Renewable and Sustainable Energy Reviews 112 (2019) 960–977

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

Current status and future perspectives for energy production from solid biomass in the European industry

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A R T I C L E I N F O

Keywords:
Bioenergy
Solid biomass
Industry
Process heat
Cogeneration
Europe

A B S T R A C T

Industrial heat is important in Europe's energy consumption and dominated by fossil fuels. Therefore, promoting renewables in this sector is vital to move Europe towards a low-carbon economy. Since solid biomass is the only renewable with significant industrial use, it is crucial to know the status of its present use and to analyze the prospects of its future utilization by the industry. The current European industrial energy consumption is reviewed, with a focus on bioheat. The available solid biomass feedstock and energy conversion alternatives are examined, along with future perspectives for further biomass consumption in several industrial sectors. Defining global strategies for industrial heat is not easy because of the diversity of industrial processes. Combustion dominates industrial heat production from biomass, but gasification systems are already commercially available. Combined heat and power production is mainly based on steam cycles. The full temperature range required by industry can be attained with biomass efficiently. The use of biomass-fired systems is generalized in the industries that generate solid biomass by-products, but the implementation of additional, more efficient and alternative biomass uses should be sought. Biomass penetration into sectors with no own biomass resources is more difficult. Major barriers are the high investment costs of biomass systems, strong competition with fossil fuels, and feedstock availability and security of supply. Although Europe's solid biomass production and consumption are almost balanced, the pressure on resources is increasing. Therefore, it is important that resources are monitored and that sustainability is taken into consideration.

1. Introduction

The industrial sector accounted for 29% of the global total final energy consumption, having seen a 44% increase in the energy use of fossil fuels between 1973 and 2016 [1]. Despite the relatively higher increase in the consumption of waste and renewables (128% rise in the same period), fossil fuels still dominate the world's final energy consumption in industry, and coal is the most used energy source (30% share in 2016, with a growth of 132% from 1973 to 2016).

In the European Union (EU), the industrial energy consumption also plays a significant role (10929 PJ, 23% of the EU's final energy consumption in 2017 [2]), but contrary to what has been globally happening in the world, it has been decreasing because of structural changes in the economy and efficiency improvements. Presently, most of the demand for energy in the EU28 industry is met through the direct use of fossil fuels and electricity, which, for its part, continues to significantly rely on fossil fuels [2]. The share of the direct use of renewable energy sources (RES) for the EU28 industrial final energy consumption was small (9% in 2017) and biomass was the only RES with significant use (93% of the RES used in the industry was solid biomass, 3% municipal waste and 2% biogas). This renewable fuel offers the possibility, sometimes through pre-processing technologies, of greater industrial uptake of clean, low-carbon technologies, and is especially well suited for heat and combined heat and power (CHP) production and therefore for industrial use (around two thirds of the final energy demand of the EU28 industry is in the form of heat [3,4]). However, several barriers hamper an increased use of biomass by the industry, and although many bioenergy projects are technically feasible, they are not implemented [5].

With the current policies, the EU will not reach the proposed 80% reduction in its domestic greenhouse gas (GHG) emissions by 2050 compared to 1990 [6]. New policies and major investments, both private and public, are needed in the next decades to achieve this goal, and all sectors (electricity, heat and transport) need to contribute. In this

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https://doi.org/10.1016/j.rser.2019.06.022
Received 16 November 2018; Received in revised form 13 May 2019; Accepted 10 June 2019
Available online 26 June 2019

Abbreviations			
CEPCI –	Chemical Engineering Plant Cost Index	GHG –	Greenhouse Gas
CHP –	Combined Heat and Power	ICE –	Internal Combustion Engine
ECN –	Energy Research Centre of the Netherlands	OECD –	Organization for Economic Co-operation and Development
EU –	European Union	ORC –	Organic Rankine Cycle
EU28 –	28 Member States of the European Union	RES –	Renewable Energy Sources

context, market-based mechanisms and subsidies are important instruments; however, today's reality shows that subsidies are not directed to heat: In the world, around 80% of the subsidies to renewables are directed to the power sector and only 1% to heat [7].

Promoting the deployment of RES for heat production, including in industry, is important to achieving the EU28 goal of moving towards a competitive, sustainable low-carbon economy. There is a large untapped potential to increase the penetration of RES, biomass included, in industry. To realize this potential, a clear picture of the current industrial energy use is required, along with an assessment of the environmental and economic performance of the current and future utilization of RES. This review focuses on solid biomass, because it is the foremost RES in industry and is expected to remain in that position in the future [8,9]. The analysis focuses on heating, but also considers CHP, because of its importance in several of the EU28 manufacturing sectors. The conversion of biomass into electricity alone is not considered in this review.

Some studies analyze the potential for renewable energy in industrial applications [9–12], or the technologies, economics or policy instruments for driving a shift to a sustainable industry [13–18]. When the studies focus on the industrial use of biomass, they usually address specific industries [19–24] or technologies [8,25]. To the authors' best knowledge, none of the existing papers analyzes the current status of biomass energy consumption by industry and the perspectives for its future use, together with a review of the technologies available for its conversion and of the feedstock production, consumption and characteristics. This work combines these issues into a single review, providing the reader with an integrated, synthesized overview and allowing a comprehensive understanding of the perspectives for additional use of biomass by industry. Although this is done in a European context, several topics covered in this paper are also relevant when assessing the potential of further industrial biomass use in other regions. Additionally, the deployment of further biomass by the EU28 industry is likely to be linked to imports and to affect other world regions that export biomass, increasing the pressure on their natural resources.

2. Energy consumption by the EU28 industry

In the EU industry, there was a 24% decrease of the final energy consumption from 1990 to 2017 (Fig. 1). The importance of the sector in EU28 final energy consumption has also been declining, from a 34% share in 1990 to 23% in 2017. There was a decrease in the industrial final energy consumption of all fossil fuels and derived heat, with a marked decrease for solid fuels (by 70%) and oil (by 56%), and a less pronounced decrease for gaseous fuels (by 22%) and derived heat (by 20%). Inversely, the consumption of RES and non-renewable wastes (municipal and industrial) has been steadily increasing (Fig. 1). The former increased by 76%, while the latter increased by more than four times. The industrial electricity consumption presents a non-monotonic behavior, with identical consumption in 2017 and 1990.

The biggest share (84%) of the EU28 final energy consumption in industry in 2017 was met through the direct use of fossil fuels, such as natural gas, coal and oil, and electricity, which still greatly relies on fossil fuels (mainly coal and natural gas). Natural gas and electricity are the most commonly used energy carriers, with more than two thirds of the final energy consumption (Fig. 2). RES had a relatively small expression.

2.1. Heat demand

Unlike electricity or transport fuels, heat is rarely sold off-site, not requiring metering, which results in a generalized lack of heat demand data [26]. The Eurostat statistics do not disaggregate the energy consumed in industry into its end-uses (e.g., process heat, power), and most of the EU countries do not provide national end-use balances for industry. The inexistence of official data that allows understanding the structure of heat demand in industry hinders demand-oriented energy

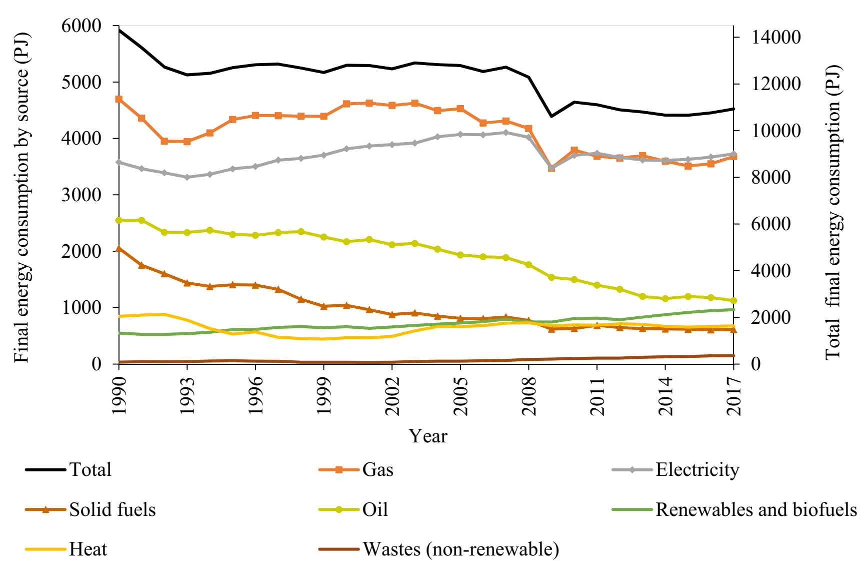

Fig. 1. Temporal evolution of the final energy consumption in industry by energy carrier for EU28 from 1990 to 2017 (Data source: [2]).

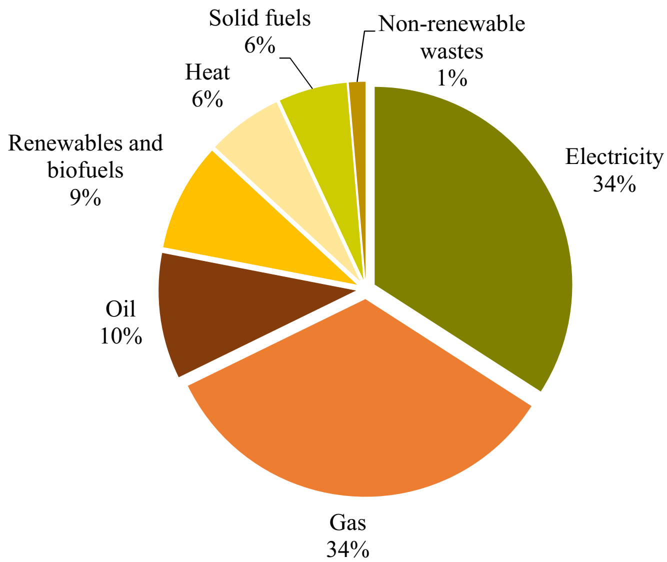

Fig. 2. Share of energy carriers in the final energy consumption in industry for EU28 in 2017 (Data source: [2]).

strategies. The European Commission is aware of the importance of having more knowledge on the heating and cooling sector and of its important contribution to the EU's energy and climate objectives. Consequently, recent efforts have been made to characterize and define strategies for this sector (e.g., Ref. [27]).

