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Commoditization of biomass: dry torrefaction and pelletization—a review

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Abstract

Biomass is one of few renewable energy sources that is not intermittent and may be used in the same way as fossil fuels. There are some important constraints, imposed by the nature of biomass, that do not allow it to become a tradable commodity in the same way as solid fossil fuel. Torrefaction is a thermal process that is used to upgrade raw biomass into solid biofuel, more uniform with respect to its properties. Properties are changed in a way that makes torrefied fuel resemble coal more closely. That opens up some new opportunities in terms of use of biomass in furnaces designed for coal, without necessitating major changes to the installation. Biomass pre-treated this way is more suitable for co-burning with coal. Pelletization is a densification process that allows the specific energy density of biomass to be increased. The process makes biomass more uniform in size. This is beneficial with respect to transport cost, other handling operations (loading, unloading, feeding) and storage. This article gives an overview of dry torrefaction technologies, changes in fuel properties due to torrefaction and possibilities of combining torrefaction with pelletizing. Everything is analyzed in the context of a single goal—increasing the use of biomass by making it a commodity fuel.

Keywords: Commoditization of biomass, Torrefaction, Pelletization

1. Biomass as a fuel

Biomass is an energy source that is considered neutral in terms of CO_2 emissions [1]. That statement is based on a simplification. Carbon dioxide is always released as a product of combustion when carbon is burned. However, biomass absorbs carbon bound in CO_2 particles during photosynthesis. Carbon along with oxygen and hydrogen is one of the three main elements present in biomass, namely in three main carbohydrate compounds (cellulose, hemicelluloses and lignin) that form the orthotropic, composite organic structure of plants.

It is important to state that the carbon neutral assumption above is only valid when biomass is harvested in a sustainable manner. In practice, it means that annual biomass growth surpasses annual harvest. There is a dire need for careful assessment, since biomass is always an integral part of complicated ecosystems [2]. Some find it tempting to simply leave biomass in situ and use it as a carbon sink. Nevertheless, some facts make harvesting a better option. In many cases harvesting forms an important part of management systems that enhance biomass growth [2] and therefore CO_2 absorption. For ex-

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Email addresses: `krzysztof.moscicki@pwr.edu.pl` (Krzysztof Jerzy Mościcki[*]), `lukasz.niedzwiecki@10g.pl` (Łukasz Niedźwiecki), `P.Owczarek@utwente.nl` (Paweł Owczarek), `mateusz.wnukowski@pwr.edu.pl` (Mateusz Wnukowski) ample growth is much more vigorous in terms of young trees than old ones, which imposes a cap on unmanaged forests. After reaching this cap the forest reaches saturation point and is no longer able to act as a carbon sink [3, 4]. There is also an increased risk of a wildfire in unmanaged or poorly managed forest [5].

The natural origin of biomass poses many difficulties with its use as a fuel. Biomass varies vastly with respect to its structure and relative quantities of constituents (cellulose, hemicellulose, lignin and extractives) and elements. As regards energy conversion and logistics this creates problems.

Two main types of biomass that may serve of potential use as fuel are woody biomass and herbaceous biomass. Woody biomass is often called lingocellulosic biomass, because trees typically contain quite significant amounts of lignin. Herbaceous biomass consists mainly of hemicellulose and cellulose and contains only minimal lignin. It is mostly represented by perennial plants, which in many cases are grown as crops. Both woody and herbaceous biomass may be grown exclusively as fuel or for other purposes (construction materials; raw material for furniture, paper or clothing, food, etc.). The latter seems to be wiser since it lets biomass avoid competition for suitable land. It may also improve economics both for the main product and for biomass, which is a residue in that case and delivers additional revenue instead of being an unwanted burden. Some caution is necessary in that case since a part of the biomass has to be left in situ (one way or another) in order to maintain nutrients and organic matter in the soil. Both in terms of agriculture and forestry there are management practices that allow both goals to be achieved simultaneously [2].

The first problem related to biomass logistics that reveals itself at the very beginning of the biofuel supply chain is the low specific energy density of biomass compared to fossil fuels, both with respect to mass (MJ/kg) and volume (MJ/m^3). A similar situation occurs with bulk density (kg/m^3). This makes transportation of biomass much more expensive, as more container volume is required to transport an equivalent amount of energy. This obstacle may be overridden by using biomass produced locally, but local demand and supply often do not match up.

Water content is an unnecessary weight in terms of biofuel logistics and is undesirable when it comes to combustion, since it takes significant amount of energy to evaporate water.

Another negative feature of biomass on the general economics is its inhomogeneity in terms of properties. That requires dedicated designs of energy conversion devices (boilers, gasifiers, etc.) that vary depending on properties of the biomass used. It lacks the benefits of mass-produced devices and economies of scale (since it is used locally). It also introduces an additional risk in terms of fuel availability due to seasonal unavailability and might introduce various technical problems and lower the performance of the device.

Although most of the installations that convert the chemical energy bound in fossil fuels utilize same conversion route (mostly combustion coupled with Rankine cycle), it is not straightforward to change fuel, as there are some significant differences between fossil fuels and biomass. In most cases retrofitting is required prior to the use of biomass in a dedicated fossil fuel installation. Biomass may partly replace coal in installations that co-burn those two solid fuels. Amounts of biomass reaching a couple of percent (by mass) may be co-fired without any significant changes in combustion system and auxiliary devices [6].

A major problem especially related to the combustion of herbaceous biomass is high alkali (K, Na) and chlorine content. Due to their relatively low evaporation temperature compounds of these elements may evaporate in the combustion chamber and later condense on the superheater tubes, triggering problems with fouling and high temperature corrosion.

Fouling is caused by deposits of the previously mentioned compounds, unburned char and ash that stick to the molten deposits and make it grow by volume. It causes problems with heat exchange and flue gas flow within the heat exchanger area.

