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

Project Final Report
Publishable Summary

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1 Executive summary

The European project SECTOR aimed at shortening the time to market for torrefaction technologies. A consortium with 21 partners from industry and science worked from 2012 to 2015 mutually on this goal successfully.

In torrefaction, biomass is heated up in an oxygen depleted atmosphere to approx. 200-320°C, removing water, partially volatile matter and destroying the fibrous structure. In combination with pelleting or briquetting, biomass materials can be converted into high-energy-density bioenergy carriers with improved behaviour in (long-distance) transport, handling and storage. Torrefaction also creates superior properties for biomass in many major end-use applications.

With these properties, torrefaction is seen as an enabling technology for the large-scale trade and implementation of biomass not only within Europe. Its potential end-user markets are co-firing and co-gasification in coal fired power plants, small to medium scale heat and combined heat and power (CHP) application as well as material uses such as chemicals. Also, torrefied fuels may provide a basis for liquid biofuels via gasification due to their superior and homogeneous quality. On the input side, torrefaction has the potential to broaden the feedstock base (e.g. straw, inhomogeneous residues).

The research work spanned the complete value chain. The biomass potential analysis provided data on woody and agricultural biomass, both as residue and energy crops. 21 feedstocks were chosen for tests in laboratory, pilot and demonstration scale. These included torrefaction and densification to optimize the quality of the torrefied fuels as required from end users. The properties included e.g. energy density, durability, dusting, grindability and hydrophobicity. Also the torrefaction processes were optimized in regards of costs and sustainability e.g. through heat integration concepts. The produced pellets were subjected to logistic tests in terms of long term storage and handling. The tests, varying the amount of stored material, duration, form and ambient conditions, such as humidity, revealed no major game stoppers for the optimized pellets. The assessment for end use in the above mentioned fields were based on extensive tests in existing plants and through modelling (CFD). Torrefied pellets also proved to be fit for application here.

The technical work has been accompanied by safety assessments, development of ISO standards (ISO 17225-8; both analysis and products; two large Round Robin Tests for existing and new methods performed), techno-economic assessment of major biomass-to-end-use value chains and a complete sustainability assessment. These revealed a broad range of scenarios were the application of torrefied fuels are superior to traditional biomass (i.e. white wood pellets).

Torrefaction is on the brink of commercialisation. The main market was seen in co-firing within coal fired power plants. The motivation for their operators are either quotas to be fulfilled resp. national support schemes or the use of (torrefied) fuels from biomass as a more economic option compared to the combined price of coal and emission certificates (EUA). The prices of both stayed lower than expected, leading to less competitiveness of torrefied material. Operators still interested in co-firing biomass started investing in equipment to use conventional biomass such as mills and storage. Through these lock-in investments, torrefied material loses its advantage of its application in the existing equipment for coal. Plant operators still interested in torrefied material face the problem of securing volume: to achieve relevant co-firing shares, they need to contract several torrefaction plants for longer terms, which the operators approach rather reluctantly. In turn, investors find it hard to obtain financing for large torrefaction plants, needed to supply power plants, without longer term purchase contracts. Therefore, a new market strategy is needed focusing on small and medium application and markets outside Europe, were the market opportunities are still substantial due to the non-existence of traditional biomass carrier routes (e.g. Asia, South Africa). Within Europe, first successful established business cases can further strengthen confidence in torrefied fuels and induce the final step for market implementation.

2 Context and main objectives

The torrefaction of biomass materials is considered to be a very promising technology for the promotion of the large-scale implementation of bioenergy. Torrefaction-based bioenergy carriers have been included as one of the seven value chains in the Implementation Plan and Technology Roadmap of the European Industrial Bioenergy Initiative (EIBI) and as part of the Strategic Energy Technology Plan (SET plan). This will accelerate innovation in cutting edge European low carbon technologies, increase Europe's security of energy supply and give a boost to the European energy industry sector towards improved sustainability.

Torrefaction has the potential to make a significant contribution to an enlarged raw material portfolio for biomass fuel production inside Europe by including both agricultural and forestry biomass. The main focus lies on residual materials. It may enable the opening of new feedstock sources worldwide and allow import into Europe in an economically and environmentally sustainable manner. For example, due to the high energy density of torrefied and densified materials, typically 3-5 times higher than the original biomass, the energy requirements for intercontinental transport can be limited to only a few per cent of the energy content of the bioenergy carrier. This is similar to the transport energy levels for coal. Due to the consistent quality of the torrefied product, it is possible that trading schemes similar to those for coal can be applied. With respect to the end-use, torrefaction-based bioenergy carriers may form a good starting point for (thermo-chemical) biorefinery routes.

Torrefaction starts with heating biomass in a low oxygen environment to a temperature of 200-340 °C. At these temperatures, a dry, torrefied product is obtained, which is stable, brittle and water resistant. This makes it much easier to grind than the parent biomass material and reduces the risk of spontaneous ignition and biological degradation in storage. By combining torrefaction with pelletisation or briquetting, biomass materials can be converted into a high-energy-density commodity solid fuel or bioenergy carrier with improved behaviour in (long-distance) transport, handling and storage, and also with superior properties in many major end-use applications. SECTOR project was focused on the further development of torrefaction-based technologies for the production of solid bioenergy carriers up to pilot-plant scale and beyond, and on supporting the market introduction of torrefaction-based bioenergy carriers as a commodity renewable solid fuel.

The specific objectives of the project were:

- 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 the product and 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)

This aimed to support the market introduction of torrefaction technology under strict sustainability boundary conditions. It has been of primary importance to feed the results of this assessment into international forums and groups involved in the development of sustainability criteria for specific biomass resources.

3 S&T results and foregrounds

The following chapters describe the work performed in the project. The work packages (WP) are structured along the value chain. Work packages 1 (Project Management) and 10 (Dissemination) are not described as they are of supportive nature to the research WPs. The detailed results can be found in the Deliverables of the project (referenced by DX.X) and various other publications listed at https://sector-project.eu/scientific-publications.14.0.html.

3.1 WP 2 Selection of relevant biomass feedstock

The first objectives of this WP was to provide a condensed assessment of worldwide available biomass potential studies for the production of torrefied pellets from both forest and agricultural feedstock (D2.2), and of the market demand with a special emphasis on co-firing with coal in pulverised coal fired-boilers (D2.4).

