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Production of Solid Sustainable Energy Carriers from Biomass by Means of Torrefaction

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Torrefaction Technology and Strategy Report

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Abbreviations used

CEN/ISO	European Committee for Standardisation
CENER	FUNDACION CENER-CIEMAT
ECN	Energy research Centre of the Netherlands
EERA	European Energy Research Alliance
EIBI	European Industrial Bioenergy Initiative
GHG	Greenhouse Gas
IEA	International Energy Agency
ISO	International Organization for Standardization
LHV	Lower Heating Value (MJ/kg)
M&E balance	Mass and Energy balance
MeOH	Methanol
MSDS	Material Safety Data Sheets
NHV	Net Heating Value, equivalent to LHV (MJ/kg)
NTE	Net Thermal Efficiency (%)
TEC	Thermal Energy Consumption (kWh/kg)
UmU	UMEA University
VTT	Technical Research Centre of Finland

1 Introduction

This report summarizes the key results of the SECTOR project, in order to facilitate the establishment of policy instruments that can optimally support the implementation of torrefaction technologies and the use of torrefied biomass fuels in the European context. The numerous deliverables (reports) stated here have been mutually elaborated by the SECTOR partners and can be accessed via www.sector-project.eu.

1.1 About SECTOR

The SECTOR project is a major collaborative effort of 21 partners from 9 European countries who are working jointly together to advance the state of the art of torrefaction as one of the major technologies to achieve the EU renewable energy targets. The SECTOR project is funded by the European Union through the 7th Framework Programme, and has a total budget of 10.29 million Euros. In short, the objectives of SECTOR are

- Support the market introduction of torrefaction-based bioenergy carriers as a commodity renewable solid fuel
- Further development of torrefaction-based technologies (up to pilot-plant scale and beyond)
- Development of specific production recipes, validated through extensive lab-to-industrial-scale logistics and end-use performance testing
- Development and standardisation of dedicated analysis and testing methods for assessment of transport, storage, handling logistics and end-use performance
- Assessment of the role of torrefaction-based solid bioenergy carriers in the bioenergy value chains and their contribution to the development of the bioenergy market in Europe
- Full sustainability assessment of the major torrefaction-based biomass-to-end-use value chains
- Dissemination of project results to industry and into international forums (e.g. EIBI, EERA, CEN/ISO, IEA and sustainability round tables)

1.2 About this deliverable

This report provides a comprehensive overview of the work done in SECTOR on various issues related to torrefaction technologies as of November 2015, varying from the availability of suitable biomass feedstock to the optimisation of production of torrefied biomass pellets and the utilisation in the target markets.

The aim of this report is to provide state of the art information on the technical and commercial opportunities for commercial market introduction of torrefaction technologies to national and European policymakers. Policy makers are also addressed through the collaboration with IEA Bioenergy, as the author of the underlying document is also active as task leader of the responsible IEA Bioenergy task on Biomass Combustion and Cofiring.

This report will also be used to support the standardisation work in the responsible ISO 238 committee and the development of the EN ISO 17225-8 standard on “Graded thermally treated and densified biomass fuels”. Amongst others, Eija Alakangas of VTT is involved in both SECTOR and the mentioned ISO standardisation committee.

2 Biomass feedstock available

Within Work Package 2 of SECTOR, a market assessment was performed of suitable woody and agricultural biomass resources and energy crops that are or could be made available for torrefaction processes. Based on this assessment, torrefaction experiments were later performed in the project on a representative selection of these resources available.

2.1 Woody biomass resources

From the SECTOR deliverables D2.2 and D9.1, it can be concluded that woody biomass resources are important for providing wood for material as well as energetic use. The demand is expected to increase further due to the continuously growing population as well as the expected increasing demand for biomass for fulfilment of climate policy goals. Wood is the most important fuel in developing countries in Africa, Asia and Latin America, and the global consumption is likely to increase. Forests play a crucial role in the global supply of wood.

The total wood energy potential in EU-27 is about 506 Mm^3 or 3 700 PJ annually (Table 2.1). The largest forest energy potential sources are round wood/stem wood (39%) and forest residues (32%). 458 Mm^3 for other uses and 346 Mm^3 for energy use. 92 Mm^3 is available as by-product from the wood processing industry and another 52 Mm^3 as post-consumer wood.

The biggest forest energy potentials in Europe can be found in France, Germany, Finland, Sweden, Italy, Poland and Romania. Wood supply in central Europe is expected to remain more or less stable. Regions with significant growth potentials are mainly US South, South America, Russia and Africa. In the medium term also Canada is an attractive sourcing region.

Table 2.1: Summary of woody biomass resources in Europe.

Source	Solid Mm3	PJ/a
Stem wood	195.7	1 438
Landscape management wood residues	0.1	514
Forest residues	166.4	1 186
By-products and residues from wood processing industry	92.2	644
Used wood	52.0	397
Total EU-27	**506.26**	**3 664**
Ukraine	9.3	67
North-West Russia	103.9	748
Belarus, Norway, Switzerland	6.6	157

2.2 Agricultural by-products

Agricultural by-products and residues can be divided in two main categories: herbaceous by-products and residues and woody by-products and residues. Herbaceous by-products and residues are considered to be those crop residues, which remain in the field after the crop is harvested; their nature is diverse, depending on the crop, method of harvesting, etc. Woody by-products and residues are by definition those produced as consequence of pruning and regenerating orchards, vineyards and olive plantations. Normally, herbaceous crops are cultivated in arable land, whereas woody plantations are considered permanent crops.

The largest potential of primary agricultural residues comes from common cereal straw, followed by rape straw and corn straw. The largest total potentials are in France, Germany and Spain (Table 2.2). Differences in growth conditions, soil quality, soil type and texture complicate estimates of the residue potential, but in general 20 to 30% of the potential straw can be used for bioenergy. Straw potential in EU-27 is reported in different studies and varies from 560 to 982 PJ/a. The straw potential is well spread over practically whole Europe, but countries like France, Germany, Poland, Italy, Hungary and in the future UK have the largest potentials. In Denmark there is the largest concentration of straw although the potential remains limited compared to the larger EU countries. Countries which show particularly large increases towards 2020 and 2030 are France, Poland, Hungary, Romania, UK and Denmark.

Secondary agricultural residues include processing residues generated from the harvested portions of crops during food, feed, and fibre production. The largest part of the potential comes from sugar beet bagasse followed by sunflower and rice husks. The largest potentials are in France, Germany and Spain. The share of different residues on total potential varies significantly in different countries.

Table 2.2 Summary of agricultural biomass potential in Europe

Resource	PJ/a
Cereal straw	560-983
Sugar beet	25 -36
Sunflower	34
Rice husk	9
Corn residues	85
Pruning residues, total	423
Vineyard residues	14
Olive tree prunings	28
Energy crops, vegetable diet	3 465
Energy crops, mixed diet	742
Perennial herbaceous biomass	1 642
Agricultural residues (sugar beet, legume, potato, oil plants)	656

Sources: BEE, Böttcher et al. 2010; RENEW, Seyfried et al. 2004; DBFZ, Thrän et al. 2010; BIOMASS FUTURES, Elbersen et al 2012; MTT, Pahkala & Lötjönen 2012

2.3 Energy crops

The potential for **energy crops** is influenced by factors applied to guarantee food security. The basic approach of this assessment is to evaluate how much area is needed for food and feed production and if the total arable land area in a specific country exceeds this. The difference can be used for cultivation of energy crops. The cropland area in EU-25 of about

94 million hectares has the theoretical potential to produce on average 12.1 tons biomass per ha from Miscanthus, 7.1 from poplar and 5.3 from reed canary grass.

- Reed canary grass shows relatively higher productivities in Northern Europe compared to poplar and Miscanthus. As a results, experience with the use of Reed canary grass as an energy source is focused in Northern Europe, e.g. Finland.
- Miscanthus is already grown on several thousand hectares in UK. Other countries in Europe that plan to use Miscanthus as an energy crop to a larger degree are Switzerland and Germany. The potentials earlier calculated for Southern and Nordic countries are not considered realistic. In North Europe, Miscanthus does not grow because of the cold climate conditions.
- Poplar finds optimal growth conditions in Central and Western Europe.

Table 2.3 Summary of the potential for energy crops in Europe

Resource	PJ/a
Miscanthus	3 324 – 7 651
Reed canary grass (theoretical)	8 110
Woody crops (poplar, theoretical)	12 713
Short rotation coppice	2 576 – 5 447

Sources: BEE, Böttcher et al. 2010; RENEW, Seyfried et al. 2004; DBFZ, Thrän et al. 2010; BIOMASS FUTURES, Elbersen et al 2012; MTT, Pahkala & Lötjönen 2012

2.4 Raw materials selected for testing in SECTOR

Clean and dry lignocellulosic biomass sources, containing substantial fractions of cellulose, hemicellulose and lignin are the most obvious choice for torrefaction, as these materials become more compatible with existing pulverized coal fired power plants. It does not make much sense to torrefy biomass that is already compatible with coal, such as meat and bone meal which has already good grindability characteristics and high calorific values. The chemical composition of the biomass material is also a factor to consider. Because of the relatively low temperature of the torrefaction process, most critical chemical fuel components (alkali metals, chloride, sulphur, nitrogen, heavy metals and ash) remain in the fuel after torrefaction. This makes clean biomass feedstock the preferred option for the foreseeable future.

