Biomass for Industrial and District Heating

Isabel Malico

Abstract The industrial sector, the world's largest energy consuming end-user, is a major greenhouse gas emitter. It heavily relies on fossil fuels, with only a small contribution from renewables, and of these, only biomass (mainly primary solid biofuels) is not marginal at a global scale. Several factors contribute to the limited adoption of renewables within the industry. The sector's extraordinary diversity and complexity make a one-size-fits-all solution impossible. Industrial energy consumption varies significantly among different sub-sectors and even within each sub-sector, depending on production composition and industrial processes. Energy-intensive industries typically consume substantial amounts of process heat, while non-energy-intensive ones tend to rely more on electricity. Given the importance of energy-intensive industrial sub-sectors, finding solutions to decarbonise process heat is crucial. Process heat encompasses various applications, technologies, energy sources, temperatures and delivery methods. There is substantial demand for high-temperature process heat (>500 °C), with only a limited number of renewable energy options available, including bioenergy. Bioenergy holds the potential to contribute to the decarbonisation of industry but requires tailored solutions for each sub-sector and context. This chapter presents key commercially available biomass heat production systems, which vary in configuration, technologies and scale, with similarities to district heating systems, also discussed.

Keywords Process heat · High-temperature heat · Bioenergy · Conversion technologies · Combustion · Gasification · Co-combustion

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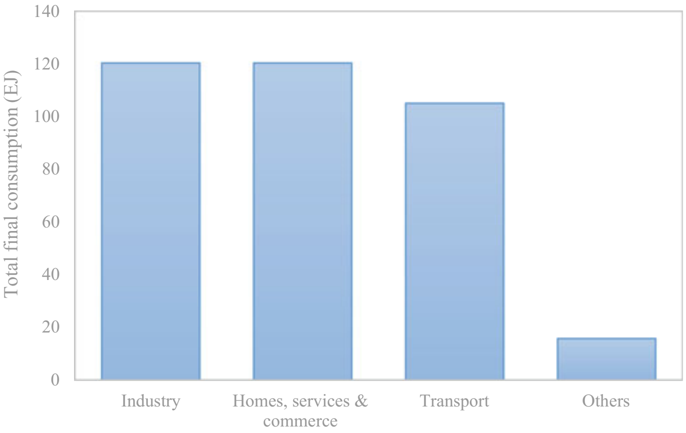

Fig. 1 Total final energy consumption in the world in 2020 by end-use. (*Data source* [1])

1 Introduction

In 2020, the industrial sector accounted for one-third of the world total final energy consumption, approximately 120 EJ (Fig. 1), slightly surpassing the combined consumption of the residential, commercial and public service sectors, which also totalled around 120 EJ [1].[1] With this consumption, industries were the world's largest energy consuming end-use sector, closely followed by the group formed by the residential, commercial and public service sectors (addressed in chapter "Biomass for Domestic Heat").

While the industrial and the residential, commercial and public services sectors have similar final energy consumptions, industries account for more than twice the share of total direct greenhouse gas emissions from end-use sectors compared to the residential, commercial and public buildings (37% versus 16%) (Fig. 2). The term "direct" excludes indirect emissions from the electricity and heat generation consumed in the end-use sectors. The discrepancy between these two sectors reflects the difficulties in the penetration of renewable energy sources in the industrial sector, a challenge addressed in this chapter.

Given the significant contribution of the industrial sector to global greenhouse gas emissions, decarbonising this sector becomes crucial in order to reduce greenhouse gas emissions and keep global warming well below the 2 °C threshold above pre-industrial levels, achieving climate goals [2].

The significance of the industrial sector in total final energy consumption varies across different world regions. China, a highly industrialised country, has the highest share (Fig. 3), with over half of its total final energy consumption (54%) attributed

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[1] Note that these figures exclude the non-energy use of fossil fuels (for example, the fuels used as feedstocks to make products such as plastics and chemicals or bitumen used as road surface).

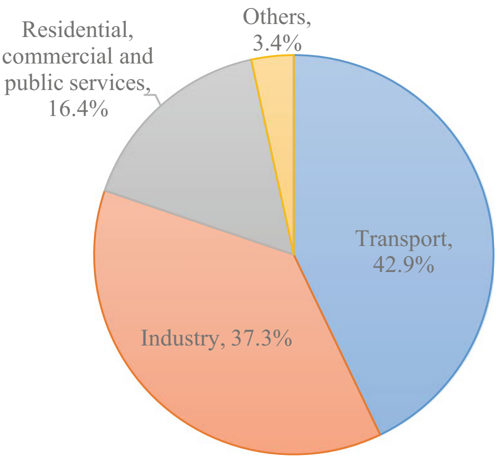

Fig. 2 Share of the different end-use sectors in the greenhouse gas emissions from end-use sectors in the world in 2020. (*Data source* [1])

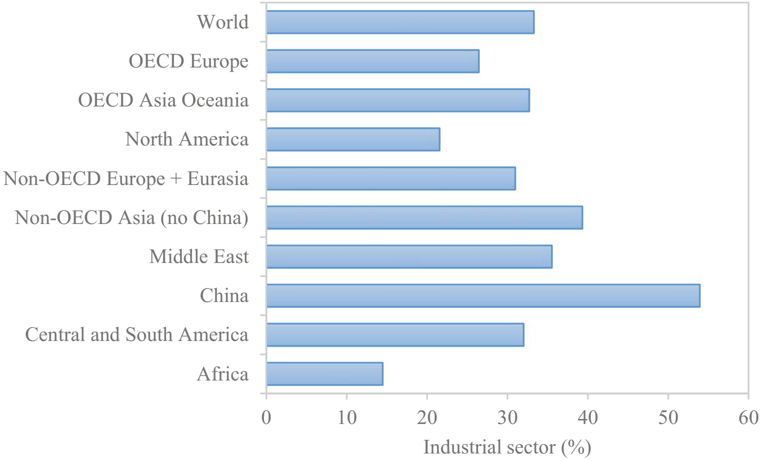

Fig. 3 Share of the industrial sector in the total final energy consumption for different regions in 2020. (*Data source* [1])

to industry in 2020 [1]. In contrast, Africa has the lowest share, with less than 15% of its total final energy consumption dedicated to industrial activities [1].

In 2020, biofuels and waste accounted for just 8.4% of the energy consumed in the global industrial sector [1] (Table 1). Despite this relatively modest contribution from bioenergy, it stands out as the sole renewable energy source (RES) with substantial direct use by the industry worldwide. The industrial sector primarily relies on fossil fuels to meet its energy needs, with nearly 60% of the total energy used in global industry in 2020 derived directly from fossil fuels, mostly coal, followed by natural

Table 1 Share (in %) of the different energy sources in the world industrial energy consumption in 1990 and 2020. (*Data source* [1])

	Coal	Crude oil + oil products	Natural gas	Biofuels and waste	Other RES	Electricity	Heat
1990							
World	25.4	18.5	20.2	5.7	0.0	21.6	8.6
Africa	26.4	26.8	8.7	15.5	0.0	22.6	0.0
Central and South America	7.5	26.0	15.2	31.1	0.0	21.2	0.0
China	72.6	8.9	1.1	0.0	0.0	12.8	4.6
Middle East	0.4	41.9	49.4	0.0	0.0	8.3	0.0
Non-OECD Asia excluding China	38.5	20.8	4.5	21.5	0.0	14.5	0.2
Non-OECD Europe and Eurasia	14.3	12.8	21.7	0.0	0.0	19.0	32.2
North America	14.0	16.4	38.6	4.7	0.0	26.2	0.2
OECD Asia and Oceania	22.1	35.8	7.4	2.8	0.1	31.8	0.0
OECD Europe	21.2	18.8	24.0	4.4	0.0	26.7	5.0
2020							
World	26.3	10.4	21.2	8.4	0.0	28.4	5.2
Africa	16.1	18.5	20.6	18.9	0.0	26.0	0.0
Central and South America	7.6	17.1	15.3	34.5	0.0	25.5	0.0
China	42.8	8.1	9.1	0.0	0.0	32.7	7.3
Middle East	2.0	14.8	70.3	0.0	0.0	12.8	0.0
Non-OECD Asia excluding China	35.0	11.7	9.8	21.1	0.0	22.0	0.5
Non-OECD Europe and Eurasia	20.0	7.8	25.7	2.2	0.0	22.3	22.1
North America	5.2	8.4	47.4	11.4	0.0	26.2	1.5
OECD Asia and Oceania	18.5	17.1	17.4	5.7	0.1	39.2	2.0
OECD Europe	8.4	10.1	30.9	10.7	0.1	34.1	5.7

gas [1]). The share of electricity used by the industries has been increasing in importance, and in 2020, this energy vector was the most used energy source, accounting for 28.4% of the industrial energy consumption [1]. Some of this electricity, and also of the derived heat, comes from renewable energy sources; therefore, the use of renewable energies in the industrial sector was higher than what can be directly observed in Table 1. However, global electricity generation continues to rely on fossil fuels (*cf.* chapter "Biomass for Power Production and Cogeneration"), as does the generation of derived heat (*cf.* Sect. 4).

In 2020, Central and South America (35%), non-OECD[2] Asia (excluding China) (21%) and Africa (19%) stood out as regions where biofuels and waste had the most significant share in the industrial energy consumption [1]. These regions also had important biomass consumptions in the residential sector (*cf.* chapter "Biomass for Domestic Heat"), and Central and South America was the world region with the highest share of biomass in the energy sector (*cf.* chapter "Biomass for Power Production and Cogeneration"). Combined, non-OECD Asia and Central and South America accounted for 60% of the biofuels and waste used by the industry in 2020, followed by North America (16%) and OECD Europe (13%) [1].