In EU28, most of the energy consumed in industry is in the form of heat. Survey methods were combined with bottom-up models by Ref. [3] to determine the energy demand of industrial end-users and establish a full end-use energy balance by country. It was concluded that the share of heating in the final energy demand of the EU28 industry in 2012 was 71%, of which 60% for process heating and 11% for space heating [3] (Fig. 3). Another study estimated that eight important and energy-intensive sectors of the EU28 industry used 66% of their final energy for process heating in 2013 [4].

The industrial processes and energy conversion technologies used in the several manufacturing sectors (and also sub-sectors) are very diverse, and so is the share of heat consumption. Heating takes the largest share in the most energy-intensive industrial sectors (Fig. 4). In EU28, 84% of the process heat is consumed in five industrial sectors, specifically in the iron and steel; chemical and petrochemical; non-metallic minerals; pulp, paper and printing; and food, beverages and tobacco industries. The promotion of energy efficiency and of the deployment of RES, namely biomass, in these manufacturing sectors has a big influence on the overall reduction of the energy consumption and on the environmental impact of the EU28 industry.

In 2012, 76% of the process heat demand was met through the direct use of fossil fuels (Fig. 5). Natural gas alone was responsible for 36% of the industrial final energy consumption, and was mainly used to produce heat above 500 °C. Coal, the second most used fuel for process heat production, was almost entirely utilized in the generation of high temperature heat (like "other fossil fuels"). Biomass was the fourth most used fuel with a share of 11%. Even though biomass can be used to produce high temperature heat, in 2012 it was mainly utilized to supply heat at temperatures below 200 °C. The deployment of other RES is minimal in the EU28 industry.

Most of the process heat demand in EU28 was above 500 °C (Fig. 5). The same conclusion was drawn by Ref. [29] for 2015. The iron and steel, chemical and petrochemical, and non-metallic mineral industries are important consumers of heat at high temperatures. High temperature heat is usually provided by direct heat produced by industrial furnaces [3]. To deliver heat at lower temperatures, individual boilers and CHP units are used [29]. Although only 38% of the heat delivered to the EU28 industry is characterized by temperatures below 200 °C, important energy consuming sectors, such as the pulp, paper and printing; and food, beverages and tobacco are dominated by low temperature industrial processes.

When looking at the geographical distribution of process heat consumption in EU28, Germany has the highest consumption, followed by Italy, the United Kingdom, France and Spain [3]. These five countries accounted for almost 60% of EU28's process heat in 2012 [28], and also have the biggest share of industrial final energy consumption (57%) [2]. Natural gas is relevant for process heat production in most EU countries (Cyprus, Finland, Iceland, Malta and Sweden are exceptions). Coal is particularly significant in eastern European countries and in countries with an important iron and steel industry. As far as RES are concerned, biomass has particular relevance for process heat production in Sweden, Latvia, Finland and Portugal.

2.2. Solid biomass

Eurostat reports biomass final energy consumption in the EU28 industry, but does not disaggregate this consumption into end-use. Looking at the estimates of Ref. [3] for EU28 and 2012, all industrial

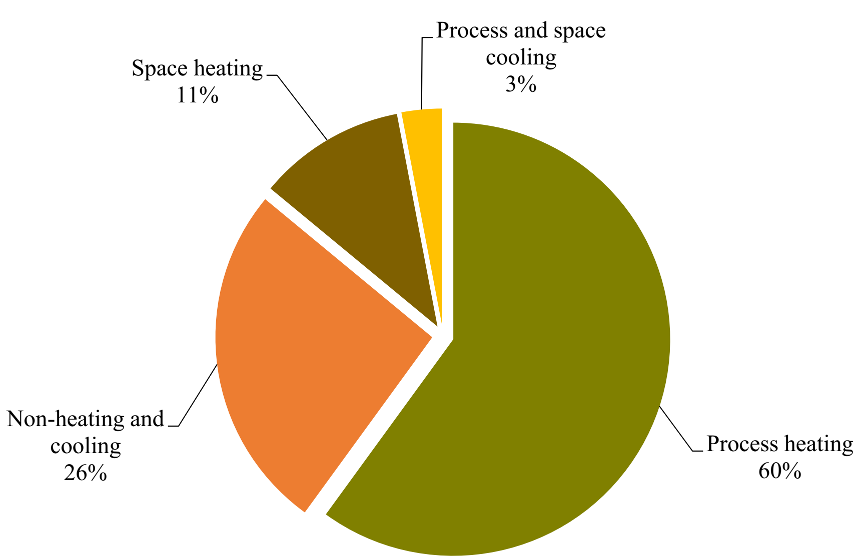

Fig. 3. Share of the different end-uses in the final energy demand in industry for EU28 in 2012 (Data source: [28]).

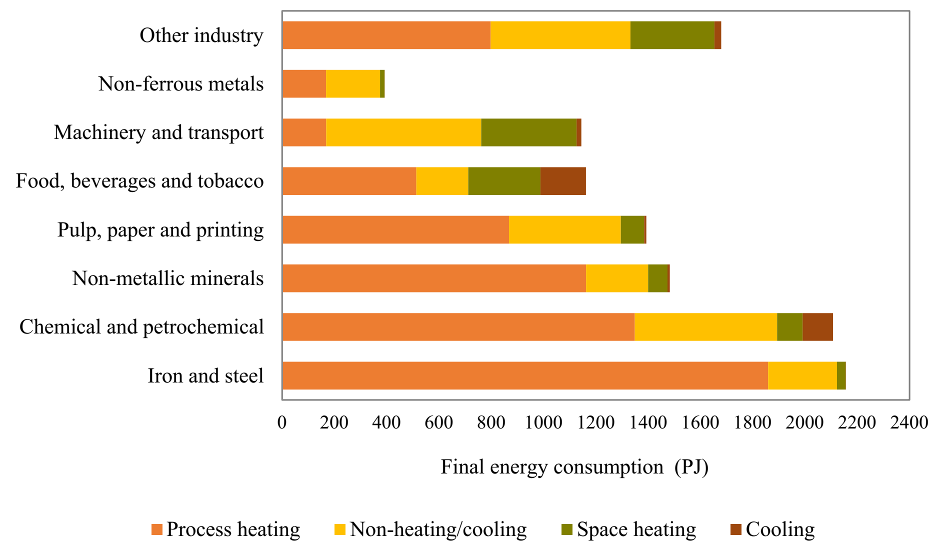

Fig. 4. Final energy consumption by end-use in industrial sectors for EU28 in 2012 (Data source: [28]).

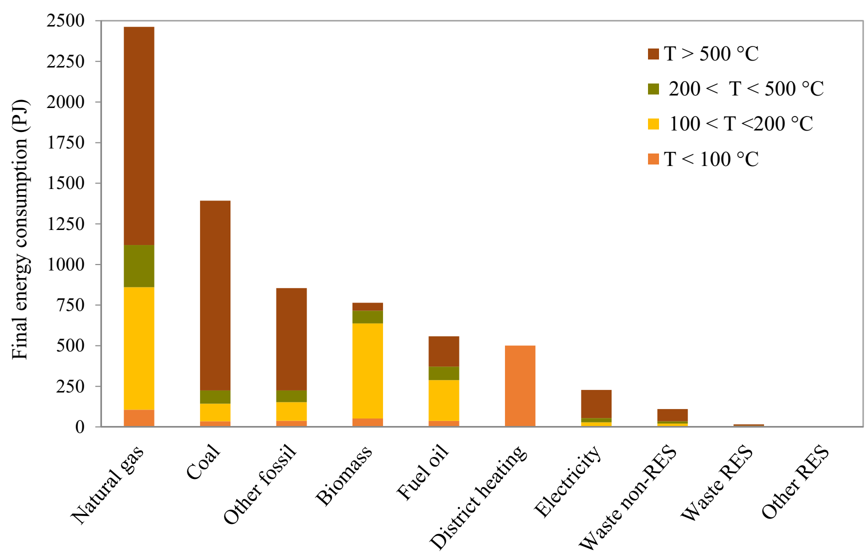

Fig. 5. Final energy consumption for process heat in industry by energy carrier and temperature level for EU28 in 2012 (Data source: [28]).

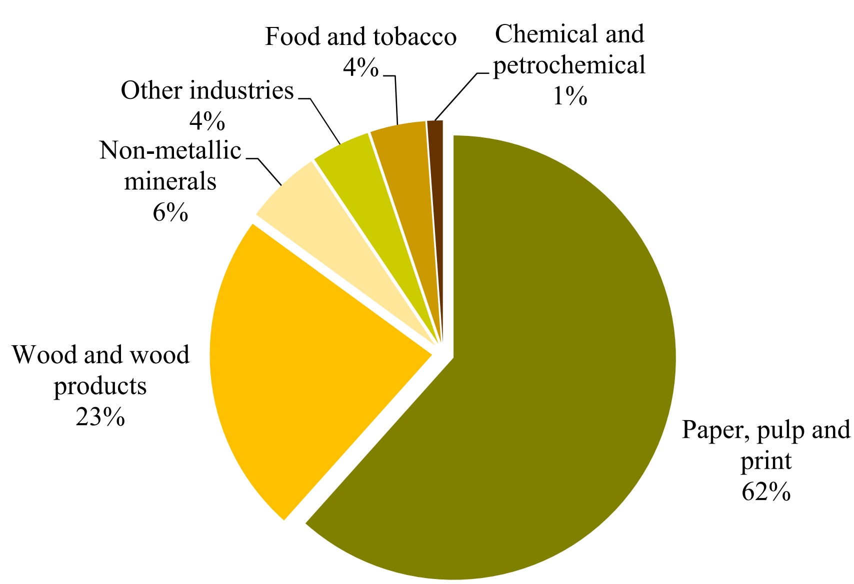

Fig. 6. Share of the different industrial sectors in terms of solid biomass final energy consumption for process heat for EU28 in 2017.

solid biomass final energy was directed to process heat production (none for cooling, space heating or other uses). Also Ref. [29] concluded that in 2015, EU28 industry used almost virtually all biomass for process heat. Assuming that all biomass is used for process heating and using Eurostat statistics [2], Fig. 6 presents the solid biomass final energy consumption for process heat in different EU28 industrial sectors in 2017.

