MUSIC

Market Uptake Support for Intermediate Bioenergy Carriers

WHITE PAPER:
TORREFIED BIOMASS

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List of Acronyms

ATEX – Explosive Atmospheres

Cfix – Fixed Carbon

EFB – Empty Fruit Bunch

EPC – Engineering, Procurement and Construction

EU ETS – EU Emissions Trading System

FP – Feed to Product ratio

FPBO – Fast Pyrolysis Bio-Oil

GHG – Greenhouse Gases

HGI – Hardgrove Grindability Index

HTC – Hydrothermal Carbonization

IBCs – Intermediate Bioenergy Carriers

IBTC – International Biomass Torrefaction Council

IMO – International Maritime Organization

IMO – International Maritime Organization

IMSBC - International Maritime Solid Bulk Cargoes

ISO – International Standardization Organization

LHV – Low Heating Value (alternative to NCV)

LULUCF - Land-use, land-use change and forestry

MO – Microbial Oil

NCV – Net Calorific Value (alternative to LHV)

R&D – Research & Development

RDF – Refused Derived Fuel

RED II – Renewable Energy Directive (EU) 2018/2001

SECTOR - Production of Solid Sustainable Energy Carriers from Biomass by Means of Torrefaction. EU funded project (GA 282826)

SRF – Solid Recovered Fuel

TB – Torrefied Biomass

TRL – Technology Readiness Level

TS – Technical Specification

VOCs – Volatile Organic Compounds

1 Introduction

Intermediate bioenergy carriers (IBCs) is a term used for biomass that is processed to energetically denser materials, analogous to oil, coal and gaseous fossil energy carriers. This means that they are easier to transport, store and use.

The MUSIC project will support the market uptake of three types of IBCs by developing feedstock mobilization strategies, improved cost-effective logistics and trade centres. IBCs covered in MUSIC include fast pyrolysis bio-oil (FPBO), torrefied biomass (TB) and microbial oil (MO).

IBCs are formed when biomass is processed to energetically denser, storable and transportable intermediary products analogous to coal, oil and gaseous fossil energy carriers. They can be used directly for heat or power generation or further refined to final bioenergy or bio-based products. IBCs contribute to energy security, reduce greenhouse gas emissions and provide a sustainable alternative to fossil fuels in Europe.

Torrefied biomass

Biomass is the oldest actively managed energy source of mankind. It comes in handy and is widely available, relatively easy to ignite and control during combustion. Nevertheless, combustion limitations of raw biomass soon became apparent and led to the development of biomass upgrading techniques thousands of years ago.

Upgrading by thermal treatment, which means combining drying and (partial) devolatilization, has been a cultural technique for at least 5000 years. Thermally treated biomass allows for better storability and preservation, provides higher energy density, can produce higher temperatures, are easier to control in their combustion, burn cleaner and thus allows for the development of more refined production processes in many sectors.

The traditional thermal treatment of biomass is charcoal production, a process aiming at very high carbon and energy content in derived solid products. Charcoal has many advantages, although the process itself is “dirty” as it produces a number of toxic gases and is energetically inefficient if implemented by using the traditional charcoal kilns.

Reports on transferring the process into a modern, resource-efficient economy started in the 19th century and found expression in numerous patents. A couple of initial examples were developed during WWII but a real attempt for an efficient industrial implementation seems to have been initiated by the French company Pechiney in the 1980s. The first decade of the 21st century saw ECN contributing massively with its R&D on the topic and the first new technological and business initiatives were located in The Netherlands, Belgium, France and the US (non-chronologically listed).

The path from R&D to testing, integration, demonstration, growth, and maturity was arduous for the torrefaction sector, as it was for many other technologies before, and a number of experiences gained in the building of the wood pellet sector were repeated in the torrefaction sector. In addition, without considering process control and system integration issues, common to new technology approaches, or management shortcomings, the sector was hit quite hard by developments in the European biomass to coal co-firing market. When the first initiatives were implemented and it was possible to announce running demonstration plants and continuous production, thermal generation of electricity in the EU came into a crisis. Previously, if a Northern European based utility was talking publicly about an upcoming demand for 15 million tons of biomass pellets – preferably torrefied (black) pellets – it would start to tender many of its thermal power plants for sale two years later. The first transatlantic shipments of torrefied biomass pellets in 2012[1] did not continue because the purchasing power plant was shut down. Thus, uncertainty in biomass co-firing regulations in the Netherlands, conversion projects that surprisingly received no support together with a lack of clarity about the risks of upscaling and the profitability of industrial production of torrefied biomass led the industry from the euphoria

[1] New Biomass Energy from Mississippi

of the early years to a broad level of stagnation. It was a chicken-and-egg situation, in which financing was only possible with purchase contracts for products, which in turn are only subscribed when there is certainty of production in an existing plant. However, until the middle of the second decade of the 21st century and thanks to the continued willingness of individual investors to take risks, a new upswing began and the first industrial-scale plants (>100.000 metric ton annual capacity) began to take shape.

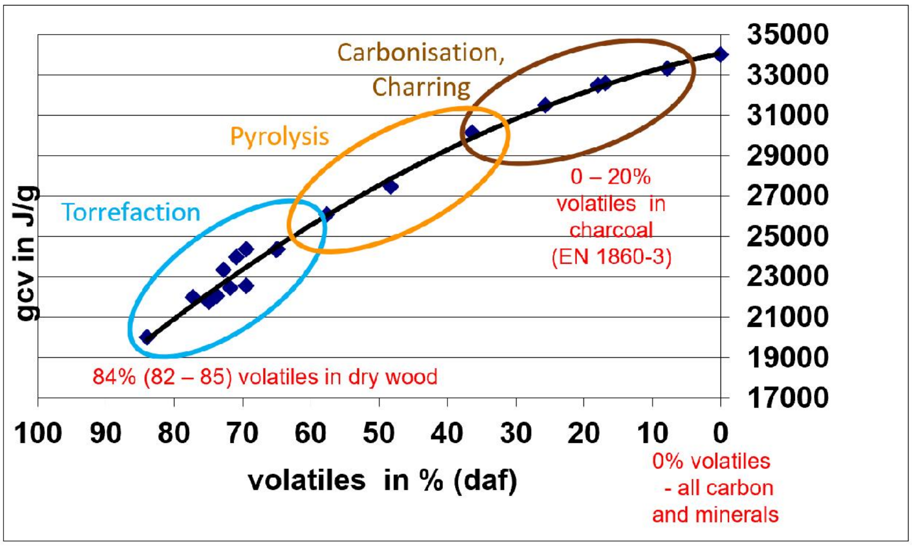
Torrefaction of biomass aims to produce advanced solid fuels and open the markets in different directions. On the feedstock side, a large number of demonstrations have shown that even non-woody biomass such as agricultural residues can be converted into acceptable fuels. On the other hand, torrefied biomass also shows that the resulting biogenic carbon carrier can be employed in other uses than in the power plant sector. In the last few years, more and more applications in various industrial sectors have become apparent. The steel, cement and other industries that use carbon from fossil fuels to cover energy needs in any segment of their production processes are now testing torrefied biomass as semi-finished by-products or simply as a process input material.

This document has been prepared by IBTC, the International Biomass Torrefaction Council, an organization whose mission is the promotion of torrefaction, the corresponding technology and the use of torrefied biomass in energy applications and beyond. This publication is driven by the enthusiasm of IBTC and its members for mild to intensive thermal treatment of biomass and the resulting products. Other than being a review, it is intended to describe the current state of technology and production, where and how products are used, the existing experience with different biomass, which sectors demand can be expected for products of the torrefaction process, where there is potential for optimization and therefore a need for research, and also how the products compare in terms of sustainability.

2 Torrefaction of biomass

Torrefaction, in the view of the authors, is the term that describes thermal treatment of any solid biomass in an inert atmosphere with the aim to separate a part or all volatile matters in solid biomass and to concentrate carbon. Depending on temperature levels, residence times and technological approaches, various products will result, causing an overlap with the naming of other processes.

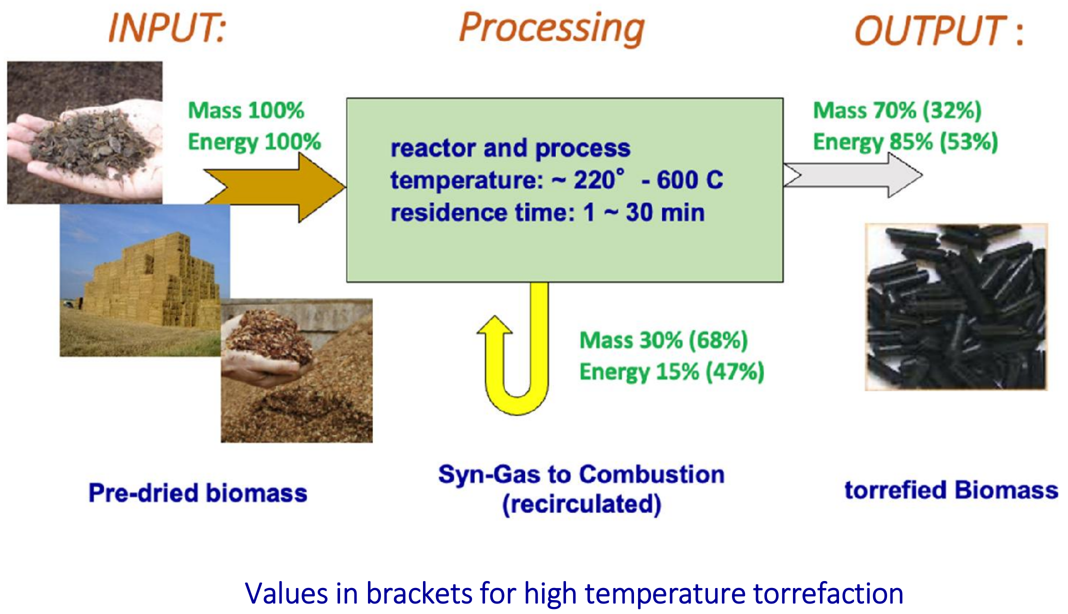
Figure 1 Products along the high temperature torrefaction curve



Source: IBTC, M. Wild

Torrefaction is a process that aims to improve properties of biomass. The product formed is a brownish blackened version of the input material. In the 1930s the process was recognized for the first time as a method to upgrade biomass. In the 1980s torrefaction received serious attention in France with the aim of applying the product in metallurgical applications. During the revival of the process at the beginning of this century, the main interest came from power stations to replace coal. Now – 20 years later – product properties have been numerously investigated by researchers all over the world. Roughly 10 years ago the first commercial production was planned but faced difficulties in coming into operation. Most of these plants were later closed. Nonetheless, the product has superior properties, and the use of torrefied biomass as raw material and fuel is highly efficient and sustainable. Therefore, the interest in torrefaction is greater than before and is to be found in many applications.

Figure 2 Torrefaction process input/output of mass and energy



Source: IBTC, M. Wild

2.1 Decomposition mechanisms

The torrefaction operating window is typically defined by an operating temperature between 220° and 600 °C and carried out in an inert atmosphere. In some processes oxygen is allowed, but essentially inert conditions are a prerequisite for initiating the desired decomposition mechanisms and limit the mass/energy depletion through oxidation reactions.

Biomass consists of three major polymer structures that are present in large percentages. These are hemicellulose, cellulose, and lignin. The behaviour of these structures during torrefaction determines the properties of the product and the thermal balance of the production plant. The most thermolabile polymer is hemicellulose and in torrefaction this structure dominates the decomposition behaviour. As the thermostability of hemicellulose holds well up to 250 °C, torrefaction starts to become attractive from this temperature and higher. On the other hand, above 300-320 °C the thermostability of cellulose starts to drop severely. Therefore, above these temperatures one cannot maintain the desired mass and energy yields and moreover some of the desired product properties will be lost.

The key element of the decomposition reactions that occur during torrefaction is that they emit relatively more oxygen than carbon in the gas phase. That is, the resulting gaseous reaction products – volatiles – consist of different types of oxygen containing molecules (H_2O, CO, CO_2, acids, ketones, alcohols). As oxygen does not represent calorific value, a discrimination takes place between mass and energy retainment of the solid product. The role of dehydration reactions is very relevant to this process as the water molecule consists of 88% oxygen (in weight %) and is the most dominant decomposition reaction in the torrefaction operating window. This is the main reason why the volatiles are very rich in H_2O and have a relatively low calorific value.

