

Possible effects of torrefaction on biomass trade



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Lead authors:

Michael Wild
Michael Deutmeyer

Co-authors:

Douglas Bradley
Bo Hektor
J. Richard Hess
Lars Nikolaisen
Wolfgang Stelte
Jaya Shankar Tumuluru
Patrick Lamers
Svetlana Proskurina
Esa Vakkilainen
Jussi Heinimö

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1 Introduction

Commitments to reduce greenhouse gas emissions, the wide spreading understanding that we have to fade out coal and legally binding EU 20-20-20 targets are all strong motivating factors to reduce the use of fossil fuels in favour of renewable energy. Global pellet production for energy EU has grown from 3 MT in 2003 to 27 MT by 2014 and is projected to reach 50 to 80 MT by 2020 according to AEBIOM.

This 27MT break down into 10 MT which are consumed for Power production or in CHP, the remaining majority is consumed for heat production, mostly in Europe. Instability in legal framework conditions have led to stagnation in the pellet consumption for power in most of continental Europe, UK incentives favour 100% biomass plants, and producers are gathering sufficient biomass supply contracts to justify conversion of several units in coal power plants. Denmark and now back in the game The Netherlands will increase future consumption as is foreseen for Belgium, France and Sweden.

Pellets are now being imported to Europe long distances—from the Canadian west coast through the Panama Canal, from the U.S. South and, at times, from as far away as Australia and South Africa. While Europe has plans to increase the supply of biomass locally, it is acknowledged that imports will be necessary in order to achieve increasing renewable energy targets in the future.

Today's energy pellets, however, have a very narrow feedstock base that primarily includes soft wood biomass in the form of wood chips or saw dust—only a fraction of overall raw biomass available for bioenergy uses and bioenergy trade. Current wood pellet specifications and qualities are still inferior to those of the substituted fossil fuels, such as coal and gas, when it comes to transportability and usability within the existing infrastructure.

Low-cost preconditioning technologies of raw biomass that can convert and modify different sources of solid biomass into a **specification-driven bioenergy feedstock** with similar or even better characteristics as coal and could greatly enhance trade and usage of biomass in the existing transportation and conversion infrastructure.

Among a number of technologies that could be used to meet this end—such as flash pyrolysis (e.g., Ensyn), conventional or hydrothermal full carbonization (e.g., AVA CO₂, Sun Coal), steam explosion (e.g., Zilkha, Arbaflame), or chemical treatment, a mild pyrolysis process called **torrefaction** (e.g. AIREX, Solvay, Torrc coal, TSI, ACB, RFT,RBE, CEG, CMI etc) stands out as a very promising technological option, attracting significant interest and financial resources for further technological development and commercialization.

Torrefaction is these days on the verge of commercialisation. Beside a sheer volume of scientific studies¹, engineering initiatives not only a number of demonstration plants but now also first commercial plants are in operation respectively construction. The torrefaction technology seems to have left the valley of death behind, not without losses only in the adventurers but even in respectable companies and investors, and the current development leaves little doubt that this technology will find its way into the biomass-to-energy value chain in the next years.

This study focuses on the possible effects torrefaction may have on future international biomass trade. Costs estimates are limited to techno-economics, and risks, profit, organization development, competence building, and other transaction costs are not included.

After a short description of the torrefaction technology and current initiatives followed by discussion on densification of torrefied biomass, the extent torrefaction might open up new biomass feedstock sources is assessed. The following chapters explore how densified, torrefied biomass will perform along the logistical chain of long-haul international

¹ e.g. SECTOR project under FP7 - www.sector.eu

transport and present a picture of the current status in permissions and regulatory assessment which does include the discussion of health and safety aspects. The consumption of torrefied biomass is not limited to co-firing fuel in coal power plants. Alternative uses in industry are discussed in a separate chapter. Finally, the effect on international biomass trade will be discussed, and the findings summarized in the concluding remarks.

2 Torrefaction technologies and initiatives for improving biomass feedstock specifications

2.1 The generic torrefaction process

Torrefaction is a thermochemical treatment process for carbonaceous feedstock such as biomass. It takes place under atmospheric conditions and within a temperature range of approximately 230 to 300°C. Its process parameters are similar to those used in the roasting of coffee beans, and its effect on treated biomass can be described as a mild pyrolysis. With increasing final torrefaction temperature, the amount of volatiles being emitted during the process increases while hemicellulose, lignin, and cellulose are being decomposed.

Figure 1 shows physiochemical, structural, and colour changes in biomass at different temperature regimes. At temperatures ≥ 200 , the drying is more destructive in terms of breakage of inter- and intra-molecular, hydrogen, C-O, and C-C bonds, and the cellular structure of the biomass is disrupted and becomes more brittle. Tumuluru and Hess (2015) summarized the research finding highlighting the advantages of torrefied biomass in terms of physical, chemical and logistic properties (Figure 2).

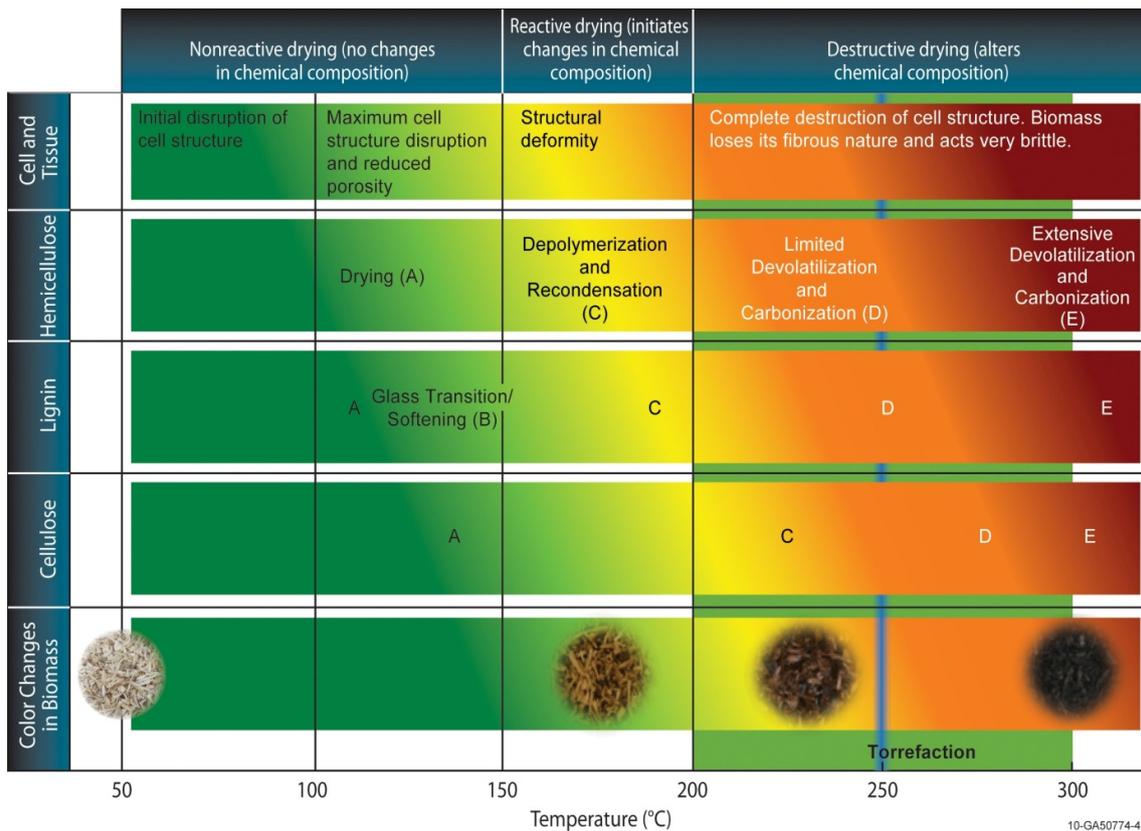
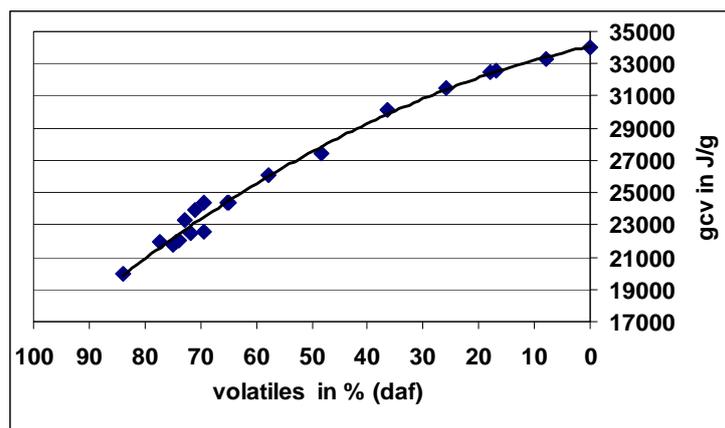


Figure 1. Physiochemical, structural, and colour changes in biomass during torrefaction (Tumuluru et al. 2011).



Figure 2. Research findings on physical, chemical and storage properties of torrefied biomass (Tumuluru and Hess 2015)

Figure 3 describes how overall mass-energy density increases with higher pyrolysis temperatures. Generally desired product qualities of torrefied biomass such as volumetric energy content, grindability, and hydrophobicity increase with higher process temperatures, while mass yields decrease from 85% at ~240°C to almost 50% at ~300°C and energy yields decrease from 90 to 60%, respectively, based on dry material. Particle size and connected heat transfer rate of individual feedstock in connection with residence time at certain temperature does form technical challenge to translate the correlation depicted in figure 3 in homogeneously torrefied product. Depending on the technical and economical parameters of the final biomass-to-energy value chain, different torrefaction regimes and torrefaction technologies will be required in order to achieve optimal economic results.



- Experimentally verified: all points derived from experiments
- Shown here: results for wood, similar results for miscanthus and other biomass
- Depending on reaction conditions (T, t)

Figure 3. Biomass carbonization curve – overall mass energy density increases with higher pyrolysis temperatures (Dr.Martin English,ofi, 2010)

2.2 Important technological approaches

Different existing reactor designs have been tested for their suitability for the torrefaction process. These include ovens, rotary-drum dryers, multiple-hearth furnaces, torbed reactors, and, indirectly, heated screw reactors. All of these existing reactor designs need to be modified in order to offer a gas-tight reaction chamber, cope with exothermal reactions during the process, master the handling of tar-rich volatiles to prevent condensation and clogging, and allow efficient energetic use of the gases emitted during the process in order to reduce operational costs.

In addition to these reactor types, new reactor designs are being tested that are specifically dedicated to the torrefaction process. The most important among these are compact moving bed and fluidized moving bed concepts.

In order to produce a homogenous product, each torrefaction process has to make sure that feedstock particle size is within design limits of individual reactor. Some reactor types depend on little variation individual particle size some are less sensitive. However, all particles experience the same temperature curve only a differentiation in residence time a homogeneous product can result as with increasing particle size and particle-size distribution, the needed residence time generally increases.

All these reactor concepts could differ substantially in respect to key performance indicators, such as heat-transfer control, mechanical reliability, capital cost, up-scale potential, robustness, and operability.

Different biomass feedstocks might favour different reactor types. Low bulk density and low average particle size might favour reactors with a short reaction time, such as a torbed reactor, while slow moving bed reactors are more suitable for larger particle sizes and higher bulk density to accommodate the necessary throughput. A more detailed analysis of these different processes will be dealt with in a separate IEA bioenergy task 32² paper.

Torrefied biomass will differ in homogeneity in respect to the grade of torrefaction, both between different particles as well as within each particle. Heating value per mass and grindability are functions of torrefaction grade, and heating value per volume is a function of both torrefaction grade and subsequent densification technology applied. The wide spectrum of biomass sources opened up through torrefaction for the bioenergy industry exacerbates these differences in the final output.

Therefore, suitable specifications for torrefied biomass for their subsequent end uses must soon be developed in order to commoditize this evolving new bioenergy feedstock. Currently within the development of ISO 17225-8 dealing with thermally treated biomass a clear specification for torrefied biomass products can be expected.

2.3 Current state of torrefaction technology

Currently, a number of European, North American and Asian torrefaction initiatives have commissioned first demonstration respectively commercial torrefaction plants. Some are operated under a continuous regime, some are used for testing and optimisation purposes hence are operated only partially.

Table 1 shows an overview and a qualitative assessment of the different torrefaction technologies. These assessments are based on expert interviews and are only a rough indication for each technological approach.

² <http://www.ieabcc.nl/>

Table 1 Rough qualitative assessment of torrefaction technologies (Source: IEA Task 32).

Criteria	Description
process control	How the process is steered during operations and how the optimal temperature curve is maintained during exothermal and endothermal reactions of the feedstock introduced
mixing of fuel	How the feedstock particles are mixed inside the reactor to allow for a homogenous end product quality
proven technology	Extent existing technology is being used or newly introduced technology is reliable
tar formation and handling	Ability of the system to prevent either tar production or handle tars being produced without causing clogging during long term operation
quality of product	Homogeneity of torrefaction for each particle produced as well as the homogeneity among the total production
capability of processing low density biomass	Process performance on low-density, mostly agricultural herbaceous biomass such as straw, miscanthus, switchgrass, corn stover, etc.
availability	Total working hours realistically feasible during continuous operation per year
potential for up scaling	Future technical potential to increase the total output per unit as opposed to increasing the total set of units
foot print of equipment	Total dimension of equipment in respect to total capacity per unit
throughput	Current total capacity per unit/reactor
conversion costs	Overall conversion costs, including operating and capital expenditure (OPEX / CAPEX)

In light of the increased investment in technology development and commercialization, it can be assumed that torrefaction will become commercially available within the next two to three years.

Although seen as a kind of jack of all trades a couple of years ago the big breakthrough for torrefaction is to date still awaited. What were reasons, which did lead to a much slower development than originally expected?

As first reason clearly the difference between promise and performance of some of the first movers in the sector has to be mentioned leaving several potential consumers and strategic partners frustrated turning its back to torrefaction. The array of different products presented to them as torrefied biomass or biocoal did also confuse potential customers. Many of these materials came not even close to expectations or minimum requirements, leading to further scepticism.

Table 2. Verified torrefaction initiatives

Developer	Technology	Location(s)	Production capacity (ton/a)	Scale and status Pilot scale: - 500 kg/h Demo scale: > 0,5t/h - 2 ton/h Commercial scale: > 2ton/h	Full integration (pre-treatment, torrefaction, combustion, heat cycle, densification)	Status
Clean Electricity Generation (BV, UK) Solvay (FR) / New Biomass Energy (USA) Topell Energy (NL) Arigna Fuels (IR) Torr-Coal B.V. (NL)	Oscillating belt Screw reactor Multistage fluidized bed Screw conveyor Rotary drum	Derby (UK) Quitman (USA/MS) Duiven (NL) County Roscommon (IR) Dilsen-Stokkem (BE)	30,000 80,000 60,000 20,000 30,000	Commercial scale Commercial scale Commercial scale Commercial scale Commercial scale	Yes Yes Yes Yes Yes	Available/operational Available/operational idle Available/operational Available/operational
Airex (CAN/QC) Andritz (AT) Andritz (DK) / ECN (NL) BioEndev (SWE) CMI NESA (BE) Earth Care Products (USA) Grupo Lantec (SP) Integro Earth Fuels, LLC (USA) LMK Energy (FR) Konza Renewable Fuels (USA) River Basin Energy (USA) TSI-Teal Sales Inc (USA)	Cyclonic bed Rotary drum Moving bed Dedicated screw reactor Multiple hearth Rotary drum Moving bed Multiple hearth Moving bed Rotary drum Fluidized bed (Aerobic) Rotary drum	Bécancour (CAN/QC) Frohnleiten (AT) Stenderup (DK) Holmsund, Umea (SWE) Seraing (BE) Independence (USA/KS) Urnietta (SP) Greenville (USA/SC) Mazingarbe (FR) Healy ((USA/KS) Rotterdam White Castle (USA/LA)	16,000 8,000 10,000 16,000 Undefined 20,000 20,000 11,000 20,000 5,000 7000 15,000	Demonstration scale Demonstration scale Demonstration scale Commercial demo Demonstration scale Demonstration scale Demonstration scale Demonstration scale Demonstration scale Demonstration scale Demonstration scale Demonstration scale	Yes Yes Yes Yes Yes Yes Yes Yes Yes Yes Yes Yes	Available new ownership stand by Available Unknown Available/operational Unknown Unknown Unknown Unknown Unknown in comissioning Available/operational
Agri-Tech Producers LLC (US/SC) Airex (CAN/QC) Airex (CAN/QC) CENER (SP) Terra Green Energy (USA) Wyssmont (USA)	Screw conveyor Cyclonic bed Cyclonic bed Rotary drum Multiple hearth Multiple hearth	Raleigh (USA/NC) Rouyn-Noranda (CAN/QC) Trois-Rivières (CAN/QC) Aoiz (SP) McKean County (USA/PA) Fort Lee (USA/NJ)	Undefined Undefined Undefined Undefined Undefined Undefined	Pilot stage Pilot stage Pilot stage Pilot scale Pilot scale Pilot scale		Available/operational Available/operational Available/operational Available/operational Available/operational Unknown
CEA (FR) Rotawave, Ltd. (UK)	Multiple hearth Microwave	Paris (FR) Chester (UK)	Undefined Undefined	Laboratory scale Laboratory scale		Available/operational probably closed
Bio Energy Development & Production (CAN) Horizon Bioenergy (NL)	Fluidised bed Oscillating belt	Nova Scotia (CAN/NS) Steenwijk (NL)	Undefined 45,000	Unknown Commercial scale	 Yes	Unknown Dismantled to CEG

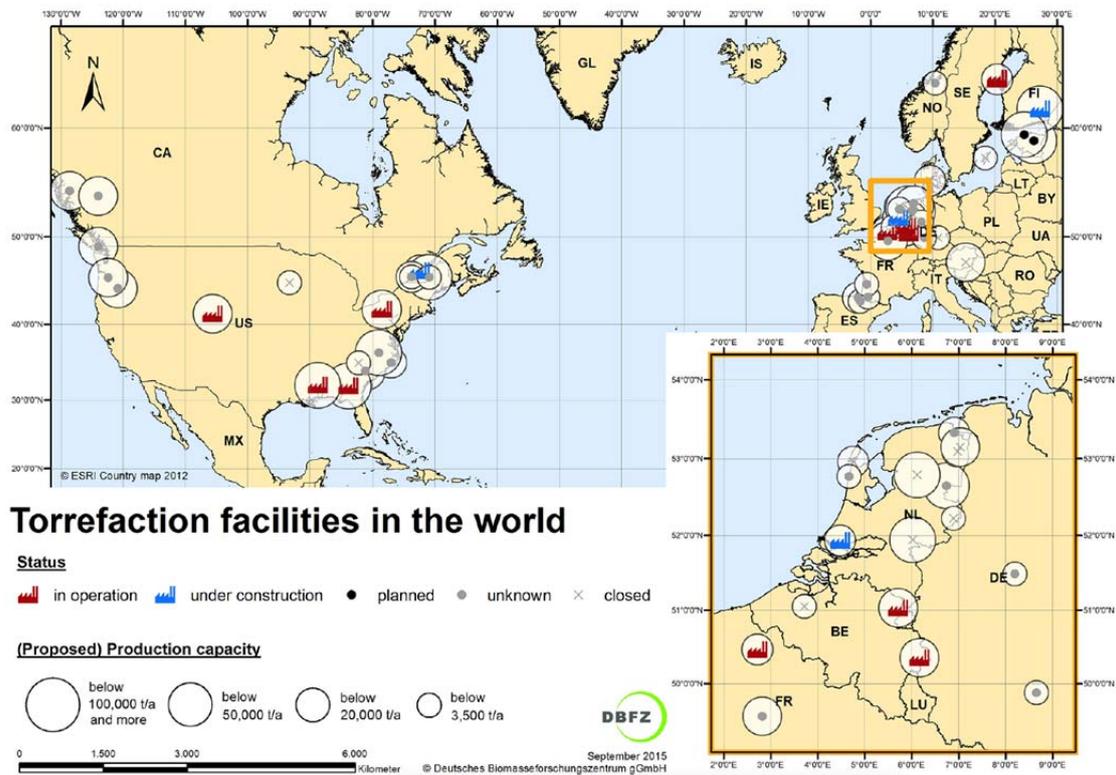


Figure 4. Worldwide activities of biomass torrefaction facilities with different development status (the status “unknown” describes initiatives which have been active in the last years but whose current status could not be verified; the lacking information policy indicates difficulties in operation, their dominance shows the recession in current torrefaction developments) (Thrän et al, 2016)

The fact that in the last years almost a standstill if not a sharp reduction in co-firing of biomass with coal, the first target market for torrefied biomass, did make it almost impossible for new suppliers to become successful, almost independent from the materials offered. Other regions on the Globe have seen delays and uncertainties in the co-firing regulation as well, namely Japan but also South Korea.