The raw materials are divided into three sub-groups:

1. Wood based fuels – round wood/stem wood, forest residues, other virgin wood, industrial by-products and residues, used wood
2. Agricultural biomass – herbaceous (cereal straw, corn, sunflower), woody (vineyard, olive trees);
3. Energy crops – herbaceous (Miscanthus, Reed canary grass), woody (poplar, willow, olive prunings)

Livestock residues, municipal solid waste or food industry residues are not included in D2.2, because these feedstocks are too challenging for torrefaction at the moment. The following tables give an overview of the findings (Table 1 and Table 2).

Table 1: Summary of woody biomass resources in Europe

Source	1,000 m^3	PJ/a
Stem wood	195 656	1 438
Landscape management wood residues	59	514
Forest residues	166 438	1 186
By-products and residues from wood processing industry	92 164	644
Used wood	52 000	397
Total EU-27	506 258	3 664
Ukraine	9 300	67
North-West Russia	103 900	748
Belarus, Norway, Switzerland	21 862	157

Table 2: Summary of agricultural biomass and energy crops potential in Europe

Resource	PJ/a	Source
Cereal straw	560	BEE, Böttcher et al. 2010
	600	DBFZ, Thrän et al. 2010
	960	BIOMASS FUTURES, Elbersen et al 2012
	983	MTT, Pahkala & Lötjönen 2012
Sugar beet	25	BEE, Böttcher et al. 2010
	36	MTT, Pahkala & Lötjönen 2012 (EU-25)
Sunflower	34	BEE, Böttcher et al. 2010
Rice husk	9	BEE, Böttcher et al. 2010

Resource	PJ/a	Source
Corn residues	85	BEE, Böttcher et al. 2010
Pruning residues, total	423	BIOMASS FUTURES, Elbersen et al 2012
Vineyard residues	14	BEE, Böttcher et al. 2010
Olive three prunings	28	BEE, Böttcher et al. 2010
Energy crops, vegetable diet	3 465	BEE, Böttcher et al. 2010
Energy crops, mixed diet	742	BEE, Böttcher et al. 2010
Perennial herbaceous biomass	1 642	BIOMASS FUTURES, Elbersen et al 2012
Agricultural residues (sugar beet, legume, potato, oil plants)	656	MTT, Pahkala & Lötjönen 2012
Miscanthus	3 324 – 7 651 18 100 (theoretical)	RENEW, Seyfried et al. 2004 BEE, Böttcher et al. 2010
Reed canary grass (theoretical)	8 110	BEE, Böttcher et al. 2010
Woody crops (poplar, theoretical)	12 713	BEE, Böttcher et al. 2010
Short rotation coppice	2 576 – 5 447	RENEW, Seyfried et al. 2004

WP2 has prepared a demand side report including an estimation of the demand at power plants, co-firing ratios, technical obstacles, impact on performance and investments and estimate of the acceptable price level of torrefied biomass (D2.4). For preparation of D2.4 a questionnaire regarding coal-fired power stations and torrefied material producers was send out. The purpose of the questionnaire to power plants was to give an estimation of the demand at power plants, co-firing ratios, technical obstacles, impact of performance and investments and an estimate on acceptable price level of torrefied biomass.

Power plants stated that in general, there is good potential for the use of torrefied biomass in coal plants, either for co-firing or complete conversion. However, there are still a number of uncertainties which still need to be resolved.

Pros (compared to “white wood pellet”)

- Increased energy density for transport
- Improved grinding in existing coal mills
- Increased throughput in existing coal mills
- Potential for reduced storage costs (outdoor storage is unproven, but higher energy density beneficial for indoor storage)
- Potential reduction in corrosive elements – could increase use of cheaper agro-biomass, but reduction currently unproven

Cons

- Higher price
- Dustiness, and explosive properties of this dust
- Off-gassing?
- Uncertainty in supply quantities and consistency
- Benefits not fully demonstrated yet

The second aim of WP2 was to select raw material for the experimental tests for WP3. The selection was based on results of the resource assessment study (D2.2) and resulted in D2.1 (Profiles of selected raw materials – Part 1). Property data were collected from 21 different raw biomass materials, which were determined according to the partners’ interest and in correspondence to the results of the existing biomass potentials. Classification of the raw material was based on standard EN 14961-1:2012. The final selection of raw material for testing in WP3 was carried out before June 2013 and resulted in D2.3 (Profiles of selected raw materials- part 2), which provided an update of D2.1. Feedstock profiles selected in D2.1 were reviewed and their relevancy in the remainder of the project discussed with partners involved, in order to propose new materials for torrefaction and/or pelletisation, or remove uninteresting material from previous selection, all based on lab and pilot test carried out in WP3. Also thermogravimetric analysis (TGA) values and information on this was added after tests in WP3 with additional property data and final results of biomass potential review. Partners agreed to select 21 raw materials for laboratory or pilot tests with increased emphasis on straw, forest wood and their residues. The assessment study (D2.2) was updated in June 2015 with information on forest wood supply costs from the INFRES project and with biomass potentials from the BioBoost project.

Main impacts of WP2:

- The progress beyond state of the art in WP2 was the combination of a variety of existing studies with a focus on materials suitable for torrefaction, which has not been done before.
- This gave a comprehensive overview and a starting point for material selection with regard to torrefaction and leads to added value for the project partners and the wider torrefaction community.
- Results of questionnaires on quality demands of producers and end users helped to find key research challenges for further development in other WPs.
- Requirements of raw material and quality issues helped WP8 to develop a product standard ISO 17225-8 for thermally treated densified biomass.

3.2 WP 3 Torrefaction

The objective of this work package was to further optimise the torrefaction technologies both to broaden the feedstock range and to allow the production of solid sustainable energy carriers with properties meeting the requirements set by the subsequent densification, logistics and end use. In this development and optimisation the economic, environmental and social prospects had to be ensured.

During the lab-scale tests a broad range of 21 different feedstocks, selected within WP2, were torrefied by means of thermo-gravimetric (TGA) analyses as well as a batch torrefaction reactor. These tests served as a quick scan to observe the behaviour of different materials under a broad range of torrefaction conditions, with only limited amount of samples and effort required to obtain a large matrix of results. Both the TGA and batch reactor tests provided the degree of torrefaction as a result of the operating conditions, while exothermic behaviour was determined through batch reactor tests. These test not only provided an idea how material would behave during torrefaction but also provide the operating conditions for the pilot torrefaction tests. Combined with feedback from WP 6 and 7, the torrefaction conditions were optimised in close conjunction with WP 4 to come to dedicated recipes for different feedstocks.