The relative importance of fossil fuels in the industrial sector has been declining, albeit at a slow rate (averaging 0.4% per year over the last three decades [1]). However, between 1990 and 2020, the consumption of fossil fuels by the industry increased 45%, from 48 to 70 EJ, following the growth in energy consumption by the industry [1]. During this period, crude oil and oil products were the only fossil energy sources to experience a decrease in consumption, while the industrial demand for coal and natural gas increased, both in quantity and share (even though, in the last decade, global consumption of coal by the industry has been decreasing (Fig. 4)).

The consumption of biofuels and waste by the global industry in 2020 (10 EJ) was approximately 2.5 times higher than in 1990. Moreover, there was and even more significant relative growth in other renewable energy sources, such as geothermal and solar, which had a more than six-fold increase over the last 30 years [1]. However, despite the importance of promoting the adoption of these RES by the industry, they still have no expression in the global industrial energy consumption.

The large majority of the biofuels and waste consumed by the industrial sector in 2020 were primary solid biofuels, accounting for an average of 93% worldwide. However, in certain regions, industrial waste also constituted a significant share [1]. When only the renewable fraction of waste is considered, worldwide, solid biofuels represented nearly the entire biomass consumption by the industry worldwide.

The remainder of this chapter is structured as follows. It begins with a description of how energy is consumed in the industrial sector. Given that the industrial sector predominantly consumes energy in the form of heat on a global scale, and forest biomass is particularly well-suited for heat generation, Sect. 3, focus on presenting the most relevant biomass heat production systems used in this sector. While these systems vary in terms of configuration, technologies and scale, some share significant similarities with those used in district heating. Consequently, district heating systems

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[2] OECD stands for Organisation for Economic Cooperation and Development.

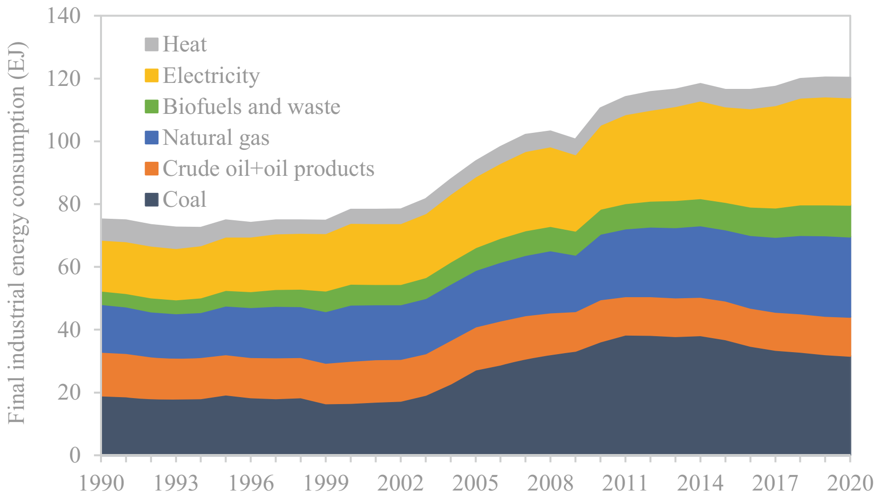

Fig. 4 World final energy consumption in the industrial sector by energy source from 1990 to 2020. (*Data source* [1])

are discussed at the end of this chapter. On the other hand, the topic of combined heat and power (CHP) generation, which is very important for both applications, will not be addressed in this chapter; instead, it will be covered in chapter "Biomass for Power Production and Cogeneration", when power production based on forest biomass is described. The chapter ends with some final conclusions.

2 Industrial Energy Consumption

Industries consume electricity for operating industrial equipment (e.g., motors, compressed air systems), as well as for lighting, space heating, cooling, ventilation and powering computers and other electric equipment. Additionally, they demand heat for process heating and water and space heating.

The structure of energy consumption in the industrial sector is highly complex, with significant variations among different industry sub-sectors and even within the same sub-sector, among industrial facilities [3, 4]. Typically, the majority of industrial facilities purchase electricity from electrical utilities or independent power producers. Some also generate electricity for self-use and/or for sale, often through CHP systems. While the purchase of derived heat also exists, it is not as common to sell heat off-site as it is for electricity or transport fuels [5], primarily due to the challenges associated with heat distribution.

The distribution of energy consumption across various end-uses (power, process heating, space heating and process and space cooling) in the industrial sector depends on the composition of industrial sector production and the specific characteristics of existent industrial processes. A comprehensive understanding of how energy is consumed in the world's industry is currently lacking, as there are no global official statistics that disaggregate the energy consumed in industry into its end-uses. In general, heat plays a significant role in the energy consumed by the industries. However, because heat generally does not require metering, and heat markets are often local and dispersed, there is a general gap in heat demand data [5]. This gap hinders demand-oriented energy policies for the sector [4].

Some countries are aware of the need for more information on the heat and cooling sectors and their importance for the energy transition towards a sustainable low-carbon economy. For example, the European Union (EU) defined its strategy for the heating and cooling sectors in 2016 [6], set indicative targets for the EU countries to increase the annual share of renewable energy sources in heating and cooling [7], and supported and published studies to increase the knowledge on the heating and cooling sectors (e.g., [8–10]). As a consequence, information on the characteristics of the consumption in the industrial sector exists for these regions. Presenting a description of this information does not characterise but helps to form a picture of the energy needs of the world's industry. In this regard, the next paragraphs briefly present the EU's industrial energy consumption.

In the European Union, the industrial sector was the third largest energy consumer, accounting for 26% of the total final energy consumption in 2021 [11]. Similarly to what happens in the world, the industry of the EU 27 Member States (EU27) rely on electricity and the direct use of fossil fuels (33% and 49% of the final industrial energy consumption, respectively) [11]. Natural gas (33%) was by far the most consumed fossil fuel [11]. The renewable contribution to the EU27 came primarily from primary solid biofuels (90.6%), with some contribution of renewable municipal waste (3.6%), biogas (2.2%), liquid biofuels (1.9%) and ambient heat (1.6%) [11].

Five industry sub-sectors contribute the most for the EU27's industrial energy consumption (Fig. 5): chemical and petrochemical (21.5%), non-metallic minerals (14.1%), paper, pulp and printing (13.5%), food, beverages and tobacco (11.6%), and iron and steel (10.2%). Understanding how energy is consumed in these industries and promoting energy efficiency and renewable energies is critical to be able to reduce the overall impact of the industrial sector on the environment.

A full end-use energy balance for the EU27 industry revealed that, in 2012, 57% of the energy was consumed for process heating, 10% for space heating, 3% for cooling and the remainder (30%) was mainly used for mechanical applications driven by electricity (Table 2) [12]. Another study, focusing on eight energy intensive sub-sectors that consumed 98% of the EU28 (EU27 + the United Kingdom) industrial final energy consumption in 2013, concluded that process heating consumed 66% of the total final energy consumption and electricity had a 26% share [13]. More recently, a study by TU Wien [10] focused on space heating concluded that 8.7% of the EU27 industrial energy consumption in 2017 was for space and water heating. These studies show that most of the energy used by the European Union's industry is in the form of heat, specially process heat.

Industrial processes vary significantly by industry sub-sector and so do their energy needs. The most energy intensive industry sub-sectors typically consume

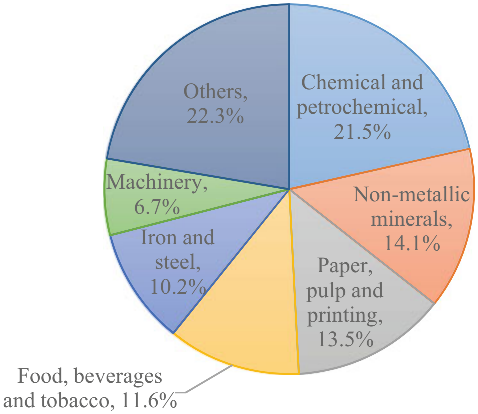

Fig. 5 Share of industry sub-sectors in the final industrial energy consumption in EU27 in 2021. (*Data source* [1])

Table 2 Share (in %) of various energy end-uses by industry sub-sector in EU27 in 2012. (*Data source* [12])

	Process heating	Space heating	Non-heating and cooling	Cooling
Chemical and petrochemical	61.7	4.1	28.8	5.4
Non-metallic minerals	76.3	4.7	18.4	0.6
Paper, pulp and printing	60.9	5.4	33.2	0.5
Food, beverages and tobacco	43.6	21.9	20.2	14.4
Iron and steel	85.2	1.5	13.3	0.1
Machinery and transport	14.5	27.3	56.7	1.5
Non-ferrous metals	40.6	3.7	55.5	0.2
Total industry	57.1	10.1	29.9	3.0

a large share of heat (Table 2). For example, 87% and 66% of the energy consumed by the iron and steel and chemical and petrochemical sectors in the EU27 in 2012 was heat. On the other hand, non-energy intensive industries, like the manufacturing of machinery, generally consume more electricity than heat.

The direct use of fossil fuels, especially natural gas, dominates the heat consumption in the European industry (Fig. 6). Natural gas accounted for 36% of the final energy consumption for process heating in the EU27 countries in 2012, followed by coal and other fossil fuels. In general, approximately three quarters of the energy demand for process heating was met with fossil fuels. Biomass provided 12% of the energy used for process heating and was the only renewable energy source used directly by the industry with some expression.