In 2017, the EU industry final energy consumption of solid biomass was around 898 PJ [2]. The EU28 industrial sectors that consumed the most solid biomass for process heat are those that generated biomass residues, such as the pulp, paper and printing; and the wood and wood products industries, which were responsible for 85% of the industrial biomass final energy consumption. Of some relevance is the non-metallic mineral sector, which, despite not generating biomass residues, accounted for 6% of the EU28 biomass consumption for process heat.

Some industrial establishments are autoproducers and produce electricity and heat, which is in part delivered to users outside the plant. This is common, for example, in the pulp and paper industry, and in the production of wood-based panels, where solid biomass is often used in CHP systems [30–34].

3. Feedstock

Generically, solid biomass for energy purposes can be obtained from: residual organic matter extracted from forests and uncultivated lands; energy crops; wastes and residues produced in industrial, agricultural and forestry activities; and municipal wastes. It is mostly used directly by the industry (e.g., wood chips, bark or nut shells), but upgraded solid biofuels are also used (e.g., pellets, charcoal or torrefied biomass). One of the reasons for the use of upgraded biomass is efficiency. In some industries (e.g., iron and steel) it is not efficient to use raw biomass; therefore it suffers a thermal treatment that increases its energy density. Another reason for biomass upgrading is that it is easier and cheaper to transport and store biomass that was previously densified, which is particularly important when biomass is consumed in a place other than that of its generation.

The most recognized technologies available to convert biomass into upgraded solid biofuels are pelletization, pyrolysis and torrefaction [35]. The first two are mature and commercially available, while torrefaction entered the commercial demonstration phase and is on the verge of commercialization [36]. Reviews on solid biomass upgrading can be found, for example, in Refs. [36–41]. Solid biomass can also be converted to liquid or gaseous biofuels [42–45], which however are not often used in the processing industry today [2].

3.1. Current production and consumption of solid biomass

In EU28, the energy production from solid biomass increased by 134% from 1990 to 2017 (Fig. 7). In 2017, the primary energy production from solid biomass (excluding charcoal) was 3986 PJ, which corresponded to 12.5% of the total primary energy production and 69% of the biomass primary energy production [2].

The largest contribution for solid biomass fuels comes from the woody biomass. Forest products are used for many different purposes, energy being only one of them. 78% of the EU28 roundwood production in 2017 was used in wood-based industries for sawnwood and veneers; or for pulp and paper production, while the remaining 22% was used as fuelwood [2]. The share of primary wood products used for energy may be underestimated in some countries, because of existing informal ways of getting the biomass.

To date, pellets are the upgraded biofuel mostly used in Europe, although with a relatively small expression. In 2016, they represented 9% of the total solid biomass energy consumed in EU28, corresponding to around 21.7 Mt [46]. The largest producers of wood pellets are Germany, Sweden and Latvia, but France, Estonia, Austria, Portugal, Poland, Romania and the Czech Republic play also a relevant role [2]. The structure of the wood energy markets has changed with the growth of solid biomass use for energy purposes [47,48]. Today, there are several established markets for the trade of solid biofuels. Particularly relevant for industrial applications are wood chips and refined fuels such as wood pellets and wood briquettes [49–51]. Industrial pellet [52] and charcoal [53] markets depend on imports outside the EU.

In 2017, 22% of the EU28 solid biomass energy corresponded to final energy consumption in the industry (Fig. 8). Most of the solid biomass was used in households and by the energy sector in main activity producers. Autoproducers in industry also consumed a significant part of the EU28 biomass [2].

3.2. Potential production and consumption of solid biomass

EU28 is presently almost self-sufficient in terms of solid bioenergy. However, the region has been a net importer in the last decades, passing from a dependency rate of 0.5% in 1996 to 4.8% in 2017 [2]. The expected increase in solid biomass consumption both from energy and non-energy markets and a limited capacity for sustainable domestic biomass production raises concerns about the future biomass availability in EU28. Many studies are focused on the future availability of sustainable biomass in Europe (e.g., Refs. [54–58]). Other focus on the different possible uses of biomass and their future implications either in terms of energy-demand, economics and/or environment (e.g., Refs.

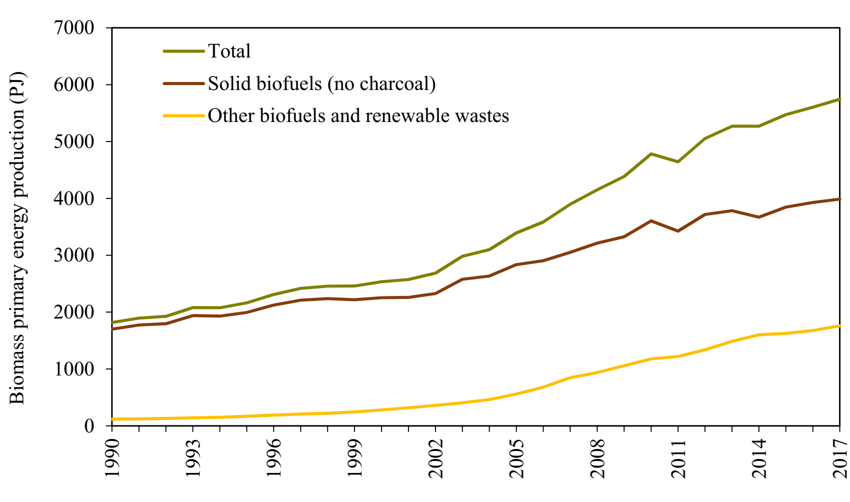

Fig. 7. Biomass primary energy production for UE28 from 1990 until 2017 (Data source: [2]).

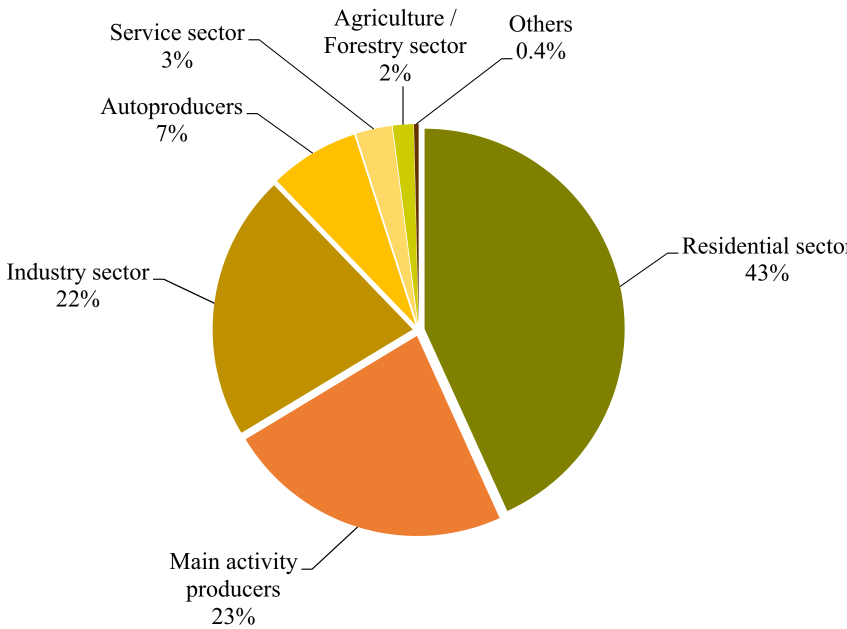

Fig. 8. Share of the different end-uses of solid biomass in EU28 in 2017 (Data source: [2]).

[59–62]).

According to Ref. [58], in Europe in 2030, the total energy available from forest biomass alone will vary between 119 and 186 Mtoe. These values are above the today's gross inland consumption of solid biomass and the projected total solid biomass primary demand to meet the 2020 targets defined in the National Renewable Energy Action Plans projections (118 Mtoe [57]). However, they are not above the expected demand in 2030 [63]. A significant future contribution to solid biomass availability could come from agriculture and forest energy crops. Ref. [58] estimate that in 2030 the European potential of agricultural biomass production will remain untapped, concluding that the demand for bioenergy will be clearly lower than the potential. Several other studies (e.g., Refs. [24,54–57,64–68]) quantify the biomass that can be produced in Europe. The range of estimates is wide and results are primary influenced by the approaches and methodologies used, which are not harmonized [68–74]. Relevant sources of difference between the studies are: type of potential (e.g., theoretical, technical, economic and sustainable) [68,70–75] and of biomass (e.g., agriculture and forest residues, energy crops) considered [68–71], spatial resolution [71,73,75], data used (e.g., crop yields, biophysical data, categories of land use, other non-energy indicators) [69–71,73,74,76,77] and timeframe [69,71,77].

Most of the wood used for energy purposes in Europe originates from uncertified forests [78]. If sustainability criteria are imposed to solid biofuels, the future expected availability of biomass that can be used by the industry could lower. So far, EU countries rely on their sustainable forest management rules and some on additional sustainability criteria to determine if projects are eligible for subsidies [79]. However, the European Commission has already considered binding sustainability criteria for solid biomass in its proposal for a recast of the Directive on the promotion of the use of energy from renewables [80]. The impacts of different policy options for EU action on bioenergy sustainability are discussed by Ref. [58].

Different energy and non-energy markets compete for biomass. This competition could change the amount of biomass available to the industry. According to Ref. [11], if the current transport policy is maintained, the industry will have limited access to biomass resources and a further electrification of the industrial sector will be promoted (Ref. [81] discusses the implications of the electrification of key energy-intensive industrial sectors). Apart from its use for biofuel and electricity production, biomass gains increasing interest as feedstock for the chemical industry, since it can replace fossil fuels for the production of bulk chemicals (e.g., acetic acid, ethylene, methanol, ethanol or acetone) [82]. The uncertainties in sustainable biomass supply and the existence of many markets competing for a limited resource make planning difficult [10], and thus biomass resources should be monitored in relation to their demand, taking into account sustainability constrains [55].

The amount of biomass that can be dedicated to the world industry by 2050 was estimated by Ref. [11] based on a sustainable biomass supply projection of 150 EJ/a and the assumption that no more than 1/3 of the biomass is directed to industry. In another study, Ref. [61] estimated the future global energy use of biomass and concluded that secondary bioenergy demand is driven by the building and transport sectors, while industry and non-energy uses will grow moderately. According to this study, the most effective use of bioenergy for emission reduction is in the electricity sector. The study of Ref. [62] compares the use of biomass for the production of liquid biofuels, heat and power, and biomaterials and, differently from Ref. [61], concludes that none of the pathways has a decisive advantage as far as GHG emissions are concerned. Several other studies discuss possible future developments of the consumption of biomass (e.g., [59,60,83–90]), but show diverging pictures. Moreover, not all consider its energy use by the industry.

