass, waste, landfill gas, and biofuels. This is 8.3 % of the total energy consumption. Most important biomass fuels are biogenic solid fuels, biogas, and biogenic waste. Biogenic solid fuels contribute the most to heat production, whilst biogas to electricity production [5]. The share of biomass in the heat sector in 2018 reaches 12.2 % (530 PJ out of 4335 PJ total; see also Fig. 2). However, since 2007 not much development can be seen (10 %) [5].

Regarding the industrial heat use of biomass in Germany, only data for biogenic solid fuels is available. A total of 95 PJ heat is generated for industrial use from biomass with a share of almost 18 % (see Fig. 3) [5]. This data is summarized in Tab. 2.

3.2 Process Heat Utilization in Important Product Sectors

As introduced before, this review paper focuses on industrial heat demand above 200 °C (see Sect. 2.2).

Industrial high temperature heat applications can vary in a wide range, according to temperature, application of the heat, and quality demands. Thus, easy and general statements are not possible. Moreover, to decide about the feasibility of biomass utilization, the heat-consuming process itself has to be investigated and the characteristics have to be defined. Within this paper, the goal is to analyze the most heat-consuming subsector. According to Tab. 1 and Tab. 2 [7, 33, 34], the main energy-consuming subsectors in industry are "iron and steel", "non-metallic minerals" (wherein cement and clinker is included), "pulp and paper", "chemicals", "wood and wood products", and "food and beverages".

Figure 2. Development of the share of biomass use in heat production in Germany (1990–2018).

Figure 3. Share of biogenic solid fuels in the industry compared to heat production by biomass in Germany.

Table 2. Heating and cooling demand in comparison to biomass utilization with focus to industrial process heat worldwide, EU, and Germany data 2015–2018 [5, 10, 20, 28–32].

	World [EJ]	EU [EJ]	Germany [EJ]
Total demand for heating and cooling[a)]	200	22.0	4.3
Industrial process heat demand (> 200 °C)[a)]	43.0–54.9	3.7–4.6	1.2
Biomass potential	56–160	33[a)]	1
Biomass used for heating purposes	41.7	3.7	0.5
Biomass used for industrial process heat (all)	~3.5	~1.0	0.1

[a)] including Eurasia

Especially, on worldwide view as well as in EU28 context, data on process heat is rarely available. Therefore, data for final energy consumption for subsectors is taken as basis for derived values. German correlations between final energy consumption and heat within the main processes of a subsector and the correlations between total heat demand and process heat demand (temperature above 200 °C) were used to get an estimation for process heat demand with temperatures above 200 °C [34]. Other process steps, other relative shares of processes as well as lower efficiencies like in Germany could change the picture quite significantly. But, for the main energy-consuming processes, the most energy-consuming production steps are quite equal and efficiency losses will differ for all energy-consuming aspects in a rather similar way. Thus, the estimates can only give an appropriate picture. For each subsector a range of uncertainties is provided.

3.2.1 Food and Beverages

In this subsector the total energy demand in the world was 7.0 EJ in 2011 [7]. Based on German relations the heat demand above 200 °C is 0.3 EJ a^{-1}. It is the largest manufacturing subsector within the EU28 and creates quite a lot of biomass residues and side products. Most of the heat demand is below 200 °C (83 %). Thus, the high-temperature process heat demand would be in the range of 0.05 EJ a^{-1} based on a final energy consumption in this subsector of 1.3 EJ in 2017 [33]. Only very few biomass is used, due to costs. According to the significant regional differences a quite big uncertainty could be assumed. However, in the end, for some countries higher shares and other country lower shares could occur, and due to the low share of process heat above 200 °C even doubling of the demand will not change the relevance according to other subsectors. In Germany, about 150 PJ of heat was utilized in 2013 [26, 34]. Thus, the amount of high-temperature heat is rather small, i.e., less than 10 PJ for Germany [26], and this subsector will not be in further focus in this paper.

3.2.2 Wood and Wood Products

Worldwide, only about 1.3 EJ were used in this subsector in 2011 [7]. Like in the food and beverages subsector, most of the heat supply is below 200 °C. So, high-temperature heat demand is estimated to be about 0.1 EJ a^{-1}. In the EU28, this subsector is the one with the highest incorporation of solid biomass for final energy supply (57 % in 2017 – about 0.21 EJ compared to the demand of 0.37 EJ). This is due to high amounts of biomass waste with easy-to-combust qualities. Required temperatures for drying, pressing, and heat treatment are up to 500 °C, but only for few processes [33]. This means the demand of process heat with more than 200 °C is roughly about 0.03 EJ a^{-1}.

Processing of wood to high-quality products is quite equal all over the world. Differences occur from the deepness of processing chains. For industrialized countries, the share of process heat above 200 °C will be quite similar to Germany, while for developing countries it might be much lower and the relevance will decrease further. For Germany, the high-temperature demand might be below 10 PJ. Therefore, this subsector is not of high interest according to use more biomass for heat, but as a source of biomass resources of quite high quality that can be transferred from low-temperature heat supply to high-temperature processes in other subsectors.

Iron, steel, and non-ferrous metals (including coke for steel). An energy demand of 34.5 EJ (2011) worldwide is counted by International Energy Agency (IEA) for this subsector (power and fuels, as well as reduction coal) [7]. Based on German relations, the worldwide process heat demand with temperatures above 200 °C is 28.5 EJ a^{-1}. About 94 % of the heat demand is above 500 °C and direct heating is dominating. Currently, in the EU28 almost no biomass is used in this subsector to supply 1.17 EJ of final energy consumption in 2017 (electricity and heat without coke). According to German relations, this means a high-temperature process heat demand of 1.4 EJ a^{-1} including the coke.

