Possible effect of torrefaction on biomass trade

IEA Bioenergy

Task 40: Sustainable
Internatioinal Bioenergy Trade

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Published in November 2012

IEA bioenergy task 40

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June 2012

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1 Introduction

The Kyoto protocol to reduce greenhouse gas emissions, high world oil prices, and now legally binding EU 20-20-20 targets are combining to produce strong motivation to reduce use of fossil fuels in favour of renewable energy. EU demand for pellets has grown from 3 MT in 2003 to 13 MT by 2010 and is projected to reach 50 to 80 MT by 2020 according to AEBIOM.

One third of European demand is expected to be from large power producers. In the last decade, Dutch power producers increasingly co-fired with biomass in coal power plants, initially driven by a lucrative feed-in-tariff. UK incentives favour 100% biomass plants, and producers are gathering sufficient biomass supply contracts to justify building these large plants. Various incentives in Belgium are redirecting large volumes of pellets to Belgian power plants.

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 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. Prime Energy Solutions), or chemical treatment (e.g. Zilkha)—a mild pyrolysis process called torrefaction stands out as a very promising technological option, attracting significant interest and financial resources for further technological development and commercialization.

Although torrefaction is not yet commercially available, the sheer volume of scientific studies[1], engineering initiatives, and respectable companies and investors involved leaves little doubt that this technology will find its way into the biomass-to-energy value chain by the end of this decade.

This study focuses on the effect torrefaction might have on international biomass trade by 2020. 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 technology and current initiatives, 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 transport and at the end-use conversion plants. The torrefaction process will be compared with two other important preconditioning technologies: simple pelletization and flash pyrolysis. Finally, the effect on international biomass trade will be discussed, and the findings summarized in the concluding remarks.

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

2 Torrefaction technologies and initiatives for improving biomass feedstock specifications

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 2 shows physiochemical, structural, and color 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. Figure 2 describes how overall mass-energy density increases with higher pyrolysis temperatures.

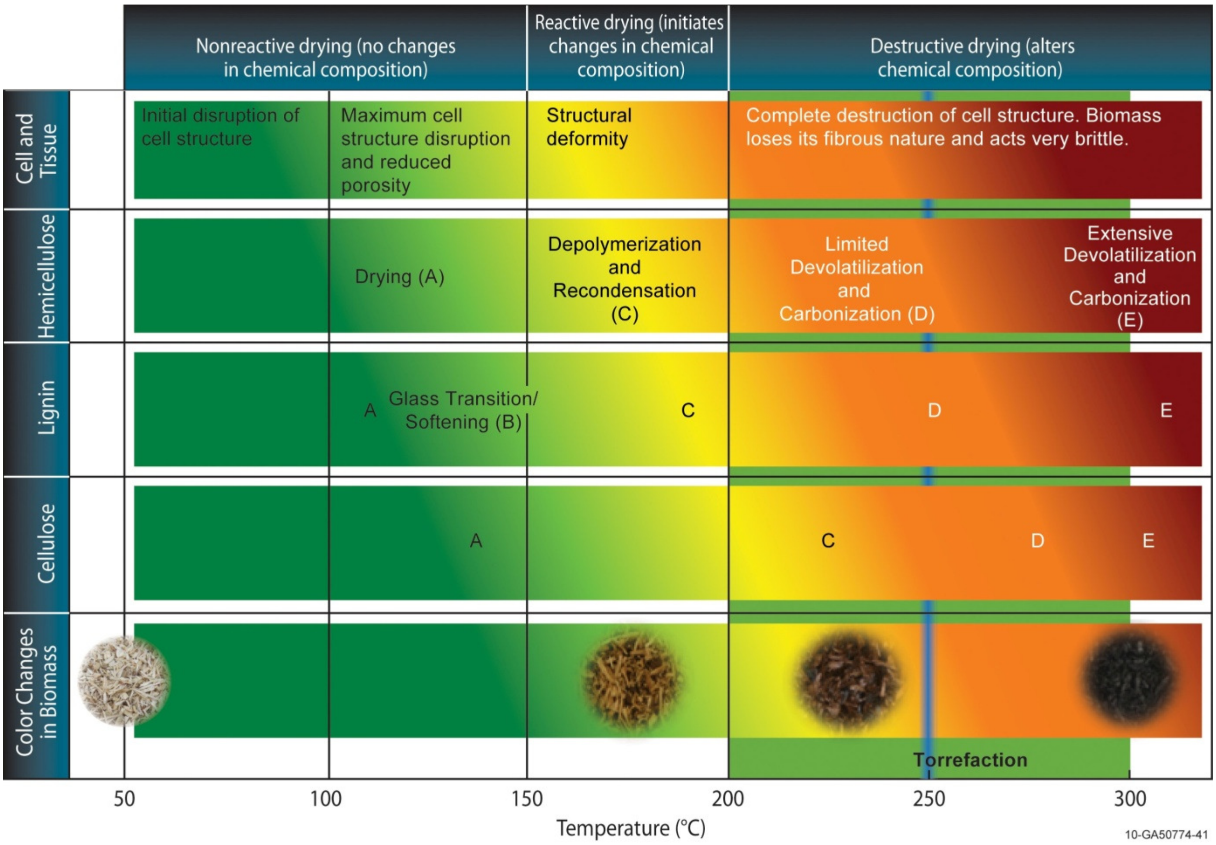
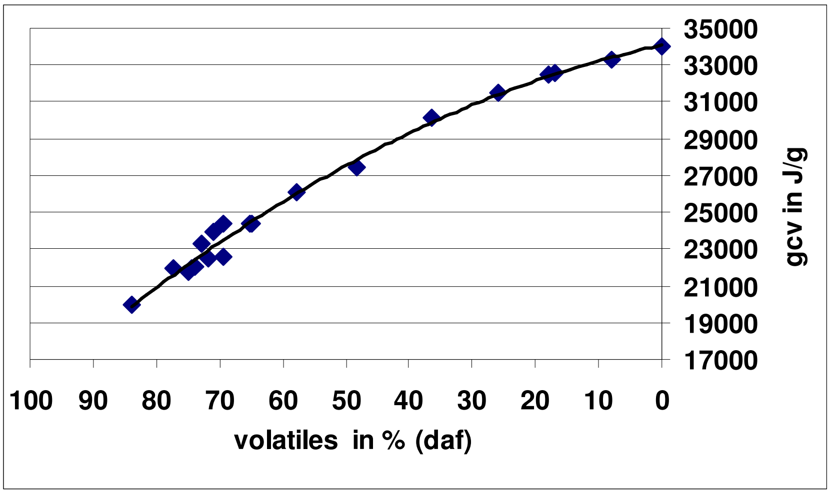


Figure 1. Physiochemical, structural, and color changes in biomass during torrefaction [Tumuluru et al. 2011].



- 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)
  source: ofi, Dr. M. Englisch

Figure 2. Biomass carbonization curve – 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.

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.

Important technological approaches

Different existing reactor designs are currently being 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 make 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 varies little in width and individual particles experience the same temperature curve and residence time. 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 32[2] 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.