Within SECTOR, 21 types of raw materials were selected for further testing on lab and pilot scale. These materials cover the whole range available based on classification of origin and sources of solid biofuels according to EN 14961-1 standard. A wide range has been chosen to include forestry biomass, agricultural biomass, industrial woody residues etc. Wood chips from coniferous stem wood without bark have been taken as a reference material for all experimental activities (Spruce as one possible example). Wood chips from broadleaf small sized stem wood with bark (Beech as one possible example) has been taken as second reference material. While laboratory testing includes all materials, pilot testing concentrated mainly on these two reference materials.

Based on the biomass resource assessment performed and an internal discussion with SECTOR project partners, the materials presented in Table 2.4 were finally selected for experimental work in the SECTOR project. In the selection process, highest priority was given to resources that were considered to provide the highest potential on the short term.

Table 2.4 Selected materials for testing in SECTOR

No.	Selected feedstock	Test type to perform
1	Delimbed coniferous stem wood without bark: Pine and spruce (Reference raw material 1)	Lab and pilot
2	Logging residue, coniferous	Lab and pilot
3	Straw, wheat (Nordic conditions)	Lab
4	Used wood – post consumer wood, recycled wood, chemically untreated	Lab and pilot
5	Bark	Lab
6	Delimbed broadleaves stem wood with bark: Beech (Reference raw material 2)	Lab and pilot
7	Poplar	Lab and pilot
8	Straw (Oat and wheat, Southern conditions)	Lab and pilot
9	Prunings from olive trees - woody biomass	Lab and pilot
10	Eucalyptus	Lab and pilot
11	Paulownia	Lab and pilot
12	Bamboo	Lab and pilot
13	Palm oil residues (e.g. oil palm fruit bunch, palm kernel or shell)	Lab
14	Bagasse	Lab and pilot
15	Corn cobs	Lab
16	Miscanthus	Lab
17	Sun flower residues	Lab
18	Willow (Salix)	Lab and pilot
19	Reed canary grass	Lab
20	Straw, barley (Nordic conditions)	Lab
21	Rape straw	Lab

The biomass properties acceptance for the different torrefaction facilities involved in SECTOR is rather similar. In general, the moisture content should not be too high (typically not more than 10-20%) and particle dimensions should be between some millimetres up to some tens of millimetres. In addition, amount of fines should be low and the biomass should have proper handling properties, i.e. should not show bridging behaviour during handling.

2.5 Torrefied biomass produced in SECTOR for testing

Within SECTOR, about 77 tons of torrefied biomass were produced from various biomass resources. Most of this torrefied material was used to produce pellets (about 41 tons). From this amount, about 17 tons of pellets were actually used in the project for combustion tests, milling tests, stockpile tests, hydrophobicity tests, etc. In addition, some 2 tons of non-pelletized torrefied material were delivered for densification lab tests, logistic tests, grinding tests and fuel characterization.

3 Torrefaction technologies

3.1 Basic principles

Lignocellulosic biomass typically contains approx. 80% volatile matter and 20% fixed carbon on dry mass basis. During the torrefaction process, solid biomass is heated in the absence of or drastically reduced oxygen to a temperature of approx. 250-320°C, leading to a loss of moisture and partial loss of the volatile matter in the biomass. With the partial removal of the volatile matter (about 20%), the characteristics of the original biomass are drastically changed. The tenacious fibre structure of the original biomass material is largely destroyed through the breakdown of hemicellulose and to a lesser degree of cellulose molecules, so that the material becomes brittle and easy to grind. The material then changes from being hydrophilic to becoming hydrophobic. With the removal of the light volatile fraction that contains most of the oxygen in the biomass, the heating value of the remaining material gradually increases from 19 MJ/kg to 21 or 23 MJ/kg for torrefied wood and eventually 30 MJ/kg in the case of complete devolatisation resulting in charcoal.

Although there are some variations in the range of process conditions applied for the various reactor concepts, the basic concept for torrefaction and densification processes is the same and commonly incorporates heat integration, see Figure 3.1.

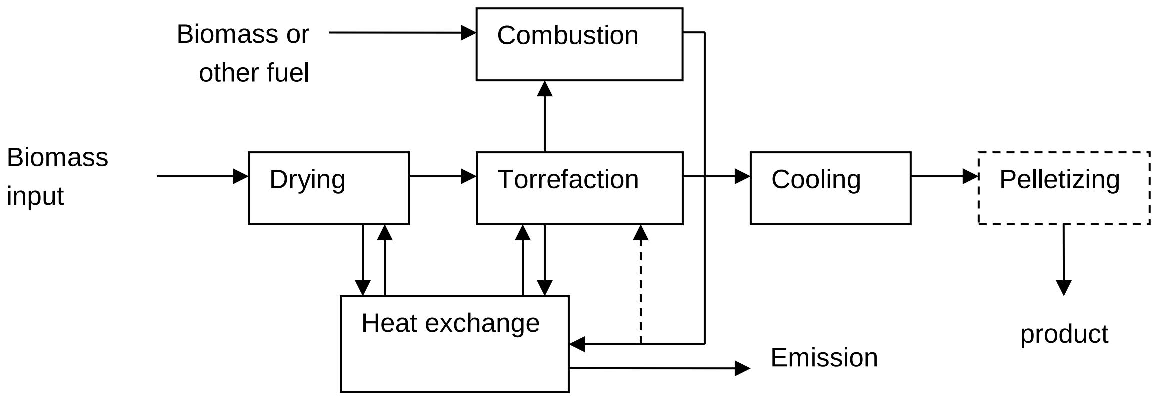

Figure 3.1 Overview of heat integration options.

The thermal energy required for the drying and torrefaction process is delivered by combustion of torrefaction gas, occasionally assisted by an auxiliary fuel. In a properly designed and operated torrefaction system, the energy contained in the torrefaction gases may be sufficient to sustain both the drying process and the torrefaction process. However, this strongly depends on the moisture content of the incoming biomass (latent heat requirement) and the required degree of torrefaction (the degree of mass loss and the availability of combustible volatiles). It is therefore important to dry the biomass before it enters the torrefaction reactor, since moisture entering the torrefaction reactor results in more humid torrefaction gas which lowers the adiabatic flame temperature. For very wet torrefaction gas, there might not even be sufficient energy contained in the gas to reach a temperature for complete combustion (at least 900ºC required). For this reason, moisture content of incoming biomass to the torrefaction reactor should normally not exceed approx. 15%. However, depending on the torrefaction concept and the economics of the feedstock considerably higher moisture content may turn out to be beneficial. The net efficiency of an integrated torrefaction process is approx. 70 - 98%, depending on the reactor technology, concept for heat integration and the biomass type.

3.2 Reactor concepts

Different reactor technologies which were originally developed for other applications have been modified to perform torrefaction. Some torrefaction technologies are capable of processing feedstock with only small particles such as sawdust whereas others are capable of processing large particles. Only a few reactor types can handle a wider range of particle sizes. This means that selection of technology needs to be done based on the characteristics of the feedstock, or alternatively, the feedstock needs to be pre-processed before entering the torrefaction reactor. The need for size reduction equipment, such as scalpers for handling over-sized material or sieves for extraction of small particles will increase capital as well as operating cost of a torrefaction facility. This must be offset against the lower costs of feedstock that requires such pre-processing.

Table 3.1 provides an overview of the most important reactor technologies and the companies involved.

Table 3.1 Overview of reactor technologies and some of the associated companies

Reactor technologies	Companies involved
Rotating drum reactor	Andritz (AT), Atmosclear S.A. (CH), BioEndev (SWE), CENER (SP), EarthCare Products (USA), Teal Sales Inc (USA), Torr-Coal (NL)
Screw reactor	Agri-tech Producers (USA), Arigna Fuels (IR), Biolake (NL), Solvay Biomass Energy (USA)
Herreshoff oven / multiple hearth/tray reactor	CEA (FR), CMI-NESA (BE), Integro Earth Fuels (USA), Terra Green Energy (USA), Wyssmont (USA)
Fluidized bed reactor	Airex (CAN), Bioenergy Development & Production (CAN), Topell (NL)
Microwave reactor	Rotawave (UK)
Moving/fixed bed	Andritz/ECN (DK/NL), AREVA (FR), Grupo Lantec (SP), LMK Energy (FR), New Earth Renewable Energy Fuels (USA), Torrec (FI)

3.3 Pelletisation

By pelletizing torrefied biomass, a number of advantages can be achieved in transport, handling and storage in comparison to torrefied biomass chips as the intermediate product. While the volumetric energy density (in GJ per m^3) of torrefied biomass chips is more or less equal to that of the original material (wood chips), the compression step increases this by a factor of 4 to 8 leading to significant cost savings in shipping and storage, shipping meaning transportation with truck, train or ocean vessel. The pelletized product can be pneumatically transported to intermediate storages or the coal pulverisers or hammer mills and is less sensitive to degradation and moisture uptake when compared to wood chips or pulverized fuels [1].

However, torrefied biomass is more difficult to press into firm pellets than raw biomass. The energy consumption of the pelletisation process itself is higher per ton of torrefied biomass if compared to e.g. wood pellets (about 150 kWh/ton vs 50 - 60 kWh/ton), although research is ongoing to reduce this. The pelletisation process is also accompanied by challenges such as low pellet quality, high friction, heat generation and wear on the mechanical parts of a pellet press. This was confirmed by experimental research work carried out in SECTOR on pelletisation of a broad diversity of torrefied biomass types and torrefaction process parameters [2].