The pilot tests have been conducted in existing pilot-scale reactors with different reactor concepts and capacities, a total of 12 feedstocks were selected for pilot tests, with each technology testing between 3 to 6 feedstocks, as well as one reference feedstock for all plants to compare the mass and energy balances. These tonne-scale batches of torrefied material were used to conduct pelletisation and briquetting tests ranging from lab- to industrial-scale in WP 4, and subsequently for logistics and end-use testing in WP 6 and. The total pilot production summary is provided in Table 3.

Table 3: Summary of pilot torrefaction trials

No.	Selected feedstock	Partner responsible	Pilot test temperatures (ºC)	Pilot production [kg]		
				CENER	ECN	UmU
1	Delimbed coniferous stem wood without bark, (Pine as reference raw material 1)	ECN, UmU, CENER	240, 270, 260, 280, 291, 300, 308, 315	15.341	3.738	3.400
2	Logging residue, coniferous	UmU	286, 308, 325	-	-	3.400
3	Delimbed broadleaves stem wood with bark, (Beech, reference raw material 2)	CENER	270	4.619	-	-
4	Poplar	CENER, ECN	270, 280, 290, 300	8.466	4.058	-
5	Straw (Oat and wheat, Southern conditions)	CENER	250, 260, 270	8.680	-	-
6	Prunings from olive trees – woody biomass	CENER	250, 260, 270	1.836	-	-
7	Eucalyptus	CENER	250, 260, 270	196	-	-
8	Paulownia	CENER	250, 260	6.052	-	-
9	Bamboo	ECN	245, 255, 265	-	1.487	-
10	Bagasse	CENER	250, 260	Cancelled	-	-
11	Willow (Salix)	UmU	286, 308, 330	-	-	3.400
12	Spruce	ECN	240, 260, 280	-	16.973	-
			Subtotal	**45.190**	**26.255**	**10.200**
			TOTAL		**79.809**	

Pine was selected as reference material to execute pilot tests in all three pilot torrefaction plants. These tests were conducted in conjunction with elaborate analyses of the feedstock, product and gaseous process flows described in Deliverable D3.5, in order to produce accurate mass and energy balances of the different processes. The mass and energy balances were reported in Deliverable D3.4, and a comparative overview of the different technologies is provided in Table 4. The table demonstrates that 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. It should be noted that the UmU plant had not been optimised when the test took place.

Table 4: Main results and parameters from M&E balances of different pilot plants for pine torrefaction

Partner	Torrefaction technology	Heat transfer type	Mass yield [% db]	Energy yield [% db]	Net thermal efficiency [%]	Thermal energy Consumption [kWh/kg prod.]	Production capacity[1] [t/a]
CENER	Indirectly in- and externally heated rotating shaft	Indirect heating	79.0	90.5	92.1	0.46	31,041
UmU	Rotating drum	Indirect heating	75.7	87.9	83.6	0.30	114
ECN	Directly heated moving bed	Direct heating	81.3	87.6	92.4	0.34	112,682

The optimisation of the efficiency and economic feasibility of torrefaction processes by integrating the torrefaction step with existing forestry operations or biomass power and heat production has been elaborately described in Deliverable D3.2. This report includes a stream-lined mass and energy balance calculation of three stand-alone torrefaction processes based mainly on data provided by the partners within WP3 and WP5. Several integration cases were considered and economically assessed. The results indicate that large-scale stand-alone plants lead to the cheapest production costs which are in close proximity of white wood pellet market prices as displayed in Figure 1. The feedstock dominates a significant part of the production costs, hence the choice of location is evident. Furthermore the integrated options also demonstrate significant production cost reduction potential in comparison with the base case stand-alone plant, particularly for integration at saw mills and pulp mills.

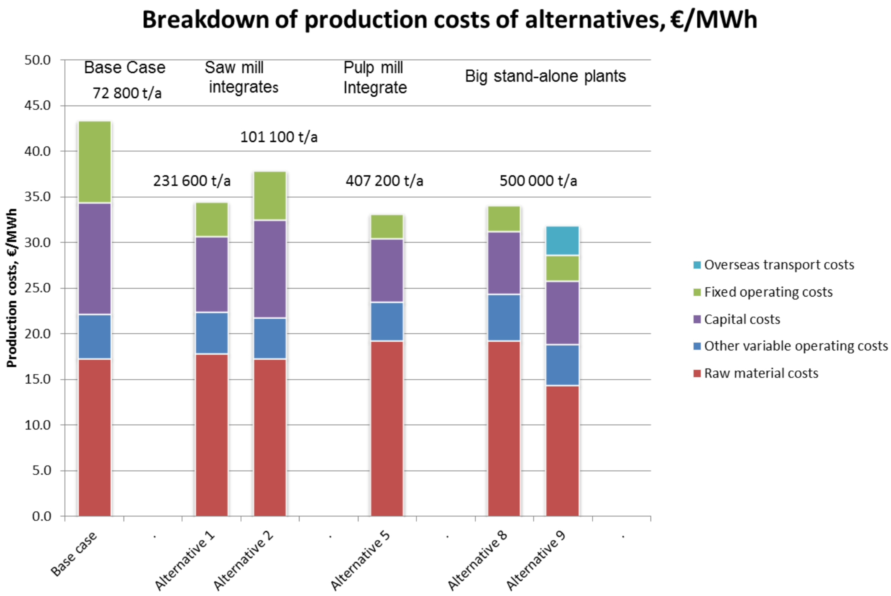


Figure 1: Overview of production costs of integrated and stand-alone torrefaction plants

In Deliverable D3.7, the purchase power for torrefied wood pellets over white wood pellets was determined. All additional costs for biomass co-firing excluding fuel costs were calculated for both 10% and 30% co-firing and 100% firing on energy basis. This was done for a 400MW_{el} power plant in the Netherlands with 6,000 annual operating hours. A loan

[1] Based on 8000 operating hours per year at full load

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 Figure 2. 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% and 100% firing. 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 imply that at a co-firing share of 30% or 100% firing, an excess price for torrefied wood pellets of 1.59 €/GJ or 5.72 €/MWh. The significantly lower investment costs could also offer flexibility to utilities when incentives for co-firing are subject to fluctuation.