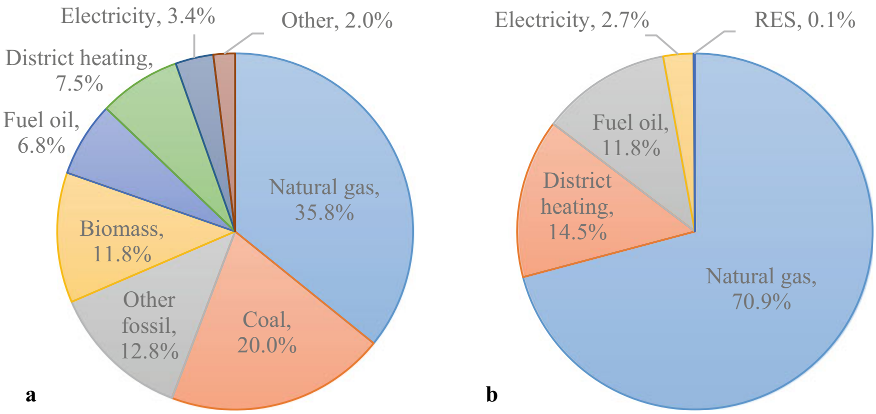

Fig. 6 Share of energy sources in the final energy consumption **a** for process heating and **b** in space and water heating in industry for EU27 in 2012. (*Data source* [10, 12])

The importance of the direct use of fossil fuels is even larger when it comes to industrial space and water heating (Fig. 6b). In 2012, natural gas and fuel oil accounted, respectively, for 71 and 12% of the energy needs for this end-use in EU27 countries. Moreover, the direct use of renewable energy sources for space and water heating in the EU27 industry was negligible and the only way that renewables penetrated was indirectly through electricity and district heating, which are partially produced from renewable energy sources. Of the two, the largest share in industrial heating belongs to district heating, which accounted for, respectively 15% and 8% of the energy consumed for space and process heating in the EU27 in 2012.

The energy sources used for process heating are much more diversified than for space and water heating, reflecting the very large diversity of technologies used for process heating. Indeed, the term process heat refers to a huge variety of applications, using different technologies and energy carriers (e.g., steam, liquid water, air) at different temperature levels. The latter is of particular importance when addressing the decarbonisation of the industrial sector.

More than half of the process heat consumed by the EU27 industry in 2012 was above 500 °C (Fig. 7); the same occurring in EU28 in 2015 [14]. High-temperature heat represented the large majority of the process heat consumed by the iron and steel (94%), non-metallic minerals (72%), and chemical and petrochemical (66%) industries in EU27 in 2012 [12]. In contrast, other industry sub-sectors that are also large energy consumers mostly consumed heat below 200 °C (in the paper, pulp and printing, and the food, beverages and tobacco, the share of process heat below 200 °C in the total process heat consumed was, respectively, 94% and 83% [12]).

The need for high-temperature heat was essentially met by the direct use of fossil fuels (91%) [12]. Moreover, supplying process heat at temperatures above 500 °C represented 84% of the coal, 76% of the "other fossil fuels" and 55% of the natural gas consumed by the EU27 industry in 2012 [12].

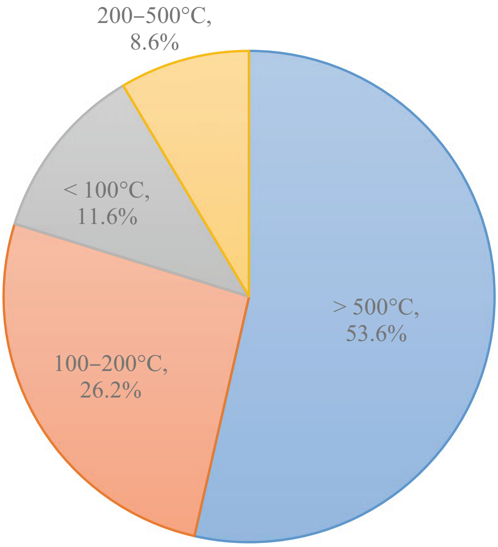

Fig. 7 Share of temperature levels in the final energy consumption for process heating in industry for EU27 in 2012. (*Data source* [12])

Not all the renewable energy sources and technologies are able to provide high-temperature process heat [15]. In principle, various solid biomass products are able to provide high-temperature heat [4, 15] but in practice, in the EU27 in 2012, 83% of the biomass used by the industry met process heat needs with temperatures below 200 °C and only 17% was used for process heat at temperatures above this level [12] Furthermore, solid biomass was mainly used by industry sub-sectors that generate residual biomass, such as the pulp, paper and printing, and the wood and wood product industries (see chapter "Sources and Distribution of Forest Biomass for Energy" for a description of the secondary wood residues generated by the wood-based industries). Together these sub-sectors consumed 85% of the final energy consumption of solid biomass in the EU27 industry in 2021 (Fig. 8). On the other hand, with a 6% share, the non-metallic mineral sector does not generate residual solid biomass, but still consumes a noteworthy proportion of solid biomass.

Process heat was virtually the only final energy use of biomass in the EU27 industry in 2012 [12]. This does not mean that industry does not generate electricity from biomass. However, the electricity generated by the industry is accounted for in transformation and not final energy consumption (*cf*. chapter "Biomass for Power Production and Cogeneration"). For example, the pulp and the wood-based panels industries commonly consume solid biomass in CHP systems for the production of heat and power [16–19].

Other than temperature, the way heat is delivered to the load is also important and diversified. Some industrial processes are continuous and require large amounts of energy to heat large volumes of materials, while others operate in batch mode, heat small quantities of materials and require precise temperature control [20]. In certain industries heat is provided directly to the material, in others indirectly. For example, in blast furnaces used in the steel industry, the flue gases are in direct contact with

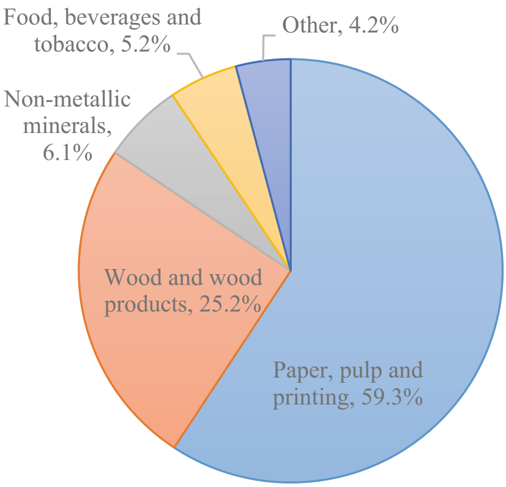

Fig. 8 Share of industry sub-sectors in the final energy consumption of solid biomass in industry for EU27 in 2021. (*Data source* [11])

the iron ore and are used for its reduction [21], whereas in the production of food and beverages, direct heating with solid fuels such as coal is generally not suitable since the flue gases contain pollutants that contaminate the products [22].

Other analyses characterise the industrial energy consumption in different regions and help form a picture of the needs of the world industry and the pathways available to decarbonise this sector. For example, the United States Energy Information Administration (EIA) regularly publishes the results of its Manufacturing Energy Consuming Survey [23] and the Australian Renewable Energy Agency recently published a report on the renewable options for industrial process heat where the consumption of the Australian industrial sector is analysed [24]. Complementing these analyses, several studies focus on specific industry sub-sectors, such as the iron and steel [25, 26], chemical [27, 28], cement [29, 30] or pulp and paper [31, 32] industries.

Even though a detailed characterisation of the world industrial energy needs is not available, the following can be stated:

- Industry is very diverse and the energy needs of the different industry sub-sectors and facilities are varied and complex.
- A few energy-intensive industry sub-sectors account for a large share of the world energy consumption and greenhouse gas emissions (of particular relevance are the chemical, iron and steel and cement industry[3]) but, a non-negligible part of the industrial energy consumption is dispersed by very different industries.
- Energy-intensive industry sub-sectors typically consume a large share of heat, mainly process heat.

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[3] In 2020, these three sectors accounted for almost 60% of the world industrial energy consumption and more than 70% of the industrial CO_2 emissions [33]. The emissions from industrial processes are included in this value, which for some industrial processes (e.g., cement and lime production) are important [34].

- Demand for high-temperature heat in industry is substantial.
- High-temperature process heat can only be supplied by certain technologies and energy sources, whereas for the lower temperatures (200 °C) much more options are available [9, 15, 35].
- High-temperature process heat is today largely supplied by fossil fuels.
- Biomass could provide high-temperature process heat, but is mainly used in forest-based industries, which mostly require low and medium temperature process heat.

The decarbonisation of the industrial sector is a challenging task. Adding to the difficulty of providing high-temperature heat through low-carbon technologies, heavy industrial facilities have typically long lifetimes, are capital intensive and many energy-intensive products, such as steel, compete on global competitive markets and, therefore, the investment on new, low-carbon technologies poses real risks [9, 33]. Moreover, industrial players are generally averse to risk and have short payback time expectations [24]. Bioenergy may be part of the solution to decarbonise industrial heat, with several studies focused on the topic [4, 15, 21, 30, 35–37], but the solutions are dependent on the industry sub-sector and specific context with no one-size-fits-all solution.

3 Biomass Systems for Industrial Heating

As seen previously, globally, in the industrial sector most of the energy is consumed for process heating, but space heating is also worthy of reference and is relatively more important in the less energy-intensive sub-sectors, such as machinery and transport equipment or the food, beverages and tobacco (e.g., [4, 10]). Several technologies are available for the production of space heating within industrial facilities (e.g., combustion-based equipment fuelled by renewable and non-renewable fuels, ambient pumps, solar thermal systems). Alternatively, heat can be supplied via district heating (see Sect. 4 for a description of district heating systems based on biomass).