Biomass itself is not favorable, but charcoal, semi-charcoal, or torrefied biomass could be used [33]. The share of process heat above 200 °C can differ by different production processes like steel from electricity-based processes or by combustible fuels. Although, the efficiency of the processes can differ significantly, even between industrialized countries. But, even with 25 % less of energy demand for high-temperature process heat this subsector is very important. In Germany, in 2013 more than 560 PJ of high-temperature heat above 200 °C – most of it above 1000 °C – was utilized [26]. Due to costs and drawbacks according to metal quality no significant use of biomass is recorded.

3.2.3 Non-Metallic Minerals

Worldwide roughly 13.9 EJ of energy was utilized in 2011 in this subsector [7], i.e., roughly about 11 EJ a^{-1} of high-temperature heat demand for industrial processes. In the EU28 the final energy consumption is about 1.43 EJ. Only about 3 % is provided by biomass in 2017. Process heat above 200 °C means a demand of 1.1 EJ a^{-1} [33]. The main energy-consuming processes are cement (almost 60 %), glass, and ceramic production. About three quarters of the heat demand is above 500 °C, with the main process steps requiring 1000 °C, respectively [33]. Significant biomass utilization takes already place in the field of cement generation. Up to 20 % is recommended, but experiments have shown that with adequate pretreatment of the biomass even higher shares are possible [35]. From the technical side no restrictions for increasing biomass shares in cement production are given [36].

Glass and ceramic production are based on very-high-temperature processes, where electric heating is often difficult. Thus, gas flames are frequently used, due to low contamination by combustion particles. Biomethane or gas from thermochemical gasification of solid biomass could be used [36, 37]. For industrialized countries, processes and efficiencies might be quite equal. The share of the different products may differ, but overall the share of high-temperature heat might vary only in a range of +/– 10 %. For developing countries, efficiency losses might be quite higher and sometimes more natural low temperature could be included, so that the share of high-temperature heat might even be higher. But, this would only emphasize the relevance of this subsector.

In Germany in 2013, roughly about 150 PJ of high-temperature heat is needed for cement production and around 50 PJ for glass and ceramic production [26]. While for cement most of the heat demand is in the range of 500–1500 °C, in the glass and ceramic industry more than three quarters need a temperature level above 1500 °C [26]. Thus, only a gas flame could supply this, when electrical heating by a lightning flash is not possible.

3.2.4 Chemicals and Petrochemicals

In 2011, almost 15.4 EJ was utilized in this subsector worldwide. Besides basic chemicals a lot of very different processes are established for a variety of different products. There could be some energy savings in the future by better cogeneration of different products and better catalysts [7]. According to German relations, almost 13 EJ a^{-1} is used in this subsector for industrial process heat with temperatures above 200 °C. Within the EU28, this very diverse subsector evolved to the one with the highest final energy demand in industry: 2.2 EJ in 2017. Only 0.5 % was supplied by biomass. About 67 % of the heat demand is above 500 °C [33]. Thus, the demand for high-temperature process heat is according to German relations about 1.8 EJ a^{-1}. Main energy-consuming products are ammonia, steam cracking of naphtha and gas oil, chlorine alkali, nitric acid, adipic acid, hydrogen and other synthesis gases, soda ash, aromatics, and carbon black [36].

Under the assumption of a fully decarbonized economy in 2050, quite some of these processes will disappear, due to stopping the use of crude oil and natural gas. Some differences in efficiency and in the relation of the amounts of chemicals produced can occur. But, as most of the processes need temperatures above 200 °C, only few variations will occur as soon as the industry is established in a country. Therefore, the authors estimate a quite low variation of less than +/– 10 %.

From a German point of view, the temperature demand above 200 °C is mainly occurring for basic chemicals. In Germany, about 340 PJ was used in 2013 [26]. The main processes are ethylene from naphtha and other sources, carbon black, and methanol [34]. All temperature levels up to above 1500 °C are needed [26]. Thus, waste heat recovery and combined production are important steps to reduce the energy demand. But, this means quite big production sizes with challenges in sufficient biomass supply and storage if a change should be made. Together with bioeconomy strategies some additional advantages could occur.

3.2.5 Pulp and Paper (including Print)

Almost 6.6 EJ was used by pulp and paper production, whereas the most energy-demanding process is the pulping. A lot of energy can be saved by increasing the recycling of used paper [7], i.e., 0.2 EJ a^{-1} of process heat demand above 200 °C. In the EU28, about 1400 PJ of final energy was consumed in 2017. About 83 % of the heat demand is in the range of 100–200 °C. Overall, biomass has a share of 38 % in 2017 [33]. By optimized processes this subsector might get self-providing in heat and power by using its own production residues [38]. This might be economically feasible and easy to achieve, but it would not come up with the best renewable solution.

Most of the low-temperature heat could be supplied by waste heat recovery, concentrating solar thermal as well as geothermal in combination with high-temperature heat pumps. Thus, the biomass demand could be reduced significantly. For the EU28, the final energy demand for this subsector is 1.4 EJ in 2017. This means according to German relations a demand of 0.05 EJ a^{-1} of high-temperature process heat [33]. Due to the very low share of high-temperature processes and missing reasons for bigger differences in the processes a significant increase in relevance is not to be assumed. In Germany, 2013 only less than 10 PJ of process heat with more than 200 °C was recommended. Thus, in the context of this paper, this sector is not of high relevance, even though 150 PJ of low-temperature heat is needed in 2013 [26].