Current state of torrefaction technology

Currently, a number of mostly European torrefaction initiatives have prompted construction and commissioning of the first commercial torrefaction plants. These facilities include:

- **Stramproy Green Investment** (SGI) at Steenwijk, Netherlands, with a capacity of about 90.000 t/a based on their own torrefaction technology (http://www.stramproygreen.nl/)
- **Andritz**, ACB Technology, Frohnleiten, Austria, with a capacity of 7,000 t/a based on their proprietary indirectly heated rotary-drum technology, offered as an integrated solution within turnkey processing plants (http://www.andritz.com/)
- **Andritz,** ECN Torrefaction Design, Stenderup, Denmark, with a capacity of 7.000t/a based on pressurized moving bed reactor (http://www.andritz.com/)

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[2] http://www.ieabcc.nl/

- **Renogen** (4EnergyInvest) at Amel, Belgium, with a capacity of about 42.000 t/a based on SGI's technology, including SGI's technical improvements (http://www.4energyinvest.com/)
- **Idema** (Grupo Lantec) at Urnieta, Spain, with a capacity of about 25.000 t/a based on Thermya's Torspyd technology (http://www.grupolantec.com/)
- **Topell** at Duiven, Netherlands, with a capacity of about 60.000 t/a based on the adapted torbed reactor technology (http://www.topellenergy.com/)
- **New Biomass Energy,** USA with a capacity of with a capacity of 80.000t/a based on inhouse developed indirectly heated rotary drum technology (http:// www.newbiomass.com/)

Some have already started to produce initial runs of torrefied wood. All are still in the process of improving their technology and have not yet started regular and continuous production.

Besides these most advanced initiatives, there are a number of others that are still at laboratory- or pilot-plant stage, including:

- CDS (UK, Torr-Coal (NL), Bio3D (F), BioEndev (S), in the case of rotary drying drum
- Rotawave (UK) in the case of rotary-drum and microwave technology,
- BTG (NL), Biolake (NL), FoxCoal (NL), ETPC (S), Agritech producers (USA) in the case of screw-conveyer reactor
- CMI-Nesa (B), Integro Earth Fuels (USA) in the case of multiple-hearth furnace and
- ECN (NL) and torrsys (USA) in the case of compact moving-bed technology.

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.

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)**

technology / criteria	**screw conveyer**	**rotary drum**	**rotary drum & microwave**	**multiple hearth furnace**	**moving bed**	**vibrating conveyer**	**Torbed reactor**
process control	🟢🟢	🟡	🟢	🟢🟢	🟢	🔴	🟡
mixing of fuel	🟡	🟢🟢	🟡	🟢🟢	🟡	🟢🟢	🟢🟢
proven technology	🟢🟢	🟢	🟡	🟢🟢	🟢	🟡	🟢
tar formation and handling	🔴	🔴	🟢	🟡	🟢	🔴	🟡
quality of product	🟡	🟡	🟢	🟢🟢	🟢	🔴	🟡
capability of processing low density biomass	🟡	🔴	🟢	🔴	🟢	🔴	🟡
availability	🟢	🟢	🟡	🟢🟢	🟢	🟡	🟡
potential for up scaling	🔴🔴	🟢	🟢	🟡	🟢🟢	🟢	🟢🟢
foot print of equipment	🟡	🟡	🟢	🟡	🟢	🟢	🟢🟢
throughput	🔴	🟢	🟢	🔴	🟢	🟢	🟢🟢
conversion costs	🔴	🟢	🟢🟢	🔴🔴	🟢🟢	🟢	🟢

very good	🟢🟢
good	🟢
medium	🟡
bad	🔴
very bad	🔴🔴

source: M. Deutmeyer

Table 1. Rough qualitative assessment of torrefaction technologies.

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.

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 resource available within their catchment area.

The greater the distance the resource is from the point of use, the greater the pressures 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. Establishment of preprocessing 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.

Hess et al. (2009) describe a feedstock supply system design concept that incorporates distributed preprocessing depots (Figure 1) to address these challenges by taking various biomass resource types and preprocessing 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 preprocessing depots will be based on the local biomass production systems.

Preprocessing depots will likely be located near existing rail and highway infrastructure, 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.

As compared to biorefineries and other complex and capital-intensive pretreatment technologies (pyrolysis, gasification, and combustion), locating torrefaction at preprocessing depots will require low capital investment, which facilitates adaptability and reconfiguration for regionally specific resources and management systems.

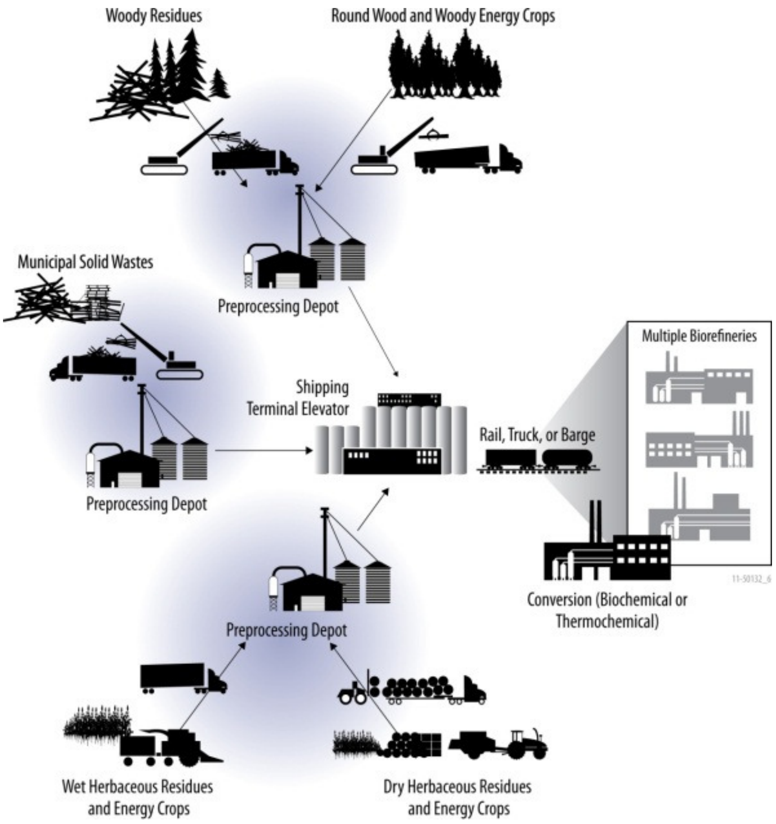

Figure 3. Locating torrefaction at distributed preprocessing depots may provide the ability to turn unstable, low-density raw biomass into a stable, dense, on-spec commodity feedstock compatible with existing commodity-distribution infrastructures and national and international market structures.

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) ratio[3] solids that are suitable for commercial and residential combustion and gasification applications (Tumuluru 2011).

Combining torrefaction with other preconversion technologies may also increase market opportunities. Combined torrefaction and densification (i.e., pelletization) can increase the energy density of biomass by about five times. Combined torrefaction and densification also produce a biomass feedstock better suited for blending with coal, offering improved milling and handling

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

characteristics and allowing the two to be blended prior to coal milling, which can potentially increase cofiring ratios (Tumuluru 2012).

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 preprocessing raw biomass into stable, flowable, 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 feedstocks by improving energy density and oxygen-to-carbon ratio of the feedstock may make product more valuable to biorefiners and increase demand.

3.2 Markets in general

Technically, all biomass resources are suitable for torrefaction, and studies have found that the physical and chemical properties of both woody and herbaceous biomass significantly improve after torrefaction (Bridgeman et al., 2008). However, torrefaction is limited in its ability to address feedstock property concerns for specific conversion methods, such as the high ash content in straw and some wood wastes, that can cause fouling or corrosion in thermochemical conversion reactors. Other technologies may be incorporated at the preprocessing depot to manage undesirable properties like high ash content, but near-term markets for industrial use will likely come from clean, homogenous resources that require minimal preprocessing (primarily size reduction) prior to torrefaction to produce a suitable feedstock.