The weak demand for torrefied biomass made it impossible for the performing producers and also the machinery suppliers to come even close to the prices they expected to achieve with their products leaving some of them frustrated as well deciding to shelf activities (and technologies) until conditions turn brighter again.

In this situation some of the performing companies in torrefaction took action and did establish the International Biomass Torrefaction Council IBTC within AEBIOM organisation. The IBTC was established to help readjusting the picture potential clients did gain over the years on torrefied biomass and further to deal with all non-competitive issues in the torrefaction industry.

Beside classical PR activities the IBTC has since its establishment focused on activities to allow an easier uptake of torrefied biomass by the market. Starting from the initiation of a standardisation process (see chapter 8) and several initiatives concerning regulation on trading (REACH) and transportation regulations (IMO, IMSBC) also activities have been conducted to make regulators aware of torrefied biomass and help them to understand the way it can be organized within the wealth of products on the market.

Above reasons have led to a torrefaction sector looking very different from the one presented in the 2012 study. Many parties have left, new ones have joined in. However, bottom line is that a constant development towards industrialisation is seen although much slower than expected. Today not only co-firing is seen as key customer for product. Heating and

also cooling applications did move more and more into the centre of concern as well as a parallel development of torrefaction processes for non woody biomasses.

All of this does lead to a sector which can still not be characterised as mature and well established in the markets, however, many obstacles have been eliminated or elimination is in process, new application scenarios have been developed, answers to the rising scepticism to woody biomass have been developed and last but not most important, process control has been achieved by many companies and their technologies.

2.4 *Densification of torrefied Biomass – Current status and lessons learned*

Torrefied biomass is usually compacted into pellets or briquettes before it is leaving the torrefaction facility and shipped to distributors and end-users. The key advantages of pressing torrefied biomass into pellets and briquettes are a higher energy density per volume, resulting in lower transportation and storage costs. In case of torrefied wood, the bulk density can be increased from 200-400 kg/m³ for the torrefied wood chips to about 650-720 kg/m³ for torrefied pellets, depending on species and processing conditions (Bourgeois and Doat 1984, Bridgeman et al. 2008, Fehrs 1999). Similar bulk densities were achieved at torrefied biomass compressed into briquettes of 50mm diameter. The standardized shape and size of pellets and briquettes is an advantage for trade and process automation. Potentially hazardous dust is removed from torrefied biomass during densification operations, and dust emissions from pellets and briquettes during loading, unloading and conveying operations are lower as for the loose torrefied biomass. Densification can therefore be considered as an indispensable process operation to meet the end-users quality demands for a stable, safe and easy to handle product.

The homogeneous size and shape of pellets and briquettes in combination with technical standards/specifications for thermally treated, solid biofuels that are currently under development by the ISO TC-238 for ISO 17225-8, are important requirements for turning energy carriers from torrefied biomass into a commodity fuel.

The technical specifications of graded pellets produced from thermally treated woody biomass, suggested by the ISO TC-238 for ISO 17225-8 (Alakangas 2014) are closely related to existing standards for wood pellets and define the size of pellets made from torrefied biomass to be 6-8 mm in diameter and 3.15 to 40 mm in length and a bulk density of ≥ 650 kg/m³. Briquettes vary in size and shape and in correlation to the existing standards for biomass briquettes, no exact size definition has been suggested for briquettes made from torrefied biomass. The suggested bulk density is the same as for pellets ≥ 650 kg/m³.

The difference between briquettes and pellets is not only the size but also the production process. Pellets are produced in a pellet mill by continuous feeding, flow, compaction and extrusion of biomass through the press channels of a die. The biomass is forced by a roller into the opening of a press channel and compacted by the force exerted by the roller onto the biomass. High friction in the press channels results in the generation of high pressure, required to compact the biomass into a pellet (Stelte 2012). Briquettes are produced by compacting a fixed volume of biomass in a mold or through a nozzle (continuous process) using a piston press. In both cases heat and pressure result in a flow of polymers present in the biomass and subsequent hardening and bond formation resulting in a stable compact body.

The reason why torrefaction producers often choose pelletization over for briquetting is simply due to the wide acceptance of wood pellets as a commodity fuel, their greater bulk densities and the possibility for vacuum pumping.

Pelletization of torrefied biomass has for long time been an underestimated bottleneck in the production process for torrefied energy carriers and a fall-string in the process development and commercialization for many torrefaction initiatives and start-up companies. Although pelletization can be regarded as an established and straightforward process for the production of conventional wood pellets, it could not be applied directly onto torrefied biomass. Major challenges that had to be overcome were a significantly higher energy uptake of the pellet press due to high friction and low pellet quality (Stelte 2012).

All torrefaction initiatives and start-ups have faced technical challenges to pelletize or briquette torrefied biomass and only the ones who have succeeded to solve the technical problems sustained on the market.

A lot of progress has been made in optimizing the pelletizing/briquetting process of torrefied biomass during the past five years and today it can be said that the process has reached a mature state where it is no longer a problem to densify torrefied biomass into a pellet and briquette of high quality (Bourgois and Doat 1984, Klass 1998).

A more fundamental understanding of the pelletizing process and numerous test in lab, bench, pilot and production scale have resulted in an incremental improvement of the pellet quality. Industrial research projects have been supplemented by international research and development projects such as the European research projects "SECTOR" and "LogistEC" founded by the European Commission and numerous privately funded research projects, mainly in Europe, North America and recently also in Asia.

Key factors that have been optimized were species, degree of torrefaction, pelletizing temperature, moisture addition, pelletizing die length and diameter, die rotation speed and particle size. The addition of additives is an extra cost factor and only applied if conventional process optimization fails (Bienert et al. 2014).

The quality of torrefied pellets has evolved to a very high standard over the past years that by far outperform the quality of conventional wood pellets with respect to calorific value, moisture resistance and grindability (Bourgois and Doat 1984, Bridgeman et al. 2008, Fehrs 1999).

However the already high quality is often met with wrong and even unrealistic expectations on the consumer site. The reason for this mismatch is that in the early days of torrefaction, unrealistically high figures for bulk densities (up to 900 kg/m³), calorific values (up to 25 MJ/kg) and moisture resistance (can be stored outside for long time like coal) have been communicated throughout the bioenergy community that at least for bulk density and complete water resistance finally could not be matched. These over optimistic pretensions should likely be categorized as "wishful thinking" and were not based on actual process knowledge.

More realistic values for the bulk density of pellets produced from torrefied biomass, under economically feasible processing conditions, are 680 to 720 kg/m³ (Klaus Trattner 2014). The ISO TC-238 has suggested 650 kg/m³ as a minimum value for the bulk density of pellets made from torrefied biomass (Alakangas 2014), compared to 600 kg/m³ for conventional wood pellets. Calorific values of pellets made from torrefied biomass are directly linked to the degree of torrefaction (temperature and retention time of biomass in the torrefaction reactor) and the used raw material. Realistic values for the Gross calorific value are somewhere between 19-23 MJ/kg (d.b. / ash free) (Bienert et al. 2014).

The storage properties of pellets made from torrefied biomass have been widely discussed and extensively investigated during the past years. It is important to keep in mind that most of today's coal power plants keep a coal supply for no longer than about two weeks running time. Keeping more would result in unnecessary costs and logistics. Storage tests for pellets made from torrefied biomass have shown that the pellets cannot be stored outside over longer periods (McKeever 1998, Rooney 1998, Tumuluru et al. 2010). They are however resistant to moisture uptake and can be stored outside for short periods. Outside storage for up to two weeks, as a typical power plant situation would require is therefore a possible option. Outside storage of pellets for several weeks and months results in a loss of quality at least of the top layer of a heap.

3 Increased catchment area and broader feedstock base via torrefaction

One of the principal challenges of establishing lignocellulosic biofuels, biopower, and other bioproduct streams as self-sustaining enterprises is organizing the logistics of the feedstock supply system in a way that maintains the economic and ecological viability of supply system infrastructures while providing the needed quantities of resources. Under the current state of technology, the only economically self-sufficient biorefining designs are those sited in locations with sufficient volumes of resources available within their catchment area.

The greater the distance between resource and point of use, the greater the cost of mobilization and resulting pressure on supply-system logistics; thus, the economics for accessing smaller or more remote resources are not favourable, and they become stranded from centralized, large-scale operations. This is because biomass—in its raw, “as harvested” form—presents a number of challenges for use as a fuel in large-scale applications due to its low energy density and inherent variability in material properties (Kenney et al. 2013). Establishment of pre-processing or upgrading capabilities early in the supply chain can help overcome the barriers to an economically viable biomass supply system, including non-uniform handling requirements, aerobic instability, and low bulk and energy density (Searcy et al. 2014).

Hess et al. (2009) describe a feedstock supply system design concept that incorporates distributed pre-processing depots and centralized terminals (Figure 5) to address these challenges by taking various biomass resource types and pre-processing them into products that are dense, aerobically stable, on-spec for specific conversion facilities, and capable of being managed in existing material-handling infrastructures. The capacity and configuration of pre-processing depots will be based on the local biomass production systems and on the respective markets depots will sell into.

Pre-processing depots will likely be located near existing infrastructure (e.g., rail and highway), supporting efficient distribution of their feedstock product and emerging in a fashion similar to existing grain elevators and producer-cooperative facilities. Depots are envisioned to house mechanical, thermal (torrefaction), and chemical systems that perform the operations necessary to produce uniform commodity feedstocks that can be transported safely and cost-effectively over great distances. Depending on the depot configuration, processing costs range from US\$30.80 to US\$62.50 per tonne of output material (Lamers et al. 2015a). Multiple depot set-ups are possible. Feedstock stability, bulk density, and improved flowability can be met via conventional pelleting processes, while additional processing steps such as leaching or chemical treatment can be added to increase feedstock quality control. The economic burden of each design depends greatly on the energy consumption of the respective processing equipment.

As compared to biorefineries and other complex and capital-intensive pre-treatment technologies (pyrolysis, gasification, and combustion), locating torrefaction at pre-processing depots will require low capital investment, which facilitates adaptability and reconfiguration for regionally specific resources and management systems. Furthermore, outsourcing pre-processing to decentralized depots with the resulting harmonization of in-feed material into the biorefinery not only reduces operational and capital expenses but also enhances biorefinery processes (Lamers et al. 2015b).

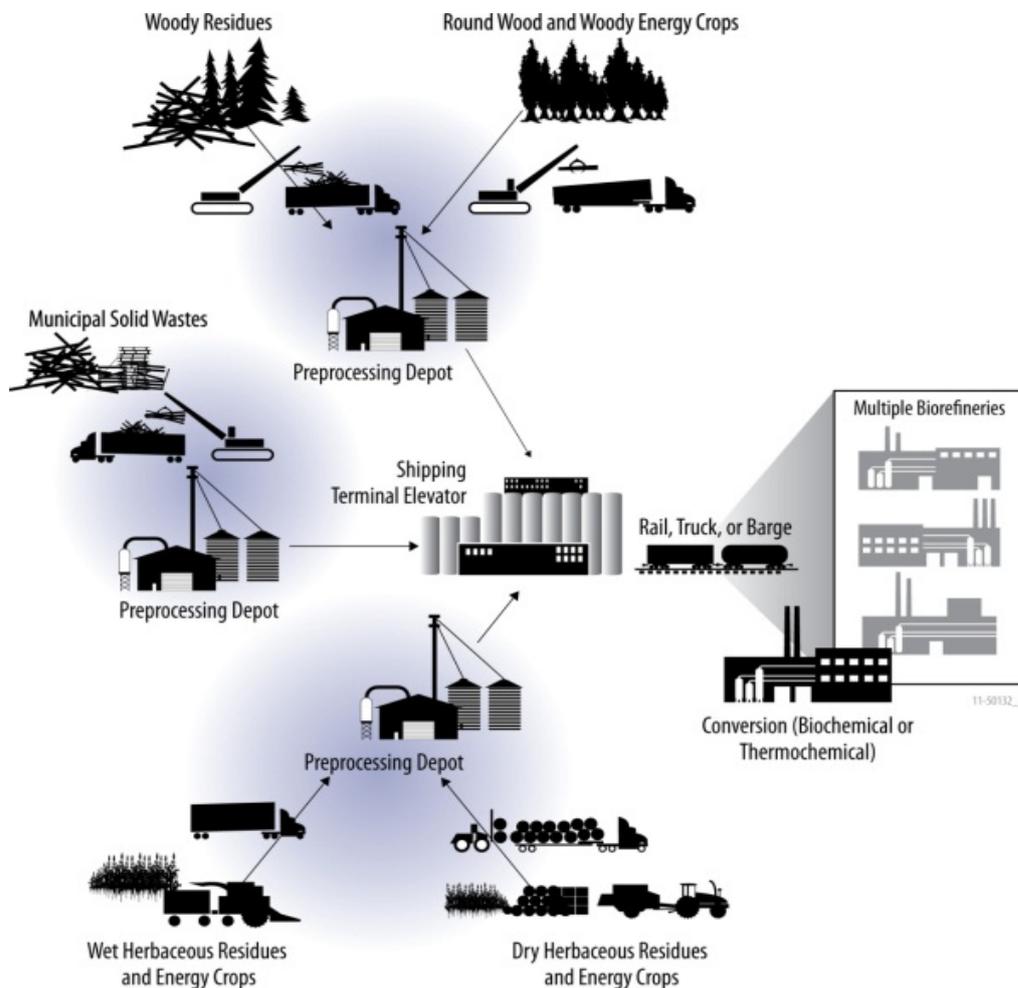


Figure 5. Locating torrefaction at distributed pre-processing depots may provide the ability to turn unstable, low-density raw biomass into a stable, dense, on-spec commodity feedstock compatible with existing commodity-distribution infrastructures and national and international market structures (Searcy et al. 2015).

Pre-processing depots or collection centres which take care for pre-processing and upgrading of the biomass by torrefaction will have an even higher importance when agro by products or biomasses like grasses or SRC are the raw material. As storing of this materials is more difficult than is the storing of round wood a pre-processing not long after harvesting or collection will be of advantage.

Initiatives seen today based on sugar cane straw and SRC in form of grass plantations do not only show great economic potential but will also depend in their success from the right sizing of torrefaction plants and connected collection costs. Sugar cane is collected for the sugar processing, hence the straw and other by-products such as bagasse do appear in large volumes in centralised manner, there will be an almost fixed ratio between the size of the sugar mill and the size of the torrefaction plant.

Different in SRC and grasses. Here the feedstock is not only planted and grown dedicatedly but also harvested right in time for production. It can be expected that in this feedstock area torrefaction plants i.e. pre-processing centres will be dimensioned smaller but more numerous.

3.1 Implementing regionally distributed torrefaction to make additional biomass resources available

A technology like torrefaction that cost-effectively lowers biomass moisture content while increasing material stability has the potential to lower supply-chain cost, particularly over large distances. Biomass torrefaction offers other advantages and has been shown to be a technically feasible method for converting raw biomass into high-energy-density, hydrophobic, compactable, grindable, and lower oxygen-to-carbon (O/C) ratio³ solids that are suitable for commercial and residential combustion and gasification applications (Tumuluru 2011). Van Krevelan diagram drawn for different variety of coals and corn stover and switchgrass torrefied at different temperature and residence time is indicated in Figure 5. Increasing the torrefaction temperature and time reduced H/C and O/C ratio and moved them closer to coals.

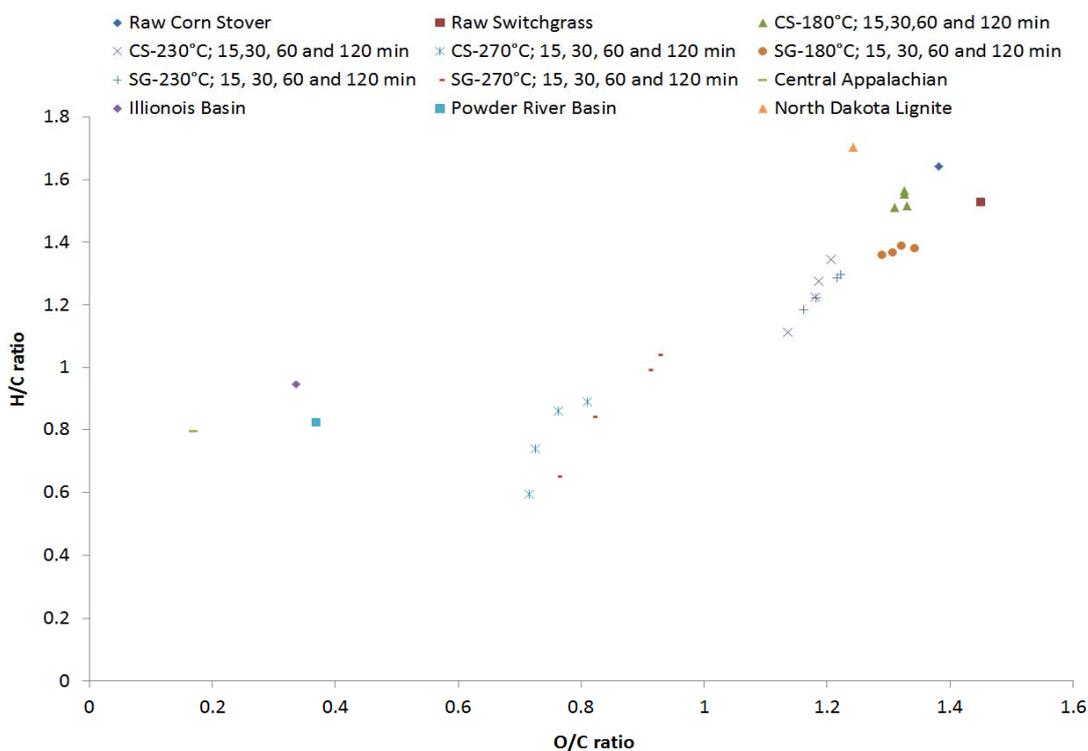


Figure 6. van Krevelan diagram for corn stover and switchgrass at different torrefaction temperature and residence time (Tumuluru, 2015).