A relevant factor for biomass utilization by the industry is its price. There is a large variation of prices according to the energy system location, or biomass type, quality and quantity acquired. Additionally, predicting future costs of biomass is challenging and dependent on many factors such as local supply chains, resource availability, sustainability criteria, policy choices or competing uses for biomass. Currently, different entities such as Argusmedia, FOEX and Propellets Austria report several commercial price indexes, which cover different European regions and fuels (e.g., wood pellets, wood chips, forest biomass residues, saw logs and birch logs). As far as future biomass prices are concerned, and just to give some examples, Ref. [56] estimate that in Europe in 2020 the price of farm gate domestic solid biomass ranges from 1.0 to 11.8 €/GJ (respectively, wood processing residues and energy crops). Other study states that, in a low energy price scenario in OECD Europe in 2030, the prices of biomass waste and biomass from energy plantations are 5 and 13 USD/GJ, respectively [9].

3.3. Solid biomass by member state

The previous section refers to the EU as a unique entity; however the reality of the different member states differs in the potential of solid biomass, its use and policies.

In 2017, the different EU countries consumed solid biomass for energy in different ways (Fig. 9). Many used most of it in the residential sector (in Malta, Croatia, Romania and Greece more than 80%), while others for electricity production in main activity producers (Denmark and Estonia more than 50%). Ireland was the only country that used more than half of its solid biomass in industry (53%), but in Finland, Sweden, Slovakia and Portugal the share of this sector was above 40%. On the other extreme, Malta, Estonia, Croatia and Italy consumed less than 5% of its biomass in industry.

In 2017 (Fig. 10), the largest EU28 producer of energy from solid biomass was Germany (503 PJ), followed by France, Sweden, Finland and Italy (328–452 PJ each). These five countries accounted for 51.2% of the total solid biomass primary energy production of the EU28. Poland, Spain, Austria, Romania and the United Kingdom had a share of 25.3%, and the Czech Republic, Portugal, Hungary and Latvia 10.5%. The remaining fourteen countries have productions lower than 75 PJ. Most countries are net importers of solid biomass for energy. Malta imported all solid biomass it consumed for energy, but the quantity was small. The second most import-dependent country was Denmark, whose primary production accounted for 46.3% of the gross inland consumption. The country with the largest imports was the United Kingdom and the largest exporters Latvia and Germany [2].

The availability of woody biomass for energy in 2012 by member state was calculated, for example, by Ref. [24] based on Ref. [91]. The countries with largest (> 1100 PJ) availability are Germany, Sweden and France and those with the lowest Luxembourg and the Netherlands (< 20PJ, excluding Cyprus and Malta that do not produce woody biomass for energy). Five of the remaining countries present values below 100 PJ (Ireland, Denmark, Greece, Belgium and Croatia), six between 100 and 200 PJ (Slovenia, Bulgaria, Estonia, Lithuania, Slovakia and Hungary), eight between 200 and 400 PJ (Latvia, Portugal, the Czech Republic, the United Kingdom, Spain, Italy, Austria and Romania) and two between 500 and 900 PJ (Poland and Finland). The countries with the largest production are also the largest consumers (Germany, France, Sweden, Italy, Finland, United Kingdom, Poland, Spain, Austria and Romania).

To express the possibility of additional local supply of solid biomass for process heat generation by member state, Fig. 11 presents the ratio of the biomass potentials calculated by Ref. [24] and the biomass gross inland consumption reported by Ref. [2] for 2017. Important potential exists in Slovenia, Slovakia, Latvia, Estonia, Ireland, Sweden, Luxembourg, Romania, Portugal, France, Bulgaria, Finland, Lithuania, the Czech Republic, Poland, Germany and Austria.

3.4. Biomass characterization for energy use

Solid biomass for energy purposes presents favorable characteristics like renewability, carbon-neutrality, versatility, high reactivity, high specific surface area and, for some types of biomass, low sulphur and

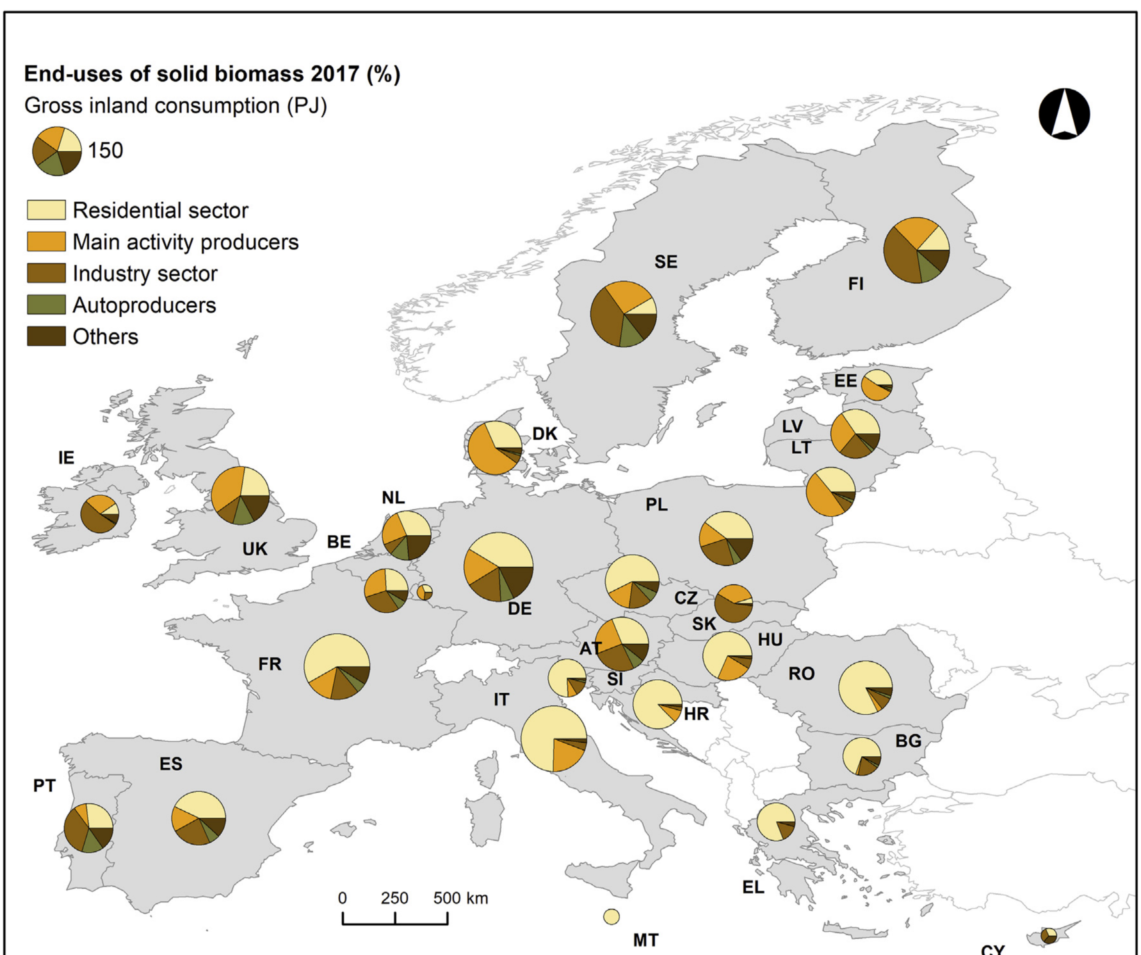

Fig. 9. Gross inland consumption and share of the different end-uses of solid biomass for energy for EU28 in 2017. The diameters of the pies are proportional to the gross inland consumption of solid biomass of the member states (Data source: [2]).

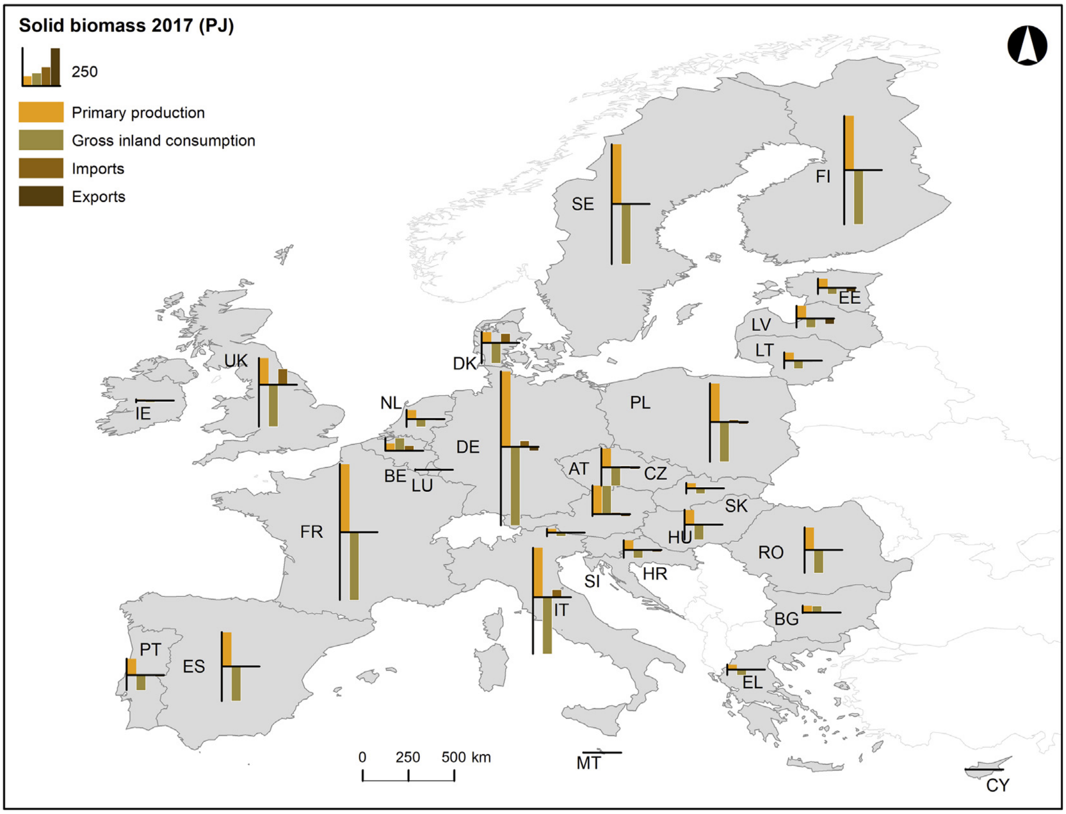

Fig. 10. Primary production, gross inland consumption, imports and exports of energy from solid biomass for EU28 in 2017 (Data source: [2]).