The mechanical strength of the resulting torrefied pellets can in some cases be similar to conventional wood pellets. Lignin plays an important role in the internal binding of the pellet and so does the moisture content. During the torrefaction process lignin partly degrades, depending on the process conditions. Therefore, preparing a strong pellet requires optimization of the process conditions during torrefaction as well as pelletisation such as increased pelletisation temperature or exerting high pressures. A number of companies involved in torrefaction consider using binders such as glycerin, paraffin, molasses, lignin, bio plastics or condensable fraction of torrefaction gas. Injection of water mist in the torrefied material prior to the pelletisation appears to also improve the binding characteristics. This area is subject to intensive research at this time.

There is still a lot of research ongoing on the optimal selection of densification process parameters depending on the torrefaction conditions. In general, many parameters influence the pelletizing properties of the torrefied biomass. With regard to the biomass species, pellets from torrefied poplar, beech, pine and spruce exhibit the highest mechanical strength, while pellets from torrefied sun flower husks, palm kernel shell, forest residues and straw have a much lower mechanical strength.

The degree of torrefaction has a strong influence on the densification properties of torrefied biomass. An increase in torrefaction degree usually results in an increase of the energy required to compress biomass into a pellet and the energy required to move/extrude the pellet from the press channel of a pellet mill (friction forces). The pellets mechanical properties usually decrease with an increasing degree of torrefaction.

Adding the proper amount of water to the torrefied biomass and increasing the pelletising die temperature lowers the compression energy and friction and results in stronger pellets.

The amount of electrical energy required for pelletisation may vary in the order of 80 to 210 kWh/ton depending on biomass type, moisture content and particle size, type of mill and pellet die chosen as well as dimensions of the press channel. In general, adding more energy during the pelletisation process results in warmer pellets, which are also more durable.

The use of additives has only shown to have a limited effect on pellet quality. The energy for compression is lowered by using additives, but this is most likely already accomplished by adding water and proper conditioning before pelletisation.

During the course of the project, the partners involved in SECTOR have significantly improved their ability to produce pellets with high mechanical durability, typically increasing from less than 90% to over 96%, thereby meeting quality requirements of the typical end users [3].

3.4 Mass and energy balances

For typical process conditions, characteristics of raw biomass used and torrefaction degree, the energy contained in the volatiles released during the torrefaction process (torgas) is of the same order of magnitude as the heat required to drive off moisture contained in the feedstock.

Figure 3.2 illustrates the Energy Yield, defined as the lower heating value (LHV) of the torrefied product divided by the total LHV of the input biomass against the moisture content of input biomass. It is assumed here that the volatile gases released during torrefaction are combusted to dry the input biomass and supplemented with combustion of additional biomass fuel. The thermal process efficiency depends on the removal of volatiles and the moisture content of the input biomass used.

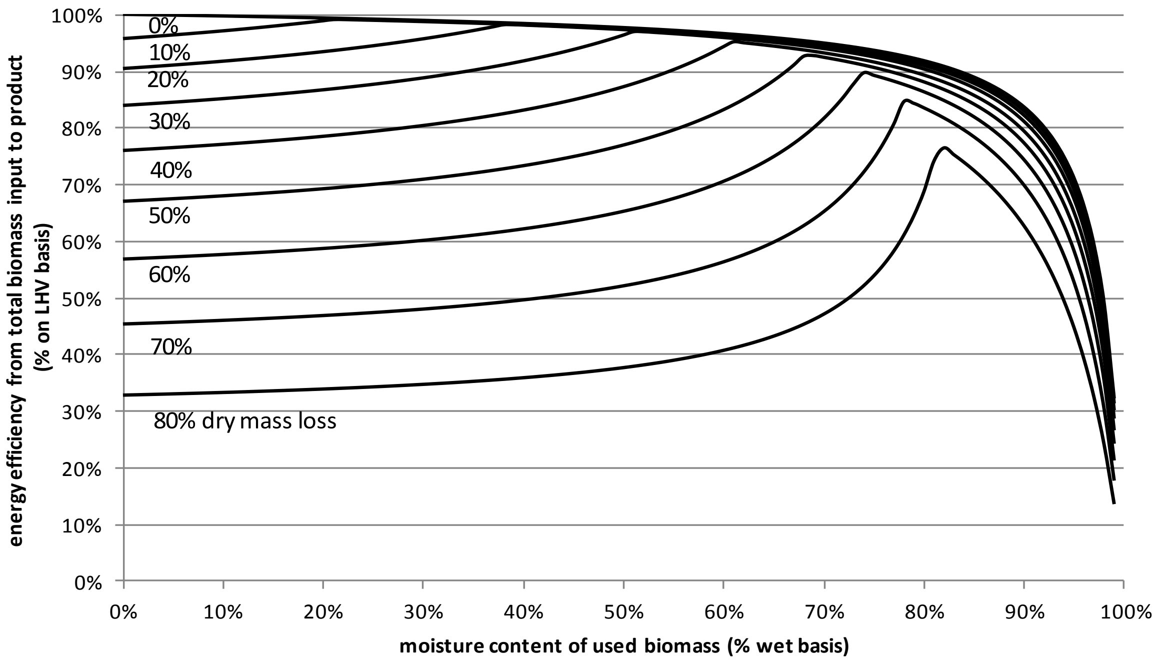

Figure 3.2 **Theoretical Energy Yield of an integrated torrefaction process, assuming clean wood (0.5% ash content) as raw material and heat requirement of the dryer of 2.9 MJ per kg of water evaporated (75% efficiency) [1].**

Figure 3.2 shows that for typical torrefaction conditions where about 20% of the dry mass is removed in the form of volatile gases (often named ‘torgas’), the thermal energy efficiency of a torrefaction process with proper heat integration shows very high conversion efficiencies exceeding 90%, since the energy contained in the removed volatile fraction can be used to provide heat for the dryer and the torrefaction process. The process efficiency drops with higher devolatisation rates (more than about 20 - 30%) and lower moisture content biomass, because the energy contained in the released volatiles is more than what is required for removing moisture in the biomass dryer. The process efficiency is also less than optimal for wet biomass fuels (e.g. green wood, fresh grasses, etc.) due to the inefficiency of the dryer.

For the demonstration facilities involved in SECTOR, energy balances were produced as well [4]. As Table 3.2. confirms, a relatively high efficiency around or above 90% can be achieved[1]. A high energy yield combined with significant mass reduction implies that the energy contained in raw material is concentrated in less mass, thus leading to a higher calorific value of the product compared to the biomass resource used.

The Net Thermal Efficiency (NTE) parameter involves the complete torrefaction process and includes all energy in- and outputs of the process and pre-treatment of the feedstock. The NTE is mainly influenced by biomass moisture content, mass yield of the torrefied product, energy integration and heat losses [5]. NTE values of cases including heat integration (ECN and CENER) are very similar. In both cases energy loss is very similar both for flue gas and radiation heat. For UmU technology, NTE and TEC parameters are not comparable with the

[1] For the UmU case, energy yield is lower, however this demonstration plant does not yet have optimal heat integration options applied.

ECN and CENER ones, because in the UmU mass and energy (M&E) balance the energy integration has not been taken into account.

Table 3.2 Main results and parameters from M&E balances of different technologies of pilot test plant in SECTOR project for pine torrefaction [4]

Partner	CENER	UmU	ECN
Torrefaction technology	Indirectly in- and externally heated rotating shaft	Rotating drum	Directly heated moving bed
Heat transfer type	Indirect heating	Indirect heating	Direct heating
Mass yield	79% db	75.7% db	81.3% db
Energy yield	90.5% db	87.9% db	87.6% db
Net thermal efficiency (NTE)	92.1%	83.6%	92.4%
Thermal energy consumption	0.46 kWh/kg	0.30 kWh/kg	0.34 kWh/kg

4 Characteristics of torrefied biomass

Torrefaction results in a high quality fuel, with characteristics that are partly shifted from biomass towards coal. From the data in Table 4.1 it can be concluded that torrefaction yields a number of important advantages, which will be discussed below.

Table 4.1 Variety in fuels suitable for biomass co-firing [6]

	Wood	Wood pellets	Torrefaction pellets	Charcoal	Coal
Moisture content (% wt.)	30 – 45	7 – 10	1 – 5	1 – 5	10 – 15
Lower heating value (MJ/kg)	9 – 12	15 - 18	20 – 24	30 – 32	23 – 28
Volatile matter (% db.)	70 – 75	70 – 75	55 – 65	10 – 12	15 – 30
Fixed carbon (% db.)	20 – 25	20 – 25	28 – 35	85 – 87	50 – 55
Density (kg/l) Bulk	0.2 – 0.25	0.55 – 0.75	0.75 – 0.85	~ 0.20	0.8 – 0.85
Bulk energy density (GJ/m^3)	2.0 – 3.0	7.5 – 10.4	15.0 – 18.7	6 – 6.4	18.4 – 23.8
Dust	Average	Limited	Limited	High	Limited
Hygroscopic properties	hydrophilic	hydrophilic	hydrophobic	hydrophobic	hydrophobic
Biological degradation	Yes	Yes	No	No	No
Grindability	Poor	Poor	Good	Good	Good
Handling	Special	Special	Good	Good	Good
Quality variability	High	Limited	Limited	Limited	Limited

4.1 Moisture content and hydrophobicity

The drying and subsequent torrefaction processes removes all water from the original biomass. In addition, during the torrefaction process OH-groups are substituted by unsaturated non-polar groups, which results in a great loss of water adsorbing capacity. The hydrophobicity of torrefied material makes the fuel less sensitive for degradation (rotting), self-heating and moisture uptake.