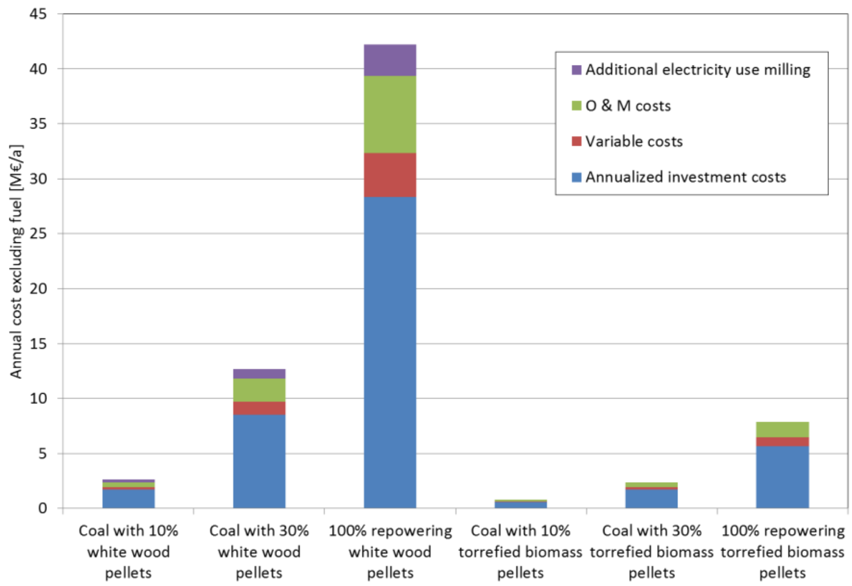


Figure 2: Annual cost of (co-)firing white wood pellets and torrefied wood pellets at 10% and 30% co-firing, and 100% firing share excluding fuel costs

The optimization of torrefaction processes towards direct (co)production of bio-chemicals and biomaterials was also investigated. An economic assessment was carried out for three different torrefaction cases including the recovery of chemicals in Deliverable D3.6. The results indicated that co-production and valorisation of chemicals could reduce the production costs of torrefied pellets significantly. The assessed cases were a stand-alone base case, new sawmill and new torrefaction plant integrate, and a large overseas stand-alone plant utilizing local wood. The organic chemicals are recovered from the torrefaction gas and can be used partially substitute phenol in phenol-formaldehyde resins for plywood production, or as biodegradable pesticides as described in Deliverable 7.1.

Impact:

The results and experience that were gained by the WP3 partners during the SECTOR project had been indirectly used during operation of lab-, pilot- and demonstration reactors. Examples are the broadening of the feedstock portfolio, such as the triticale torrefaction trials at ECN as part of the EU FP7 LogistEC project. But also the scaling-up of the technology to demonstration scale at the Industrial Demonstration Unit in Sweden (Umea) and the Andritz/ECN demo plant in Denmark. Furthermore numerous consultancy and R&D projects with other parties (feedstock owners, torrefaction developers and end users) have started afterwards that deploy knowledge gained in the SECTOR project.

The experiences from and input for large-scale co-firing trials with torrefied pellets were also exchanged with the SECTOR project partners, through tests at NUON/Vattenfall Buggenum

IGCC, The Netherlands (2012/2013), RWE/Essent AMER-9, The Netherlands (Topell pellets, Nov/Dec 2013), and DONG Energy Studstrup-3, Denmark (Andritz pellets, Apr 2014).

Furthermore the SECTOR project provided direction to future R&D, this will lead to broadening experience for alternative feedstocks (agricultural residues, invasive species and other alternatives) and the focus on upfront, in-situ or downstream removal of inorganic components, to produce high-quality fuels from low-quality feedstocks.

3.3 WP 4 Densification

Due to change of the chemo-physical properties of biomass during torrefaction, the densification properties of the biomass material are altered compared to raw biomass. The main objective of WP4 was thus dedicated to characterize and optimize the densification properties of different torrefied biomass materials according to end users requirement based on tests in lab and bench scale densification units (pellets and briquettes).

Torrefied biomass has to be compacted into solid bodies due to its porous and brittle structure, low density, to avoid dust and dirt formation during handling (health & explosion risk) and its overall poor handling properties. Densification of torrefied biomass through pelletization & briquetting is increasing the volumetric and hence the energy density of the original biomass resulting in lower storage and transportation cost. Furthermore, dust emissions are reduced and the product has a standardized size and shape, which eases handling, trade and processing. The used technology is adapted from wood pellet/briquette production. There were however some challenges when processing torrefied biomass, which were addressed in this project. A major problem observed under the pelletization of torrefied biomass has been the high friction generated during processing. The energy uptake of a pellet mill was up to 150 kWh/t compared to 50-60 kWh/t for untreated wood. Connected issues were heat generation in the pellet mill (risk of fire / dust explosion), lower capacity and more wear on the pellet mill parts. Also the pellet quality (durability, density, surface structure and moisture resistance) was below the requirement and end-user expectations.

The SECTOR project has taken these production related issues as a starting point for process optimization and quality improvements of torrefied energy carriers. A screening of densification properties to provide knowledge to the other project partners was made using the laboratory scale pelletization equipment at DTI. Tests were conducted in a single pellet unit at DTI with more than 50 samples, including spruce, pine, poplar, bamboo, willow, straw, mixed residues and more exotic biomass types such as sun flower husks torrefied under various conditions. Materials were received from project partners torrefaction units at ECN, CENER, UmU, SLU, Topell. The results have been used to optimize the processing conditions for the large scale densification trials (Table 5).

Table 5: Large scale densification trials

No.	Selected feedstock	Partner responsible	Torrefaction Temperatures (ºC)	Pilot test production			
				CENER	ECN	SLU	DTI / CF Nielsen
1	Delimbed coniferous stem wood without bark, (Pine as reference raw material 1)	ECN, UmU, CENER	240, 270, 260, 280, 291, 300, 308, 315	11.680	1.200	581	-
2	Logging residue, coniferous	UmU	286, 308, 325	-	-	581	-
3	Delimbed broadleaves stem wood with bark, (Beech, reference raw material 2)	CENER	270	4.236	-	-	-
4	Poplar	CENER, ECN	270, 280, 290, 300	7.685	3.800	-	-
5	Straw (Oat and wheat, Southern conditions)	CENER	250, 260, 270	7.258	-	-	-
6	Prunings from olive trees – woody biomass	CENER	250, 260, 270	1.836	-	-	-
7	Eucalyptus	CENER	250, 260, 270	146	-	-	-
8	Paulownia	CENER	250, 260	6.157	-	-	
9	Bamboo	ECN	245, 255, 265	-		-	600
10	Bagasse	CENER	250, 260	Cancelled	-	-	
11	Willow (Salix)	UmU	286, 308, 330	-	-	581	-
12	Spruce	ECN	240, 260, 280	-	4.666	-	600
			Subtotal	**38.998**	**9.666**	**1.743**	**1.200**
			Total	**51.607**			

Throughout the project, pellet quality data have been compiled for the quality analysis of the produced pellets. The produced pellets and briquettes were analysed according the European standard for wood pellets EN-14961.