In total, about 53 EJ a^{-1} of the industrial heat demand above 200 °C is used worldwide (43–55 EJ a^{-1}), 4.4 EJ a^{-1} (3.7–4.6 EJ a^{-1}) and 1.1 EJ a^{-1} for the EU28 and Germany, respectively. The most relevant subsectors are “iron and steel”, “non-ferrous metals”, “non-metallic minerals”, especially cement, clinker and glass, ceramics as well as “chemical and petrochemical” production (Fig. 4).

Technologies for combustion, gasification, and pyrolysis of biomass are market-ready (TRL 9) or even market-available (TRL 10) [33]. Therefore, replacements of coal or natural gas are possible. Without doubt, there is potential for technical improvements and adapted process steps.

4 Perspectives of Biomass Use for Industrial Heat Processes

4.1 Results from Various Scenarios and Simulations

A full transition of the energy system is needed, if net zero emission of global warming gases is intended. Therefore, a lot of institutes and organizations have studied and modeled, how

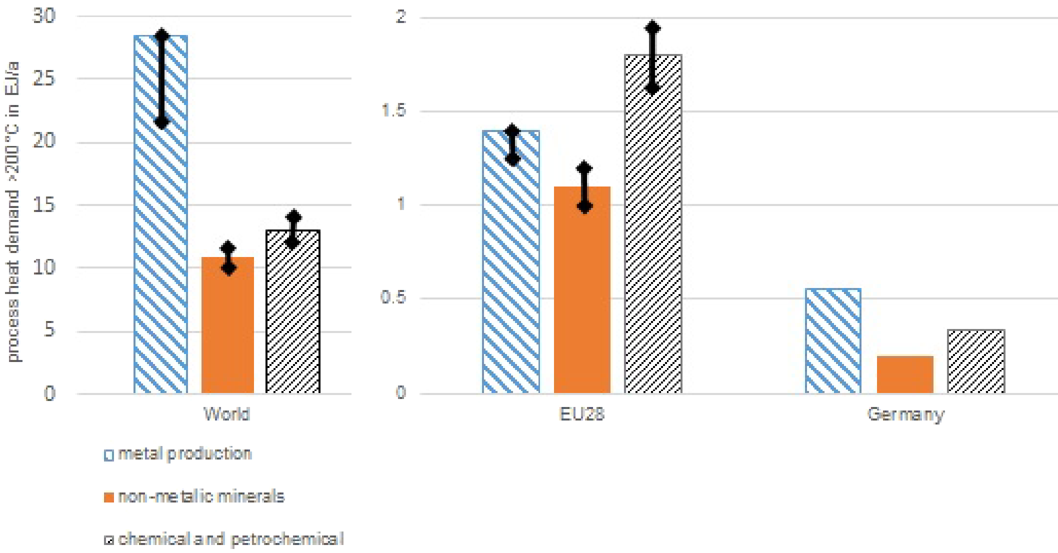

Figure 4. Industrial heat demand above 200 °C worldwide (2011), EU28 (2017). and Germany (2013) of the most relevant subsectors.

a future energy system could look like. Results from these works can be compared to identify driving forces, patterns, or stable technologies and concepts among them. The Deutsches Biomasseforschungszentrum (DBFZ) has set up a scenario database for this comparison. Moreover, the authors have made their own simulations about a possible future use of biomass for heat generation in Germany using the UFZ optimization tool "BenOpt" [23].

4.1.1 Scenario Database of DBFZ for Germany

Energy and climate scenarios are becoming increasingly important for political decision-making. In Germany, the number of scenarios has been increasing, many of them with the goal of describing energy transition, global heating gas (GHG) reduction, decarbonization or building up an energy system based on 100 % renewables. Whilst for Germany only few studies were available in 2000, today around 60 of them describe the entire energy system by 2050. Several further studies deal not with the whole system, but with single energy sectors, e.g., transport or electricity. A total of 155 scenario studies have been identified by the authors and registered in the scenario database developed at the DBFZ, using Microsoft Access [39]. The analyzed studies are dealing with the German energy system by 2050. The metadata of all studies is recorded in MS Excel environment, including title, author, financing institution, year of publication, and the URL.

In 57 % of the studies analyzed, politicians commissioned the study, in 18 % nongovernmental organizations (NGOs), in 15 % industrial actors, and in 10 % research institutes. To proceed with data gathering and processing and to assure high quality of the work, a coding guideline was developed. It includes a detailed description of the ways data has to be searched, registered, processed, and documented. The data of the studies was implemented into the Access database. A search among all data is possible by categories (total energy, electricity, heat or transport), scenario study, year of publication, parameters of the scenarios, or the target years the scenarios are dealing with, up to 2050.

An analysis of this DBFZ scenario database has shown that many studies cover renewable energies in general (over 150), but contain less quantitative information on biomass and bioenergy and very few on the heating sector. A total of 40 scenarios dealing with heating aspects were analyzed in detail, but few information about process heat and biomass in process heat was found; see the last two components in Fig. 5.