Figure 4.1 illustrates the hygroscopic characteristics of one type of torrefied pellets as a function of time and relative humidity at a certain ambient temperature. The figure shows that the hydrophobicity improves with the degree of torrefaction. The use of binder or additive and other types of feedstock may show slightly different results.

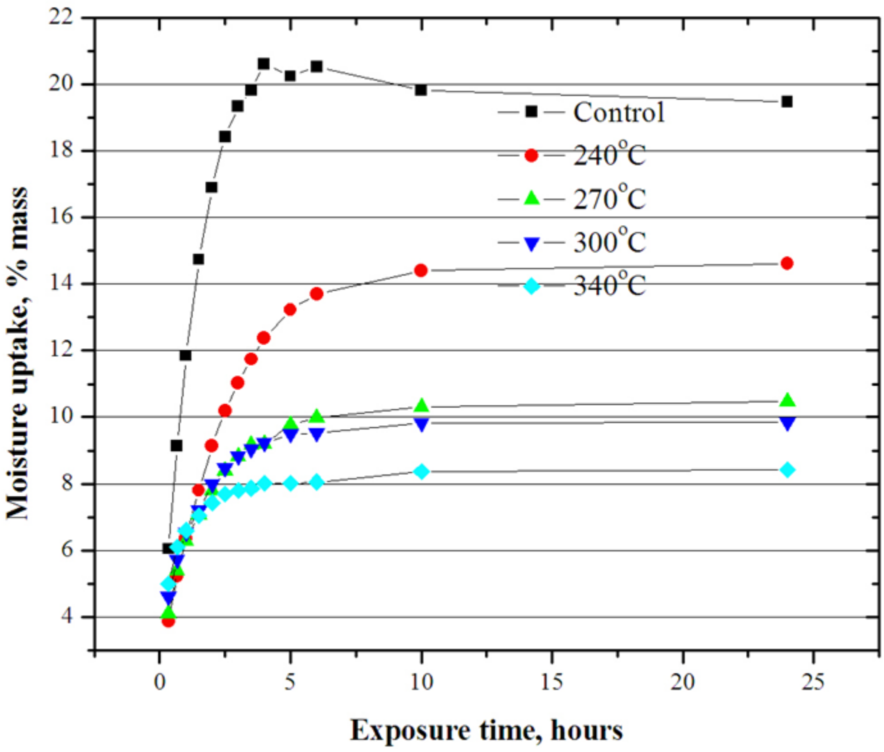

Figure 4.1 **Hygroscopicity of 6 mm pellets made from torrefied wood at temperatures from 240 - 340°C. The reference is regular white pellets, tests were done at 30°C and 90% relative humidity (RH). UBC/CHBE, Feb. 2011.**

In addition to the hygroscopic adsorption there is also absorption of water if exposed to moisture in liquid form (e.g. rain). In this case, water may enter a pellet of torrefied biomass through cracks in the outside surface. This may seriously affect the mechanical durability, e.g. through freeze and thaw cycles.

The water absorption has shown a tendency of generating leaching of unknown composition. In SECTOR, some preliminary work has been done to examine the composition of eluate [7].

ISO Technical Committee 238 is developing testing standards for determination of hygroscopicity (sorption of relative humidity in air), absorbance of water and freezing characteristics. The hydrophobicity is not the focus of determining the weather-resistance of torrefied pellets but rather the effect on durability caused by hygroscopic sorption, water absorbance and destruction of the mechanical integrity of the pellets. Therefore each one of these test are completed with a standard durability test.

In SECTOR, experiments were performed on water take up in a climatic chamber, which can be interpreted for the outer layer of an outdoor stockpile [8]. The experiments revealed that after long term exposure to humid air (90% rel. humidity), an increase in moisture content was observed from about 2.5 - 3 wt.% immediately after production up to 10 - 11.5 wt.%. This increase in moisture content does not significantly affect the mechanical durability of properly pressed pellets, but pellets that already have a relatively low mechanical durability before exposure are further weakened. It is therefore essential that pellets exhibit a high mechanical durability after pelletisation.

4.2 Calorific value

Through the removal of moisture and some organic compounds from the original biomass, the calorific value gradually increases from 19 - 21 MJ/kg of the original biomass (depending on the moisture content) to 21 or 23 MJ/kg for torrefied biomass. A higher torrefaction degree leads to a higher calorific value, but usually also a lower process efficiency. A fundamental difference with charcoal is the difference in volatile matter; in torrefaction processes the aim is to maintain volatile matter (and thereby energy) as much as possible in the fuel while in typical charcoal production processes, the volatiles are removed from the biomass[2].

4.3 Chemical composition

During the torrefaction process, most of the inorganic components remain in the fuel. Since part of the dry matter in the original biomass is lost during the process, the ash content increases slightly.

Recent research indicates that through the torrefaction process, a significant amount of chlorine (up to 90%) can be removed from the original biomass [9]. This implies that chlorine related corrosion impacts can be significantly reduced through the torrefaction process.

4.4 Transportation issues

During torrefaction, the bulk density decreases due to the decrease in mass (moisture and volatiles) while the product almost maintains the original volume. In non-densified form the torrefied material is relatively difficult and expensive to handle and transport, due to the low energy density (3 to 3,3 GJ/m^3) and the high risk for dust emissions. Pelletizing torrefied biomass mitigates these problems and makes the product significantly better for long distance transportation.

The added costs of pelletisation may be justified by the reduction in transportation costs (e.g. from Eastern Europe or North America to Western Europe). In case biomass is available near the power plant where it is used, this may not be the case, provided the power plant can process non-pelletized material. Transportation distances are therefore an important factor for the design of the torrefaction installation and the business case.

With regard to health and safety aspects, REACH registration has been performed and Material Safety Data Sheets (MSDS) have been developed. Based on extensive safety tests carried out, the US Department of Homeland Security has issued a 3-years permit to allow for shipment of torrefied biomass [10]. Adequate product standards are currently developed that should provide confidence to end users that the torrefied products offered meet the customer requirements. It is expected that a new ISO standard will be made available soon. Other regulations for transportation by rail or road may also apply in local jurisdictions.

[2] There are some interesting developments in advanced charcoal production, where the aim is to form secondary char from part of the volatiles to increase char yield and process efficiency.

4.5 Self-heating

Not much research has been done so far on the behaviour of torrefied biomass as far as self-heating and ignition are concerned. In SECTOR a number of torrefied product safety studies were performed [11]. Research involved small scale oxidation tests (TGA), medium scale self-heating and torrefaction tests (TBR) as well as larger scale self-heating measurements (in big bags). Some important findings are listed below:

- Directly after production, the temperature of freshly torrefied material first increases. The temperature rise increases with the torrefaction degree. If a big bag is filled with freshly torrefied material, the recorded temperatures are highest in the middle of the big bag. For example, temperature increases from 45 to 70°C have been observed for torrefied beech wood.
- Compared to freshly torrefied wood chips, freshly torrefied chopped straw adsorbs a higher quantity of oxygen and the oxidation also starts at lower temperature, being approximately 40°C vs. 80°C for wood chips.
- The oxidation temperature of freshly torrefied materials (wood chips and straw) is the same at approximately 180°C.
- Ignition temperatures of torrefied biomass species (forest residues, spruce, pine and poplar) appear to be within the same temperature range between 210 - 230°C.

With this information at hand, no conclusions can be drawn for a specific case regarding the risk of self-heating, but in general it appears that the risks of self-heating are not larger than for wood pellets.

4.6 Dust explosions

One of the key concerns for large power plants is the risk of dust generation during storage and handling since there are concerns that the dust could be highly explosive as is the case for dust created during the handling of normal wood pellets.

In SECTOR, explosibility tests were carried out to verify the behaviour of dust from torrefied biomass pellets. The minimum ignition energy (MIE) of sample powders was determined using a modified Hartmann tube as the explosion vessel, following the European Standard EN 13821:2002. The results showed that particularly dust from torrefied spruce, raw spruce and dust produced by a cutter mill has a relatively low minimum ignition energy of 3 - 10 mJ, while dust from other biomass types and produced in other ways usually exhibit a somewhat higher MIE [12]. It implies that one has to take similar precautions as for wood pellets from the same material.

4.7 Grindability and feeding aspects

Through the torrefaction process, biomass material becomes brittle due to the breakdown of hemicelluloses and, to a lesser degree, lignin and cellulose. These components normally comprise the fiber structure, which limits the grindability in a conventional coal pulverizer.

Compared to the original woody biomass, milling torrefied wood in a hammer mill requires about 50 - 85% less energy consumption and increases the throughput by about 2 to 6.5% [13]. The grindability also depends on the torrefaction technology, mill type, milling conditions, biomass characteristics and feed-in arrangement.