Another key issue in the SECTOR project has been to develop production recipes for an optimized product and production process. This aim has successfully been reached by an incremental improvement of pellet quality throughout the project.

Parameters optimized were:

Raw materials
Torrefied hardwoods, softwood and agricultural residues have been tested in SECTOR. Species-related differences result in different processing requirements and product quality.

Torrefied hardwoods such as poplar, beech and willow were relatively easy to pelletize compared to other torrefied wood species. Especially torrefied poplar resulted in high product quality while observing a moderate increase of friction.

Torrefied softwoods such as spruce and pine can be pelletized into high quality pellets by optimization of torrefaction and pelletization parameters.

Torrefied grasses and husks can be regarded as “challenging” raw materials with respect to mechanical quality of the pellets (durability and strength). However, process adjustments can improve the quality significantly.

Degree of torrefaction
Generally, high torrefaction degrees (long torrefaction time and/or high temperatures) result in a more severe degradation of the biomass polymers hemicelluloses, celluloses and lignin.

- The greater the degree of torrefaction the more difficult it is to establish inter-particle bonds required to form a stable pellet
- Removal of hydrogen bonding sites (less H-bonding)
- Depolymerisation (less polymer bridges)
- Destruction of fibre structure (less fibre entanglement)

Moisture addition

- Water acts as a plasticizer lowering the softening temperature of lignin
- Reduction of friction
- Improving of bonding (better pellet durability and strength)

Additives (Lubricants / Binders)

- Additives can be used to reduce friction (lubricating effect) and to improve the pellet strength (inter-particle bonding)
- Oils, lignin and carbohydrates have been tested in SECTOR
- No additive could be identified that could both reduce friction and improve pellet strength at the same time

Temperature during pelletization

Increasing the temperature during pelletization reduced friction and improved pellet strength (softening and flow of biomass polymers) as shown in Figure 3a

Design of pelletizing die

- Capacity highest at 8 mm (Figure 3b)
- 6, 8, 10 and 12mm dies (diameter) have been tested with 6 mm resulting in the highest durability (Figure 3c)

Rotation speed / Holding time in press channel

- Slower speed/lower capacity results in slightly higher durability of the pellets (prolonged time in the press channel where pellet is exposed to heat and pressure)
- Capacity is related to rotation speed of the die
- More studies required to confirm this
- Same for holding time in briquetting press → keeping the briquette under heat and pressure improve the stability

Particle size

- increased particle size resulted in a decrease of the pellet density,
- small particles occupying all available empty spaces in the bulk and thus increasing the density.
- pellets pressed from smaller particles are shorter with higher bulk density

Combined effects:

Parametric study varying degree of torrefaction, moisture content, particle size and densification temperature has been conducted

- Mutual correlations between torrefaction and densification parameters have been found.
- Results are published here: Rudolfsson M, Stelte W, Lestander TA (2015) Process optimization of combined biomass torrefaction and pelletization for fuel pellet production–A parametric study. Applied Energy, 140:378-384.

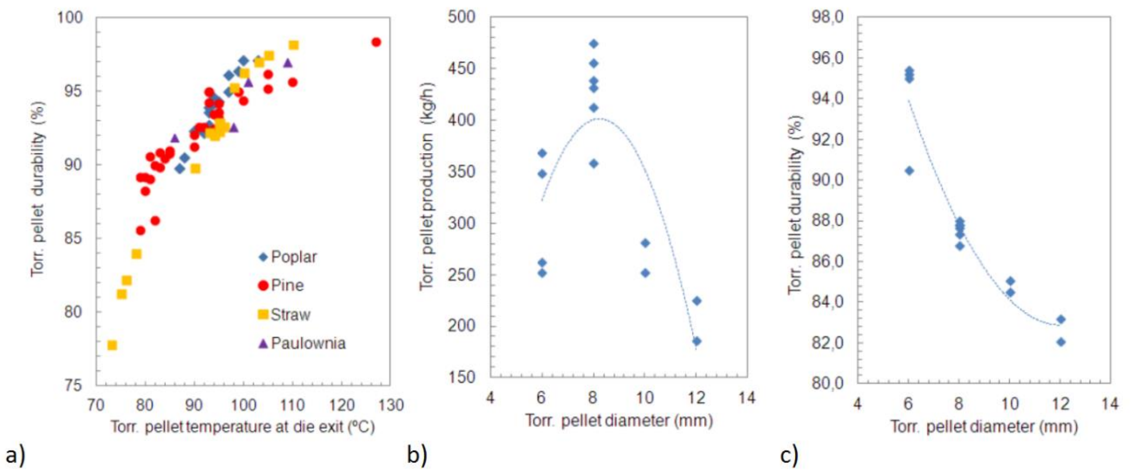


Figure 3: a) Pellet durability in correlation to pelletizing temperature b) pellet production capacity in dependency of the pelletizing die diameter c) pellet durability dependency of the pelletizing die diameter

3.4 WP 5 Demonstration Tests

The main objective of WP5 was the production of sufficient amounts of pellets from torrefied biomass for the logistics and end-use testing in WP's 6 and 7, besides other smaller amounts for other WP's. The production of these torrefied materials should be optimised in order to obtain the quality demanded for logistics and end-use.

The Topell plant was already operating at the start of the project so pellets from forest residues were produced since the first month of the project. However, these pellets did not meet the quality requirements for some of the tests programed in WP's 6 and 7 in terms of mineral content in the product, torrefaction degree and pellet durability, mainly as a result of the instability of the combustor in the plant. Some of the pellets produced were delivered to several partners, upon their request.

In the last quarter of 2012 Topell decided to make a major overhaul of the plant, changing the combustor, improving the heat integration of the torrefaction plant and optimising the milling and pelleting steps.

In June 2013 Topell restarted the plant with the new equipment and production of pellets could be achieved in August. Through optimisation of production recipes, the required product quality could be achieved in October. All the amounts of pellets demanded by the different partners of the project were produced until the end of 2013 and shipped to the different project partners between 2013 and 2015, satisfying all the product demands within the project.

After achieving optimisation of torrefaction and pelleting processes, mass and energy balances of the whole plant but also specifically of the milling and densification steps were developed in order to allow comparison between the different torrefaction techniques within the project and as an input for value chain and feasibility studies in WP9 respectively.