High temperature corrosion is a problem of a chemical nature and works in between the tube surface and the deposit. It weakens the alloys the tubes are made of, which is dangerous for pressurized devices and shortens the lifetime of the device.

Lastly, there is a problem related to the grinding of solid biofuel. This problem is technology dependent and important in terms of technologies that require fuel to be delivered into the reactor in pulverized form, such as pulverized fuel boilers, or some gasification and pyrolysis technologies. Smaller particles mean there is a greater surface area available for reactions between solids and gases. With a particle size increase reactions become heat transfer dependent and mass transfer dependent, which makes them go slower compared to reactions driven by chemical kinetics.

Although this problem might be solved by the use of another technology, it is still beneficial in some cases to use Pulverized Coal boiler technology, because of the relatively small heat inertia that makes it especially suitable for use, for example, as a spinning reserve. This could become increasingly useful in light of the growing amounts of intermittent renewable energy sources (namely wind and solar) being connected to the grid.

Combustion and co-firing in PC boilers in many aspects is very size dependent. Particle size affects parameters such as combustion efficiency (the furnace is always designed for a certain retention time of the particles in the reaction zone), amount of unburned carbon in the ash and the stability of combustion [7]. Higher volatile content in combination with higher oxygen content makes biomass more reactive, which in turn makes less demanding requirements in terms of comminution. The literature mentions that biomass burners require particle size of approximately 1000 μm, while coal is usually ground below 100 μm [8]. The Hardgrove test, which is a standard test for determining the grinding properties of coal, is based on the amount of particles (after grinding) smaller than 75 μm [7, 9]. Despite the fact that the required particle size is one order of magnitude bigger, according to the literature comminution requires energy of between 20 and 150 kWh/t for biomass [8] (depending on biomass size). For coal, typical values range between 7 and 36 kWh/t [8, 10]. It is even more energy consuming when comminution energy is compared with respect to the same mechanism. In the case of ball mills it is compaction and friction [11]. For that case, the literature states 1,900 kWh/t for fine grinding with an attrition mill (with d_{50} of approx. 105 μm) [10]. This is the main reason why old co-combustion installations, without separate grinding devices for biomass, were only able to achieve a small share of biomass. In terms of gasification and pyrolysis based on pulverized technologies, 200 μm is reported to be a proper particle size (kinetically controlled reaction) [10]. Since biomass grindability can be derived directly from plant morphology [11], it seems reasonable to assume that both the energy consumption and additional investment cost required for biomass dedicated auxiliary devices might be reduced substantially when proper pretreatment technology is introduced.

2. Pelletization

Pelletizing is well-established technology for the densification of many different materials that are originally in a loose form. Loose material gains in density and becomes more uniform in terms of shape. That makes it easier to handle and enables much more efficient loading and unloading operations. It is necessary for example to pelletize iron ore prior to feeding to a blast furnace [12], despite the fact that pelletizing itself does not significantly increase the bulk density of the ore.

Pelletizing is widely used in the food processing industry. Pelletized products include animal feed for various species and animal bedding [13, 14]. The latter is especially attractive, because it enables full automation in animal breeding [15]. Since densification and material handling are key issues in solid biofuels logistics, pelletizing seems an obvious solution for these problems.

Densification during pelletizing is performed mechanically by applying high pressure and squeezing material through die. Biomass has to be dried and ground prior to pelletization. This process typically requires feedstock particle size within an order of magnitude of 1 mm and moisture content of between 10 and 15% (for some designs 20% moisture content is reported) [16]. At the beginning feedstock is heated up to 50–100°C both for drying and softening of the lignin, afterwards mechanical densification is applied at approximately 150°C [16].

Moisture content plays an important role in densification. If feedstock is either too dry or too wet, then the pressure required for densification is substantially higher [16]. Further on pellets are subject to cooling and screening. Undersized material is usually re-circulated at the beginning of the process line. Good quality product is stored in an intermediate storage silo.

Presently there are two dominating technologies, namely the ring die and the flat die pellet press. The principle is the same, since it is based on pushing portions of feedstock material through openings inside the die. Only shape of the die is different. The energy consumption of the pelletizing press is usually 50 to 60 kWh/t of product [17].

As regards solid biofuels, pelletizing is a fully mature technology with developed technical standards for the products [18]. Developing a standard most likely helped this technology become incorporated into existing fuel supply chains. According to the body responsible for standards in Europe (CEN—Fr. Comite Europeen de Normalisation) a standard is a document, designed for common and repeated use, to be used as a guideline or definition. It is both consensus-built and approved by a recognized body [19]. Standards are voluntary, consensus-based and bring together all interested parties such as manufacturers, consumers and regulatory bodies. Although a standard as such does not impose any regulations, particular regulations may refer to related standards.

The European Committee for Standardization (CEN), under committee TC 335 published 27 technical specifications (pre-standards) for solid biofuel during 2003–2006. These technical specifications were later upgraded to full European standards. These standards handle among others classification and specification (EN 14961) and quality assurance for solid biofuels (EN 15234). Both are multipart standards. Part 1 of EN 14961 includes all solid biofuels and is targeted at all user groups and will be most likely used by industry. Working group 2 of CEN/TC (Technical Committee) 335 is currently developing two separate parts for wood pellets. EN 14961-2 is a standard for wood pellets for non-industrial use. EN 14961-6 is a standard for non-woody pellets for non-industrial use. Both standards for non-industrial use aim to standardize pellets for small appliances such as are used in households, small commercial and public sector buildings.

All methods to test fuel properties stated in these standards also have standards of their own. For example EN 15210-1 is a standard for determination of the mechanical durability of pellets, EN 15150 describes the method for determination of particle density, EN 14775 sets a standard method for determination of ash content, etc.

All the efforts made towards commoditization of biomass through pelletization seem to have brought success. According to Eurostat [20] the production of wood pellets in EU-27 countries rose from 7.9 million metric tons in 2010 to 10.5 million tons in 2012. Pellets seem to be a viable form for long distance transport, since the import of wood pellets into Europe nearly doubled from 2.6 million tons in 2010 to 4.5 million tons in 2012.