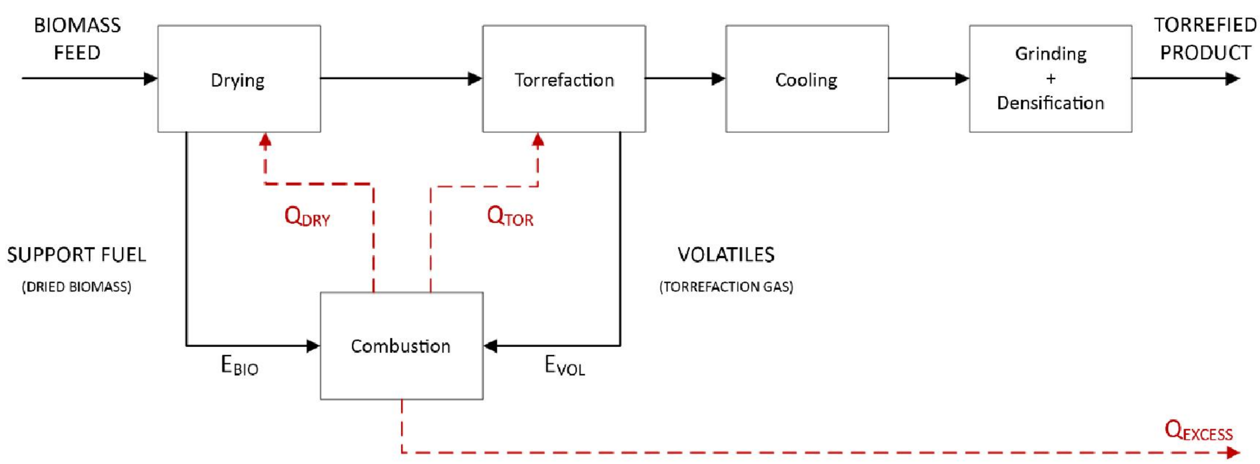
The solid properties from feed to torrefied product are mainly changed by the destruction of hemicellulose and the dehydration reactions. Larger reaction products (larger fractions of the polymer structures) may or may not vaporize and can either react with other gaseous molecules or with radical positions within the solid matrix (inside particles). This is a process called repolymerization and leads to charred structures of hydrophobic nature.

2.2 Process principles and general mass and energy balance

From molecular level to macro phenomena, the torrefaction process is both a mass and energy splitter that hence differs from a "normal" white pelleting operation. The feed to the torrefaction process is split into a solid product and volatiles, the latter comprising of a mix of reaction products. It also consists of substances that may just evaporate, including the physically bound water that came in with the feedstock. Moreover, the process takes place at elevated temperatures so that the torrefied solid product needs to be cooled. The volatiles contain organics with relatively low boiling points and therefore cooling the gas will initiate condensation of these substances.

Energy splitting imparts a new "feedback" loop in the process. As the energy content of the volatiles cannot be fully absorbed by the heat duty of torrefaction, heat utilization of the volatiles' gas (by combustion) needs to be coupled with a drying process. This drying process is required to pre-dry the biomass, as otherwise the torrefaction gas would be too diluted with water to combust.

Figure 3 Steps of the torrefaction process



Source: Yilkins

The process can operate at the autothermal point when a certain energy balance is reached, causing the liberated energy by combustion of volatiles to match the energy needs of torrefaction and drying. Above the autothermal point, the applied torrefaction severity results in an excess heat from the volatiles' combustion. Below the autothermal point, a support fuel is required to thermally balance the process (viz., biomass in the picture above).

$$Q_{DRY} + Q_{TOR} + Q_{EXCESS} = E_{VOL} + E_{BIO} \text{ (General energy balance)}$$

$$Q_{DRY} + Q_{TOR} = E_{VOL} \text{ (Autothermal operation)}$$

The thermal efficiency of the process is at its maximum[2] as long as the process is balanced at- or below the autothermal point. Above it, an excess heat is generated and needs to have a useful application (e.g. power production or heating application). When the excess heat cannot be economically utilized, it is important to operate the plant at or below the autothermal point, as otherwise the stack loss will increase at the cost of an increased biomass intake. This is never a favoured but instead a costly situation, since biomass feedstock is the main cost-driver.

The above stipulates that the mass and energy balance of torrefaction is strongly coupled with the product properties, and that economic limitations exist to the degree in which some properties can be improved (e.g., Cfix or NCV). Hence the torrefaction severity is to be chosen carefully and cannot be increased unlimitedly.

Both the achieved product properties and the mass and energy balance are influenced by two important feedstock parameters: particle size (distribution) and moisture content. Moisture content specifically has a strong impact on practically all aspects of the plant. Control over moisture content is therefore one of the most important objectives of a torrefaction plant, especially since small deviations in moisture to the torrefaction reactor can significantly alter the reaction temperature and subsequently the thermal system due to changes in volatiles loading.

The Feed to Product (FP) ratio is a key performance indicator as it represents the effectiveness with which the feedstock is used. For a 50% moist feedstock, the feed to product ratio of a white pelleting plant is typically 2.0. For a torrefaction plant this could be about 2.65. The higher FP ratio of torrefaction suggests that more feedstock is required, and this would be a drawback. The reality is that the higher FP ratio is the essence of torrefaction: energy densification by retainment of energy (higher NCV) but loss of mass. As long as the feedstock energy remains in the product (operation below the autothermal point), a high feed to product ratio is desirable. As is paid for the energy, the feed to product ratio is better evaluated in energy: $GJ_{product}/GJ_{feed}$. Then it would appear that the efficiency of a white and black pelleting plant is quite similar.

[2] The thermal efficiency of the process is a technology dependent parameter and different for each technology supplier.

2.3 Property changes and relation to the mass and energy

The changes in properties that biomass faces during torrefaction are the result of the decomposition mechanisms described earlier. The increased calorific value is due to the carbon retainment in the solid and the hydrophobic nature due to the loss of OH groups to which water may attach. The excellent grindability characteristics – the key property that initiated the co-firing interest – is mainly due to the destruction of hemicellulose (loss of the “cement” or binding function in biomass). The torrefied product is also known to improve the combustion process in terms of fouling and emission characteristics due to the reduction of smoke forming molecules. These are already liberated in the solid fuel during the torrefaction process (decomposition of hemicellulose).

Many authors/researchers have investigated the property changes and their relationship to torrefaction conditions, species, and origin. In many cases conditions are varied without mentioning their subsequent economic impact. This impact on economic proceeds via the mass and energy balance in the first place, besides - of course - the additional value added to the product. It is important to recognize that the improvement of properties is limited by the thermal efficiency of the process. This especially accounts for the increment of NCV or Cfix levels of the product. As soon as the process is operated above the autothermal point, the stack loss will start to increase and energy that could have been in the product is lost. The end-user would need to pay a premium price when properties need to be changed more than the thermal efficiency allows. If electricity, heat or chemicals are co-produced with black pellets, this does not hold as strongly. Then fuel parameters can be increased as the economics are completely different.

3 Technologies available on the market

In essence, to heat solid product to a certain temperature and separate appearing off-gases from solids is neither a novel technology, nor is it limited to torrefaction processes. There are plenty of processes in food industries, minerals and metallurgical industries and other sectors, that run such heating and separation processes. Hence, it is no surprise that most of today's applied technological approaches for torrefaction are based on existing set-ups for drying, roasting or calcining. Nevertheless, mentioning that torrefaction of biomass means just taking any existing heating unit "off the shelf", feeding in biomass and enjoying the continuous flow of torrefied biomass should be avoided.

Torrefaction differs from other industrial processes based on the difficulties that the pioneers in the sector had to master about 20 years ago. There is hardly any feed material that is as heterogenous as biomass in terms of size, inner heat transfer, volume/surface ratio, moisture, contamination, volatile components mix, etc. Moreover, the thermal treatment is producing a torrefaction gas that is very complex in composition and resulting handling requirements. Thus, heating up the biomass is literally the easy part. The art of torrefaction lies in the guarantee of homogenous heat distribution throughout the whole passing biomass, the exclusion of oxygen in the critical areas and the safe handling of the torrefaction gases without losing their value.

Some tables on core technologies, meaning torrefaction reactor technologies, are presented below. Depending on the raw material to be processed, one technology may have its advantages over the other but there is no technology that is the "best" for all kinds of application. The reactor type needs to be selected carefully for every project type and the key to success is in any case the integration of the reactor into the full system – preconditioning, drying, torrefaction, gas utilisation, densification and cooling.

Rotary drum Torrefaction reactor

Source: HeylPatterson

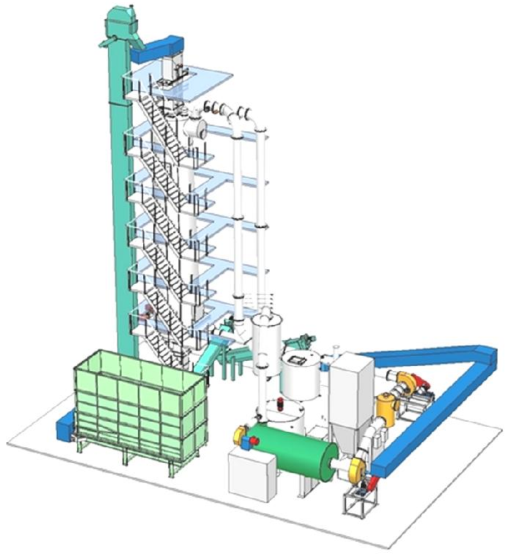
Source: Andritz, NextFuel

Advantages	Limitations
• Various methods to control torrefaction process (length, slope angle, rotation speed, temperature, filling level) • Drum can be directly and indirectly heated • Available for all temperature ranges • Uniform heat transfer • Ability to take a wide range of biomass sizes and waste types • Classification of particles – smaller particles will pass faster • Widely proven technology for biomass drying and heating	• Lower heat transfer • Poor temperature control • May increase fines due to friction between biomass and drum wall • Typical unit capacity is at 10-12 t/h input, or 5 t/h torrefied product. Utilization of larger drums in biomass high temperature treatment is not practiced.

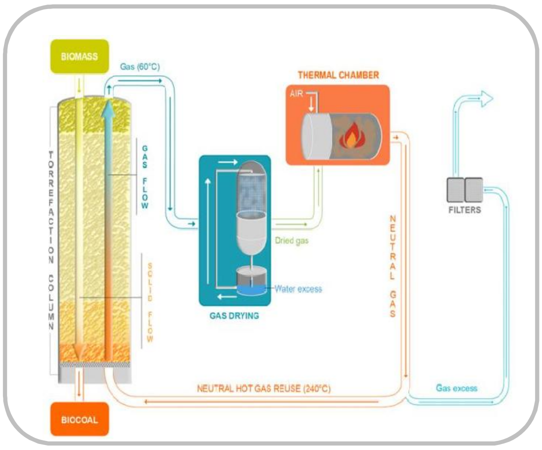
Special Adjustments

- Indirect heated drums are standard for torrefaction
- Baffles or tube bundles increase heat transfer and efficiency and simplify control
- Calciner style reactors with very good temperature control

Moving bed reactor



Source: Andritz



Source: LMK

Advantages	Limitations
• Relatively simple, low cost reactor • High throughput capacity • No moving parts • Also applicable for materials of lower density • Good heat transfer • Simple control by temperature and volumetric throughput	• Difficult temperature control and subsequent control of homogenous heat distribution in the bed • Risk of gas channel formation in biomass leading to non-uniform torrefaction • In case that partial compression of biomass particles occurs, pressure drops resulting in system shut down can be observed

Vibrating belt reactor

Source: Perpetual Next

Advantages	Limitations
• Better temperature control • Ability to take a wide range of biomass sizes • Easy control of residence time through the speed and length of the belt, respectively vibration frequency • Proven technology in biomass drying industry	• Homogenous particle size necessary • Not suitable for materials of low bulk density • Limited upscaling potential since capacity is dependent on the surface area of the belt (other systems are volume dependent) • Potential of clogging with torrefaction tars of open belt structures • Temperature limitation • System has many mechanical parts, which increases maintenance costs • Large footprint (large surface required)

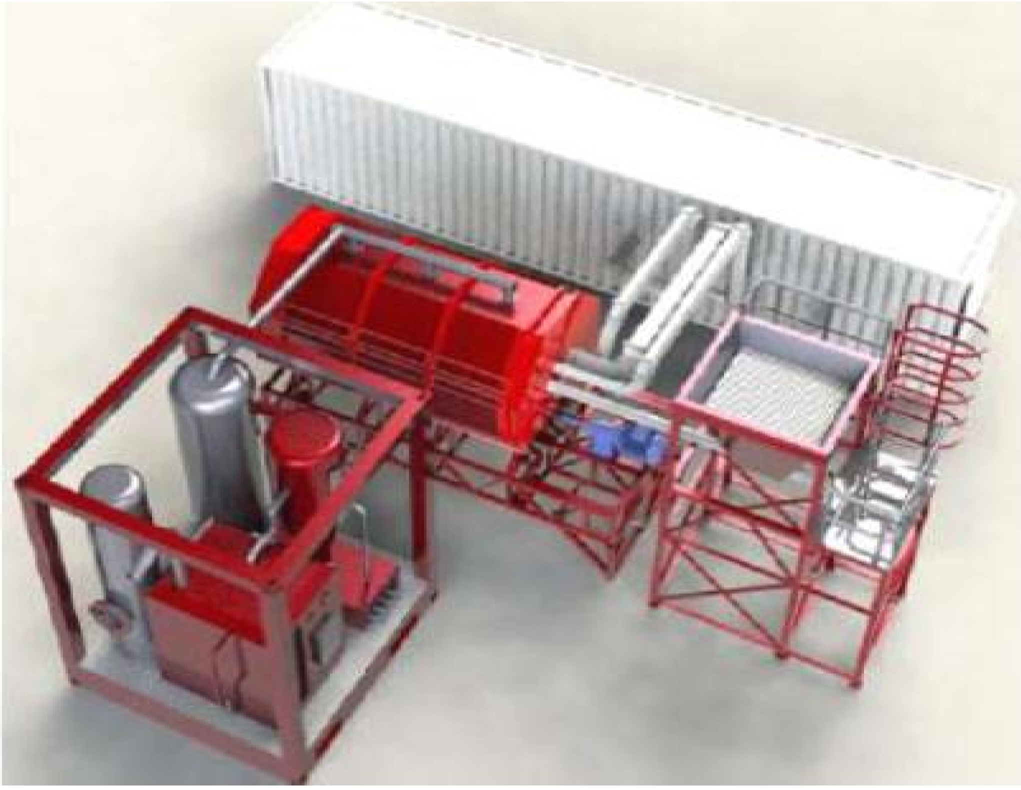
Special Adjustments
• Steel belts only - because of high temperatures • Vibrating belt

