A review on torrefied biomass pellets as a sustainable alternative to coal in power generation

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Received 8 June 2013; received in revised form 26 April 2014

Abstract

The torrefaction of biomass is a thermochemical process based on the de composition of hemicellulose, which is the dominant reaction, while the cellulose and lignin fractions remain almost unaffected. Torrefaction of biomass improves its physical properties like grindability, particle shape, size, and distribution, pelletability, and composition properties like moisture, carbon and hydrogen contents, and calorific value. The already higher energy density can be increased further by a pelletizing step after torrefaction. These improved properties make torrefied biomass particularly suitable for co-firing in power plants. Co-firing biomass with fossil fuels is one of the solutions to reduce the greenhouse gas emissions of existing power plants. Several studies on torrefaction of biomass for heat and power applications have been documented in the literature, which need to be reviewed and analysed for further actions in the field, because significant gaps remain in the understanding of the biomass torrefaction process, which necessitate further study, mainly concerning the characterization of the torrefaction chemical reactions, investigation of equipment performance and design, and elucidation of supply chain impacts. This is the main objective of the present review study, which consists in three parts. The first part focuses on the mechanism of biomass torrefaction. It is followed by a review of biomass co-firing with coal. Finally, market opportunities for the process are discussed.
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Keywords: Biomass Pellets; Torrefaction; Sustainability; Co-firing; Power Generation

1. Introduction

Biomass as a sustainable energy resource has recently attracted more interest from both political and scientific perspectives. However, these biomass energy resources need special attention and more expensive solutions in terms of storage, handling, milling, and feeding compared to existing systems used for coal [1]. Especially in pulverized firing systems, size reduction of biomass material is much more demanding than for coal due to its fibrous and more tenacious structure. Other challenges with biomass include low energy density and great inhomogeneity of biomass fuels [2]. Torrefaction, also known and described as mild pyrolysis in many recent research studies [3-12], is a thermal conversion technique that allows to improve the energy density of biomass, consisting basically in the heating of biomass to moderate temperatures in the absence of oxygen and under atmospheric pressure. During the treatment, biomass starts to decompose and releases combustible volatile matter, mainly composed by organic compounds, together with moisture. Thereby, the energy density of the torrefied biomass is increased. Moreover, during torrefaction the structure of the biomass is changed, becoming powdery and thus much easier to grind [13]. This effect would lower the energy demand during size reduction of the biomass prior to combustion or pelletizing. Furthermore, if torrefaction is combined with pelletizing, the energy density of biomass fuels increases significantly and thus energy and emission savings could be made in the transport of fuel [14].

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Torrefaction is a thermochemical treatment process that involves heating biomass at temperatures of 200–300 °C in the absence of oxygen, during which the biomass partly decomposes, releasing different types of volatiles [1]. The final product of the process is the remaining solid, which is referred to as torrefied biomass if it is produced from woody biomass [14]. Considerable energy densification can be achieved by torrefaction, as the remaining solid typically contains up to 90% of the initial energy content but only 70% of the initial weight of the biomass feedstock [17].

Biomass is completely dried during torrefaction and its hygroscopic nature changes to hydrophobic [20]. Uptake of moisture after torrefaction is very limited. This implies that biological degradation does not occur anymore. Torrefaction also improves the grindability characteristics of biomass, which can be a great advantage when co-firing with coal in existing coal-fired power stations [21–23]. Indeed, due to the increased calorific value, hydrophobic nature, and better grindability, the properties of torrefied biomass approach those of coal [24].

Torrefied biomass, usually in the form of woodchips, presents a low volumetric density, so densification is usually required to improve transport and storage conditions. Densification is also desirable because it reduces dust formation and increases the mechanical strength of the product [25, 26]. Densification of torrefied biomass may be done through pelletizing [27, 28].

The combination of both torrefaction and pelletizing stages results in the torrefied biomass pellets (TBP's), an energy dense biomass solid fuel with many similar properties to coal, such as high bulk and energy density, high calorific value, hydrophobic nature, and improved grindability compared to untreated biomass. These properties make TBP's an attractive fuel especially for co-firing in coal-fired power stations [29]. Because of these advantages, TBP's are attracting increasing interest.