The fact that standards require a statement of origin of upgraded biomass makes it traceable. This as a consequence enables proper certification and ensures overall sustainability of the supply chain.

3. Torrefaction

3.1. General description

Torrefaction is proposed as the next milestone on the way of turning biomass into a commodity. In the torrefaction process (sometimes called roasting, slow or mild pyrolysis [21]) biomass is heated up to approximately 200–350°C. Depending on the severity of the process fibrous, tenacious and hydrophilic biomass is being transformed to more hydrophobic material, which is also more brittle and contains less volatiles. Generally speaking, it resembles coal much more than biomass.

During the torrefaction process feedstock material is heated up, dried and then kept for some time in an inert gas atmosphere that eliminates the possibility of combustion. During the residence time inside the reactor devolatization process occurs and the feedstock becomes subject to decomposition.

Most of the process product is solid, but some of it is gaseous and some liquid (condensable volatiles [21]). Process gas (called torgas) is usually recycled in order to maximize process efficiency. In many cases the torgas itself is not sufficient and a part of the feedstock has to be burned to obtain the necessary amount of heat. Among condensable volatiles acetic acid and water are dominant [21]. Non-condensable volatiles consist mainly of carbon dioxide and carbon monoxide [21, 22].

Initial moisture of the biomass is the main issue in terms of process efficiency. Water is driven off by drying at approx. 100°C and further heating removes water bound chemically due to thermo-condensation reactions that typically occur at temperatures over 160°C [21].

Another important parameter in terms of efficiency is the heat of reaction. The literature is not clear on the values of this parameter and it is not even clear whether the reaction is endothermic or exothermic neither for torrefaction of biomass nor for pyrolysis of its main constituents (cellulose, hemicelluloses and lignin) [21]. Reported values for cellulose vary between -510 (exothermic) and 120 (endothermic) kJ/kg. For hemicellulose it is between -363 and 42 kJ/kg and for lignin the values vary between -455 and 79 kJ/kg [21]. For torrefaction the reported heat of reaction varies widely between -1200 and 1500 kJ/kg [21]. Reported values are not sizeable and there is a certain amount of heat necessary to heat up the feedstock and start the reaction.

The typical quantitative description of the process is usually given as the mass yield (1) and energy yield (2) [22, 23]. These coefficients take into account both mass loss and energy densification of a torrefied material.

$$Y_{mass} = \frac{m_{product}}{m_{feed}} \cdot 100 \qquad (1)$$

where: Y_{mass}—is mass yield, %; m_{feed}—is dry ash free mass of feedstock, kg; $m_{product}$—is dry ash free mass of output material, kg.

$$Y_{energy} = Y_{mass} \cdot \frac{HHV_{product}}{HHV_{feed}} \cdot 100 \qquad (2)$$

where: Y_{energy}—is energy yield, %, HHV_{feed}—higher heating value of feedstock material, kg; $HHV_{product}$—higher heating value of output material, kg.

Regardless of the possibility of achieving some gains, if the reaction is exothermic, the temperature of the performed reaction introduces a substantial heat loss (due to the temperature difference between the reactor and the ambient air). Therefore optimizing the reactor might not necessarily mean maximizing retention time inside the reaction. Overly long retention time for the feedstock would also mean a substantial decrease in product output (smaller amount of processed feedstock per annum). This would lead to an increased capital cost per ton of the product.

3.2. Review of different torrefaction technologies

At present torrefaction is a widely discussed technology, due to its potential to enable the use of additional biomass resources and make it a tradable commodity [24]. There are many different designs of torrefaction reactors existing and many companies are involved in the development of this technology.

3.2.1. Rotating drum reactor

The rotating drum reactor is a well-known and proven technology. It has been widely used for cement kilns. It has a small market share in waste incineration plants [25]. It is also widely used as a biomass dryer [24]. Biomass is torrefied inside a big rotating drum inclined at a small angle. The angle of incline along with rotation make the material slide down the drum. The drum is heated by hot gases. This process can be controlled by varying the temperature of the incoming gases and rotational speed of the drum. This design can be adjusted to various biomass types by varying the angle of incline and the length of the drum.

3.2.2. Screw reactor

A screw reactor is a simple design based on a screw auger. This technology is proven and used in many different feeding devices as well as in briquetting machines [6]. The reactor works continuously and one or multiple augers transport biomass through the reactor. This reactor technology can be considered as proven [17]. A screw reactor is often heated indirectly using an inert medium either inside a hollow wall or a hollow screw. However, there are variations where heat is applied directly [17]. The reactor is relatively inexpensive. Scalability is limited because the ratio of screw surface area to reactor volume decreases for larger reactors. Some sources mention that scaling up is reasonable up to 40 cm of the inner diameter of the reactor [24].

Table 1: Advantages and disadvantages of a rotating drum reactor [17, 24]

Advantages	Disadvantages
Uniform heat transfer due to good mixing of sliding bed	Low heat transfer (despite good uniformity)
Ability to process wide range of biomass sizes and types	Poor temperature control
Proven technology for various applications	Increased dust output due to friction between processed biomass and drum walls
	Limited upscaling ability. Higher capacities require modular setup
	High cost

3.2.3. Herreshoff oven (Multiple Hearth Furnace)

A multiple hearth furnace is a continuous type reactor. It consists of multiple layers. Each layer performs a part of the torrefaction process. The temperature gradually increases one layer after another from 220 to 300°C [17]. Biomass is introduced from the top side of the reactor on a horizontal plate and pushed mechanically inside. Then it falls to another plate and is pushed to the outside and falls through another hole. This process is repeated many times depending on the amount of stages designed. Multiple layers cause uniform mixing and gradual heating of biomass. Heat is applied per individual reactor layer directly by the use of burners and steam injection. Burners, depending on their design, may use either gas or pulverized solid fuel, therefore it is possible to use either a part of the feedstock or a part of the final product.

