Biomass and Bioenergy 89 (2016) 184–200

Contents lists available at ScienceDirect

Biomass and Bioenergy

journal homepage: http://www.elsevier.com/locate/biombioe

Research paper

Moving torrefaction towards market introduction – Technical improvements and economic-environmental assessment along the overall torrefaction supply chain through the SECTOR project

Daniela Thrän [a, b, *], Janet Witt [a], Kay Schaubach [a], Jaap Kiel [c], Michiel Carbo [c], Jörg Maier [d], Collins Ndibe [d], Jaap Koppejan [e], Eija Alakangas [f], Stefan Majer [a], Fabian Schipfer [g]

[a] DBFZ Deutsches Biomasseforschungszentrum gGmbH, Torgauer Straße 116, 04347 Leipzig, Germany
[b] UFZ Helmholtz–Zentrum für Umweltforschung GmbH, Permoserstraße 15, 04318 Leipzig, Germany
[c] ECN Energy Research Centre of the Netherlands, 1755 ZG Petten, The Netherlands
[d] Universität Stuttgart, Pfaffenwaldring 23, 70569 Stuttgart, Germany
[e] Procede Biomass BV, Vlierstraat 111, 7544GG Enschede, The Netherlands
[f] VTT Technical Research Centre of Finland Ltd., Koivurannantie 1, FI-40400 Jyväskylä, Finland
[g] Technische Universität Wien, Gusshausstrasse 25/370-3, A-1040 Wien, Austria

ARTICLE INFO

Article history:
Received 18 September 2015
Received in revised form
2 March 2016
Accepted 3 March 2016
Available online 30 March 2016

Keywords:
Torrefaction
Solid biofuel
Sustainability
Standardization
Densification
Market implementation

ABSTRACT

The large-scale implementation of bioenergy demands solid biofuels which can be transported, stored and used efficiently. Torrefaction as a form of pyrolysis converts biomass into biofuels with according improved properties such as energy density, grindability and hydrophobicity. Several initiatives advanced this development. The first pilot-scale and demonstration plants displayed the maturity and potential of the technology.

The European research project SECTOR intended to shorten the time-to-market. Within the project 158 Mg of biomass were torrefied through different technologies (rotary drum, toroidal reactor, moving bed). Their production led to process optimization of combined torrefaction-densification steps for various feedstocks through analysing changes in structure and composition. The torrefied pellets and briquettes were subjected to logistic tests (handling and storage) as well as to tests in small- and large-scale end-uses. This led to further improvement of the torrefied product meeting logistics/end-use requirements, e.g. durability, grindability, hydrophobicity, biodegradation and energy density. Durability exceeds now 95%.

With these test results also international standards of advanced solid biofuels were initiated (ISO standards) as a prerequisite for global trade of torrefied material. Accompanying economic and environmental assessment identified a broad range of scenarios in which torrefied biomass perform better in these areas than traditional solid biofuels (e.g. white pellets), depending e.g. on feedstock, plant size, transport distances, integration of torrefaction in existing industries and end use. The implementation of industrial plants is the next step for the technology development. Different end user markets within and outside Europe can open opportunities here.

1. Introduction

This paper is a condensed summary of final results from the project SECTOR (Production of Solid Sustainable Energy Carriers from Biomass by Means of Torrefaction), which was funded by the European Union's Seventh Programme for research, technological development and demonstration (GA no. 282826). The project aimed at shortening the time to market of torrefaction technology to provide high density bioenergy carriers, spanning the complete value chain, which it achieved successfully.

Large scale implementation of bioenergy is expected to increase [1–9], and high energy density commodities form the key to

* Corresponding author. DBFZ Deutsches Biomasseforschungszentrum gGmbH, Torgauer Straße 116, 04347 Leipzig, Germany.
E-mail addresses: daniela.thraen@dbfz.de (D. Thrän), kiel@ecn.nl (J. Kiel), Joerg.Maier@ifk.uni-stuttgart.de (J. Maier), JaapKoppejan@procede.nl (J. Koppejan), Eija.Alakangas@vtt.fi (E. Alakangas), schipfer@eeg.tuwien.ac.at (F. Schipfer).

http://dx.doi.org/10.1016/j.biombioe.2016.03.004
0961-9534/

establish this. In Europe, adapted biomass fuels for co-firing in coal power stations could significantly support the fulfilment of the political targets – the provision of 20% of the primary energy consumption through renewable fuels until 2020, and 27% until 2030 – with relatively minor technical adaptations and at acceptable costs [2,10].

This requires bioenergy carriers that behave similarly to coal during logistics, milling, combustion and gasification in order to use the existing infrastructure. Crucial properties are the net calorific value, required energy for milling, particle size distribution, mill capacity and pneumatic feeding. Another short term application is the use of bioenergy carriers in small and medium scale boilers. Here, an optimal alignment between boilers and bioenergy carriers regarding heating value, volatile matter and moisture, bulk density and fuel pellet dimensions has to be established [3,4]. In the long term, the use of bioenergy carriers to produce bio-chemicals and bio-fuels via gasification routes is expected.

One approach to provide these bioenergy carriers is the torrefaction of solid biomass, such as wood and herbaceous material [4,11]. During torrefaction, as a form of mild pyrolysis, water and part of the volatile matter are removed which results in a brittle and to a certain degree hydrophobic intermediate. By combining torrefaction with pelletization or briquetting, solid biomass materials can be converted into a high-energy-density commodity energy carrier with additional advantageous fuel properties compared with white wood pellets, such as improved grindability, higher water resistance and good biological stability. These torrefied biomass pellets can be provided in a constant, end-user specific quality [1,5]. This indicates that logistics, handling and conversion of torrefied biomass pellets may occur in a fashion that is more comparable to fossil solid fuels such as coal. Additional value could be created by reclaiming the volatile matter that is released during torrefaction, as wood vinegar or resin substitute [6,12].

Technical development of this pre-treatment of solid biofuels has been intensified during the last decade [7,8,13,14]. Technology development and implementation is currently pushed with different research and demonstration projects mostly in the European Union and North America (Fig. 1).

The main issues in torrefaction development at the start of the project (2012) have been process control, heat integration, process upscaling, ensuring product quality that allowed large scale handling, outdoor storage and end use as well as flexible input materials [15]. Torrefaction of non-woody biomass is an additional relevant issue as large biomass potentials especially from residues have been identified in several assessments [16,17]. Market implementation and integration are further important subjects for research.

The SECTOR project included these as major issues into its work program. The overall objective was to produce torrefied biomass pellets with properties similar to those of coal to enable its substitution without major adaptations of existing conversion installations. The project achieved continuous production ensuring the required properties and proved the applicability of torrefied material in major end uses.

The project included different torrefaction technologies, densification methods, logistic and storage testing, end use application in small-, medium- and large-scale combustion and gasification units. Furthermore assessments of the overall value chain were conducted and several standards of fuel characterisation were prepared. 21 partners from 9 countries contributed to this project. More than 150 Mg of torrefied biomass have been produced from 12 different raw materials. These have been tested in about 30 different setups with respect to behaviour during logistics and end use.

Two major framework conditions were set by analysing the global and European biomass potential (most interesting in EU: wood/wood residues (3.7 EJ a^{-1}) and straw (0.56–0.982 EJ a^{-1}) and by identifying the end user needs (application specific values for net calorific value, ash mass fraction, particle size distribution, moisture and price) [18]. The optimization work within SECTOR is based on these findings.

This paper will summarise the results in the different research areas of the SECTOR project and conclude the market readiness of torrefied solid biofuels. It will commence with the description of the results from torrefaction and densification test performed in the different facilities (chapter 2), followed by the results of the logistic, storage (chapter 3) and end use application tests (chapter 4). Based on these results we provide an assessment of the fuel quality, the environmental and economic aspects of torrefied biomass in comparison to other solid fuels (untreated woody biofuels and coal) and discuss proposals for appropriate fuel standards and declarations, including sustainability requirements (chapter 5). Finally, we discuss the market opportunities with regard to promising application fields (chapter 6) and conclude with suggested market implementation strategies and the remaining research demand (chapter 7).

2. Torrefaction and densification

The combination of biomass torrefaction and densification potentially results in superior properties for the use of biomass in many major end-use applications such as co-firing and co-gasification in coal fired power plants. Torrefaction and densification of biomass result in solid bioenergy carriers that display a high extent of homogeneity in comparison with the corresponding untreated feedstock. This offers several advantages, amongst others: it can be traded as a commodity, storage and handling does not need to be dedicated to a specific feedstock, and milling and feeding occurs in a steady manner. The combined optimization of torrefaction and densification is necessary in pursuit of high-quality solid bioenergy carriers.

During torrefaction, biomass is heated to temperatures between 250 and 350 °C in an oxygen depleted environment. In this temperature range hemicellulose is the most reactive component present in lignocellulosic biomass followed by lignin, while cellulose is the most thermally stable [19]. Due to the fact that the hemicellulose strength is severely weakened during torrefaction, the torrefied biomass becomes brittle, which eases comminution and subsequent densification into sustainable solid bioenergy carriers, such as pellets and briquettes. Upon moderate torrefaction temperatures lignin is typically only slightly affected and can serve as binder during the densification process. Therefore, different performance parameters need to be considered that affect both the pretreatment process (e.g. net energy efficiency and the resulting production costs) as well as the product quality. The most important product characteristics are the energy density (in order to avoid de-rating of the power plants), grindability (to use the existing mills also used for coal), mechanical durability (to prevent loss of mass during transport and avoid dust formation), hydrophobicity and biological stability (required for storage) [4,9,11,20]. Therefore, also storage and end use application of the torrefied biomass have been tested (see chapter 3 and 4).

Within SECTOR, about 12 different biomass feedstock have been torrefied (e.g. pine, spruce, poplar, forest residues, bamboo, straw, Paulownia), conditioned and densified at pilot- or demonstration scale. The composition of a large number of torrefied materials that are described in this paper can be found in the online Phyllis2 database [21]. This has resulted in further optimization of the torrefaction technologies under development by: 1. broadening the feedstock range, 2. allowing the production of solid sustainable