The main results achieved within this WP are:

- Proof of concept of Topell's torrefaction system in 2013 at commercial scale.
- Achieved continuous production of torrefied material and pellets from torrefied biomass at commercial scale with a smooth and easy operating system.
- Achieved and demonstrated continuous production of pellets from torrefied biomass at commercial scale with the product quality required by end consumer (co-firing biomass in power plants). All the product demand within the project was satisfied.

- Achieved and demonstrated full heat integration within the plant, including using the gas produced during torrefaction process to supply most of the heat demand of the plant, including the drying and the torrefaction steps.
- Proofed the viability of co-milling and co-firing with coal up to 25 wt-% on one coal mill/burner.
- Proof that for torrefied pellets lower quality feedstock can be used compared to wood pellets.

Potential impact:

- Development of torrefaction plants based on Topell's torrefaction technology by parties involved in the energy sector.
- Promote torrefied wood pellets as a sustainable energy commodity in large and small scale applications substituting fossil fuels and wood pellets.
- Promote the use of low quality feedstocks for energy purposes by upgrading them via torrefaction.

The results achieved in WP5 allowed demonstration of Topell's torrefaction technology at commercial scale. Being the only party up to date able to demonstrate its own torrefaction technology at commercial scale promoted Topell to a leading position in the torrefaction technology market. The positive results obtained in small but also in large scale tests in other work packages within the project when using Topell torrefied wood pellets (eg. WP6 storage tests and WP7 co-milling and co-firing tests) have demonstrated the ability of torrefied pellets to be processed in existing equipment and facilities, most important to existing coal fired power plants. Through all these tests the superior characteristics of torrefied wood pellets have been also demonstrated compared to white wood pellets when replacing coal but also in biomass based energy equipment and plants.

All these advances have promoted the current interest that parties around the world are showing towards developing torrefaction plants to use biomass resources scarcely used up to date, while upgrading streams currently with low or none market value, which is a benefit not only for Topell but also for the whole torrefaction technology developers and product suppliers.

Capitalising on technology and production successes of Topell Energy between 2008 and 2015, Blackwood Technology has taken over Topell technology and engineering team to further develop and commercialise its technology and torrefied products since November 2015. As a result Blackwood Technology is already working on engineering of different projects towards construction of torrefaction plants in the near future.

3.5 WP 6 Logistics

The objective of this work package was the assessment of the transport, handling and storage properties of torrefied and densified biomass. The results of these logistics tests were to induce interactive adjustment of the torrefaction and densification process and of the physical and chemical requirements for the feedstock.

Dry matter losses for torrefied pellets, white wood pellets, a blend of coal and torrefied wood pellets and torrefied wood pellets obtained after outdoor storage trials were subjected to climate chamber experiments. 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 are displayed in Figure 4, which demonstrates that white wood pellets are much more prone to biological degradation while torrefied biomass pellets are much more resistant to biological activity, thereby also reducing the risk of self-heating. These results have been addressed in Deliverable D6.6.

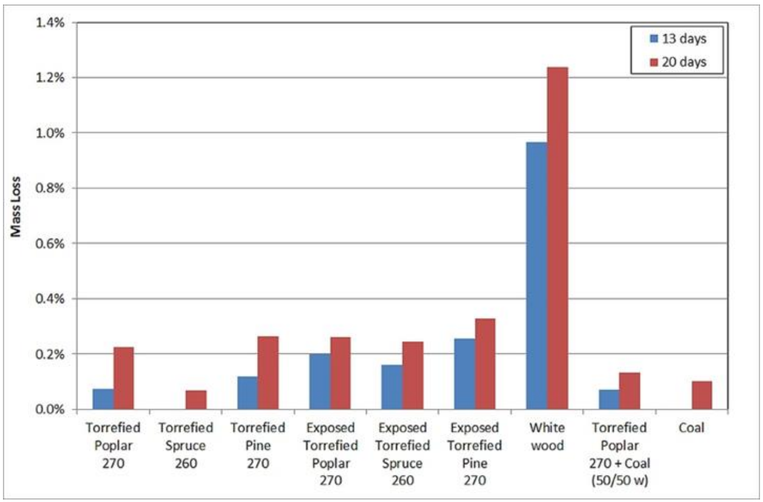


Figure 4: Climate chamber biological degradation test with different materials

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 Figure 5. 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 appear to affect the MIE, and as such the explosivity. As such, existing explosion mitigation systems could be used to mitigate any risks during milling of torrefied biomass pellets. The results have been described in Deliverable D6.5.

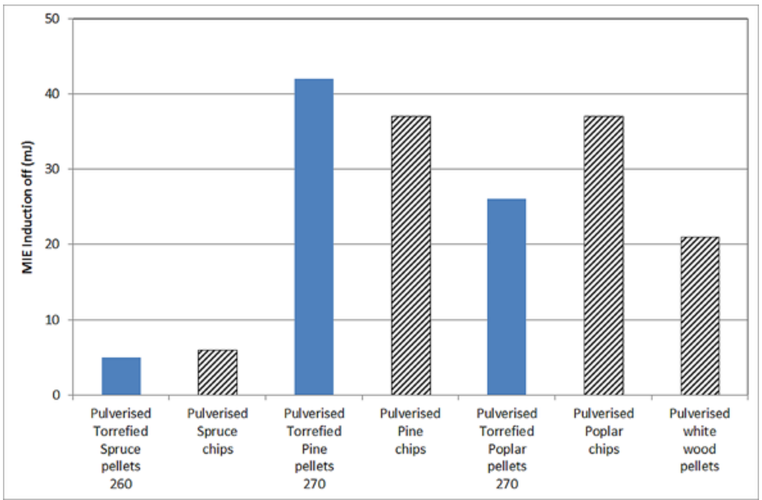


Figure 5: Minimum Ignition Energy (MIE) of dust samples obtained from pellets and chips (corresponding original material) through a cutter mill (fraction below 63 µm and dried at 75 °C)

Small-scale outdoor storage tests have been conducted to simulate the pellet behaviour in the surface layer of larger stockpiles. Precipitation and drying appeared to have the largest impact on the bulk density and the mechanical durability, pellets with a high initial mechanical durability display improved weather resistance. Covered outdoor storage that merely shields the rain only appears to affect torrefied pellets with a relatively low mechanical durability. In case the mechanical durability was higher than 96-97%, no adverse effects were noticed during the storage period. This implies that for elongated storage periods longer than one or two months simple technologies could be used to cover torrefied pellets from the rain, such as sheeting.