As mentioned in other parts of this study combining torrefaction with other pre-conversion technologies does increase market opportunities and is also in some kinds necessary to allow torrefied biomass to be transported hence are pre-condition to enter the market. Combined torrefaction and densification (i.e., pelletization) does increase the energy density of biomass by five to eight times. Combined torrefaction and densification also produce a biomass feedstock better suited for blending with coal, offering improved milling and handling characteristics and allowing the two to be blended prior to coal milling, which can potentially increase co-firing ratios (Tumuluru 2012). At the same time torrefied biomass that appears in a very constant geometrical format will allow technology developers, such as but not only gasification technology developers,, to work on appliances focused on and optimized for a very narrow variation of feedstock fuel.

³ lower ratios than in untreated biomass in order to increase the energy content per mass unit

This has potential to increase available resource in a variety of ways:

1. Improved supply/demand economics—Lower supply chain costs may allow payment of higher grower prices, which is demonstrated to move more resource into the system
2. Expanded feedstock supply system and markets—Managing resource diversity locally—by pre-processing raw biomass into stable, flow able, and uniform products that can be easily transported over great distances using existing handling and transportation systems—facilitates greater resource access
3. Establishment of new product markets—Upgrading feedstock by improving energy density and oxygen-to-carbon ratio of the feedstock may make product more valuable to biorefineries and increase demand.

4 Improved performance of torrefied biomass in downstream logistics and conversion

Advantages in logistics—namely higher energy density and hydrophobicity, supposed leading to significant cost advantages and simplifications in handling—were among the major driving forces behind torrefaction-technology development. This chapter will investigate whether those theoretical assumptions live up to today's first practical experience in the shipment of torrefied biomass.

The logistics chain from the torrefaction plant to the consumer's combustion chamber can be broken down to the following elements:

- Loading to truck/train/barge
- Secondary transport to ocean vessel
- Loading the vessel
- Shipping
- Unloading/reloading to truck/train/barge
- Tertiary transport
- Unloading
- Storage
- Internal transport and handling
- Grinding

Hence, loading, transport in truck/train/barge, transport in large volume vessels and grinding have to be evaluated. Advantages in this part of the value chain will have to make up for the disadvantages of higher investment, slightly increased quantity of raw material, and likely higher operational costs in the processing plant in respect to white wood pellets.

Logistics and handling costs are a function of weight/volume of product to be transported and of simplicity in handling. At the writing of this report, there is limited practical experience available on torrefied product as there has been only a few long-haul bulk shipments of torrefied product. However, trucking and transportation in containers has been observed in larger numbers.

First, torrefied biomass is not suitable for transport directly after the torrefaction process. The material is too brittle and too light in weight to be transported or stored cost efficiently. Although torrefaction hardly changes the physical size of the original raw material, weight is dramatically reduced. Water content and some volatiles are removed, resulting (according to ofi Vienna) in a weight reduction of wood chips of 50% of moisture, resulting in a mass reduction from approximately 400kg in 1 m³ raw material to below 180kg in torrefied chips. Further, the brittleness of torrefied biomass will lead to large proportions of dust as explosive as wood dust. This would classify torrefied product a hazardous good, with plenty of negative impacts on costs.

Hence, torrefied product must be densified. The most common techniques are pelletization and briquetting. With ongoing tests in both techniques in the labs of many machinery producers and related research institutions, producers and consumers there is still no homogenous picture if there will be one prevailing technique or the techniques will be applied in parallel one to the other eventually addressing different product markets.

After struggling first to reach any densification, it seems that, today, the major pellet-mill producers have succeeded in forming pellets from torrefied biomass. Discussions with pellet-mill manufacturers point to the fact that at an increasing grade of torrefaction, the densification process becomes more problematic. Further, big differences in the densification behaviour of torrefied product from different species or biomasses are evident. This is not surprising and does comply well with experiences in pelletizing other feedstocks. Binders are seen generally a good help, but to date, there is no consensus to which binders should be used and how these binders will be regarded by the consumers and their regulators. Authors

could, to date, witness only two continuous pelletizers and one continuous briquetting of torrefied material in operation, all working with and without binders⁴.

So far, data on achieved pellet particulars and densities show some significant variation. While originally ECN published a density of 800kg/m³ of their TOP material, Andritz is publishing rather conservative figures of “only” up to 650kg/m³. In the only witnessed transatlantic transportation of torrefied pellets so far, carried out by the U.S. producer New Biomass Energy, the average density of their product was 735 to 750kg/m³.

As it seems that industry has settled at a degree of torrefaction⁵ of biomass, such as wood by eliminating 5 to 15% of the volatiles, only a net calorific value (NCV) of the product of 20 to 24 GJ/mt (averaged to 21 GJ/mt for further calculation) can be expected. A conservative average of 700 kg/m³ bulk density would yield 16 GJ/m³. Respective figures of industrial wood pellets are 17GJ/mt and 10.7 GJ/m³. Thus, an advantage of approximately 23% for weight-based calculations (23% more energy transported at the same maximum weight) and of approximately 37% for volume-based calculations (37% more energy transported at the same maximum volume) might be expected for torrefied product, based on these specifications.

Some economic effects for selected end users

Transportation

Transportation costs, despite often being charged per weight, are mostly determined by available transportation volume for higher-stowing cargo, while handling is charged purely on a weight basis. Hence, cost advantages of approximately 37% can be achieved in rail, barge, and oceangoing-ship transport where volume and not weight is the limiting factor in comparison with wood pellets on a per GJ basis, while for loading and unloading, as well as for trucking, a 23% advantage is realistic since both are calculated or limited by weight.

Table 4. Calculation of transportation costs of wood pellets and torrefied pellets (Calculation by M. Wild, 2011)

	secondary transport	storage	loading	shipping	un/reloading	tertiary transport	unloading	Total
typical costs US\$	15	2	5	40	5	15	2	84
savings %	0–23%	23%	23%	37%	23%	37%	23%	28%
savings US\$	0	0.46	1.15	14.8	1.15	5.55	0.46	23.57

For a typical supply chain from the Americas to Europe, where a production plant might be approximately 200 km from port of loading, with the secondary transport to the port done by truck, shipping to take place in Handymax vessel, and tertiary transport by train from port of unloading to a 300-km-distant power plant, costs and cost advantages will, in total, lead to an approximate 28% savings, or US\$23 per mt. This absolute figure increases with rising distances and rising costs for transportation in general. Further sensitivity to changes in costs of almost all cost factors decreases, helping to reduce economic risk in operating supply chains.

Calculation of costs along a supply chain is obviously dealing with moving targets. While in respect to the 2011 figures the costs of pure shipping have fallen significantly (today would on this routes rather be in the low to mid 20’s), secondary and tertiary transport have moved upwards slightly until the collapse of the oil price. By this the relative savings to be achieved

⁴ New Biomass Energy, Torrocoal, ACB

⁵ definition degree of torrefaction according to ofi, Dr. M. Englisch

by torrefied product along the supply chain, remain almost unchanged, the absolute savings do vary. The lower the total costs the lower the absolute savings and as this absolute savings will determine the economic viability of an investment into torrefaction the drop in transportation costs has increased the pressure on the shoulders of the torrefaction companies.

Despite monetary advantages, the increased energy density does have an equally positive effect in carbon footprint of the product, not to mention that more energy brought in per vessel—a typical 45,000m³ loading-volume vessel will deliver 661.5 instead of 481 TJ—will reduce congestion in ports, wear and tear on all involved transport and handling machinery, etc.

However, it must be emphasized that insufficient experience with bulk shipping of torrefied pellets exists. The above calculation assumes that no extra requirements and costs will appear in respect to transporting wood pellets. This fails to take into account the eventual danger of dust explosion, self-ignition, and off-gassing of the torrefied product. Evidence is growing that none of those this dangers is either for real or cause any additional requirements.

Storage

Chapter 5 will discuss the topics of off-gasing, self-heating and explosivity and health and safety aspects proving that torrefied biomass is in no aspect behaving inferior to wood pellets. For this reason here the issue of improved water resistance and the options to piggy back on existing supply chains will be looked at.

To date, there is no evidence that torrefied pellets at ambient temperature cannot be stored in any kind of storage employed in the wood-pellets chain. This is valid not only for the storage itself but all auxiliary equipment in loading and unloading storage. Higher energy density will lead to savings because less room would be required as will, probably, less movement of loading/unloading equipment.

So there is no doubt that torrefied densified biomass can use existing wood pellet chains. But is it the same with the existing coal chains, which are cheaper in building and operation because the product transported and stored is water resistant.

Within the SECTOR project ECN⁶ undertook a long term test on outdoor storage and handling of torrefied biomass and related this to both coal and white wood pellets. A complete hydrophobic character of the torrefied pellets could not be proven by this tests but a behaviour close to that of coal and a clear advantage against white wood pellets was shown.

⁶ New results of the SECTORproject: Production of Solid Sustainable Energy Carriers from Biomass by Means of Torrefaction; M.C. Carbo (ECN), S. Leiser (ECN), J.H.A. Kiel (ECN), D. Thrän (UFZ), J. Witt (DBFZ) ECN-L--14-027



Figure 7. White wood pellets and torrefied wood pellets stored outside. Picture taken after 12 days

The tests were carried out over a period of 10 months in Europe on flat top and on peaked heaps of 3 to 4 metric tonnes of torrefied wood pellets exposed to all kinds of climatic influences as appearing in the year of 2013 (sun, wind, rain) and did cause results very much confirming that outdoor storage does not destroy the product nor does it harm the qualities of the product significantly as a whole.

- The temperature on the piles did very closely go in parallel to the ambient temperature (little higher in the heaps)
- The moisture content of the pellets did increase continuously both on the outside layers as within the core of the pile
- This did result in decrease in mechanical durability of pellets from the outside layers only
- The calorific value (LHV) on dry matter basis has nearly been unchanged, very minor losses due to leachate and biological activity

Similar results have been reported by Andritz⁷ testing torrefied wood briquettes at their ACB plant in Frohnleiten, Austria, where the produced briquettes have been exposed for 43 days to outdoor conditions with 21 rainfalls (3>20mm/m²) have been reported. In private conversations Andritz reported even better results with 50mm pellets and the advanced control over the briquetting process achieved during activities in 2014.

⁷ Doris Thammer, Torrefaction of Biomass, August 2013



Figure 8. ANDRITZ ACB Weathering tests

Table 5. Effects of water uptake Andritz ACB

Sample	Diameter [mm]	TG [%]	DS [%]	Water uptake [%]	Durability [%]	Density [kg/dm ³]
Original Sample	71	25	97%	2	96	1,14
Sample 1	71	25	92%	1	84	1,14
Sample 2	71	25	93%	1	91	1,16

However, authors did learn also from tests such as putting torrefied wood pellets for 200 hours completely under water (eventually even freezing them) and testing their durability after such exposures. Results after this tests were, no wonder, dissatisfying. To decide if such tests reflect conditions fuels are naturally exposed to and if passing of such tests is precondition for accepted fuels remains with the individual consumer. The ECN analyses on water uptake and outdoor storage concluded with remark that strategic reserves at coal power plants are stored usually for 2 weeks at the open

storage area and torrefied pellets analysed for 10 month of storage at such outdoor coal storage area did still not degrade significantly or have lost their consumable fuel character.

Biological Degradation

Plants or fractions of it once cut are subject to biological degradation by a couple of processes. True in nature but as well in accumulations created by humans. In nature a welcome and necessary process biological degradation does cause issues when biomass is transported or stored for a longer period. Not only is the mass reduced and devaluation of the volume traded or stored is the effect but also are products of the ongoing biological processes causing negative impact. Off Gassing will be addresses in a separate paragraph.

In recent testing ECN did proof that independent of wood species processed, the biological degradation of this wood once torrefied is significantly lower than that of non torrefied wood stored under similar conditions. The losses in dry matter were significantly higher with non torrefied wood and the gap was widening the longer the biomass was stored.

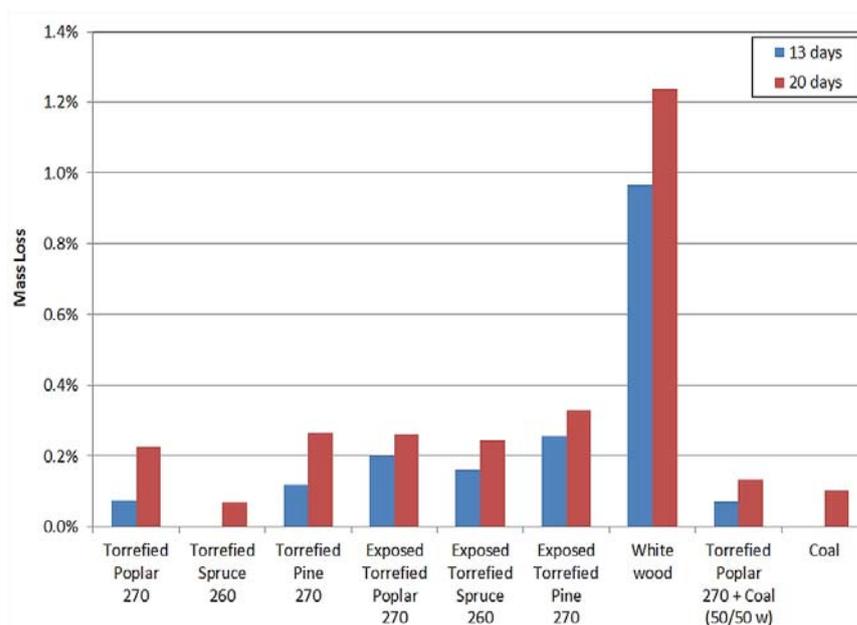


Figure 9. Mass Loss of wood versus torrefied wood over time (Source: Carbo et al. 2015b)

Grinding (milling)

Grinding the fibrous, elastic biomass to sizes suitable for co-firing is an energy-intensive and difficult exercise, particularly when undertaken with standard coal mills. As a result, almost all power plants engaged in co-firing have established separate biomass (pellet) milling and a following burner feed-in system. This need for investment in the area of 70 to 80 million € per plant is one of the barriers power plant managers face in engaging in co-firing. If torrefied biomass could be milled with existing coal mills, using the already existing coal-handling equipment, it would not only be preferred by power plants, but would also allow them much more flexibility in plant operation. They could easily switch between coal and biomass in order to realize short-term production optimums.

The Hardgrove Index (HGI) usually expresses grindability of coal in the power sector. Lacking a dedicated indicator for grindability of torrefied material or biomass in general the HGI is used for comparative determination of characteristics also for biomass. Not published results of the SECTOR project suggest to keep HGI testing method as reference but adopt the size of the screen in the testing unit in relation to the faster burn out rate of torrefied biomass versus the coal tested.

On average, a power plant operator would expect coal with an HGI from 50 to 80. The higher the values the better because less energy is consumed in milling. Wood pellets show HGI in the low 20s. Although it is commonly agreed that Hardgrove testing is not the best grindability test for woody material, the discrepancy in the HGI values shows that it is approximately four times more energy intense to mill wood than coal. Torrefied product has shown HGIs in the low to mid 50s, a substantial advantage over wood pellets, bringing torrefied biomass close to the particulars of coal. Reports on the energy needed are as low as 10 to 20% of the comparable energy requirements for milling of raw biomass (Ciolkosz and Wallace 2011). Figure 10 depicts differences between coal and biomass grindability, indicating that no separate milling process needs to be established. However, these results have been produced in test facilities, and a final judgment on how torrefied pellets will mill in existing coal facilities will be gained only when the first large-scale samples (in thousands of tons) have made their way through the power plant installations.

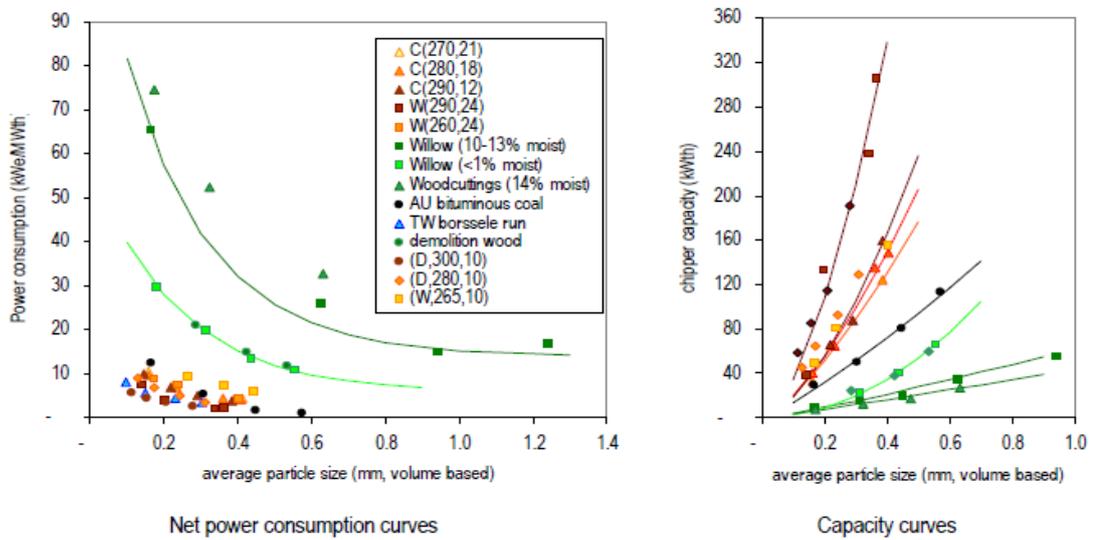


Figure 10. Grinding power consumption and mill capacity, Torrefaction for biomass co-firing in existing coal-fired power stations (Bergman et al. 2005).

Easier grindability of torrefied biomass not only offers an economic and capacity advantage for cofiring, but torrefaction opens up a totally new path for industrial-sized biomass gasification through the use of adapted, state-of-the-art, coal gasifiers to torrefied biomass. Either in mixture with coal or as a 100% feedstock, adequately milled torrefied wood can be introduced into entrained-flow slagging gasifiers via a dense-flow transportation system under high pressures. Torrefied wood would thereby enable any existing coal gasification installation to introduce green carbon into its syngas stream and along its downstream product portfolio leading to, for example, greener fertilizer, greener synthetic fuels, and greener plastics.

Fuel Morphology after milling

It is not only the energy used for the grinding but more so the shape of the resulting particles which is of importance to the quality of combustion in co-firing but not only there. Research by ECN did show that the “sphericity” of ground coal is best matched by ground torrefied biomass pellets and the shape of this particles of ground torrefied biomass pellets is very different to the one achieved when only grinding wood or wood pellets (Carbo et al 2015a).