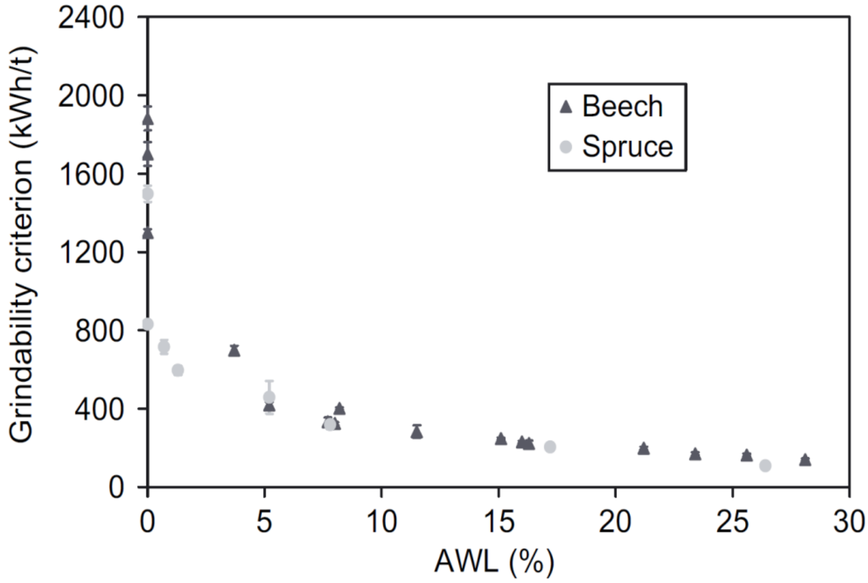

Figure 4.2 Grinding energy required to reduce the particle size below 200 μm, per ton of material that has the top size of 200 μm. AWL stands for Anhydrous Weight Loss (Dry Matter Loss) [14]

In SECTOR, grindability tests were performed on various mill types and the influence on milling energy consumption, particle size and feedability was evaluated [15]. The rigorous tests performed in a hammer mill, standard HGI mill as well as in coal mills (bowl and roller mills and a fan beater mill) confirmed that torrefaction significantly improves grindability of biomasses. Hardgrove Index Values between 23 and 53 were measured for torrefied biomass. This can be compared to bituminous coals, which are mostly from around 40 for difficult to mill coals to values in excess of 70 for softer, more friable coals. Co-grinding in coal mills is feasible and may improve the particle size of the product rather than separate grinding in the same mill followed by mixing especially in the case of a bowl (roller) mill.

Feeding of torrefied biomasses is also improved compared to non-thermally treated biomasses. This is attributed to the decreasing content of hemi-cellulose, with the result that the pulverized grinds are more spherical and therefore less prone to bridging and agglomeration which often happens when feeding non-thermally treated biomasses due to their lengthy fibrous nature. This was confirmed by full-scale co-gasification trials of torrefied and pelletized biomass and coal in the 253 MW Willem-Alexander Plant (WAC) of Vattenfall in Buggenum, Netherlands. In total, approximately 1 200 tonnes of biomass were used during the tests at a biomass share of 70% on energy basis. Unloading, storage, reclaiming, blending with coal and conveying of the torrefied material with the existing mechanical installation was basically possible. To reduce the dust emissions, new dust suppression equipment (such as water dispersion systems) were installed. The milling was not an important issue at WAC power plant, earlier small scale tests had indicated the grindability of the tested fuel was sufficient enough. The sluicing and feeding system worked stable and no problems were reported [15].

4.8 Combustion characteristics

Many different factors determine the behaviour of a fuel in a certain combustion installation, such as heating value, moisture content, ash content, reactivity and particle size. The calorific value of torrefied wood can reach a value close to coal and is typically very dry (moisture content lower than 5%). It contains less ash than coal (0.7 to 5% db, compared to 10 to 20% db for coal) and has a higher reactivity, largely due to the high amounts of volatile matter (55 - 65% db compared to 10 - 12% db for coal). The relatively low nitrogen and sulphur concentrations and combustion temperatures result in low NO_x and SO_2 emissions, as for the original biomass.

The behaviour of torrefied biomass in small scale biomass boilers and in pulverized coal fired boilers is described in more detail in sections 5.1 and 5.2.

5 Suitability of torrefied biomass in potential end markets

The required product quality parameters for torrefied biomass pellets depend on the market outlet. Within SECTOR a preliminary inventory was made of the technical product requirements if used for co-firing, co-gasification, small scale combustion as well as for the use as a resource for chemicals and biomaterials [16]. The key characteristics for large scale utilization relate to storage and handling properties, milling, co-firing and co-gasification properties. For small scale utilization, ash content is also relevant.

5.1 Small scale biomass boilers

The direct replacement of wood pellets by torrefied biomass pellets in existing boilers may result in some unwanted side effects as the fuels behave differently. For example, torrefied biomass has a relatively lower amount of volatiles and a slightly higher amount of fixed carbon. This implies that more energy is released on the grate, whereas less energy is released in the gas phase. If torrefied pellets are used in an existing and unmodified wood pellet boiler, this carries the risk of unburned carbon in the ash.

Yet, CFD work and combustion trials performed in SECTOR on torrefied biomass pellets [17, 18] indicated that a pellet boiler can in principle be designed to optimally accommodate the deviating characteristics of torrefied biomass fuels in respect to wood pellets. Some important issues are:

- Higher combustion temperatures may occur. This requires use of materials that can resist higher temperatures of grate and combustion chamber. It may also result in molten ash (slag) being formed on the grate, which is more difficult to remove from the furnace. Slag may also result in the clogging of air supply nozzles.
- Torrefied softwood pellets need a longer burnout time in order to completely convert the higher amount of carbon in the fuel. Adaptations of the grate and the burnout zone are therefore required. Due to the lower combustion rate, the fuel bed height increases.
- Adaptations are required of the control system in order to define the distribution of primary and secondary air supply and the residence time of the fuel on the grate as well as the fuel feeding rate.
- Due to the higher expected fuel bed temperatures of torrefied fuels, the emission of products of incomplete combustion (CO, OGC and PM) is largely similar or even lower to that of wood pellets. However, the higher bed temperature may also result in an increased volatility and emission of fine particle emissions. For small scale heating appliances it is therefore required that future fuel standards are based on the same critical components and that they define similar limits as already established for wood pellets.
- The combustion tests performed reveal that the combustion efficiency can be as good as or even better for torrefied wood pellets as achievable with wood pellets when tested at full or partial load. Under variable load operation (i.e. load cycle) an even higher

efficiency may be possible. This seems to be applicable for top feed and underfeed stoker boiler types. Compared to moving grate furnaces, underfeed stoker boilers appear to be better capable of using reduced qualities of torrefied fuels and pellets with larger diameters.

- The characteristics of torrefied biomass pellets may in practise vary significantly as a result of variations in torrefaction conditions, input material, and the kind of production chain (integration of the densification step). It is difficult if not impossible to guarantee optimal quality for small- and medium-scale use under these varying conditions. The boiler control needs to be capable to deal with these varying characteristics of torrefied pellets.

5.2 Co-firing with coal

For large-scale use in biomass cofiring or co-gasification with coal, the power producers involved in SECTOR (Vattenfall, RWE and E-ON) started in SECTOR to make an inventory of potential issues that could affect the integrity of five particular coal fired power plants and coal fed gasifiers when introducing torrefied biomass [19]. By the end of the SECTOR project, this was followed by a more thorough evaluation of these issues [20].

A key issue is the durability of the pellets in relation to the actual moisture content and the consequent dusting problem. From D6.3 it was observed that today's pellets from torrefied biomass typically exhibit a relatively high mechanical durability exceeding 96% [3]. Nevertheless the installation of dust suppression equipment (such as water dispersion systems) might be required to avoid excessive dust formation during handling.

Another issue is related to self-heating and self-ignition and consequential safety measures that must be applied. From D6.4 it was observed that self-heating can be expected shortly after production of torrefied pellets, after which the product stabilises. Self-heating issues are therefore considered to be well manageable.

In order to use the fuel in residential areas, odour and consequential safety aspects are relevant. First experiences from practise indicate that this can be managed in such cases, e.g. by using dust suppression equipment or enclosed storage silos.

The effects on milling and feeding, overall plant efficiency and optimal blending to ensure a homogeneous mixture with coal, are highly relevant as well as the associated requirements. As section 4.7 concluded, it appears that torrefied biomass pellets can be used in existing mills together with coal.

Finally, the combustion behaviour of torrefied biomass in the existing burners and the furnace needs to be similar to coal. Some of the key combustion related issues were investigated in SECTOR through pilot scale tests and CFD analysis of two representative full scale pulverised coal fired plants [21, 22]. These effects are all manageable in practice:

- Burning torrefied material will reduce the amount of ash, simply since the torrefied fuel and the original biomass used to produce the torrefied fuel typically contains significantly less ash than coal.

- If torrefied fuel is used, more volatiles and less fixed carbon enter the furnace. If the same particle size distribution is used as for coal, less unburned carbon ends up in the fly ash. However this does not necessary imply that the Loss on Ignition (LOI) in the fly ash also decreases, since the fuel contains less ash as well. When increasing the particles size of torrefied biomass to a particle size comparable to wood dust that is normally used for cofiring, the amount of unburned carbon in the fly ash will increase significantly. It is therefore advised to grind biomass to a similar particle size as coal.
- Since more fuel gas is produced when burning torrefied material, the combustion reaction will extend higher up in the combustion chamber. When coal is completely replaced by torrefied biomass, the flame size can increase up to about 25%. The flame will also start more quickly and grow backwards towards the burner. This is attributed to the increased reactivity of the fuel, which is largely caused by the significantly increased internal surface area of the fuel particles due to the evaporation of volatile matter. Depending on the type of burner, parts of the burner can increase in temperature by about 100 - 200 K.
- When burning torrefied biomass, significantly less NO_x and SO_2 is formed due to the lower fuel nitrogen and sulphur concentrations. CO emissions are comparable to coal.