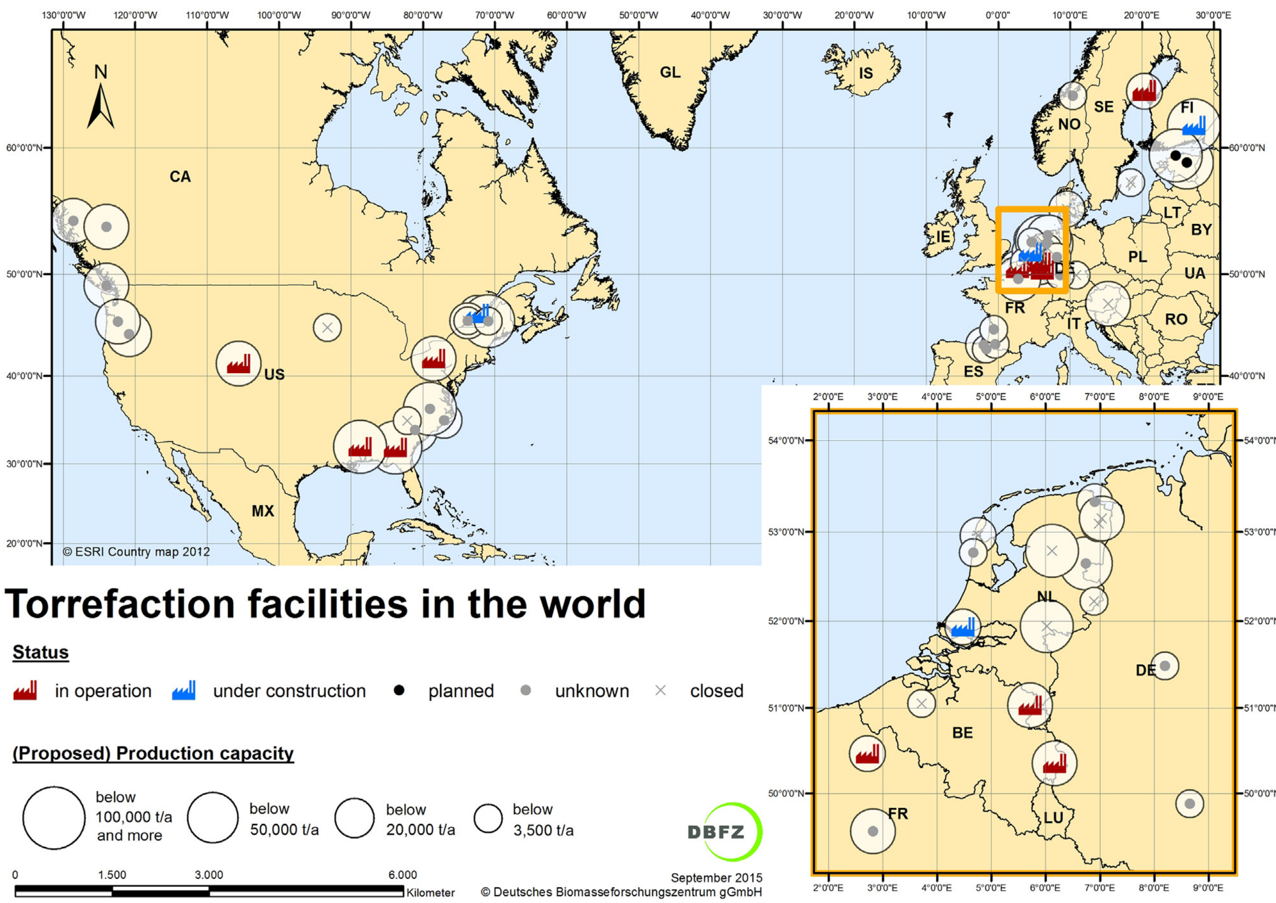

Fig. 1. Worldwide activities of biomass torrefaction facilities with different development status (the status "unknown" describes initiatives which have been active in the last years but whose current status could not be verified; the lacking information policy indicates difficulties in operation, their dominance shows the recession in current torrefaction developments).

energy carriers with properties that meet end use requirements for transport, handling and conversion, and 3. the exchange of best practices between different technology developers. Lab-, pilot- and demonstration-scale torrefaction and densification facilities were used to demonstrate that the optimization of the product quality demands an integrated approach between torrefaction and densification. This approach has led to the development of dedicated recipes for different feedstock, with this optimization of the product quality being directed through elaborate mapping of the end use requirements for torrefied bioenergy carriers. This paper will mainly focus on the production, logistics and end use of torrefied wood pellets.

2.1. Torrefaction

The tests in SECTOR covered different reactor technologies, which are either under development or commercially available for the torrefaction of biomass. These can be roughly divided in directly heated technologies where torrefaction off-gases are directly contacted to heat up biomass to the desired torrefaction temperature, as well as indirectly heated technologies where an intermediate medium or a physical separation is deployed to transfer heat from combustion gases to the biomass. An overview of developers, technologies and associated reactor designs is provided in Table 1. Within the SECTOR project ECN, CENER, Umeå University and Topell Energy collaborated to further optimize their torrefaction technologies.

Prior to the torrefaction process most of the moisture is removed through drying. During torrefaction, part of the volatile matter is converted to gas. For woody biomass this typically results in weight losses up to 30%, with approximately 10% of the initial calorific value released through off-gases that also contain volatile condensable components [23]. In most torrefaction technologies under development these off-gases are combusted to provide the energy required for drying as well as pre-heating of dried biomass to torrefaction set point temperatures. The differences in net thermal efficiency between different torrefaction technologies under development in the SECTOR project were small when the same feedstock was used. This is attributable to the heat integration; low-temperature heat is used for drying and flue gas losses are minimized [24].

The product quality of the material is typically described by the degree of torrefaction, which is defined as the anhydrous weight loss observed during the torrefaction process. The torrefaction temperature and residence time determine the degree of torrefaction [25]. An increase of temperature and/or residence time will result in an increase of the degree of torrefaction. It should be noted that such an increase will also lead to increased mass losses through biomass devolatilisation during torrefaction, and as such to higher production costs associated with the increased feedstock demand to maintain the same production capacity. Increased degrees of torrefaction tend to lead to higher net calorific values, although the increased conversion of lignin may require the use of a binder during downstream densification. Herbaceous streams

Table 1
Selected existing torrefaction reactor technologies and their developers (developers involved in the SECTOR project are marked in bold) [22]. Except for the plants of Solvay Biomass Energy and Topell Energy, the plants are pilot and demo scale for R&D activities.

Reactor technology	Technology developers & suppliers	Production capacity (* in planning/commissioning)
Rotary drum	Torr-Coal (NL)	4500 kg h^{-1}
	BioEndev (SE)	0.15 kg h^{-1} and 2100 kg h^{-1}*
	CENER (ES)	100–400 kg h^{-1}
Turbo dryer	Wyssmont (US)	6000 kg h^{-1}
Toroidal fluidised bed reactor	Topell Technology (NL)	8000 kg h^{-1}, currently mothballed
Screw reactor	Solvay Biomass Energy (US) (former New Biomass Energy LLC)	33,300 kg h^{-1}
Moving bed reactor	ECN (NL) Andritz/ECN (DK)	50–100 kg h^{-1}
		1000 kg h^{-1}
	Thermya/Areva (FR)	2500 kg h^{-1}
Fluidised bed reactor	River Basin Energy	1000 kg h^{-1}* (NL) and 6000 kg h^{-1} (US)

generally display increased reactivity compared to woody biomass, therefore relatively lower torrefaction operating temperatures typically are used to prevent excessive mass losses during torrefaction. The increased reactivity of herbaceous biomass in comparison with woody biomass is attributed to the relatively higher volatile matter mass fraction possibly combined with some catalytic activity of the higher inorganic mass fraction.

During most of the pilot-scale torrefaction trials in the SECTOR project, elaborate product and off-gas characterization were conducted. This facilitated the preparation of mass and energy balances for different feedstocks that were subsequently used in the economic and sustainability evaluations; the use of data obtained during large-scale continuous trials provides results that will closely resemble commercial plant operation. Fig. 2 provides an example of a mass and energy balance for the ECN technology based on measurements during pilot-scale trials with pine chips. It should be noted that given the moderate torrefaction temperature of 270 °C, the combustion of a small additional fraction of the feedstock is required to provide the heat for drying and heating the biomass up to the torrefaction set point temperature. The mass yields and ultimate product composition during torrefaction of biomass streams in the pilot facilities are typically homogenous and predictable, with any deviations being compliant with analysis acceptance repeatability criteria [26]. The ash mass fraction usually remains unaffected during torrefaction, and therefore slightly increases as a result of the decreasing volatile matter mass fraction. The mass and energy balance indicates a slight decrease of the ash mass fraction, which is attributed to the uncertainty during sampling and analysis; minor deviations like these are commonly observed at very low ash mass fractions. The electric energy used for milling of the torrefied chips, pelleting and cooling of the pellets has been included in the thermal energy balance, since it is assumed that the electric energy is fully converted to heat through friction. Water is used as lubricant and binder during pelletization, roughly half of it evaporates during pelletization while the other half ends up in the torrefied pine pellets. The equilibrium moisture of torrefied biomass pellets typically ranges between 5 and 10%.

2.2. Densification

Densification experiments have been performed at lab-, pilot- and demonstration-scale at DTI, CENER, ECN, Umeå University and Topell. The main parameter for the densification quality is the mechanical durability of the processed material under specific test conditions in accordance with the existing standard for white wood pellets EN 15210-1:2009 [27]. The durability of torrefied pellets varies with regard to different feedstock and degree of torrefaction.

Torrefied hardwood species such as poplar, beech and willow were relatively easy to pelletize, while torrefied softwood species such as spruce and pine required significant optimization of torrefaction and pelleting parameters to obtain high quality pellets. Herbaceous biomass proved to be the most challenging species to pelletize, although significant improvements were established in time for pelleting of torrefied cereal straw, as can be seen in Table 2. Upon increasing mechanical durability the appearance of the pellets transforms from dull to shiny. For both softwood and herbaceous biomass, the optimized parameters involved the degree of torrefaction, the moisture of feedstock, particle size of feedstock, diameter/length ratio of the die and its rotational speed.

In general, an increased degree of torrefaction results in more difficulties to establish inter-particle bonds that are required to form high-quality pellets. This is attributable to the removal of hydrogen bonding sites, depolymerisation and the destruction of the fibrous structure (less entanglement). The addition of water or steam acts as a plasticizer during pelleting through reduction of the softening temperature of lignin. Furthermore it reduces friction and improves bonding. A smaller particle size distribution of the torrefied feedstock improves the pellet density, with smaller particles occupying the available voids in the bulk. It should be noted that smaller particle size typically requires more energy for grinding, while too small particles sizes do not build up friction in the channels of the die. Pellets with the highest mechanical durability were obtained with die channel diameters of 6 mm, while the highest production capacities were established with die channel diameters of 8 mm. Slight reductions of the die rotational speed will positively affect the mechanical durability. Future improvements should be directed to further reduce the energy consumption of the pellet mills, which is directly proportional to wear and associated maintenance intervals.

3. Logistics of torrefied material

The transport, handling and storage properties of torrefied and densified biomass were assessed through small-scale storage and outdoor stockpile tests with the aim to test the behaviour of torrefied material in real case conditions, e.g. in a real coal handling line. Special focus was dedicated to the hydrophobicity and explosivity as well as the biological degradation of the material during storage and transport. The results of these tests were used to proactively adjust the process conditions and recipes in the torrefaction and densification processes to further optimize the product quality.