In general, according to our database for Germany in the heating sector biomass shows the highest possible share (up to 70 %) by 2050, whereas only a maximum of 10 % of biomass

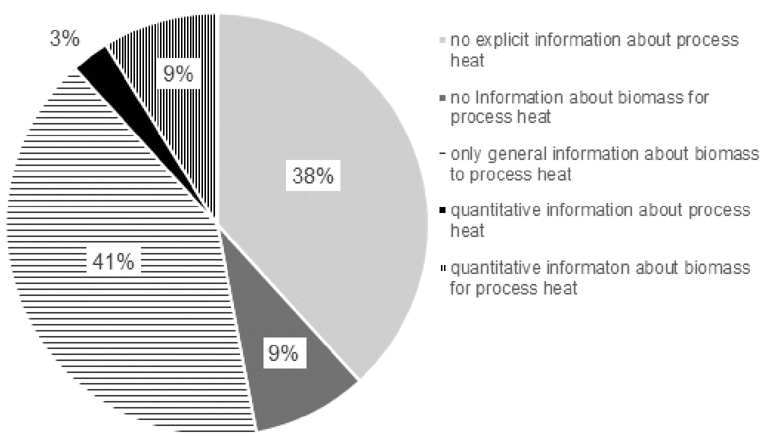

Figure 5. Representation of biomass heat in the analyzed scenarios for the German energy system in perspective of 2050.

share is foreseen for the electricity sector and a maximum of 63 % share of biomass within the transport sector (Fig. 6).

Fig. 7 illustrates the share of biomass in the heating sector by 2050, based on nine scenario studies, which contained some information.

On a closer inspection of industrial heat supply based on biomass, studies provide particularly descriptive information. For example, in [50] is assumed that power and low-temperature heat demands can be supplied by renewable energies other than biomass. Consequently, considerable amounts of biomass are available, which can be used much more effectively, e.g., for high-temperature processes in industry, than for low-temperature heating applications in buildings [50].

In [51], significant parts of process heat from electricity, cogeneration with biogas for high-temperature processes, coke for iron production, and other renewable fuels will be provided from biomass in 2050. Biomass also plays a role especially at temperatures above 500 °C in [45]. Similar assumptions are made in [49].

When looking at some of the climate scenarios [43], it is assumed that biomass use will increase significantly from 20 PJ (2010) to around 390 PJ (2050). Biomass is mainly employed in two areas of industry, namely, steam generators and industrial furnaces. The steam generators provide heat up to 500 °C and are particularly applied in the food, paper, chemical, and plastics processing industries. Industrial furnaces generate heat at a level of over 1000 °C. They are designed according to the respective processes and have various restrictions with regard to the use of fuels.

One study of the authors focuses on the heating sector in Germany using the optimization model BenOpt [23, 52]. After reducing the total amount of sustainable biomass available in Germany for energy purposes by defining shares for transport and electricity, the model calculated an economic optimal use of biomass in the German heat sector, while fulfilling the defined climate targets in Germany until 2050. Besides several subsectors for private household as well as trade and commerce heating, four subsectors for industrial heat applications were

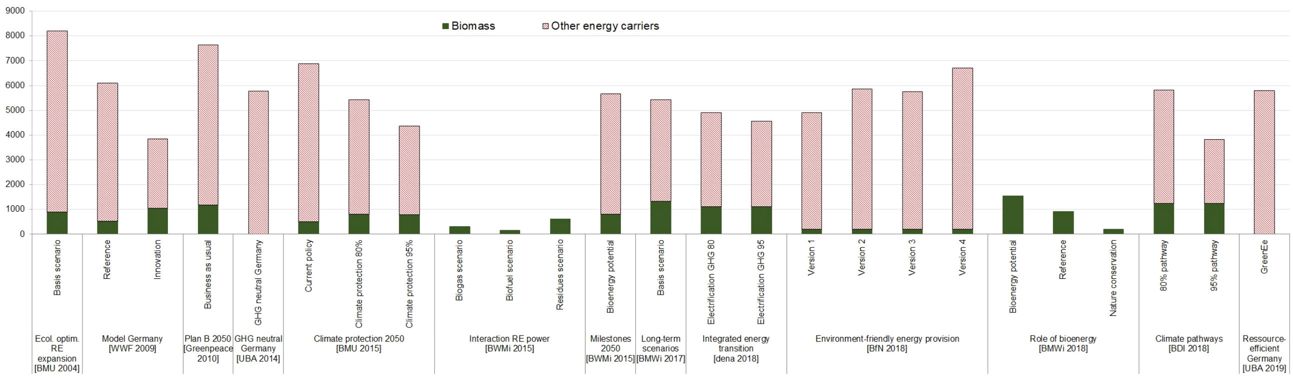

Figure 6. Share of biomass in the energy sector by 2050 according to scenarios for Germany.