The use of natural gas to generate the sweep gas through the reactor contributes to the moisture level and as a consequence moisturizes the torrefied material [17]. This might not necessarily be a disadvantage, because a certain degree of moisture is desirable later on for pelletization, to improve pellet durability after extrusion [17]. The typical processing time for this type of reactor is 30 minutes from top to bottom.

Table 2: Advantages and disadvantages of screw reactor [17, 24]

Advantages	Disadvantages
Relatively cheap	Uneven heating of processed material with hot spots near hot surfaces
Flow of biomass is mechanically enforced, therefore chance for plugging is smaller	Poor heat exchange due to limited mixing of processed biomass
Proven technology	Limited scaling up potential
	Potential to integrate densification with torrefaction in one device

3.2.4. TORBED reactor

A TORBED reactor is a proven technology for various applications. In this type of reactor the heat carrying medium is blown from the bottom of the bed past stationary angled blades, with velocities ranging from 50 to 80 m/s [17]. In principle it resembles fluidized bed technology, but the inlet angle in combination with high velocities gives feedstock particles both vertical lift and horizontal movement [26]. Name TORBED is derived from the toroidal pattern that particles in the bed follow. The major advantage for this type of bed is the fact that the rotation enables high turbulence and therefore substantial heat transfer between feedstock particles and the carrying gas. This allows the bed to be quite flat (small in the vertical direction) which in turn enhances exchange of the heat even more because the surfaces of the blades allow good radiation heat exchange [26] (although it might not be very significant in comparison to combustion technologies using that bed—because of the lower temperature range for torrefaction).

Impact velocities of the gas stream leaving the

Table 3: Advantages and disadvantages of MHF reactor [17, 24]

Advantages	Disadvantages
Good heat transfer	Relatively large size of the reactor
Good temperature control	Less sustainability and smaller total CO_2 reduction if fossil fuel is used to produce the process heat
Ability to take a wide range of biomass types and sizes	
Scalable technology (7–8 m of diameter possible)	

blades are many times higher than velocities required to entrain the particles; however, they are dissipated against the large surface of the shallow bed. This way the superficial velocity of the carrying gas is low enough to keep smaller particles within the bed [26]. The reactor is shaped in a way that helps to maintain fine particles, because the freeboard cross-section (horizontal cut) surface gets bigger vertically.

3.2.5. Microwave reactor

Microwave applications are quite new among thermal process technologies. However, there are some applications as regards drying. Wroclaw University of Technology has its own experimental installation for plasma pyrolysis/gasification of biomass and waste that utilizes microwaves [27]. The literature names only one supplier of microwave technology for torrefaction—UK based Rotawave. The company claims that this technology uses multiple electromagnetic frequencies simultaneously [28]. It also states that this technology utilizes a specially designed ceramic phase separation drum.

It is well known that water has its resonance frequency within the microwave frequency band. Therefore it is reasonable to assume that this reactor is able to process biomass with quite a high moisture content and the moisture might even enhance a more even temperature distribution throughout the feedstock. Also penetration of feedstock is not mass transfer dependent, as gas is heated up only insignificantly by microwaves (it is mostly heated up by hot feedstock). The big disadvantage is a need for electricity, which in the case of a small scale installation in distant locations might mean a need for an independent power source.

Table 5: Advantages and disadvantages of the microwave reactor [17, 24]

Advantages	Disadvantages
High and relatively uniform heat transfer	Low maturity of technology
Large specific throughput (due to high heat transfer)	Need for electricity
Heat transfer less dependent on biomass size (possibility to use large biomass particle sizes)	Need for its own electricity generation unit in off-grid, distant locations
Possibility to use poor quality and non-uniform feedstock (e.g. logging residues)	Difficult mass flow control (it is impossible to use an auging device made of metal inside the reactor due to microwaves)
Good temperature control	
Modular	

3.2.6. Compact moving bed reactor

Compact moving bed reactors are relatively simple technology that applies similar principals as fixed bed reactors in gasification (countercurrent reactors strictly speaking). These reactors do not include moving parts. Biomass is fed from the top of the reactor and moves down gradually. The heat carrying gaseous medium enters from the bottom and moves countercurrent with respect to the biomass. The torrefied product leaves the reactor at the bottom. Volatile products along with inert gas are removed at the top of the reactor. This process is performed at approximately 300°C and the residence time is approximately 30...40 minutes.

This reactor, like other similar designs of the type, is very vulnerable to funnel flow [29]. Funnel flow is a type of solid particle flow with uneven velocity distribution along the bed. This in consequence means variable retention time and in consequence a variable and uneven degree of devolatization and carbonization.

Another type of flow instability is sifting [29]. This means that smaller particles flow in between spaces left by bigger particles.

These factors make the reactor vulnerable to uneven particle size distribution and in consequence make it unsuitable for low grade biomass. Moreover, high pressure drop throughout the bed makes this technology energy consuming [17]. This presents maintenance and process control problems and may lead to frequent shutdowns.

Table 6: Advantages and disadvantages of moving bed reactor [17, 24]

Advantages	Disadvantages
Relatively simple and low cost reactor	Vulnerable to uneven particle size distribution (limited biomass size and type acceptable)
No moving parts inside the reactor	High pressure drop throughout the bed
	Non-uniform temperature distribution (especially with indirect heating)
	Difficult temperature control
	Risk of unequal degree of devolatization and decarbonization (due to uneven retention time)
	Unproven scale up potential

3.2.7. *Belt reactor*

A belt reactor is a proven technology widely used for biomass drying. Biomass is fed into the reactor and transported across the reactor using a moving, porous belt. The biomass on the belt is directly heated by a hot gaseous medium flowing through the reactor. In this type of reactor multiple belts are usually placed one on top of the other. While biomass particles fall from the top belt to the bottom one, mixing of particles takes place, leading to a more homogenous product.