3.1. Small-scale storage and handling tests

Numerous small-scale indoor and outdoor storage experiments were conducted within the project, and these mainly serve to mimic the behaviour of torrefied material at the surface of stockpiles. The small-scale outdoor storage experiments largely confirm the findings described in Paragraph 3.2, although covered outdoor

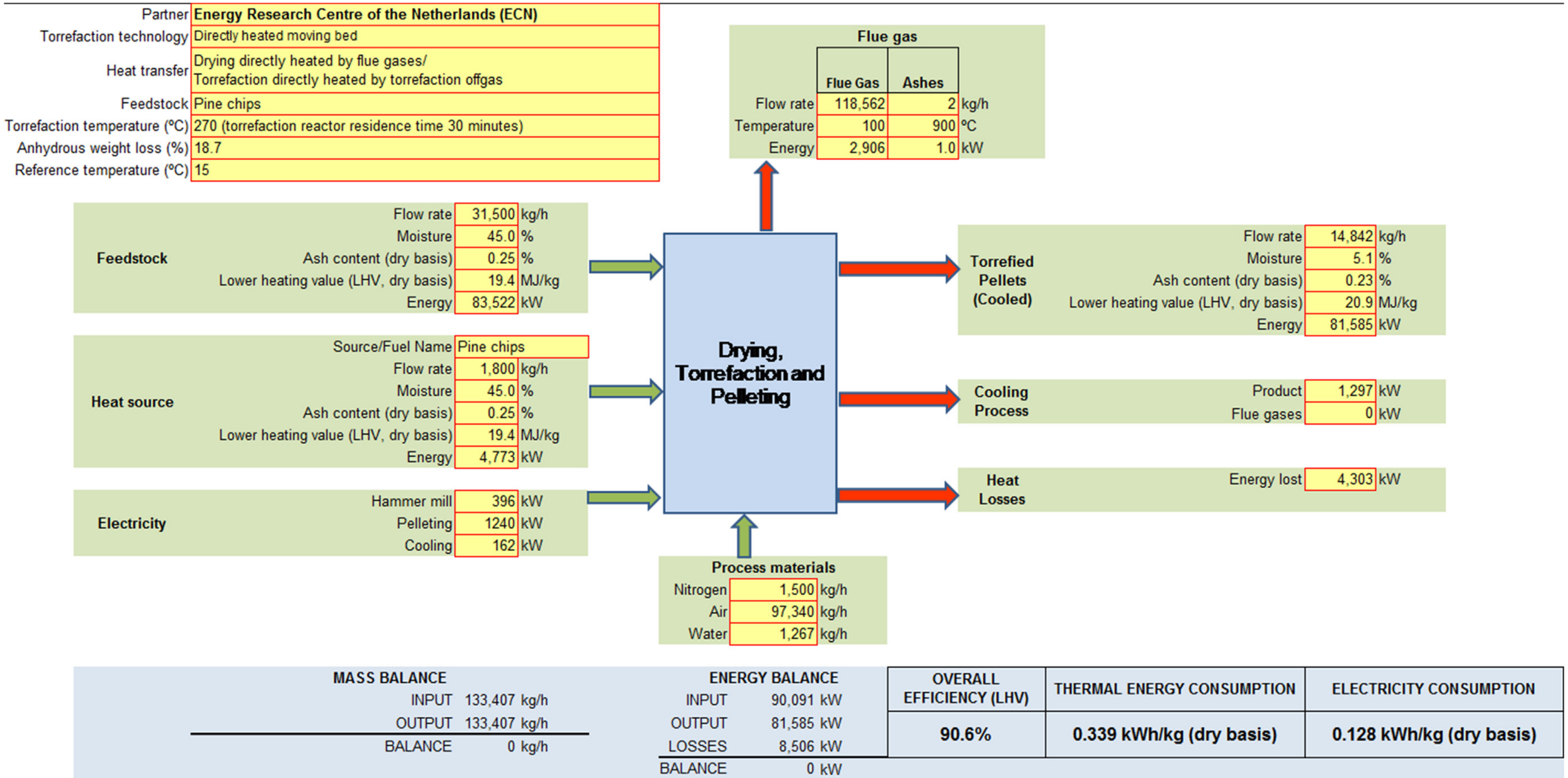

Fig. 2. Mass and energy balance of the ECN moving bed technology for pine chips.

Table 2
Optimization of mechanical durability of torrefied pine and straw pellets at CENER in the ring-die pellet mill.

Date	Durability in %	Pine	Date	Durability in %	Straw
October 2012 Torrefied at 290 °C	88.8		February 2013 Torrefied at 270 °C	84.2	
January 2013 Torrefied at 290 °C	92.3		September 2013 Torrefied at 270 °C	94.3	
June 2013 Torrefied at 290 °C	94.7		October 2013 Torrefied at 270 °C	96.6	
November 2013 Torrefied at 290 °C	95.7		November 2013 Torrefied at 270 °C	97.6	

storage did not result in any degradation of the torrefied wood pellets unlike the observations for white wood pellets. Fig. 3 displays the results of the dry matter losses that were obtained during storage trials of pellet samples in the climate chamber at ECN. The samples were stored for 20 days at a temperature of 22 °C and a relative humidity of 95%, resembling a typical humid summer morning in the Southeast of the USA. The results imply that white wood pellets are much more prone to biological degradation while torrefied biomass pellets are much more resistant to biological activity, thereby reducing the risk of self-heating.

Torrefied biomass pellets and the corresponding raw biomass chips were pulverized using a cutter mill, and the obtained dust samples were used to determine the Minimum Ignition Energy (MIE) in accordance with the standard EN13821:2002. These tests demonstrated that pulverized torrefied spruce pellets and raw spruce chips were the most sensitive to ignite for the dust fraction below 63 μm, as displayed in Fig. 4. This figure also shows that the MIE of torrefied wood pellets appears to be related to the material that is used as feedstock, and that torrefaction does not increase the explosivity of biomass. Consequently, existing explosion mitigation systems could be used to mitigate any risks during milling of torrefied biomass pellets.

3.2. Outdoor stockpile tests

Three outdoor stockpile tests were conducted within the SECTOR project, during these tests torrefied pellets displayed increased water resistance compared to white wood pellets. White wood pellets are well-known to swell and disintegrate upon the slightest exposure to rain, to the extent that discharging of transport ships will cease at the first drop of rain. During the first weeks of the testing, the surface layer of approximately 15 cm

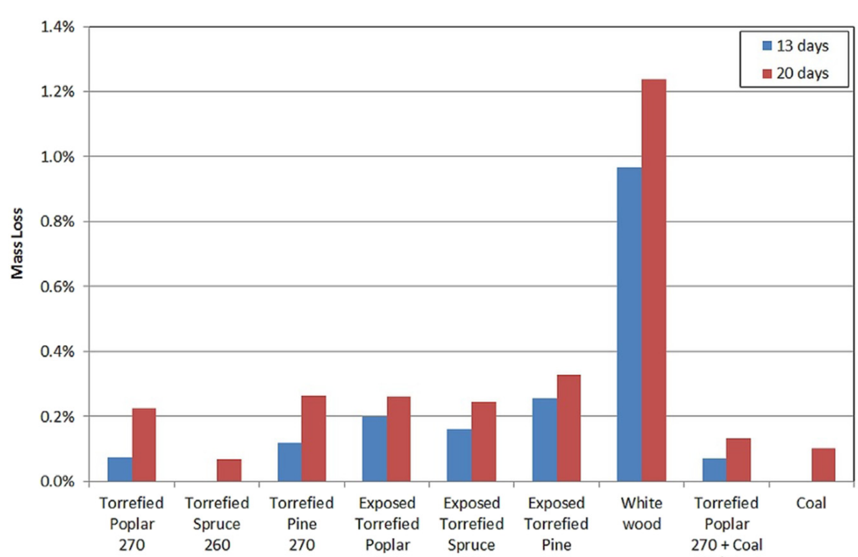

Fig. 3. Climate chamber biological degradation tests with torrefied wood pellets, torrefaction temperature displayed in °C [28].

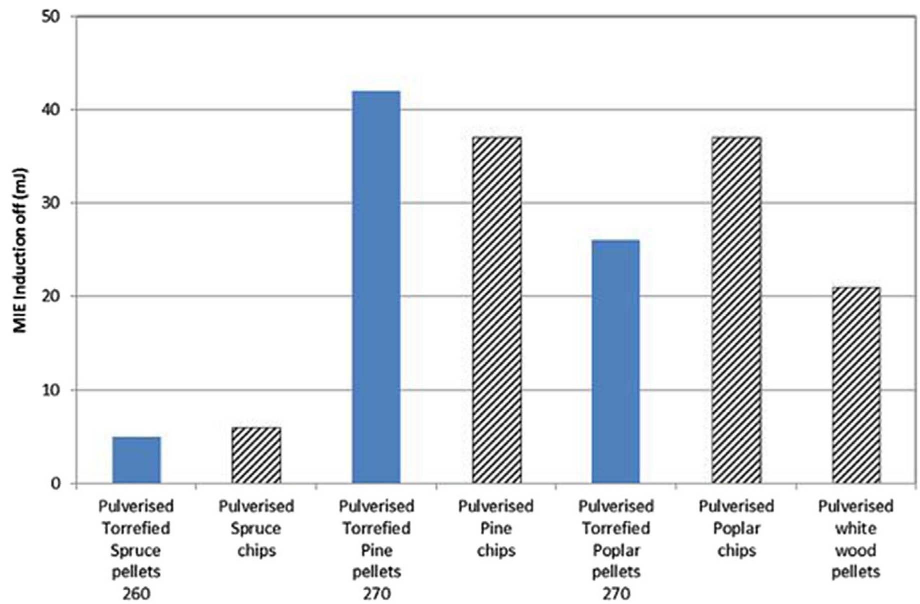

Fig. 4. Minimum Ignition Energy (MIE) of dust samples obtained from pellets and chips (corresponding original material) through a cutter mill (fraction below 63 μm and dried at 75 °C), torrefaction temperature displayed in °C [28].

demonstrated large increases in moisture and corresponding decreases in mechanical durability of the torrefied pellets. At a depth of approximately 15 cm from the surface a layer of fines was formed during all tests, which proved rather impenetrable both for moisture seepage into the pile, as well as for sampling probes. The latter was exemplified by stockpile tests conducted at Topell, two cubic piles of 1 m^3 or 700 kg were stored for a period of one and two months, and subsequently excavated and analysed by layers of 10 cm [29].

For the large quantities of material needed by power plants, the degraded surface layer would be a small fraction of the total delivery. It is therefore possible to envisage a situation where degradation of this portion of the fuel could be acceptable in return for the greater logistical flexibility of being able to establish temporary (e.g. 1 month) stocks outside and to allow discharge and movement of biomass materials in more inclement weather conditions. The excavation of the stockpile may however need to take place in a different manner than with coal, i.e. the entire height of the stockpile should be scooped up at once to prevent the formation of a subsequent surface layer that could be affected again. It may be possible to extend storage periods through the use of sheeting or simple covers to prevent direct rain exposure – these systems would be lower in costs than the fully enclosed storage required for white wood pellets.

The results of the outdoor storage tests conducted by EON are summarized in Fig. 5. Two stockpiles of approximately 4 Mg each were erected on a surface area of 2 × 2 m and a height of roughly 1.5 m, one with a flat surface and one with a peak surface. The middle sample was obtained 40 cm below the surface. The figure provides the mechanical durability of torrefied spruce pellets during the first 70 days of outdoor uncovered storage. The mechanical durability of torrefied spruce pellets inside the pile stays more or less intact while the pellets on the surface display a reduced mechanical durability, in analogy with the other outdoor storage tests. The sampling occurred at set intervals during a time frame of one year, thus involving varying weather conditions. The observed fluctuations in the mechanical durability of the pellets sampled from the surface of the pile are the direct result of rainfall in case of lower durability and dry periods in case of higher durability.

White wood pellets require to be shielded from the ambient atmosphere during the entire value chain, while torrefied wood pellets display improved storage and handling behaviour. The outdoor stockpile tests revealed that the tested torrefied pellets appeared to be unsuitable to be stored outdoors uncovered for long durations, i.e. during one year. During this timeframe, the moisture in the piles increased gradually, hence lowering the net calorific value of the material and potentially reducing the plant efficiency. However, storage periods of a few weeks up to a month are deemed feasible. It should be noted that the pellets used were produced prior to the optimization work in torrefaction and densification, and therefore it may prove more robust and allow storage periods to be extended.