Because of the diversity of existing industrial processes and heating principles, a high diversity of technologies (e.g., boilers, kilns, blast furnaces, ovens, dryers) are available to generate process heat, varying in size from small-scale systems of a few kilowatts to large-scale systems of the order of megawatts. Among the factors that are important for the choice of the technology used are: the characteristics of the industrial process and heat demand, properties of the available fuels, costs and performance of technologies and legislation [38–40].

Combustion-based process heating systems are responsible for the generation of a large share of the energy used by the industry and are employed in almost every industry segment [20]. In this type of process heating system, heat is generated by the combustion of a fuel (usually with air, but other oxidants are also used) and distributed to the process. Biomass is not the most used fuel but common in certain industrial sub-sectors (*cf.* Sect. 2). The systems can be categorised into two groups: direct heating systems, where flue gases are in direct contact with the material being processed, and

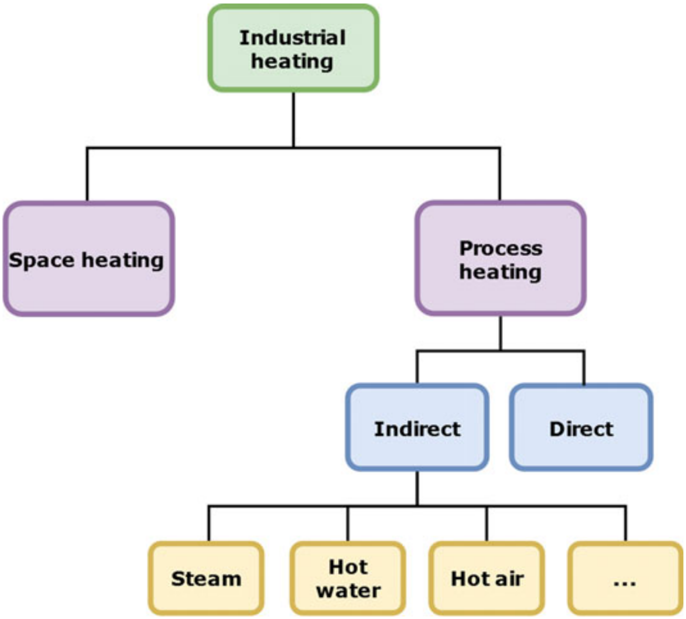

Fig. 9 Industrial heating

indirect heating systems, where flue gases transfer the heat to a heat transfer fluid (e.g., steam, hot water, hot air), which then delivers heat to the production process (Fig. 9).

Typically, high-temperature process heat is generated in direct systems [36]. There are many types of equipment used, depending on the specificities of the industrial process. Examples include furnaces used in the chemical and petrochemical [41–45], food, beverage and tobacco [46], iron and steel [47, 48], non-ferrous metals [49], non-metallic minerals [50–53] and pulp and paper [18] sub-sectors. Currently, most of these applications rely on fossil fuels, but some involve biomass co-firing with other fuels (e.g., in cement kilns [53]) or 100% biomass firing (e.g., in small blast furnaces [54]).

Although direct heating also provides heat at low and medium temperatures, such as in the case of the cork industry [55], most technologies used for the lower temperatures involve indirect heating, usually with steam as the heat transfer fluid [36]. For the generation of low- and medium-temperature process heating, diverse biomass conversion technologies are available and commonly used.

In contrast to many small-scale biomass energy conversion systems used for residential heating (*cf.* chapter “Biomass for Domestic Heat”), typically, industrial systems are automatically fed, involve advanced process control systems and pollution control equipment. Figure 10 presents an example of a possible layout of a solid biomass system used to indirectly provide process heat to an industrial process.

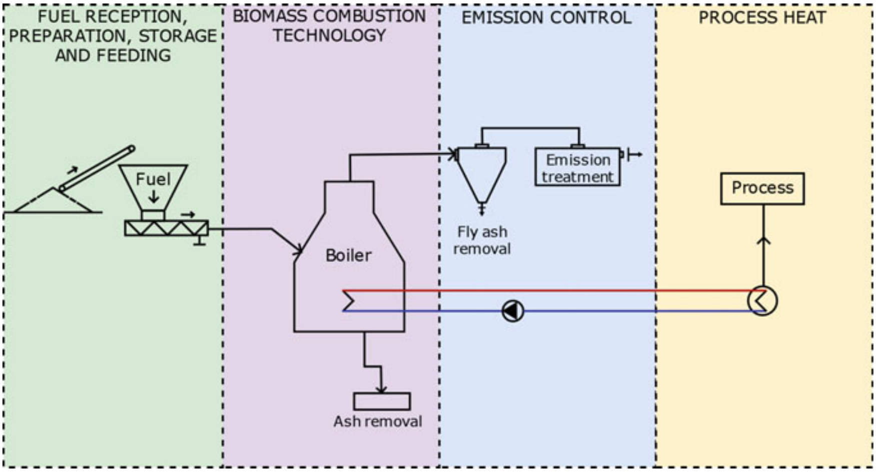

Fig. 10 Example of a layout of a process heat generation system fired with solid biomass

The configuration of biomass systems for process heat generation varies based on factors such as the scale of the system, operational requirements and the characteristics of the fuel feedstock. Typically, these systems integrate different facilities, components and equipment.

Usually, facilities that receive, store, preprocess and/or automatically feed the fuel into the energy conversion system are required. The logistics of biomass delivery and reception are intricately linked to the layout of the facility and the chosen storage methods. Unloading and/or transporting fuel to storage or processing areas can adopt fully automated, fully manual or hybrid approaches involving a combination of automation and manual intervention.

To ensure compliance with environmental and health standards, potentially optimise costs and align with the requirements of the energy conversion process, biomass often undergoes pre-processing before storage and energy conversion (see chapter "Forest Biomass as an Energy Resource" for a description of biomass pre-processing methods).

The storage of solid biomass can encompass both indoor and outdoor facilities, with some applications requiring both long- and short-term storage solutions, while others only short-term storage before directly feeding biomass into the conversion equipment.

The biomass feeding systems should be automatic and equipped with metering capabilities, enabling precise control over the amount of biomass supplied to the conversion equipment. This control ensures efficient conversion and consistent generation of heat, important in industrial contexts.

Moreover, environmental protection policies generally impose limits on pollutant emissions arising from combustion. Consequently, it becomes imperative to implement mitigation measures and control systems that align with legal mandates. This measures and systems can involve the use of advanced combustion technologies, air pollution control equipment (e.g., scrubbers, fabric filters, electrostatic precipitators, cyclones) and optimisation of operational practices to minimise emissions [38, 56, 57]. Choosing the right technology depends on factors such as the specific biomass material, combustion equipment and desired energy output.

Another integral part of the heat generation system fired with solid biomass is the collection of ash formed during combustion. A portion of the inorganic matter content of the biomass fuel is removed from the system in the form of solid ash particles and agglomerates that are collected at the bottom of the combustion chamber. Additionally, small ash particles and inorganic vapours are caught up by the combustion gases and are transported through the flue gas duct, being collected in specific equipment (e.g., electrostatic precipitators, fabric filters, cyclone separators).

At the centre of solid biomass systems designed for process heat generation is the equipment that converts the fuel into thermal energy. Most of the systems employed by the industry are based on the direct combustion of biomass, but some industries use systems based on gasification [15]. Both combustion and gasification technologies will be described below.

Combustion

Medium- and large-scale systems for biomass combustion rely on several technologies that are commercially available and mature. Most of these technologies can be categorised into three groups: fixed bed, fluidised bed and pulverised fuel combustion, depending on the flow conditions inside the combustion chamber [38, 40].

In fixed bed combustion, biomass fuel is fed onto a grate, where it burns with the primary air that flows through the bed, supplied through the grate from below (Fig. 11). Secondary air enters the combustion chamber above the bed to support further combustion of the gases and particulate matter that are formed during the initial burning process. The name “fixed-bed” originates from the fuel forming a bed that remains on the grate due to gravity, in contrast to what happens in fluidised bed combustors, where the particles of fuel are suspended.

Fix bed combustion systems can have different configurations and are further categorised into grate furnaces (overfeed stokers) and underfeed stokers, depending on the way fuel is fed into the combustion chamber. As the name indicates, in overfeed stokers, the biomass is supplied from above the grate, while in underfeed stokers from below. Different technologies of both underfeed and overfeed stokers exist, each with its own design and operational characteristics. Examples of mature technologies are fixed, moving, travelling, vibrating or rotating grate firing furnaces, cigar burners or horizontal-feed, side-ash discharge underfeed stoker [40, 57–59].