Cyclone torrefaction reactor

Source: Yilkins

Advantages	Limitations
• Low residence time (<100 s) • Large throughput due to fast heat transfer and low residence time • Scalable technology (to 25 t/h) • No moving parts (low maintenance)	• High utility fuel demand for preconditioning (sizing) of feedstock • Homogenous, small particle size necessary • Volumetric reactor capacity is limited • High temperature leads to a greater loss of volatiles • Risk of tar formation due to relative higher loss of volatiles

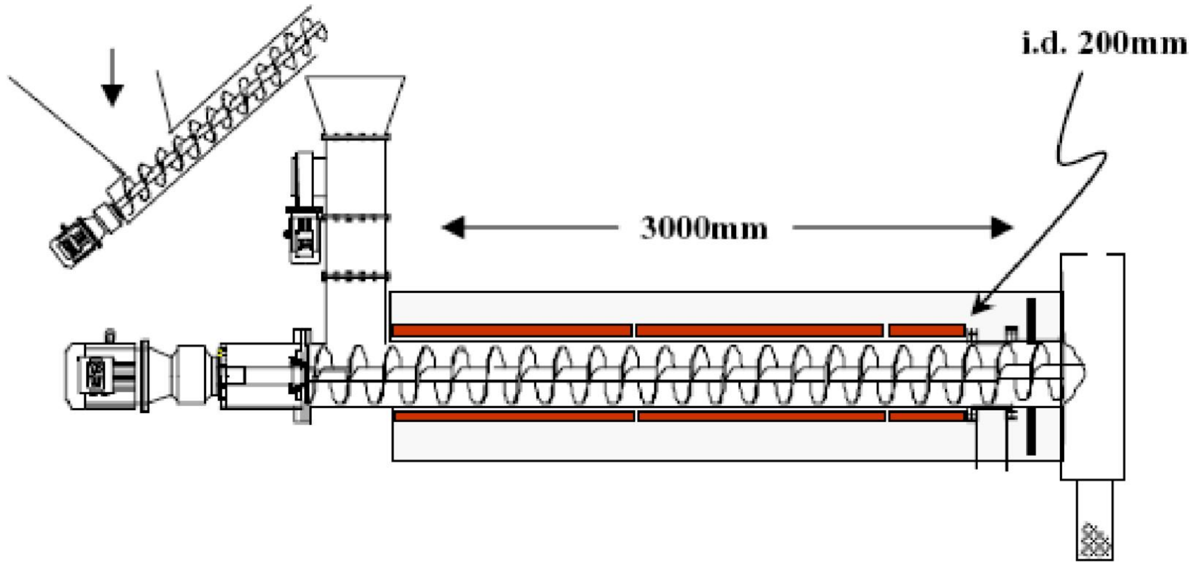
Plant layout with Microwave torrefaction reactor



Source: ECN

Advantages	Limitations
• Radiation based heat transfer instead of convection and conduction • High heat transfer and fast torrefaction • Heat transfer less dependent on the size of the biomass particle - ability to use large size biomass • Very responsive in the control • Modular	• Used mostly in preservation of timber for outdoor application • Unproven technology for drying or torrefaction of biomass - effects of rapid heating of biomass not known • Electric energy main source • Uniformity of biomass heating seems problematic • Requires integration with other conventional heaters to achieve uniform heating

Heating screw reactor (augers)



Source: ECN

Advantages	Limitations
• Relatively cheap reactor • Better biomass flow • Ability to take a wide range of biomass sizes • Proven technology	• Unequal torrefaction as mixing inside biomass streams through screw channels is limited • Need for thermal oil as a heat-transfer medium • Limited heat-transfer to inner layers of the biomass stream • Limited scaling potential as the ratio of screw surface area/biomass volume is less attractive with larger screws • Risk of tar condensation in cooler zones and char formation in overheated zones

Multiple hearth reactor

Source: CMI

Advantages	Limitations
• Ability to take a wide range of biomass sizes • Scalable technology (8 m of diameter possible)	• Increased risk of torrefaction gas condensation • Making process less sustainable. Gas combustion leads to moisture production in the flue gas. This causes lower efficiency in the combustion of the flue gas.

4 Enlarging biomass feedstock portfolio

If we look at the bioenergy sector in general, nowadays wood is the most important biomass used for energy production. Nevertheless, the increasing interest for biobased solutions in the framework of bioeconomy, using wood as a replacement of fossil-based products such as plastics and some textiles or as a replacement of concrete in construction, etc., is adding some competition and, as a consequence, could possibly reduce the offer, increase the price or incentivise regulations to limit its utilization. These are all strong drivers for widening the feedstock base and including alternative biomass that are actually cheaper, abundant and sustainable. As a drawback, those biomass types are usually more "difficult" feedstocks.

This foremost concerns lower quality woody residues, like pruning, treetops, branches, roots, bark and leaves, but may also include non-woody biomass from agriculture (e.g., straw, corn stalks and cobs), fast growing plants such as perennial grasses, including switchgrass and miscanthus, animal residues (e.g., manure) and residues from food/feed production (e.g., nut hulls, culled products). Moreover, mixed waste streams such as organic fraction of the municipal solid waste and various organic matter containing industrial waste streams may be of interest.

Why are these biobased feedstocks generally more "difficult" to handle for energy purposes than clean woody biomass? First, many of them have lower density and inferior transport, handling and storage properties than clean woody biomass. Straw, but even more so, empty fruit bunches (from palm oil production) are good examples. Secondly, the moisture content is often high. For energy purposes, this moisture content does not benefit the process; on the contrary, a lot of energy is required to evaporate the moisture. Thirdly, for a large share of these woody residues and non-woody biomass feedstock, the fraction of inorganics (ash) is substantially larger and more problematic than for clean woody biomass. While clean woody biomass has typically an inorganics fraction of only 1-2 wt%, this may be up to over 20 wt% for the non-woody alternatives. Moreover, these inorganics may be more problematic in terms of containing higher levels of alkali metals (in particular potassium), chlorine, sulphur and heavy metals.

Especially in thermochemical processes, like combustion and gasification, the inorganic constituents in biobased feedstock may create, besides pollutant emissions, a series of operating problems like, slagging, fouling, corrosion, and catalyst poisoning. Moreover, ash recycling (to close the nutrient cycle) or utilization may be challenging. In particular, alkali metals and chlorine may lead to fouling, (fouling-induced) corrosion and catalyst poisoning. Heavy metals may lead to increased emissions (when highly volatile), increase fouling and catalyst poisoning and may also have a negative impact on ash quality and utilisation.

4.1 Can torrefaction facilitate the widening of the biobased feedstock base?

Generally, these non-woody biomass resources are still available worldwide and are largely underutilised. However, the “difficulties” indicated above pose major hurdles for their application in biobased energy and chemicals production. This leads to the question: Can torrefaction play a role to unlock the potential of these non-woody biomass resources and facilitate their application?

Clearly, just as for clean woody biomass, torrefaction can do a perfect job in converting biomass into a high-density bioenergy carrier with good transport, handling and storage properties (e.g., water resistant, lower propensity to biodegradation, thermally stable, pelletizable with low dust contents, low explosion risks, etc.). In that respect, torrefaction has a similar impact for all types of lignocellulosic biomass. Actually, the lower density and inferior transport, handling and storage properties of these resources are even larger (economic) incentives to apply torrefaction. Furthermore, when pneumatic transport or grinding to micron-sized particles is required by the end user, torrefaction can play a fundamental role both in making the biomass materials “flowable”, or in decreasing the power demands for size reduction, especially in the case of tough materials like straw or empty fruit bunches (EFB). Also, for mixed feedstocks containing plastic fractions, like refuse derived fuel (RDF) or solid recovered fuel (SRF), torrefaction (combined with pelleting) may be an effective process to yield a high-quality energy carrier.

However, torrefaction is not the panacea to overcome all “difficulties”. Very wet biomass streams require a lot of energy to evaporate the moisture content. Typically, for the combination of thermal drying and torrefaction, biomass feedstock should contain less than 50% moisture to allow for attractive business cases. In case of initially higher moisture contents, it could be considered to apply natural drying or mechanical drying first to reach a moisture level below 50%; e.g., letting straw or grasses dry in the field. Otherwise, in general, wet processing like anaerobic digestion or hydrothermal carbonization (HTC) processing is to be preferred for these wet streams.

With respect to the latter, hydrothermal processing in the lower temperature regime (HTC at typically 170-280 ^{o}C at around 20 bar) is one of the preferable options and is sometimes also named wet torrefaction, since it is also aimed at obtaining a solid product with similar physicochemical changes of the hemicellulose, cellulose and lignin described above. However, this is outside the scope of this white paper.

Torrefaction (dry) also has its limitations concerning dealing with high and/or problematic inorganics contents. At the relatively low temperature level of torrefaction, most of the inorganics are non-volatile and thus stay in the solid product. Although, some like chlorine and sulphur may partially devolatilize and end up in the torrefaction gas, which requires special precautions in the torrefaction gas processing, e.g., to prevent corrosion. The devolatilization behaviour of inorganics generally depend on their speciation, i.e., on the chemical form in which they are present in the biomass.

In general, however, the limited devolatilization of the inorganic fraction means that on mass basis (and to a lesser extent on energy basis) the torrefied product has a higher inorganics content than the original biomass (given the mass loss mainly due to hemicellulose decomposition). And clearly, the inorganics composition is directly related to the inorganic composition of the original biomass. In this respect, the negative properties of the original biomass resulting from the non-volatile components are hardly changed by the torrefaction process and possibly even more emphasized by concentration, the product kind of mirrors the feedstock in this respect.

4.2 Torrefaction coupled with other unit operations to control the inorganics content

Although torrefaction by itself provides limited options to influence the inorganics content of the resulting solid bioenergy carrier in a positive way, combination with other unit operations may help. First, mechanical sieving or other separation methods may be applied to separate extraneous inorganics. For example, biobased feedstock may contain sand and stones, which may be separated in this way. In addition, torrefaction may be combined with washing to remove water-soluble inorganics and other sticky non-soluble inorganics. This is relevant in particular for the soluble alkali metals and chlorine and the sticky insoluble fine sand or clay particles, which are usually present in biomass as soil contaminants. In addition, the application of HTC (wet torrefaction) as was demonstrated by the TORWASH® technology[3] could remove the alkali metals of the initial biomass although this is not included in the scope of this document.

Several studies have shown that a combination of torrefaction and washing can be both effective and economically feasible. Depending on the biobased feedstock and the process layout, up to over 90% of the potassium and virtually all the chlorine can be removed in this way. Clearly, much care should be taken to optimize the overall process layout, including minimizing fresh washing water consumption, washing water recycling, counter-current washing, dewatering after washing and finding a proper solution for the washing effluent. Moreover, alongside with the inorganics, part of the “soluble” organic matter ends up in the water after washing. This organic matter can be used either as source of “green chemicals” if it is harvested from water or used to produce biogas by digesting the water effluent. An important issue is whether to conduct the washing prior to, or after, the torrefaction, i.e., pre- or post-washing, with pros and cons for both. In general, pre-washing gives a better solubility and thus higher removal efficiencies, but the dewatering may be more difficult / energy consuming. On the other hand, post-washing will yield slightly lower removal efficiencies.

[3] https://www.tno.nl/en/focus-areas/energy-transition/roadmaps/towards-co2-neutral-industry/biomass-to-fuels-and-feedstock/torwash-technology-successful-for-waste-water-treatment-and-recycling-plastics/

However, the solid product after torrefaction has become more hydrophobic, which has a negative impact on the solids-water contacting. However, this generally has a positive effect on dewatering. Mechanical dewatering can bring the moisture content down to <50% levels. A recent study by TNO[4], comparing pre- and post-washing for roadside grass, straw and miscanthus, revealed that for relatively dry biomass, like naturally dried straw, post-washing of torrefied biomass is economically more attractive than pre-washing, although indeed it led to a (slightly) less effective removal of water-soluble inorganics like potassium and chlorine. Moreover, post-washing seems to produce an effluent with lower organic load since the "soluble" organic fraction is decomposed and evolved out of the gas phase during torrefaction. On the contrary, for wet biomass, such as roadside grass, pre-washing appeared more profitable.

[4] Abelha, P., and Kiel, J.H.A.: *Techno-economic assessment of biomass upgrading by washing and torrefaction.* Biomass and bioenergy, vol.142, article 105751, 2020.