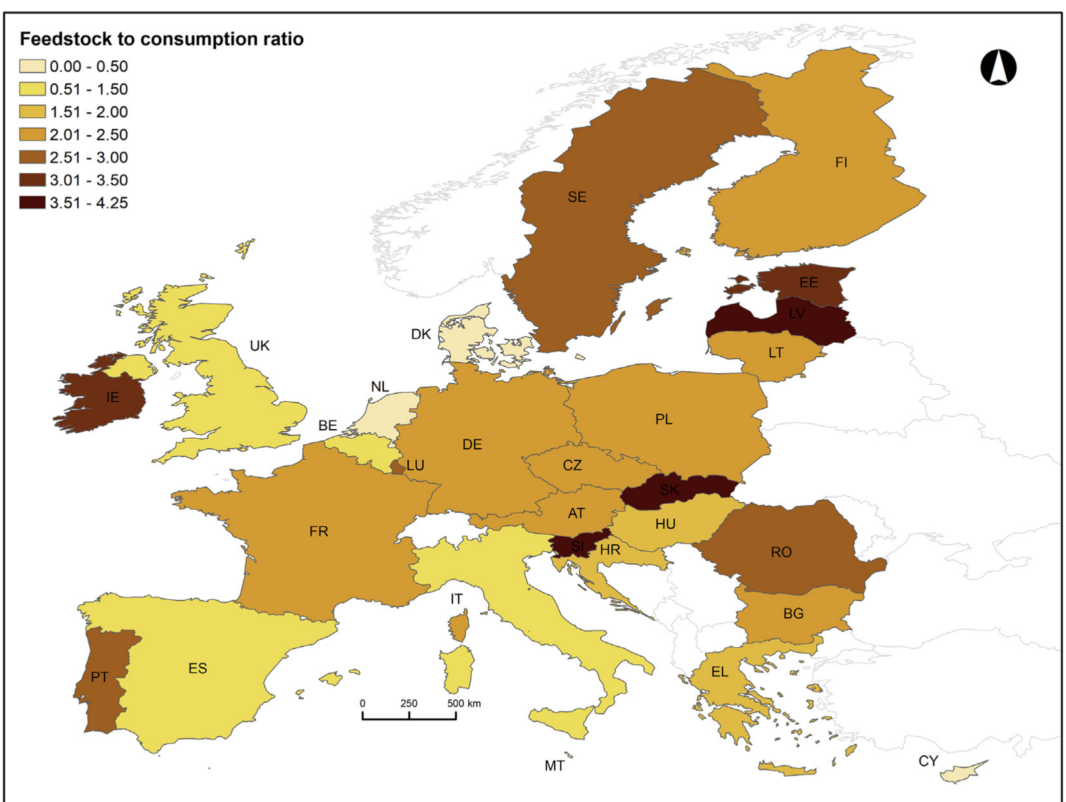

Fig. 11. Ratio between biomass potentials and biomass gross inland consumption for EU28 (Data source: [2,24]).

ash contents, local availability and low cost. However, it also presents the following disadvantages when compared to fossil fuels: low heating value, low bulk density, poor grindability, low energy density and high moisture content. These disadvantages can be circumvented by the upgrading of biomass. Among the available upgraded biofuels, charcoal has the highest percentage of fixed carbon and heating value [35].

To use solid biomass as a fuel, one needs to know and understand its physical, chemical and combustion properties; the last are also dependent on the oxidizer and process. The properties considered the most important in terms of biomass thermochemical conversion are: elemental composition, ash content, volatile matter content, moisture content, heating value and bulk density [92]. Table 1 presents a compilation of properties for some relevant solid biomass fuels taken from an online database maintained by ECN [93]. The properties of a medium rank coal are also shown, since biomass has high potential for co-firing with coal and/or for its substitution. The fuels presented in Table 1 were chosen to illustrate what is written below.

Typically, the most abundant element of dry solid biomass is carbon (30–60 wt%), followed by oxygen and hydrogen [94]. Nitrogen, sulphur and chlorine are also found, usually in quantities less than 1 wt% [94], and despite their small concentrations, they are important because of the related air pollutant emissions. Inorganic elements are also found in solid biomass: wood (illustrated in Table 1 by poplar, willow, pine or generically wood) contains low ash contents (from less than 1 to 3 wt%), while some agricultural materials (in Table 1 wheat straw and rice hulls) high ash content (20 wt% for straw and husks) [95]. The composition and total ash content of biomass influence the design and operation of combustion systems because of the contribution of some elements to ash fouling and slagging [96–98], while others to corrosion and pollution [95,99].

Generally, raw solid biomass (first 6 fuels in Table 1) has high volatile matter content and relatively low carbon content (compared to coal) [99], which leads to relevant advantages of biomass fuels for thermochemical energy conversion [100]. The high volatile matter content is responsible for the high reactive nature of solid biomass fuels [100] and makes biomass a good potential feedstock for, for example, indirect gasification processes [99] and pulverized combustion [101]. However, the comparatively high oxygen content contributes to low heating values, which in conjunction with typically low bulk densities leads to low energy densities. The bulk density of solid biomass is an important parameter because it influences the necessary storage volume and the process control of the fuel supply systems [102]. The bulk density range of solid biomass is wide, from about 20 kg/m^3 for loose materials [103] to around 900 kg/m^3 for solid wood [92].

Another disadvantage of raw biomass can be a high moisture content, which leads to a decrease in the heating value and combustion efficiency. Most biomass fuels cannot sustain combustion with moisture contents above around 65% and, when burning fuels with a moisture content above 50–55%, most combustors require a supplemental fuel and may emit products of incomplete combustion, like CO [94]. Besides influencing the combustion behavior and the adiabatic flame temperature, the moisture content of biomass also affects the volume of flue gas produced per unit energy, and the size of the combustion chambers [102]. Wet biomass fuels need longer residence time, which result in larger furnaces. The moisture content of biomass fuels shows extreme variations, ranging from less than 10% for cereal grain straw for up to 50–70% for forest residues [92].

The low heating value and bulk density of biomass can be improved through thermal treatment and densification. Densification, such as pelletization or briquetting, increases the bulk density of biomass to above 700 kg/m^3 [103]. Thermal treatments make biomass more similar to coal and globally more attractive for thermochemical conversion (this is the case of charcoal and torrefied biomass; see Table 1). Torrefaction, a mild thermal treatment, results in a partially carbonized fuel with lower volatile matter content and moisture than the original feedstock. Whereas, charcoal production, which involves higher temperatures, results in a feedstock with much lower volatile matter and moisture than the initial biomass. They can be combined with densification, improving significantly also the bulk density of biomass fuels [104]. Another biomass property that can be improved by thermal treatment is grindability [105–108], which is important to reduce the energy consumption required for grinding (because of their fibrous nature, most biomass materials are more difficult to grind than coal [105,109]).

4. Biomass-based heat and CHP production

Biomass can be converted into bioenergy by thermochemical, biological and chemical processes. The thermochemical conversion of biomass is the most common [109] and well suited for solid biomass conversion into energy. There are mainly five thermochemical paths available for heat and CHP production: combustion, gasification, pyrolysis, hydrothermal processing and hydrolysis to sugars (Fig. 12).

Fast pyrolysis is mostly suited for the production of bio-oil [110]. However, the cost, corrosiveness and instability during storage have impeded its commercial utilization [111] (In Europe only a few commercial pyrolysis plants are in operation [112]). Bio-oil can also be produced by hydrothermal processing of biomass, especially of wet feedstocks such as grain wet-milling by-products [113]. However, this technology is still in a demonstration phase [60,113,114]. Thermal depolymerization of biomass followed by catalytic upgrading of the sugar to fuel molecules is still under-investigation [111]. Slow pyrolysis is traditionally used to produce charcoal, which does not have a significant industrial use in Europe [2]. As far as gasification is concerned,

Table 1
Solid biomass fuel properties (Data source: [93]).

	Poplar wood	Willow wood	Wood chips (hybrid poplar)	Bark (pine)	Wheat straw	Rice hulls	Pellets (wood)	Wood torrefied at 250-290 °C	Char (willow, 550 °C)	Bituminous coal
Proximate Analysis (wt% dry)										
Fixed carbon	13.71	15.01	20.30	26.60	17.71	37.83	17.58	24.68	82.20	56.18
Volatile matter	85.07	83.40	77.90	71.80	75.27	38.80	82.20	72.20	11.60	34.23
Ash	1.22	1.59	1.80	1.60	7.02	23.37	0.22	3.12	6.20	9.59
Ultimate Analysis (wt% dry)										
Carbon	49.42	50.19	44.00	53.90	44.92	37.86	47.30	53.00	81.70	74.14
Hydrogen	6.00	5.90	5.50	5.80	5.46	4.75	6.76	5.50	2.40	4.79
Oxygen	43.07	42.22	47.70	38.26	41.77	33.49	46.02	37.87	8.60	9.85
Nitrogen	0.23	0.10	1.00	0.40	0.44	0.23	0.15	0.45	0.40	1.27
Sulphur	0.05	-	0.00	0.03	0.16	0.31	0.01	0.04	0.04	0.36
Moisture content (wt%, wet basis, as received)	4.80	43.50	9.20	5.00	8.15	8.00	7.00	8.00	0.10	3.00
Higher Heating Value (MJ/kg) (dry)	19.50	18.56	16.40	21.37	17.94	13.3	19.32	20.70	34.90	30.13

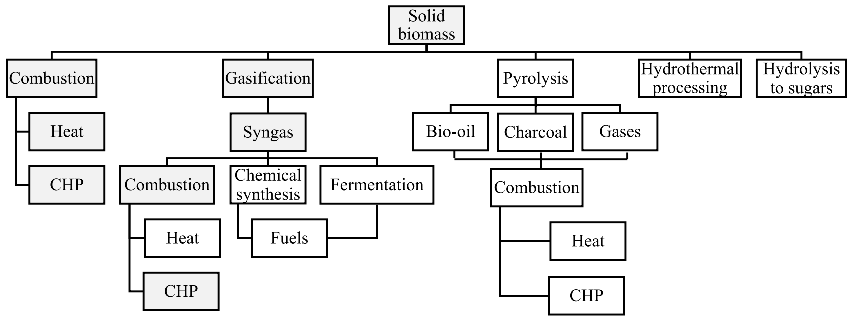

Fig. 12. Thermochemical paths for production of fuels, heat and CHP (solid fill indicates the technologies that are in a commercial stage and generally used).

the technology is still in an early commercial stage [60], but is currently used, to a small extent, for electricity or CHP production [99]. From the thermochemical paths presented in Fig. 12, combustion is the most widely used and mature [115,116] (over 90% of the bioenergy generation relies on combustion [109]).