The larger stockpile tests revealed that torrefied pellets appear to be unsuitable to be stored outdoors uncovered for long durations of for instance one year. During this timeframe the moisture content in the piles increased gradually, which will in time lower the net calorific value of the material resulting in higher fuel input to reach the same thermal output in the power plant. Long term storage can take place outdoors provided that the stockpiles are covered, either by a mechanical structure or perhaps even by plastic sheeting.

Shorter storage periods of a few weeks or months appear feasible, although in the surface layer of the stockpile, being the first 10-20 cm, degradation of torrefied pellets will be observed, as displayed in Figure 6. The excavation of the stockpile therefore might 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 another surface layer. The dust obtained from the degraded surface layer of torrefied pellets displayed a minimum ignition energy that was approximately an order of magnitude higher than for dust generated from white wood pellets, implying that the dust generated during handling of degraded torrefied pellets is less prone to explode.

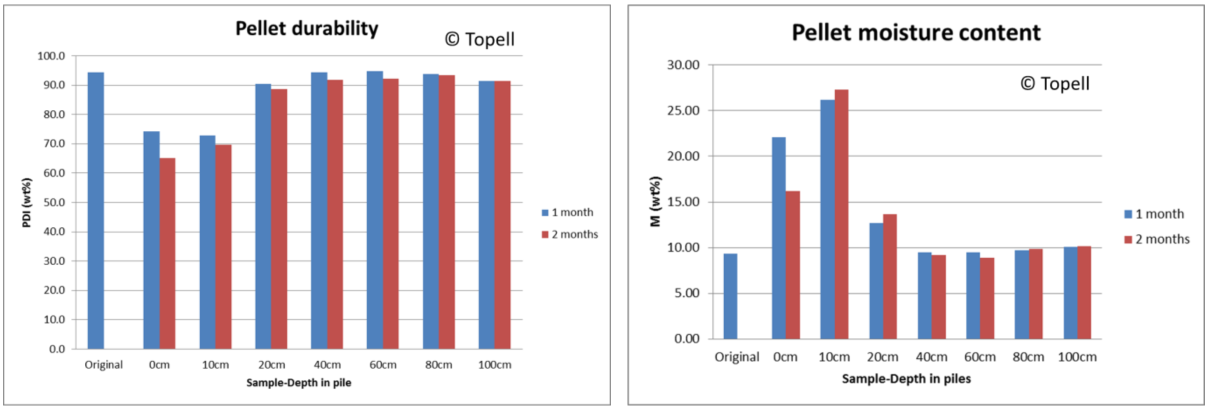


Figure 6: Mechanical durability and pellet moisture content at different depth of the stockpile after 1 and two months of direct outdoor exposure

The tests showed that while water absorption and degradation of the surface layer occurred in the first few days of testing, water penetration into the centre of the pile took longer time. In theory when translating these results to the full scale and stockpiles with much greater volume to surface area ratio, it could therefore be expected that only a small percentage of the fuel would suffer from moisture absorption prior to consumption.

Excluding the impact of the increased moisture content, the basic chemical analysis of the fuels throughout testing did not show any significant differences. Temperature monitoring within all the piles did not give any evidence of self-heating, with temperatures generally tracking those of the ambient air, although temperatures in the centre of the piles were usually somewhat higher.

The torrefied pellets displayed increased water resistance compared to white wood pellets. White wood pellets are well-known to swell and disintegrate on any exposure to rain, to the extent that transport ships will cease discharging at the first drop of rain. For the first few weeks of the testing, only the surface layer of the pellets showed increases in moisture content and corresponding decreases in mechanical durability. For the large quantities of material needed by power plant, this surface layer would be a low percentage 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 or to allow discharge & movement of biomass materials in more weather conditions. Evaluation of the necessity of this flexibility and whether it provided a sufficient value case to justify the use of torrefied material as opposed to white wood pellet would have to be undertaken on a plant by plant basis.

The results that were obtained from this work package provided valuable data that debunk a number of biased assumptions about torrefied materials. Within the SECTOR project it was proven that the Minimum Ignition Energy for dust explosion of torrefied wood is a function of the feedstock, and not of the torrefaction process. Torrefied wood pellets proved to be less vulnerable to biological degradation and are hydrophobic, which reduces self-heating tendencies. Higher torrefaction temperatures tend to result in relatively lower self-ignition temperatures, however the dependency between catalytic effects of inorganic components and the self-ignition temperature could not be clearly established. Torrefied wood pellets demonstrated much better weather resistance than white wood pellets, which makes discharging and on-site logistics and storage more straightforward. Outdoor storage is possible for a number of weeks/months; the pile surface will be affected but this is a minor share of a total pile volume. Longer term storage should be covered simply by sheeting. The mechanical durability of the pellets is a good indicator for weather resistance, however it should be noted that it is important to attain a uniform low moisture content of the pellets to allow for proper mutual comparison (in accordance to the standard pellets are to be tested as received, which simply does not provide accurate results for pellets that have been stored outdoors).

The small-scale outdoor storage protocol has also been used in Dutch national torrefaction co-firing project “Pre-treatment/INVENT”. Furthermore the developed hydrophobicity test method will likely be included in the revised ISO standard for thermally treated materials.

3.6 WP 7 End-use

The implications of introducing torrefied biomass in existing pulverized coal-fired boilers and gasifiers were investigated in close collaboration with power producers within the project. In this respect, an inventory of potential issues that could affect the integrity of representative coal-fired boilers and gasifiers when introducing torrefied biomass was made. The possibility for utilization of torrefied biomass in small-to-medium scale commercial pellet boilers (traditionally operated with non torrefied, white wood pellets) was considered and investigated. While the handling aspects such as milling and feeding were an important part of the investigations, torrefaction-based bioenergy carriers or byproducts of torrefaction were also evaluated as a possible feedstock for bio-refinery applications.

Co-milling coal and torrefied biomass pellets in a coal mills

The possibility of co-milling torrefied biomass together with coal in coal mills was demonstrated by tests performed in industrial mills, e.g. roller mills and ball and ring mills. The advantage of this approach would be to reduce infrastructure investment costs and provide more incentive for coal-fired power plants seeking to reduce their CO_2 emissions by co-firing with torrefied biomass. The results of the work are reported in detail in Deliverable D7.9 and D7.10.