The review of recent literature about new developments of biomass converting processes suggests that torrefaction is a promising technique to improve the performance of biomass for energy utilization [30-34]. Despite a number of important studies implemented as described above, there still remains a lot of torrefaction information that is not recognized in sufficient detail concerning economic issues of torrefied biomass [35-39]. Several studies have been documented and substantial amounts of data are available in the literature and need to be reviewed for further actions in this field, being this the main objective of the present study, which aims to significantly contribute by analysing and gathering some of the most recent studies of biomass torrefaction, with emphasis on the mechanism of biomass torrefaction process applied to the particular case of co-firing with coal, and also about market opportunities and developments.

2. Torrefaction Process

2.1. Raw materials

In theory and as stated in the studies previously referred, all lignocellulose biomass can be torrefied. In recent years, torrefaction of lignocellulose biomass has attracted more interest in research resulting from its potential applications. In order to recognize the role played by torrefaction in improving the properties of biomass, a number of studies have been implemented [40-41]. However, there are technological limitations on the allowable variation in feedstock properties. This implies that if a torrefaction plant is based on only one type of feedstock, its design can be specific. The type of biomass used has an impact on the mass and energy yield of torrefaction [42].

Woodchips are currently used in energy production, but through torrefaction and pelletizing, the properties of the fuel can be enhanced and a significant energy densification is achieved [43, 44]. The main source of forest woodchips used in energy production is currently forestry waste [45–47] produced by chipping or crushing of woody material. The particle size of chips varies between 3 and 50 mm, depending on the raw material and the chipper [48].

The moisture content of woodchips is between 30 and 60%. The moisture content depends on the source of the woodchips and especially on the length of time for which the biomass has been left to dry on the harvesting site before chipping [49].

The energy content of woodchips depends on the moisture content: the higher the moisture content, the lower the lower heating value (LHV) which indicates how much energy can be obtained from the fuel upon combustion [50]. The bulk density of woodchips also depends on their moisture content: the higher the moisture content, the higher the bulk density [51]. Typical ranges for the moisture content, energy content, bulk density, and energy density of woodchips are presented in Table 1.

See Table 1 at the end of the manuscript.

Although the potential of wood energy harvested is rather high, not all of this biomass energy is available at reasonable costs [52]. The greater the demand for woodchips, the higher the production costs tend to become, because the location of wood harvesting has to be extended further from the end user and to less favourable places [53].

2.2. Torrefaction and pelletizing

Torrefaction is a thermal pre-treatment method that improves the fuel properties of biomass and makes it more suitable for co-firing with coal. When combined with pelletizing, torrefaction results in energy-dense pellets with a high calorific value and other properties such as a hydrophobic nature and improved grindability characteristics compared to untreated biomass [54]. The torrefaction and pelletizing process consists of five steps: drying, torrefaction, grinding, pelletizing, and cooling as schematically described on Fig. 1 [55–57].

See Fig. 1 at the end of the manuscript.

Drying is usually necessary for feedstocks with high moisture content in order to lower the moisture content of the feedstock to around 20% before it is fed into the torrefaction reactor [58], as shown in Fig. 2. Among all process steps, drying has the largest heat demand, unless the initial moisture content of the feedstock is low [59].

See Fig. 2 at the end of the manuscript.

Next steps occur in the absence of oxygen, where the biomass is heated to the desired process temperature. During this phase, physically bound water is released and the biomass is completely dried [60].

The torrefaction process begins when the temperature reaches 200 °C. During torrefaction the biomass partly decomposes, releasing several types of volatile compounds. It loses relatively more oxygen and hydrogen compared to carbon, which leads to an increase in calorific value on a mass basis [61]. The remaining torrefied biomass, as shown in Fig. 3, contains 90% of the initial energy content but only about 70% of its initial mass [62].

See Fig. 3 at the end of the manuscript.

Although torrefaction leads to a higher calorific value on a mass basis, it does not increase the volumetric energy density of the biomass much. Pelletizing significantly increases the volumetric energy density of the torrefied biomass, facilitating transport and storage, leading to savings in logistics [63].