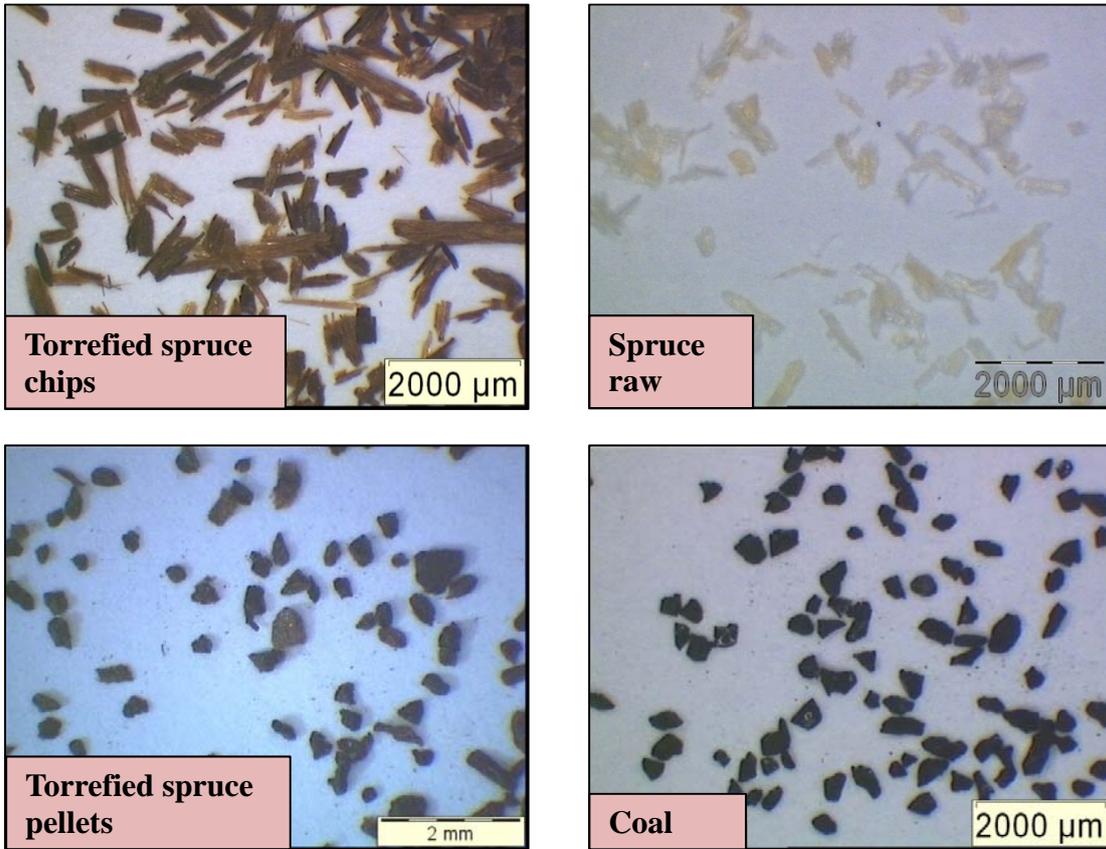


Figure 11. Shape of resulting particles after milling of raw spruce, torrefied spruce chips, torrefied spruce pellets and coal (Carbo et al. 2015a)

5 Health and Safety and relevant Regulation for Transport and Handling of torrefied biomass

Health and safety issues, Transport regulation

Health and security issues concerning torrefied biomass were beside the technological issues the main activities of research and development activities in the sector. The following issues have been in the centre of investigation:

1. Fire-related hazards
2. Self-heating, off-gassing, dust explosions
3. Mitigation measures and fire fighting
4. Health concerns
5. Exposure to airborne dust, fungi, moulds
6. Exposure to off-gassing emissions and oxygen-depleted air
7. Other risks, including other exposure risks, trauma, etc.
8. Transportation

Along the supply chain transported product is exposed to mechanical stress, moisture and temperature variations. All of this will not have only an impact on product quality itself but may or may not cause certain risks. To make sure those risks are managed well and operating personal is aware of the risks products need to be tested, classified and described in respective forms. Classification may but need not necessarily result in special requirements in transport means (for instance the requirements of CO₂ fitted bulk carrier vessels) with corresponding effects on transportation costs.

Producers of torrefied biomass do have a clear interest to produce a product not classified different to competing products on the market, i.e. wood pellets or steam exploded pellets.

This chapter does summarize results of tests and analysis undertaken to characterize the behaviour of the products while stored, handled and transported. All results do proof so far that no negative difference to the behaviour of wood pellets has been found.

Phyosanitary Requirements

The exposure to heat within the production process guarantees that no organism in or on the biomass survives. Because of this sanitization, the requirement for phytosanitary certification is waived, as it is for wood pellets, but not for wood chips and other biogenic feedstock.

Explosivity

One of the key risks in handling, storing and transportation of biomass is seen in the explosive character of the products dust. Explosivity of dust from torrefied pellets has been confronted in in several tests with the explosivity of dust from wood chips or wood pellets (Rubik et al. 2012, VTT 2013, Mak 2011).

The core findings were summarized best by Michiel Carbo of ECN (Carbo et al. 2015a):

- Clear link between MIE torrefied pellets with MIE raw material
- Native dust has high MIE's
- Dust from handling low durability pellets (< 93%) is more ignitable → aim for pellet durability ≥ 95%

- Handling dust from torrefied wood pellets is equally ignitable as handling dusts from white wood pellets

This results were confirmed in tests published by VTT (2013).

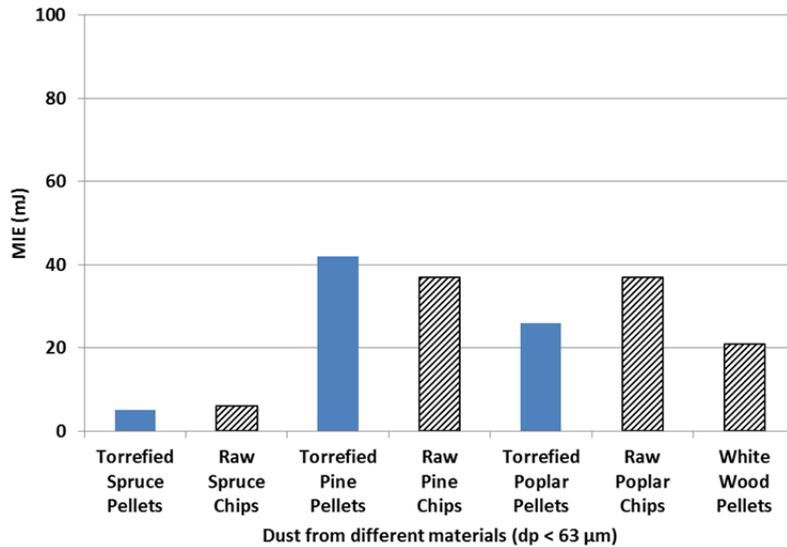


Figure 12. MIE (Minimum Ignition Energy) comparison of dust from raw vs torrefied wood species

Table 6. Kmax of torrefied wood dust versus dusts of wood and coal

	Explosion pressure Pmax	Rate of pressure rise Kmax	Limiting Oxygen Concentration LOC
Torrefied wood dust	9.0	150	11
Wood dust	9.1-10.0	57-100	10-12
Peat dust	9.1-11.9	120-157	13.5
Lignite dust	9.4-11.0	90-176	13-15
Coal dust	8.9-10.0	37-86	14

The explosion class, defined as a function of the Kmax values. The torrefied wood dust is a class St1 dust (weak, normal) same as most fuel dusts.

On top of explosivity parameters the flammability and self-heating characteristics are of key importance for the characterisation and classification of products in logistics. Testing according IMO standards is required. IMO 4.1 for flammability and IMO 4.2 for self-heating properties.

Based on the test results Mak (2011), it is concluded that the investigated sample of crushed torrefied wood pellets is not flammable and has no self-heating properties in the sense of the criteria laid down in the United Nations Recommendations on the Transport of Dangerous Goods, Manual of Tests and Criteria, fifth revised edition. Consequently, the material does not need to be classified as a flammable solid or as a self-heating substance.

IMO, IMSBC

The main legislation governing safe carriage of solid bulk cargoes is the International Maritime Solid Bulk Cargoes (IMSBC) Code [International Maritime Organisation, London 2013], which became mandatory on January 1, 2011, under the SOLAS Convention and does provide guidance and regulation for shippers, ship owners and the P&I clubs (vessel insurance) on the international shipping of bulk cargoes.

Torrefied wood (not torrefied agro products) is within the IMSBC allowed to be shipped in bulk provided the vessels are CO2 fitted- equipped with fixed gas fire extinguishing systems (CO2). This is already a positive development for torrefied biomass as it was seen before similar to charcoal, which is prohibited, to be shipped in bulk on board of vessels and in many jurisdictions also by rail cars.

Still it seems that clarity on the hazardous status of torrefied and densified biomass need to be gained respectively recognized by IMO. VTT does in its testing on IMO 4.1 (flammability) and IMO 4.2 (self-heating) come to the clear conclusion that “that the investigated sample of crushed torrefied wood pellets is not flammable and has no self-heating properties in the sense of the criteria laid down in the United Nations Recommendations on the Transport of Dangerous Goods, Manual of Tests and Criteria, fifth revised edition. Consequently, the material does not need to be classified as a flammable solid or as a self-heating substance.” (179)

However, in Resolution MSC 354(92) amendment to the IMSBC, the IMO classifies Wood Pelletised as MHB – Material Hazardous in Bulk.

Once more experience in bulk shipments is gained a clear position will result and based on the VTT testing shippers will have good arguments and proof on their negotiation with ship owners respectively their P&I clubs.

The U.S. Coast Guard provided temporary permission for in-port handling, loading to vessels, and shipping of torrefied product.

Nevertheless, transporting torrefied biomass in bulk will always increase the likelihood of dust generation while handling and transporting the material. Dust from torrefied biomass does behave similar to wood dust of same particle size (M.Carbo, 177). On that basis one would expect that torrefied biomass is categorised same as for instance wood chips. However, the brittleness of the material will simply result in bigger amounts of dust along the logistics chain hence increasing the risk for any accidents because of the dust. Severe dusting has been observed in some of the unloading processes but has not been observed as a general character of torrefied and densified products. Therefore it seems not only from economic but mostly from safety point of view very recommendable to compact the torrefied biomass into pellets or briquettes.

Producers do confirm that further improvement in densification is one of the ongoing optimisation undertakings with the objective to increase durability further which will lead at least to lower dust formation and further increased water resistance.

MSDS – Material Safety Data Sheet

Safety data sheets (SDS) or Material Safety Data Sheets (MSDS) are the main tool for ensuring that suppliers communicate enough information along the supply chain to allow safe use of their substances and mixtures.

Safety data sheets include information about the properties of the substance (or mixture), its hazards and instructions for handling, disposal and transport and also first-aid, fire-fighting and exposure control measures⁸. The provision of the SDS is the duty of the individual supplier of the products.

A template for a MSDS for torrefied biomass has been developed by the IBTC in co-operation with the SECTOR project (Solid Sustainable Energy Carriers from Biomass by Means of Torrefaction⁹ (SECTOR), co-funded by the European Commission and led by Deutsches Biomasseforschungszentrum (DBFZ) and is published as Deliverable D8.6 under the Sector publications (https://sector-project.eu/fileadmin/downloads/deliverables/SECTOR_D8.6.__DBFZ__final.pdf)

⁸ echa.europa.eu/regulations/clp/safety-data-sheets

⁹ Website: www.sector-project.eu

Clarifying necessity of REACH registration

Whether a registration under REACH for torrefied material is required cannot be determined unequivocally at the present time. The biomass feedstock does not require it, neither from lignocellulose plants nor from agriculture residues. By subjecting the biomass to a heat treatment in an oxygen deficient environment the resulting product is more comparable to coal, which is not under the obligation to register and is covered by the regulation in Annex V/7. The question is if the heat treatment can be considered as a chemical treatment or not (see Article 3/39), the torrefaction process tends to modify the natural occurring substance somewhat (see Article 3/40) by mainly removing water, and weakening the strength of the hemicellulose. (FN Sector, D 8.6 p4f)

To clarify the question whether a registration is necessary or not, a group of IBTC (International Biomass Torrefaction Council) members has formed a Torrefied Biomass REACH consortium. Lead by Renewable Fuel Technologies Ltd of UK a SIEF (Substance Information Exchange Forum) agreement to submit a joint registration dossier to ECHA was established. IBTC does serve as first contact point.

ISO 17225-8 Thermally treated Biomass

Initiated by the IBTC in 2012 the ISO working group on solid biofuels created a new work item proposal which was later on broadened to cover thermally treated biomass products in general. The discussion process and work on the standard is well advanced and it can be expected that within the year 2016 either a ISO Technical Specification or a full ISO standard will be released under ISO 17225-8. In the process of discussion separate categories have been developed within the overall work item. The discussion within the ISO working group is not a public discussion but interested parties may contact the national standardisation committee and become a party to the process.

Customs Code

Currently torrefied biomass is classified under the charcoal customs code 44029000. At the time authorities did this classification no standard on torrefied biomass was available and information provided might have been not concurrent. Hence a classification according visual appearance was taken. When the ISO standard will be completed a more homogenous picture on the characteristics of torrefied biomass will be documented and this might result in a re-classification. This on attempt of the producers and shippers of torrefied biomass as charcoal is classified hazardous in many regulations where torrefied biomass has proof not to be hazardous.

Transportation on European rail and road will require registration through Nomenclature harmonisée des marchandises (NHM).

Table 7. Supply Chain Comparison

	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 chips 44012100 soft wood, 44012200 others	4401 3020,440131..	in process, today charcoal code but changes expected
	lower quality chips and forest industry by-products (bark) 44013080		after ISO standard is completed

REACH	Excepted	Excepted	unclear, clarification with ECHA in progress
ISO standard	17225-4	17225-2	17225-8 in progress
EN Standard	14961-4	14961-2	
EVALUATION			
Quality Determination	Moisture	fulfilling standard and class	fulfilling standard and class
	Size	certification	NCV
	bark content	NCV	finer
	NCV	finer	ash&ashmelting
			grindability
HANDLING			
Hazards	may be subject to oxidation leading to CO	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	low>15% moisture		MHB
STORAGE AND SEGREGATION			Segregation as for class 4.1 materials
Loading/Handling	free trimming	free trimming	free trimming
weather precautions/water sensitive	no	yes, as dry as practicable	cargo shall be kept as dry as practicable
open storage	yes	no	short term yes, long term no
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
storage factor in vessel ft ³ /mt	85-230	53-59	49-54
kg/m ³	150-400	600-660	650-800
IMSBC group	B	B	B

6 Economic potential of torrefied biomass production and use

At the moment, there is no market in place for torrefied pellets in practice; therefore, no information is available on market prices. The capital costs on pure machinery for a torrefied pellet plant are somewhat 10 to 25% higher than those of a conventional wood pellet plant. However, with some variations by region, the labour, operation, and maintenance and administration costs seem the same as with traditional pellets. Some reports do show a higher electricity consumption when pelletizing torrefied biomass, however, as many producers seem to go into briquetting this may turn the productions electricity consumption even below standard wood pellet plants.

Commercial offers for torrefaction plants are strictly confidential for the time being and the lack of plant in operation does lead to a shortage in information about real CAPEX needs. Andritz AG moving out of torrefaction has also withdrawn one of the view companies offering the torrefaction lines under EPC. Most other companies in torrefaction do offer certain specialised machinery either for the torrefaction itself (torrefaction island, torrefaction reactor etc.) or the densification units (briquetting, pelleting). Hence it is up to the project developer to either find an EPC or undertake the selection and combination of all machinery by himself including infrastructure and auxiliary equipment. Project developers of standard pellet plants will not need to readjust significantly if going into the developing of torrefaction plants. There is almost no difference in the entire layout, the infrastructural needs and the operational needs and habits comparing standard wood pelleting plants to torrefaction plants.

Batidzirai et al. (2013) estimate that the short-term production costs for torrefied pellets will be between 3.3 and 4.8 US\$/GJ (3.1 and 4.5 €/GJ) (Lower Heating Value, LHV), falling to 2.1-5.1 US\$/GJ (2.1-4.8 €/GJ) (LHV) in the long term. Thus, at such cost levels, torrefied pellets would become competitive with traditional pellets. The above-mentioned study concludes that during the early commercialisation of torrefaction technology, costs may actually rise rather than decrease, because of uncertainties in initial cost estimates for scaling up of pilot and prototype facilities. This leads, for example, to high contingency costs. Only after the installation of a commercial-scale unit operated at its stated capacity can optimisation of the design effectively take place. Batidzirai et al. (2013) suggest this phase being reached in 2015. Table 8 shows the results of considering various scales and accordant production costs for torrefied pellets with today's technology.

Table 8. Economic figures for torrefaction plants in 2012 (Batidzirai et al. 2013)

Cost item	Scale of plant (in thousands of tonnes of TOPs):				Units
	50	100	250	500	
Capex	23.4	38.1	72.3	117.5	M\$
Capex/year	2.7	4.4	8.4	13.7	M\$/yr
Opex/year	1.9	3	5.8	9.4	M\$/yr
Electricity costs	0.3	0.5	1.4	2.7	M\$/yr
Production costs	97.7	80.4	66.2	51.7	\$/tonne
Production costs excluding feedstock costs	4.8	4	3.3	2.6	\$/GJ

Based on the assumed learning rate and scaling effects, the production costs presented in Table 9 for torrefied pellets can be obtained in the future. The costs shown below exclude biomass feedstock costs.

Table 9. Projected torrefied-pellet production costs by 2030 (assuming six capacity doublings) (Batidzirai et al. 2013)

Cost item	Scale of plant (in thousands of tonnes of TOPs):				Units
	50	100	250	500	
Capex	22.7	36.7	69.1	109.8	M\$
Capex adjusted to reflect pre-learning uncertainties	27.3	44.0	83.0	131.8	M\$
Capex/year	3.2	5.1	9.7	15.4	M\$/yr
Opex/year	2.2	3.5	6.6	10.5	M\$/yr
Electricity costs	0.2	0.4	0.9	1.9	M\$/yr
Costs	111.2	90.4	69.1	55.1	\$/GJ
Costs	5.1	4.15	3.2	2.6	\$/GJ

As economic data is most sensitive for the companies supplying torrefaction technology or operating a torrefaction plant, no falsification of above data from 2013 could be generated so far. However, it seems that CAPEX expectations have come down further and especially the CAPEX adjustment is not needed anymore. Here the torrefaction technology suppliers had to learn the hard way that the solid biomass market is not open to pay a significant premium for a fuel independent of the expected advantages. Presenting an economic comparison of torrefaction and conventional pellet production based on an end-use point of view, Ehrig et al. (2013) concluded that the production costs from the pre-treatment phase are much higher for torrefied pellets, but these can be partly compensated for by reduced transport and logistics costs. This conclusions must be challenged as the conclusions taken from prices offered today for first off plants will not be valid when regular plants will be supplied to the market as described in Table 9. However, increased costs for capital and operation in respect to white wood pellet production need to be out weight by the savings along the product supply chain. As those costs, especially shipping, are at an almost all time low – see chapter 4 – torrefaction companies are exposed to an even higher cost competition with white wood pellets chains.