5 Process efficiency, mass and energy balance

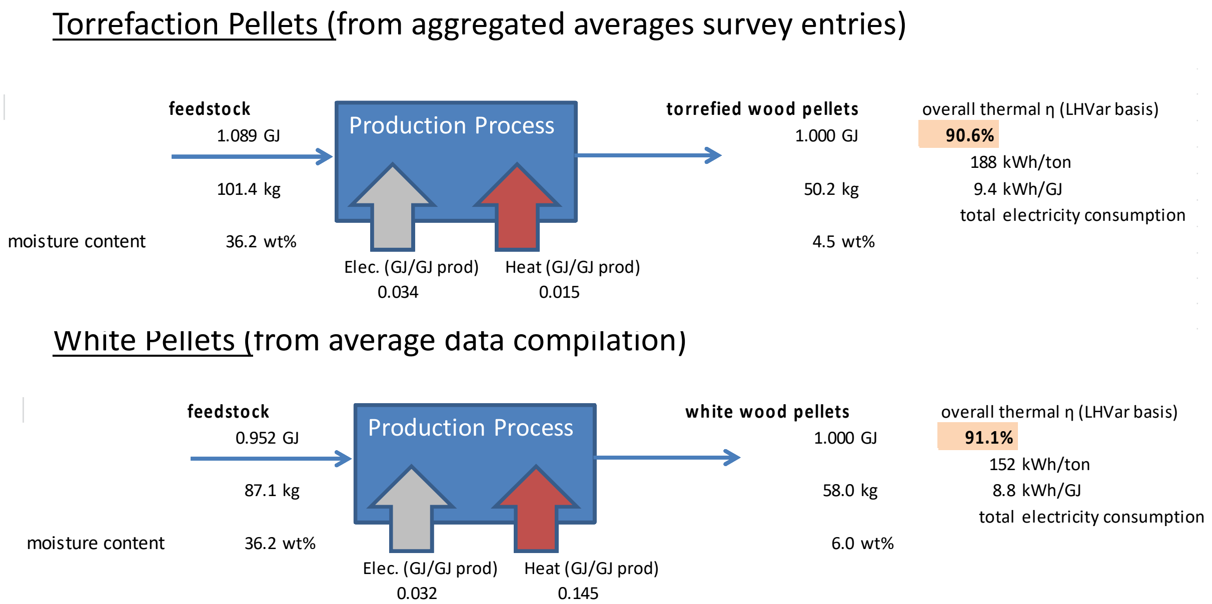
At a time when not a single kWh should be wasted and when it is clear that the maximum possible benefit must be derived from every sustainably obtained raw material, the question arises as to how efficient torrefaction is in comparison to other possible uses of the raw material biomass.

If torrefied biomass is used as a pure energy source in coal-fired power plants or other power/heat plants, torrefied biomass is to be compared with white wood pellets and for this reason the IBTC commissioned a consortium formed by ECN, Umea University and CENER in 2017 to compare the mass and energy balances of the torrefaction companies that are members of IBTC with the known average of the wood pellet industry.

The result was very clear. The production process of torrefied biomass is equally efficient to the production of white wood pellets. This is because in all analysed torrefaction set-ups the energy content of the torrefaction gases had been utilised as energy source for the process, substituting plenty of auxiliary fuel for the wood drying process used in both the white wood pellet and the torrefied pellet production.

Having proof that at producer gate the products are identical from a mass and energy (M&E) balance point of view, it is obvious that in a full Life Cycle Analysis (including the logistics part of the supply chain) torrefied biomass will come in much more efficient than any other solid biofuel.

Figure 4 Mass and energy balance of torrefied pellets in comparison with white wood pellets



Source: ECN/UMEA/CENER

5.1 High Temperature Torrefaction

For high-temperature torrefaction, the balance looks somewhat different to the results presented above.

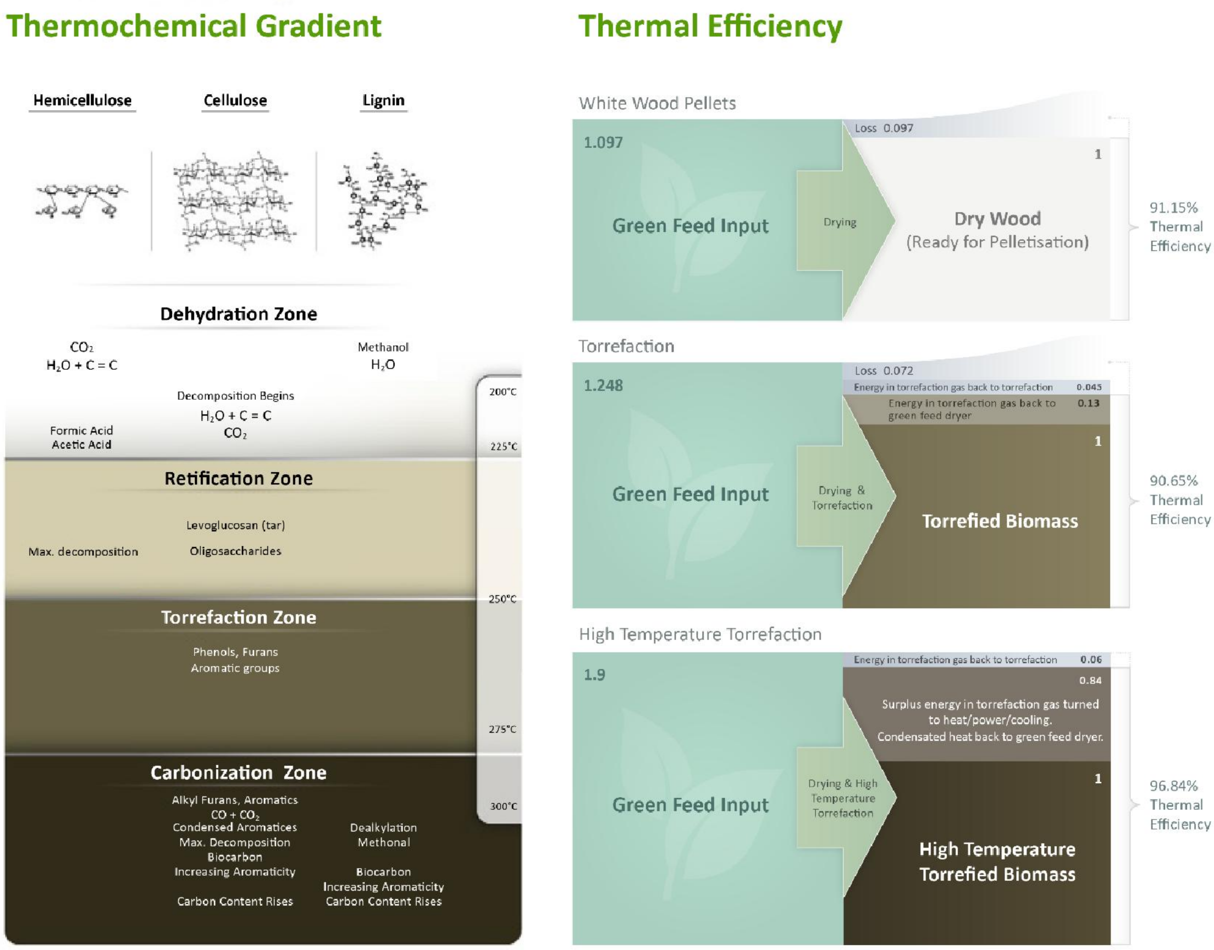
A much higher mass fraction is transformed from raw material into gas. The energy content of this gas is often significantly higher than the process requirements for drying and high-temperature torrefaction. Therefore, it is common to combine these processes with processes that can take advantage of surplus gases. On the one hand, these can be used for energy: gas is thermally converted, and the hot gases are used for steam processes or other energetic uses like district heating, cooling, process energy in industry, etc. On the other hand, an array of solid biogenic products with high carbon content will take shape – eventually custom-made for client groups or sectors of consumers, such as metallurgical processing or carbon black substitution.

However, there are also more and more initiatives to extract individual chemical components from gas before it is thermally utilised. This is a very broad field of activity that began to open up a few years ago and that has already shown a multitude of technological as well as entrepreneurial initiatives.

From the point of view of value creation, high-temperature torrefaction represents a new category.

In addition to fuel or process material production for international markets and the resulting income for processors, there is also a much higher regional value added to the areas where biomass is procured through torrefaction gases. This does not only help the business case of the processor itself by presenting an investment opportunity with multiple income streams but will at the same time help to build up local structures and reach in many global regions some of the 17 SDGs (Social Development Goals) of the United Nations.

Figure 5 Thermal efficiency of pelletization, torrefaction and high temperature torrefaction processes



Source: IBTC, M. Wild

6 Torrefied Biomass Densification

Biomass becomes very brittle during the torrefaction process. As such it has the advantage to easily grind in mills. The flip side of this fact is that torrefied biomass is grinding itself partly during transport and handling. Dust is always a hazard, and wood dust, independent if from natural wood or torrefied wood, is an explosive substance. Hence torrefied biomass requires densification after torrefaction to form easily and safely tradeable products.

6.1 Influence of torrefaction on the pelletability of biomass

Shortly after the market launch of wood pellets for energy use at the end of the 1990s, systematic investigations showed that different types of wood differ significantly in terms of their pelleting properties, due to their chemical composition. This does not refer to the proportion of cellulose, hemicellulose and lignin, but to the proportion and composition of the so-called "extractive substances". These are, on the one hand, the group of waxes and resins that influence the throughput in pelleting, and on the other hand, the group of polyphenols and polysaccharides (such as starch) that affect the quality of the pellets. These research studies[5] have also already shown that the addition of starch as a binder significantly increases the binding capacity in the pellets. The reason is that the 5-hydroxymethylfurfural formed from the starch during the pelleting process forms particularly stable polymers with the lignin of the wood.

This introduction to the basic interrelationships in pelleting is important for understanding why, with increasing intensity of torrefaction, pelleting of the resulting products becomes increasingly difficult. Already during drying (in practice, this is particularly evident in high-temperature drying in drum driers as opposed to the gentler drying in belt driers), torrefaction in particular leads to the expulsion of the above-mentioned "extractive substances", which are so important for optimum pelleting and which are contained as VOCs (volatile organic compounds) in the drier exhaust air or in the torrefaction gas. The binding properties inherent in biomass that used to be present in the wood are lost.

Accordingly, biomass that are slightly torrefied, i.e., still "light brown" and wood-like, generally can be pelletized with good results and at relatively low energy inputs, since the natural binding forces of biomass are still present to a sufficient extent. Dark brown to black biomass which have been more intensively torrefied are more difficult to pellet. Higher forces in the pelleting press and thus higher energy inputs are required - as practice clearly shows. As for extremely

[5] Sources:

- Sitzmann, W., Puls, J., Knöll, A.: Der Pelletierprozess als Voraussetzung für die energetische Nutzung von Nebenprodukten der holzverarbeitenden Industrie, Annual Meeting of Process Engineers, September 29 – October 1, 1999, Leipzig, Germany
- Knöll, A., Puls, J., Sitzmann, W.: Holzpellets – Brennstoff aus Resten heimischer Nadelhölzer, Poster, LIGNA-fair, May 10 – 15, 1999, Hanover, Germany

torrefied biomass with a calorific value close to 30 MJ/kg, the practician will notice that these products hardly "smell" anymore. A clear indication that volatile components of the class of "extractive substances" are hardly present anymore. Even with the highest pelleting forces (and thus energy inputs), it is almost impossible to produce pellets conforming to standards from such products. With decreasing binding properties of the torrefied biomass, however, it is increasingly important to use binders. Based on empirical values, the line between good pelletability and difficult pelletability can be assumed in the calorific value range of 19 - 21 MJ/kg.

Conditioning of torrefied biomass for pelleting

It is crucial that the torrefaction is as homogeneous as possible; the particles should have as uniform a degree of torrefaction as possible down to the core. To this end, the product to be torrefied and later pelletized must have the narrowest possible particle size distribution. Upstream of the pelleting press, a device for adjusting the water content as well as for adding binder ought to be provided.

Binders

For an overarching discussion of the additives and binders topic, please see 6.4.

Energy requirement for pelleting

The energy requirement for pelleting strongly depends on the intensity of torrefaction. For slightly torrefied products, the mechanical energy input required for pelleting is roughly the same as for pelleting non-torrefied biomass (approx. 50 - 60 kWh/t for softwoods). In the case of more intensively torrefied products, the energy inputs required for pelleting are generally higher (80 - 100 kWh/t), depending on whether a binder is used and, if so, which binder.

Requirements on the machines

Basically, the common regulations regarding ATEX and the Machinery Directive must also be observed when processing torrefied biomass. Also, with regard to the requirements on the machines, it is important to consider the intensity of torrefaction and its effects on relevant parameters such as particle size (dust), ignition temperatures and ignition energy, which must be evaluated on a project-by-project basis. Slightly torrefied biomass can usually be processed with the same safety precautions as non-torrefied biomass.

Conclusion

Due to the extremely different properties of the biomass before torrefaction, the different torrefaction processes and the resulting variety of products with a corresponding great diversity of physical and chemical properties, the process step of pelleting should always be factored as early as possible into the process development for the production of torrefied pellets.

6.2 Torrefaction after pelleting

Coal-fired power plants demand fuels with properties similar to those of coal: hydrophobicity (storage of the fuels in the open is possible), brittleness (grinding by means of the coal mills already available in the power plant) and as high a calorific value as possible, similar to that of coal. "White pellets" meet these requirements only to a limited extent.