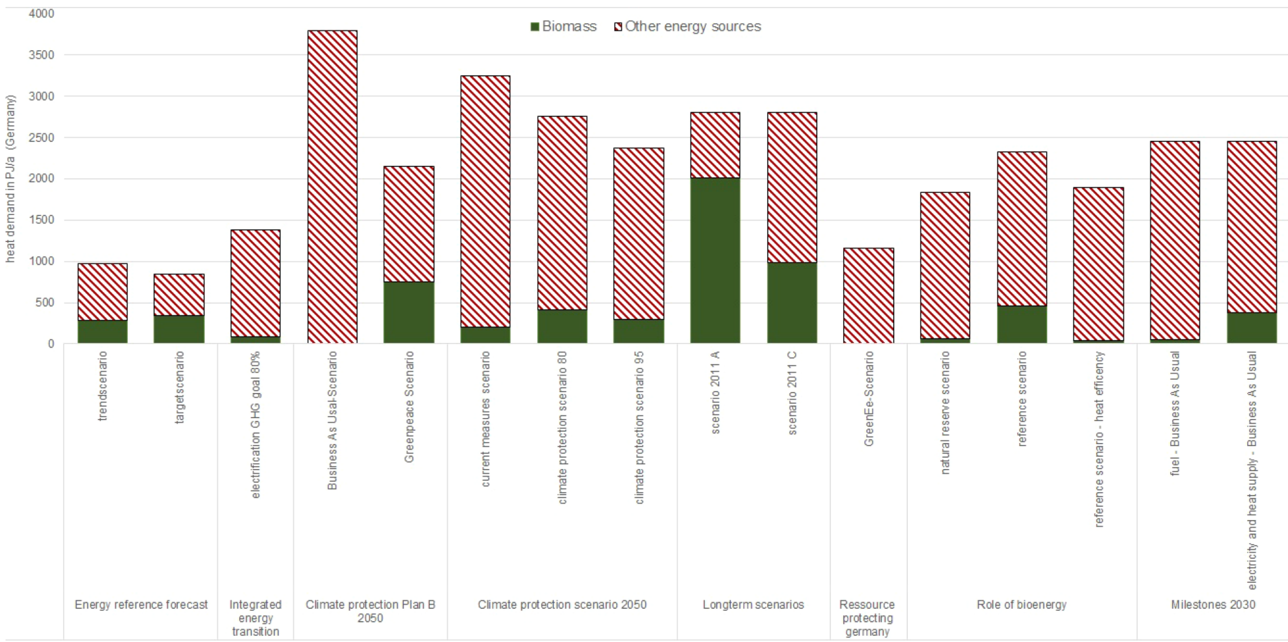

Figure 7. Supply of the heat demand in Germany by 2050 based on scenarios including the estimated share of biomass.

included according to the temperature levels: < 200 °C, 200–500 °C, 500–1500 °C. Additionally, a special subsector to compare bio-coal for steel production with conventional coal was included.

The results of the study demonstrate that in all scenarios a major share of the available biomass is optimally used in industry heat applications. In addition, the utilization of biomass in high-temperature heat applications is found to be the most cost-efficient way to fulfil the 95 % reduction target in 2050; see Fig. 8.

However, the industry sector is depicted in a low level of detail, due to the limited available data basis. Consequently, no conclusions can be drawn as to exactly which industry applications the biomass should be used for. Further research in this direction was identified by the authors.

4.1.2 International Data

According to scenarios dealing with net zero GHG emissions in Europe by 2050, the demand from the industry is reaching almost 3.6 EJ for industry process heat and over 100 EJ globally [53]. A higher demand of around 5.4 EJ is expected in the Heat Europe Roadmap [54]. A study of 100 % renewable energies gives even higher expectations of 13.3 EJ by 2050 [55]. Worldwide, the industrial heat demand is expected to increase up to 108 EJ by 2050 [55]. The sustainable development scenario of IEA assumes an increasing share of biomass among renewables in the industrial energy supply worldwide with up to 10.9 EJ by 2030 [56].

4.2 Perspectives on Important Product Sectors According to the German Example

In this subchapter, the most important industrial heat utilizing subsectors will be discussed regarding their 2050 perspectives and supply technologies according to all the steps described in the scheme in Sect. 2.4. At the status of this article the results are mostly qualitative and are based on the available literature and the authors' knowledge from their own research.

4.2.1 Food and Beverages

In general, food supply will remain an important subsector. The heat demand of this sector, in line with the food demand, will depend strongly on population development, average