The above mentioned technologies are primary conversion technologies, which convert solid biomass into heat or fuels. When heat is generated by combustion, it can be used directly or, alternatively, converted into electricity. For the latter, secondary energy conversion technologies are needed. In this process, not only the electricity generated, but also the rejected heat can be used. There are various secondary conversion technologies available (steam turbines, steam engines, organic Rankine cycles (ORC), Stirling engines, internal combustion engines (ICE), gas turbines and micro-turbines), and their use depends also on the primary conversion technologies.

4.1. Heat production technologies

4.1.1. Combustion

Typical process heat generators are boilers, dryers, kilns, furnaces and ovens. The full range of temperatures required by industrial processes can be covered by different types of biomass [10]. Some industrial processes require continuous heating of large amounts of material, others require precise heating of small batches. Combustion technologies span, therefore, a wide range of scales, from a few kilowatt to multi-megawatt. The choice of the combustion system depends not only on the energy demand, but also on the fuel characteristics, cost and performance of technologies and legislation (for a detailed analysis see for example Refs. [103,109,117–119]).

4.1.1.1. Direct heating. Certain industrial processes require high temperatures and specific combustion equipment that transfers heat directly from the flue gases to the process [8]. Direct heating is also used to produce low or medium temperature heat (e.g., in the cork industry [120]). The reader is directed to the following references for a description of the details of specific combustion equipment used in the following industrial sectors: iron and steel [35,121], chemical and petrochemical [122–126], non-metallic minerals [127–130], pulp and paper [33], food, beverage and tobacco [131], and non-ferrous metals [132].

An option for the production of high temperature heat with biomass is co-firing with coal (simultaneous burning of these two fuels). It is potentially applied in existing coal-fired facilities with little modifications and better environmental performance [133,134]. Although it is mostly used for the generation of electricity, it is also adopted by industrial users (e.g., in the cement industry [135]), expanding the industrial use of biomass [103]. Co-firing of biomass with coal is a low cost strategy to ensure reduction in net CO_2, SO_x, and often NO_x emissions [136]. When compared to dedicated biomass facilities, co-firing can increase the efficiency with no need for a continuous supply of biomass [137].

4.1.1.2. Indirect heating. Low and medium temperature heat is usually transferred to the process through a heat delivery medium (typically steam) [8]. Even though biomass is not widely used for process steam production, there is a large potential to produce low and medium temperature steam (< 400 °C) from biomass [9]. Combustion boilers are the most used technology for the conversion of solid biomass into thermal energy in the majority of the industries [118]. The technologies

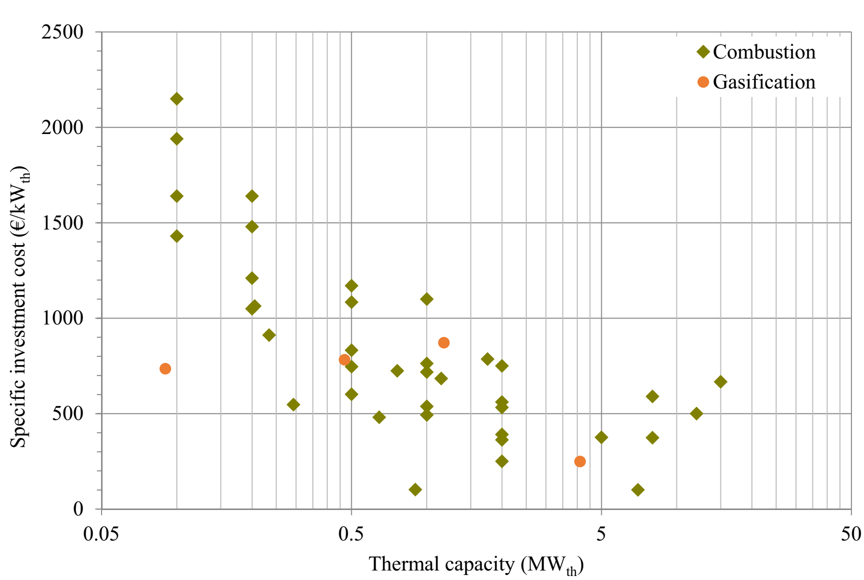

Fig. 13. Specific investment costs of biomass heating systems as a function of capacity (Data source: [60,147,150–153]).

usually used for the systems with the lowest capacities (< 20 MW_{th}) are fixed bed boilers and for the highest fluidized bed boilers (> 20–30 MW_{th}) [8]. Biomass pulverized combustion can also be utilized, as in the chipboard industry [109], but this is not so common, and the technology is usually used in thermal power stations for electricity generation [101].

Depending on the properties of the biomass, the fuel feeding technique and the type of grate used, fixed bed combustion systems have different configurations. Examples of mature technologies are stationary, reciprocating, travelling or vibrating grate firing furnaces, underfeed stoker or cigar furnaces (a description of these technologies can be found in Refs. [109,138–140]).

Fluidized bed combustion relies on two mature technologies: bubbling and circulating fluidized bed combustion [141,142]. Both systems operate at atmospheric pressures, but pressurized versions that operate at higher pressures exist. The current research is not focused on pressurized fluidized bed combustion [143].

Typically, fixed bed boilers are used for smaller capacities than fluidized bed boilers, present lower costs and lower efficiencies. The efficiency of the conversion system is essential to determine the performance of bioenergy systems. Fuel type and excess air have a decisive effect on efficiency (fuels with low heating values and high moisture content can result in efficiencies 25% lower than fuels having low moisture content and high energy content and each 15% reduction in excess air can result in around 1% increase in efficiency [144]).

The costs of biomass combustion systems for the production of heat are quite variable depending on the conversion technology and type of emission control equipment used, feedstock storage capacity and whether or not pre-processing of biomass occurs (e.g., size or moisture reduction). Other factors that can influence the total cost of the biomass systems are related to piping, electrical and civil works [145–147]. According to Ref. [148], the investment costs in wood-fired heating systems is in the range of 323-827 USD/kW_{th} and the annual operating and maintenance costs (excluding fuel costs) vary between 69 and 127 USD/kW_{th}. Fig. 13 presents the compilation of specific investment costs of biomass heating systems versus installed capacity. The data refers to different locations and years and is presented in nominal values (i.e., the original data was used, only converted to Euros when needed). The values are illustrative, but clearly indicate that higher system capacities lead to lower specific investments. We have compared nominal with real costs (calculated with consumer price [2] and CEPCI [149] indexes) and basically the same conclusions can be drawn.

4.1.2. Gasification

Gasification is used to convert biomass into a low molecular weight gas combustible mixture (syngas), which can then be burned. Even though coal was the first fuel to be gasified, biomass is more readily gasified than coal because of its higher volatile matter content [111]. A review on biomass gasification can be found, for example, in Refs. [99,116,154–157].

Solid biomass gasification in a closed-coupled biomass gasification-boiler is a technology commercially available [150]. Two types of gasifiers exist: directly and indirectly heated gasifiers. They differ in the way heat is provided to the gasification reactions. In the former, partial oxidation is promoted to generate the required heat, in the latter heat is transferred by a heat exchanger. The calorific value of the syngas is higher in indirectly heated gasifiers (typically 18–20 MJ/Nm^3) compared to directly heated gasifiers (typically 5–14 MJ/Nm^3) [99].

In directly heated gasifiers, air is the most used oxidant, but different combinations of nitrogen, steam and oxygen have also been used [99]. As in combustion, gasification can occur in fixed or fluidized bed reactors. Entrained-flow reactors were also developed, but have limited applicability with biomass [99]. Fixed-bed reactors were developed for smaller scale applications and are simple to operate and maintain [99]. They can be divided in updraft and downdraft gasifiers. In updraft gasifiers, the oxidizer and biomass flow in counterflow and, despite their simplicity, large quantities of tars are formed, which may cause operating problems [99]. In the cocurrent design (downdraft gasifiers) tars are much more efficiently converted [99]. Fluidized bed gasifiers are divided into bubbling and circulating fluidized bed reactors [157].

Biomass gasification and subsequent syngas combustion can produce high temperature process heat [9]. However, the production of process heat through gasification is among the lowest value applications of syngas, so it is more common to combine gasification with a secondary technology to produce CHP [99]. Heat production with gasification is less expensive than electricity production because syngas quality requirements are not so tight. One of the advantages over direct biomass combustion is that syngas can be used with minimal clean-up [111]. Apart from heat and/or power, gasification can be used to produce fuels and chemicals, which offers the prospect of gasification-based biorefineries [111,158].

4.1.3. Pyrolysis

Pyrolysis is the decomposition of organic matter in the absence of oxygen to produce liquids, gases and char. The percentage of these products depends on the biomass composition and rate and duration of heating [111,112]. The process is generally optimized for the production of solids or liquids [103]. The traditional slow pyrolysis process produces mainly charcoal, while fast pyrolysis bio-oil [110,112]. Torrefied biomass is obtained through light pyrolysis. Apart from charcoal production [38], pyrolysis is not in a mature commercial stage and efforts are needed to optimize the process to increase its techno-economic attractiveness [112]. A review on biomass pyrolysis can be found, for example, in Refs. [108,110,112,159–162].