4. Torrefied biomass applications

The various implications of introducing torrefied biomass in existing pulverized coal-fired boilers and gasifiers were investigated in close collaboration with power producers within the SECTOR project [30]. An inventory of potential issues that could affect the integrity of representative coal-fired boilers and gasifiers when introducing torrefied biomass was made. The impacts on milling and feeding, burners, combustion behaviour, process-ash/slag behaviour, reactivity, gas composition and emissions were investigated and are presented here.

Experimental investigations covered a range of torrefied biomass fuels sourced from clean woody biomass, forestry residues and agro-residues, while tests were performed in facilities ranging from lab scale to industrial scale. The experimental work was also supported by CFD simulation for prediction of continuous full scale applications. This section identifies operational aspects that would need to be adapted when handling torrefied biomass, while also proffering the properties of torrefied biomass that would need further improvement.

4.1. Co-milling coal and torrefied biomass pellets in a roller mill

Co-milling of bituminous coal and torrefied wood pellets was demonstrated in a bowl (vertical roller) mill at medium load

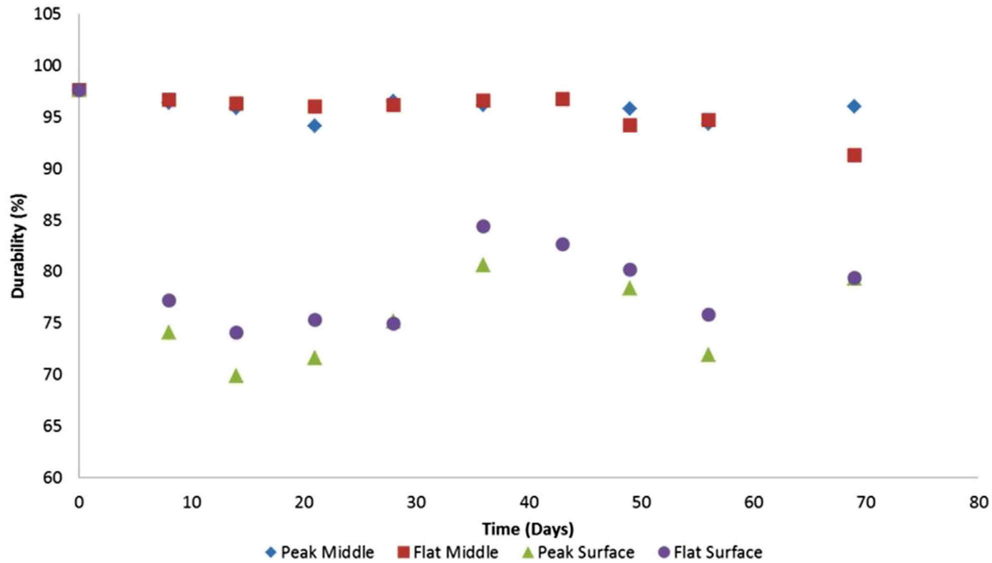

Fig. 5. Mechanical durability of torrefied spruce pellets torrefied at 285 °C as function of time/location in peak top and flat top stockpiles during outdoor tests at EON [29].

(400 kg h^{-1}) for torrefied biomass shares of up to 32%. The mill was calibrated with bituminous El Cerrejon coal (from Colombia, moisture of 11.7%) by means of fineness analogous to power plant requirements (Fig. 7). Pelletized torrefied spruce (torrefied at 285 °C, moisture of about 8%) was added stepwise while the throughput was kept constant.

During co-milling experiments, power consumption rises (for 13.5%–58.5% mass fraction of torrefied biomass) as inhomogeneity of feedstocks increase (Fig. 6). With the further increase in torrefied biomass share (58.5%–100%), energy consumption decreases again slightly (see Fig. 6) probably due to a more homogeneous feedstock as well as a decrease in the classifier speed by about 25%.

The torrefied biomass "parent" size represents original particle size of materials before been pressed into pellets. Part of the goals of the test was to evaluate whether the particles within the pellets were reduced in size in addition to the obvious disintegration of the pellets. For 100% torrefied biomass, due to the classifier speed reduction by 25% (in order to prevent filling up of the mill), the pellets are disintegrated back to their original particle sizes (before pelletization) with minimal degree of fractionation (Fig. 7). Co-milling improves this degree of fractionation substantially in addition to the pellet disintegration. The mill can handle white pellets also but the conditions (i.e. classifier speed, gas flows etc.) would have to be adapted with higher derating.

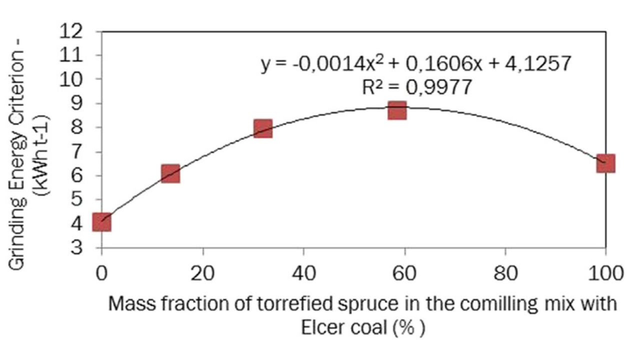

Fig. 6. Graph shows the average grinding energy for the various settings in a bowl mil (with vertical rollers). 0% represents pure coal, while 100% represents pure torrefied spruce pellets torrefied at 285 °C.

The particle size distribution of raw (parent) feed into the mill (torrefied biomass pellets and bituminous El Cerrejon coal) is also shown in Fig. 7.

During torrefaction, the hemi-cellulose fraction which is responsible for the fibrous nature of biomass is degraded, thereby improving its grindability [31–33]. The results demonstrate that co-milling would produce a finer product size distribution rather than dedicated milling (Fig. 7). Finally, pulverized raw wood particles are very heterogeneous and needle shaped. The shape of the torrefied wood is closer to coal than raw wood and this favours conveyance in conventional coal pneumatic feeding systems.

4.2. Co-firing in pulverized coal boilers

4.2.1. Emission behaviour and ash characteristics at 500 kW pilot scale

The key combustion related issues were investigated in single-burner pilot scale facilities (500 kW) at University of Stuttgart (Germany) [34]. Based on experimental data generated by combusting SECTOR torrefied material, the following conclusions were drawn:

- The co-fired flames as well as torrefied biomass flames were more elongated compared to coal flames which were shorter and more intense. The coarser torrefied biomass particles would require longer heat-up times and subsequently combustion [34]. Burn-out was however not negatively affected at the furnace outlet.
- Replacing coal with biomass or torrefied biomass leads to lower NO_x and SO_2 emissions. During 50% un-staged combustion of torrefied wood and coal, a 10% reduction of NO_X emissions was measured compared to coal, while NO_X emissions during torrefied wood un-staged combustion represents a 71% reduction of the NO_X levels measured for coal combustion (Fig. 8). Air Staging will further reduce the NO_X during 50% co-firing with torrefied biomass by another 59% and for torrefied wood combustion by another 20%. For coal, air staging is already established as an effective measure for NO_X reduction.
- Sulphur from the coal reduces the formation of KCl from biomass in deposits through the preferable formation of potassium sulphate. This was confirmed by measured HCl in the

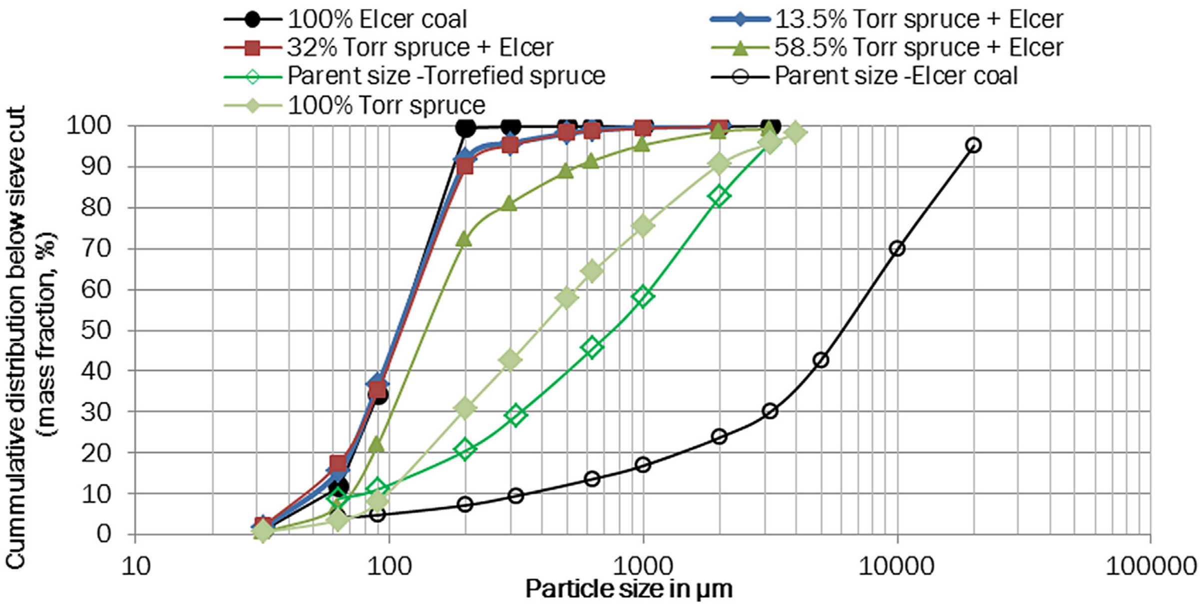

Fig. 7. Cumulative mass distribution with respect to particle size determined by sieve analysis before and after co-milling in a roller mill (400 kg h^{-1}). Parent size of coal simply implies raw coal sizes, while for torrefied pellets, parent size represents original particle size of material before been pressed into pellets.

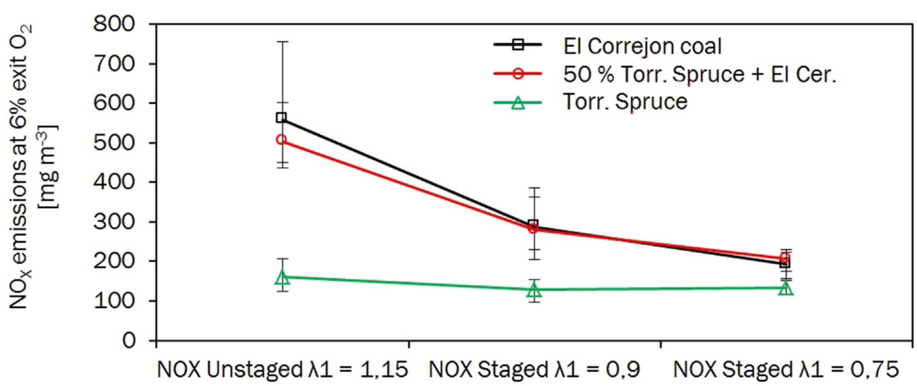

Fig. 8. Impact of air staging at primary lambda λ1 0.9 and 0.75. NOx emissions during El Cerrejon coal and torrefied spruce (co)firing in down-fired 500 kW pilot scale plant.

flue gas in the case of co-firing, whereas KCl containing deposits with low ash melting points were found in the case of combustion of torrefied wood [34]. Similarly, coal containing aluminosilicate ashes also reduce the formation of low melting alkali silicates and consequently the slagging tendency [34].