Similar to fixed bed combustion, fluidised bed combustion also involves the upward stream of primary combustion air supplied to the combustion chamber from the bottom. However, in fluidised bed combustion, this air is introduced at a sufficiently high velocity to maintain the bed in suspension, creating a “fluidised” state

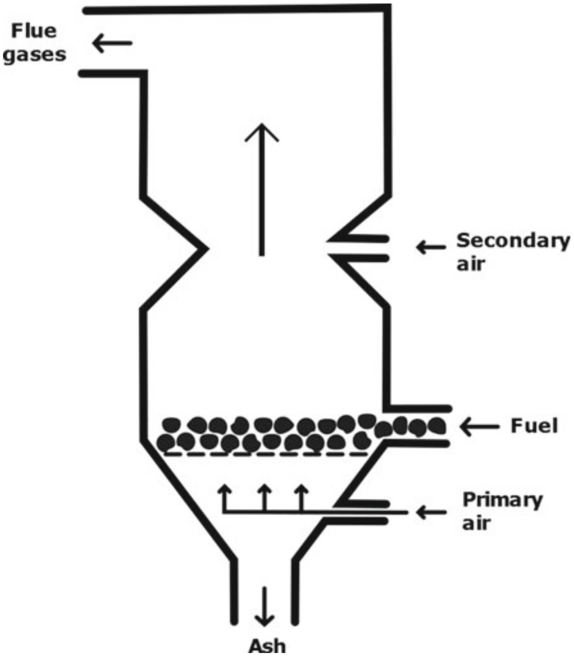

Fig. 11 Sketch of a grate furnace, a type of fixed bed combustor

(Fig. 12). In this technology, fuel is fed into a bed of suspended heated granular material (e.g., silica sand, dolomite), which constitutes the majority of the bed, usually accounting for 90–98% of the mixture of fuel and bed material [40]. The combination of intense heat transfer and mixing enhances combustion, promoting complete and efficient combustion while allowing low excess air. This reduces the volume of flue gases, allowing a more compact design, which is particularly beneficial for large-scale applications.

Fluidised bed combustion can be categorised into bubbling fluidised bed and circulating fluidised bed [60, 61]. The primary distinction between these two lies is the fluidisation velocity, which is notably higher for circulating fluidised combustion. As a consequence, in this technology, the bed material, which is smaller than in bubbling fluidised bed, is carried with the flue gases. Larger particles tend to either remain fluidised near the furnace bottom or get transported after undergoing size reduction due to the chemical reactions, thermal stresses and mechanical stresses [62]. The operation of circulating fluidised bed furnaces involves a cyclone directly linked to the combustion chamber, which separates and captures particles contained in the flue gases and recycle them to the fluidised bed for complete combustion.

Fluidised bed systems operate at atmospheric pressures, although variations that operate at elevated pressures have been developed. They are characterised by higher efficiencies, but are more complex and have higher associated costs [20]. The current research emphasis is primarily directed towards conventional atmospheric fluidised

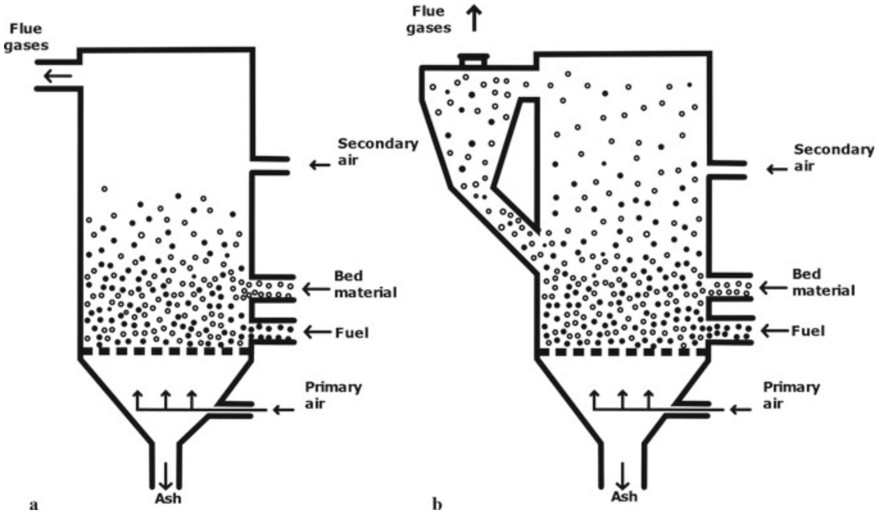

Fig. 12 Sketch of **a** bubbling fluidised bed furnace and **b** circulating fluidised bed furnace

bed combustion with limited attention given to the investigation of pressurised fluidised bed systems [63].

Pulverised fuel combustion, also called entrained flow or dust combustion, is most widely employed in coal-fired power stations [64], but not so common for biomass combustion. In pulverised fuel combustion furnaces, finely pulverised fuel alongside air are introduced in the combustion chamber (Fig. 13). Within the furnace, these particles heat up, releasing combustible gases and quickly reacting with oxygen, because of the small particle sizes. This technology is characterised by high efficiencies and allows very good load control and fast load changes [40, 65].

Disadvantages of pulverised fuel combustion are the requirement to burn biomass with low moisture content (<20 wt % wb) and small particle sizes (<5 mm) [38] and sensitivity to changes in fuel quality [57]. When pulverised fuel combustors are fired with solid biomass, if the particles are not already small because they originate from a specific industrial process, energy must be spent in grinding and drying the feedstock.

Table 3 presents the typical capacities, fuel requirements and performance for fixed bed and fluidised bed biomass combustion, the two types of technologies mostly used for the generation of process heat from biomass. The values presented are for reference and should be read with care since many of the parameters may be dependent on a specific technology within these combustion typologies. For example, the fuel delivery system also influences the size of the particles and grate furnaces with pneumatic conveyers for fuel delivery require particle sizes up to 5 mm, while sliding bar conveyers allow fuel 100 times larger [38].

Biomass fixed bed and fluidised bed combustion are the most commonly used technologies for the generation of heat. Biomass fixed bed combustion is typically

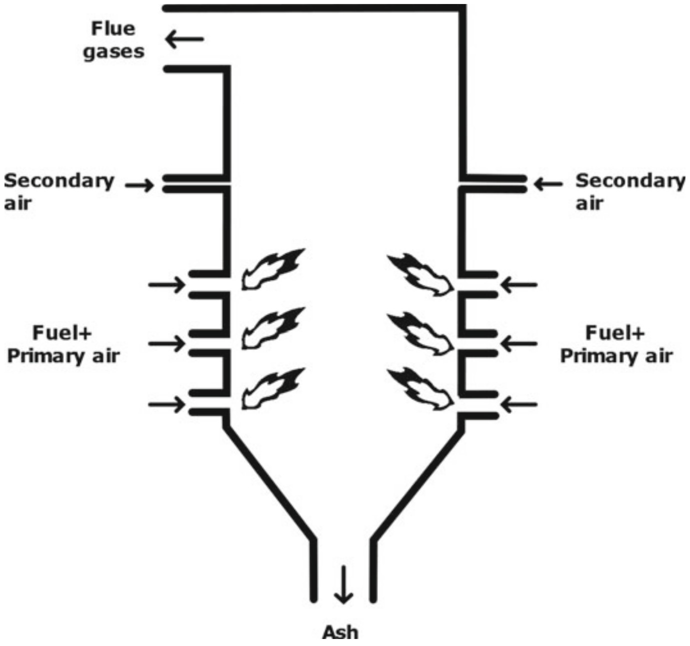

Fig. 13 Sketch of a pulverised fuel combustor

used for capacities below 20 MW_{th}, while fluidised bed combustion is preferred for capacities above 20–30 MW_{th} [36, 64]. Generally, both technologies offer considerable flexibility regarding moisture and ash content [65]. However, while fixed bed combustion systems are flexible in terms of fuel particle size, fluidised bed systems require smaller particle sizes [38, 65]. Additionally, fixed bed combustion allows for the mixture of various types of wood fuels [65] and is commonly used for low-grade fuels (e.g., demolition wood) [64]. Generally, these systems have lower capital and operational costs than fluidised bed systems, but are characterised by lower efficiencies [40]. Biomass pulverised combustion, although occasionally used in industry sub-sectors like chipboard manufacturing [40], is not as widely adopted for process heat. Instead its primary and more common application is in thermal power stations [68] (*cf.*, chapter “Biomass for Power Production and Cogeneration”).

Gasification

An alternative approach to the conventional method of direct combustion involves gasification. During gasification, biofuels are converted into a low molecular weight combustible gaseous fuel mixture commonly referred to as syngas (for further details

Table 3 Comparison between fixed bed, bubbling fluidised and circulating fluidised bed combustion (based on [38, 40, 57, 60, 65–67])

	Fixed bed combustion	Bubbling fluidised combustion	Circulating fluidised combustion
Typical thermal capacity	100 kW_{th}–20 MW_{th}	5–15 MW_{th}	15–100 MW_{th}
Fuel flexibility	Good; all wood fuels and most types of biomass	Good; various types of biomass	Good; various types of biomass
Flexibility to fuel particle size	High; allow varying particle sizes with a minimum size of 5 mm	High but for smaller sizes (<25 mm)	High but for smaller sizes (<50 mm)
Maximum moisture content	60%	60%	60%
Maximum ash content	50%; low for underfeed stokers	50%	50%
Partial load operation	Good	Requires special technology	Requires special technology
Combustion efficiency	94–97%	~99%	Up to >99%
Capital costs	Medium to low	High (but lower than CFB)	High
Operation and maintenance costs	Medium to low, depending on the technology	High	High

CFB Circulating fluidised combustion

on the composition and denomination of the gaseous fuels that results from gasification, please consult chapter "Forest Biomass as an Energy Resource"). One of the advantages of syngas over the original solid biofuels is its flexibility and the wide array of potential applications. These applications range from the generation of heat to the production of advanced biofuels and chemicals, passing through the generation of combined heat and power.

Within the scope of industrial heating only (cogeneration will be explored in chapter "Biomass for Power Production and Cogeneration"), once generated in the gasifier, syngas can be burned to provide process heat. This forms a closed-coupled biomass gasification-combustion system, a technology commercially available [69]. When a high-quality clean gas is essential for the process, syngas will undergo treatment to eliminate tars and particulate matter before combustion. This results in a much cleaner fuel than the original solid biomass.