Residence time can be easily controlled by the belt speed. The reactor could be considered as a perfect plug flow reactor, with similar residence time for all particles in the bed.

A major disadvantage of this type of reactor is the risk of clogging the open structures (pores) of the belt due to tars or small particles. Output volume is limited, because of the limited thickness of biomass traveling on the belt. This also makes it less suitable for biomass with low densities, because it makes the specific output of the product very low (in kg/h) with respect to investment costs. Temperature control inside the reactor is very limited, because this process can be controlled only through the temperature of the inert gas entering the reactor. The large space requirement is a major issue in upscaling.

Table 7: Advantages and disadvantages of the belt reactor [17, 24]

Advantages	Disadvantages
Proven technology	Possible clogging of belt pores (by tars and fines)
Excellent control over residence time	Specific capacity is surface dependent (most other reactors are volume dependent)
Perfect plug flow reactor (even residence time for all particles)	Limited scalability potential
Ability to take various range of biomass sizes	Limited temperature control
Relatively low investment cost	High maintenance cost due to many mechanical parts

4. TOP process

In order to make biomass a commodity, torrefaction by itself is not sufficient. Low volumetric energy density remains a disadvantage (Tab. 8). Although heating value (which is in fact energy density per mass unit) increases, bulk density remains low. In practice, this means that the transport is volume limited. Pelletization of torrefied biomass seems to be an obvious choice in this case. Torrefaction analysis, from a product point of view, shows the opportunity the process itself gives in terms of further densification. Devolatization leaves feedstock material much more porous prior to the torrefaction process. This makes perfect sense, since gases need to find their way out of solid particle, due to internal pressure rise, which is qualitatively coherent with the Clapeyron equation (in an isolated system an increase in gas temperature always causes an increase in pressure). Eventually the material structure is not strong enough to contain the gases and ruptures. This should leave more space (pores) within the torrefied particle and give opportunities in terms of both comminution and pelletizing.

In practice the theoretical analysis holds true. As Table 8 shows, the torrefied material has lower bulk density than raw biomass (wood chips). Also torrefied pellets have higher bulk density compared to traditional wood pellets, which brings it much closer to coal.

The situation is different in terms of pelletization. The literature reports that the energy required for the pelletization of torrefied wood is approx. 150 kWh/t (compared to 50–60 kWh/t for pelletization of raw wood) [17].

There might be a couple of explanations. There is presently no research published on the cohesiveness of torrefied biomass. However, it seems reasonable to assume that it is more cohesive than raw wood, because a more porous structure would also mean a greater outside surface of particles. Therefore, pressing through a pellet press might be more energy consuming, but until more research results are published there is no way to assess that influence at present. Another explanation is improper use of binders. Currently, binding is done by adding steam or hot water [17]. The literature states that torrefied materials may require some additional binding materials (e.g. glycerine, dried distilled grain or soybean) [17]. This is also plausible because material which is not properly bound, has to be recirculated back to pelletization in order to avoid material losses. That might increase the specific energy requirement for pelletization, because a part of the material uses the same amount of energy multiple times (depending on the recirculation ratio).

The literature states that some producers (Topell) observed lower energy consumption for pelletization—45 kWh/t—with the right recipes for binders [17]. It needs to be borne in mind that the concentration of lignin in torrefied biomass rises with the torrefaction temperature [23]. This might serve as a natural binder if a proper softening temperature is achieved during pelletization.

Overall it is possible that both explanations are partly correct and there is no straightforward way to transfer from pelletizing raw biomass to torrefied biomass using traditional pelletizing equipment. It definitely means that there is potential for further improvement in that matter.

Since torrefied material needs to cool down after the torrefaction process, and the pelletized material has to be heated up prior to the pelletization process, the integration of these two processes seems to be an obvious choice. The literature uses the TOP process for the Combined Torrefaction and Pelletization process [24, 30].

Table 9 compares some properties of TOP pellets in comparison to other forms of biomass. It seems worth mentioning that pellet strength is considered very good compared to traditional pellets. In both cases dust formation is limited. Due to its hydrophobic nature water uptake is limited, which as a consequence makes it less vulnerable to swelling. This is probably due to the internal structure, which does not have so many “capillary type”, porous formations that could enhance water penetration.

5. Altered properties of torrefied material

The torrefaction process changes various properties of biomass. Not only those that enable more efficient transport (energy density) but also those that enable easier handling (hygroscopic/ hydrophobic nature).

However, some crucial properties, important at the power plant (or other energy conversion technology facility) are also subject to change. Grindability increases, which offers potential savings in both energy consumption for grinding equipment and investment costs of auxiliary devices in co-firing power plants. Many combustion properties related to the chemical and proximate composition of biomass are also altered by the torrefaction process.

5.1. Grindability

There is no doubt that torrefaction has an influence on the grindability of biomass. However, much depends on the methodology, i.e. the mill used to perform the experiment, and on the screen used inside the mill, which determines size reduction. The results obtained should be treated with caution, because using a different mill may lead to different results [11].

Some literature sources find a linear relation between specific energy density and torrefaction temperature [31]. Table 10 shows a substantial decrease in specific energy consumption (kWh/t) for grinding. Tests were performed using a Retsch SM 2000 heavy-duty knife mill [31], which is a suitable device for biomass but not the best one for grinding brittle materials (cutting dominates and compression and friction are almost negligible [11]). The bottom sieve of 1.5 mm was used in this particular study, because this size is supposed to be suitable for pelletization later on [31].

Another study, focused on fine grinding energy [10], showed completely different results. Feedstock was pre-ground with a knife mill (Retsch SM 1) with an 8 mm sieve. Ground feedstock was then sieved once again with 4 mm and 2 mm sieves. Particles between 4 mm and 2 mm were used in the final test to determine the necessary comminution energy. The test was performed with the use of a Retsch ZM 1 ultra centrifugal mill and a sieve with a mesh size of 500 μm. In the ultra centrifugal mill size reduction takes place by impact and shearing effects between the rotor and the fixed ring sieve [32]. That makes this device resemble a ball mill much more than a knife mill and makes the results more meaningful in terms of co-pulverization with coal in power plants.