However, the higher the degree of torrefaction, the easier it is to achieve these properties from biomass-based raw materials. As described under the section 6.1, however, increasing torrefaction entails a drastically increasing energy requirement in the subsequent pelleting process. Here, the requirements of the power plants collide with what is technically feasible or reasonable in terms of energy.

Hence the idea of reversing the process predominantly used at present (torrefaction and subsequent pelleting). Thus, by first producing "white pellets" making use of the biogenic binders ("extractive substances") and then torrefying the pellets, the following advantages are gained[6]:

- Manufacturers of wood pellets can expand their product portfolio by adding an additional torrefaction line to subsequently torrefy "white pellets", either completely or in part. Wood pelleting plants can be easily retrofitted.
- Compared to wood chips, for example, wood pellets used for torrefaction have a narrow particle size distribution and homogeneous lumpiness. "Over processing" or "under processing" of the raw material mixture is minimized. The degree of torrefaction can be perfectly adjusted for all particles by means of the retention time, which is particularly true for discontinuously operated torrefaction reactors.
- The narrow particle size distribution provides advantages especially in the operation of fluidized bed torrefaction reactors.
- And the most important advantage: The total energy consumption in the production of torrefied pellets is significantly lower than in conventional processes. Reason: The energy required for the pelleting step is drastically lower than for the pelletization of (especially intensively) torrefied biomass.

Disadvantage: Torrefaction of "white pellets", however, results in a loss of mass due to the process and thus reduces the bulk density. This can be counteracted by pre-pelleting the "white pellets" produced in advance somewhat more intensively.

[6] Sources:
- Int. Patent Application: PCT/EP2012/076433.
- Manouchehrinejad, M.; Mani, S.: *Torrefaction after pelletization (TAP): Analysis of torrefied pellet quality and co-products,* Biomass and Bioenergy, 118, November 2018, p. 93 – 104
- Yoshida, T., Nomura, T., Gensai, H., Watada, H., Sano, T. and Ohara, S.: (2015) *Upgraded Pellet Making by Torrefaction - Torrefaction of Japanese Wood Pellets,* Journal of Sustainable Bioenergy Systems, 5, 82 - 88

6.3 Briquetting

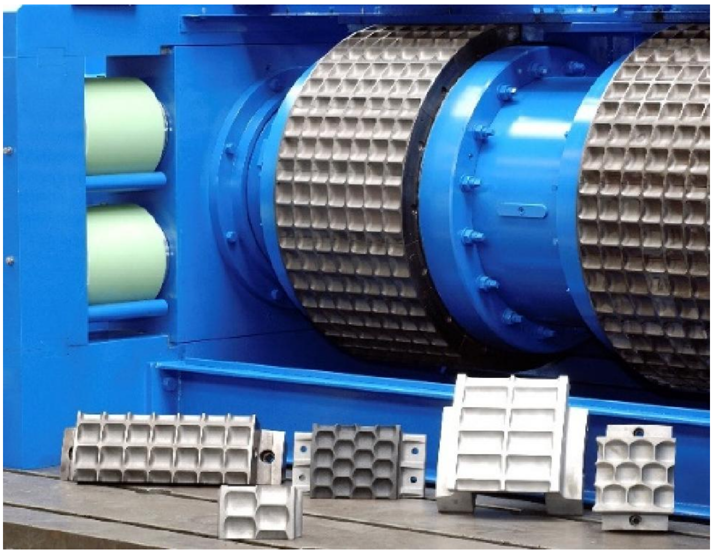
Whatever is true for pelleting is true for briquetting as well, the binding characteristics of torrefied biomass are weak and hence to produce high density durable torrefied biomass briquettes requires a lot of know-how and eventually some binders, especially for the high temperature torrefied materials.

Briquetting is a process that facilitates the compression of volatile or voluminous powders into several compact and stable forms. It is a summary expression for various technologies to compact materials.

Torrefied materials can be processed into briquettes by Roller Presses (Roller Briquetters), Extrusion and Mechanical presses.

When briquetting by roller briquetting, the powdery material is passed between two rollers that rotate in opposite directions. Ensuring a consistent shape and size, the densification step offers many advantages regarding the use of the material and, in some instances, is an essential prerequisite for further downstream processing.

Figure 6 Pressing rollers for briquetting machine of various sizes and shapes

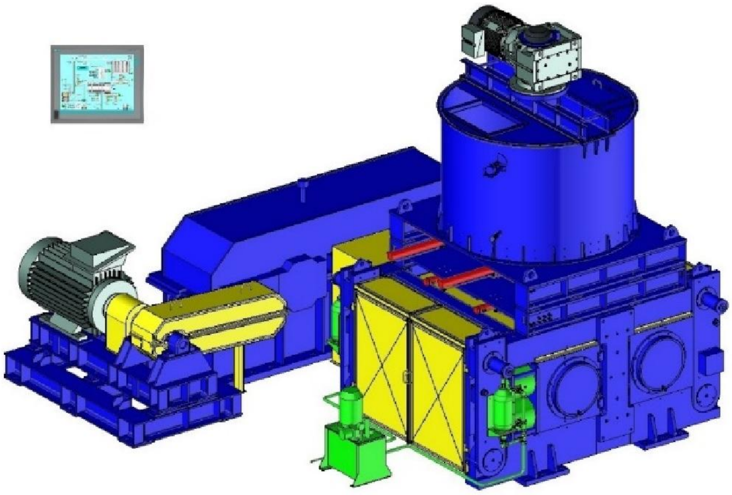


Source: Crespel & Deiters GmbH Technical applications

Briquetting units (Figure 8) transform either hot or cold fine materials (from –40 °C to +1000 °C) into various shapes, sizes and volumes (up to >600 cm^3), depending on the defined characteristics of the end product. The densification process significantly reduces the volume of the processed powder(s) to produce briquettes with a true density up to 5 g/cm^3. The capacity of a briquetting line can range from 50 kg/h to 100 t/h.

Obtained at low or high pressures (from 5–180 kN/cm^2), the briquettes then undergo mechanical or heat treatment, if required, depending on the characteristics of the treated material and the end product.

Figure 7 Cold briquetting unit with frame, drive, hydraulic, feeding and control system



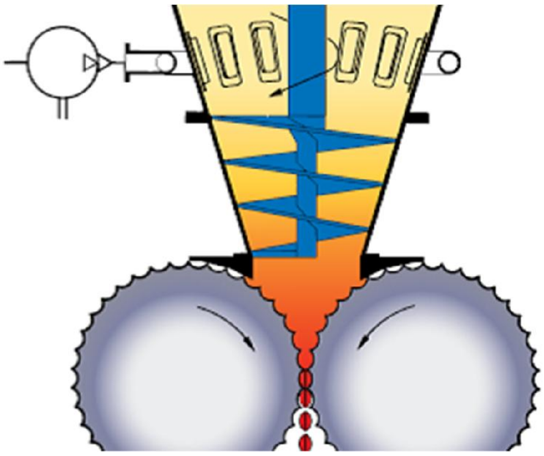
Source: Sahut-Conreur

Often, roller presses are gravity fed from a hopper. When handling a torrefied biomass — a lightweight raw material with bulk densities of approximately 150 kg/m³ — a pre-densification step is recommended with active/force feeding for efficient processing.

The successful compaction of a torrefied biomass[7] essentially requires the use of a binder and homogenous mixing with the raw material (see 6.4). For highly aerated products, the force feeder (Figure 3) can be equipped with a deaeration system (vacuum pump) to remove the air contained in the material.

[7] Source: Carsten Mergelmeyer, Crespel&Deiters GmbH Technical applications; Nicolas Juster, Sahut-Conreur

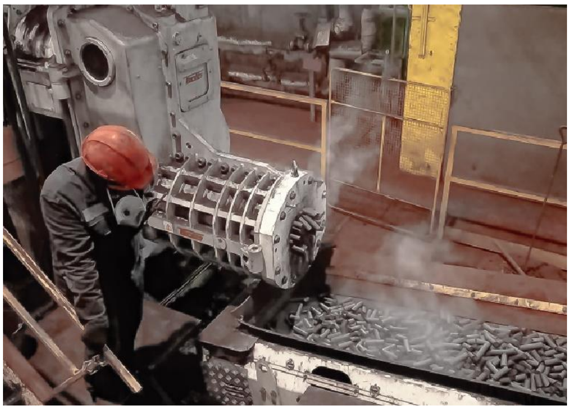
Figure 8 Force feeder equipped with one or two conical screws



Source: Sahut-Conreur

Briquetting by Extrusion: this technology implements a combination of high pressure (up to 60 bar) under a vacuum environment. This process results in the production of denser briquettes with higher calorific values compared to other agglomeration technologies.

Figure 9 Extrusion of torrefied biomass in progress



Source: Talleres Felipe Verdés S.A

The obtained product has a cylindrical shape. This technology has high flexibility in dimensions, being able to produce any diameter with the same equipment by means of different extruding dies.

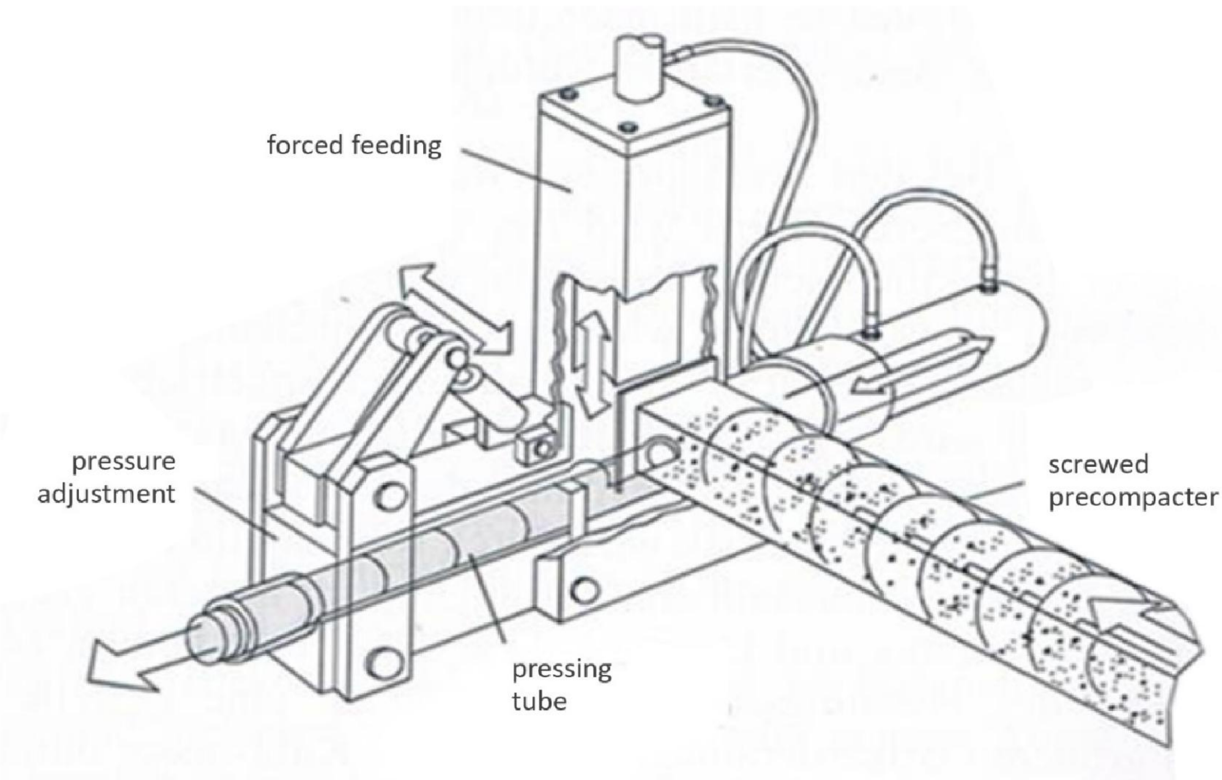
The extrusion technology allows working with a wider range of moistures, allowing to obtain briquettes from materials up to 40% moisture, thus avoiding a previous drying step with several materials[8].

[8] Source: Julio Gómez Izquierdo, Talleres Felipe Verdés S.A

Mechanical presses or piston presses apply pressure discontinuously by a piston on material, not necessarily powder, into a cylinder. The incoming raw material is pressed against the compacted material inside the pressing tube and leaves the die in the rhythm of the piston action. Through pressure and friction forces inside the pressing tube, the material is strongly heated, and cooling mechanisms might be considered.

Briquettes resulting from these presses are currently seen in 50, 70 and 100mm diameter. Length is variable or can be defined by cutting/breaking at intended length.

Figure 10 Schematic representation of a piston briquetting machine



Source: energypedia.info

6.4 Additives and binders

As explained in section 6.1, the drying and the torrefaction processes are significantly damaging the inherent binding properties of the biomass. Indeed, the "extractive substances" (waxes and resins + polyphenols/polysaccharides) are for most of it expulsed during the drying and torrefaction process.

Therefore, binding agents are almost a must in torrefied biomass densification.

Today, the availability of application-specific binders can make a significant contribution to a holistically optimised process. Major advances are also being made in the development of binder concepts that promote the water resistance of agglomerates.