At the end user, the torrefied fuel delivered seems currently to be neck and neck with conventional pellets. Conversion of 'premium' torrefied pellets to heat for domestic use is still in a pilot phase, hence commercial comparisons are not viable yet. In contrast, the conversion of industrial torrefied pellets is at the same cost level as that of industrial wood pellets. This means that torrefaction offers certain opportunities to replace or complement conventional wood-pellet production and supply. Suppliers will use the same logistics and means of transport as for wood pellets (a fact confirmed by a biofuel trader in personal communication), supply costs are reduced slightly (9%) on account of higher bulk density (relevant for transport by train and ship), and supply costs can be decreased approximately 10% by taking advantage of the higher energy density.

Suopajärvi et al. (2014) show that the energy return on investment (EROI) of torrefied wood in the steel industry seems attractive. Working from the Finnish example in steel production in Ruukki, Suopajärvi et al. (2014) conclude that the CO₂ reduction potential could be from 1 Mt to 1.4 Mt annually.

Illustration: Torrefied biomass vs. other fuels, comparison of costs in once case

Comparison of torrefied and regular wood pellets in terms of cost at delivery and energy consumption shows that torrefied pellets are competitive against conventional pellets. Mobini et al. (2014) present a model that is applied to an existing wood-pellet supply chain in British Columbia and analyse the difference in price between torrefied pellets and wood pellets. The case study shows that the integration of torrefaction into the wood pellet production and distribution supply chain leads to lower delivery cost to existing and potential markets, due to the increased energy density and lower distribution costs. The delivered cost of torrefied pellets (€/GJ) in North-West Europe is 9% lower, than that of regular pellets. Thanks to efficient transport, the energy consumption and the CO₂ emitted along the supply chain are decreased for torrefied pellets. Integration of torrefaction into the wood-pellet production and distribution supply chain could result in less expensive and cleaner biofuel.

The estimated cost of torrefied pellets stored at the international port in North Vancouver was 148 CN\$/t (about 105 €/t), which is 38% higher than that of regular pellets by weight. However, this can be offset by lower distribution, storage, and handling costs. The higher energy density of torrefied pellets and their lower handling and storage costs make the cost of delivered torrefied pellets comparable in the case of transportation by sea (Mobini et al., 2014).

Transporting torrefied biomass with coal offers possibilities. Bradley (2014) demonstrates the benefits of shipping torrefied pellets with coal. If we supply 10% torrefied pellets with 90% coal by ship, the result could be 2–3 times less expensive per shipment than a supply chain for 100% wood pellets.

7 Impact of torrefaction on international trade

Preliminary conclusion on the impact of torrefaction on the upstream and downstream value chain

So far it has been shown that torrefied biomass—once it becomes available in large volumes—will have a significant effect on the development of bioenergy markets. The bioenergy market, the large-scale heat and power production segment in particular, are looking for a biomass commodity that allows for an easy integration into existing conversion plants and logistical systems. A biogenic product with characteristics similar to coal is wanted. Neither wood chips nor wood/agro pellets fulfil these criteria satisfactorily, and they only allow for limited co-firing ratios if de-rating of the power plant need to be avoided (10% limitation seems quite common, a few stray instances report up to 30% depending on the grade of adaptation of the feeding system, coal mills and boilers). Torrefied biomass has proven, in laboratory scale, that 100% firing regimes are possible with minimum adjustments to the coal power plant's combustion unit and at significantly reduced de-rating compared to woody pellets.

In respect to the wood pellet supply chain as operated today, torrefied biomass creates many win-win situations along the value chain. Upstream, the broadening of the feedstock base and a lower sensitivity in homogeneity of the input material create the biggest advantages. Downstream, the hydrophobic nature of torrefied biomass allows, to some extent, open storage and transportation. Higher energy density will lower specific transportation costs, brittleness of the torrefied biomass product will allow co-milling in existing coal mills, and combustion characteristics almost superior to those of coal will allow easy substitution in co-firing or complete conversion at lower costs. All parties along the value chain—including raw-material owner/providers, processors, transporters, stevedores, shippers, and consumers—experience benefits from torrefied biomass compared to wood or agro pellets.

Fewer coal plants would be required to adopt co-firing to reach total green-power production targets, and utilities can therefore concentrate on co-firing in those locations that are best placed for efficient biomass sourcing and logistics, such as coal plants with low-cost logistical access to deep-sea harbours. Coal power plants could even transition totally to torrefied biomass feedstocks, leading to much lower emissions of sulphur and heavy metals. All of these effects would support the initial economics of green-power production and, by so doing, support the future growth of this industry. Making biomass properties more like fossil coal also opens up the usage of already existing (and installed) coal gasification technologies for large-scale, tar-free, and pressurized syngas production, leading to even higher conversion-to-power efficiencies when applying the Integrated Gasification Combined Cycle (IGCC) technology to green synthetic fuels such as BTL or other green chemicals.

What are the expected trade flows (volumes and directions)?

In compacted form, as pellets or briquettes, torrefied biomass offers significant reductions in transportation costs in long-distance transportation. At given costs per GJ delivered, the biomass catchment area for each consumer is significantly increased, and torrefied compacted biomass could become a globally traded bioenergy carrier.

Technically, it seems torrefied biomass can substitute for coal completely. Steam coal consumption will grow from 6 today up to 9 billion tons per year in 2030 (IEA 2010), with growing demand mostly through China and India. Even without torrefied biomass as a substitute for coal in existing supply chains, the continuous growth in coal demand and the increasing competition for this resource will lead to a strong demand for torrefied biomass in Asia, which, in the not-so-distant future, could replace Europe as the main consumer of torrefied biomass. Beside utilisation of local biomasses international trade will be boosted with traditional biomass suppliers like Canada, the US and Brazil as players but also new entries. First wood pellet projects in Eastern Siberia as seen today are just a hint what massive flows of biomass products easier in handling could be mobilised from that area addressing because of its relative vicinity markets in China and Japan. As well as flows of woody and agricultural biomass from Southeast Asian countries into China and India, seem possible as the result of such a development.

Torrefied biomass may also offer many Sub-Saharan African regions, with their good growing conditions, opportunities as bioenergy-exporting regions, although sustainability concerns such as food security, land rights and environmentally and socially sound production need to be ensured.

All torrefied biomass producers, wherever located throughout the world, will initially consider the European market, and first trade flows will likely focus on European demand. However, South Korea and Japan are also developing infrastructure for torrefied biomass consumption and will, not long after Europe, place demand in the market..

While demand for biomass, and especially torrefied biomass, will rise in Europe based on the legal obligation to achieve 20% renewable energy production by 2020, significant demand for imports of energy biomass might also develop in highly industrialized Asian countries that have clear goals for increasing their share of bioenergy production but insufficient biomass endowments Demand for biomass import to Japan and South Korea might reach substantial volumes by 2020 while at the same time bioenergy goals of India and China will be increased as well.

Though not directly cost competitive with steam coal at today's coal and CO2 market conditions the uptake of torrefied biomass in regions of extreme growth in coal demand – China, India - may be driven strongly by the need to increase security of supply. A second leg in supplies provided by torrefied biomass might be very welcome by strategic departments of power utilities. The fact that torrefied biomass will ship from different ports and maybe also utilise different vessel classes might contribute to higher price stability of torrefied biomass in respect to coal. Wood pellets have proven of the past decade such lower volatility in pricing. The origination of the biomass from different sources/companies/countries in comparison to imported coal can help to diversify a country's energy portfolio, and domestic production can improve the trade balance and increase jobs locally hence become an important issues for several importing countries.

If international growth in demand for torrefied biomass occurs, a faster development of needed infrastructure has to follow in order to allow for sustainable use of the existing biomass resources. If supply cannot meet demand by significant margins, chances are high that those biomass sources with already existing access will be used beyond sustainable levels of removal.

What kind of trade/logistical infrastructure is needed or can be used for future torrefied biomass flows?

Because of the hydrophobic nature of torrefied biomass, handling will be easier in comparison to wood pellets or other water-sensitive bulk cargos. Torrefied biomass can be handled using the existing wood pellet infrastructure for loading, trucking/railing, or shipping. The material can be easily and inexpensively stored in sheltered pellet stockpiles like warehouses or silos. Wood- and agro-pellet infrastructure can be used for torrefied biomass immediately.

There are additional considerations for handling torrefied biomass in parallel with coal logistics infrastructures. The material's hydrophobic qualities may be insufficient in these systems, and test runs with larger quantities will be needed to demonstrate that torrefied biomass will not soften when exposed to weather for longer periods of time and that certain components of the torrefied biomass will not be washed out by rainwater and converted to poisonous wastewater.

In general, when handling this material, it seems advisable to keep torrefied biomass somewhat moist to prevent dry torrefied biomass from breaking down into dust and increasing risk of dust-explosion.

How fast can the needed infrastructure be develop and how will it be financed?

Development of the logistical infrastructure depends on the necessary capital being directed into the torrefied biomass market. As always when projects need finance, three key issues need to be covered sufficiently:

(1) *Guaranteed availability of raw material at given prices and quality* – a limiting factor in all biomass projects, but the broadening of possible feedstock basis for torrefied biomass projects will ease this limitation and bring additional, as yet inaccessible, supplies to the market.

(2) *Processing technology necessary to start operation on time and at guaranteed performance* – first industrial-scale torrefaction units will begin operation in 2012; from 2013 the market will see the start of the roll out of torrefied biomass technologies, but technological uncertainties will keep the development in slow motion compared to what can be expected from 2014 onwards. From that time forward, global players in machinery, , may penetrate the market efficiently with torrefied-biomass technology and provide the necessary technology performance guarantee.

(3) *Off-take of the product at cost-covering prices* – seems to be a given in the case of European off-takers. In other parts of the world, torrefied biomass will have to compete with coal, and CO₂ cost approaches to biomass will be important considerations.

Nevertheless, the market has not kick started yet and prerequisite to start it off the chicken and egg situation torrefaction technology is in today need to be overcome. Very typical for new technologies both parties on the market, risk averse as they have to be, are waiting for the other side to move first. The producers, generally willing to implement torrefaction technology and produce torrefied biomass, do need long term security that their product will be sold at return expectation satisfying prices, hence waiting to get long term off take contracts from bankable customers. The buyers on the other side, generally willing to buy, do need first prove that all promises concerning torrefied biomass are kept and if once so expect certainty if not to say guarantees on quality, volume and pricing, all of this from bankable suppliers. Therefore suppliers would have to provide burn samples and volumes for testing at the power plants far smaller than economically viable for a torrefaction plant. Very significant contributions to overcome this almost dead locked situation have been seen from an independent producer in Mississippi. However, one producer is insufficient to build a market and hence this deadlock has the potential to cause the torrefaction market to take off with a major delay only. Especially power plants undergoing conversion from coal to biomass within the next few years do need today reliable specifications of fuel to be burned to evaluate and properly design eventually needed technology adjustments. If specs and supply security is not provided soon the conversion will be implemented on basis of wood pellet requirements which will not rule out technically combustion of torrefied products in the future as well but will have caused all the costs of conversion for wood pellets and hence not allow for price upmarks for torrefied product resulting from reduced investment at power plant.

It seems today that torrefied biomass project developers have good reason to believe that these key issues will develop to their advantage soon helping them for project finance. With production under development and off-take guaranteed, the logistics infrastructure will become available, especially if the wood pellet and coal infrastructures can be used for torrefied biomass logistics. Eventually, it might be the technology suppliers and their capacity to supply the needed machinery that limits the growth of the torrefied biomass supply market.

In general, the fact that torrefied biomass is infrastructure compatible should facilitate the adoption and utilization of the torrefaction technology, once it becomes commercially available, over conventional preconditioning technologies. On the basis of the historical wood pelletization technology adaption curve,¹⁰ total torrefied biomass production capacity could grow from almost zero today to millions of tons within the next 10 years. Torrefaction might even be a substantial contributor to achieving the estimated biomass demand by 2020, up to 50 to 80 million ton per year in Europe alone if above described dead locked situation is overcome soon.

What are the possible developments for trade of torrefied biomass until 2020?

Once the assumed storage, handling, and combustion characteristics of torrefied biomass are verified, the demand for this product in Europe alone can, *ceteris paribus*, easily cross the 50 million BDT-per-year threshold by 2020. Europe will most likely start to compete with the same market makers as steam coal today: China, India, other Asian countries, as well as the U.S. Volumes consumed in these countries by then could be even larger than in Europe. If this situation finally occurs, the biomass-for-energy market will transition from the buyers' market of today into the sellers' market of the future.

¹⁰ 2003 - 3MT / 2010 - 13MT / 2020 - 50 MT

7.1 Possible industrial consumers of torrefied biomass, by region

Europe

In Europe, the use of torrefied biomass in industry seems promising. Total residual-material availability for bioenergy in Europe is about 4.2 EJ (IEA, 2012). The biggest demonstration applications of torrefaction technology are found in various EU countries, among them the Netherlands, Sweden, France, Finland and Spain, which have built demonstration plants starting up within the last two years. These plants are paving the way for commercial plants and creating opportunity for torrefied-biomass trade within Europe and beyond.

The Europe will be the driver in the development of the market simply by providing immediate demand for torrefied biomass. This demand will surely be measured in single-digits numbers of millions of metric tonnes, if the expectations for torrefied biomass hold¹¹.

Demand for torrefied biomass by the industrial sector could be seen in Northern Europe, in countries such as Germany, Sweden, and Finland. For instance, Wang et al. (2014) presented a SWOT analysis of the biocoal (including pyrolysis and hydrothermal carbonization) sector in Finland. The study showed that, in the beginning, replacing fossil fuels with biocoal would require large investments in setting up infrastructure and distribution systems, developing technology, upgrading production facilities (the projected investment is 30–40 million euros for a plant with a 0.2 Mt/a production capacity), and modifying applications (e.g., investment in co-firing technology and equipment). Later, the cost of biocoal will decline significantly with expanded production, increase of related technology applications, and maturity of the market.

One of the main drivers of biomass development and torrefied-biomass demand is dependence on fossil fuels. Germany and Italy account for 47% of the total EU consumption of Russian natural gas. The relevant Russian pipelines pass through Ukraine to Italy, Austria, and Hungary. For these countries, the use of biomass and new technology could decrease this dependency.

Drivers for torrefied biomass development in the relevant industries for the EU:

- National Renewable Energy Action Plans (NREAPs) for meeting the 20-20-20 goal by 2020 stimulating new developments in biomass technology, including torrefaction.
- In the iron and steel industry and equally in the cement industry, great potentials to reduce CO₂ emissions via torrefied biomass (the EU, alongside Australia, introduced forest-based biomass use, with a focus on increasing the use of biomass in the steel industry).¹²
- In the chemical and mechanical forestry industries, bioenergy use already being quite well established in many European countries, especially in the Nordic region (Europe and the USA are the historically important production area for the petrochemical industry).
- A goal of decreasing dependence on fossil-fuel imports.
- Good infrastructure for torrefied biomass's transportation.

In the near future, torrefied-biomass use in industrial applications could constitute 5–10% of all biomass use in the EU.¹³

In the future, pulp and paper industry will import regionally produced biomass instead of purchasing fossil energy and could extend the industry's mission from simply manufacturing low-margin products into new products such as 'green' power and

¹¹ Possible Effect of Torrefaction on Biomass trade (IEA Bioenergy Task 40, 'Sustainable International Bioenergy Trade'), June 2012.

¹² Web site <http://www.ulcos.org/en/>

¹³ Status Overview of Torrefaction Technologies (IEA Bioenergy Task 32, 'Biomass Combustion and Co-firing'), December 2012.

torrefied biomass. It could improve the efficiency and profitability of their traditional core business. The use of biomass, primarily for process heat, could increase in the pulp and paper industry significantly (Bajpai, 2013). The main European leaders in this industry are three Nordic companies SCA, Stora Enso and UPM. These companies maintain contact with various research centres and organisations and are interested in new trends in bioenergy, including torrefaction.

Both the chemical and petrochemical and the cement industry have room for sensibly increasing their use of biomass. However, these industries will reach their potential in this regard only if there are concerted efforts for them to do so. If torrefied biomass becomes commercialized, it will create new options for the cement industry, an industry in which several companies see good potential to increase their use of biomass and the biodegradable fraction of waste in their energy production.

In the petrochemical industry's historically important production areas in Europe (and US), the investment choices inherent in this shift of emphasis are now beginning to affect the availability and price of some petrochemical intermediates significantly. Producers increasingly consider basing their production processes on biomass, a renewable and abundant resource. Greater biomass use looks promising. Investment in biorefineries that can make profits and diversify risk through production of a range of products will play a crucial role in wider biomass deployment in the chemical and petrochemical industry.

Africa

For Africa, new biomass technology mostly is far off, however, the availability of raw materials, low-cost labour, and favourable conditions for import to the EU render it possible to create traditional biofuel production in the long term, followed by production of new biofuels such as torrefied biomass. Much of Africa has great potential to become an important exporter of bioenergy. For example, about 0.30 EJ of charcoal was produced by Nigeria, Congo, Ethiopia, Ghana, and Tanzania collectively in 2011 (after Brazil, with 0.14 EJ).¹⁴ Modern technology and farming infrastructure will be required to make regions in Africa competitive in the biofuel market. While South Africa seems promising in terms of biomass development and establishing torrefaction plants, the use of torrefied biomass in industry does not seem predictable before 2025.

Asia

In Asia, China's (including Hong Kong) industry is an important energy consumer. In 2013, industry of China consumed 40 EJ of energy, which is about 70% of Asian industry's total consumption. Although, according to the statistics Chinese industrial sector does not consume biomass, it might be possible for this to occur in the future. In China, biomass use in industry can be forecasted to increase, because of the strong steel and iron industry and paper and paperboard industry, along with very ambitious plans for the use of renewable energy, wherein biomass plays an important role in the renewable-energy mix. However, it is very unlikely that China will be a nation exporting biomass. It might well choose to import biomass in the future to support its energy plans¹⁵; after the import of biomass, torrefied biomass might be visible from a long-term perspective. Currently, China is one of the leading steel-production countries. It is possible that torrefied biomass will attract the attention of this industrial sector.

In other parts of Asia, it is possible to foresee new biofuel products with which bioenergy use will become quite well established in industrial applications. The company APP Group (Asia Pulp and Paper)¹⁶ which is one of the world's largest pulp and paper companies has set a target for biomass development. South-East Asia's lowest-cost feedstock is residual material from palm oil and other processing plants, most prominent in Indonesia and Thailand. Also, these two places

¹⁴ International Renewable Energy Agency. Global Bioenergy: Supply and Demand Projections (working paper for REMAP 2030), September 2014.

¹⁵ International Institute for Sustainability Analysis and Strategy. Possibilities of Sustainable Woody Energy Trade and Impacts on Developing Countries, January 2014.

¹⁶ Web site at <https://www.asiapulppaper.com/>.

present the most abundant source of agro-residues, an abundant source though slightly more costly. The USA, Europe, and Japan have seen their share of the market contract in favour of Asia and the Middle East. Producers in Asia are starting to prefer the use of biomass in the petrochemical and chemical industry (Panorama, 2012).