Biomass resources that have more homogenous, uniform ultra-structure in terms of distribution of tissues (Esau, 1964), such as debarked, woody biomass, produce a more uniformly torrefied product compared with other agricultural and mixed species of biomass. Initially, key resources are expected to be woody biomass from mills and urban wood, as they are relatively low cost, available now, and can be accessed year-round. Forest wood in the form of harvesting residues and slash is available now, but it is more costly to access, and sustainability issues have to be resolved. Energy crops and plantations will be a major source of biomass in the future, but it will take time to consolidate land, arrange planting, confirm sustainability, and establish new supply chains.

While not compacted torrefied wood provides a number of benefits, it is not very dense, and the cost of transport may make it uneconomical to move long distances. Increasing bulk density by pelletization can improve economics, and pelletized torrefied wood would compete directly in current wood pellet markets, including those for particularly large power and district heating plants. Table 2 compares indicative feedstock properties of wood, wood pellets, and torrefied pellets to coal-based fuels. Note that bulk density is improved and comparable to coal. Energy density of torrefied pellets is higher than untorrefied pellets, and low moisture content, hydrophobicity, and increased resilience to degradation are additional advantages.

	Wood	**Wood pellets**	**Torrefied pellets**	**Coal**
Moisture content (% wt)	30–45	7–10	1–5	10–15
Calorific value (MJ/kg)	9–12	17–18	20–24	23–28
Volatiles (% db)	70–75	70–75	55–65	15–30
Fixed carbon (% bd)	20–25	20–25	28–35	50–55
Bulk density (kg/l)	0.2–0.25	0.62–0.67	0.65–0.85	0.8–0.85
Volumetric energy density (GJ/m^3)	2.0–3.0	10.5–12.0	15.0–18.7	18.4–23.8
Dust	Average	Limited	Limited	Limited
Hygroscopic properties	Hydrophilic	Hydrophilic	Hydrophobic	Hydrophobic
Biological degradation	Yes	Limited	No	No
Milling requirement	Special	Special	Classic	Classic
Handling requirements	Special	Easy	Easy	Easy
Product consistency	Limited	High	High	High
Transport cost	High	Average	Moderate	Low

Table 2 Indicative properties of different biomass and coal-based fuels, NREL

Currently, Europe is the major market for wood pellets that are transported long distance. Canada supplied Europe with 1.6 million tonnes of pellets in 2010, mostly from British Columbia through the Panama Canal, and the U.S. supplied Europe with about 0.8 million tonnes, all from the southeastern states. New pellet markets include Korea, which just implemented an ambitious series of renewable energy targets, and Japan. Canada exported 100,000 tonnes to Japan in 2010, and exported 50,000 tonnes to Korea in 2011, making a toe-hold in this market. The Korean market is projected to grow from nothing in 2010 to 15 MT by 2020. Forecasts for European demand vary considerably, from 30 MT to 150MT by 2020. In China, manufacturing growth rates exceeding 10% p.a. have resulted in equally large demands for power, until now primarily from coal. However, China has just adopted its new 5-year energy plan, focusing much more on renewable energy. As many as 40 large new biomass combustion power plants have been built in the last 5 years, using agricultural residues from surrounding farms, but many Chinese companies considering importing pellets or other densified biomass. The EU member states intend to supply as much biomass as possible from domestic sources, subject to reasonableness of costs and security of supply. Many sources exist, but importing biomass appears to be a lower-cost option in many cases. Russia has considerable biomass, but ensuring consistent supply and sustainability remains to be proven.

Europe

Table 3 shows availability of lignocellulosic residues in eight European countries[4] as well as the range of costs for this biomass. France, Germany, Poland, and Spain have considerable agricultural residue, while Sweden and Finland have considerable forest processing residue. An assessment conducted in Europe estimates total residue availability for bioenergy at 4200 PJ. Agricultural and wood processing residues comprise 79% of available residues. The lowest cost is likely to be forest processing residues that are already at centralized plants (as low as 1.1€/GJ) because no further transport is required. Wood from chipping trees and logs comprises only 13% of available residues, and most will be at high cost. Roadside hay is also projected to be only 2€/GJ on average, depending on the country and volume. The amount of construction residue is small, but it carries a negative cost because the cost of land filling is eliminated. The highest cost resources will be logging chips, whole-tree chips, and raw material from energy plantations. The European study VIEWLS concluded that there is sufficient biomass potential for biofuels and bioenergy heat and power, but only if most of available residues were allocated to energy, and only if energy crops are included because potential residues are insufficient to meet demand. The study showed[4] that € billions can be saved by importing lower-cost biofuels to the EU instead of supplying biomass locally.

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[4] Impact of 2nd Generation Biofuels on Trade- IEA Task 40 Biotrade- Bradley D., Pelkmans L.

	Ag	Forest Processing	Logging Chips	Tree Chips	Roadside Hay	Construction	Total
France	343.9	251.6	68.5	35.7	17.4	19.1	736.2
Germany	206.9	221.0	60.1	29.8	24.0	32.1	573.9
Sweden	24.3	256.8	69.9	41.5	2.6	0.1	395.2
Poland	165.7	127.8	24.6		11.3	15.0	344.4
Finland	20.1	211.7	57.6	36.0	1.5	3.0	329.9
Romania	146.4	52.0	4.2		6.5	8.7	217.8
Spain	141.5	36.7	10.0	13.9	11.9	2.7	216.7
UK	113.8	34.7	9.4	5.1	17.3	1.8	182.1
Other EU27	491.1	456.4	120.6	43.3	51.6	41.9	1,204.7
Total	1,653.7	1,648.7	424.9	205.3	144.1	124.4	4,200.9
Cost (€/GJ)	1.1–3.9	1.1–2.6	1.4–6.7	4.2–8.1	2.0	-4.6	

Table 3 Residue Availability in Europe (PJ)[5]

US

The U.S Departments of Energy (DOE) and Agriculture (USDA) recently released the *U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry* (US–DOE 2011)[6]. At a stumpage price of $60 per dry ton, the near-term annual availability of forest and wood waste resources for bioenergy applications is estimated at 97 million dry tons, increasing to 102 million dry tons by 2030 (US–DOE 2011). If costs are such that higher stumpage prices can be offered, the impact on resource availability is good, and $80 per dry ton increases the annual resource availability to 119 million dry tons in the near term.

As supply-chain infrastructure and markets become established, demand promotes additional resource availability through woody energy crop development, with near-term availability of ~6 million dry ton and 126 million dry tons available by 2030 (US–DOE 2011). Development of

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[5] Biofuel and Bioenergy Implementations Scenarios- Final Report of VIEWLS WP5

[6] http://www1.eere.energy.gov/biomass/pdfs/billion_ton_update.pdf

technologies to manage undesirable properties in agricultural residues and herbaceous energy crops will greatly increase resource availability for a torrefied, densified feedstock product stream. The *Billion-Ton Update* projects a baseline biomass availability of 914 million dry tons of forest resources, agricultural resources, and energy crops in 2022. High-yield production scenarios project availability of 1168 to 1322 million dry tons of the same resources in the same time frame (US–DOE 2011).