During agglomeration, binders (for instance starch based) change both the properties and effects of the end product. When conditioned with water, these excipients develop a gel-like structure that binds fine particles and acts as a lubricant during the pressing process. When drying begins (after pressing), they then act as hardeners. In this way, starch-based binders offer numerous advantages that are both ecologically and economically beneficial, including

- improving durability
- reducing abrasion and dust formation
- lowering the energy consumption of the pelleting plant
- reducing maintenance and wear costs.

For the efficient use of such a process agent, suitable conditioning of the torrefied biomass is required and has a significant influence on quantity of binder required.

Depending on end use and resulting requirements (durability, drop durability, crush strength, water resistance, odour protection etc.) formulations of binders can be individually adjusted

Distler/Sitzmann[9] quote from experience, that hydrophobic binders (e.g., from plastics) have produced good results in terms of pellet quality and water stability and - given the proper selection of components - have made it possible to pellet products that would otherwise be impossible to pellet. These plastics can also be produced from renewable raw materials in keeping with the biorefinery concept - a path that should indeed be followed.

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[9] Source: Distler, T. and Sitzmann, W.: *An investigation on additives for pelletizing highly torrefied biomass, 2018*. In: Biofuels, Bioprod. 10.1002/bbb.1919

Other binders[10] that we have heard about being tested so far, which is not necessarily a complete list of tested binders.

- Starch with or without additives
- Molasses and hydrated lime
- Molasses and other additives
- Coal tar pitch
- Wood tar
- Lignosulphonates
- Resins and hardeners
- Glucosidic (e. g. molasses, starch)
- Inorganic solutions (e. g. sodium silicate)
- Clays (e.g., bentonite)
- Thermoplastic (e. g. bitumen, pitch)
- Mortar-type (e. g. cement, hydrated lime)
- Non-glucosidic organic solutions (e. g. resins)
- Fibers (e.g., paper fluff)

[10] Source: Carsten Mergelmeyer, Crespel&Deiters GmbH Technical applications; Martin Englisch, BEA GmbH

7 Product trade formats and standards

It has already been explained why torrefied biomass needs to be densified before entering the market.

Now, first, there is no rule without an exception, and this is torrefied biomass powder, which is traded over short distances in special tanker trucks connecting the torrefaction plant directly with a carbonized biomass dust consumer, which is also equipped to handle safely the powder without any health hazards.

Aside of this, today only a marginally consumed exception of torrefied biomass is densified into the format of pellets or briquettes through different technologies. In an ideal world, resulting products should be tradeable globally and standardization of products did prove to be a good means to help the dissemination of a thereby generally accepted product specification.

For this reason, IBTC initiated in 2012 the inclusion of torrefied and thermally treated biomass into the universe of ISO 17225 - Solid Biofuels, where Part 8 deals exclusively with thermally treated biomass and is currently in the upgrading from a Technical Specification to a full standard.

Figure 11 Pellets with cylindrical shapes and diameters of 6-10 mm produced in flat or ring die pellet presses.

Source: Andritz AG

Figure 12 Pellets produced in disc pelletizers

Source: IBTC, M. Wild

A relative soft and lightweight agglomeration of particles for certain applications. Not suitable for long distance bulk transport.

Figure 13 Briquettes with cylindrical shapes

Source: Andritz AG

Briquettes with cylindrical shapes produced in extruder briquetting presses or mechanical / piston briquetting presses.

Figure 14 Briquettes produced in roller presses

Source: IBTC, M. Wild

Briquettes produced in roller presses can have almost every shape, from the well-known pillow shape to puck- egg or even cylinders. Problematic for lower torrefied materials (sponge effect) but most efficient with higher carbonized materials that will anyhow need a binder.

7.1 Standardisation of torrefied biomass products

Torrefaction of biomass is an umbrella term behind which stands a variety of processes applied to a variety of different biomass types. Therefore, there is always a need for detailed information in the discussions between producers and consumers of the products. This is of course interesting for individual productions, but if a larger market is to be served and if the consumers are to secure their access to the products via several producers, it is essential that the products are identical and interchangeable and that this is clear to both the producers and the consumers.

In 2013, one of the first activities of the just founded IBTC was to initiate a standard for torrefied biomass. In addition to the companies involved in torrefaction, many researchers, above all Eija Alakangas, supported the initiative and an NWIP (New Work Item Proposal) was started within the framework of ISO 17225 Solid Biofuels. As a first step, in 2016 this resulted in ISO TS 17225-8, Technical Specification (TS) of thermally treated biomass. While this white book is being produced, the corresponding ISO committee has decided over the course of regular evaluations to upgrade the TS to a full standard. This is being developed by a working group, together with formats to make the standard as flexible as possible to accommodate the multitude of applications already known today but also the ones that may emerge in the future and their resulting requirements.

While the original TS for thermally treated biomass was still very much oriented to the structure of white wood pellets, it can be assumed that the next publication, the full standard, will partly depart from this orientation and many of the limit values may no longer be related to mass but to energy content. This will take into account the possible degrees of torrefaction and the resulting concentration of some non-volatile components.

Overall, the TS has already made a big step towards a general understanding of torrefied biomass products. The full standard, which is now being developed, will make a further contribution to the understanding of products and product groups, the interchangeability of products from different producers, and their commoditization.

7.2 Logistics aspects of torrefied biomass

Standard storage, handling, and transport issues of natural or densified biomass only, like off-gassing, fungi attraction, decomposition through microbiological activities or self-heating are much less important to the point of being insignificant if the natural biomass becomes a torrefied and densified product.

Table 1 Comparison of typical characteristics relevant for transport, storage and handling

	WOOD CHIPS	WOOD PELLETS or BRIQUETTES	TORREFIED WOOD PELLETS/BRIQUETTES
DOCUMENTS			
Certificate of Origin	yes	yes	yes
Subject to Phytosanitary Regulation	certificate required	no	no
IMO 4.1 flammability		no	no
IMO 4.2 self heating			no
IMSBC	yes p 287f	yes p 289f	MSC 92/26/Add.1 p37
HS code			
Customs code	high quality chips44012100 soft wood, 44012200 others	4401 3020,440131..	44029000
	lower quality chips and forest industry by-products (bark) 44013080		
REACH	excepted	excepted	no registration required
ISO standard	17225-4	17225-2	TS 17225-8,
EN Standard	14961-4	14961-2	from ISO
KEY QUALITY CRITERIA			
Quality Determination	moisture	meeting ISO 17225-2	meeting ISO 17225-2
	size	certification	NCV
	bark content	NCV	fines, durability
	NCV	fines, durability	ash & ash melting
			grindability
			water absorption
HANDLING			
Hazards	may be subject to oxidation leading to CO	may be subject to oxidation leading to CO	
		swelling if exposed to moisture	

				dusting		dusting
Fire risk/self ignition		low>15% moisture				MHB
Stowage and segregation						segregation as for class 4.1 materials
Loading/handling		free trimming		free trimming		free trimming
Weather precautions/water sensitive		no		yes, must be kept dry		cargo shall be kept as dry as practicable
Open storage		yes		no		short term yes, long-term depending on product
Closed storage needed		no		yes		no/yes
Offgassing observation needed		in closed storage yes		yes		no
Ventilation requirements		recommended		recommended before entry		testing before entry, vent if necessary
Stowage factor in vessel ft3/mt		85-230		53-59		49-54
Bulk density (kg/m^3)		150-400		600-660		650-800
IMSBC group		B		B		B

8 EU sustainability requirements – advantages of torrefaction

Following the aim to achieve carbon-neutrality by 2050, EU has introduced further regulations for greenhouse gas (GHG) emissions mitigation.

The Revised Renewable Energy Directive II[11], commonly designated as RED II, supports the EU target to increase the renewable energy consumption share to 32% by 2030. It includes a set of sustainability criteria that bioenergy installations with a total rated thermal input equal to or exceeding 20 MW need to fulfil. Biomass feedstock from agricultural residues is only considered sustainable when national authorities have monitoring or management plans in place to address the impacts on soil quality and soil carbon. Additionally, this feedstock cannot be obtained from lands with a high biodiversity value or high carbon stock, or lands that were peatlands, unless evidence is provided that the cultivation and harvesting of that raw material does not involve drainage of previously undrained soil. Forest biomass feedstock shall come from a country with laws, or at least management systems, applicable in the harvest area to ensure legality of harvesting and sustainable management of the forest ecosystem. It should also comply with the land-use, land-use change and forestry (LULUCF) criteria. Additionally, biomass power and heat plants with operations starting after January 2021 and January 2026 should achieve 70% and 80% in GHG savings, respectively, as defined in the GHG saving methodology set out in the Directive. The RED II is currently under revision, hence the criteria described above might change.

Furthermore, to scale up investments in sustainable activities, the EU developed a classification system, establishing a list of environmentally sustainable economic activities, denominated the EU Taxonomy[12]. Projects for heating/cooling and power generation from bioenergy, to be considered as green activities, need to comply with the feedstock criteria from RED II and achieve at least 80% of GHG emission savings in relation to the fossil fuel emission factors defined in the same Directive. Electricity generation installations with a thermal input between 50 to 100 MW need to apply high-efficiency cogeneration technologies or meet an energy efficiency level associated with the best available techniques ranges to be considered for sustainable funding. Power plants with a thermal input above 100 MW should fulfil one or more

[11] EC: *Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the Promotion of the Use of Energy from Renewable Sources*. Official Journal of the European Union, 328, 2018. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L2001&from=EN (accessed 04.02.2022).

[12] EC: *Annex 1 supplementing Regulation (EU) 2020/852 of the European Parliament and of the Council by establishing the technical screening criteria for determining the conditions under which an economic activity qualifies as contributing substantially to climate change mitigation or climate change adaptation and for determining whether that economic activity causes no significant harm to any of the other environmental objectives*, 2021. https://ec.europa.eu/finance/docs/level-2-measures/taxonomy-regulation-delegated-act-2021-2800-annex-1_en.pdf (accessed 04.02.2022)

of the following criteria: reach an electrical efficiency of at least 36%; apply highly efficient combined heat and power technology; or use carbon capture and storage technology.

There is currently an untapped potential on the use of agricultural residues and wood waste, which has not been exploited yet as those biomass types bring along few challenges or worse characteristics in comparison with fresh wood.

Table 2 Woody biomass resources and agricultural biomass potential in Europe[13]

Biomass feedstocks	Annual potential (PJ/a)
Woody biomass resources	
Stem wood	1438
Landscape management wood residues	514
Forest residues	1186
By-products and residues from wood processing industry	644
Used wood	397
Agricultural biomass potential	
Cereal straw	776
Sugar beet	31
Rice husk	9
Corn residues	85
Pruning residues, total	423
Vineyard residues	14
Olive three prunings	28
Agricultural residues (sugar beet, legume, potato, oil plants)	656

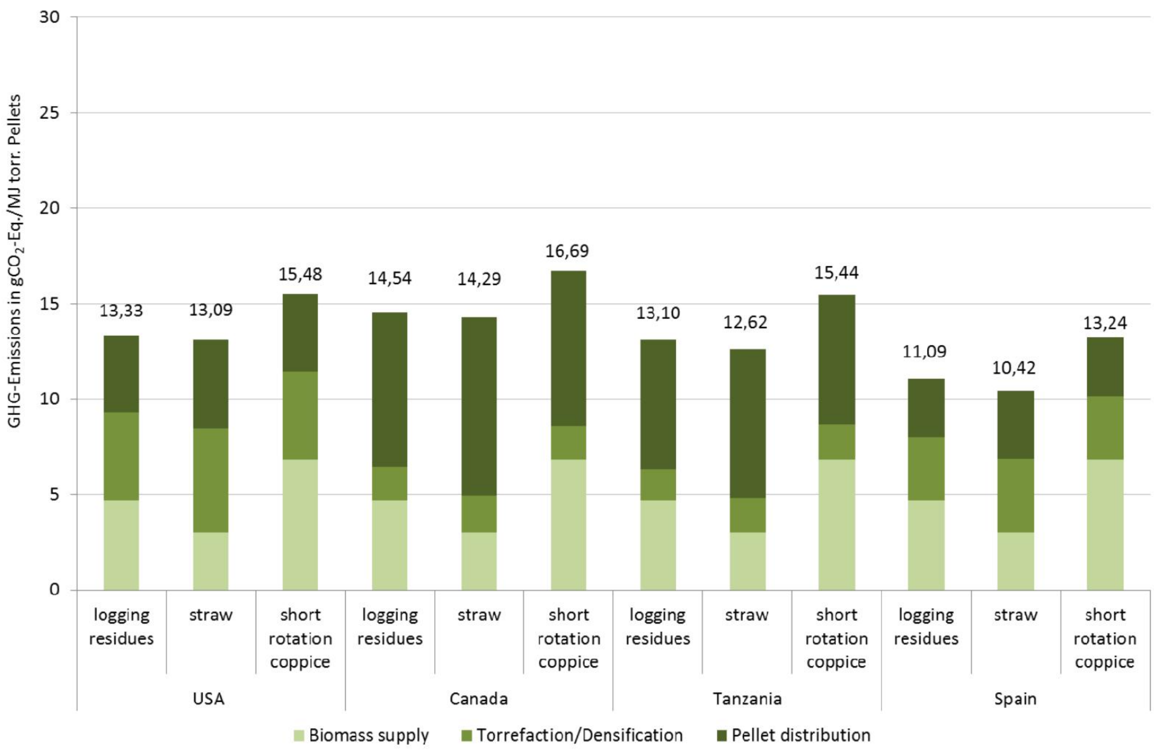
Agricultural residues include primary residues, which originate from harvest operations - e.g., straw, leaves, corn stover, stalk, husk, bagasse, and cob – and secondary residues, which originate from industrial processing - e.g., pit, shell, peeling, husk, and bagasse. Life cycle analysis of torrefaction pellets made with different biomass feedstocks suggests agricultural residuals might be less GHG intensive. Furthermore, the default GHG emission factors included in RED II are lower for agricultural residues with a density lower than 0,2 t/m^3 compared to woody biomass feedstocks, even for longer distances. This indicates that there are sustainability advantages in using these types of feedstocks. Although the production pathways

[13] Biedermann, F., Brunner, T., Mandl, C., Obernberger, I., Kanzian, W., Feldmeier, S., Schwabl, M., Hartmann, H., Turowski, P. and Rist, E.: *Production of Solid Sustainable Energy Carriers from Biomass by Means of Torrefaction*, 2016. https://cordis.europa.eu/docs/results/282/282826/final1-sector_fpsr_rev_final.pdf (accessed 04.02.2022)

included in RED II do not include a torrefaction step, it is assumed that it would not have significant impact in the results, as the torrefaction process is fuelled partly by the combustion of the energy containing gases released during the same process, which are considered carbon neutral sources.