4.2. CHP production technologies

When compared to conventional power plants, biomass fuels are more efficiently used when generating simultaneously heat and power (typical overall efficiencies are above 80%, e.g., Refs. [163,164]). In Europe, CHP systems are widely used in the pulp, food processing or chemical industries [165]. Presently, industrial CHP power plants predominantly rely on natural gas, but biomass is becoming more important (13% share in total transformation input in 2017 and the second most used source) [2].

4.2.1. Primary conversion technologies

The primary conversion technologies commercially available for biomass conversion into CHP are combustion and gasification. Combustion is used to produce both heat and CHP, while gasification is mostly used to produce CHP (also electricity alone, but this is outside the scope of the present review). Combustion is the most common conversion route in CHP systems [166]. One of the main advantages of CHP production through gasification, compared to direct biomass combustion, is the higher electric efficiency for smaller plants [167]. Tar and char contents of syngas are usually high and require gas cleaning before use in ICEs or gas turbines [99].

As in the case of heating-only applications, co-firing with coal is also an interesting option. It is gaining popularity for CHP applications and can be applied to a large variety of combustor types [118]. A description of co-firing of biomass in coal-fired boiler plants can be found, for example, in Refs. [109,136].

4.2.2. Secondary conversion technologies

Secondary conversion technologies can be classified into those where the combustion products are used as the working fluid (e.g., direct-fired gas turbines) and those where a second fluid acts as the working fluid (e.g., steam turbines). The latter are well suited for direct biomass combustion since the engine will not be damaged by fly-ash particles and metals contained in the flue gases, while the former require gas cleaning [109].

4.2.2.1. Steam turbines. Conventional steam turbines are the most utilized technology in combustion-based biomass-fired CHP plants [118,144]. They are mature, typically below 50 MW_e [144] and can operate economically from a capacity of 1 MW_e [168]. The electric efficiency of steam turbines is dependent on the installed capacity (large capacities have relatively high efficiencies, while small capacities low [109]). Typically, electric efficiencies are in the range of 15–35% [118].

Organic Rankine cycles are similar to conventional steam cycles, but operate at lower temperatures. They can recover waste heat or use a dedicated heat source [169]. Biomass ORC CHP plants are commercially available and used for capacities of up to 8 MW_e [170]. They are the most widespread biomass technology based on combustion below 1 MW_e [171]. ORCs have lower investment and maintenance costs [109], better partial load operation [172] and better electric efficiencies than steam turbines with the same capacities [109], but still the efficiencies are relatively low (10–20%) [172]. A compilation of specific investment costs of several biomass-fired CHP technologies versus installed capacity in presented in Fig. 14. The data refers to different locations and years and is presented in nominal values. As in the case of Fig. 13, nominal and real costs were compared and the same conclusions can be drawn. The values are illustrative, but show that ORCs have lower specific investment costs than steam turbines. Typically, steam turbines gain economic advantage for high capacities.

Steam turbines are also a mature technology for biomass-fired CHP plants based on gasification [60].

4.2.2.2. Internal combustion engines. Syngas can also be burned in internal combustion engines, generally in small systems [144]. ICEs are simple and relatively robust to syngas impurities [99]. This results in simpler and cheaper cleaning systems when compared to other options (see Fig. 14 for specific investment costs). However, the operation and management costs are high, as well as NO_x emissions [99]. Gasification combined with ICEs is commercially available [99] and the most common option for the gasification route [185]. However, complexity of operation leads to the current low cumulative installed capacity [184]. Typical electric efficiencies range from 15 to 40% [186].

4.2.2.3. Other cycles. Another commercially available technology for biomass CHP are Stirling engines. They are appropriate for small capacities up to slightly more than 100 kW_e and with typical electric efficiencies of 15-30% [109]. Their electricity output and heat-to-power ratio make them more suited for residential and commercial applications [187]. Important advantages over ICEs are the possibility to use flue gases directly (though they must be as clean as possible) [109] and the lower maintenance requirements [187].

Steam engines are a mature technology for small powers (25 kW_e-1.5 MW_e) with efficiencies comparable or slightly higher than steam turbines [109]. They have higher part-load efficiency than steam turbines [109], but have been replaced by more economical applications in some countries [188].

The use of solid biomass in indirect-fired and direct-fired gas turbines is still in a development stage [109], as are fuel cell-gasification systems [189].

5. Future perspectives for European industrial biomass consumption

The promotion of a sustainable industrial use of biomass should consider various technological, economic, environmental and social aspects [21]. Since these aspects vary significantly in different world regions and countries, there is no unique global solution for biomass use for process heat [21]. Additionally, each industrial sector has its own specific challenges for further deployment of solid biomass energy.

Deep decarbonization of energy-intensive industries for the production of basic materials will not be driven by improved economic performance, but by long-term climate policies [17]. Many energy-intensive industries for the production of basic materials operate in international commodity markets, based on standard products, large volumes and price competition. They are, therefore, affected if differences in carbon cost arise because of different national policies, which may lead to industry relocation and loss of competitiveness [17].

The type of policy to increase the rate of deployment of bioenergy in industry needs to be identified and developed for each conversion technology and location. The maturity stage of the different technologies can affect the choice of policies [26]. In the case of mature technologies, like combustion, incentives and education policies can encourage the deployment of biomass, educate potential users and train installers. Technologies close to mass market, like gasification, are suited for regulatory policies to promote the increase of the technology reliability and the decrease of costs. Technologies at an earlier maturity stage, like fast pyrolysis, call for incentives for further research and development, demonstration, sharp cost reduction and performance increase.

The next sections briefly describe, in a European context, the

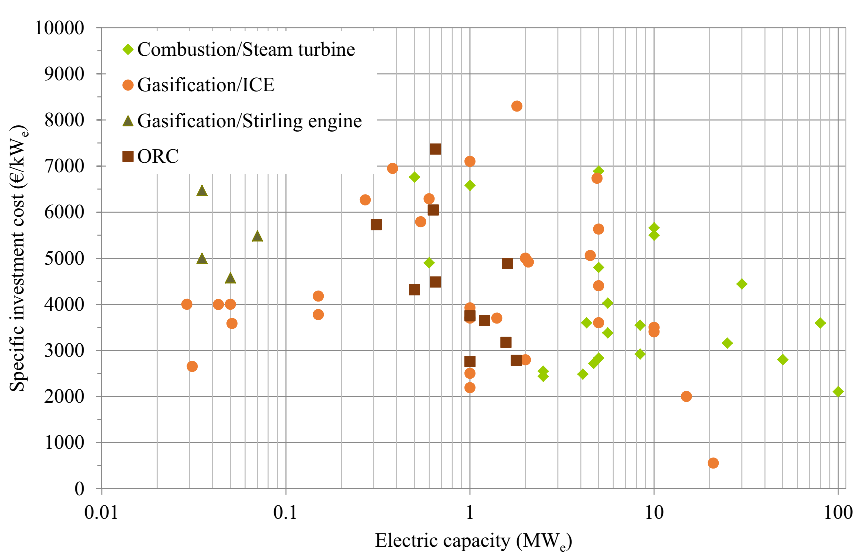

Fig. 14. Specific investment cost of biomass CHP systems as a function of capacity (Data source: [60,144,150–153,173–184]).

current energy consumption and future perspectives for the use of solid biomass in the most relevant sectors in terms of energy demand and/or biomass utilization.

5.1. Pulp and paper

In 2017, the final energy consumption of the EU28 pulp, paper and printing industry was 1438 PJ (13% of the final energy consumption in industry) [2]. Manufacturing of pulp, paper and paperboard consumes more than 98% of the energy demand of this sector [190]. The industry requires essentially heat between 100 and 200 °C (83% of the process heat demand is within this level) [3]. CHP production is common in this sector (in 2016, the electricity produced at site, 96.0% of which with CHP, bought from the grid and sold were, respectively, 51.2, 56.8 and 11.6 TWh [191]).

This sector already uses a significant amount of solid biomass. For example, recovery boilers are both used to recover chemicals contained in black-liquor and to produce process steam [33,192]. In EU28, the share of biomass in the final energy consumption of this sector was 38% in 2017 [2]. When adding the share of biomass utilized in generating electricity and part of the heat sold to third parties (quantities not accounted for in the final energy consumption), the biomass share in 2016 was 59% [191]. Among EU28 countries, the biomass incorporation in the pulp and paper sector varies from 0% in Italy to 89% in Sweden [193]. This fact alone indicates that there might still be room for further biomass incorporation in this sector.

The pulp and paper industries can buy biomass instead of fossil fuels and extend their traditional products to 'green' power and torrefied biomass in order to increase the efficiency and profitability of their traditional core business [25]. In fact, importing biomass for self-consumption may not be needed in some pulp mills. Modern chemical pulp mill designs will allow the mills to become self-sufficient in energy and produce surplus energy from their residues [14]. Also [194], refer that implementing new separation and drying technologies can reduce the energy intensity of the pulp and paper industry and that better energy intensity and utilization of by-products can result in a carbon neutral sector. A more radical change that challenge core ideas in the industry is the conversion of the pulp and paper mills into biorefineries producing not only conventional fibers for paper products, but also chemicals, materials and energy [195].

5.2. Wood and wood products

In 2017, the final energy consumption of the EU28 wood and wood product industry was 371 PJ (3% of the final energy consumption in industry) [2]. The sector integrates three main sub-sectors: sawmilling and planning of wood, manufacture of furniture, and manufacture of products of wood and cork. The last accounts for more than half of the purchases of energy products within the whole sector [2]. Within the wood and wood products industry, several operations are energy-intensive, namely those of drying, pressing and heat treatment, with required temperatures up to 500 °C [34,120].

The industry generates large quantities of solid biomass residues, a fraction of these being used internally to produce energy or traded in the bioenergy market (e.g., pellet production). It is the EU28 industrial sector with the highest percentage of solid biomass incorporation for energy purposes (57% of sectoral final energy consumption in 2017 [2]). In almost all EU countries the share of solid biomass in the final energy consumption of the sector was over 30% in 2017, and in Belgium, Denmark, Ireland and Luxemburg this share was above 70% [2].