4.2.2. Co-firing in pulverized coal boilers: CFD assessment of full scale application

CFD analyses were carried out on two anonymous but representative full scale pulverized coal-fired plants in preparation for a larger-scale industrial test campaign with the SECTOR torrefied material at end of 2015 in Finland. Both plants were front wall fired, and equipped with swirl burners burning hard coal.

Combustion of torrefied material will reduce the amount of inorganics in the overall fly-ash, simply because the torrefied fuel (just as the original raw biomass) contains significantly less amount of ash than coal (0.4%–5% on a dry mass basis, compared to 5%–20% for coals) [35]. If the same particle size distribution is used for torrefied biomass co-combustion as for coal combustion, a reduced mass of 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 also contains significantly less ash. Coarser particles size of torrefied biomass lead to a higher amount of unburned carbon in the fly ash. More fuel gas is produced when burning torrefied material causing the combustion reaction to extend higher up in the combustion chamber as displayed in Fig. 9. When coal is completely replaced by torrefied biomass, the flame size can increase up to about 25%. The torrefied biomass flame will also start more quickly and grow backwards towards the burner.

The results of co-firing tests demonstrate that this is feasible without significant adaptations. Blending (torrefied) woody biomass with coal lowers SO_X emissions mainly as a result of dilution [36]. NO_X emissions have a more complex dependency on the nitrogen mass fraction. Other factors such as furnace and burner configurations also impact the final NO_X emissions. Due to the lower nitrogen mass fractions in torrefied biomass, it is also possible to reach lower NO_X emissions. Recent research indicates that through the torrefaction process, a significant amount of chlorine (up to 90%) can be removed from the original biomass [37]. This would imply that chlorine related corrosion impacts can be significantly reduced through the torrefaction process. There may be impacts on power plant integrity such as superheater corrosion, ash deposition, ESP or SCR performance, etc. It is anticipated that

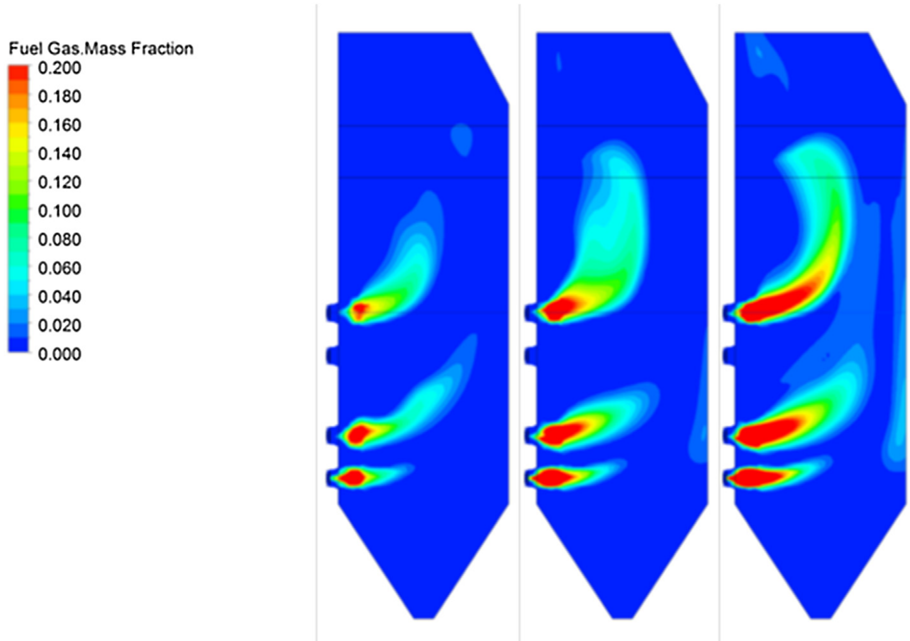

Fig. 9. Simulated fuel gas mass fraction during combustion of: left: 100% hard coal, middle: 50% hard coal/50% torrefied biomass, right: 100% torrefied biomass.

these effects are similar for torrefied biomass and raw biomass, as the inorganic composition of the fuel is not negatively affected during torrefaction.

4.3. Co-gasification in entrained flow reactors: evaluation of feasibility

The feasibility of operating the various systems with different torrefied materials compared to their standard reference fuels was evaluated. The co-gasification of torrefied biomass and coal were carried out at different facilities up to 240 MW.

Transport, handling, unloading, milling and feeding did not result in any major issues in any of the facilities. Available infrastructure for conventional operation was utilized. To reduce the risk of powder explosions, a dedicated (water spray) dust suppression system was installed in the full-scale plant. Gasification performance and efficiencies attained for torrefied materials were generally reported to be improved or approximately in the same range as for the reference wood. Gasification plant efficiency, i.e. the ratio between available energy in the cooled syngas and the thermal energy in the corresponding fuel after taking the power consumption of the mill into account was also improved by torrefaction because of the reduced milling energies. Products of incomplete gasification were found to remain in typically the same or somewhat lower levels as for the reference fuels. For the most severely torrefied biomass, significantly reduced methane mass fraction in the syngas was reported [38–40].

4.4. Torrefied biomass use in small-to-medium scale pellet boilers

Torrefied wood pellets have the potential to provide at least the same or even a higher combustion efficiency as is achievable with wood pellets. This is based on combustion technology screening of torrefied wood pellets in state-of-the-art pellet heating systems such as understoker, grate and overfed boilers up to 50 kW of thermal output [41]. The air ratio and air staging as well as the control settings may need some adaptations and this depends on the specific boiler technology applied. The higher fixed carbon mass fractions in torrefied fuels however lead to increased need for burnout time, making adaptations necessary. The level of pollutant emissions is largely similar to that of wood pellets, given that similar wood resources are used. This was observed for CO, VOCs, NO_x and PM emissions. Due to the higher expected fuel bed temperatures of torrefied fuels, fine particle emissions may increase and a higher share of slag formed. Measures to inhibit slagging are therefore of major relevance.

4.5. Utilization of torrefaction condensates

The quality and utilization potential of condensates can be affected by temperature ranges. Separation of compounds from the mixture may prove difficult and possibly not so economical. However, the total condensates formed at $\leq$280 °C could be utilized 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 pelletization of torrefied products. Due to the low heat transfer in the slow pyrolysis reactor, the reactor may not be representative of all torrefaction plants [12]. At a pilot scale torrefaction plant (ECN), tens of kilograms of birch torrefaction condensates at different torrefaction temperatures using the slowly moving bed pilot reactor was produced, and successfully demonstrated for partial substitution of resins used in plywood production [42].

5. Assessment of fuel properties and environmental economic performance

This chapter presents final results of the SECTOR-project according to the fuel characterisation and its standardization status, the climate implications by pellet use and trade as well as economic considerations regarding the application of torrefied fuel in mono- or co-firing plants. Torrefied biomass is intended to substitute fossil fuels. Therefore in all subchapters of the assessment comparisons to fossil fuels can be made.

5.1. Characterisation of torrefied fuels

Torrefied biomass can be an opportunity to increase flexibility of the fuel supply and improve the conversion performance of existing biomass systems in medium and small scale applications. Each fuel is characterised by specific fuel properties which will be typically defined in a product standard. For market implementation reasons (e.g. requirements on handling, transport and storage), consumer acceptance (e.g. to order defined fuel qualities) as well as for conversion plant developers (e.g. input material, the fuel particle size) it is important to know the characterising fuel parameters.

Fuel Properties. In Table 3 selected chemical and mechanical–physical product properties of torrefied wood pellets were compared to existing solid biofuels and coal. Through the torrefaction process, the material becomes a dry biogenic material, which is stable, brittle and water resistant. The lower moisture of torrefied material by contrast with conventional wood chips/pellets results from the release of a higher amount of volatile matters (decomposition of hemicellulose, cellulose and lignin). Therefore, the torrefied material is also characterised by a higher energy density as well as a reduced biological degradation in storage and thus favourable for long distance transport. Furthermore, this results in cost advantages for transport and storage of the torrefied material compacted in form of pellets or briquettes (see chapter 3).

However, depending on the biomass raw material and the torrefaction process conditions (see chapter 2) the favourable minimised biological activity and water resistant features vary slightly and can differ in stability over time. Therefore, an additional fuel parameter was described in SECTOR to define the water resistance or hydrophobicity of a torrefied material in form of the term "water absorption" [33,43].

The homogenous quality of torrefied fuel and the similarity of selected fuel parameters of torrefied wood with coal (e. g. moisture , energy density) offer optimal conditions for the use in co-firing coal-power plants in order to substitute fossil fuels (Table 3). To describe the adopted fibrous biomass structure of the torrefied material, which eases the processing in existing mills of coal power plants, a new fuel characterisation parameter has been defined as "grindability" in SECTOR [12].

However, more analysis work and end use application tests have to be done with torrefied material of non-woody biomass to set limits for its application in different end use pathways and to favour its market entrance as well.

Product Standardization. On the initiative of SECTOR project partners, the International Organisation for Standardization (ISO) Technical Committee 238 (ISO/TC 238) has started to draft an international product standard for torrefied pellets and briquettes made from woody and non-woody (herbaceous, fruit and aquatic) biomass in February 2013 [35,36]. The standard development is focused on "Graded thermally treated and densified biomass fuels" for industrial and non-industrial use and will be published as ISO 17225-8 as well as in Europe as EN ISO 17225-8. Thermal treatment includes processes such as torrefaction, steam treatment (explosion pulping), hydrothermal carbonization and charring, which all represent different exposure to heat, oxygen, steam and water. After the discussion and adaption of first standard drafts within the committee and by involving the International Biomass Torrefaction Council (IBTC) its publication is foreseen by the end of the year 2016.

The highest quality classes (TW1a and TW2b) for thermally treated woody pellets and briquettes are recommended for non-industrial use (residential and other small-scale applications). Also other TW classes for woody biomass TW2a, TW3a and TW3b were drafted. Additional classes (TA1, TA2 and TA3) were developed for non-woody biomass. These classes are suitable only for industrial use or small-scale boilers specially designed for non-woody biomass. In the coming draft international standard (DIS) woody biomass classes are divided into two tables based on net calorific value on dry basis. The threshold value in the current version is 21 MJ kg^{-1} on dry basis. If the net calorific value on dry basis is higher than 21 MJ kg^{-1}, it is proposed to mark classes by TW1a, TW2a and TW3a and if it is lower, then they are marked by TW1b, TW2b and TW3b. Moisture (M, % of mass) and fines (F, particles less than 3.15 mm) should be stated at the point of delivery. Table 4 lists the normative (mandatory) properties for thermally treated densified biomass fuels. In all classification tables, ash melting behaviour is informative (voluntary) and it is recommended to state all characteristic temperatures shrinkage starting temperature (SST), deformation temperature (DT), hemisphere temperature (HT) and flow temperature (FT) in oxidising conditions.

Within the SECTOR project, two international Round-Robin-Tests (interlaboratory tests performed independently several times) were conducted to prove the application of existing chemical and physical test methods for torrefied material. The existing

Table 3
Comparison of selected properties of torrefied material with wood chips, pellets and coal [34,44], adapted according to ISO 06/2015 (moisture/heating value/bulk density); the related parameter definition is also given in Table 4.