Table 10: Mean particle diameter and specific energy consumption for grinding torrefied biomass [31]

Feedstock	Mean particle diameter, mm	Specific energy consumption for grinding, kWh/t
Untreated PC	0.71	237.7
TPC - 225°C	0.45	102.6
TPC - 250°C	0.42	71.4
TPC - 275°C	0.27	52.0
TPC - 300°C	0.13	23.9
Untreated TLR	0.74	236.7
TRL - 225°C	0.57	113.8
TRL - 250°C	0.53	110.4
TRL - 275°C	0.46	78.0
TRL - 300°C	0.36	37.6

PC—Pine Chips; TRL—Torrefied Logging Residues

From a combustion point of view, both the amount of material that goes through the sieve and the particle size distribution are important. The results of particle distribution for the described research are shown in Fig. 1 and Fig. 2.

Although it is possible to use the same sieve as the one used in real mill in a power plant, it seems to be reasonable to use the standard test for coal (Hardgrove test). This result (Hardgrove index—HGI) allows one to predict particle size distribution during the comminution of brittle solid fuels (like coal) [7]. Literature sources claim that HGI values for miscanthus and willow torrefied at 290°C with residence time of 60 minutes are comparable to some standard reference coals (Fig. 1 and Fig. 2) [7].

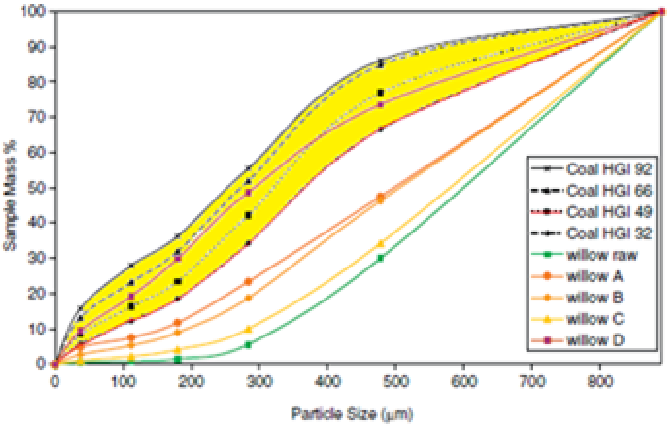

Figure 1: Particle size distribution curves for untreated and torrefied willow. The area of typical size distribution for two extreme reference coals are marked in yellow [7]

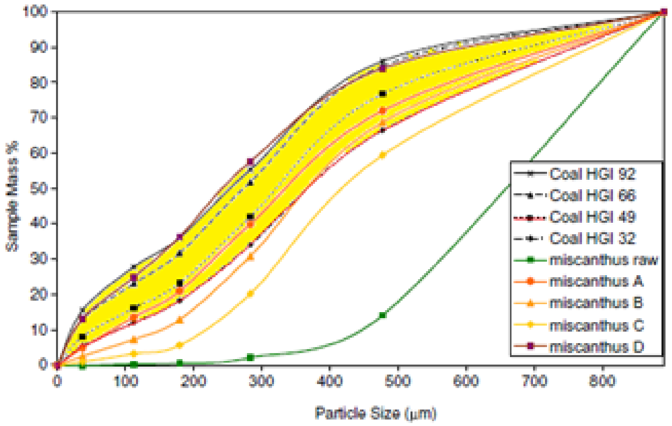

Figure 2: Particle size distribution curves for untreated and torrefied miscanthus. The area of typical size distribution for two extreme reference coals are marked in yellow [7]

The test for the Hardgrove index is made using a special ball mill and uses as an indicator the amount of the sample that passes through a sieve with a 75 μm mesh [33]. Therefore the result is meaningful in terms of comminution in a typical power plant mill.

However, a simple comparative analysis (between raw and processed material) may also serve as an indicator in order to find optimal process parameters, knowing the comminution device mechanics in the analyzed chain of unit operations. For this reason the mean arithmetic diameter (3) may be used [8].

$$D_{ma} = \frac{\sum p_i \frac{\varphi_{i+1}+\varphi_i}{2}}{\sum p_i} \qquad (3)$$

where: D_{ma}—mean arithmetic diameter; p_i—percent of sample weight retained in tray i; φ_i—mesh size of tray i; φ_{i+1}—next bigger mesh size over tray i.

5.2. *hygroscopic properties*

Torrefaction, especially along with pelletizing, allows one to handle reduced volumes of material. However, the hydrophobic character of the torrefied product might provide a possibility to avoid weather protected storage.

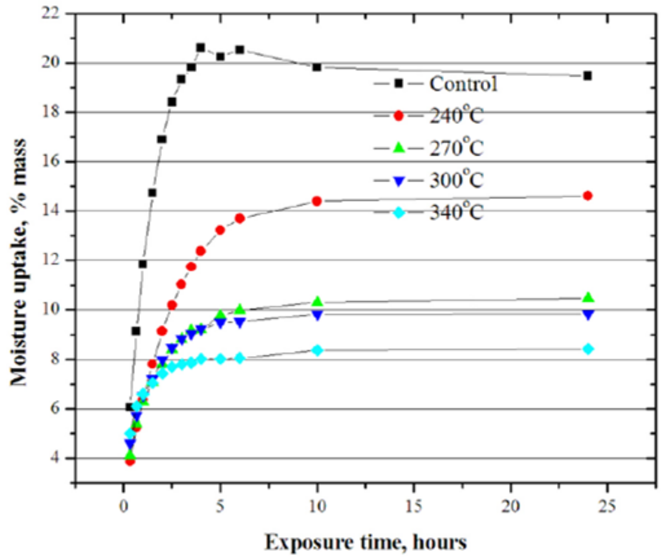

Figure 3: Hygroscopicity of 6 mm pellets made of wood torrefied at temperatures ranging from 240 to 340°C [17]

During torrefaction OH groups are substituted by non-polar groups. As a result water adsorbing capacity is significantly reduced [17]. This makes the fuel less sensitive to biodegradation, self-heating and moisture uptake. Fig. 3 shows the hygroscopic characteristics (sorption of relative humidity in ambient air) of torrefied and pelletized wood, depending on different torrefaction temperatures. Tests were done at controlled conditions of 30°C and relative humidity of 90%.