Canada

With one of the world's largest forestry sectors, Canada is regarded as a storehouse of biomass. Before the 2007/2008 world financial meltdown, Canada produced 21 million BDt[7] of mill residue (sawdust, bark etc) annually, and in 2007 had a surplus of 1.8 million BDt[8]. When demand for Canadian lumber fell as a result of the U.S. housing crisis, mill residue production also fell, and there was no surplus in 2009. Canadian sawmill production grew 20% in 2010 based partially on U.S. exports, but more importantly on new lumber exports to Asia. The industry will now look to Asia, including rebuilding post-tsunami Japan, for markets rather than waiting for a U.S. recovery. As such, Canada expects to have surplus of 3 to 5 million BDt (52 PJ) of mill residue by 2013. There are 21 million BDt of bark in old mill piles, much of it in Quebec and Ontario. Provinces are releasing 22 million BDt (379 PJ) annually of harvest residue for energy, mostly already at roadside. There is 9.8 million BDt of urban wood waste and agricultural biomass is estimated at 17.3 BDt annually. In total, the surplus is estimated at 779 PJ with an average cost of 1.67€/GJ (0.18 to 2.7€/GJ), shown in Table 4. Canada has a modern industrial economy and a good transportation/port system. The pulp and paper industry has been declining due to global competition, and has been looking increasingly to divert wood resources to energy, both for domestic use and export. Although Canada has renewable targets, growth in domestic demand for pellets and CHP is slow, and therefore there is an excellent opportunity for export.

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[7] Bone Dry tonnes = Oven Dry tonnes

[8] Canada Report on Bioenergy 2009- Climate Change Solutions, July 7, 2009

Canada	PJ	Cost €/GJ
Ag Res	293	0.72
Mill Res	52	0.90
Hog Res	34	0.18
Forest Res	379	1.54
Forest chips	146	2.69
Urban	168	0.36
	779	1.67

Table 4 Canada Residue Surplus[8]

A potential source of forest residue from dead and dying trees may provide a significant near-term torrefied-product market opportunity. Pine beetle infestation has been widespread in western Canada, and according to National Resources Canada (2011), at the current rate of spread, 80% of mature pine trees in British Columbia will be dead by 2013 (over 35 billion ft^3 of trees). The beetle epidemic affects forestlands throughout the western Canadian provinces and the U.S. states of Colorado, Idaho, and western Wyoming.

South America and Caribbean

Brazil is a major producer of both forest products and sugar cane. In 2008 Brazil produced 219 million tonnes of cane and 19.5 billion litres of ethanol (first generation). Most sugar-cane bagasse is burned inefficiently in sugar and ethanol plants for heat; however, steam saving actions, minor investments and new cane production can yield 25 million BDt of surplus bagasse at 50% moisture. In addition, there are 31 million BDt of trash (leaves and stalks) available in the field. The forest industry had an estimated 65 million BDt of surplus biomass in 2005, and 70 million BDt in 2010, including inefficiently used sawmill residues and rarely used field residues. Biomass transportation costs are high, and conversion to energy-dense biofuels is best done in Brazil. Currently, the focus in Brazil is on expansion of first-generation ethanol production from sugar cane, yet there is a huge amount of other biomass waste available to convert to other biofuel products for export. Pellet production and export has only begun in the last couple of years.

In 2002, **Argentina** had 2,230 sawmills producing 94 million m^3 of wood[9] and yielding 4 to 5 million tonnes of unused wood waste. Recently it was estimated that there were several million tonnes of waste forestry biomass on rivers within barging distance of major ports[10]. **Chile** has a major forestry industry, about 1/3 the size of Brazil's. In 2007, Chile manufactured 60,000 tonnes of wood pellets, exporting about 20,000 tonnes. The distances to market and older port facilities make pellet exports a challenge; however, with current low shipping rates and a lower cost per GJ of shipping liquid biofuels, Chile could be a biofuels exporter.

Southeast Asia

Southeast Asia has been identified as a major source of biomass from forests, plantations, and processing facilities, as shown in Table 5. The lowest-cost feedstock is residue from palm oil and other processing plants, most prominent in **Indonesia** and **Thailand.** A slightly more costly, but abundant source is agro-residues, again with Indonesia and Thailand having the greatest potential.

	Indonesia	**Malaysia**	**Philippines**	**Thailand**
Forest residues	250	250	20	20
Agro-based wood residues	750	200	350	150
Field-based agro-residues	1,850	80	600	1,000
Agro processing residues	600	150	300	450
	3,450	680	1,270	1,620

Table 5 Residue Technical Potential Asian Countries (TJ)[11]

New Zealand and Australia

New Zealand has a large forest-products industry. In 2010, 20.5 million m^3 of wood was harvested, 99.9% from plantations. Establishment of plantations, primarily Radiata Pine, peaked at 100,000 ha annually in 1994, and it has been declining since. However, harvesting of this fast-growing species was begun in 2005, with 43,500 ha harvested in 2010. Of 22.5 million m^3 harvested in 2010, 9.5 million m^3 was exported as logs, primarily to China and Australia, and 13 million m^3 was processed in

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[9] The First Hewsaw to Argentina, Dario Rodriguez

[10] World Maritime Biofuel Shipping Study- IEA Bioenergy Task 40, July 2009

[11] FAO Regional Wood Energy Development Program in Asia

New Zealand, 63% as sawlogs and 26% to pulp mills. Saw mills and plywood mills together produced 4 to 6 million m^3 mill residues. Pellet production in New Zealand in 2010 was a relatively minor 60,000 tonnes from 12 plants. One plant has plans for expansion to 300,000 tonnes by 2014, yielding total production of 360,000. Most of this will be exported. There is considerable potential for pellet manufacture from plantations.

There are 163 million hectares of forest in Australia. There are approximately 43 MT of fibre available for pellet manufacture, of which 24 MT are agricultural residues, but these are targeted mostly to direct combustion, gasification, or pyrolysis. Similarly, there are 9 MT annually of sugar-cane bagasse and trash, primarily in Queensland, but this is regarded to be more appropriate for pyrolysis, gasification, or combustion. The greatest opportunity is to grow new Eucalyptus plantations for pelletizing.

Africa

A global study on bioenergy potentials[12] projected that sub-Saharan Africa had great potential for exportable biomass to 2050; however, estimates were largely theoretical and based on quantum leaps in arable-land utilization and full utilization of modern production techniques. Production scenarios varied from 58 EJ/y to 252 EJ/y in 2050. In 2007 VTT estimated regional technical biomass potentials for Africa at 165 Mtoe (1EJ/y), of which half were energy crops, 40% were agricultural residues, and 10 % was bagasse. Though the VTT estimate was for "technical" potential rather than realistically achievable volume, with the support of the World Bank and other funding sources, potentials can be turned into reality. While energy crops and the gathering of agricultural residues may form part of biomass supply in 15 to 20 years, initially the most realistic source is existing forest wood.

For example, in Namibia there are 10 to 12 million hectares of land infested by invasive acacia thorn bush, and the government is trying to reverse this encroachment to restore wildlife habitat and ranch-land productivity. Each infested hectare has 10 to 11 tons of standing Acacia; therefore, there are over 100 million tons of Acacia wood that can be used as biomass feedstock. In Mozambique, there are thousands of hectares of palm plantations suffering from yellowing disease. They must be harvested for energy or be lost. While these are intriguing sources for development and export, it is unlikely that they will be developed without a special investment vehicle, like the Bio-trade Equity Fund proposed by IEA task 40.