Pelletizing also reduces dust formation and increases the durability of the product [64]. After pelletizing, TBP's are cooled and stored (Fig.4).

See Fig. 4 at the end of the manuscript.

The heat demand of the drying and torrefaction processes can be met, at least partially, through combustion of the released torrefaction gas. Torrefaction gases consist of organic compounds, water, CO, and CO_2. If the energy content of torrefaction gas is sufficient to balance the heat duty of drying and torrefaction, the process is self-supported. If self-supporting operation is not possible, a thermal energy utility is needed to produce the rest of the heat required by the process [65].

A thermal energy utility is also needed when pre-drying of wet biomass is necessary. However, even in cases where auxiliary energy is needed to thermally balance the whole process, torrefaction gases satisfy a major part of the total heat requirement [64]. The opportunity to utilize torrefaction gases for heating the process reduces the energy utility consumption of the process and leads to high process efficiency [67].

Electric power is needed to size reduction and pelletizing stages, so the energy demand of these process steps cannot be met through combustion of torrefaction gas. However, power consumption for size reduction is reduced when the biomass is torrefied first compared to size reduction of untreated biomass. This reduction in power consumption can be as high as 80% [68].

2.3. Fuel properties

The disadvantages of biomass as a sustainable alternative fuel to coal and other fossil fuels are mainly attributed to its low energy density, high moisture content, and heterogeneity [69]. Low energy density implies that transportation costs per energy unit are higher and that more storage space is needed, making biomass logistics expensive. High moisture content decreases the calorific value of biomass and thus the amount of energy that can be obtained from it upon combustion. The wetter the biomass is, the lower its calorific value and fuel quality are, and the combustion of such fuels affects power plant efficiency adversely [70]. The heterogeneity of biomass can also cause problems in the final conversion stage.

Wood pellets are often seen as a solution to some of the major disadvantages of using biomass as a sustainable alternative fuel [71]. Wood pellets have a higher energy density, higher calorific value, and lower moisture content than woodchips or untreated biomass. Like TBP's, they are also uniform in size and more homogenous regarding fuel quality. Wood pellets are made up of small particles, and, unlike biomass of larger particle size, can be readily crushed in coal mills, resulting in particles that can be fed into pulverized-fuel burners just like coal powder [72].

However, there are also some disadvantages to wood pellets. Despite their lower moisture content, wood pellets retain the hygroscopic nature of wood and remain vulnerable to water, although to a lesser extent than chips and other untreated biomass. The possibility of biological degradation can cause storage problems and implies that special precautions need to be taken in the logistics chain in general. Another disadvantage is that pellets production has traditionally been limited to only a few types of feedstocks, mainly sawdust, shavings, and bark, which are by-products of the wood processing industry, although lower-quality industrial pellets that are suitable for large-scale use can also be made from woodchips and other types of wet biomass [73].

The potential feedstock for TBP's (Fig. 5) is larger than for wood pellets, and does not rely as heavily on the wood processing industry [74].

See Fig. 5 at the end of the manuscript.

Concerning biomass, one of the greatest disadvantages of both woodchips and wood pellets is that their share in the fuel mix when co-firing with coal remains small—up to around 10–15% of the fuel mix—unless substantial modifications are made to the existing coal infrastructure [75]. For TBP's, the co-firing ratio could be as high as 50%. If wood pellets are to be co-fired in coal power plants, substantial modifications have to be carried out, such as creating storage facilities and separate transport, milling, and feeding systems, and these would be very expensive [76]. But, such modifications might not be necessary for TBP's, which can, at least in theory, be stored on the coal yard and milled and fed in together with the coal [77].

Being able to use existing coal infrastructure for TBP's would be ideal, as it would allow a larger biofuel share to be reached at low additional costs. Even though the on-site handling properties of TBP's seem promising, more experience of how co-milling TBP's affects the coal mill and of the storage behaviour of TBP's is still needed to fully back up these assumptions. But, even if TBP's required the same technology that is used for co-firing conventional pellets at higher ratios, the additional investments and operational costs would be roughly 30% smaller due to the lower volumes required for the same thermal capacity [78].