Despite its hydrophobic nature, which reduces water adsorption (chemical mechanism), torrefied pellets might also absorb water (physical mechanism) if they are exposed to moisture in liquid form (e.g. rain) [17]. This free, unbound moisture might be lost much faster, with the kinetics resembling that of a pile stored coal.

In general proper standards are needed to obtain comparative results. ISO Technical committee 238 is working on developing standards for the determination of hygroscopicity, absorbance of water and freezing characteristics [17]. This is important not only to determine the weather resistance but also to assess the mechanical integrity of pellets, which in turn might lead to an increase in the formation of fine particles, which brings an increased risk of a dust explosion [17].

The mechanical integrity of torrefied pellets might be affected by water in many ways:

- pellet swelling due to water sorption
- the binders used during pelletization of torrefied material might be sensitive to water
- freezing of water absorbed inside pores remaining in the torrefied pellet (freeze-thaw action)
- possible biological decomposition

5.3. *properties determined via proximate and elemental analysis*

The results of elemental analysis give a concentration of the elements that are most abundant in solid fuel. These include carbon, hydrogen, oxygen, nitrogen (sometimes sulfur) and all other elements bound in inorganic compounds and stated as ash.

Properties that could be determined via proximate analysis are:

- moisture content
- volatile matter
- ash
- fixed carbon (a difference between initial dry mass and volatile content with ash)

Along with torrefaction temperature the change of each of these values becomes increasingly significant and more similar to coal. Combustion properties of upgraded biomass (kinetics, combustion temperature) are also different, and it seems justified to assume that they are closer to coal than unprocessed biomass.

Table 11: Techno-economic comparison of torrefaction, TOP, pelletization and pyrolysis [17]

	Torrefaction	TOP	Raw wood pelletization	Pyrolysis
Process efficiency, %	92	90.8	84–87	66–70
LHV, MJ/kg	20.4	20.4–22.7	17.7	17
Mass density, kg/m^3	230	750–850	1200	500–650
Energy density, GJ/m^3	4.6	14.9–18.4	7.8–10.5	20–30
Specific capital investment, M€/ton	0.17	0.19	0.15	0.19–0.42
Production cost, €/ton	58	50	54	75–104

6. Commoditization of torrefied products

There are many possible ways to organize biomass supply chains for long distance transport. Although the investment costs of plant producing TOP pellets, mentioned by the literature, are higher (Table 11) the production cost per metric ton of the product seems to be slightly lower (Table 11). It should look even better when the heating value is taken into account. Assessments show that TOP is a cost competitive option for many different end uses (power plant firing, co-firing, Biomass Integrated Gasification Combined Cycle and Fisher-Tropsch liquid fuel production) [16].

In order to make biomass a commodity biomass should become a material that is easy to trade. To achieve this goal material handling, i.e. loading and unloading operation, as well as transport and storage should be relatively easy, as it is in the case of coal. As was mentioned earlier, torrefaction and pelletization can make biomass, from various origins, more homogenous in terms of many different properties.

Currently, in the long distance supply chains the main issue is long distance, overseas transport which is subject to regulation by the International Maritime Organization. Pellets made from raw biomass are currently transported in bulk with large ocean vessels [17]. Charcoal is also subject to IMO regulations, but bulk transport is not allowed due to its reactive nature [17]. This makes the transport of the product much more expensive since it has to be packed prior to shipment [34], which introduces additional unit operations in the supply chain (packing and unpacking).

To become an IMO approved commodity torrefied pellets must be classified under an acceptable standard and fulfill certain, predictable criteria of quality and have definable safety attributes [6]. Typically a product standard and an international safety code issued by the IMO is a prerequisite for liability insurance for large fuel supply contracts [17]. At present torrefied biomass does not have either a standard or a safety code, therefore it is treated in the same way as charcoal due to some minor similarities and no other document to be referred to.

It seems to be a justified conclusion that the main obstacle to TOP becoming a commodity is a lack of proper standards. The ISO/TC 238 committee is currently working on product quality standards and specific test methodologies for torrefied materials. This standard will most likely classify the torrefied material according to its moisture content, ash content, bulk density, fixed carbon content, volatile content and minimum net calorific value as received [17]. It shall be published under the ISO 17225-1 standard.

Since by definition standards are voluntary, consensus-based and bring together all interested parties—any organization may aspire to write its own standard. Dutch experience on torrefaction is quite extensive. The Dutch Torrefaction Association made an attempt to develop its own standard [35, 36]. It seems to have some advantages over the the standard developed by ISO, because it states some important properties that ISO omitted. These are namely [36]:

- additives and binders: weight % of pressing mass; type and content; slagging inhibitors or any other additives (maximum allowed amount is expected to be 20% wt., beyond that raw material would be considered a blend instead of wood).
- mechanical durability (similarly to traditional pellets [37])
- amount of fines (though this one seems to be not so necessary since mechanical durability seems to give a more relevant result to the subject)
- Hardgrove Grindability Index
- hydrophobic behavior (both in open air and swelling behavior in water)
- content of nitrogen, sulfur, chlorine and trace elements
- ash melting behavior (fluid temperature in oxidizing atmosphere).

The latter two seem to be important improvements in terms of fouling and high temperature corrosion, which are potential problems in power plant boilers. HGI is crucial in terms of co-grinding with coal. Information about binders is also important with respect to both of the mentioned problems and present some risk related to plant emissions. DTA has also prepared a form document that may be used to determine safety attributes of torrefied pellets [38].