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[12] A Quickscan of Global bioenergy potentials to 2050- Smeets E, Faaij A, Lewandowski I- 2004

Russia

The CIS and Baltic states are major sources of woody biomass. A study on Regional Biomass Potential in 2050 projects woody crop potential at 45 EJ in 2050, 5 EJ in residues, and 33 EJ in forest surplus; however, these estimates are highly conjectural. A less theoretical study indicated that the annual supply from northwest Russia was 3.5 million m^3. That amount could increase 53%, to 5.1 million m^3, if the annual allowable cut could be used completely and 106% higher, to 7.2 million m^3, if thinnings could be used at a full scale. However, the lack of a business culture, the bureaucracy, 6-month winters, language difficulties, and even personal safety together create seemingly insurmountable barriers to developing large-scale export business for bioenergy in Russia.

What are the additional biomass sources that can be mobilized?

Despite the differences in the several technological approaches towards torrefaction, almost all of them can torrefy all kind of solid biomass to the degree where all typical characteristics of a torrefied biomass are reached. However, torrefaction neither changes any of the characteristics of the ash building elements in the raw material nor reduces these elements. Hence, all feedstock not fulfilling the necessary criteria in respect to ash-melting temperatures and alkali contents will either need additional chemical treatment or remain outside certain biomass–to-energy value chains. (As in most of the torrefaction processes described today, the partly devolatilization of biomass seems to be accompanied with at least some reduction of organically bound chlorine.)

In addition to opening up certain biomass qualities for the bioenergy market, cost advantages in logistics enlarge the catchment area for certain biomass hubs and thereby increase the overall economic potential for biomass at a given market prize.

How could supply markets develop?

Assuming a total long–haul, internationally traded annual volume of energy biomass of around 100 million BDt by 2020, the total biomass potential then sums to around 4 billion BDt per year.

In case that at least 10 percent of this potential can be freed for export purposes, the aggregate numbers of the worldwide technical and economic availability of sustainable woody and agricultural biomass for export—both residual as well as dedicated—clearly outnumbers the potential demand for internationally traded biomass until 2020 by more than a factor of four.

Therefore, no real pressure on existing biomass sources will be experienced if growing worldwide demand for traded biomass makes even use of the existing biomass sources. The foremost bottlenecks for the development of these resources are timely investments in the necessary transportation and preconditioning infrastructure to mobilize these resources. Without adequate storage and handling facilities at sea ports, without efficient inland transportation infrastructure and pelletization or even torrefaction plants, much of these resources cannot be mobilized or brought to the international market.

The abundance of existing resources in respect to the expected growth in international demand by 2020 leads to the conclusion that production of torrefied biomass will be focused on the conversion of woody biomass. Woody biomass shows much better combustion and gasification behaviour for the ensuing end-use technologies, can be produced on an extensive basis, and causes much less (in some cases not recyclable) extraction of nutrients.

Before starting to mobilize "stranded" biomass resources, torrefied biomass will primarily start to broaden or substitute—especially within long haul international transportation chains—established, ordinary woody energy biomass value chains in the form of wood pellets or wood briquettes. Along such value chains, torrefaction exerts its biggest economic advantage and might develop into *the* energy biomass commodity for international trade.

The regional focus for this development will probably be in countries with a low risk profile in respect to foreign investments (legal system, political system, wars), sustainability issues (rain forests, indigenous people), or climate (droughts, fires, other extreme weather conditions). Regions such as those in North America—especially the southeastern USA, western or eastern Canada—as well as areas of Australia probably rank highest in surplus biomass meeting the desired attributes.

Only after picking these lowest-hanging fruits might torrefaction "conquer" other, primarily non-woody, biomass resources, again starting in those most preferred biomass regions of the world, until pressures of volume/prizes divert significant investments in regions of South America, Subsaharan Africa, Asia, or Russia.

It is not to be expected that larger numbers of torrefied biomass units will be established in Europe although Europe will be the driver in the development of the market simply by forming the immediate demand for torrefied biomass. This demand will surely be measured in single–digits of million metric tons by 2013 *if* expectations for torrefied biomass prove true.

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, larger quantity of raw material, and likely higher operational costs in the processing plant.

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 little practical experience available on torrefied product as there has been only one long-haul bulk shipment of torrefied product. However, trucking and transportation in containers has been observed.

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 from 1 m^3 of wood chips of 50% of moisture, resulting in a mass reduction from approximately 400kg in raw materials to below 180kg in torrefied chips. Further, the brittleness of torrefied biomass will lead to large proportions of explosive 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, there is still no homogenous picture on what the finally prevailing technique will be.

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 behavior 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 at to which binders should be used and how these binders will be regarded by the power companies and their regulators. Authors could, to date, witness only two continuous pelletizers of torrefied material in operation, working both with and without binders[13].

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 torrefaction[14] of biomass, as shown in Table 2, 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.

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[13] New Biomass Energy and Topell

[14] definition degree of torrefaction according to ofi, Dr. M. Englisch

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.

5	**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

Table 6 calculation of transportation costs of wood pellets and torrefied pellets, M. Wild

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.

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 45,000m^3 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 danger of dust explosion, self-ignition, and off-gassing of the torrefied product.

Storage

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. Higher energy density will lead to savings because less room would be required as will, probably, less movement of loading/unloading equipment.

However, the big argument for torrefied pellets has always been its hydrophobicity and the resultant possibility to use the existing open coal stockyards. There is no doubt, as proved by numerous examinations, that torrefied biomass itself develops a hydrophobic character. This means that, even if exposed to water, the torrefied biomass will absorb no water. But as torrefied biomass is traded in densified form, the pellets, particularly briquettes, will need to show the same behavior as the torrefied material itself.

UBE, Japan, has tested torrefied pellets by drowning them for 200 hours in water and trying to mill them thereafter. Although the pellets did remain generally in shape, the hardness was almost completely lost and the milling results were dissatisfying. The investigation show that the material itself is not absorbing any water; however, the surface of the pellets, although visually shiny and slick, does form cracks and rifts, allowing water to enter the pellet and negatively influence its milling characteristics. Nevertheless, torrefied pellets are far less sensitive to water, and their exposure to rain during loading or unloading procedures seems of much less (if any) influence on quality of product than is seen in wood pellets.

Further work on the pelleting/briquetting technology seems necessary to help utilize the full advantages of the hydrophobic character of the torrefied material, which would allow port operators and power plants to use coal yards for stocking torrefied biomass. This applies also to the binder issue addressed earlier in this text.