In addition, there could be other effects on power plant integrity such as superheater corrosion, ash deposition, ESP or SCR performance, etc. In general it can be stated that these effects are similar for torrefied biomass and raw biomass, as the inorganic composition of the fuel is not negatively affected.

5.3 Co-gasification with coal

A potential market outlet for torrefied biomass is the use in entrained flow gasifiers which are normally fueled with coal. The issues regarding handling, storage and fuel feeding are similar as for pulverized coal fired power plants. Particular safety issues are expected with regard to dust explosions.

In SECTOR, experimental research was carried out on the use of torrefied biomass in entrained flow gasifiers (EFG), using various pilot and demonstration plants. There were no real showstoppers observed. However, a number of issues request further attention, such as a correction of the modified ash and slag behaviour in comparison to coal, using fuel mixing and additives [23]. Another issue is the difference in gas composition and heating value [24].

5.4 Production of chemicals and biomaterials

Within SECTOR, specific research was carried out by VTT and ECN on the presence and potential utilization options of the condensable fraction in torrefaction gasses [25]. This was done at different condensation temperatures and for different biomass species. Condensate mass yields may vary from about 3 - 8%, depending on torrefaction temperature. The main chemical found was acetic acid, but also hydroxymethylfurfural (HMF) and levoglucosan were found. Wood vinegars obtained at the lower temperature phase (<240 °C) are promising, for example, to be used as biodegradable pesticides to replace synthetic ones. The condensates obtained at the higher temperature phase may have potential in wood protection or as a binder in pelletisation of torrefied product. A possible application of the latter could be the partial replacement of phenol-formaldehyde resins in plywood production.

6 Fuel specification and issues for trade

When trading torrefied biomass, it is important that the fuel specifications are properly defined, and that measurements of key fuel characteristics are undisputed. The ISO 17225-8 standard which is currently being developed is expected to improve the definition of the defined quality of traded torrefied biomass. Further, the existing measurement standards that are in place for determining these key specifications for solid biomass, need to be verified for torrefied biomass as well.

6.1 Suitability of existing analytical methods

A round robin test was carried out within SECTOR amongst 43 laboratories from 17 countries to validate if the existing analytical methods for determination of key parameters of biomass fuels as used for the existing EN 14961 standard “Solid biofuels — Fuel specifications and classes — Part 1: General requirements” can also be used for torrefied biomass [26].

In general, the existing analytical methods can be used for torrefied fuels. For some of the standardised solid biofuels test methods e.g. ash content analysis (EN 14775), moisture content analysis (EN 14774-1 and 2), Chlorine and Sulphur content analysis (EN 15289), CHN analysis (EN 15104), the round robin test revealed that the performance data for torrefied material obtained are comparable to the performance data for solid biofuels given in the standards (based on the results from the round robin in the BioNorm II project). These results are satisfactory, because these methods are applicable without any adoption for torrefied material.

Some remarks can be made for the suitability of existing analysis methods for net calorific value, ash melting analysis and minor elements, often due to obvious reasons such as too low concentrations or inhomogeneity of the samples. Further work is needed to verify this.

6.2 Development of an ISO standard

A common European and international standard is currently being developed for “Graded thermally treated and densified biomass fuels”, which will be published in Europe as EN ISO 17225-8. In this regard, thermal treatment includes processes such as torrefaction, steam treatment (explosion pulping), hydrothermal carbonization and charring, all of which represent different exposure to heat, oxygen, steam and water.

To support this process, a proposal for a new EN ISO product standard is drafted in the SECTOR project [27]. It is currently expected that the preparation of this standard will be finalised by Dec 2015.

When the standard is finally available, it is expected that product quality can be better defined, which is essential for market development and trade.

6.3 Development of an MSDS sheet

Material Safety Data Sheets (MSDS) are required for many chemicals (including torrefied biomass fuels) in the framework of the European REACH regulation EC No. 1907/2006 (REACH). The availability of an MSDS ensures free trade of certain products between countries and business partners as they describe and quantify the safety issues.

Currently torrefied material does not have a safety classification under International Maritime Organization (IMO) and cannot be transported by ocean vessels without special permission since the product has similarities with charcoal, which is prohibited to be transported in bulk [1].

Within SECTOR a specific MSDS-template was produced for torrefied biomass which has to be modified to the users' product properties [28]. This template is already publicly available and can be filled in for a specific shipment.

7 Effectiveness of CO_2 mitigation

The effectiveness of achieving net CO_2 savings in the full supply chain incl. end use have been explored in the SECTOR project for various end uses [29]. This evaluation was done for four representative supply chains, in which (torrefied) biomass was supplied from countries with different socio-environmental and climatic conditions to the Netherlands. The results were compared to conventional white wood pellets.

7.1 Indirect CO_2 emissions caused

The results for the indirect CO_2 emissions related to various supply chains are summarized in Table 7.1. In general, the results for the supply of torrefied pellets to the Netherlands range between 11.5 g CO_2-eq./MJ pellets (Spain) and 18.8 g CO_2-eq./MJ pellets (Canada) depending on various factors such as the local conditions, transportation distances etc.. The results for the supply of conventional pellets range between 10.2 g CO_2-eq./MJ pellets (Spain) and 17.5 g CO_2-eq./MJ pellets (Canada).

Table 7.1 GHG-emissions of conventional and torrefied pellets from different supply chains per MJ of product (g CO_2-eq./MJ pellets)

Country of origin	USA		Canada		Tanzania		Spain	
Type of pellets	**Conven-tional**	**torrefied**	**Conven-tional**	**torrefied**	**Conven-tional**	**torrefied**	**Conven-tional**	**torrefied**
Cultivation	1.8	1.6	1.8	1.6	1.8	1.6	1.8	1.6
Transport to pellet plant	1.6	1.4	1.6	1.4	1.6	1.4	1.6	1.4
Pelletizing/Torrefaction	4.2	7.5	4.2	7.5	1.8	3.1	3.1	5.5
Transport to Europe	5.0	4.2	9.9	8.3	8.1	6.8	3.7	3.1
Total	**12.5**	**14.6**	**17.5**	**18.8**	**13.3**	**12.9**	**10.2**	**11.5**

The growth, harvesting and transportation of wood material lead to similar GHG emissions for all cases. Due to the higher energy density, the transportation of the torrefied pellets leads to lower GHG-emissions compared to the transportation of conventional pellets.

Yet, the relatively high energy demand for the pelletisation of the torrefied biomass outbalanced this advantage for torrefied pellets in case it is produced in a country with a relatively high GHG emission factor (Canada, US and to a lesser degree Spain). An exception is the supply of (torrefied) pellets from Tanzania, where relatively low GHG emissions from electricity production apply. In such cases, torrefaction leads to lower indirect GHG emissions than conventional pellets.

7.2 Avoided CO_2 emissions

To counterbalance the indirect GHG-emissions from the supply of (torrefied) pellets from different origins, the avoided direct and indirect GHG emissions from the replacement of fossil fuels have been investigated for various end use markets in SECTOR deliverable D9.6 [30]. The results are summarized in Table 7.2 for use of the torrefied biomass from Table 7.1.

Table 7.2 GHG emissions of the conventional fuel, and from the use of conventional and torrefied pellets from different supply chains per MJ of product (derived from [30])

Application	Unit	Conventional fuel	Conventional pellets	Torrefied biomass
Cofiring with hard coal	kg CO_2 eq/MJ_e	0.30	0.06-0.08 72-80% reduction	0.03-0.06 80-87% reduction
Replacing natural gas in 15 kW boiler	kg CO_2 eq/MJ_{th}	0.73	0.22-0.31 58-70% reduction	0.15-0.21 71-79% reduction
Production and combustion of methanol	kg CO_2 eq/MJ_e	2.15	1.25-2.01 5-42% reduction	0.95-1.55 28-55% reduction

The results show a GHG mitigation potential of the pathways investigated for co-firing between 72% (conventional pellets from short rotation coppice produced in the US) and 87% (torrefied pellets produced from straw in Spain). Due to the slightly lower upstream emissions, the results for the application of torrefied pellets show slightly lower overall GHG emissions compared to the heat production based on conventional pellets.

Another possible application where torrefied biomass could find a direct outlet is for small scale natural gas fired boilers. The results in Table 7.2 indicate that this yields a GHG mitigation potential between 58% (conventional pellets from short rotation coppice produced in the US) and 79% (torrefied pellets produced from straw in Spain). This is lower than the use of the pellets in co-firing applications due to the lower CO_2 emission factor of natural gas. In case a carbon intensive fuel is replaced (e.g. coal briquettes), the figures favour small scale heat over biomass co-firing.

In addition to the generation of heat and power, the production of biomethanol (MeOH) as one interesting chemical that could be produced from (torrefied) woody biomass was also investigated. The GHG mitigation potential varied between 5% for the production of MeOH from conventional pellets made from short rotation coppice wood in the USA, to 55% for the production and use from MeOH based on torrefied pellets made from straw in Spain.