Canada

Biomass use is not popular in Canada as in most European countries. In the pulp and paper and in the non-metallic-minerals industry, biomass use could be increased in Canada. There is a large-scale torrefaction demonstration application in Canada. Also, for instance, Airex Energy and Diacarbon will have a combined production capacity of 0.04 Mt/a of torrefied pellets in 2015. Production for the export could be possible in consequence of the large forestry sector and excellent opportunities for export of torrefied biomass. Accordingly, afterward, the possibilities offered by torrefied-biomass production could attract the attention of industrial sector within the country. Drivers for torrefied-biomass development by the industries in Canada:

- One of the world's largest forestry sectors: a potential source of residual material from dead and dying trees, which may provide a significant near-term torrefied-product market opportunity.¹⁷
- A modern industrial economy and a good transportation system.¹⁷
- Dynamic bioenergy-policy development at province and/or regional level, with the Renewable Fuel Strategy, the EcoEnergy Innovation Initiative, Investments in Forest Industry Transformation (IFIT), and support and promotion of forest bioenergy.
- In the pulp and paper industry, big Canadian companies such as Resolute Forest Products (Quebec) trying to reduce the consumption of fossil fuel by means of renewables, mainly biomass.

The magazine *Canadian Biomass*¹⁸ states that there is an increase in demand for wood pellets in Canada, especially British Columbia, and it is expected that a domestic market will emerge when the availability of torrefied material increases. Thanks to excellent raw-material resources and strong know-how in selling wood pellets (throughout Canada but particularly in British Columbia), Canada could also be the leader in supplying torrefied biocoal to the world market seeking green alternatives, if proper investments are made in process development.

US

The largest-scale torrefaction applications are found in the US. Torrefied-biomass production could significantly increase biomass trade in the US market. New Biomass Energy LLC is launching a joint venture with Solvay for expansion of torrefied-biomass production. The company's plant in Quitman, Mississippi is the largest torrefaction facility in North America. This project planned to establish an annual production capacity of 0.25 Mt by the end of 2014. Solvay Biomass Energy will promote its torrefied wood pellets for electricity production in Europe and Asia. The joint-venture company is capable of producing torrefied pellets at a commercial level.

A study at North Carolina State University developed and validated a technical and economic model for the production of lignocellulosic torrefied biomass for its utilisation in the solid biofuels industry, with a focus on production and as-delivered costs for potential manufacturers in the US. The results show that the production of torrefied lignocellulosic biomass can be profitable for US manufacturers, although one must factor in the high sensitivity of biomass cost, capital expenditure (Capex), and technology affordability for large-scale production. Also, the addition of carbon credits to the financial indicators for a torrefaction facility may become a key element if the market finds the right set of conditions and regulations in the US. Preliminary analysis indicates that an increase in carbon-credit prices may dramatically benefit the torrefied-biomass business (Pirraglia et al. 2012).

¹⁷ Possible Effect of Torrefaction on Biomass trade (IEA Bioenergy Task 40, 'Sustainable International Bioenergy Trade'), June 2012.

¹⁸ Web site at <http://www.canadianbiomassmagazine.ca/>.

Although the production of torrefied biomass could be more export-oriented, possibilities for the local use of torrefied biomass in industrial applications can be found in US.

Drivers for torrefied-biomass development in industry in US:

- High biomass production potential (~48 GJ/a *per capita*).¹⁹
- The Energy Independence and Security Act of 2007 (EISA), which sets goals for biofuel production through 2022, emission-limit-compliance strategies at the state level, and standards set by other organisation that have helped to drive federal policy.
- The US being one of the main producers of paper and paperboard.
- A world-leading position in steel and iron production.
- A potential, future binding requirement to reduce carbon emissions in the power sector under the Clean Power Plan 2015²⁰ which applies to existing power plants.

Australia

Targets are in place for increased biomass use in Australia²¹. It has potential for development in Australia's innovative steel-oriented sectors. However, torrefied biomass cannot be predicted, at least in near-future terms. The non-metallic-minerals industry gets less than 1% of the energy it consumes from biomass, so a great increase in biomass use is not predicted for this industry. In the paper, pulp, and print industry, biomass use could significantly increase when torrefied biomass finds its niche.

Drivers for torrefied biomass's development by the industries in Australia:

- The greatest opportunity being to establish new eucalyptus plantations for pelletising.
- Australia's iron and steel industry being among the most dynamic and innovative steel sectors in the world.²²
- The EU and Australia's introduction of forest-based-biomass programmes in steel production.²³

Brazil

Brazil has high biomass potential (~75 GJ/a *per capita*), as a major producer of both forest products and sugarcane. Use of biofuels is focused on supply security for the internal market. The overarching programme Fundo Clima promotes energy from biomass. Currently, biomass covers approximately 35% of the energy consumption of Brazil's iron and steel industry. Biomass gasification could be one of the most promising technologies for replacing natural gas. It could not only yield benefits for sustainability and responding to global-warming issues but also decrease dependence on imports (half of the natural gas consumed is imported, mainly from neighbouring country Bolivia).

Brazil is the world's largest producer of charcoal, accounting for 11% (5 Mt) of total production in 2010, with that charcoal used mainly for the production of pig iron. Charcoal is still used for iron-making on an industrial scale in Brazil. ArcelorMittal Bioenergética produces charcoal from eucalyptus-based forestry operations. This charcoal is used to fuel iron furnaces in Juiz de Fora or exchanged for pig iron with local producers.²⁴

In the iron and steel industry, the huge amount of available biomass waste creates huge drivers for torrefied-biomass development. However, the lack of much experience in biofuel products' use (pellet production and export began only in

¹⁹ M. Junginger, S.C. Goh, & A. Faaij. International Bioenergy Trade (IEA Bioenergy Task 40).

²⁰ United States Environmental Protection Agency, <http://www2.epa.gov/cleanpowerplan/clean-power-plan-existing-power-plants>

²¹ Australian Bioenergy Roadmap, 2008.

²² Australian steel institute <http://steel.org.au/about-our-industry/>

²³ Web site: <http://www.ulcos.org/en/>.

²⁴ United Nations Industrial Development Organization. Renewable Energy in Industrial Applications, an Assessment of the 2050 Potential, 2011.

the last couple years) and the large investments required for torrefied-product technology mean that the share of this product could be increased but only very slowly for the near future.

From a long-term perspective (20–30 years), it is possible to see big changes in biomass use by the country’s industries. Carvalho et al. (2013), assessing large-scale biomass-gasification facilities in Brazil, gives reason to believe that industries such as those producing iron, steel, and non-metallic minerals will see increased biomass use mainly on account of torrefied biomass within the country.

In Brazil, despite the possibilities for use of torrefied biomass in the iron and steel industry (see Table 10), the impact of torrefied-biomass use by Brazilian industry on the international biomass trade, in general, could not be predicted with reliability. Currently, Brazilian participation in the world solid-biofuel market remains insignificant (Escobar et al. 2014).

Japan

In Japan, which is a big importer and consumer of coal, co-firing of biomass, such as wood pellets and wood chips, with coal is becoming popular in some locations. In the wake of the 2011 earthquake striking eastern Japan, the country is finding new means of energy production. One of them involves attention to a plan to supply the surplus power from the paper industry to power companies.

The Japanese government introduced a programme²⁵ of incentives for firms selling power produced from renewable sources. However, because of the demand for coal, which is the lowest-cost option, and competition with other renewables, a large increase in biomass use is not so readily predictable.

Japan’s paper and pulp industry seems to hold promise for increased use of biomass. At present, the pulp and paper industry has a large share of its energy consumption covered by biomass, mainly by using black-liquor gasification and wood chips, and has plans to increase this share. From a long-term perspective, torrefied-biomass use could have a role in Japan’s pulp and paper industry. Japan is one of the main producers of paper and paperboard.

Based on the current biomass use by various industries in individual regions and the technical possibilities of torrefied biomass use a scenario for biomass and torrefied biomass demand by industry in the various regions can be developed (see Table 10). The countries/regions covered in Table 10 were assessed for their attractiveness in terms of torrefied-biomass production, willingness to use it, and/or actual use and on the basis of which industry has a leading position (e.g., iron and steel, ceramics, or paper and pulp).

Table 10. Current biomass use and predicted biomass and torrefied-biomass use, by region.

Region	Current industrial biomass use and proportion of the total biomass consumption for energy (IEA ²⁶)	Prediction of consumption by industry in 2025		
		Biomass	Torrefied biomass	Most attractive industries for torrefied-biomass use
EU-28	1 EJ (9%)	13%	5–10%	Pulp and paper, non-metallic minerals
Africa	0.8 EJ (32%)	35%	Low	
Asia	2 EJ (5%)	7%	0.5–1%	Iron and steel, pulp and paper
Canada	0.3 EJ (10%)	13%	2–3%	Pulp and paper, non-metallic minerals
US	1 EJ (11%)	14%	2–3%	Non-metallic minerals, pulp and paper
Australia	0.1 EJ (11%)	15%	1–2%	Pulp and paper
Brazil	1.5 EJ (42%)	43%	1–1.5%	Iron and steel, pulp and paper, non-metallic minerals
Japan	0.1 EJ (3%)	3.5%	0.5–1%	Non-metallic minerals, pulp and paper

²⁵ Japan Renewable Energy Policy Platform (JREPP), Renewable Japan Status Report 2010.

²⁶ International Energy Agency. World Energy Balance, 2013.

7.2 Possible markets for torrefied pellets

There are remarkable market possibilities for torrefied-biomass in Europe. Because of considerable differences between European countries with regard to renewable energy subsidies, the market's creation may be driven by subsidy mechanisms in certain countries (such as Sweden, Finland, and Austria). Cost competitiveness will play a crucial role in the positioning of potential torrefied-pellet production facilities in Europe and, consequently, in demand for torrefied biomass.

Technical Research Centre of Finland (VTT) has predicted²⁷ that if a market for torrefied pellets develops, future trade flows of torrefied pellets will follow the same routes as the current wood pellet trade (see Figure 13).

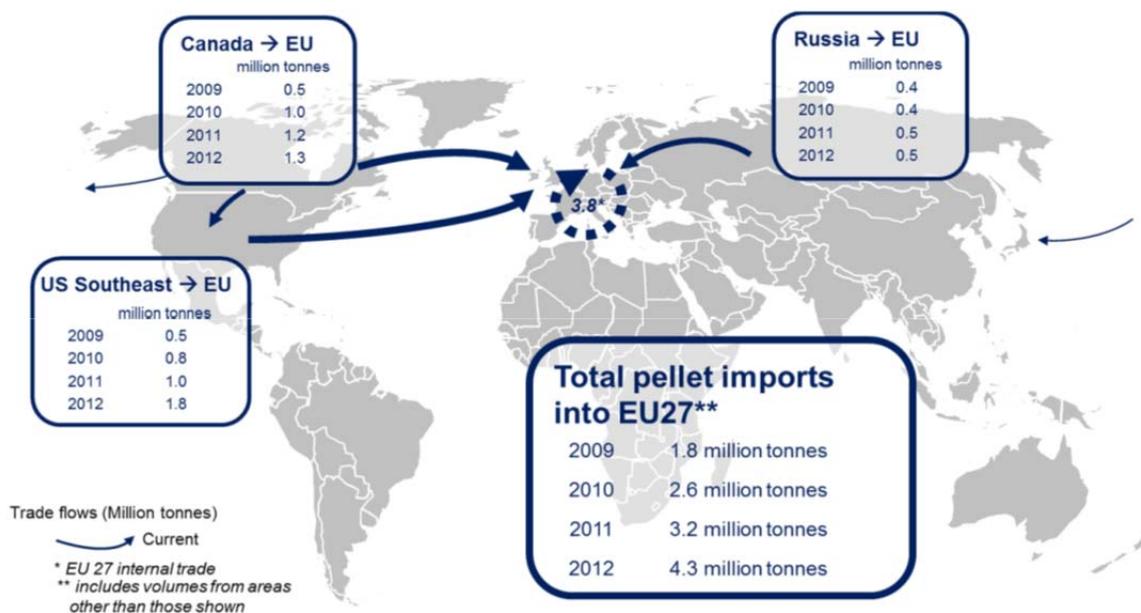


Figure 13. Global wood-pellet trade flows (for Pöyry), according to VTT data.

The leaders in torrefied-biomass production are likely to be the USA and Canada, while Europe could provide the main consumer markets. Given the unstable economic situation and restrictions on Russian wood pellets' production and export, large volumes of torrefied pellets or torrefied biomass from Russia are unlikely.

Europe will be the main consumer in terms of torrefied biomass's use in industrial application. If the challenges are eliminated and the assumed storage, handling, and combustion characteristics of torrefied biomass are verified, the demand could increase in Europe and easily reach the 50 Mt/a threshold. Europe will most likely start to compete with the market-makers for steam coal today: China, India, and other Asian countries, along with the USA. The volumes consumed in these countries by 2020 could be even larger than the equivalent figures in Europe. If this situation finally manifests itself, the biomass-for-energy market will transition from the buyers' market of today into the seller's market of the future.²⁸

²⁷ VTT. Wood Torrefaction – Market Prospects and Integration with the Forest and Energy Industry, 2014.

²⁸ Possible Effect of Torrefaction on Biomass Trade (IEA Bioenergy Task 40), November 2012.

7.3 Green House Gas emissions along the torrefied pellets value chains

Not too seldom the driver behind the use of biomass or the substitution of a conventional fuel by biomass is the reduction in GHG emissions. Therefore, a positive comparative value in GHG emissions in relation to conventional fuels such as coal or natural gas but also in respect to other biomass fuels, such as wood pellets or straw pellets may power the demand for torrefied fuels across the sectors of demand.

Within the SECTOR project the GHG emissions have been calculated applying the LCA methodology according to ISO 14040:2006 and ISO 14044:2006.²⁹

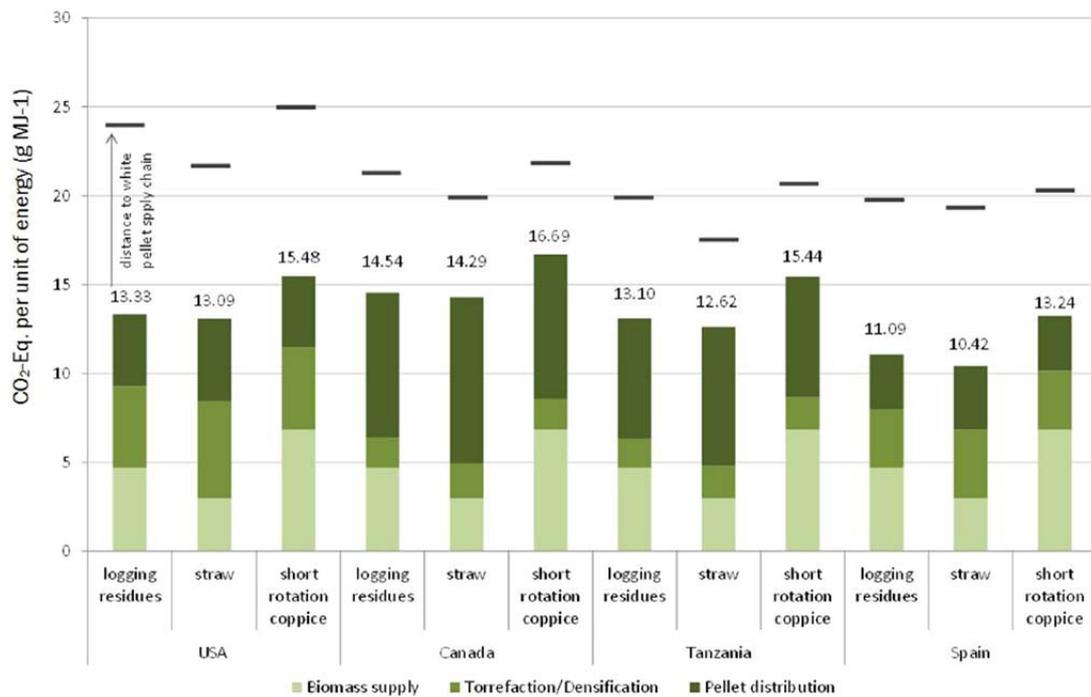


Figure 14. GHG-emissions from the supply of torrefied pellets from different feedstock types and locations compared to white pellets (Thrän et al, 2016)

Values depicted in Figure 14, resulting from calculations based on different feedstock from different locations, do show clear advantages in GHG emissions of torrefied pellets against normal wood pellets according ISO 17225-2 or straw pellets. Although the for individual sites the source of drying and torrefaction energy (waste heat, biomass or natural gas) or the emission factor of the local electricity may have an influence on the absolute value, it was proven that especially the advantages along the logistical chain do result in substantial reduction in GHG in respect to other compacted biomass (4-10g/MJ). The assessment by the SECTOR project members of GHG savings in different applications of the fuel substituting coal or natural gas are shown in Table 11.

²⁹ D. Thrän, et al., 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), <http://dx.doi.org/10.1016/j.biombioe.2016.03.004>

Table 11. GHG-emissions reduction compared to conventional fuel, and from the use of conventional and torrefied pellets from different supply chains per MJ of product (Thrän et al, 2016)

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: CO₂-Eq. of 0.3 kg MJ⁻¹ (electric output); nat. gas: CO₂-Eq. of 0.07 kg MJ⁻¹ (thermal output); MeOH: CO₂-Eq. of 2.15 kg MJ⁻¹.

In the various end user applications torrefied biomass does lead to significant GHG reduction if substituting conventional energy carriers. Applied in co-firing substituting hard coal a reduction of 80-87% can be expected, approximately 10 percent points higher reduction in respect to white wood pellets as currently in use. Even in heat applications substituting natural gas the reduction expected will be in the range of 71-79%, so 3/4th of the GHG relevant emissions will be cut through the application of torrefied biomass, again about ten percent points better than white wood pellets. If torrefied biomass is substituting carbon intensive fuels in heating such as coal briquettes it is likely that the GHG savings are even better than in the best co-firing scenario.

7.4 SWOT analysis of torrefied biomass in industrial use

As can be seen from the foregoing discussion, torrefied biomass in industrial application has strengths and weaknesses, and it faces both opportunities and threats. Based on the information of this report, Table 12 presents a SWOT analysis of torrefied biomass in industrial applications.

Table 12. SWOT analysis of torrefied biomass in industrial applications

<p>Strengths</p> <ul style="list-style-type: none"> - Has low chipping costs - Is easier to handle - Is more practical to ship and store - Has promising-seeming technical potential - Decreases CO₂ emissions significantly, especially in pollution-heavy industries such as the steel industry - Decreases dependence on fossil fuels (can compete with coal) - Offers high quality, with characteristics comparable with those of coal 	<p>Weaknesses</p> <ul style="list-style-type: none"> - Is not well known in many countries - Exists in competition with power plants and CHP - Requires additional investments, and the cost of electricity, financial costs, and other costs are high - energy losses in the process
<p>Opportunities</p> <ul style="list-style-type: none"> - Provides a new market for employment - Uses torrefied wood pellets, a carbon-neutral resource, so qualifies for renewable-energy subsidies in many countries - Is a solution that reduces CO₂ emissions - Offers a lower per-ton cost (with torrefied pellets) in handling and transport (20% more energy by weight) - Offers easy transport over long distances 	<p>Threats</p> <ul style="list-style-type: none"> - New technology - Not yet being commercialised - Competition with power plants and CHP - Availability of only a limited amount of charcoal when competition with other uses of biomass are considered - Limited information on the economy of torrefied biomass's use in industry

Torrefied-biomass development could compete with exploitation of other forms of biofuel that are currently under research. For example, coal–water fuel (CWF), which is biocoal as slurry mixed with water, may have potential as a fuel for large diesel engines used in industry and for vessels. Several studies (Lee et al. 2014, Gong et al. 2014) show that CWF has features similar to those of crude oil, with attractive complex flow and combustion characteristics.