The SECTOR project performed a study[14] to investigate the potential environmental impacts – with a focus on GHG emissions for various pathways for the production and application of torrefied and non-torrefied biomass. Different feedstocks (logging residues, straw, short rotation coppice) and locations (USA, Tanzania, Canada and Spain) for the torrefaction and densification process were assessed, while the material was considered to be transported to Europe (Netherlands). A summary of the results achieved is presented in Figure 15. The authors of the study indicate that due to the due to the higher energy density, the transportation of the torrefied pellets leads to lower GHG emissions compared to the transportation of conventional pellets.

Figure 15 GHG-emissions from the supply of torrefied pellets from different feedstock types and locations



Source: Sector project Deliverable 9.8

[14] Majer S. et al. 2015. SECTOR Project: Production of Solid Sustainable Energy Carriers from Biomass by Means of Torrefaction (GA 282826). Deliverable No. D9.8 Executive summary of WP 9 results. https://sector-project.eu/fileadmin/downloads/deliverables/D9.8_Executive_Summary_of_WP9_results_Final.pdf (accessed 04.02.2022)

9 Economic benefits of torrefaction

9.1 Reduced feedstock cost

Feedstock price seems to have the most significant influence on the production costs for torrefied fuels[15]. Torrefaction leads to higher heating values, which lower the costs after production (through reduced mass/volume in transport), thus allowing the possibility to access the most competitive prices for biomass feedstock while complying with GHG criteria in the EU.

Additionally, torrefaction technology allows for a broadened feedstock range, compared to wood-based biomass fuels, which is sometimes still not commercialized. Not only this provides cheaper feedstock for torrefied fuels production, but it also contributes to lower price volatility of torrefied pellets and therefore more predictability of returns.

Table 3 presents a cost assessment for different biomass feedstocks in some EU member states from a project report published in 2013. Since that time, market conditions may have changed, but generally the impact of the rising energy prices on the cost of alternative biomass feedstocks is lower. This is confirmed by the cost assessments performed for several advanced[16] and strategic[17] case studies performed within the MUSIC project.

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[15] Biedermann, F., Brunner, T., Mandl, C., Obernberger, I., Kanzian, W., Feldmeier, S., Schwabl, M., Hartmann, H., Turowski, P. and Rist, E.: *Production of Solid Sustainable Energy Carriers from Biomass by Means of Torrefaction*, 2015 https://www.sector-project.eu/fileadmin/downloads/deliverables/SECTOR_D3.2_VTT__final.pdf (accessed 04.02.2022)

[16] Reumerman, P. et al. 2021. Market Uptake Support for Intermediate Bioenergy Carriers. MUSIC, Horizon 2020 project no. 857806, WP5, D5.3: Set of four Advanced Case Studies (Public Edition). https://www.music-h2020.eu/publications-reports/MUSICD5.3SetoffourAdvancedCaseStudies_publicedition.pdf (accessed 15.07.2022)

[17] Reumerman, P. et al. 2021. Market Uptake Support for Intermediate Bioenergy Carriers. MUSIC, Horizon 2020 project no. 857806, WP5, D5.5: Set of four Stategic Case Studies (Public Edition). https://www.music-h2020.eu/publications-reports/MUSIC_Strategic_Case_Study_Report.pdf (accessed 15.07.2022)

Table 3 Cost assessment of different feedstocks for biomass fuels production in six EU Member States[18]

	Austria	Finland	Germany	Greece	The Netherlands	Poland
Commodity	**€/t free field side/forestry road/waste yard or producer**					
Straw (minimal costs)	35	34	32	38	34	36
Straw (price)	80 to 180	n.a.	160	144	144	n.a.
Forestry residues (price)	30 to 80	25 to 80	30 to 80	(30 to 80)*	30 to 80	30 to 80
Organic municipal waste (gate fee)	-15 to -60					
Surplus manure (price)	-	-	-10**	-	-15 to -25**	-
Waste wood (gate fee)	-60 to -25	-60 to -25	-60 to -25	-60 to -25	-60 to -25	-60 to -25
Land scape & road side management (price)	66 - 81					
Food processing residues (price)	0 to 180	0 to 180	0 to 180	0 to 180	0 to 180	0 to 180
Energy crops (price)	80	80	80 to 160	80 to 150	80 to 150	80

* theoretical price, no harvester, forwarder and chipper available; **In parts of the country; n.a.: not available; -: no surplus manure

9.2 Reduced production costs

Due to similarities in torrefaction fuels composition and coal, torrefaction allows for easier integration of biomass in existing coal infrastructures. Integration into an existing CHP plant does not reduce the production costs substantially, but integration in other operations (sawmills, pulp and paper mills) however does. Torrefied pellets can also offer advantages to the power/heat plant due to extra savings for storage and maintenance compared to biomass that is not thermally treated.

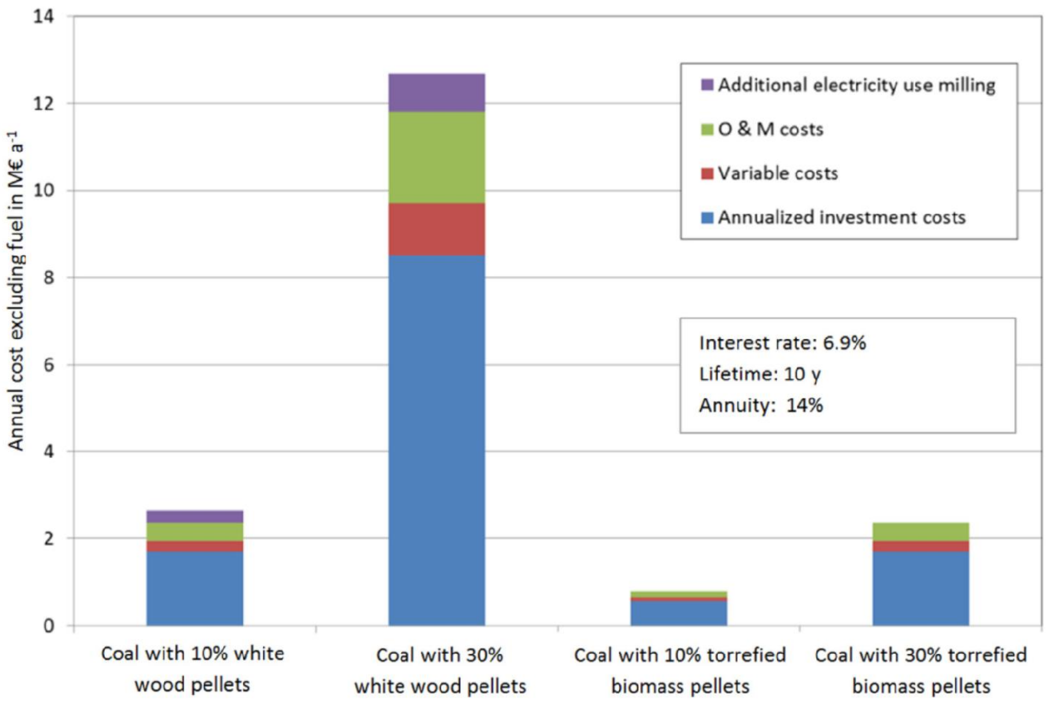
[18] Balcazar, H., Fougret, C.M., Geigle, K.P., Gust, S., Hagen, E., Lappas, A., Lenz, K., Maier, J., Papadopoulou, E., Parton, R. and Pudelko, R.: *Biomass Based Energy Intermediates Boosting Bio-Fuel Production-Bioboost.* 2013. https://bioboost.eu/uploads/files/bioboost_d1.1-syncom_feedstock_cost-vers_1.0-final.pdf (accessed 04.02.2022)

Table 4 Production costs of torrefied wood pellets in different plants set-ups[19]

Case	Stand-alone torr. plant nordic region	Stand-alone torr. plant nordic region	Stand-alone torr. plant SE USA	New sawmill and torr. plant integrated	Existing sawmill and new torr. plant	Existing pulp mill and new torr. plant
Output capacity in t a^{-1}	72,800	500,000	500,000	231,600	101,100	407,200
Fixed operating costs in M€ a^{-1}	3.99	8.70	8.70	5.39	3.47	6.71
Variable operating costs in M€ a^{-1}	9.87	74.56	57.66	31.73	14.00	58.5
Annualized capital costs in M€ a^{-1}	5.44	20.95	21.23	11.68	6.84	17.34
Total costs in M€ a^{-1}	19.30	104.2	87.58	48.80	24.31	82.54
Production costs in € a^{-1}	265	208	175	211	240	203
Production costs in € MWh^{-1}	43	34	29	34	38	33
Market price of wood pellets in € MWh^{-1}	30	30	30	30	30	30
Price compared to base case in %	100	79	66	79	91	76
Price compared to market price in %	145	114	96	115	126	111

Particularly for co-firing, torrefaction could highly reduce production costs, compared to white wood pellets.

Figure 16 Annual cost of co-firing white wood pellets and torrefied wood pellets[20]



Note: fuel costs are excluded

[19] Thrän, D., Witt, J., Schaubach, K., Kiel, J., Carbo, M., Maier, J., Ndibe, C., Koppejan, J., Alakangas, E., Majer, S. and Schipfer,: *Op. cit.*

[20] Thrän, D., Witt, J., Schaubach, K., Kiel, J., Carbo, M., Maier, J., Ndibe, C., Koppejan, J., Alakangas, E., Majer, S. and Schipfer, F.: Moving torrefaction towards market introduction – Technical improvements and economic-environmental assessment along the overall torrefaction supply chain through the SECTOR project. Biomass and Bioenergy, 2016, 89.

9.3 Increased revenues from GHG savings

Increased GHG savings allow for additional revenues from allowances trading in carbon markets, such as EU ETS, and from sales of renewable energy certificates in countries where quota/certificates systems apply (e.g., Flanders region in Belgium[21]).

Pathways investigated for co-firing with torrefied pellets recorded GHG mitigation potentials between 72% and 87%, relatively to coal. GHG savings in the range of 58% and 79% (relatively to natural gas) were calculated for replacement of gas in small-scale natural gas fired boilers. Moreover, an IEA[22] study shows a GHG reduction of 81.3% and 83.9% for white wood pellets and torrefied pellets respectively for a supply chain between the southeast of the US and Europe (UK/ARA region). Overall, it seems that torrefied biomass has the capacity to achieve higher levels of GHG savings compared to conventional pellets under the appropriate conditions.

Table 5 GHG emissions reduction of conventional pellets vs torrefied biomass[23]

Application[a]	Conventional pellets	Torrefied biomass
Co-firing with hard coal	CO_2-Eq. of 0.06—0.08 kg MJ^{-1} (electric output) 72—80% reduction	CO_2-Eq. of 0.03—0.06 kg MJ^{-1} (electric output) 80—87% reduction
Replacing natural gas in 15 kW boiler	CO_2-Eq. of 0.22—0.31 kg MJ^{-1} (thermal output) 58—70% reduction	CO_2-Eq. of 0.15—0.21 kg MJ^{-1} (thermal output) 71—79% reduction
Production and combustion of methanol	CO_2-Eq. of 1.25—2.01 kg MJ^{-1} (electric output) 5—42% reduction	CO_2-Eq. of 0.95—1.55 kg MJ^{-1} (electric output) 28—55% reduction

[a] The reference levels for the three applications are: 1: hard coal: CO_2-Eq. of 0.3 kg MJ^{-1} (electric output); nat. gas: CO_2-Eq. of 0.07 kg MJ^{-1} (thermal output); MeOH: CO_2-Eq. of 2.15 kg MJ^{-1}.