8 Economic aspects

8.1 Production costs of torrefied pellets

The production costs of biomass torrefaction pellets has been evaluated in SECTOR deliverable 3.2 [31] for various scales and degrees of process integration. A base case was assumed of a medium scale stand-alone torrefaction plant in Europe of 72 800 t/a, with production costs of 40 €/MWh. A significant fraction of this is fuel cost, at 18 - 25 €/MWh. A larger production plant located overseas (500 kt/y) and fed with cheaper biomass feedstock (15 €/MWh) results in significantly lower production costs (29 €/MWh).

Integration into an existing CHP plant does not reduce the costs substantially. Integrating the production of torrefied pellets in other operations however (sawmills, pulp and paper mills) generally results in significantly lower production costs. The assessment indicated a cost reduction of 5 - 24% compared to the stand-alone base case EU plant. This is largely due to the larger production capacities possible, and the lower feedstock costs (e.g. excess forest residue).

8.2 Costs of delivery and competition with wood pellets

The economic benefits of the use of the product against wood pellets has been evaluated in SECTOR deliverable 9.5 [32]. The impact of various influencing factors has been evaluated, e.g. production location (EU or Canada/US), resource supply distance, torrefaction plant size, product distribution distance in Europe and scale of the end user. With these influencing factors, the costs of delivery vary between 36 and 63 Euro per MWh, with comparable supply cost figures of torrefied and white pellets for the large set of permutations simulated.

The study confirms that a larger torrefaction plant size and longer transportation distances benefit torrefaction pellets over white wood pellets. For shorter distances and small scale pellet production, conventional white pellets seem to be preferable. The production costs of torrefied pellets also depend significantly on the bulk density and consequently cost of supply of the used feedstock to the torrefaction facility.

As the European demand for pellets increases, the production and use of torrefaction can become more competitive with wood pellets. This is mainly due to fact that the local resource then needs to be supplemented with additional material that comes from overseas, and torrefaction then reduces the costs of delivery.

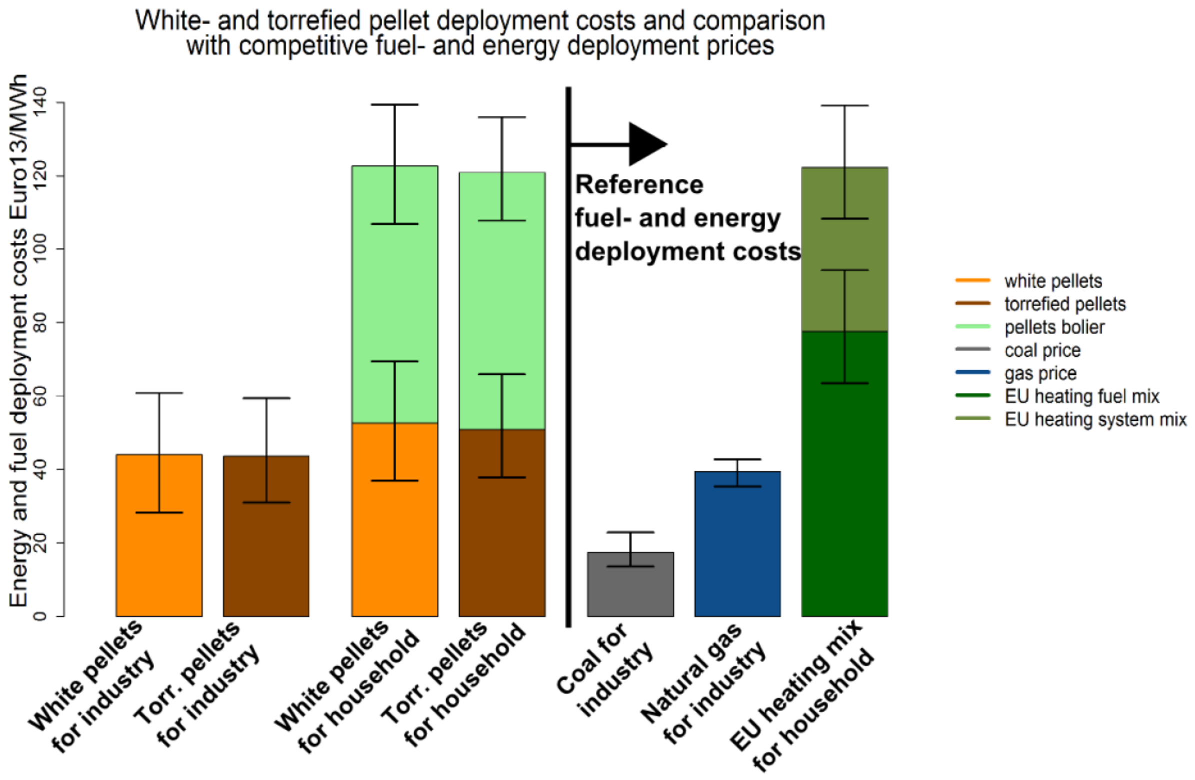

Figure 8.1 **Medians and 2nd (lower part of error bars) and 3rd (upper part of error bars) quartile of white pellets (WP) and torrefied pellets (TP) for large scale and household application. Deployment costs for pellets are directly compared with the industry prices for coal (grey) and natural gas (dark blue). For household pellets a pellet stove (levelled costs in light green) is considered to compare the costs of heat deployment with an averaged heating fuel and system mix for the European Union. [32]**

8.3 Implications for co-firing

The above graph shows that although the fuel cost of torrefied pellets for co-firing is significantly higher than coal, it is about the same as wood pellets (although being a premium fuel). At the power plant, the use of torrefied biomass pellets as compared to wood pellets can lead to cost savings, as was assessed in SECTOR deliverable D3.7 [33]. This deliverable concluded that co-firing of torrefied pellets becomes interesting at levels where mixing of coal and biomass before milling is no longer possible, i.e. at levels >10% co-firing. In those situations the co-firing of torrefied pellets results in lower investment costs and (non-fuel) operating costs compared to white wood pellets. These lower costs can be used to partly compensate for the higher costs of torrefied pellets. An estimation of a price increase for torrefied pellets of 0.9€/GJ (at co-firing shares below 10%) and 1.6€/GJ (at 30% co-firing) compared to white wood pellet was calculated. This would imply that typically, torrefied wood pellets would be preferred over white wood pellets in case of higher percentages of co-firing.

Further it is important to realize that there is often a window of opportunity for harnessing these cost benefits, i.e. there is only a real benefit if the associated investments for modifying a plant to enable the use of wood pellets can be avoided.

8.4 Small scale use

The economic perspective of small scale utilization of torrefied pellets is similar to wood pellets, as the cost of supply and the cost of equipment are almost the same. In both cases, fuel costs are typically lower than the typical EU fuel mix, while the equipment (a pellet boiler) is more expensive than a gas or oil fired boiler. The bottom line is that both conventional wood pellets and torrefied pellets can be made attractive if local (financial) conditions are attractive, i.e. short distances to a pellet producer, high taxes on fossil fuels, investments grants etc.

As for pellets used for co-firing, cost benefits occur for torrefied wood pellets if material is transported over long distances (from the harbour to the final customer), and if the fuel is produced in large quantities.

8.5 Implications for other industrial sectors

The costs of delivery for larger industry sectors can be in the same range as for coal fired power plants. As Figure 8.1 illustrates, the cost of delivery are typically higher than natural gas or coal, therefore financial incentives need to be in place to enable economic feasibility.

9 Strategy for surmounting market introduction barriers

Torrefaction technologies are currently on the edge of commercial availability, with a handful of torrefaction technology companies able to provide commercial offers for realization of a full scale commercial plant [10]. SECTOR has made a great scientific contribution to further improvement of torrefaction technologies, which is illustrated by the large interest from the torrefaction and energy industry globally.

Apart from the technical challenges that were addressed in SECTOR, there are also various commercial challenges that have made it difficult to introduce torrefaction technologies rapidly into the global market. These have resulted in delays in market introduction, and even bankruptcy of a number of torrefaction technology developers. This chapter provides insight into the growing pains of the industry, and the roles that various stakeholders in the supply chain should take in order to make the whole supply chain work.

9.1 The low CO_2 price is a problem for replacing coal

In terms of volume, the largest potential for application of torrefied biomass is in replacing coal. In EU 28 alone, 285 Mt of hard coal and 421 Mt of lignite were consumed in 2014 [34]. If only 10% would be substituted, this would imply that approx. 70 Mt/year of torrefied biomass could be used in the 100 European coal fired power plants. To put this figure into perspective: the current global production of pellets is only about 25 million tons/year.

Price parity with coal is however essential to enable commercial market introduction of torrefied biomass for co-firing. The relatively low CO_2 price is however a major hurdle for the business case, as the CO_2 penalty alone is insufficient to switch from coal to torrefied biomass. Although the EU tries to increase the market price of CO_2 by “backloading” EU emission allowances for CO_2, the actual effect is still limited for the time being. For this reason only in countries with additional co-firing support schemes (e.g. UK, Netherlands, Belgium), co-firing or 100% conversion could still grow significantly in the next couple of years.

It is important that CO_2 emission allowances are tightened in order to increase CO_2 prices, and that additional support schemes are put into place by individual EU member countries to facilitate co-firing of (torrefied) biomass.

9.2 Lock in due to investments already made

In case coal based power producers have already made investments to enable large scale use of white wood pellets, it is too late to benefit from the potential cost savings of torrefied pellets as compared to wood pellets that have about the same cost of delivery per GJ.