8 Possible new industrial users of torrefied biomass

8.1 The role of biomass in industry

Global energy consumption grew steadily by around 2% a year in 1990–2000 and probably it will grow more in 2000–2020. Industry involving transportation is one of the major end users of energy. The industrial sector when coupled with transportation was responsible for more than half of the world’s energy consumption in 2012 (see Figure 15). The industrial sector will continue to be a big consumer, with energy consumption accounting for over half of the energy delivered globally in 2040.

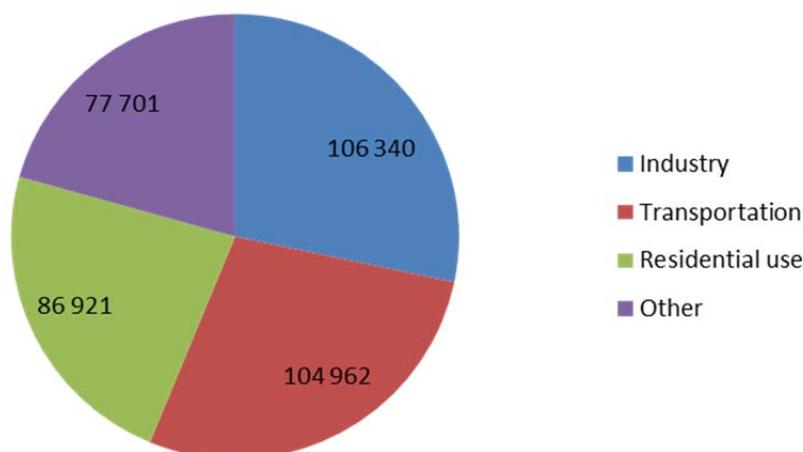


Figure 15. World energy consumption (376 EJ in total) by sector in 2012 (in PJ).³⁰

As a major consumer of energy, the industrial sector is also one of the main sources of pollution. To contribute to the global target of halving energy-related emissions by 2050, industry should reduce its direct fossil based emissions by 20%. Bioenergy plays a crucial role in achieving significant emission reductions in the energy sector. Demand for biomass is expected to increase threefold by 2050.

Biomass use in the industrial sector could be one of the solutions for reaching environment-related targets. Currently, 7.8 EJ of the biomass obtained (17% of total use) is used by industry (see Figure 16). Followed by the residential sector, industry heads the tables in biomass use. In the industrial sector, demand is forecast to reach 21 EJ in 2030. Accordingly, industry has great potential for increasing the use of biomass, including new technologies for the new kinds of biofuels utilised. Figure 17 presents the distribution of biomass use by industry.

Use and trading of biomass for energy purposes differ significantly between countries. This is mainly due to variations in the types and volume of biomass resources available and in energy-policy objectives. In 2013, total consumption of biomass by industry was 8 EJ. Different regions of the world display different biomass consumption profiles (see Table 13), depending on the phase of industrial development, structure of the industry, and local biomass resources. Based on observed historical trends and projected growth in population and GDP in developing countries, International Energy Agency (IEA) scenarios suggest that significant change in industrial production will appear in the next 20 to 40 years. In most regions of OECD (Organisation for Economic Co-operation and Development) membership, industrial development

³⁰ International Energy Agency. World Energy Balance, 2012.

will accelerate, while growth in China will flatten out or decline. The OECD estimates most significant economic growth will take place in developing countries (non-OECD countries).

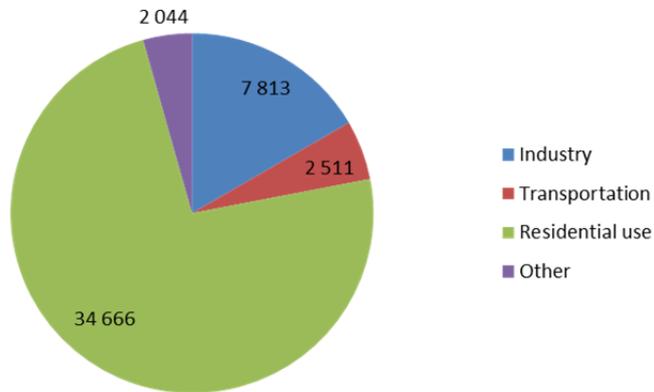


Figure 16. Consumption of biomass (47 EJ in total) by sector in 2012 (in PJ).

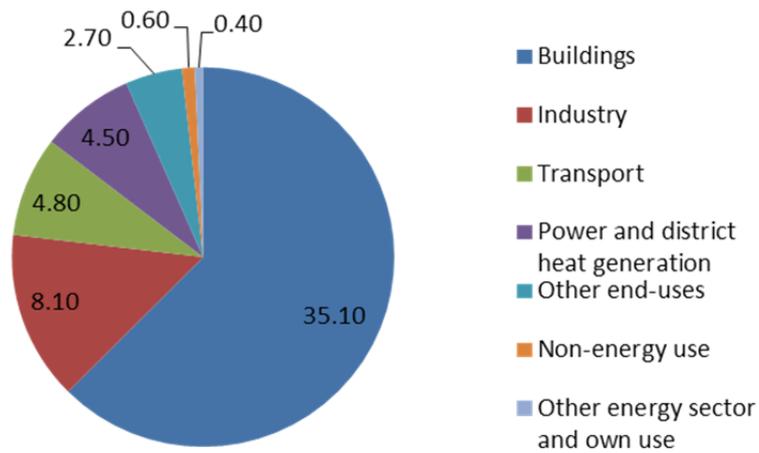


Figure 17. Distribution of biomass use by industry (56 EJ in total), 2010 (in EJ).

Table 13. The contribution of industrial biomass in the total energy consumption in various regions (source: IEA³¹)

Region	Energy consumption (EJ)			Major industrial sectors consuming biomass and waste for energy
	Total	Industry	Biofuel and waste	
Asia	182	55	2	Food and tobacco (total consumption 2 EJ) 0.2 EJ Non-specified (industry) (total consumption 10 EJ) 2 EJ
Africa	23	3.5	0.8	Non-specified (industry)
Canada	8	2	0.3	Paper pulp and print (total consumption 0.5 EJ) 0.3 EJ Non-metallic minerals (total consumption 0.06 EJ) 0.005 EJ
United States	63	11	1	Chemical and petrochemical (total consumption 2 EJ) 0.01 EJ Non-metallic minerals (total consumption 0.7 EJ) 0.012 EJ Paper pulp and print (total consumption 2 EJ) 1 EJ Wood and wood products (total consumption 0.3 EJ) 0.2 EJ Food and tobacco (total consumption 1 EJ) 0.03 EJ Non-specified (industry) (total consumption 1 EJ) 0.1 EJ
Mexico	5	1	0.06	Food and tobacco (total consumption 0.09 EJ) 0.06 EJ Non-specified (industry) (total consumption 0.7 EJ) 0.004 EJ
Australia	3	1	0.1	Chemical and petrochemical (total consumption 0.1 EJ) 0.004 EJ Non-metallic minerals (total consumption 0.1 EJ) 0.001 EJ Paper pulp and print (total consumption 0.05 EJ) 0.015 EJ Wood and wood products (total consumption 0.02 EJ) 0.01 EJ Food and tobacco (total consumption 0.2 EJ) 0.09 EJ Non-ferrous metals (total consumption 0.4 EJ) 0.002 EJ
EU-28	46	12	1	Chemical and petrochemical (total consumption 2 EJ) 0.1 EJ Non-metallic minerals (total consumption 1.5 EJ) 0.2 EJ Paper pulp and print (total consumption 1 EJ) 0.5 EJ Food and tobacco (total consumption 1 EJ) 0.04 EJ Wood and wood products (total consumption 0.7 EJ) 0.2 EJ
Japan	13	3	0.1	Non-metallic minerals (total consumption 0.3 EJ) 0.02 EJ Paper pulp and print (total consumption 0.4 EJ) 0.1 EJ
Brazil	10	3	1.5	Iron and steel (total consumption 0.5 EJ) 0.15 EJ Chemical and petrochemical (total consumption 0.3 EJ) 0.003 EJ Non-metallic minerals (total consumption 0.4 EJ) 0.1 EJ Food and tobacco (total consumption 1 EJ) 0.8 EJ Paper pulp and print (total consumption 0.4 EJ) 0.3 EJ
Rest of the world	36	21.5	1.1	
Total (world)	389	113	8	Iron and steel (total consumption 20 EJ) 0.15 EJ Chemical and petrochemical (total consumption 16 EJ) 0.06 EJ Paper pulp and print (total consumption 5 EJ) 2 EJ Non-metallic minerals (total consumption 16 EJ) 0.4 EJ Transport equipment (total consumption 2 EJ) 0 PJ Machinery (total consumption 6 EJ) 0 PJ

8.2 New technical possibilities for torrefied biomass in industrial applications

Thanks to the high fuel quality, torrefied biomass is very attractive for combustion and gasification applications. In addition, use of torrefied biomass may be possible in many contexts, among them co-firing of biomass with coal in large coal-fired power-plant boilers, use as fuel in decentralised or residential heating systems, and use as a convenient fuel for gasification and also a potential feedstock for chemical industries and a substitute for coke in blast furnaces for reduction of carbon footprints (Bassu, 2013). This part of the study discusses the possibility of biomass conversion through torrefaction in several industries outside that of power generation involving CHP and power plants.

³¹ International Energy Agency. World Energy Balance, 2013.

8.2.1 The iron and steel industry

Biomass use

In 2013, the iron and steel industry consumed 20 EJ of energy that represented approximately 18% of the world final energy consumption by industry, of which 0.15 EJ was produced via biofuels and waste (see Table 10). Worldwide energy intensity³² remained relatively stable in the steel industry over the most recent decade, decreasing from 21.2 GJ/t in 2000 to 20.2 GJ/t of primary energy consumption in 2010.³³ World crude steel production was 1.4 billion tonnes (60 EJ) in 2010.

On account of the energy intensity of steel production, its reliance on carbon-based fuels and reactants, and half volume of steel produced (with about 30 EJ) in 2010, the iron and steel industry is the largest industrial source of fossil CO₂ emissions. To meet global 2020 2DS (2°C Scenario) targets, the iron and steel sector must limit the growth in its energy consumption so as to reach no more than 32 EJ in 2020 (12% above 2010 levels) and reduce its CO₂ emissions by 247 Mt. Biomass may be among the possible options for reaching these targets. The metal's production is usually powered by carbon-based fossil fuels such as mineral coal. One tonne of pig iron – steel with impurities melted with coal – emits nearly two tonnes of carbon while the creation of one tonne of steel that is produced with biomass removes just over a tonne of greenhouse gases from the atmosphere in relative terms.³⁴

The EU and Australia have introduced forest-based biomass programmes in steel production. Ultra-low CO₂ Steelmaking (UCLOS)³⁵ is a consortium of 48 partners, of which eight core members serve as leaders representing the European steel industry. The project focuses on charcoal production processes and developing creative biomass supply, which can decrease CO₂ emissions.

Possibilities offered by use of torrefied biomass

The steel sector requires high-quality fuels for its industrial processes, and many common biomass fuels fail to meet the required criteria. One possible biomass-fuel solution can be to replace coking coal with torrefied wood. Several studies have investigated the possibility of using torrefied biomass in the iron and steel industry (Babich et al. 2010; Suopajärvi et al. 2012).

Gasification research examining Brazilian biomass and its applications in the iron and steel industry is being undertaken by Finnish-Brazilian a research group. In the first phase of the project, gasification tests of potential biomass sources are being performed and material balances evaluated for an iron-pellet indurating furnace (Carvalho et al. 2013).

Possibilities for the use of torrefied biomass in the iron and steel industry were investigated in a research project carried out at the University of Oulu, in Finland (Suopajärvi et al. 2013; Suopajärvi et al. 2014). Suopajärvi et al. (2014) suggest that there should be a wide range of suitable biomaterial-based raw materials (from forest chips to tall-oil pitch) and products (by-products from crude tall oil's distillation) for blast furnace (BF) iron making. Depending on the fossil reducing agent replacement ratio, the need for biomass (wood) could be substantial. For example, the possibility of torrefied biomass use was investigated in the Ruukki Oy's steel plant, which has approximately 2.2 Mt of steel production per year in Raahе, Finland. Results show that full replacement of pulverised-coal injection with charcoal injection (150–200 kg/t hot metal) could be possible. In this case, a maximum annual need is evaluated as 0.4 Mt of charcoal and around 2.7 million m³ of green wood (e.g., forest chips). Torrefied biomass provides an efficient means of reducing fossil CO₂ emissions in the Finnish iron and steel-making industry. There is substantial potential to decrease the fossil CO₂ emissions of steel-making in the blast furnace.

³² Energy use by unit of industrial value-added.

³³ International Energy Agency. Tracking Clean Energy Progress 2013, 2013.

³⁴ Web site at <http://www.unep.org/>.

³⁵ Web pages at <http://www.ulcos.org/en/>.

In France, Fick et al. (2014) considered and evaluated the possibilities of replacing a certain proportion (20%) of the fossil fuels used for pig-iron production with renewable biomass, in the case of an iron-making plant in Lorraine, France. Fick et al. (2014) demonstrated that wood and crop residues were able to meet all the requirements in these cases if they undergo a pre-treatment step before being used in the iron-making process: either carbonisation or torrefaction at a high temperature to produce solid char with properties similar to those of fossil coal. Torrefied biomass could be used in pulverized burning technology. In addition, the study report stated that using torrefied and pulverised biomass in the blast furnace would decrease CO₂ emissions and could thus yield economic benefits. With a price of 30 €/t of CO₂, replacing 20% of the coke by injecting charcoal fines through the nozzles is anticipated to offset 14.7% of the smelting plant's greenhouse gas (GHG) emissions and increase its profitability over 3 €/t of steel.

John et al. (2011) show that one of the promising options involving biomass use in that industry might be pulverised fuel injection. Several studies demonstrate that of all of the applications considered for biomass-derived renewable carbon materials, pulverised fuel's injection into the blast furnace has the greatest potential for net reductions in CO₂ emissions (John et al. 2011; Hasanbeigi et al. 2013).

According to Konza Renewable Fuels LLC³⁶, the introduction of torrefied biomass in all phases of production that involve coal or derivative products of coal is crucial. Global steel production is dependent on coal, which accounts for almost 70% of the steel produced today. Metallurgical coal or coking coal is a vital ingredient in the steel-making process. Roughly nearly 800 Mt of coking coal (representing 33 EJ) was used in the production of steel in 2011. Konza Renewable Fuels concludes that torrefied biomass is the only logical choice of alternative fuel that has the desired traits for seamless blending with coal.

8.2.2 The chemical and petrochemical industry

Biomass use

In 2013, the chemical and petrochemical industry consumed 16 EJ of energy, accounting for about 14% of the world final energy consumption by industrial sector, of which only 0.06 EJ was produced from biofuels and waste (see Table 10). Biomass use in the chemical industry is quite well established in many countries, especially in the Nordic region. These industries can use their own by-products in their energy production, which makes the investments in bioenergy economically viable (Alakangas et al. 2012).

The 2DS (2°C Scenario) levels³⁷ describe an energy system consistent with an emissions trajectory that recent climate-science research indicates would give an 80% chance of limiting the average global temperature increase to 2°C. In this scenario, the emissions from fuels in the chemical and petrochemical sector in 2020 are around 350 million tonnes of CO₂ lower than the 4DS (4°C Scenario) levels. The required reductions are of more than 27% of the sector's 2010 emissions. To accelerate its efforts to reduce fossil fuel based CO₂ emissions, the sector will need to apply advanced membrane technologies, introduce biomass as a feedstock via gasification or fermentation, deploy carbon capture and storage (CCS), and take other measures.³⁷

Although the petrochemical industry is a mature industry, the landscape continues to change. The historically important production areas (the USA, Europe, and Japan) have seen their share of the market contract in favour of Asia and the Middle East. Petrochemical-industry actors are increasingly considering basing their production processes on biomass, a renewable and abundant resource. From the chemistry standpoint, biomass presents an opportunity to develop new intermediate molecules, which, whether or not combined with existing ones, enable the development of new finished

³⁶ Web site at <http://www.konzarf.com/>.

³⁷ International Energy Agency. Energy Technology Perspectives, 2012.

products, with diverse properties. Figure 18 presents the integration of biomass into production structures.

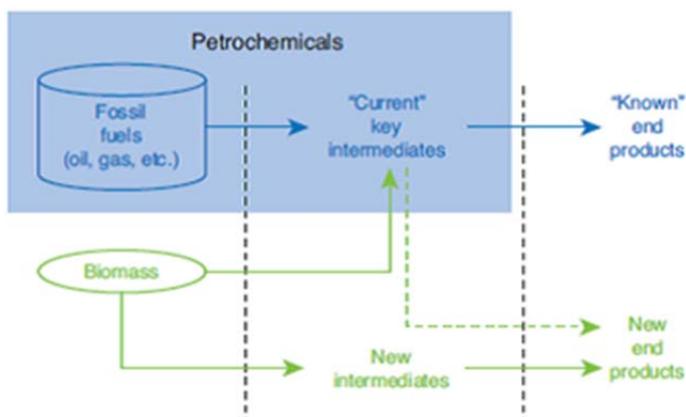


Figure 18. Integration of biomass use into production structures.³⁸

Before biomass can be used in the petrochemical industry, improvements in production processes are needed. For instance, some processes' overall efficiency is still being studied, production costs might be higher than those of traditional petrochemical channels, and there are issues of technological barriers and economic viability.

The plastics industry represents 40% of petrochemical industry's output by volume. The contribution of bio-based products was estimated at just 0.3% in 2010, representing global production of a little over 0.7 Mt of biomaterial-sourced plastics. Differing scenarios forecast production of between 3.5 Mt and 5.0 Mt in 2020. Regardless of the assumptions adopted and despite the annual growth rate of around 20% in 2010–2020, the penetration of bio-sourced plastics materials relative to total plastics production will remain very low: below 2%. The US was among the first countries to develop processes for converting biomass into plastic materials. Of the emerging regions, South America will have the capability of producing 18% bio-based plastics by 2020, though producing almost none in 2007, at 1% of global capacity, with an annual growth rate approaching 50% for the period 2007–2020, largely as a result of lower sugarcane production costs.

Possibilities offered by use of torrefied biomass

Currently, biomass use in the chemical and petrochemical industry is under intensive research. According to Taarning et al. (2011)'s analysis, biomass is not optimal for the petrochemical industry in the long term, because of the insufficient amount of biomass available to meet the demand for fuel and on account of differences in chemical characteristics between biomass and other fuels. However, the authors see great potential for biomass's development in the chemical industry if challenges such as the need for large investments can be addressed.