	Wood chips	Wood pellets	Torrefied wood pellets	Coal
Moisture (%)	30–55	7–10	1–10	10–15
Net calorific value (Q, MJ kg^{-1}) as received	7–12	15–17	17–24	23–28
Volatile matter (VM) (%, mass, dry basis)	70–84	75–84	55–80	15–30
Fixed carbon (C_f) (%, mass, dry basis)	16–25	16–25	22–35	50–55
Bulk density (BD) (t m^{-3})	0.20–0.30	0.55–0.65	0.55–0.80	0.80–0.85
Energy density (E) (GJ m^{-3})	1.4–3.6	8–11	12–19	18–24
Hygroscopic properties	Hydrophilic	hydrophilic	moderately hydrophobic	hydrophobic
Biological degradation	Fast	fast	Slow	none
Milling requirements	Special	special	standard (feedstock-specific)	standard
Product consistency	Limited	high	high	high
				
	© Kay Schaubach/DBFZ	© Thomas Siepmann/pixelio.de	© Kay Schaubach/DBFZ	© Gabi Schönemann/pixelio.de

Table 4
Selected normative properties to be specified for ISO 17225-8 draft international standard [5,45]. Note: this is a proposal of working group 2 of ISO/TC 238 for DIS version, and values can be changed in the final draft international standard (FDIS), which will be discussed in April 2016. The standard foresees the use of weight percentage (w-%) as unit which is not used in this paper.

Property, standard for analysis	Unit	Remarks
Raw material, ISO 17225-1:2014		To be stated from ISO 17225-1:2014/Table 1, Woody biomass. ISO 17225-8 list approved raw materials more detailed for each classes
Diameter, D and Length L, ISO 17829	mm	Diameter classes for TW1a[a], TW1b and TW2a, TW2b, TW3a and TW3b from 6 to 25 mm for pellets. Less length classes for TW 1a. TW1b and TW2a, TW2b, maximum length 40 mm for TW1 classes, and maximum length for TW2 and TW3 classes is 50 mm depending on the diameter of pellet. For briquettes actual diameter and length or width is stated depending on shape of briquettes.
Moisture, M[c], ISO 18134-1, ISO 18134-2	%[b]	Moisture on wet basis is 8% or 10% depending on traded form (pellet or briquette) and raw material and class
Ash, A[c], ISO 18122	% (dry mass)	From A1.2 to A10 depending on classes and raw material. Lowest class for TW1a and TW1b.
Mechanical durability, DU[c], ISO 17831-1	% (mass as received)	From DU95.5 to DU95.0 depending on classes. Highest class for TW1a and TW1b.
Fines, F[c], ISO 18846 (<3.15 mm)	% (mass as received)	From F1 (1%) to F6 (6%) depending on classes and raw material. Lowest class for TW1a and TW1b.
Additives	% (dry mass)	Maximum 4% for TW1a and TW1b classes. Type and amount to be stated
Net calorific value, Q[c], ISO 18125	MJ kg^{-1} or kWh kg^{-1} as received	From Q16.0 to Q21.0 depending on classes, technology and raw material
Bulk density, BD[c], ISO 17828	kg m^{-3}	From BD550 to BD700 depending on classes, technology and raw material. Lowest class for pellets, which are thermally treated after pelleting.

[a] TW is symbol for the quality classes of thermally treated woody biomass.
[b] in ISO 17225 standards, unit w-% for weight percentage is used
[c] Symbols D, L, M, A, DU, F, Q and BD are designations of properties stated in ISO 17225-1:2014 and ISO 17225-8 (under preparation) standards. After symbol the threshold value is marked, e.g. M10 (moisture $\leq$ 10%).

test methods were originally developed for the characterisation of solid biomass. These Round Robin tests demonstrated that numerous established methods could be adopted for the determination of specific property parameters (e. g. determination of heating value, major and minor elements). Additionally, new fuel property parameters were analysed and the development of new test methods started within SECTOR (e. g. for grindability, hydrophobicity/water absorption) [35,36]. The project also collected property data for fuel specification standard development.

5.2. GHG-emissions of torrefied pellets supply and application

Solid biofuels are often considered as energy carriers with potentially low life-cycle greenhouse-gas (GHG) emissions. Hence, anticipated GHG-mitigation effects from the use of these energy carriers are the strongest rationale for their promotion. Considering the limited resource base, torrefaction is discussed as a promising approach to decrease the costs of logistics while increasing local biomass availability due to long distance transports.

The GHG-mitigation effects from the use of various (torrefied) biomass value chains have been investigated comprehensively within the SECTOR project [7]. This assessment has been conducted considering the actual data and project results on the mass and energy flows for the torrefaction technology, which have been compiled during the project. This allows for a detailed assessment based on primary data which would not be possible with information from available publications. Based on these mass and energy balances, GHG-emissions have been calculated using the LCA methodology according to ISO 14040:2006 and ISO14044:2006 standards.

Fig. 10 shows the GHG-emissions per MJ of supplied pellets for three feedstocks straw, logging residues and willow (short rotation coppice) and four locations (Spain, USA, Tanzania, Canada). As expected the results showed that, due to the higher energy density, the transportation of the torrefied pellets leads to lower energy specific GHG-emissions compared to the transportation of conventional pellets (e.g. CO_2-Eq. of 11.5 g MJ^{-1} Canadian straw white pellet distribution compared to a CO_2-Eq. of 9g MJ^{-1} for torrefied Canadian straw pellets).

Other major impact factors that have been identified during the assessment are the type of energy carrier (e.g. biomass or natural gas) used during the processes of torrefaction/densification as well as the emission factor of the local electricity supply. Together with the different distribution scenarios this explains the main differences between the results of the various locations. In general, the production and use of pellets from residues resulted in lower emissions compared to the use of plantation wood.

To counterbalance the GHG-emissions from the supply of (torrefied) pellets from different origins, the avoided GHG-emissions from the replacement of fossil fuels have been investigated for various end use markets [46]. The results are summarized in Table 5.

The results show a GHG-mitigation potential of the pathways investigated for co-firing between 72% and 87%. 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 5 indicate that this yields a GHG mitigation potential between 58% and 79%. 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.

5.3. Economic aspects

The economic aspects of producing and using biomass torrefaction pellets have been evaluated against those of wood pellets [6,24] (see: Table 6). The energy and mass balances based supply chain costs calculations from Ref. [24] were implemented in the BioChainS tool (Biomass-to-end-use Chain Simulation tool) to simulate a higher variety of supply chains. The tool enables the comparison of supply chains varying multiple factors.

For the production of torrefied pellets, a base case was assumed of a medium scale stand-alone torrefaction plant in Europe of

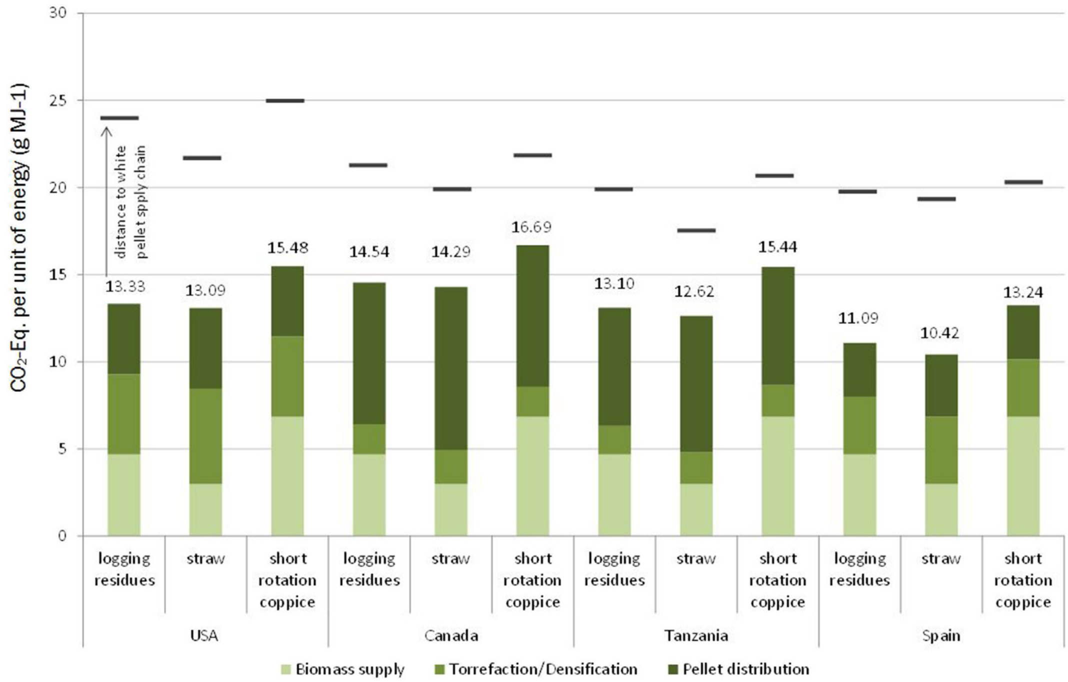

Fig. 10. GHG-emissions from the supply of torrefied pellets from different feedstock types and locations compared to white pellets [46].

Table 5
GHG-emissions reduction compared to conventional fuel, and from the use of conventional and torrefied pellets from different supply chains per MJ of product (derived from Ref. [46]).

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

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

Table 6
Production costs of torrefied wood pellets for stand-alone plants and integrated in new/existing plants [24].

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

72,800 Mg a^{-1}, with production costs of 43 € MWh^{-1}. A significant fraction are fuel costs at 18–25 € MWh^{-1}. A larger production plant located in North America (500,000 Mg a^{-1}) and fed with cheaper biomass feedstock (15 € MWh^{-1}) lowers the production costs to 29 € MWh^{-1}. All cases presented below are based on 8000 annual operating hours and a capital charge factor of 0.1175 (10% interest during 20 years).

The simulation of the supply chains illustrated decisive factors for production costs: (1) the combination of feedstock yield, availability and accessibility and (2) the production plant size.

Higher heating values resp. energy density lower the costs after production through reduced mass/volume in transport, thus increasing competitiveness to white pellets.

Integration into an existing CHP plant does not reduce the costs substantially, but integration in other operations (sawmills, pulp and paper mills) however does (5–24% compared to base case [24]). This is mostly due to the larger possible production capacities and lower feedstock costs (e.g. excess forest residue).

The purchase power for torrefied wood pellets over white wood pellets was determined in this context. All additional costs for biomass co-firing excluding fuel costs were calculated for both 10% and 30% co-firing on energy basis. This was done for a 400 MW (electric output) power plant in the Netherlands with 6,000 annual operating hours. A loan interest level of 6% was assumed (65% of the capital), a company tax level of 25% and a demanded return on equity of 12% (35% of the capital). This results in a project interest rate of 6.9%; at an economic lifetime of 10 years this results in an annuity of 14%. The results are displayed in Fig. 11.

The total annual costs excluding fuels are higher for white wood pellets than for torrefied wood pellets, particularly at an increased co-firing share of 30%. This fact can be translated to a maximum excess price that could be paid for torrefied wood pellets to achieve equal annual electricity production costs. The results in Table 7 imply that at a co-firing share of 30%, the large-scale stand-alone plants and some of the integrated concepts could produce pellets at price levels that would be economically competitive to use for utilities instead of white wood pellets. The significantly lower investment costs also offer flexibility when incentives for co-firing are subject to fluctuation [48].