Gasifiers can be categorised as either directly heated or indirectly heated, depending on the method they employ to supply heat for the endothermic gasification process. In directly heated gasifiers, also known as autothermal gasifiers, heat is generated through the partial oxidation of biomass. Conversely, in indirectly heated gasifiers, also referred to as allothermal gasifiers, heat is provided indirectly either by the gasifying agent or through heat exchangers. The way heat is provided to the gasification reactions is determinant for the quality of the syngas, with indirectly heated gasifiers typically yielding syngas with a higher heating value [70].

Another common way of classifying gasification conversion technologies is based on their fundamental operation principle, including fixed bed, fluidised bed or entrained flow designs [71]. The fluid dynamics within the gasifier has a strong influence on the mixing between solid and gas and on the performance of gasifiers [72]. In this context, both fixed bed and fluidised bed systems, the main categories of gasifiers, employ similar equipment to direct combustion systems [69].

In fixed bed gasification systems, the fuel is fed from the top and is piled on a grate, moving downwards as it suffers chemical reactions (Figs. 14 and 15). On the other hand, the gasifying gas that passes through the biomass feedstock (almost always air [73]) may be introduced at diverse positions within the gasifier, resulting in different gas flow directions.

Fixed bed gasifiers are the classical and still the most commonly used technologies for gasification [71] and are well-suited for small-scale heat and/or power generation [74]. They represent a straightforward, cost-effective and well-established technology; however, they typically yield syngas with lower heating value than other configurations [69].

In the updraft gasifiers, also called counter-current gasifiers, the gasifying agent is introduced at the bottom and, as a consequence, the gasification process proceeds downwards (Fig. 14a). The syngas leaves the gasifier at the top and ash falls from the grate to the bottom of the gasifying chamber. This type of gasifier is efficient [74] and allows using biomass with high moisture content [71], but it has a drawback in that the syngas generated typically contains 10–20% tar, necessitating significant cleaning

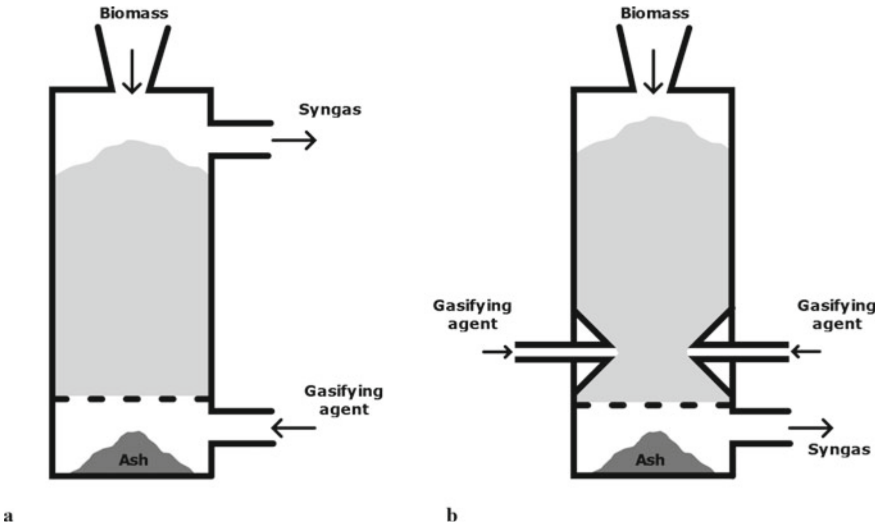

Fig. 14 Sketch of fixed bed **a** updraft gasifier and **b** downdraft gasifier

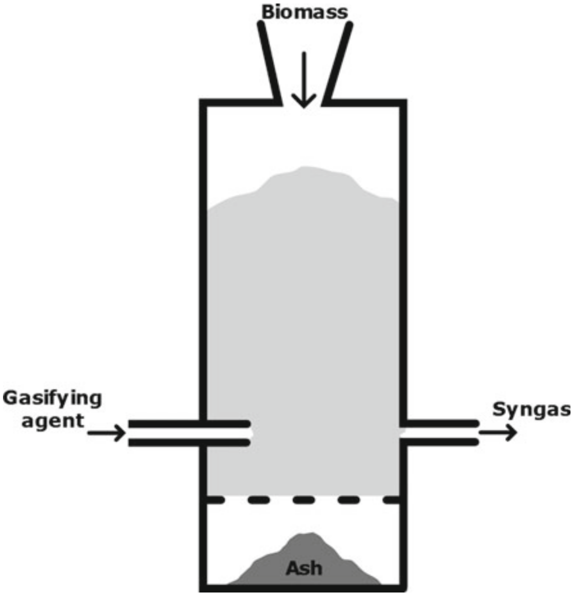

Fig. 15 Sketch of a fixed bed crossdraft gasifier

and processing before it can be used for purposes other than direct combustion [71]. Because of their inherent disadvantages, updraft gasifiers are not so widely used today [74].

In contrast to updraft gasifiers, downdraft gasifiers, also called co-current gasifiers, introduce the gasifying gas more or less at the middle section of the gasifying chamber (Fig. 14b). In this configuration both the biomass and the gasifying agent move downwards and ash falls from the grate to the bottom of the gasifier. As a consequence of the direction of the gas flow, syngas flows towards the bottom of the reactor, leaving the gasifier at a high temperature. Two types of downdraft gasifiers exist: with throat, as represented in Fig. 14b, or without throat; the former producing syngas with lower tar content [74]. While downdraft gasifiers tend to produce syngas with much lower tar content (less than 0.1%) than updraft gasifiers, they can be more complex and costlier to operate [71]. Another disadvantage is the fact that they require feedstock with low moisture content [71] and low ash content [73].

Downdraft gasifiers are widely used and are the most common technology for small-scale power generation [75]. Other main applications of the syngas produced with this technology are in boilers, dryers or direct fired rotary kilns [74].

Another type of fixed-bed gasifier is the crossdraft gasifier, also called cross-flow gasifier. In this configuration, the gasifying agent enters the reactor on one side and syngas leaves on the other side (Fig. 15). One of the main advantages of this type of configuration over the other fixed-bed types of gasifiers is the fast response time to load changes; however, crossdraft gasifiers are not widely applied and research is scarce [74].

Similar to fluidised bed combustion, fluidised bed gasification systems generate combustible gas by introducing biomass into a heated bed of suspended granular material that is fluidised by an upward flow of gas, which in the case of gasifiers is the gasifying agent. This results in an effective mixing between the gas and the different solid materials present in the gasifying chamber. The most common inert bed material is silica, but other bed materials might be an option for specific applications. For example, dolomite has a catalytic effect on the gasification process, helping reduce tar and char formation [74].

While these systems offer enhanced performance, they come with increased complexity and cost [69]. The fluidised bed design results in gas with relative low tar content but a higher level of particulates compared to fixed-bed systems [69]. Advantages of fluidised bed gasification systems over fixed bed systems include improved overall efficiency [69, 74], the capability to handle a broader range of biomass feedstocks [69, 74] with a wider range of feedstock particle size [74]. Moreover, they offer good scalability [74].

Three types of fluidised bed gasifiers exist: bubbling fluidised bed, circulating fluidised bed and dual fluidised bed gasifiers. In all, the gasifying agent is introduced in the reactor from the bottom and is evenly distributed in the gasifying chamber (Figs. 16 and 17). Similar to combustion, the primary difference between bubbling and circulating fluidised bed gasification lies in the velocity of the gasifying gas, which is higher for circulating fluidised bed gasification. Both are equipped with cyclones to separate solid particles from the syngas.

Circulating fluidised bed gasifiers are characterised by higher conversion efficiencies than bubbling fluidised bed gasifiers [74]. They are mainly used in the industrial sector (e.g., pulp and paper, cement sub-sectors) and for electricity generation [74].

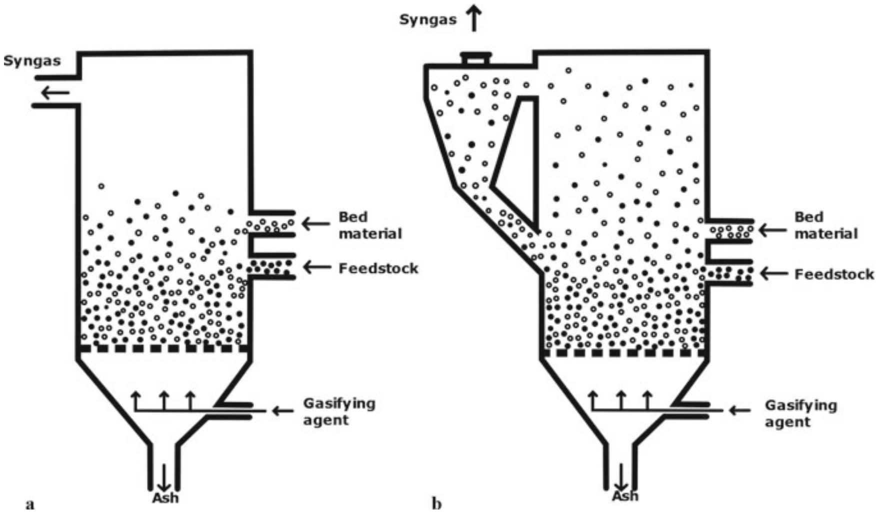

Fig. 16 Sketch of **a** bubbling fluidised bed gasifier and **b** circulating fluidised bed gasifier