The assumptions as to systems surrounding the refinery and biomass availability affect the CO₂-emissions balance for integration of biomass gasification for the H₂ production in a refinery. Johansson et al. (2012) have demonstrated the great advantages to be gained for CO₂ emissions' reduction through replacement of coal with biomass.

³⁸Panorama 2012-Petrochemicals and chemicals from biomass- IAEA INIS- Alario F., Castagna F

8.2.3 Forest industry

Biomass use

Biomass fuels play an important role in the pulp and paper industry. In 2013, paper, pulp, and print consumed 5 EJ of energy, in approximately 6% of the world final energy consumption by industrial sector, of which 2 EJ was produced by means of biofuel and waste. This is approximately 30% of all biomass used by industry (see Figure 17 and Table 10).

Pulp and paper mills are attractive locations for bio refineries. Forest industry has existing biomass sourcing chains and pulp and paper mills are often located to raw material sources, and have existing infrastructure for shipping finished products. Paper mills utilise several million dry tonnes of wood per year as raw material. Pulp and paper mills are familiar with producing power from biomass, currently obtaining 60% of their power from wood residues and spent liquors (Connor, 2007).

Commercial use of biomass in the pulp and paper industry has a long history. Nowadays, industry's demand for biomass for energy purposes is increasing, especially in Northern European countries such as Germany, Sweden, and Finland. The pulp and paper industry is an important sector in the EU-27, with around 21,000 units manufacturing pulp and paper products in 2010. In the future, competition in production of fibre will increase, perhaps partially through development of new wood and crop species and via use of waste for pulp and paper and for several other applications (Dahlquist, 2013).

Ljungstedt et al. (2011) suggest that for the pulp and paper industry, the increased demand for biomass has led to increased competition to the industry's raw material but also opened new opportunities for greater refining of intermediates and by-products.

Possibilities offered by use of torrefied biomass

As in the iron and steel industry, pulp and paper production offers an opportunity to use torrefied biomass in lime-sludge kilns. Hamaguchi et al. (2012) show that one eucalyptus-pulp mill producing 1.5M Adt/a³⁹ of bleached pulp could generate approximately 0.4 Mt/a of by-products (mainly bark) with torrefaction potential.

Testing torrefied pellets' use in the pulp and paper industry, Nippon Paper⁴⁰ conducted experiments in April 2013 with co-firing of a pulverised coal boiler at the Yatsushiro Mill (Yatsushiro, Kumamoto) of Nippon Paper Industries. They found that 25% torrefied pellets by weight could be incorporated with the boiler at maximum load. The experiments confirmed that use of torrefied biomass does not cause problems with the runnability of the boiler.

8.2.4 Non-metallic minerals (glass, ceramic materials, and cement)

Biomass use

In 2013, the non-metallic-minerals industry consumed 16 EJ of energy, for approximately 14% of world final energy consumption by industrial sector, of which 0.4 EJ was produced via biofuels and waste (see Table 10). The non-metallic-minerals industry is an important source of CO₂ emissions. The cement sector is the third-largest energy consumer in industry and the second-largest CO₂ emitter (at 88 EJ of CO₂ in 2010). The use of biomass in the cement industry offers opportunities not only to reduce production costs and dispose of waste but also, in some cases, to reduce CO₂ emissions and fossil-fuel use. Because of the high process temperature and the clinker product and limestone feedstock acting as

³⁹ Air-dried metric tonnes per year.

⁴⁰ Web pages at <http://www.nipponpapergroup.com/english/>.

gas-cleaning agents, cement kilns are well suited to waste combustion. In cement kilns, used tyres, wood, plastics, chemicals, and other types of waste are co-combusted in large quantities. This use of waste as an alternative fuel in cement kilns can contribute to lower overall CO₂ emissions if fossil fuels are replaced with alternative fuels such as biomass that would otherwise be incinerated or landfilled. One example of kiln burners in practice is presented in Figure 19.

Cement manufacture consumes large quantities of non-renewable raw materials (minerals and fossil fuels). The cement industry in the OECD countries used 66 PJ of combustible renewables and waste in 2003, about half of this industrial waste and the other half wood waste; worldwide, this industry consumed 112 PJ of biomass and 34 PJ of waste. From a technical perspective, the use of alternative fuels, mainly consisting of biomass, could be increased to 1–2 EJ/a. Figure 20 presents a diagram of biomass use in a cement kiln.



Figure 19. Use in lime kilns – an example of a kiln burner in practice, DuoFlex unit⁴¹

41 Web site at <http://www.flsmidth.com/>.

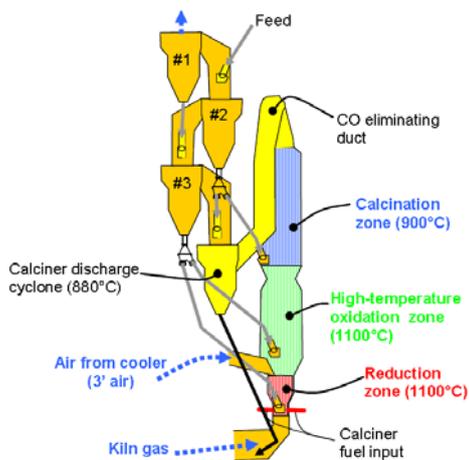


Figure 20. Use of biomass in a cement kiln.

In response to the environmental challenges, a world leader in building materials, Lafarge⁴², has set an ambitious target for increasing biomass and waste use in the cement industry. The company aims to use 50% non-fossil fuels in its cement plants by 2020, 30% of which should be biomass. In 2012, 5.4 Mt of fossil CO₂ was avoided in Lafarge's plants thanks to the use of biomass and waste. Targets of approximately 50% biomass and waste in 2020 would represent 7.4 Mt of fossil CO₂ avoided. In general, the cement industry has good potential to increase its use of biomass and the biodegradable fraction of waste in energy production.

Possibilities offered by use of torrefied biomass

Compared with the iron and steel industries, the cement industry's requirements related to fuel quality are not so strict; therefore, the latter industry represents the greatest potential for increased bioenergy use. While the less strict fuel-quality requirements and the cement industry's consumption of a huge amount of energy mean that biomass has clear potential, huge volumes of biomass are needed for the fuel mix, and this may lead to issues with the security of fuel supply (Alakangas et al. 2012). The most likely torrefied-biomass applications are co-firing with coal at pulverised-coal-fired power plants and in cement kilns, dedicated combustion in small-scale pellet burners, and gasification in entrained-flow gasifiers that normally operate on pulverised coal.

The Canadian company Airex Energy⁴³ has shown that production of torrefied biomass yielded excellent test results for co-firing. Approximately 10 tonnes of torrefied biomass was used in co-firing tests at Colacem's cement plant. The Colacem cement plant in Grenville-sur-la-Rouge, Quebec, is planned to fire Airex torrefied biocoal with conventional coal. Airex Energy is developing a two-tonne-per-hour demonstration plant in partnership with wood-pellet producer Lauzon Recycled Wood Energy that should produce over 15,000 t/a of torrefied pellets from summer 2015.⁴⁴ Another Canadian company, Diacarbon Energy, Inc., will produce 25,000 tonnes of torrefied biomass from 2015 onward, thereby displacing coal used by Lafarge Canada's cement operations in British Columbia.

⁴² Web site at <http://www.lafarge.com/>

⁴³ Web pages at <http://www.airex-energy.com/en/>.

⁴⁴ Web site at <http://www.diacarbon.com/>.

8.2.5 Transport equipment and fabricated metal machinery, equipment, and other products

Biomass use

To reach the 2DS targets, biofuel consumption must more than double by 2020. This requires solid policy support for advanced biofuels and additional government funding for research and production. Sectors of industry such as those creating transport equipment and fabricated metal products (including machinery and equipment) require large amounts of energy in their processes, yet the proportion of their energy consisting of bioenergy is negligible. However, these industries could have opportunities for biomass use in energy production, provided that bioenergy projects prove competitive with traditional energy solutions and torrefied biomass could be a long-term option.

8.3 Possible demand for torrefied biomass in industry

The use of torrefied biomass in several industries seems attractive. Information about the existing amounts of biomass consumed by these industries, biomass development, and the technical feasibility of torrefied biomass in industrial applications enables us to estimate the biomass and torrefied-biomass demand of all the industries mentioned. It is possible to predict the outlook for biomass and, accordingly, industrial torrefied-biomass demand (see Table 14).

Currently, basic data on the present volume of torrefied-biomass use in industrial application do not exist. As an aid in exploration of possible torrefied-biomass demand by industry, Table 14 was constructed, presenting the volume of today's biomass use and a prediction for biomass development. This method assists in investigating the possible volume of torrefied-biomass use by various industries and thereby ascertaining the amount of possible torrefied-biomass use in the industrial sector in general.

Table 14. Biomass use in 2012 and projected biomass and torrefied-biomass use, by industry

Industries	Biomass use as of 2012 and percentage of total consumption	Prediction for 2025	
		Biomass	Torrefied biomass
Iron and steel	0.15 EJ (1%)	2.0 %	0.4 % (60 PJ)
Chemical and petrochemical	0.06 EJ (1%)	1.5 %	Low
Pulp and paper	2.20 EJ (36%)	38–40 %	1.5 % (90 PJ)
Non-metallic minerals (glass, ceramic, cement)	0.40 EJ (2%)	3.0–3.5 %	0.8 % (150 PJ)
Transport equipment and fabricated metal products, machinery and equipment	0 PJ (0%)	0.1 %	Low
Total	2.80 EJ (0.7 %)	30 %	10 % (300 PJ)

In the chemical and petrochemical industry, use of torrefied biomass is unlikely, because of the small share of existing biomass use in total energy consumption and the weak development of biomass use in the sector in general. Also for manufacture of transport equipment and fabricated metal products, including machinery and equipment, torrefied-biomass use is not probable on the time scale considered. The strong technical possibilities do render torrefied biomass's use attractive in the non-metallic-mineral and the iron and steel industry. Torrefied biomass would increase biomass use significantly in these industries also. The pulp and paper industry currently uses a large amount of biomass, and the technical possibilities for the use of torrefied biomass seem very attractive.

The torrefied-biomass demand of industry could be approximately 0.3 EJ (see Table 14) in favourable conditions. The possible percentage of energy needs met by torrefied biomass was investigated in approximate terms. Although our method involves only a rough assessment, it aids us in making a prediction of future torrefied-biomass demand by the industrial sector.

In 2012, Hawkins–Wright⁴⁵, has predicted that global demand for torrefied biomass will exceed 70 million tonnes per year by 2020. Proceeding from our study, we suggest that torrefied biomass's use by industry could have a niche of 14–16 million tonnes within this, however with an estimated slower pace of growth.

Currently, the main consumers spurring on technological development for biomass upgrades through torrefaction are large-scale coal-burning power plants. Power and CHP plants will be the main consumers of torrefied biomass. For example, Tsalidis et al. (2014) suggest benefits of torrefied-biomass use for coal-fired power-generation plants in the Netherlands. Rousset et al. (2013) have proposed a torrefaction-based co-firing system and experimented with devolatilisation and the char oxidising kinetics of torrefied biomass. They studied boiler performance in the case of torrefied-biomass co-firing with various biomass ratios – coal only, 25% biomass, 50% biomass, 75% biomass, and 100% biomass on thermal bases. The results show that torrefaction is able to provide a technically suitable option for high ratios of substitution with biomass in the co-firing system. Without obvious decreasing of boiler efficiency and permitting fluctuation of boiler load, the case-study pulverised coal boiler could be fired with 100% torrefied biomass. This indicates that demand for torrefied biomass by coal power plants could increase, leaving the industrial sector behind.

⁴⁵ Web site at <http://www.hawkinswright.com/>.

9 Conclusion

The estimated increase in bioenergy demand in Europe, North America, and Asia will ultimately lead to an increase in international biomass trade. A survey of worldwide biomass potential clearly indicates that there are extensive, untapped biomass resources that are both technically and economically available and can be used on a sustainable basis for decades to come.

Any form of volumetric energy densification of the raw biomass feedstock that simultaneously improves its properties for downstream conversion processes greatly enhances the long-haul trade for energy biomass. It can also be shown that the torrefaction process compares favourably with "competing or complementary" approaches, such as pelletizing or flash pyrolysis.

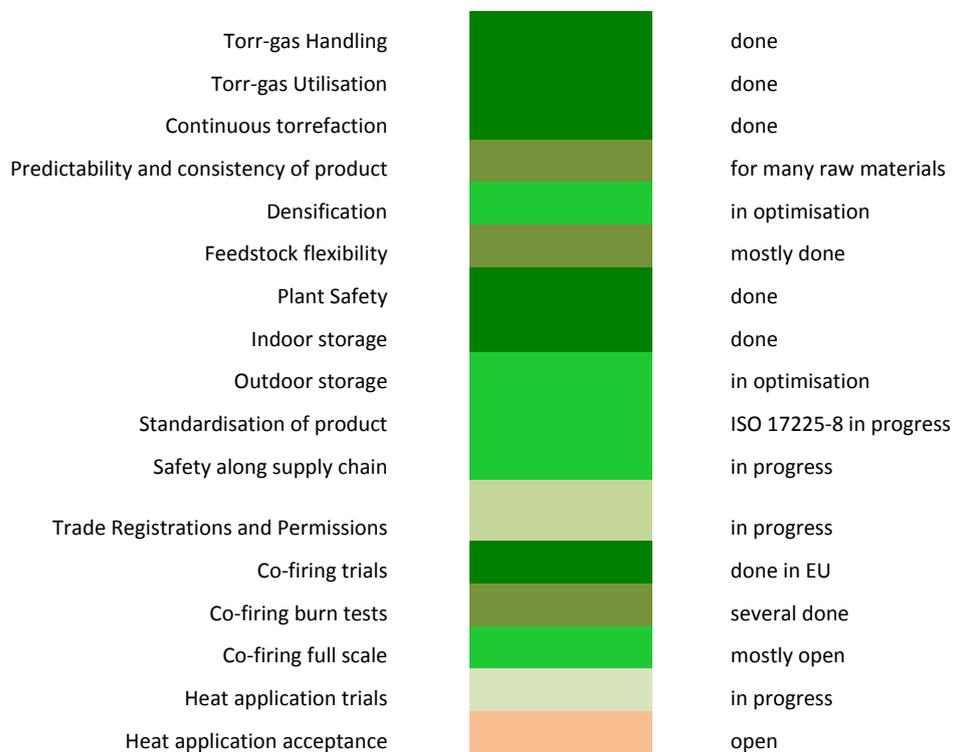


Figure 21. Torrefaction Implementation Indicator ⁴⁶

A variety of torrefaction technologies were developed. Same input material does lead to almost similar product independent of torrefaction technology implemented. Significant initiatives are engaged in technologies commercialization, with several demonstration plants already in operation and first commercial sized units nearing hot commissioning. A minimum of 2 technologies is commercially available to the market with a group of technologies right in their last steps towards full commercialisation. The current trajectory of development indicates that a broad array of technologies will become commercially available within the next 2 years. Although it seems that by now the "valley of death" for the technology developers is left behind and most of critical process steps are controlled well, same with the

⁴⁶ Wild, M.; State of Torrefaction: the path towards large scale deployment, presentation at „Black is the Colour: thermally treated biomass and its role in our future“, IEA clean coal workshop on co-firing of biomass DRAX, September 16th 2015

links along the logistical chain and in co-firing (Figure 21), there is still the “chicken and egg” problem when it now comes to the rolling out of technologies. It seems still very difficult to find investors willing to invest without a long term take or pay contract by a bankable consumer like a utility.

Torrefaction does provide clear advantages over wood pelleting or wood steam explosion processes as it not only is more flexible on feedstock, and through this providing the potential for significant savings on feedstock costs, but it can also create output products with significantly increased calorific values, reduced chlorine contents up to 1/10th of original amount in feedstock and a similarity to coal in morphology once ground by coal mills to name only a view of the advantages listed in literature.

Beside its advantages over untreated or just pelletized biomass in combustion, torrefied biomass managed to proof in recent years that the expected advantages along the whole supply chain in logistics, storage and handling are for real and will bring costs per GJ along this chain down. By doing so, it will eventually (over-)compensate the higher capital costs in the processing. In different tests, significantly improved water resistance has been shown and it has been proven that torrefied biomass, once compressed into pellets or briquettes, is of non-hazardous character in transportation. A number of full scale testing in co-firing in European power plants have proven the positive combustion results expected.

The power sector could well be the leader in torrefied biomass’s use, with industry behind. Torrefied biomass is proven for power-plant applications and will in the coming years become a central resource for co-firing of biomass with coal. Industrial-sector usage may indeed not compete with use in the power sector with regard to volumes of torrefied biomass used. Demand from industry could, however, drive development of torrefied-biomass production and markets in general.

This study has shown the technical possibilities for use of torrefied-biomass use in several industries. In the iron and steel industry, even full replacement of pulverised-coal injection with torrefied biomass injection (150–200 kg/t hot metal) could be possible. It is possible for a pulverised-coal boiler to be fired with 100% torrefied biomass without a decrease in boiler efficiency or permitting of fluctuation in boiler output. Also, in the pulp and paper industry, replacement of traditional lime-kiln fuels may be possible.

The non-metallic-mineral industry too is willing to use torrefied biomass. The most likely applications are co-firing with coal at pulverised-coal-fired power plants and in cement kilns, dedicated combustion in small-scale pellet-burners, and gasification in entrained-flow gasifiers that normally operate on pulverised coal. Use of biomass in the chemical and petrochemical industry and also for production of transport equipment and fabricated metal products, including machinery and equipment, is to date still negligible; here, torrefied biomass is the most promising of all biomasses even though the right form of application need still to be found.

Many of the consumers in these sectors do have the advantage for torrefied biomass suppliers, that the demand is much smaller than for instance in coal power plants. This can achieve a more organic growth of the production facilities, which will also be much more to the taste of the investors.

Another way of succeeding in these sectors may be through gasification of torrefied biomass. First gasification demonstration plants are in operation. Results are so far promising on two levels: first of all the energetic utilisation of gases. Second, the production of chemicals from the torrefaction gases in the normal torrefaction may open up doors to derivation of higher value products in co-production. As issues around energetic utilisation of torrefied product are no further a priority subject to research, scientists are very much focusing on chemicals derivation. Some mayor breakthroughs are to be expected here as well.

All these results will help torrefied biomass to achieve more acceptances at consumers and eliminate barriers in international trading. Market participants will also develop a clearer understanding of the products once the ISO committee will issue either a TS or full standard for heat-treated biomass under ISO 17225-8, which is planned to be in 2016. For the European clarification on REACH registration necessity is well underway.

By all this, it seems that the struggles of torrefaction on level of technological development and logistical approval seems

to be overcome and first industrial scale plants have proven scalability, the addressing of additional consumer sectors in parallel to coal/biomass co-firing has widened the potential market, the R&D concerning the processing of non woody and often significantly cheaper biomasses has proven that marketable and ISO conforming fuels will result, existing and new plants for torrefied-biomass production in various parts of the world could stimulate demand for torrefied biomass in different sectors of the economy significantly.

It seems all fundamentals for market success of torrefied biomass are today really provided and ready for market uptake. The reporting of success stories will be the duty of a future update of this study.

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