6. Market opportunities

As described in the preceding chapters, the torrefaction technology has improved significantly during the last years and is now commercially available for woody biomass. Non-woody biomass torrefaction has been investigated and improved as well but still needs further development for market readiness. Research activities now aim mostly at optimizing, e.g. technology, the overall value chain, standardization, trade registration and legal permissions [50,51].

This development is embedded in a growing bioenergy carrier market worldwide [1,9]. The European Union considers bioenergy as an integral part of the low carbon economy [52] and has set ambitious goals for the share of renewable fuels in the primary energy consumption (20% for 2020 and 27% for 2030) [10], which should support the further development and implementation of torrefaction technology [2].

The primary market for torrefied material has been seen by many producers in co-firing as one third of power supply is expected to be from large power producers [2,24]. In Europe (EU 28) alone, 285 Tg of hard coal and 421 Tg of lignite were consumed in 2014 [26,53]. An average co-firing share would result in a European market of ca. 70 Tg per year. Nevertheless, market conditions (e.g. CO_2, needed amounts) and chosen lock-in solutions from potential co-firing customers (e.g. that have already invested to accommodate white pellet) require a careful policy approach to support market introduction but also the commitment of producers and other stakeholders. Important factors here are the CO_2 emissions and possible savings, as well as the economic aspects for different end-user markets.

Regarding the development and implementation one can distinguish three focus areas for business development (Fig. 12). A main driver for business development comes from the end user markets, as end users can create a market pull for the technology. The end user markets are categorised in "torrfuel production" (torrfuel: torrefied fuel), which includes the sales to intermediaries and users. As described above, small and medium scale appliances are now considered alongside co-firing. A strategic consideration is the geographical location of producers and end users. Production and end-use in Europe can strengthen the internal energy security and present business opportunities for biomass surplus regions. The beneficial long distance transport properties of torrefied fuels allow the import into Europe from biomass surplus regions worldwide, potentially reducing CO_2 emissions and increasing

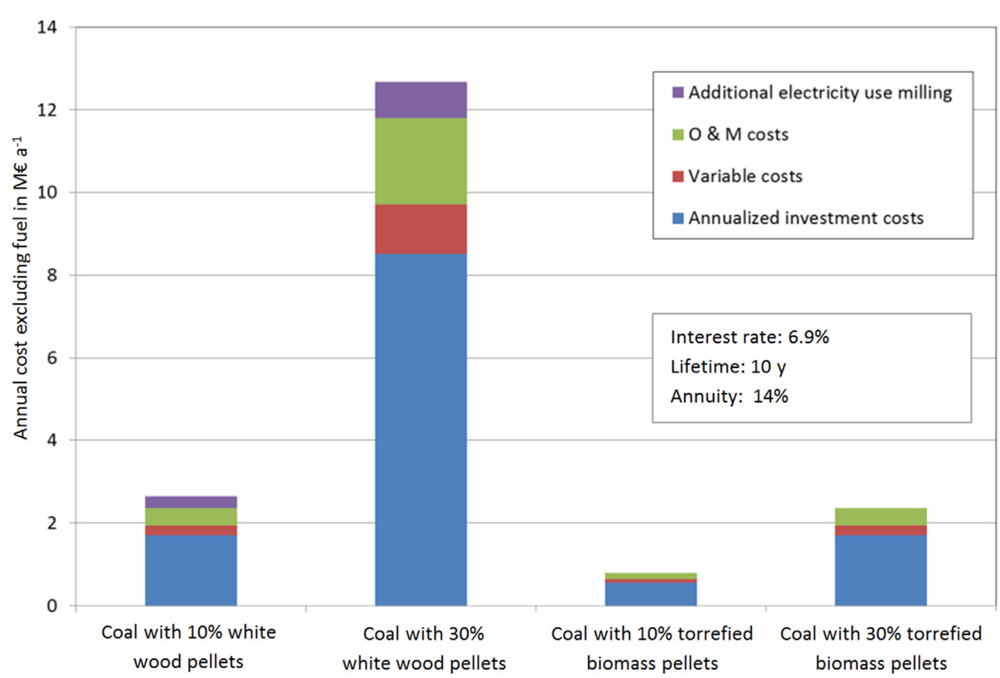

Fig. 11. Annual cost of co-firing white wood pellets and torrefied wood pellets at 10% and 30% co-firing share excluding fuel costs [47,26].

Table 7
Purchase power of torrefied wood pellets vs. white wood pellets at equal annual costs [49].

	unit	10% co-firing	30% co-firing
Excess costs of white wood pellets over torrefied wood pellets	M€ y^{-1}	1.86	10.31
Amount of biomass of pellets used	PJ	2.16	6.48
Price difference	€ GJ^{-1} (€ MWh^{-1})	0.86 (3.10)	1.59 (5.72)
Case 1: price difference at higher rate of return (12% → 15%)	€ GJ^{-1} (€ MWh^{-1})	1.08 (3.89)	2.02 (7.27)
Case 2: price difference at reduction of economic lifetime from 10 to 5 years	€ GJ^{-1} (€ MWh^{-1})	1.24 (4.46)	2.34 (8.42)

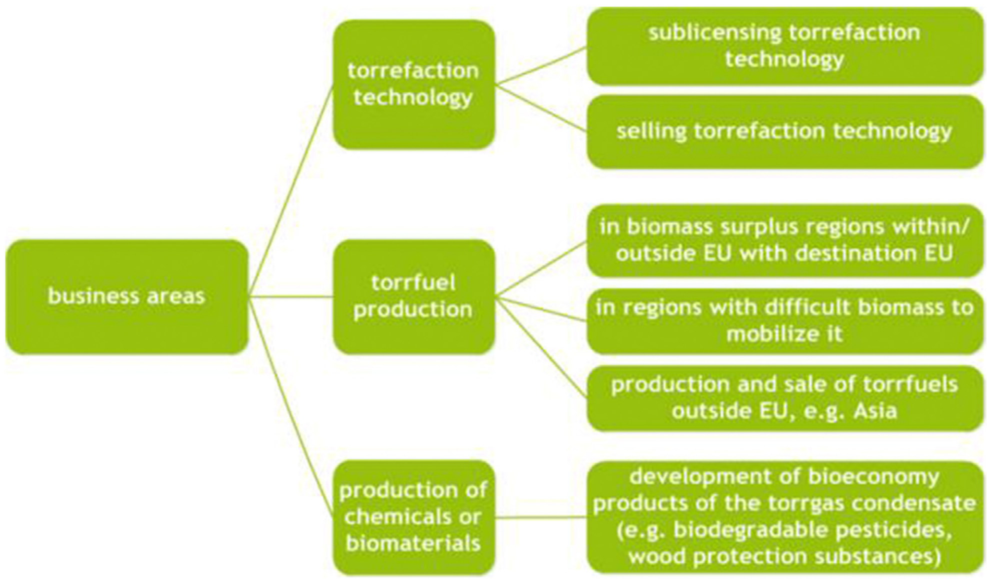

Fig. 12. Torrefaction business areas.

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. A third option within torrefied fuel production is the provision and use of torrefied fuels outside of Europe. This does not improve the energy sector in Europe directly but presents the opportunity for technology providers to establish or extend their business, thus stabilising their operation which in turn is beneficial for the torrefaction sector within Europe.

Directly connected to this scheme is the business area "torrefaction technology", where technology providers sublicense or sell technology. Thus, the technology provider is not necessarily the operator of a torrefaction plant but different stakeholders fulfil these different market roles.

Diversifying the end user markets (appliance and location) and utilizing technology as an additional product can be complemented by a third business area: "production of chemicals or biomaterials", which is a possibility of utilising by-products to improve the overall torrefaction process efficiency [54]. The latest research has shown the potential of torrefaction gas condensate to be processed into different materials not connected to energy provision, such as biodegradable pesticides and phenols for wood protection substances (see chapter 4.5). These options are far from market ready but might add to profitable business in the future for torrefaction plant operators and also support the establishment of more sustainable economies.

7. Conclusions

The SECTOR project focused on the further development and optimization of torrefaction-based technologies for the production of solid bioenergy carriers up to pilot-plant scale and beyond, including the whole process chain from torrefaction to end use application. Additional assessments of different sustainability dimensions, technical standardization needs and market introduction strategies identified the current chances and obstacles of this new technology comprehensively. The generated data can also support future research on torrefaction of biomass. The now achieved quality parameters of the torrefied material have been further specified and are in preparation for standardization.

While different torrefaction and densification technologies were applied to different biomass feedstock successfully, the further optimization of the processes and concepts can only be effectuated for specific concepts. The challenge is to proceed from demonstration to industrial scale. Market implementation strategies can act as a navigator for the next steps for the implementation of industrial plants. Different end user markets can open opportunities here:

(1) Co-firing in EU countries: For co-firing price parity with coal is essential to enable commercial market introduction of torrefied biomass. The relatively low CO_2 price is however a major hurdle for the business case. 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. It is essential that EU member countries continue their efforts on establishing substantial CO_2 market prices. In the absence of price parity with coal, it is important that countries launch additional co-firing support schemes to enable co-firing or 100% conversion, which could lead to

significant growth in the next couple of years. Recent examples of such countries are UK, Netherlands, and Belgium.

(2) Co-firing outside Europe: In case coal based power producers have already made investments to enable large scale use of white wood pellets, it could be too late to make use of the potential cost savings of torrefied pellets. For countries and regions 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.

(3) Additional market for security of financing: Securing the financing for investment is another hurdle. Compared to the 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, which makes end users hesitant to absorb torrefied fuels and sign long term offtake contracts. This makes it again difficult for an investor to obtain finances to establish a torrefaction plant. Governments could help in securing financing of such plants by arranging non-recourse financing. 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 established at the same time, to enable an optimal business case.

Parallel to end-user market development, the further development of the resource base needs specific attention. Due to the fact that almost half of the costs for torrefaction processes come from feedstock, it is important to research possibilities for reduction of the raw material costs by developing sustainable and cost-efficient supply chains for biomass. Appropriate product standards and the consideration of sustainability standards are essential to facilitate trade as well as the production of suitable end use appliances that are optimized for torrefied biomass.

So, for successful market implementation not only technical improvements but also various conducive policies are required to support the application of torrefied biomass for power supply, the heat sector and in industries, keeping in mind the differentiation in qualities and prices required.

Acknowledgement

The authors would like to thank the EU for the financial support from the Seventh Programme for research, technological development and demonstration under grant agreement no 282826 and Virginie Bellmann (DBFZ) for her support in organising and reviewing the paper.

References

[1] M. Cremers, J. Koppejan, J. Middelkamp, J. Witkamp, S. Sokhansanj, S. Melin, et al., Status overview of torrefaction technologies. A review of the commercialisation status of biomass torrefaction, in: IEA Bioenergy, 2015.

[2] M. Deutmeyer, D. Bradley, B. Hektor, J.R. Hess, L. Nikolaisen, J. Tumuluru, et al., Possible effect of torrefaction on biomass trade, in: IEA Bioenergy, 2012.

[3] M. Rudolfsson, W. Stelte, T.A. Lestander, Process optimization of combined biomass torrefaction and pelletization for fuel pellet production – A parametric study, Appl. Energy 140 (2015) 378–384, http://dx.doi.org/10.1016/j.apenergy.2014.11.041.

[4] A. Janssen, M. Carbo, D. Schneider, A. Pollex, W. Stelte, J. Gil, et al., Report on Requirements of End Users on Densified and Torrefied Materials, SECTOR Deliverable D4.1, 2013.