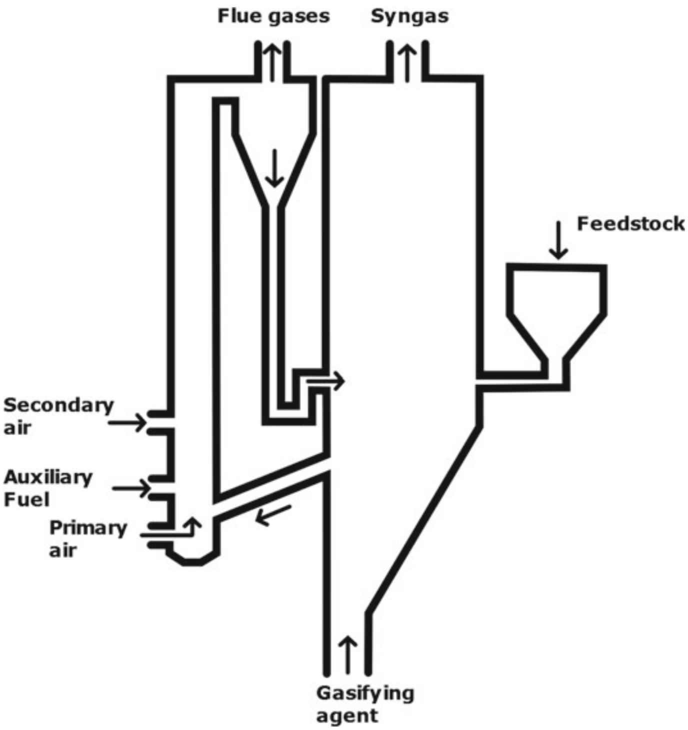

Fig. 17 Sketch of a dual fluidised bed gasifier

A dual fluidised bed gasifier is a type of allothermal gasifier with two interconnected fluidised beds: a fluidised bed gasifier, which converts biomass into raw syngas, and a fluidised bed combustor, which generates the necessary heat for the gasification reactions (Fig. 17). The two fluidised beds can be independently controlled, but are typically linked though a non-mechanical valve, which ensures the continuous circulation of the bed material that acts as a heat-carrier between the two fluidised bed reactors [72]. The reactors can be of different types, but a widely used configuration is that the gasifier operates as a bubbling fluidised bed gasifier and the combustor as a circulating fluidised bed combustor [72].

A mixture of residual char, tar and bed material coming from the gasifier enters the fluidised bed combustor, where the residual char and tar are oxidised in the presence of an oxidiser, generating heat and rising the temperature of the bed material. If needed, additional fuel may be incorporated into the fluidised bed combustor to control and maintain the temperature of the reactor [76]. Downstream of the combustor, a cyclone is utilised to separate the heat-carrying material from the flue gases. The heat-carrying material is then returned to the gasifier, while the flue gases are directed towards a heat recovery system. Biomass feedstock is introduced in the gasifier and is heated in contact with the hot bed material and with the gasifying agent, most often preheated steam. The syngas produced by a dual fluidised bed gasifier is characterised by low nitrogen and tar contents, higher hydrogen content and higher heating value [72]. However, dual fluidised bed gasifiers have higher capital and operation costs. The technology is especially interesting for converting biomass into second-generation fuels like Fischer–Tropsch Diesel or substitute natural gas due to the higher heating values and hydrogen contents [77].

Table 4 presents a comparison between the most commonly used biomass gasifiers. Other types of gasifiers were developed, such as entrained-flow reactors, but are not widely used with biomass [78].

Biomass gasification followed by syngas combustion has the potential to generate high-temperature process heat and is demonstrated in several industrial sub-sectors [79]. In comparison to direct combustion, gasification offers benefits such as a shorter response time to variable loads and more precise control over the combustion process [80]. This precision allows for improved temperature control and heat quality, which can be advantageous in specific industrial applications. However, it typically involves higher capital costs [80].

Using gasification for heat generation is generally cheaper than for producing electricity, primarily because the requirements for syngas quality are less stringent. However, utilising biomass gasification exclusively for process heat generation is one of the less economically valuable applications of syngas. As a result, gasification is often employed in combined heat and power applications [73].

Table 4 Comparison between downdraft, updraft and fluidised bed gasification with air as a gasifying agent (based on [71])

	Updraft gasification	Downdraft gasification	Bubbling fluidised bed gasification	Circulating fluidised bed gasification
Typical capacity (MW_e)[a]	<20	<10	10–100	10–100
Flexibility to fuel particle size (mm)	2–50	10–300	<5	<15
Moisture content (%)	<60	<20	<55	<55
Tar levels ($g \cdot Nm^{-3}$)	10–150	0.015–0.3	3–40	4–20
LHV ($MJ \cdot m^{-3}$)	5–6	4–6	4–7	4–6
Carbon conversion efficiency (%)	40–85	<85	70–90	80–90
Cold gas efficiency (%)	20–60	65–90	70–90	50–70
Capital costs	Low	Low	High	High

LHV Lower heating value

[a] Today most syngas is used for combined heat and power generation

Co-combustion

Co-combustion, also known as co-firing, refers to the simultaneous combustion of two or more different types of fuels in the same plant [81]. In the context of bioenergy, it involves combining biomass with another fuel, such as coal or natural gas. Co-combustion of solid biomass with coal is a process mainly used for the production of electricity, which will be addressed in chapter "Biomass for Power Production and Cogeneration". However, it is also used in industrial heating applications (for example, in the cement industry).

Co-combustion with coal has the potential to be implemented in existing coal-fired plants with minimal adjustments, leading to improved environmental outcomes [82, 83]. It is a reliable solution that, compared to using single coal firing, leads to the reduction in net CO_2, SO_x and NO_x emissions [38, 84, 85] and might result in a reduction of costs [84]. In comparison to dedicated biomass plants, co-combustion with coal offers advantages such as reduced costs [83, 85] and improved conversion efficiency [38, 84, 85] without depending on a continuous supply of biomass [84], which might be a limited resource. The technologies used for co-firing biomass with coal in power and CHP plants will be described in chapter "Biomass for Power Production and Cogeneration".

In the specific context of heat only generation, biomass can be favourably co-fired with coal in some high-temperature process heat applications such as in cement kilns, allowing, for example, for the combustion of contaminated waste wood [84, 86]. Major cement manufacturers are already actively incorporating solid biomass and other alternative fuels for co-firing to achieve cost-effective solutions [86]. The temperature requirements in the key energy-intensive processes of this sub-sector often exceed 1000 °C [13], a level that cannot be reached through conventional raw biomass combustion [15]. As a result, adoption of, for example, co-combustion and/or oxygen-enrichment is needed [15]. While recommendations suggest replacing up to 20% of fossil fuels with biomass, higher substitution rates were already successfully achieved [53]. The cement industry does not face significant technical obstacles to integrate higher levels of solid biomass [87]. However, constrains arise from the need for biomass pre-treatment, economic considerations and the local availability of biomass resources [53].

Similar to the challenges faced by the cement industry, the iron and steel sector represents another hard-to-abate industrial sub-sector with the potential to reduce carbon emissions through biomass co-firing. The utilisation of biomass as a renewable energy source in iron and steel making is among the few technically and economically viable options for curbing CO_2 emissions in the short and medium term [88]. For example, in the iron-making process, which typically relies on carbon-containing fuels, biomass can be co-fired with coke and coal in blast furnaces [21]. Wood-based feedstocks are the most suitable biomass types [35, 89], but the use of raw wood is inefficient and it is better to use charcoals, semi-charcoals or torrefied biomass [88]. The injection of biomass in blast furnaces presents, according to Suopajärvi et al. [21], the most substantial potential for biomass to replace fossil fuels within the iron and steel industry. Furthermore, biomass can be integrated into various processes to reduce the reliance on fossil-based reducing agents, such as incorporating biomass into coal blends for cokemaking [21, 88]. However, it is important to note that further research is needed and that presently biomass cannot generally compete with fossil fuels in economic terms [48].

4 Biomass Systems for District Heating

District heating is an efficient energy system, characterised by centralising thermal energy conversion within a facility and then distributing the heat produced to a group of users through a network of underground pipes. Various energy sources, such as natural gas, biomass or waste heat, are utilised to generate the heat in district heating systems. The medium for conveying thermal energy typically consists of hot water, which can be readily transported over considerable distances [88].

By centralising energy conversion, these systems can employ advanced technologies and optimise the combustion process to minimise emissions and enhance energy efficiency [90]. Furthermore, the network design enables waste heat recovery from, for example, CHP plants or industrial processes, making efficient use of heat that might be otherwise lost [91]. This heat recycling can be combined with renewable energies, substituting for fossil fuels and, therefore, minimising the environmental impact of heating.

District heating systems are versatile and can serve a diverse range of users, including residential, commercial and industrial facilities. According to the IEA energy balances, in 2020, industry was the main user for the 15.7 EJ of derived heat supplied worldwide, followed by the residential sector (Fig. 18). China (38%), Russia (33%) and Europe (20%) were responsible for more than 90% of the production of derived heat in the world [1].

Market penetration of district heating systems varies from one country to another. In nations where district heating, regardless of the energy source, is prevalent, it supplies heat to approximately half of the building stocks, driven by strong driving forces [91]. In contrast, in countries with low awareness or competitiveness, the presence of such systems is scarce [91]. Europe is the region where more district heating systems are implemented.

District heating is particularly well suited for the dense urban environment, where a concentrated user base can benefit from the shared energy infrastructure [92]. This centralised approach not only enhances energy efficiency, but also simplifies maintenance and infrastructure management. On the other hand, the economic competitiveness of district heating systems depends on the international fuel prices, concentration of heat demands and energy and environmental policies [91].