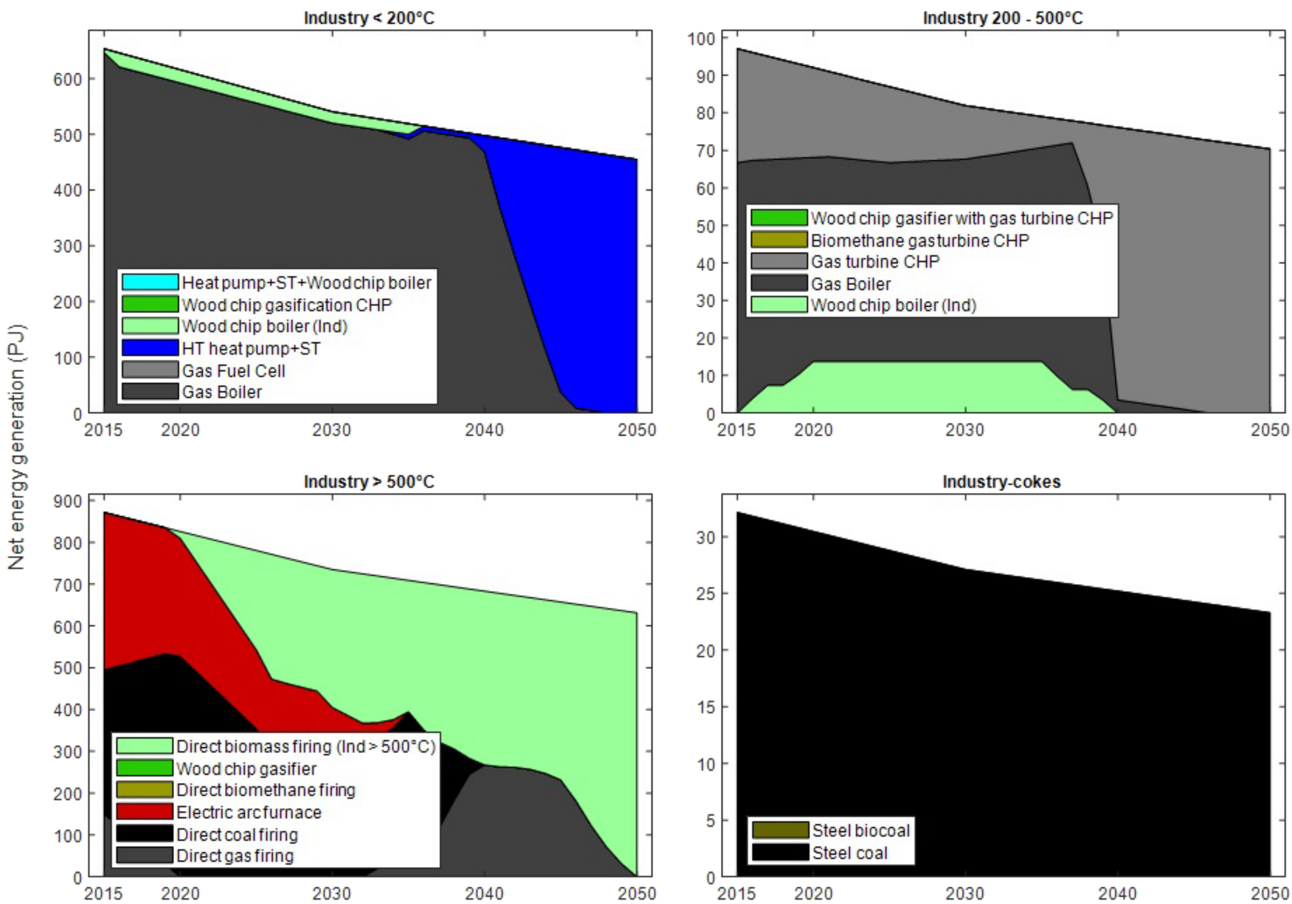

Figure 8. BenOpt modeling results for a 95 % reduction scenario with a high amount of biomass potential pre-allocated to the heat sector.

wealth of the people, and consumption behavior, like demand for meat demand and industrialized food. Thus, the development would probably be very different in the regions of the world (I1). For Germany, one might expect a rather stable demand of about 80 PJ a^{-1} of low-temperature heat and less than 5 PJ a^{-1} of heat supply above 200 °C (I2). As higher heat levels are rare, not much change is to be expected (I3).

Significant amounts of biological residues allow high levels of self-supply with energy. But, quite a lot of low-temperature heat could also be supplied by other renewables, like solar thermal, heat pumps. and geothermal, as well as waste heat from industrial high-temperature processes. During the cold season, CHP plants for renewable fuels will also supply coupled heat produced [23]. Some of the residues could be utilized as fodder and others might be transferred to gaseous or solid bioenergy fuels for other applications [57]. Thus, for the future, the authors estimate only 20 % of the low-temperature heat and the full high-temperature heat to be supplied by biomass. That means a total of roughly 20 PJ a^{-1} with a possible variation of +/– 20 % (II4). Fractions of used biomass would be only residues from the production, which are not of a sufficient quality to be employed as high-quality fuels (II5). CO_2 separation could be combined with biomethane production. But, in combination with a flexible green hydrogen uptake, the CO_2 might also be transferred to methane, and a utilization in food production might occur, also (II6).

4.2.2 Pulp and Paper

The paper demand for media might decrease in the future due to digitalization. At the moment, the requirement of packaging is growing. But, realizing a real bioeconomy, the consumption of products will decrease and more regional consumption might occur. Thus, also packaging might decline again. Therefore, the total amount of energy might even decrease a bit (I1). For Germany, less than 10 PJ of heat demand with temperatures above 200 °C might be expectable and the lower heat supply in a renewable world might be 20 % of 150 PJ a^{-1} (I2).

If waste disposal and flexible power supply are combined, on a production sight up to 40 % of low-temperature heat demand might be supplied by biomass (I3 and II4). Used biomass fractions would be residues from the production, like black liquor or bark, which are not of a sufficient quality to be used as material resources or as high-quality fuel (II5). CO_2 separation will depend on the size of the plant and the amount of biomass utilization for energy (II6). Thus, for Germany a demand of up to 70 PJ a^{-1} (+10 % to –50 %) of heat supply from biomass might be expected in this subsector.

4.2.3 Wood and Wood Products

This subsector will gain significantly in relevance, if a bioeconomy will be established consequently. Probably, more wood will be employed for construction purposes, furniture, and totally new products as well as for chemical processes (I1). The amount of heat with temperature level above 200 °C will probably not increase significantly. Thus, it will keep at a level of about 10 PJ a^{-1} for Germany. The demand for heat with lower temperature will increase probably by up to 50 % by 2050 (I2). A shift of heat demand to lower temperature is not to be expected (I3). According to the available residues with low quality, up to 20 % of the low heat demand as well as the high heat demand would probably be supplied by biomass, e.g., about 20–35 PJ a^{-1} for Germany (II4). Especially bark seems to be a promising production residue for heat generation. High-quality residues like cutting ends and sawdust might be preferred within the bioeconomy (II5). Depending on the size of the wood processing plant, BECCS could be integrated (II6).

4.2.4 Iron and steel

Our modern world is based on steel. It is not probable that we can change many applications towards other materials, but in a more sufficient world of the future the authors devise a circular economy in which no raw steel has to be produced from iron ore (I1). Melting of the raw material needs high temperatures, significantly above 500/600 °C (I2). Moreover, a shift to lower temperature levels is not possible (I3). For the production of raw iron from iron ore, a reduction agent is needed, which also helps to separate slag and iron. Here, coal is utilized up to now.

Some experiments were made with thermally treated biomass and, in principle, they were successful. However, due to the ash components of the biomass additional impurities could get into the steel. Main barrier is the high price of the coke produced from biomass. Additionally, further research for adopted biocoke production according to metal quality is needed. Nevertheless, biomass could be a favorable opportunity to start decarbonization of steel production [58, 59]. Alternatively, some companies are trying to build up the converters with hydrogen as reduction agent [60]. The required heating is typically done with electricity. Thus, a defined need for biomass might be small (20–40 PJ a^{-1} for Germany) and shrinking to zero for the future (II4).