Table 2 compares the properties of woodchips, conventional wood pellets, torrefied biomass, TBP's, and bituminous coal. As shown, TBP's are a superior fuel compared to woodchips and wood pellets with regard to calorific value, energy density, moisture content, and degradability. TBP's properties approach those of bituminous coal [79–81].

See Table 2 at the end of the manuscript.

Combined torrefaction and pelletizing produces an energy-dense biomass fuel with properties similar to those of bituminous coal. The high calorific value and high energy and bulk densities of TBP's may lead to significant cost savings in the biomass-to-energy chain when compared to state-of-the-art biofuel chains, especially in logistics [82], because the higher the energy density of a fuel is, the more energy a truck, train, or ship carrying that fuel can transport. At the same time less storage space is required, also leading to cost savings. A high energy density also brings other benefits, such as improving the functionality and decreasing the energy use of conveyors and mills at the power plant [83].

In addition to the possible savings in logistics that can be achieved when switching from untreated biomass or conventional pellets to TBP's, higher grindability is one of the key properties that make torrefied biomass and TBP's so attractive for co-firing in existing coal-fired power plants [85].

The low moisture content of TBP's facilitates storage, allowing longer storage periods than those of woodchips or wood pellets, for example, and is also expected to lead to reduced stack losses and a higher power plant efficiency compared to conventional co-firing [86].

Despite their many good fuel properties, TBP's are still a new fuel, and, unlike the case of woodchips and wood pellets, there is not yet much experience of their large-scale handling and use [86].

3. Biomass co-firing with coal

Coal is a complex polymer consisting primarily of carbon, hydrogen, oxygen, nitrogen and sulfur. It is a compact, aged form of biomass containing combustibles, moisture, intrinsic mineral matter (originating from dissolved salts in water) and extrinsic ash (due to mixing with soil) [87].

Co-firing is the simultaneous use of two or more fuels in the same furnace [88]. Co-firing biomass with fossil fuels is one of the solutions to reduce the greenhouse gas emissions of existing power plants.

There are several coal combustion technologies. One common technology is pulverized coal combustion, which is in use in several coal-fired power plants, mainly in Europe and the USA [89].

In pulverized coal boilers, the coal is first ground into fine powder in coal mills. A mixture of air and pulverized coal is then blown into the burners at the bottom of the boiler. Combustion generates thermal energy which turns water into steam. The enthalpy of the steam is then converted into mechanical energy of the turbine which turns the power generator [90]. Knowing that combustion of solid fuels in pulverized coal burners requires the fuel to be ground into very fine particles, it is easy to understand why good grindability is a desirable property for a solid fuel that is co-fired with coal.

Biomass can be co-fired with coal either directly or indirectly. Direct co-firing involves direct feeding of biomass into the coal firing system whereas indirect co-firing involves gasification of the biomass and then combustion of the product fuel gas in the boiler [91].

The simplest option for direct co-firing is to mix the biomass fuel with coal before the fuel enters the coal feeders. The mixed fuel is then processed through the coal milling and feeding system. This approach has been applied when co-firing biomass is in granular, pelletized, or dust form. Co-firing ratios have generally remained relatively low [92].This simple and less costly form of direct co-firing could be applied to TBP's as well, but at a relatively high co-firing ratio like 50% [93]. Design values of the furnace have an impact on the maximum amount of coal that can be replaced with TBP's or other biofuels without major decreases in plant efficiency [94].

The biomass fuel can also be handled separately from the coal and injected into the pulverized fuel pipework upstream or at the burners. This option can allow for higher shares of the biomass fuel in the fuel mix, but also requires some modifications to the system and increases costs when applied in existing coal power stations [95].

The most expensive option for direct biomass co-firing involves separate handling of the biomass but also combustion through a number of dedicated burners. This approach would require significant modifications to the combustion equipment and furnace [96,97].