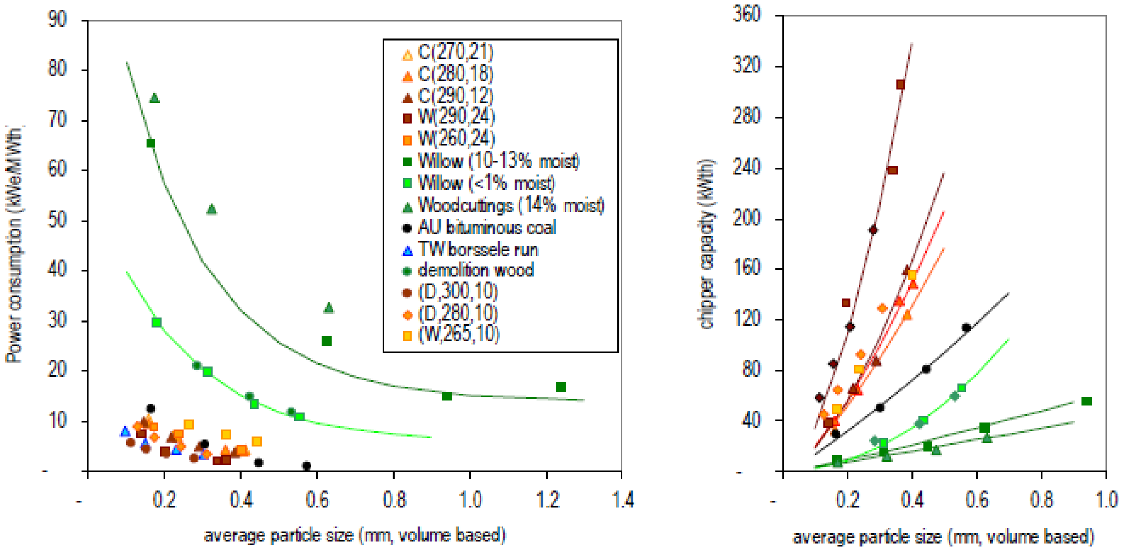
For several years, there has been a lack of knowledge about large-scale storing of ordinary wood pellets regarding the off-gassing of toxic gases, decomposition, self heating, and self ignition. After several deaths (from CO gas asphyxiation) and increased import to Europe, some research has begun. A current Danish-Swedish project called LUBA (Large-scale Utilisation of Biopellets for energy Applications) examines all the above-mentioned problems for wood pellets. Until otherwise documented, similar problems must be expected when storing torrefied pellets. New studies are necessary to get a better overview of both long- and short-term storage for torrefied pellets. In large-scale storage, appropriate for use in power plants, it is important to document how long the torrefied pellet can be stored in open air and the effect this storage has on the pellets.

Grinding (milling)

Grinding the fibrous, elastic biomass to sizes suitable for co-firing is an energy-intense 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.

Grindability of coal in the power sector is usually expressed by the Hardgrove Index (HGI). 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 4 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.

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.



Net power consumption curves

Capacity curves

Figure 4. Torrefaction for biomass co-firing in existing coal-fired power stations [Bergman et al, "BIOCOAL", ECN-C--05-013, 2005].

Health and safety issues, Transport regulation

Research and development activities in the field of health and security issues for torrefied biomass have just started, and little scientific and practical information is available today. A health and safety study would focus on the following issues:

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

All these issues must be investigated and tested in order for permissions to store and trade torrefied materials to be obtained. Torrefied biomass is to be found in none of the international coding or permission systems so far. As trade has already begun, companies have needed to apply for this "recognition and registration" on an individual basis. Austria did issue a customs tariff number, now valid for all EU. This number was issued based on charcoal class, which may need adoption once more evidence on the material characteristics of torrefied biomass are available. The charcoal classification might lead to special requirements by the P&I clubs (vessel insurance), but this is yet to be determined. The same is true for International Maritime Solid Cargoes (IMBSC) Code [*International Maritime Organisation, London 2009*], which does cover charcoals, listing potential hazards and precautions to be taken, as it does for coal. The U.S. Coast Guard provided temporary permission for in-port handling, loading to vessels, and shipping of torrefied product. Precautions similar to wood pellets are required; for example, vessel holds must be well ventilated before entry by personnel, but cargo holds may not be ventilated during journey).

Material safety data sheets (MSDSs) are available from individual suppliers and provided with their product, generally listing no special requirements in handling and transportation or health hazards. However, like wood pellets, charcoal, and coal, torrefied product introduces dust-explosion issues that must be mitigated. Further research and testing will be needed for final judgment. Transportation on European rail and road will require registration through Nomenclature harmonisée des marchandises (NHM).

The recently started project, Production of **S**olid Sustainable **E**nergy **C**arriers from Biomass by Means of **Tor**refaction[15] (SECTOR), co-funded by the European Commission and led by Deutsches Biomasseforschungszentrum (DBFZ), focuses on further development of torrefaction-based technologies for the production of solid bioenergy carriers up to pilot-plant scale and beyond, and on supporting the market introduction of torrefaction-based bioenergy carriers as a commodity renewable solid fuel. It will also address the above-mentioned issues and contribute to the integration of torrefied pellets into existing standardization schemes, as well as dealing with REACH regulation. Torrefied products need to find entry in all the above-mentioned code systems. Although today no special requirements are seen and put into force, only this clear codification will allow parties involved in the logistics of the supply chain to accept and deliver biomass orders without also accepting the risk of not fulfilling their insurance conditions, or, even worse, taking on the physical risks of the unknown behavior of the products handled.

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.

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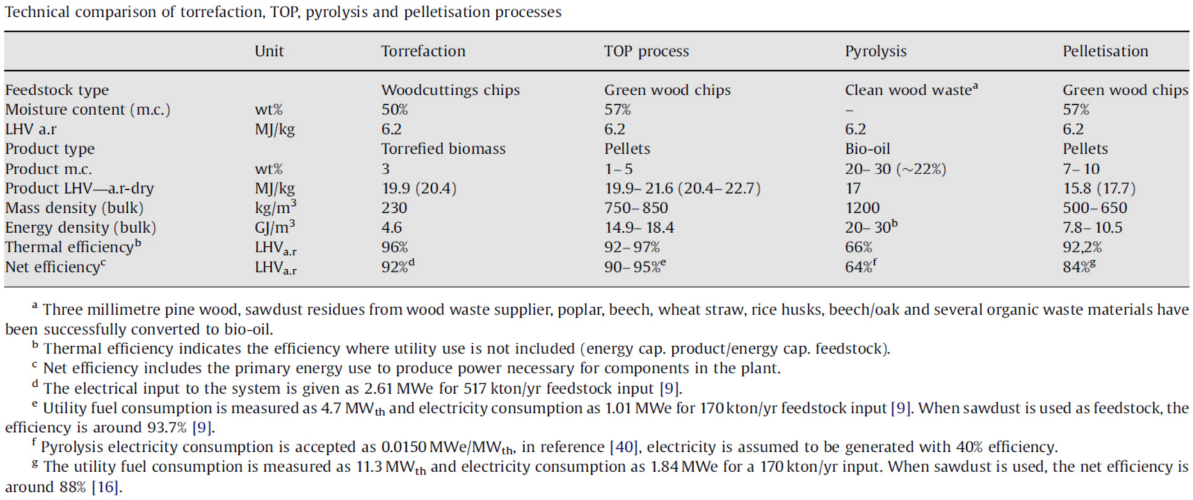
[15] Website: www.sector-project.eu

6 Comparison of torrefaction with other biomass pretreatment technologies

Any meaningful technology assessment must also compare alternative approaches beyond its specific process parameters. Besides torrefaction and the well-established pelletization process, the most important pretreatment technologies for homogenizing and densifying biomass for subsequent bioenergy use besides torrefaction are flash pyrolysis and hydrothermal carbonization. These processes are well understood, and several companies, mainly in Europe and North America, are now focussing on their development and commercialization.

This chapter discusses how the torrefaction process compares with these competing technologies in the biomass-to-energy value chain in respect to their feedstock portfolio, logistics, and end use in the bioenergy sector.

Uslu et al. 2008, in "Pretreatment technologies and their effect on international bioenergy supply," provide an excellent comparison of the effects of pelletizing, torrefaction, and flash pyrolysis on long and complex transportation chains. Table 7 summarizes the basic assumptions under which the comparison was developed.