For countries where interest in biomass co-firing has only recently started (e.g. in Asia, South Africa), torrefied biomass could provide an option to leapfrog technology without the need to invest in significant modifications of existing plants. The same is true for power plants in Europe that consider co-firing, but have not yet invested.

9.3 Diversification of end user markets to avoid growing pains

Securing the financing for investment is yet another hurdle. Compared to the total fuel requirements of a pulverised coal fired power plant, the volume of torrefied fuels that can be offered from any of the existing torrefaction companies to a single power plant is relatively small, even if compared to the total production volume of all torrefaction facilities together. This makes end users hesitant to absorb torrefied fuels in their fuel portfolio and sign long term offtake contracts. In return, investors find it difficult to obtain finances to establish a torrefaction plant.

Diversification of the end user market is required to get around this problem. Provisions for a local heat market or a relatively small market for use in higher value applications (e.g. chemicals or transportation fuels after gasification) could help in this way to get rid of the chicken and egg problem. In this case both the torrefaction facility and the end user need to be set up at the same time, to enable an optimal business case.

Conducive policies are required to support the application of torrefied biomass for co-firing, the heat sector and in industry, keeping in mind the differentiation in qualities and prices required. Suitable product standards are essential to facilitate trade as well as the production of suitable end use appliances that are optimised for torrefied biomass.

9.4 Development of torrefaction business areas

The companies involved in the supply chain for torrefied biomass can be categorised in three business areas, as illustrated below.

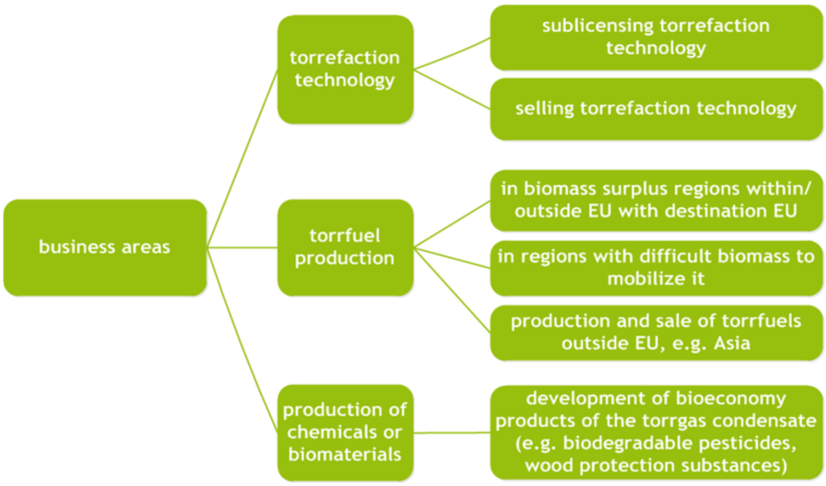

Figure 9.1 Torrefaction business areas

9.4.1 Technology development

The first business area concerns the development and commercialisation of torrefaction technologies. These companies are not necessarily involved in the commercial production of torrefied biomass, but might also sell or sublicense their technology to producers of torrefied fuels world-wide. Around 2005 there was great enthusiasm and optimism about the pace of development of torrefaction technologies, both with the technology developers and other stakeholders. However, it takes several years to develop a new thermal processing technology from technology concept to full scale production and to have a substantial impact on the world market. As long term financial commitment for R&D were lacking in many cases, various technology developers have discontinued their efforts to commercialise a technology. Nevertheless, several companies now have demonstrated a working technology, and now also offer turnkey torrefaction plants at full scale. In order for these companies to develop their technology, risk mitigation through R&D support programs is essential. A good example is the SECTOR programme itself, in which various technology developers were involved.

9.4.2 Production of torrefied biomass fuels

The second area concerns the actual production of torrefied biomass fuels, with sales to the various end users, varying from small and industrial scale users to chemical industry and co-firing/co-gasification. A strategic consideration here is the optimal size and geographical location of a production facility in between resource and end user markets.

- If production and end-use are both in Europe, this can strengthen the internal energy security and present business opportunities for remote regions in Europe with biomass surplus.
- The beneficial long distance transport of torrefied fuels allow the import into Europe from biomass surplus regions worldwide, potentially reducing CO_2 emissions and increasing energy security by diversifying the energy carrier base. As soon as torrefaction of technically more demanding feedstock is available, torrefaction can aid with the energetic and material use of these.
- The production and utilisation of torrefied fuels may also occur in markets outside of Europe, where biomass resources might also originate from other continents. This does not directly improve the energy sector in Europe but it may help technology providers to establish or extend their business, which in turn is beneficial for the torrefaction sector within Europe.

9.4.3 Valorising by-products

The availability of a new biomass conversion technology may open new business opportunities for the by-products. Research in SECTOR has shown the potential of torgas condensate to be processed into various biobased materials, such as biodegradable pesticides and phenols for wood protection substances (see chapter 5.4). These options are not yet market ready but might add to profitable business in the future for torrefaction plant operators and also support the establishment of more sustainable economies. Additional research is wanted to explore these business opportunities.

10 Conclusions

The maturation and market introduction of torrefaction technologies did not meet the exalted expectations raised 5 years ago, when it was anticipated that a significant fraction of the biomass pellets supplied today could be replaced by torrefied pellets within a short time. It has been hard to fully prove the claims made earlier on product characteristics, and several companies have gone bankrupt due to extended R&D efforts needed to meet market requirements or due to a lack of buyers.

Nevertheless, it is clear that the companies involved in SECTOR have significantly improved their ability to produce high quality products, with pellets of comparable durability to conventional wood pellets. The torrefied pellets exhibit comparable supply costs. Moreover, for the end user they provide superior handling and combustion characteristics. For woody biomass, some of the technologies are market ready or close to it. The torrefaction of non-woody biomass still needs several years of development for commercialization. If successful, it offers the possibility to turn more challenging (local) feedstock into a high quality commodity fuel.

Large amounts of biomass resources suitable for torrefaction are available in Europe, varying from forestry biomass residues, agricultural biomass, and industrial woody residues. Within SECTOR, about 77 tons of torrefied biomass was produced from various biomass resources. Most of this torrefied material was used to produce pellets (about 41 tons). From this amount, about 17 tons of pellets were actually used in the project for combustion tests, milling tests, stockpile tests, hydrophobicity tests, etc. In addition, some 2 tons of non-pelletized torrefied material were delivered for densification lab tests, logistic tests, grinding tests and fuel characterization.

During torrefaction, drying and devolatilisation results in a significant mass loss, while retaining 70 - 98% of the energy (depending on reactor technology, heat integration and biomass type). As the volume of the biomass particles remains almost untouched, it makes sense to densify the product after torrefaction to pellets. This is a challenging process as part of the lignin has been degraded during torrefaction, however recently it has been demonstrated that pellet durability of approx. 97% is still feasible, e.g. by adding some water before pelletisation. This does not imply that there are no dusting problems during handling. In fact, explosibility tests carried out in SECTOR confirmed a relatively low minimum ignition energy of 3 - 10 mJ. In order to avoid dust clouds, mist spraying may be needed in some cases.

Although individual biomass particles that are torrefied become hydrophobic, a densified particle may still be prone to water take up through surface cracks. Weathering tests in SECTOR showed that the upper 20 cm layer of a fuel pile may therefore deteriorate through water take up, in some cases followed by e.g. freeze-thaw cycles. Although torrefied biomass can in principle be transported in open air vessels or containers, long term storage as currently done for coal seems inappropriate. Self-heating appears no real issue.

Grindability tests carried out in SECTOR confirmed that the torrefaction process results in much better grindability than the original biomass, however not better than difficult to grind coals. Co-grinding with coal is considered a feasible option.

The high reactivity of the fuel is also observed during the combustion process itself, as both pilot plant trials and CFD calculations confirmed an early start of the combustion process. This likely requires adaptation of pulverized coal burners or (in case of small scale boilers) grate design. The combustion process on the grate also takes longer than coal or non-torrefied biomass, therefore radiation patterns extend over larger volumes, though this still appears manageable through adaptation of the design. Compared to raw biomass, the emissions of SO_2 and NO_x generally go down.

Torrefied biomass pellets offer similar commercial and environmental impacts as conventional biomass pellets for the cases examined. The growth, harvesting and transportation of wood material lead to similar costs and GHG emissions for both cases. The torrefaction step itself leads to additional costs. Due to the higher energy density however, the transportation of the torrefied pellets causes lower costs and lower GHG emissions compared to the transportation of conventional pellets. In general, torrefaction can therefore be preferable in case of remote pockets of inexpensive biomass resources.

Biomass co-firing is considered one of the key outlets for torrefaction, given the potential volumes requested and the potential cost savings over conventional pellets. With the current prices for coal and CO_2 however, the price of delivery is still too high to enable commercial market introduction for co-firing without substantial government support.

The heat market may be instrumental in supporting commercial application of torrefaction technologies. This requires suitable product standards to facilitate trade, as well as the production of suitable end use appliances that are optimised for torrefied biomass.

In a nutshell, torrefaction technology has matured significantly in the last years up to the point of market readiness. End user requirements can be met. But considering the current market situation, producers of torrefied pellets need to adapt their market strategies while also end users (i.e. small scale boilers) and the market framework need to adapt in order to reap the full effect of torrefied material on environmental protection and energy market security.

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