4. Market situation

The demand for biomass-derived fuels is growing globally because the large majority of the developed and in development countries try to find ways to decrease greenhouse gas emissions and reduce fossil fuel dependency for one side, and because also are trying to reduce their foreign dependency concerning energy supply. However, apart being majorly an endogenous resource, biomass can become more expensive than coal if it has to be transported long distances. Because of these economics, co-firing at some power utilities is unfeasible. Comparing fuel costs and quantities of biomass required to co-fire, another major market can be identified, that is, the market that has smaller scale boilers that pay more for their fuel than a large scale utility. An example of this medium size usage is its combustion in steam boilers located in industrial units [98,99]. The size of the unit may permit the usage of biomass due to its location within a reasonable transportation distance along with the cost of the current boiler fuel, thus allowing more to be spent on obtaining and transporting the biomass [97].

Torrefaction is a technology that has only recently begun to become commercially available. It is not yet applied on a large scale, although there are several demonstration plants in operation and commercial production is also starting with several full-scale torrefaction plants being built or planned in Europe and the USA [100].

When TBP's become commercially available, there will be potential for high demand because of their attractive fuel properties, especially if test results of their large-scale use are positive [101].

The torrefaction step represents an additional unit operation in the biomass utilization chain. The attendant capital and operating costs as well as conversion losses are, however, offset by savings elsewhere. The advantages of torrefaction are particularly pronounced for three applications at present, namely entrained flow gasification, small-scale combustion using pellets, and co-firing in pulverized coal-fired power stations [103].

Combustion in coal-fired power stations is a particularly interesting product outlet for biomass. In this application, biomass has to be fed to the reactor as a powder, which is difficult, costly, and achievable only at very low capacity in classical coal-mills [103]. Due to this limitation, wood pellets are currently the state of the art for co-firing, as they consist of sufficiently small particles [104].

The economic evaluation of co-firing coal with biomass is complex. The evaluation must include several components. The price of the biomass fuel is frequently a very important, if not the most important, determinant of a plant's economic viability, particularly if high percentages of biomass fuel are used. Biomass fuel prices can be either positive or negative within an extremely broad price range.

Operating and maintenance costs are dependent on the technology used to store, process and burn the fuels and the potential impact of fuel characteristics on plant performance, including efficiency. The latter cost projection can be complicated by the variable nature of some waste fuels [106-108].

Consequently, wood pellets also have some limitations in terms of energy content and moisture uptake during storage and transportation. Torrefied biomass, being energy dense and hydrophobic in nature, can be a good replacement for wood pellets in co-firing plants. The high fuel quality of torrefied biomass makes it very attractive for combustion applications [109].

It is difficult to predict what the future market price for TBP's will be, because a market for them does not yet exist [110]. Several authors have calculated an indicative price estimate of 30 to 40 €/MWh, but note that there is still considerable uncertainty related to the price level. The torrefied pellet price is commonly expected to be close to the price of conventional pellets on a per-megawatt-hour basis [111,112].

5. Conclusions

Interest in biomass torrefaction has grown significantly in recent years, as has knowledge of its processes and properties. The process of torrefaction is dominated by the thermal breakdown of hemicellulose to a combination of gases, condensable liquids, and solid components that, together with the cellulose and lignin present in the raw material, comprise a product suitable for utilization as fuel. Torrefied products can substitute charcoal in a number of applications such as fuel for domestic cooking stoves, residential heating, manufacture of improved solid fuel products such as fuel pellets, compacted fireplace logs and barbecue briquettes for commercial and domestic uses.

Important advantage of torrefied wood compared to untreated wood is its uniformity. Torrefaction has the potential to become an important biomass pre-treatment technology which can improve the biomass to a high quality solid fuel with good characteristics in terms of energy density, homogeneity, grindability, and hydrophobic behaviour. The main advantage of torrefaction is the improvement of energy density and grindability.

Torrefied biomass most likely requires densification if it is to be handled successfully in a bioenergy supply chain. Characteristics such as pelletizing, biological degradation, and dust forming of the solid biomass need more attention.

Due to the low moisture content of torrefied wood the transport cost is lower and the quality as a fuel better. It is easily packaged and transported, and thus constitutes an efficient fuel. The properties of torrefied biomass should lead to an improved operation in gasifiers for which the stability of the process is important. However, the production of TBP's appears to be a significant technological challenge at this point.