[21] Anciaux, S.: *Flanders: Quota system (CHP certificates)*, 2019. http://www.res-legal.eu/search-by-country/belgium/single/s/res-hc/t/promotion/aid/flanders-quota-system-chp-certificates/lastp/107/ (accessed 04.02.2022)

[22] IEA Task 32, *Status overview of torrefaction technologies A review of the commercialisation status of biomass torrefaction, 2015. https://www.ieabioenergy.com/wp-content/uploads/2015/11/IEA_Bioenergy_T32_Torrefaction_update_2015b.pdf* (accessed 04.02.2022)

[23] Anciaux, S.: Flanders: Quota system (CHP certificates), 2019

10 Applications and experiences

10.1 Steam coal substitute for pulverized coal power plants

Introducing biomass as coal substitute in pulverized coal power plants can be challenging (in terms of volumes, moisture content, heterogeneity of fresh biomass or comparably calorific value, among other challenges). Grinding raw biomass to the size of talcum powder is required, which is technically challenging and economically almost prohibitive. Hence, wood pellets quickly became the biomass format chosen by the power industry: small percentages of biomass co-firing did prove that wood pellets were possible coal substitutes and required limited effort. However, significant investments and process adjustments are necessary to increase substitution rates. These measures can be avoided if the biomass is thermally pre-treated.

The resulting torrefied biomass characteristics are more comparable to the substituted coal's, i.e., very homogenous, with an increased calorific value that can be driven up to the level of coal, with identical bulk density, easily grindable and water resistant.

Industrial scale combustion tests of torrefied biomass have been performed at coal power plants in the Netherlands, Finland and elsewhere.

10.2 Metallurgical coal substitute for the steel industry

The steel industry is one of the biggest global consumers of coal. The coal is consumed in three different steps along the process chain of a typical steel mill: the coking unit, the sintering unit and the blast furnace. All these processes can accept biomass-carbon for partial or full substitution of coal.

However, raw biomass does not fit the requirements neither of the sintering plant nor of the blast furnace. Pre-treatment is therefore unavoidable. The coking plant, basically a coal torrefaction plant, is also not designed to handle raw biomass due to its heterogeneity and high moisture content and for this reason it will also have to be fed with pre-treated biomass or substituted completely (possible substitution rates still to be experienced).

According to Fick, G. et.al[24] the blast furnace requires approximately 430kg of carbon per tonne of liquid iron, which can be introduced in two ways: either loaded as lumps at the top with the sinter or injected as powder with hot air in the tuyeres in the lower part of the furnace. If loaded from the top, a high calorific value and C content is needed, as well as certain mechanical properties. This process of producing high temperature torrefied material – charcoal – is already being used in Brazil but because of current limitations on mechanical strength only up to 20% is used as coal replacement. To be introduced in the tuyeres of the blast furnace,

[24] Fick, G., Mirgaux, O., Neau, P. and Patisson, F.: *Using biomass for pig iron production: a technical, environmental and economical assessment*. Waste and Biomass Valorization, Springer, 2014, 5 (1), pp.43-55. 10.1007/s12649-013-9223-1 . hal-00943310

biomass should have a high calorific value and be easily grindable; these requirements could be satisfied by high temperature torrefied biomass. Translated into product specifications, it requires a carbon content of 7% and more respectively a HGI <40.

Alkali metals or traces of heavy metals could have an impact on the productivity of the furnace. Therefore, it is important to experience and test different biomass species to ensure that they will fulfil requirements on the long run.

Fick, G. et al. conclude that while raw biomass does not fit the expected requirements neither at the sintering plant nor at the blast furnace; torrefied biomass and charcoal – high temperature torrefied biomass – do perform well and lead to an almost equal reduction of CO_2 emissions. Moreover, significant reductions in NO_x and SO_x can be expected.

The technical possibilities paired with the requirement for a significant CO_2 emissions reduction have led to first substitution projects in steel mills and the upstream ore processing industry on all continents. Published results are very encouraging and a significant increase in consumption of highly carbonized biomass (i.e., C content >75%) is expected within this sector, at least until the complete substitution of carbon by hydrogen in steel making will technically and economically be a viable alternative.

10.3 Additives and engineered carbons

With torrefaction, bio-carbon can be produced not only for usage as an energy carrier, but also to exploit the carbon atoms themselves. Heterogeneous low value bio-residuals can be torrefied into homogeneous carbon dense quality streams. Torrefaction is no longer limited as a solution to aid Energy Transition, but to replace fossil resources to produce goods and materials that are dependent on the carbon atom itself. Torrefaction therefore aids the non-fossil raw materials transition

A multitude of industries are using high grade carbon as an additive, as fillers and fibres in pure form or as a mixture of carbon with other additives. Usually referred to as “Carbon Black”, the carbon part is mostly derived from conventional carbon sources. Torrefied biomass, especially a high temperature torrefaction product could become a significant source for Carbon Black industry. Already today some of the torrefaction companies can achieve carbon contents of 95% in their torrefied biomass product. How far this product is fulfilling already industry standards for Carbon Black, such as the ISO, DIN or ASTM standards is still to be understood. But as it is one of the advantages of the biomass torrefaction process that the operations conditions can be varied in order to produce products to the point of clients’ requirements.

Aside of the obvious applications in road construction (asphalt) and general construction materials sectors applications are seen in the plastics industry (fillers), as rubber for industrial applications and tires, printing toners, coatings and additives to polymers to name just a few of the numerous potential application sectors torrefaction is opening up for biomass or vice versa, torrefaction is opening for these industries an access to carbon neutral carbon.

10.4 BBQ

It may sound banal to address BBQ as an application of a high temperature torrefaction product. But it is as simple as it sounds. A high temperature torrefaction product has all particulates of charcoal but is produced in a much more efficient way than most of the batch produced charcoal imported into the OECD countries. Though charcoal has its own specifications and the requirements on raw feedstock to torrefaction hence the selection process prior to heat treatment is very different from the one for the standard energy applications.

10.5 Biochar

In agreement with the International Biochar Initiative (IBI)[25], we distinguish products labelled as “biochar” from those of high temperature torrefaction by their application. Biochar goes into the soil, i.e. everything that is used to improve the quality of the soil. If the product, which has many of the same or very similar specifications, is used in a production processes, we speak of high temperature torrefied biomass or “BioCarbon”.

The plant constellation and process parameters of high temperature torrefaction processes are very similar to biocharring processes. However, the quality criteria, parameters and testing methods are very different. Fulfilling the respective requirements of applications addressed by high temperature torrefied biomass product does not necessarily fulfil required biochar criteria and vice versa. Meaning the products are not fungible per se and swapping the one with the other might cause legal but as well technical issues.

[25] https://www.biochar-international.org/wp-content/uploads/2018/04/IBI-EBC_comparison_Oct2014.pdf

11 Status of torrefaction industry

The table below gives an overview of the torrefied biomass production plants that are in operation or in earlier phases. The data originates from an IBTC consultation, conducted in mid-2021.

Table 6 Overview of torrefied biomass plants (status as of mid-2021)

Location	Status	Commissioning	Name plate capacity	Intended NCV	Product form factor
Austria	Project in Operation	Since 2013	8.000 tonnes/year	22-23 MJ/kg	Briquette 70mm diameter
Belgium	Project in Operation	Pelletizing on industrial scale expected in 2022	Powder 30.000 tons/year pellets 150 kg /hour	Powder 22-28 MJ/kg pellets 21 MJ/kg	Powder (full production) Pellets (only for test purposes)
Croatia	Project in permitting phase	2020	4.500 tonnes/year 1.000 kW electricity	C_{fix} 90-98%	Charcoal 150mm
Estonia	Project in Operation		108.000 tonnes/year	21 GJ NCV Dry	Pellet
Finland	Project in final negotiation	2023	60.000 tonnes/year	22-23 MJ/kg	Briquette 70mm diameter
Germany	Project in Operation	Since 2016	3.000 tonnes/year	C_{fix} 90-98%	Charcoal 150mm
Ireland	Project in Operation		10.500 tonnes/year	n.a.	n.a.
Portugal	Project in Operation (not yet at full capacity)	Q4 2020	120.000 tonnes Black Pellets/year 80.000 tonnes White Pellets/year	18-22 MJ/kg	Pellet
Portugal	Project Under construction	2020	100.000 tonnes/year	22 GJ	Woodchips Pellet
UK	Project in Operation		30.000 tonnes/year	20,5-30 GJ NCV Dry	Pellet, char & powder
Russia	Project in permitting phase	Q4 2021	2 x 40.000 metric tonnes/year	21-25 MJ/kg	Pellet

Location	Status	Commissioning	Name plate capacity	Intended NCV	Product form factor
Canada (BC)	Project in permitting phase	Q1 2021	100.000 tonnes/year	21 MJ/kg	Pellet
Canada (Qc)	Project in Operation	2016	15.000 tonnes/year	21 MJ/kg	Pellet
US	Project in Operation	2012	75.000 tonnes/year	25-50 GJ/MT	Pellet
US	Project in permitting phase	2022	400.000 tonnes/year	25 - 30 GJ/MT	Pellet
US (Louisiana)	Project in Operation	2017	16.000 tonnes/year	19 MJ/kg	Pellet, briquette
US (Oregon)	Project in Operation	2019	90.000 tonnes/year	21-22,5 MJ/kg	Pellet, briquette
US	Project Under construction	Q3 2021	125.000 tonnes/year	30 MJ/kg	Pellet, briquette
US (Oregon)	Project Under construction	n.a.	100.000 tonnes/year	n.a.	Softwood TorrB® torrefied biomass briquette
Indonesia	Project in final negotiation	Q1 2021	80.000 tonnes/year	21 MJ/kg	Pellet, briquette
Thailand	Project in developments	Q3 2020	15.000 tonnes/year	20 GJ	Pellet
Ethiopia	Project in final negotiation	2023	60.000 tonnes/year	22-23 MJ/kg	Briquette 70mm diameter

Source: IBTC, M. Wild

Most of the torrefaction market players have teamed in IBTC, the International Biomass Torrefaction Council.

Figure 17 International Biomass Torrefaction Council (IBTC) members

12 Summary and conclusions

Torrefaction, in the view of the authors, is the term that describes thermal treatment of any solid biomass in an inert atmosphere with the aim to separate a part or all volatile matters in solid biomass and to concentrate carbon. Depending on temperature levels, residence times and technological approaches, various products will result, causing especially at high temperature torrefaction an overlap with processes commonly referred to as “pyrolysis” or “charring”.

Torrefaction of biomass aims to produce advanced solid fuels or biocarbon products. Both woody biomass and non-woody biomass can be torrefied and the resulting biogenic carbon carrier can be used as fuel or for any other process application.

In the torrefaction technology of today, multiple technical principles have proven their worth and have been developed with complete process control and system integration to market maturity. None of them to be named “the best”. Feedstock to be processed and product specifications aimed for will be the differentiator that will finally help to choose the optimal technology set up for the individual processing project. Technology is offered in different business models - licenses offered, simple technology supplies, EPC, build and operate approaches.

The thermal efficiency of torrefaction lines is on the same level as those of wood pellet lines because all torrefaction gases in an efficient line set up are thermally recycled and utilized. In high temperature torrefaction, more energy is released in thermal oxidation of the torrefaction gases than will be consumed in the processing itself, hence surplus energy can be turned into steam, heat, power or cooling. The separation of specific chemical compounds from the gas or the dissolution of H_2 is currently in TRL 5-8 level and is seen as the next big step in capitalizing on the full capacity of torrefaction.

For the torrefaction industry, what had already become apparent in recent years manifested itself very strongly in 2021. A significant expansion in the number of industrial sectors demanding torrefied biomass is going hand by hand with a significant broadening of the torrefied biomass product range. The flexibility of torrefaction processes in terms of product parameters, which has always been presented but was hardly demanded by potential power plant customers in the past, now presents itself for some industrial sectors as the most cost-effective and easy way to sustainably replace fossil carbon in their production processes. Today, most torrefaction companies can offer in parallel with standard torrefied biomass products for energy also high temperature torrefaction biomass with a C content above 75%.

The mentioned energy surplus from torrefaction gas developing in such production regimes enable the operators to both strengthen their business models and increase the overall process efficiency. Torrefaction processes aiming for very high C contents in solid products are often co-located or integrated with other processes to maximize the advantages that can be taken from energy surpluses in torrefaction gases.

While wood has been the starting point in biomass torrefaction almost all technology suppliers can prove and have broad experience in the efficient torrefaction of all kinds of other biomass types. Agricultural residues, residues from food industry, aquatic biomass, grasses, SRC or simple roadside grass or urban park and gardening residues, all has been processed into tradeable products. Through this use of previously hardly used biomass flows, torrefaction supports the sustainable character of the products even more than through the system efficiency and the high efficiency in transport.

Common tradeable forms of torrefied products are standard pellets of 6 or 8mm and briquettes in pillow shape or cylindrical. Flat and ring die pellet systems, extrusion systems and roller presses are most common. A wide range of binders is available, necessary especially with a higher degree of torrefaction; consumer requirements and conditions along the supply chain will determine if and which binders shall be applied. Fuel products are currently described in a technical specification ISO TS 17225-8. The development into a full standard is currently in process. In parallel standardization of higher carbonized biomass is under discussion in ISO working groups.

Thus, the torrefaction industry, aside from having reached TRL9 in recent years, sees: the widening of the applications of torrefied biomass; the increase of the number of industrially operated sites; and the constant growth of the demand from various industries and for a variety of applications. This is also easing the chicken and egg situation between financing of plants and bankable off take agreements slightly and more plants than ever are in the pipeline.

The aforementioned is a long-awaited situation and a positive outlook for the years to come. The future of biomass torrefaction was almost never as positive as today

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