The biomass quality must be quite high (clean wood) and has to be thermally treated to generate biocoke, losing 2/3 of the energy, which makes the process quite inefficient (II5). Coal replacement is important, as steel production is one of the biggest heat-utilizing processes in industry with a high coal demand. However, by using electricity and hydrogen an almost CO_2-free production is possible and CO_2 removal is not necessary (II6).

For non-iron metal production some differences occur. At least some non-iron metals (today especially aluminum) will be required in the future (I1). Required temperature levels are mainly in the range above 500/600 °C (I2) without a possibility to shift to lower temperatures (I3). But, heating can be done by electrical stoves in most cases and processes could be made more flexible. Consequently, secure high power supply is not required in all steps. Thus, biomass is not needed in any case (II4).

4.2.5 Non-Metallic Minerals

For housing and infrastructure of more than 7 billion people the use of concrete will probably not be avoidable. Thus, clinker and cement production will be needed also in the future

(I1). For the process, high direct heating of the raw material is required to activate it (I2). A shift to other processes or temperature levels is not known to be possible (I3). As the material is not melting, electrical heating is hard to be realized. Direct solid fuel input (biomass) or direct flaming from gas are necessary. According to today's utilization, about 150–180 PJ a^{-1} are required only for Germany. A cost competition has to be checked towards green hydrogen (II4). Biomass should be solid and no restrictions even for waste wood are given. After drying, almost any regional wood-based biomasses could be used (II5) [61]. As the process itself emits significant amounts of CO_2, a CO_2 removal would be very promising, if the production sites are big enough (II6). This opens the chance for negative emissions by using sustainable biomass as fuel.

The state-of-the-art glass production is mainly realized by direct and indirect electric heating. Glass will probably play a significant role also in the future (I1). For the main melting and processing step, temperatures of about 1400–1500 °C are required (I2). These cannot be shifted to lower levels (I3). Heating with biomass could only be indirect due to the demands for purity in the production and therefore the needed temperatures cannot be supplied. Biomass could only be used for securing secure power supply by power plants or after conversion to gas, but both are not special industrial production cases (II4).

4.2.6 Chemicals and Petrochemicals

Within a future bioeconomy, processes will probably change but in principle basic chemicals will still be produced (I1) utilizing heat in the range of up to 500/600 °C (I2). A shift to lower temperatures might partly be possible, but not for all of the processes (I3). Heating could be supplied by electricity, biomass, or power-to-fuel (PtF) with some low-temperature input from concentrating solar thermal (CST), heat pumps or geothermal as well as waste heat and surplus electricity. As chemical processes often need defined conditions, a secure heat supply is required, so biomass would probably be an interesting option for the supply security.

A possible amount of biomass required might be around 100–150 PJ a^{-1} based on today's consumption level in Germany (II4). Due to bigger sizes of the production plants, almost all kind of biomass qualities could be used (II5). By pure oxygen combustion, CO_2 removal including a full removal of dust particles might be possible for bioenergy-based carbon capture and storage (BECCS). Utilization of the CO_2 might be difficult according to the other combustion emissions (II6).

4.3 Implementation Perspectives of Biomass to Industrial Process Heat Supply

There seem to be significant possibilities to use biomass for industrial high-temperature applications. But, besides an exergetic advantage, high GHG reductions and technical restrictions (see Sect. 2.4 and 4.2) other barriers can hinder an increased utilization of biomass (Tab. 3).

Table 3. Special barriers for biomass use for industrial heat consuming production subsectors [62].

Subsectors	Barriers
Basis chemicals industry	– Uncertainties concerning sales markets – Risks for optimized production processes – Low number of plant manufacturers
Metal production	– Regulatory aspects (e.g., heat recovery for sinter plants) – Technology development towards CCS and uncertain future technologies
Non-ferrous metal production	– Internal allocation of energy costs – Realization of measures through employees
Paper industry	– High development effort for innovative solutions – Acceptance of secondary fuels
Earth and stone industry	– High development effort – Acceptance of alternative fuels – Complexity of efficiency measures
Glass and ceramic industry	– Insufficient evaluation of measurement data from industrial furnaces – Complexity of efficiency measures for existing plants (e.g., heat recovery)
Food industry	– Lack of technical standards for investments/components (especially in SME)

From Tab. 3 three main barriers can be derived: (i) acceptance of alternative fuels independent from technical proofs by the staff, (ii) complexity of transformation process and risk of difficulties with the production at least during transformation process, and (iii) uncertainties about internal price allocation and market effects. In combination with still low gas, oil, and coal prices, these barriers gain in importance. Thus, significant CO_2 prices could encourage decision makers to handle these three barriers, as cost incentives are a strong driver in our markets [34]. Considering these barriers it is not finally clear at which CO_2 price a significant transformation towards renewable energies and biomass will start.

Additionally, implementation of further use of biomass for high-temperature heat supply depends significantly on the biomass price development. This is influenced by a lot of variables, like the speed of the implementation of a bioeconomy, climate changes, and their impact on biomass production, meat consumption, world population, and its consumption behavior, as well as developments in agriculture and forestry, also depending on sustainability and biodiversity targets, and finally the willingness of small and medium forest owners to sell their wood to the industry biomass prices moderately increased over the last decades [63].