Torrefied biomass can be also used as fuel for industrial applications. With a 30-35% fixed carbon content, torrefied wood has a promising potential as a reducer. The process of torrefaction moves the chemical and physical properties of raw biomass close to those of bituminous coal, which allows co-utilization with high substitution ratios of biomass in the existing coal-fired boilers without major modifications.

Nowadays available torrefaction technologies are basically designed and tested for biomass, so further research is required, especially on reaction kinetics, to obtain the data needed for reactor design at large scale, because several gaps still exist in the understanding of torrefaction. Research about product characteristics is also recommended in order to better understand co-firing with coal, and there is a need for continued work to optimize this option.

Acknowledgements

The authors would like to acknowledge Topell Energy BV for sharing photographs. This work was supported by FEDER funds (European Union) through COMPETE and by Portuguese funds through FCT, under Projects FCOMP-01-0124-FEDER-020282 (Ref. PTDC/EEA-EEL/118519/2010) and PEst-OE/EEI/LA0021/2013. Also, the research leading to these results has received funding from the EU Seventh Framework Programme FP7/2007-2013 under grant agreement no. 309048.

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Figure

Figure captions

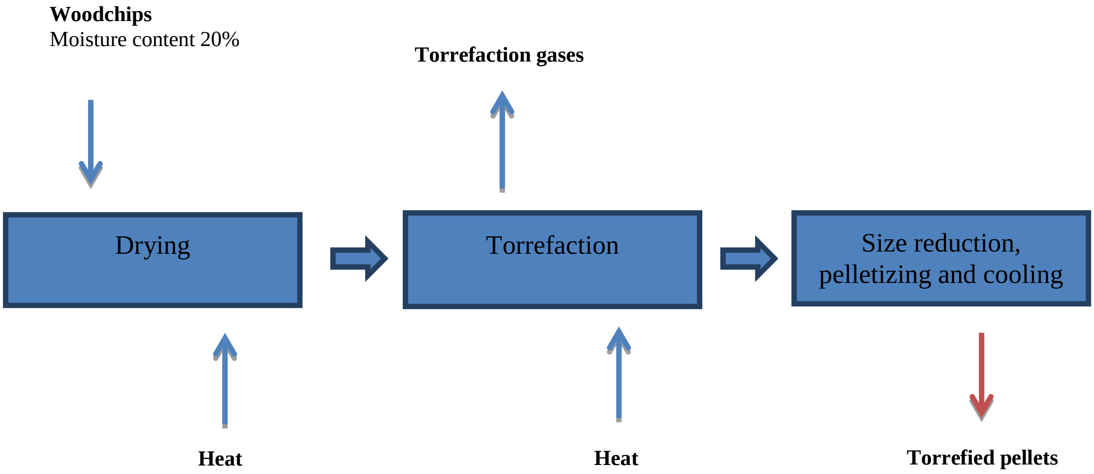

Fig. 1. The combined torrefaction and pelletizing process (adapted from [22]).