The strongest argument for the implementation of district heating systems has been the recuperation of the unavoidable heat losses from thermal power plants through the use of CHP systems, being district heating often associated to CHP plants [91].

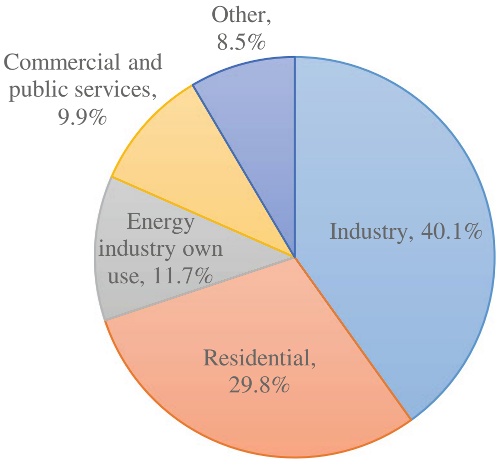

Fig. 18 Share of different users in the derived heat supplied in the world in 2020. (*Data source* [1])

In 2020, 73% of the derived heat supplied worldwide was generated in CHP plants [1].

The potential for integrating renewable energy sources in district heating is large, but, currently, most of the global derived heat generation relies on fossil fuels, especially coal and natural gas (Fig. 19), which are the two dominating energy sources used in CHP plants (*cf.* chapter "Biomass for Power Production and Cogeneration").

Despite the low share of biofuels in district heating worldwide, the supply of bioenergy by district heating is common in some countries [91]. This supply relies predominantly on CHP systems and is mostly located in the European Union [90, 91]. Additionally, biomass heat-only plants also exist, but they are primarily used in small-scale district heating systems [92]. Sweden serves as an exemplary model for a

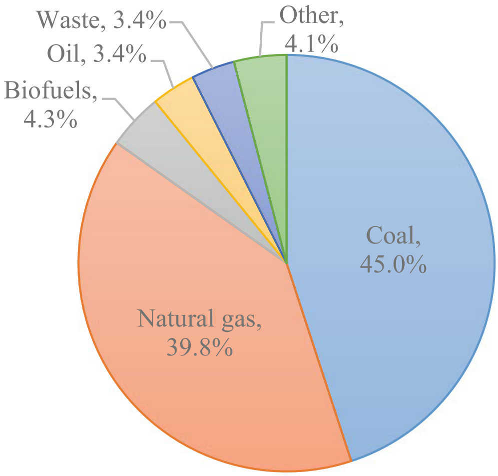

Fig. 19 Share of different energy sources in the derived heat supplied in the world in 2020. (*Data source* [1])

nation with a significant district heating system based on forest biomass. In Sweden, district heating plays a crucial role, providing over half of the heat in the residential sector [92]. As of 2020, biomass accounted for almost half of the supply of derived heat, predominantly produced in CHP plants [1].

The biomass combustion technologies used in district heating systems are similar to those used for indirect heating in industrial applications described above: mostly grate combustion, bubbling fluidised bed combustion and circulating fluidised bed combustion.

5 Final Considerations

The industrial sector, the largest energy consuming end-use sector, accounted for approximately one-third of the world total final energy consumption (around 120 EJ). Moreover, industries also significantly contributed to the global direct greenhouse gas emissions, reflecting the limited adoption of low carbon technologies in the sector. Indeed, industrial energy consumption is dominated by fossil fuels, mainly coal and natural gas. Together, these two fossil fuels represented almost half of the energy sources used by the industry in 2020.

Electricity is another of the significant energy sources in industrial facilities (28.4% of the energy consumption in industry in 2020) and its role has been increasing over time. The use of electricity is a potential indirect way of incorporating renewable energy sources in the industrial sector, but, currently, the global electricity generation is also still heavily reliant on fossil fuels.

In 2020, biofuels and waste represented only 8.4% of the energy consumed by the industrial sector. Despite the low share, the only RES with an expressive direct consumption in the industry is biomass, mostly primary solid biofuels, which represent 93% of industrial biofuel and waste consumption. The other RES like geothermal and solar have almost no expression in the industrial sector, despite showing significant relative growths.

The energy consumption in the industrial sector is highly diverse and complex, varying significantly among different sub-sectors and even within the same sub-sector. In this context, the share of the different energy end-uses (power, heating and cooling) within the industrial sector depends on its composition of production and specific industrial processes. Energy-intensive industry sub-sectors, which account for a substantial share of the world industrial energy consumption and greenhouse gas emissions, typically consume a large share of heat, especially process heat, and fossil fuels. On the other hand, non-energy intensive industries generally consume more electricity. Despite this diversity, globally, heat plays a crucial role in the energy consumed by the industrial sector and the ability to provide process heat in a less carbon-intensive manner is key to decarbonise the world's industry.

The term "process heat" refers to a wide variety of applications, technologies, energy carriers, temperatures and modes of delivering the heat to the materials being processed. Particularly important for the decarbonisation of the industry is the temperature level at which heat is delivered to an industrial process. The demand for process heat at high temperatures (> 500ºC) is substantial and not all technologies and energy carriers are able to provide it. Within the RES, biomass is one of the few renewable energy options for the direct supply of high-temperature heat. On the other hand, for the lower temperature process heat applications, much more technological options are available.

The diversity of industrial processes, energy needs and technology requirements make decarbonising the industrial sector challenging. High-temperature heat, which is essential for many industrial processes, is currently largely supplied by fossil fuels. Additional challenges for the transition to low-carbon technologies within the industrial sector are the long lifetimes of the industrial facilities, high capital costs, global market competition and industry aversion to risk. Bioenergy is one of the potential solutions, but its applicability and adequacy vary depending on the industrial sub-sector and specific context.

Combustion-based process heating systems, used in diverse industrial facilities, generate a large share of the energy consumed in the industrial sector. Most of them are fired by fossil fuels, but biomass is also used. There are two broad categories of systems: direct heating systems, where flue gases are in direct contact with the material being processed, and indirect heating systems, where flue gases transfer heat to a heat transfer fluid, which then supplies heat to the production process. Typically, high-temperature process heat is generated through direct systems. Various types of equipment are in operation, tailored to specific industrial processes, such as furnaces in chemical, non-metallic minerals, iron and steel and other industrial sub-sectors. Most of the direct systems use fossil fuels, although biomass co-firing or 100% biomass firing systems are also deployed in specific industries. On the other hand, for low and medium process temperatures, indirect heating systems are mostly used, often involving steam as the heat transfer medium. Diverse biomass conversion technologies for generating heat at these temperature levels are available and used, with a strong deployment in the forest-based industries due to the availability of secondary woody residues.

Modern industrial energy systems are characterised by automation, advanced process control systems and pollution control mechanisms. They are required to comply with environmental and health standards, and integrate advanced combustion technologies, air pollution control equipment and operational optimisations.

The industrial sector relies on various medium- and large-scale biomass combustion technologies, which vary in size, fuel requirements and performance characteristics. These technologies can be categorised into fixed bed, fluidised bed and pulverised fuel combustion based on flow conditions in the combustion chamber. Fixed bed and fluidised bed combustion are the most used in the industrial sector. Fixed bed combustion, typically used for the lower scales, offers flexibility in terms of fuel type and particle size, while fluidised bed combustion, mostly used for the larger capacities, requires smaller particles. Fixed bed systems generally have lower capital and operational costs but lower efficiencies compared to fluidised bed systems. Biomass pulverised combustion is primarily used in thermal power plants rather than for industrial process heat.

A commercially available alternative to conventional direct combustion involves gasification followed by combustion. In the gasifier, the solid biofuels are converted into a gaseous fuel mixture known as syngas, which is then burned. Syngas offers flexibility and has diverse uses, including the generation of heat or combined heat and power. When high-quality clean gas is required, syngas undergoes treatment to remove tars and particulate matter before combustion. Gasifiers can be categorised as directly heated or indirectly heated. In directly heated gasifiers, heat for the gasification reactions is generated through the partial oxidation of biomass, while indirectly heated gasifiers use the gasifying agent or heat exchangers for heating. The method of heat supply significantly affects syngas quality, with indirectly heated gasifiers typically yielding syngas with a higher heating value. Gasification technologies can also be classified based on their operation principles into fixed bed and fluidised bed gasifiers. Fixed bed gasifiers are the classical and still mostly used technology, being well-suited for small scale heat and/or power generation. For the larger scales, fluidised bed gasifiers are used. While they offer improved efficiency and scalability, they are more complex and costlier compared to fixed-bed systems.

An alternative to 100% biomass-firing is co-combustion, which involves simultaneously burning multiple types of fuels in the same plant. Even though co-combustion of biomass and coal is most commonly used for electricity generation, it also finds applications in industrial heating. Co-combustion can be integrated in existing coal-fired plants with minimal modifications. In heat-only applications, co-firing biomass with coal can be advantageous in high-temperature industrial processes, such as in cement kilns, where temperature requirements exceed what raw biomass combustion can achieve.

Since the combustion technologies employed in district heating systems are similar to those used in industrial applications, this sector is also addressed in this chapter. District heating is an efficient energy system that centralises thermal energy conversion and distributes heat through an underground network to a wide range of users, including residential, commercial and industrial facilities. Centralisation allows for advanced technologies and optimised combustion processes, reducing emissions and improving energy efficiency among other advantages. Despite their potential for renewable energy integration, many district heating systems worldwide still rely on fossil fuels, mainly coal and natural gas, although some countries have successfully implemented biomass-based district heating systems.

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