7. Conclusions

The process of biomass commoditization mimics nature. Biomass pretreatment is designed to make biomass resemble coal as much as possible. This seems obvious, since one of the main reasons why coal originally became a commodity was its set of properties which made it easy to use and trade. Similarly the pretreatment processes evolve in a “retro” direction and try to mimic the natural processes that have made coal what it is today. That also seems to be an obvious choice because usually a similar way of doing things brings similar results. The only thing that is needed, in terms of the man-made process, is to make it a bit faster.

There seems to be significant potential in terms of optimizing the TOP pelletizing process. It concerns the use of binders and other additives (i.e. slagging inhibitors) and attempts to find optimal process conditions which would include the presence of natural binders along with other properties of the final product. Finding maximum lignin formation for the torrefaction process seems to be as necessary as finding optimum process conditions in terms of other TOP properties. Some research on the cohesiveness of torrefied material should be undertaken to optimize pelletization machinery, i.e. design of the dye.

It would be interesting to measure the energy required to grind torrefied pellets, because pelletization itself has an additional impact (compression) on torrefied biomass particles, therefore the structure might be already a bit weakened and more susceptible to grinding.

Autothermal operation is usually presented as an obvious choice, however it is usually reached by producing the right amount of Torgas and with the right heating value in order to keep the process running. Since torrefaction is only an intermediate step in the fuel supply chain, final feedstock parameters should be the main concern. To optimize process efficiency a couple of factors should be balanced. One is process temperature, which causes heat losses. Another involves technical difficulties and losses related to the recirculation of flue gas left after burning Torgas back into the process. Burning Torgas in order to externally heat input inert gas is technically easier, but involves the consumption of an additional substance—nitrogen. It does not mean that the gas is being consumed from a chemical point of view, but it needs to be resupplied, which introduces additional costs.

The choice of the optimal residence time for the process is not so obvious. On the one hand there are the properties of the final feedstock. On the other hand there is a point of optimal output product stream that is economical for the capital cost of the analyzed installation. Keeping feedstock too long inside the reactor would mean small output per time unit (measured for example in kg/hour). Fortunately, both temperature and residence time have an influence on product properties and one can manage not only those two parameters separately, but both of them simultaneously. It is possible to keep one at the same level and change the other in order to obtain an optimum value. Therefore, correlation between those two parameters and all of the relevant product properties should be investigated in depth.

Since one of the main goals of torrefaction is the commoditization of biomass, the limited scalability of the reactor might not necessarily be a bad thing. It seems reasonable to try to place torrefaction, considered as a unit operation in the biomass supply chain, as close to the source of biomass as possible. Without a need for a big scale, centralized unit, the importance of scalability decreases.

Proposals made by DTA in terms of TOP properties that should be subject to testing seem to be a step in in the right direction. Only knowledge of all relevant properties would make it possible to commoditize this product, by making it predictable in terms of storage, transportation and handling operation. It seems reasonable to assume that having standards at hand would in the long term allow bulk transport on the high seas. It would also influence the development of safety procedures to avoid dangers such as dust explosions.

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Table 4: Advantages and disadvantages of the TORBED reactor [17, 24, 26]

Advantages	Disadvantages
Decoupling of hot gas mass flow and fluidizing velocity	High temperature leads to greater loss of volatiles
Substantial velocity gradient through the bed allows processing of ungraded material (fines)	Risk of undesired tar formation due to high volatile loss
High impact velocities provide high heat transfer	Formation of fine particles due to internal abrasion in the bed (risk of explosion in later stages)
Low residence time (<100 s)	High heat transfer and high temperature make the process sensitive to variation in particle size (smaller particles could potentially lose much more volatiles in comparison to bigger ones)
Large specific throughput (due to high heat transfer and low residence time)	
Shallow bed enables small solids hold up	
Ability to precisely control the product with rapid response to the control system	
Relatively low static pressure loss comparing to other fluidized bed technologies	
Process gas recirculation that is less energy consuming (comparing to other fluidized technologies)	
Scalable technology (up to 25 t/h)	
Low maintenance due to no moving parts in hot zones	

Table 8: Characteristics of selected biomass types in comparison to coal [24]

	LHV, MJ/kg	Moist. content, %	Ash, %	Bulk density, kg/m^3	Energy density, GJ/m^3
Wheat straw	14.4	15	10.2	100 (bales)	1.4
Switchgrass	18.9	10–15	5.4–6.9	140 (bales)	2.2
Sawdust	15.2	6–30	0.5–1.1	160	2.4
Wood chips	17–18	30–55	0.7–1.0	200–450	2.2–4
Wood pellets	16–17	5–10	0.4–1	550–700	7.8–10.5
Torrefied wood	19–23	1–5	<3	180–300	3.5–6
Torrefied pellets	19–23	1–5	<3	750–850	15–18
Charcoal	30–35	5–10	<6	170–220	5–8
Coal	17–33	6.5–12	10–40	800–850	25–40

Table 9: Properties of wood, torrefied wood, wood pellets and TOP pellets [30]

Property	Wood	Torrefied biomass	Wood pellets	TOP pellets
Moisture content, %	35	3	7–10	1–5
LHV, MJ/kg	10.5	19.9	15.6–16.2	19.9–21.6
HHV, MJ/kg	17.7	20.4	17.7	20.4–22.7
Bulk density, kg/m^3	550	230	500–650	750–850
Energy density, GJ/m^3	5.8	4.6	7.8–10.5	14.9–18.4
Pellet strength	-	-	good	very good
Dust formation	moderate	high	limited	limited
Hygroscopic nature	water uptake	hydro-phobic	swelling /water uptake	poor swelling /hydro-phobic
Biological degradation	possible	impossible	possible	impossible
Seasonal influences (noticeable for end user)	high	poor	moderate	poor
Handling properties	normal	normal	good	good