Technical comparison of torrefaction, TOP, pyrolysis and pelletisation processes

	Unit	Torrefaction	TOP process	Pyrolysis	Pelletisation
Feedstock type		Woodcuttings chips	Green wood chips	Clean wood waste[a]	Green wood chips
Moisture content (m.c.)	wt%	50%	57%	–	57%
LHV a.r	MJ/kg	6.2	6.2	6.2	6.2
Product type		Torrefied biomass	Pellets	Bio-oil	Pellets
Product m.c.	wt%	3	1–5	20–30 (~22%)	7–10
Product LHV—a.r-dry	MJ/kg	19.9 (20.4)	19.9–21.6 (20.4–22.7)	17	15.8 (17.7)
Mass density (bulk)	kg/m^3	230	750–850	1200	500–650
Energy density (bulk)	GJ/m^3	4.6	14.9–18.4	20–30[b]	7.8–10.5
Thermal efficiency[b]	LHV$_{a.r}$	96%	92–97%	66%	92,2%
Net efficiency[c]	LHV$_{a.r}$	92%[d]	90–95%[e]	64%[f]	84%[g]

[a] Three millimetre pine wood, sawdust residues from wood waste supplier, poplar, beech, wheat straw, rice husks, beech/oak and several organic waste materials have been successfully converted to bio-oil.

[b] Thermal efficiency indicates the efficiency where utility use is not included (energy cap. product/energy cap. feedstock).

[c] Net efficiency includes the primary energy use to produce power necessary for components in the plant.

[d] The electrical input to the system is given as 2.61 MWe for 517 kton/yr feedstock input [9].

[e] Utility fuel consumption is measured as 4.7 MW$_{th}$ and electricity consumption as 1.01 MWe for 170 kton/yr feedstock input [9]. When sawdust is used as feedstock, the efficiency is around 93.7% [9].

[f] Pyrolysis electricity consumption is accepted as 0.0150 MWe/MW$_{th}$, in reference [40], electricity is assumed to be generated with 40% efficiency.

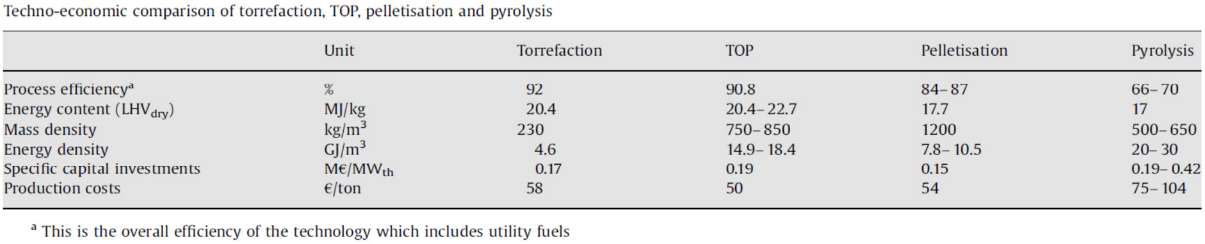
[g] The utility fuel consumption is measured as 11.3 MW$_{th}$ and electricity consumption as 1.84 MWe for a 170 kton/yr input. When sawdust is used, the net efficiency is around 88% [16].

Table 7 Technical comparison of torrefaction, TOP, pyrolysis, and pelletizing process. [Uslu et. al.]

As shown in Table 8, Uslu et al. conclude, that torrefaction and torrefied pellets (TOP), show the highest process efficiency (between 90 and 92%) and are at the lower end of production costs.

Benefits and challenges for flash pyrolysis

Pyrolysis shows the lowest process efficiency and highest production costs. Only in the case of volumetric energy density do pyrolysis oils rank highest, with 20 to 30 GJ per m³ in comparison to torrefied pellets, which reach an energy density of 15 to 18 GJ per m³.



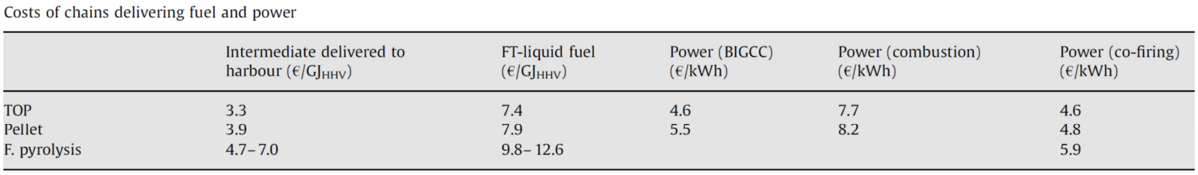
Techno-economic comparison of torrefaction, TOP, pelletisation and pyrolysis

	Unit	Torrefaction	TOP	Pelletisation	Pyrolysis
Process efficiency[a]	%	92	90.8	84–87	66–70
Energy content (LHV_{dry})	MJ/kg	20.4	20.4–22.7	17.7	17
Mass density	kg/m^3	230	750–850	1200	500–650
Energy density	GJ/m^3	4.6	14.9–18.4	7.8–10.5	20–30
Specific capital investments	M€/MW_{th}	0.17	0.19	0.15	0.19–0.42
Production costs	€/ton	58	50	54	75–104

[a] This is the overall efficiency of the technology which includes utility fuels

Table 8 Techno-economic comparison of torrefaction, TOP, pelletisation, and pyrolysis. [Uslu et. al.]

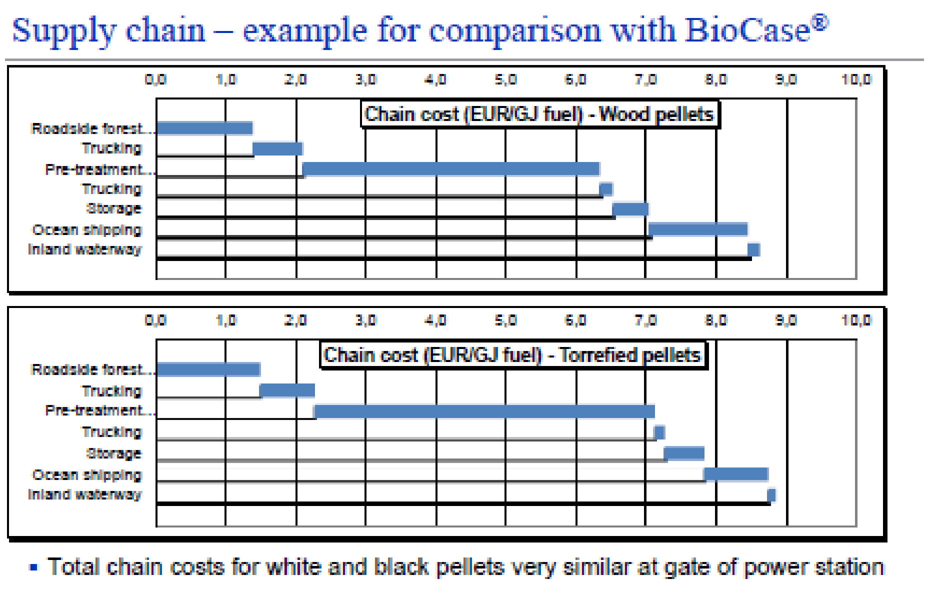
More interesting still is the overall comparison of the costs of the final end product along the bioenergy value chain for power and fuels. Here, torrefied pellets allow for the lowest production costs for each of the conversion processes considered in this paper. While the difference between torrefied pellets and wood pellets is not always significant, pyrolysis oil always shows substantially higher costs for each value chain. More recent studies such as the "Techno-Economic Analysis of Biomass Fast Pyrolysis to Transportation Fuels" by M.M. Wright et. al. from Nov. 2010 indicate costs for pyrolysis oil production in the range of 0.21 USD/ltr or about 300 €/ton and the 2012 study " Recent Developments in Biomass Pyrolysis for Bio-Fuel Production: Its Potential for Commercial Applications" by Rasul et al sets a cost range of 300 to 100 €/ton depending on plant size. Both studies show even higher costs than assessed by the Uslu paper.