The prospects of further increasing the use of bioenergy in this sector are limited; however, opportunities exist to use biomass more efficiently [196] and industry should develop strategies on energy efficiency in order to improve its competitiveness [197]. CHP systems play a relevant role in reducing GHG emissions, and are already used in large capacity systems, up to 50 MW_{th}, mostly supplied by residues and recovered wood [34]. One of the key research areas is the development and demonstration of biomass gasification systems to produce electricity more efficiently [196,198]. Also, waste heat recovery is pointed out as an energy efficiency measure with high potential of application within the wood processing activity [34,196].

5.3. Non-metallic minerals

The final energy consumption of the EU28 non-metallic mineral industry in 2017 was 1431 PJ (13% of the final energy consumption in industry) [2]. In terms of energy consumption, this sector is dominated by the cement industry, with a share of almost 60% in final energy demand [4], but glass, brick, tile and refractory production is also very important [199]. Almost 73% of the process heat demand within this sector is above 500 °C [3]. The temperatures required by the key energy-intensive processes (melting, sintering or thermal decomposition of raw materials) are often above 1000 °C [190].

In EU28, the share of solid biomass in final consumption is 3% in this sector [2]. The main cement producers are already using solid biomass as a substitute for fossil fuels [135]. For cement kilns, a 20% substitution rate of fossil fuels by biomass is recommended; however, higher values have been used with very satisfactory results [130]. The cement industry presents no technical barriers to an increase in the use of solid biomass [199]. The main constrains are related to the necessity of a biomass pre-treatment stage, economic and local availability of biomass [130]. A possible strategy to decrease the environmental impacts of cement production (and of waste disposal) is the use of ash resulting from biomass combustion [200–202]. Another possible route to increase the use of biomass in the non-metallic mineral sector is through biomass gasification or co-gasification with coal. Examples can be found in the ceramic [203,204] or glass [205] industries. Major barriers are high capital cost, sourcing suitable feedstock or storage of biomass on-site [206].

5.4. Food and beverages

The final energy consumption in 2017 in the European food, beverages and tobacco sector was 1254 PJ (11% of the final energy consumption in industry) [2]. The energy consumption of the tobacco subsector is estimated to be less than 1% of the energy consumption of the whole sector [190]. The food and beverages industry was the largest EU manufacturing sector in terms of turnover (15.4%), value added (12.8%) and employment (15%) in 2014 [207]. The sector is very diverse and uses varied manufacturing processes [199], which makes a global analysis more difficult. The industry requires essentially heat below 200 °C (83% of the process heat demand is below this level) [3].

Presently, the industry does not obtain much of its energy through solid biomass (3%) [2]. The sector produces significant amounts of biowastes that can be converted into energy; however, in most cases, these feedstocks have high moisture content [208] and are unsuitable for thermo-chemical conversion processes. In this case, anaerobic digestion is a very interesting possibility [42,209], but outside the scope of this review. Nevertheless, within this sector there are industries that have abundant low-moisture solid biomass resources suitable for combustion (e.g., rice husks [20], olive stones [210], nut shells [211] or pine cones [212]).

Although some projects are economically attractive, generally, a major barrier for the implementation of solid biomass energy systems in the food and beverages industries are the high investment costs [19]. Also, the supply infrastructure is insufficient or non-existing and biomass availability and security of supply are not guaranteed [19].

5.5. Chemical and petrochemical

The chemical and petrochemical industry was the EU industrial sector with the highest final energy consumption in 2017 (2206 PJ, 20% of the final energy consumption in industry) [2]. A decade before, this place was occupied by the iron and steel industry, having these two sectors similar final energy consumptions. The chemical and petrochemical sector is very diverse, but in terms of energy use and emissions the following processes stand out: ammonia production, steam cracking of naphtha and gas oil, chlor-alkali, nitric acid, adipic acid, hydrogen/synthesis gas, soda ash, aromatics and carbon black production [199]. The industry requires essentially heat above 500 °C (67% of the process heat demand is above this level) [3].

Presently, the industry does not obtain much of its energy through biomass (0.5%) [2]. The conversion of conventional plants into biorefineries producing bio-based chemicals offers the possibility of the industry to face the challenges imposed by the future carbon-constrained world [14] and a wider use of bioenergy within this sector [11]. Undesirable physicochemical properties, such as high oxygen content of bio-oils [161,213], still arise when using solid biomass as feedstock in this sector. Currently, sugar and starch based biomass is the most widely used route to produce chemical feedstock from biomass. However, in the future, woody biomass has to be used in order to replace the large quantity of petrochemicals currently produced [14]. The conventional production of chemicals and polymers is in some cases more energy efficient than that of bio-based chemicals [11]. Nonetheless, in the latter, biomass by-products can be converted to heat and power, decreasing the non-renewable energy used [11]. Biorefineries have the potential to increase profitability and de-risk the investments in bioenergy [11]. According to Ref. [214], the large-scale use of biomass as feedstock by the chemical industry will drastically alter the market and biomass availability will be a major challenge. Large storage capacities will also be needed, thus the use of upgraded biomass is a good solution.

5.6. Iron and steel

In the iron and steel industry, the final energy consumption in 2017 was 1166 PJ (11% of the final energy consumption in industry) [2]. Note that the Eurostat does not report energy consumed in blast furnaces as final energy consumption but as transformation input. Within the iron and steel sector, the manufacture of basic iron and steel and of ferro-alloys is the most significant energy consumer, accounting for 73% of the energy demand of the sector [190]. The industry requires primarily heat above 500 °C (94% of the process heat demand is above this level) [3], and the use of direct heating dominates the sector.

In EU28, almost no biomass is used for energy in the iron and steel industry [2]. However, there are countries outside this group with a sustained incorporation of biomass in this sector. In Brazil, 34% of the fuels consumed in the iron and steel industry is biomass [11]. The partial substitution of coal and coke with biomass in ironmaking processes is one of the few options that are both economically and technically viable in the short and medium-term [21]. Iron making requires carbon-containing fuels and biomass is the only source of renewable carbon [10]. There is a high potential of biomass use in the sector, and in certain conditions with benefits over the use of coal. The most promising ways are by: *i*) gasifying biomass to generate gas for reduction or heating, *ii*) injecting it into the blast furnace, Corex or electric arc furnace, *iii*) incorporating biomass into coal blend for cokemaking, fuel for sintering, composites and self-reducing pellets for direct reduction processes and blast furnace [21]. According to Ref. [22], the greatest potential for fossil fuel replacement in the iron and steel industry is in the charcoal injection into the blast furnace. Many of the routes to incorporate biomass into the iron and steel industry still need further research [35].

It is inefficient to use raw biomass in the steel industry because of its chemical, physical and mechanical properties. Therefore, it is better to use charcoals, semi-charcoals or torrefied biomass [21] (e.g., the higher reactivity of biomass has a negative impact on substituting coal/coke in a sintering process [215]). Note that when biomass is inserted in the coal blend to produce coke, it can be used as raw material [35], but it suffers a thermal treatment afterwards.

Today in Europe, biomass cannot compete with fossil fuels in economic terms [22,35]. Recent studies conclude that carbon taxes would be important for the use of biomass in the iron and steel industry [23], as well as a reduction of the costs of upgraded biomass [35]. Synergies between biomass-based sectors, biomass upgrading sectors and the iron and steel industry are vital to enhance sustainable biomass use [35]. Steel plants could be integrated with biomass upgrading and production of chemicals to lower the cost of using biomass and enhancing CO_2 reductions [216].

6. Conclusions

Presently, fossil fuels dominate energy production in industry and biomass is the only RES with relevant (but limited) use. Reducing GHG emissions from process heat generation, which corresponds to the largest share of the industrial energy consumed, is crucial to reaching the EU28 climate targets and deserves more political attention. Yet, developing global strategies to generate sustainable process heat is difficult because of the lack of detailed knowledge of the structure of heat demand, and because the industrial processes and energy conversion technologies are very diverse among the different industries.

Since EU28 industrial energy consumption is dominated by 5 sectors (iron and steel, chemical and petrochemical, non-metallic minerals, pulp and paper, and food and beverages), acting on these sectors has major environmental impacts. One possible strategy to help achieving the EU28 climate targets is increasing solid biomass use for energy production in these five sectors. This review shows that it is technically feasible.

Both biomass combustion and gasification equipment can provide the full range of temperatures required by industrial processes. Certain industrial sectors, though, cannot efficiently use raw biomass and benefit from the use of upgraded biomass. Charcoal and pellets are commercially available on the European market, but they are often sourced outside the EU. The most widely used and mature biomass industrial conversion technology is combustion, although gasification (followed by combustion) is already in commercial stage (currently mainly used for electricity and CHP production). In the case of CHP applications, steam turbines are mostly utilized. The choice of the most suitable technology for a specific application depends on many factors, such as the size of the systems or the associated costs.

The industrial facilities that generate considerable amounts of solid biomass by-products have often already implemented bioenergy projects. There is still margin, however, for further bioenergy valorization and/or different biomass uses. In the industrial sectors where solid biomass is not available as a by-product, biomass competes with fossil fuels and economic viability is a key-issue. The high investment costs for biomass conversion systems and the fact that the availability of the feedstock and the security of the supply are not guaranteed are issues that hinder the implementation of bioenergy projects.

Future sustainable biomass availability is one of the main uncertainties when considering a greater industrial biomass uptake. In EU28, solid biomass production has been increasing, and currently production and consumption are almost balanced. However, the increased pressure on the limited European biomass resources raises the need for monitoring biomass resources in relation to demand and to choose the most sustainable options for their use. Policies to promote further substitution of fossil fuels with solid biomass in industry should be designed, but include strong sustainability measures and consider the risk of market distortion and carbon leakage.

The highlighted research directions aimed at further bioenergy uptake by the industry are: develop and demonstrate advanced technologies to convert biomass to energy and fuels and optimize and deal with the challenges still faced in the operation of several biomass-based systems; pursue and develop strategies to further incorporate the use of industrial biomass where it is technically viable; develop and optimize cost-effective and sustainable biomass supply-chains; and design market-based mechanisms to foster investments in bioenergy.

Declarations of interest

None.

Acknowledgements

The work has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 696140 [TrustEE – Innovative market based Trust for Energy Efficiency investments in industry] and from FCT – *Fundação para a Ciência e a Tecnologia*, Portugal, under the projects UID/AGR/00115/2013 and UID/EMS/50022/2013.

The work reflects only the authors' view and the Agency and the Commission are not responsible for any use that may be made of the information it contains.

Co-funded by the Horizon 2020 Programme of the European Union

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