Especially for wood-based biomass the prices were coupled to the price developments of fossil feedstocks like, e.g., the gas price [63]. In a future carbon-free scenario, biomass prices will be decoupled from fossil prices. As a shortage on resources is probable in such a scenario, biomass prices are likely to further increase. Millinger and Thrän [13] applied a common method to estimate future price developments of energy crops based on the development of a benchmark crop; in the case of Germany, the benchmark crop is wheat. However, the future price development of wheat is derived from the developments of the last decades [64] and attached with a high degree of uncertainty.

Rising biomass prices are probably a barrier. However, they could also intensify biomass production and thus increase the availability of biomass residues at a low price level. Further research on the difficult correlations and dependencies are necessary.

Last but not least, electricity prices and their development will have a major impact. Simulations of Jordan et al. [65] showed a high sensitivity on that factor for space heating, but not for industrial applications. However, this could be a consequence of not having implemented power-to-hydrogen pathways. Decreasing prices for photovoltaic (PV) and wind power combined with further research and development achievements in the field of material adaptation for electrolysis and fuel cells could bring up a new alternative fuel or at least lower stabilized power prices for the future. This could affect quite significantly the use of biomass for high-temperature processes as biomass could have some other disadvantages (see Sect. 4.2).

Implementation of biomass for high-temperature heat supply in industry is not only a question of biomass availability and technical feasibility. But, it is also dependent on uncertain price developments in the market and especially the perspectives of green hydrogen. Therefore, further research is required to set up the right political framework for transferring the biomass to industrial processes with a stable advantage for biomass.

5 Conclusions

Industrial fuel consumption, mainly for heating processes, is responsible for roughly one-fifth of all CO_2 emissions worldwide. Scenarios based on the Paris Agreement see an important role of energy from biomass in this sector. Up to now, biomass is rarely used for industrial process heat in the special focus of this review, i.e., over 200 °C. But, for any heat generation below 200 °C almost 40 EJ a^{-1} worldwide, about 2.5 EJ a^{-1} in the EU28, and roughly 0.4 EJ a^{-1} in Germany of biomass were used. These resources might be transferred basically to high-temperature industrial heat processes. Main hindering reason were higher costs compared to gas, oil, and coal, as well as more complex processes to handle the biomass within the industrial production.

In some cases biomass qualities or sustainable availability in the regional context were not given, e.g., raw steel production from iron ore. While "food and beverages", "wood and wood products" as well as "pulp and paper" have low demand for high-temperature heat (above 200 °C), "iron and steel" as well as "non-iron metals", "non-metal minerals", and "chemical and petrochemical" have a highly significant requirement for process heat above 200 °C with 53 EJ (43–55 EJ) worldwide, 4.4 EJ (3.7–4.6) in the EU28, and 1.1 EJ in Germany, respectively. In the subsector "iron and steel" some difficulties occur according to needed biomass qualities. Thus, other technological pathways for decarbonization are under investigation, e.g., hydrogen blasts. "Chemical and petrochemical" is an interesting subsector for utilizing biomass for process heat, especially together with a change of input materials within a bioeconomy. On a short time scale, the most promising subsector seems to be "non-metal minerals". Cement, clinker, glass, and ceramics need a lot of high-temperature heat, and utilization of biomass is quite easy to be implemented at least for cement and clinker, as already significant amounts of biomass are used.

The current use of production residues and wastes in pulp, paper, wood production, and food sector mainly for low-temperature heat should be reviewed for implementing other renewables. Then, the gained biomass could be employed for high-temperature processes, if needed.

Despite the current low status of utilization, a lot of energy scenarios and simulations of future energy markets show a significant demand for biomass for industrial heat supply. But still, the scenarios exhibit significant differences in the amount of biomass demand for heating purposes, e.g., Germany 0 to a maximum of 2 EJ a^{-1} (see Fig. 7).

In principle, biomass used for low-temperature heat is more or less enough available to supply high-temperature heat for industry. But, from a more detailed technical and regional point of view, the demand for high-temperature process heat cannot be supplied so easily by just replacing oil, gas, and coal by biomass, especially under consideration of a growing bioeconomy and high regional variations of biomass availability. Therefore, biomass should be utilized in the most efficient and effective way possible. A method for decision taking is introduced by the authors to use biomass in those industrial heat-demanding processes with the least alternatives for other CO_2-free supply options with the best available technologies, e.g., cement and clinker.

Unfortunately, the reviewed literature and simulations did not give a sufficiently detailed picture for final conclusions about the most important heat-consuming industrial processes for using biomass. Thus, further research is necessary. This is (i) to gain more data about industrial processes and subsectors to identify the most relevant ones with high demand and few renewable alternatives and adequate biomass-based heat supply technologies available, (ii) to define needed biomass qualities for those high-temperature processes, (iii) to develop appropriate indicators and scenarios to identify the role of biomass by optimization models, to set up reasonable time frames for transformations, and last but not least (iv) to set up methods and measures to redirect the biomass towards the preferred heat utilization despite all of the existing barriers.

Due to the high possible CO_2 reductions, also in combination with CO_2 separation and storage, research and development in the above-mentioned areas should be intensified soon.

The authors have declared no conflict of interest.

Abbreviations

BECCS	bioenergy with carbon capture and storage
CCS	carbon capture and storage
CHP	combined heat and power
CST	concentrating solar thermal

DBFZ Deutsches Biomasseforschungszentrum gemeinnützige GmbH
EJ 10^{18} Joule
EU28 28 member states of the European Union
GHG global heating gas
Gt billion tons
IEA International Energy Agency
NGO nongovernmental organization
PJ 10^{15} Joule
PV photovoltaic
PtF power to fuel

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