Costs of chains delivering fuel and power

	Intermediate delivered to harbour (€/GJ_{HHV})	FT-liquid fuel (€/GJ_{HHV})	Power (BIGCC) (€/kWh)	Power (combustion) (€/kWh)	Power (co-firing) (€/kWh)
TOP	3.3	7.4	4.6	7.7	4.6
Pellet	3.9	7.9	5.5	8.2	4.8
F. pyrolysis	4.7–7.0	9.8–12.6			5.9

Table 9 Costs of chains delivering fuel and power. [Uslu et. al.]


Supply chain – example for comparison with BioCase®

- Total chain costs for white and black pellets very similar at gate of power station

Figure 5 total chain costs white pellets versus black pellets

More recent studies on the production and logistical costs of torrefied pellets confirm the fact that higher conversion costs on the side of torrefied pellets are almost fully compensated by lower logistic and handling costs - especially when looking at a supply chain including ocean shipping. In the case of the KEMA study[16] (Figure 5) these were 8.6 €/GJ for white Pellets and 8.8 €/GJ delivered for torrefied pellets.

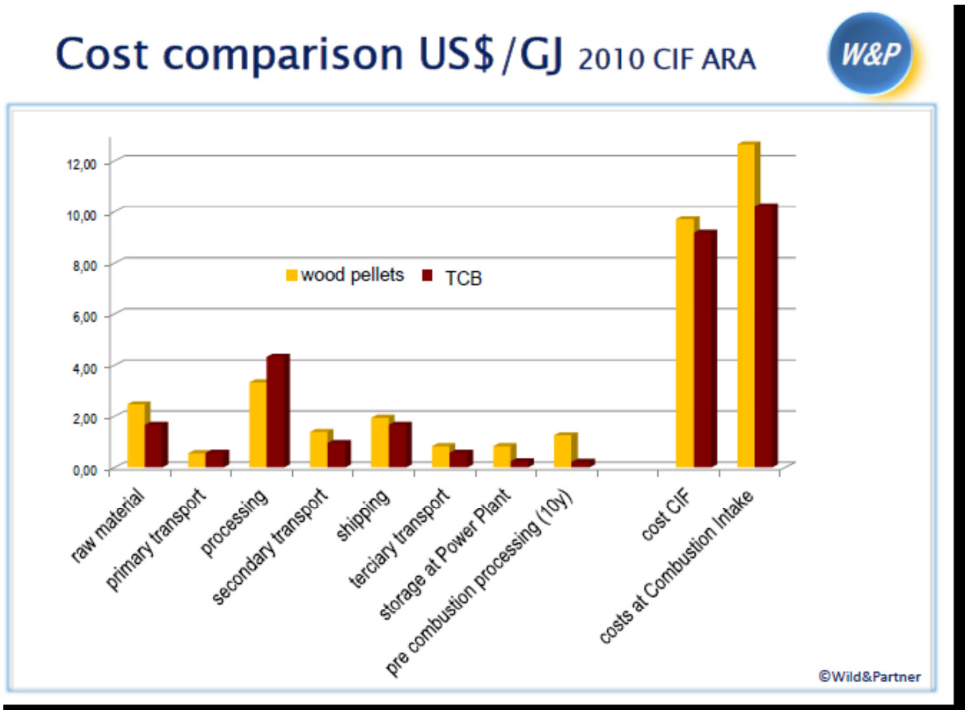


Figure 6 cost comparison wood pellets versus torrefied wood pellets

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[16] KEMA, 2012, presentation

The presentation by M. Wild[17] (Figure 6) stresses the point that the cost benefit of torrefied wood pellets (here called TCB) even increases in comparison to wood pellets when measured up to the point of combustion intake for co-firing purposes by almost 2 USD/GJ (12 USD/GJ for wood pellets and 10 USD/GJ for torrefied wood pellets).

It should be noted that flash pyrolysis can be an interesting preconditioning technology if other value chains develop in the future, such as the direct use of pyrolysis oils as crude oil substitutes in refineries, converting pyrolysis oil at high-energy efficiencies into green transportation fuels, or extracting speciality chemicals from the pyrolysis oil prior to energy conversion.

However, when it comes to industrial-scale biomass (co-)gasification or co-firing (currently the least expensive way for producing biopower), current knowledge and assumptions clearly suggest torrefied biomass as the most promising fuel.

Benefits and challenges for hydrothermal carbonization

Hydrothermal carbonization (HTC), first described in 1913 by Friedrich Bergius, is the overall exothermal conversion of biomass in an aqueous solution under pressure at about 180°C into a “biocoal” powder. The big advantage of this approach is that even without any form of preconditioning (drying, downsizing, etc.), nearly any type of biomass can be used as a feedstock. The HTC process is also highly efficient, with a carbon efficiency of about 80% and energy efficiency in the range of 70 to 90%, depending on the heat integration of the technical process.

So far, only batch processing systems are available[18], and these processes have a very low throughput and lead to prohibitively high overall conversion costs of about 100 to 150 € per ton of product[19]. The HTC process could be of interest for the production of carbon black as a soil improvement such as Terra Preta[20] and for the pretreatment and processing of aqueous organic wastes that come with negative costs.

Unfortunately, the HTC process produces significant waste water that is costly to dispose of unless it can be used as a fertilizer, and using the HTC process for the production of relatively low-cost biomass-based energy is currently not feasible .Due to lack of reliable economical and technical data for industrial scale HTC- as well as Zilkha- processes no detailed techno-economical comparison has been included in this study.

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[17] Michael Wild, 2011, presentation

[18] *See for example* www.ava-co2.com

[19] Source: FNR, Hydrothermal Karbonisierung – Stand der Entwicklung

[20] See for example http://terra-preta.de/

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 CO_2 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 such specs and supply security is not provided soon , the conversion will be implemented on basis of wood pellet requirements. This 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. Hence, it will not allow for price upmarks for torrefied products resulting from a reduced investment at the 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,[21] 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. Especially the potential conversion of already existing pellet plants to the production of torrefied pellets can speed up this process.

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, and 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.

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[21] 2003 - 3MT / 2010 - 13MT / 2020 - 50 MT

8 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.

A variety of torrefaction technologies are under development, and significant initiatives are engaged in their commercialization, with the first demonstration plants already in operation. The current trajectory of development indicates that technologies will become commercially available within the next 10 years.

Although little practical experience exists along the whole production and transportation chain of long-haul torrefied biomass trade and conversion at this early development stage, all findings of this study indicate that torrefied and compacted energy biomass has the potential to replace pellets as the most important internationally traded source of energy biomass for industrial use, such as in co-firing or even gasification in the future.

In order to make this happen, considerable investments are needed to establish the first integrated supply chains to develop from sustainable feedstock sources (e.g. supported by European utilities in order to secure long-term feedstock supplies for co-firing in coal power plants) and initiate the process of commoditization of torrefied biomass.

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