[5] E. Alakangas, Graded Thermally and Densified Biomass Fuels: Development of the ISO 17225–8 Standard, SECTOR Deliverable D8.3, 2015.

[6] F. Schipfer, K. Bienert, L. Kranzl, S. Majer, E. Nebel, Deployment Scenarios and Socio-economic Assessment of Torrefied Biomass Chains Part 2, SECTOR Deliverable D9.5, 2015.

[7] S. Majer, M. Gawor, E. Nebel, LCA of Torrefied Biomass Chains in Comparison to Reference Pathways, SECTOR Deliverable D9.6, 2015.

[8] J. Koppejan, K. Schaubach, J. Witt, D. Thrän, Torrefaction Technology and Strategy Report, SECTOR Deliverable D10.2, 2015.

[9] M. Junginger, C.S. Goh, A. Faaij (Eds.), International Bioenergy Trade, vol. 17, Springer, Dordrecht, 2014. Netherlands.

[10] European Commission, 2030 Energy Strategy, Energy (2015). https://ec.europa.eu/energy/en/topics/energy-strategy/2030-energy-strategy [accessed 30.07.15].

[11] M.J. Prins, K.J. Ptasinski, F.J.J.G. Janssen, Torrefaction of wood, Part 2. Analysis of products, J. Anal. Appl. Pyrolysis 77 (2006) 35–40, http://dx.doi.org/10.1016/j.jaap.2006.01.001.

[12] L. Fagernäs, E. Kuoppala, V. Arpiainen, Composition, Utilization and Economic Assessment of Torrefaction Condensates, Energy Fuels 29 (5) (2015) 3134–3142, http://dx.doi.org/10.1021/acs.energyfuels.5b00004.

[13] M.J.C. van der Stelt, H. Gerhauser, J.H.A. Kiel, K.J. Ptasinski, Biomass upgrading by torrefaction for the production of biofuels: A review, Biomass Bioenergy 35 (9) (2011) 3748–3762, http://dx.doi.org/10.1016/j.biombioe.2011.06.023.

[14] J. Tumuluru, S. Sokhansanj, J.R. Hess, C.T. Wright, R.D. Boardman, A Review on Biomass Torrefaction Process and Product Properties for Energy Applications, Ind. Biotechnol. 7 (5) (2011) 384–491, http://dx.doi.org/10.1089/ind.2011.7.384.

[15] J. Koppejan, S. Sokhansanj, S. Melin, S. Madrali, Status overview of torrefaction technologies. Final Report, in: Enschede: IEA Bioenergy, 2012.

[16] D. Thrän, T. Seidenberger, J. Zeddies, R. Offermann, Global biomass potentials — Resources, drivers and scenario results, Energy Sustain Dev. 14 (3) (2010) 200–205, http://dx.doi.org/10.1016/j.esd.2010.07.004.

[17] C. Weiser, V. Zeller, F. Reinicke, B. Wagner, S. Majer, A. Vetter, et al., Integrated assessment of sustainable cereal straw potential and different straw-based energy applications in Germany, Appl. Energy 114 (2014) 749–762, http://dx.doi.org/10.1016/j.apenergy.2013.07.016.

[18] E. Alakangas, M. Flyktman, Quality Demands from Producers and End Users, SECTOR Deliverable D2.4, 2013.

[19] K. Werner, L. Pommer, M. Broström, Thermal decomposition of hemicelluloses, J. Anal. Appl. Pyrolysis 110 (2014) 130–137, http://dx.doi.org/10.1016/j.jaap.2014.08.013.

[20] C. Medic, M. Darr, A. Shah, B. Potter, J. Zimmermann, Effects of torrefaction process parameters on biomass feedstock upgrading, Fuel 91 (1) (2012) 147–154, http://dx.doi.org/10.1016/j.fuel.2011.07.019.

[21] ECN Phyllis2 Database for biomass waste 2016. ECN Phyllis2 n.d. https://www.ecn.nl/phyllis2/[accessed on 20.01.16].

[22] DBFZ. DBFZ torrefaction plant database 2015. [accessed on 15.09.15].

[23] P.C.A. Bergman, A.R. Boersma, R.W.R. Zwart, J.H.A. Kiel, Torrefaction for Biomass Co-firing in Existing Coal-fired Power Stations "BIOCOAL.", Petten, The Netherlands, 2005, pp. 05–013.

[24] C. Wilen, V. Arpiainen, Report on Optimisation Opportunities by Integrating Torrefaction into Existing Industries, SECTOR Deliverable D3.2, 2014.

[25] C. Göbl, U. Wolfesberger-Schwabl, Report on Test Methods and Properties of Torrefied Biomass, SECTOR Deliverable D8.5, 2015.

[26] J. Witt, K. Schaubach, M. Ristola, V. Bellmann, D. Thrän, Final Report Based on Conference Proceedings of Final Project Conference, SECTOR Deliverable D1.3, 2015.

[27] BS EN 15210-1: 2009 British Standards Institution, Solid Biofuels. Determination of Mechanical Durability of Pellets and Briquettes, British Standards Institution, London, 2009.

[28] M. Carbo, P. Abelha, M.K. Cieplik, C. Mourão, Fuel (Pre-)processing, Pretreatment and Storage for Co-firing Biomass and Coal, Fuel Flex. Energy Gener., Woodhead Publishing, Sawston, United Kingdom, 2015.

[29] S. Weatherstone, N. Simonsson, G. Karlsson, N. Padban, A. Adell i Arnuelos, P. Abelha, et al., Final Report on Bulk Tests in Existing Storage and Handling Facilities, SECTOR Deliverable D6.7, 2015.

[30] EU FP7 Innovation Project, SECTOR n.d. http://www.sector-project.eu [accessed on 15.07.15].

[31] M. Phanphanich, S. Mani, Impact of torrefaction on the grindability and fuel characteristics of forest biomass, Bioresour. Technol. 102 (2) (2011) 1246–1253, http://dx.doi.org/10.1016/j.biortech.2010.08.028.

[32] T.G. Bridgeman, J.M. Jones, A. Williams, D.J. Waldron, An investigation of the grindability of two torrefied energy crops, Fuel 89 (12) (2010) 3911–3918, http://dx.doi.org/10.1016/j.fuel.2010.06.043.

[33] V. Repellin, A. Govina, M. Rolland, R. Guyonet, Energy requirement for fine grinding of torrefied wood, Biomass Bioenergy 34 (7) (2010) 923–930, http://dx.doi.org/10.1016/j.biombioe.2010.01.039.

[34] C. Ndibe, S. Grathwohl, M. Paneru, J. Maier, G. Scheffknecht, Emissions reduction and deposits characteristics during cofiring of high shares of torrefied biomass in a 500kW pulverized coal furnace, Fuel 156 (2015) 177–189, http://dx.doi.org/10.1016/j.fuel.2015.04.017.

[35] C. Ndibe, J. Maier, G. Scheffknecht, Combustion, cofiring and emissions characteristics of torrefied biomass in a drop tube reactor, Biomass Bioenergy 79 (2015) 105–115, http://dx.doi.org/10.1016/j.biombioe.2015.05.010.

[36] H. Spliethoff, K.R. Hein, Effect of co-combustion of biomass on emissions in pulverized fuel furnaces, Fuel Process Technol. 54 (1–3) (1998) 189–205, http://dx.doi.org/10.1016/S0378-3820(97)00069-6.

[37] T. Keipi, H. Tolvanen, L. Kokko, R. Raiko, The effect of torrefaction on the chlorine content and heating value of eight woody biomass samples, Biomass Bioenergy 66 (2014) 232–239, http://dx.doi.org/10.1016/j.biombioe.2014.02.015.

[38] F. Weiland, M. Nordwaeger, I. Olofsson, H. Wiinikka, Entrained flow gasification of torrefied wood residues, Fuel Process Technol. 125 (2014) 51–58, http://dx.doi.org/10.1016/j.fuproc.2014.03.026.

[39] M. Risberg, O.G. Öhrman, B.R. Gebart, P.T. Nilsson, A. Gudmundsson, M. Sanati, Influence from fuel type on the performance of an air-blown cyclone gasifier, Fuel 116 (2014) 751–759, http://dx.doi.org/10.1016/j.fuel.2013.08.008.

[40] N. Padban, First Experiences from Large Scale Co- Gasification Tests with Refined Biomass Fuels, Intern. Torrefaction Workshop CEBC, Graz, 2014.

[41] F. Biedermann, T. Brunner, C. Mandl, I. Obernberger, W. Kanzian, S. Feldmeier, et al., Executive Summary, SECTOR Deliverable D7.3 and D7.4, 2014.

[42] DBFZ. SECTOR, Publishable Summary, Reporting Period 2. Leipzig, 2014. Available at: http://cordis.europa.eu/result/rcn/149543_de.html [accessed on 15.07.15].

[43] C. Göbl, K. Jörg, U. Wolfesberger-Schwabl, Round Robin Report II – Validation of New Test Methods, SECTOR Deliverable D8.4, 2015.

[44] J. Kiel, Torrefaction – Process and Product Quality Optimisation, in: Intern. Conference – Biomass to Bioenergy, 2013 (Munich).

[45] ISO/CD 17225-8 Solid biofuels — Fuel specifications and classes — Part 8: Graded thermally treated and densified biomass fuels (ISO/TC 238/WG 2 N20005) 2015.

[46] S. Majer, E. Nebel, M. Gawor, F. Schipfer, L. Kranzl, M. Meyer, J. Priess, T. Chand, Executive Summary of WP9 Results, SECTOR Deliverable D9.8, 2015.

[47] V. Arpiainen, E. Alakangas, P. Kroon, M. Carbo, Report on Optimisation Potential towards the Quality of the Solid Energy Carriers, 2015.

[48] M. Carbo, S. Majer, F. Schipfer, SECTOR Specials: Value Chains, Economics and Sustainability; BioBoost and SECTOR Policy Workshop, 2015. Available at: https://sector-project.eu/fileadmin/downloads/workshop/2-5_SECTOR_Specials_Michiel_Stefan_FINAL.pdf [accessed 15.01.16].

[49] M. Carbo, P.M.R. Abelha, M.K. Cieplik, P. Kroon, C. Mourão, J.H.A. Kiel, Handling and storage of torrefied biomass pellets, World Biomass Power Mark. (2015) (Amsterdam).

[50] M. Wild, Torrefied Biomass: the Perfect CO_2 Neutral Coal Substitute Is Maturing, VGB PowerTech, 2015, pp. 72–75.

[51] D. Thraen, Exemplary Results of the SECTOR-project, ISO Meeting, York, 2015.

[52] P. Verhoef, Bioenergy in the European Context, BioBoost and SECTOR Policy Workshop, Brussels, 2015. Available at: https://sector-project.eu/fileadmin/downloads/workshop/Bioenergy_in_EUropean_context_final.pdf [accessed 15.01.16].

[53] Coal consumption statistics - Eurostat Statistics Explained. Available at: http://ec.europa.eu/eurostat/statistics-explained/index.php/Coal_consumption_statistics [accessed 31.07.15].

[54] J.J. Chew, V. Doshi, Recent advances in biomass pretreatment – Torrefaction fundamentals and technology Review, Renew. Sustain Energy Rev. 15 (8) (2011) 4212–4222, http://dx.doi.org/10.1016/j.rser.2011.09.017.