Figure

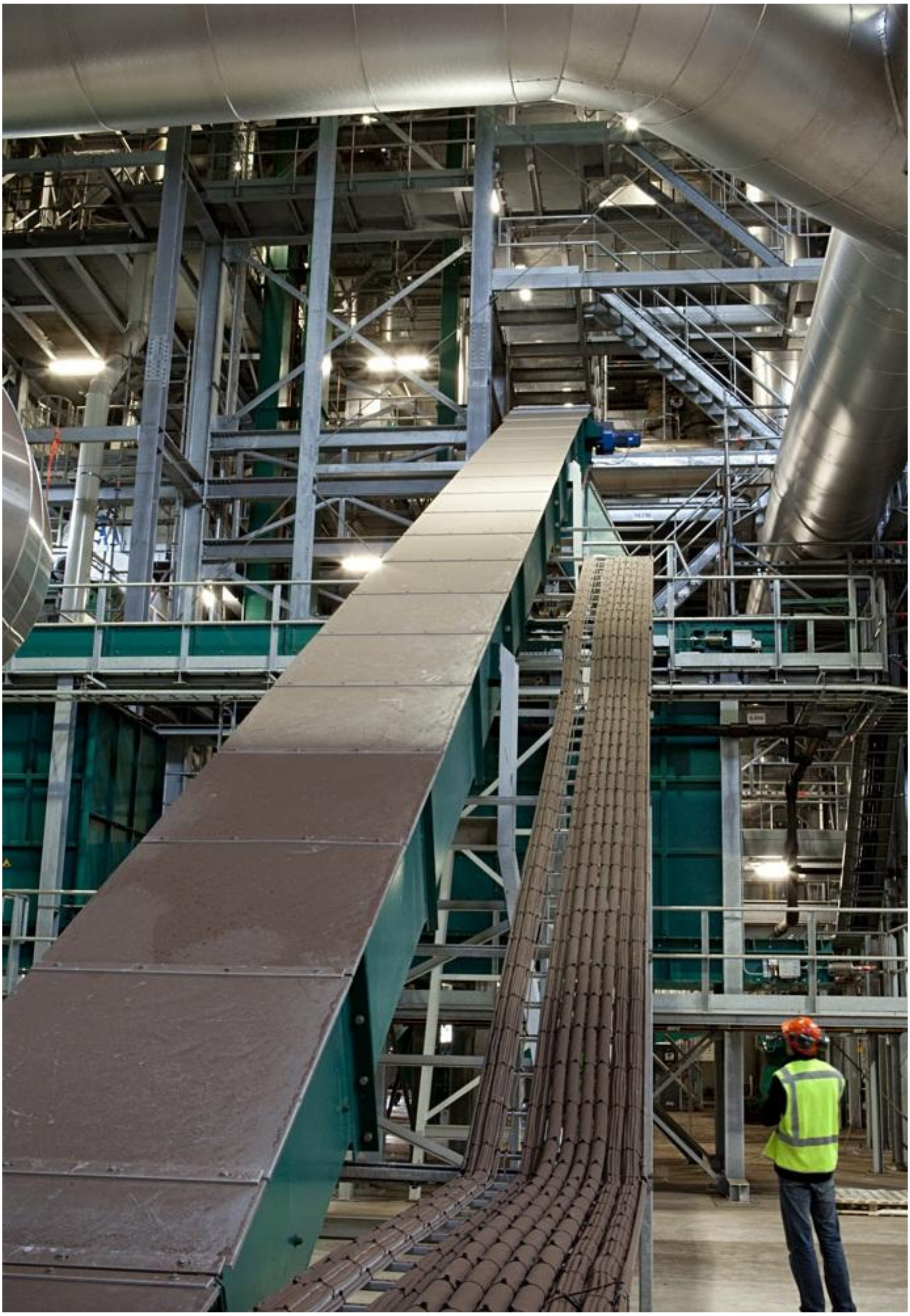

Fig. 2. Biomass feeding system to the torrefaction reactor (courtesy of Topell Energy BV).

Figure

Fig. 3. Torrefied biomass chips.

Figure

Fig. 4. TBP-production storage silo and cooling (courtesy of Topell Energy BV).

Figure

Fig. 5. Torrefied biomass pellets.

Tables

Table 1

Properties of woodchips [19].

	Moisture content % wt	Mass density kg/m^3	LHV MJ/kg	Calorific value MWh/t	Energy density MWh/m^3
Woodchips	30–60	250–400	6–13	1.7–3.6	0.7–0.9

Table

Table 2

Fuel properties of woodchips, wood pellets, torrefied biomass, TBPs, and bituminous coal.

	Wood chips	Wood pellets	Torrefied biomass	TBPs	Bituminous coal
Moisture content % wt	30–60	7–10	3	1 – 5	5–10
Mass density kg/m^3	250–400	600–650	230	750–850	800–1000
LHV MJ/kg	6–13	16.2	19.9	19–22	> 25
Calorific value MWh/t	1.7–3.6	4.5	5.5	5.2–6.2	7
Energy density MWh/m^3	0.7–0.9	3	1.3	4.2 – 5	5.6–7
Hygroscopic nature	hygroscopic	hygroscopic	hydrophobic	hydrophobic	hydrophobic
Biological degradation	yes	yes	no	no	no