The results from a large scale ball and ring mill (16t/h) demonstrate that co-milling is feasible to a high mass share of 30% of the torrefied biomass in the fuel mix. Based on industrial scale demonstrations (321MW), the combustion stability or burnout is not adversely affected by co-milling and subsequent co-firing (up to 15% thermal share). Co-milling torrefied biomass at higher shares (above 30%) in the coal mill will lead to mill derating due to the lower volumetric energy density of torrefied biomass compared to coal. The derating for white pellets will be higher due to lower volumetric energy density as well as poor grindability. Co-milling in such a coal mill would produce a finer product size distribution for the torrefied biomass rather separate milling in the same mill.

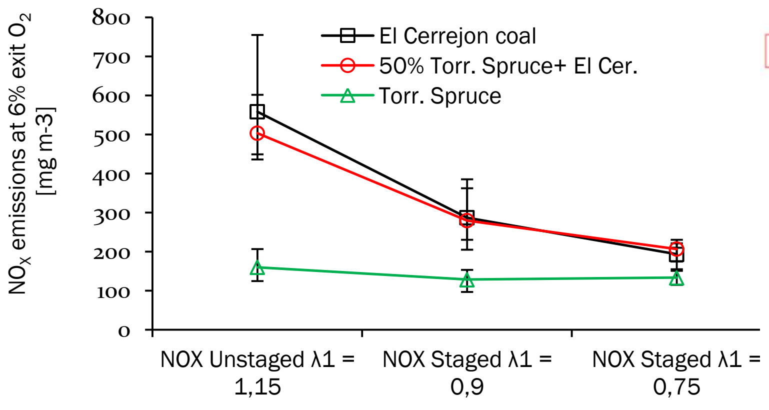
During torrefaction, the hemi-cellulose fraction which is responsible for the fibrous nature of biomass is degraded, thereby improving biomass grindability. Increase in torrefaction severity would lead to a more friable fuel and consequently a more grindable fuel. This however makes the fuel much more difficult to compact and pelletize, leading to dust problems as the pellets would not be durable enough. It is necessary to find an optimum that satisfies the handling criteria as well as the grinding properties. Finally, pulverized non-torrefied biomass particles are very heterogeneous and needle shaped. The shape of pulverized torrefied biomass is closer to coal this favours conveyance in conventional coal pneumatic feeding systems.

Co-firing in pulverized coal boilers

Tests at 500kw pilot plant scale

The key combustion related issues were investigated in single-burner pilot scale facilities (500kW) at University of Stuttgart (Germany) and Institute of Power Engineering (Poland), followed by CFD evaluations using ANSYS and carried out by Procede (Netherlands). Detailed work is contained in Deliverables D7.5 and D7.10.Based on experimental data, the following conclusions were drawn:

- Sulphur and nitrogen contents of woody biomass fuels are low. Blending woody biomass with coal lowers the emissions of SO_2 mainly as a result of dilution. NO_X emissions have a much more complex dependency on the nitrogen contents of fuels. Factors such as volatile content of the fuels, flame length, furnace and burner configurations also impact the final NO_X emissions. Due to the lower nitrogen contents, it is also possible to reach lower emissions. Primary measures such as air staging will further reduce the NO_X (Figure 7). For coal, air staging is already established as an effective measure for NO_X reduction.
- Sulphur from the coal helps to reduce the formation of KCl from biomass in deposits through the preferable formation of potassium sulphate.
- Similarly, coal containing aluminosilicate ashes also reduce the formation of low melting alkali silicates and consequently the slagging tendency. Capturing alkalis from the biomass by aluminosilicate from the coal reduces its availability possibility to condense as salts and consequently reduces fouling tendency and corrosion propensity.



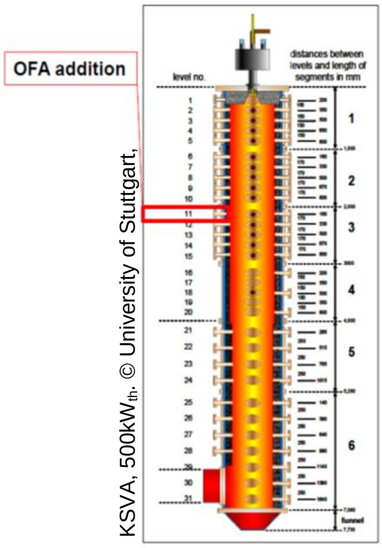


Figure 7: Impact of air staging at primary lambda (λ1) 0.9 and 0.75. NOX emissions during El Cerrejon coal and Torrefied spruce (co)firing in down-fired 500kW pilot-scale plant (right).

Co-firing in pulverized coal boilers: CFD assessments for full scale plants

CFD assessments were carried out on two typical full scale utility boilers in UK and Poland that normally burn pulverised hard coal. Detailed work is contained in Deliverables D7.5 and

D7.8. In general, it was concluded that the effects are manageable. The most important observations on the effects of replacing coal with torrefied biomass are

- 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.
- 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 25%.
- The flame will also start more quickly and grow backwards towards the burner.
- When a mixture of coal and torrefied material is used, a higher fraction of unburnt char is found in the fly ash. This is due to a lower percentage of ash from the biomass.

Co-firing in pulverized coal boilers: Full scale trials

Full scale co-firing test was successfully carried out at the Hanasaari Power Plant in Finland. During the test campaign, torrefied biomass was co-milled up to 30% mass share and co-fired up to 15% thermal share in the boiler. As comparison, white pellets were also tested (with co-firing share at about 12% thermal basis in the boiler). Detailed results are contained in Deliverable D7.10

Co-firing shares reached a 15% thermal share in the 321MW boiler. The fluctuation of CO emissions during torrefied biomass co-firing was observed to be reduced indicating a more stable combustion. Co-firing with white pellets on the other hand was characterized by higher CO emissions and fluctuations which indicates poor combustion burnout. This was verified by measurement of carbon in fly ash and bottom ash collected. The burners at the power plant are low-NO_X coal burners and the emissions of NO_X were not significantly changed during torrefied biomass co-firing compared to the coal case. Measured NO_X was 4% lower compared to the coal case. The plant is fitted with a semi-dry scrubber to keep limit values for SO_X. SO_X are directly related to sulphur content in fuel and this decreases with reduced S input from the fuel. Dust emissions after the electrostatic precipitator (ESP), at the stack for both biomass co-firing cases were lower in comparison to coal cases. ESP function depends on several factors such as flue gas composition, temperature etc. Inorganics from biomass may however have a longer term net negative impact on the ESP.

Co-Gasification in entrained flow reactors

Tests focused on evaluating the feasibility of operating the various systems with different torrefied materials compared to their standard reference fuels. Effects of different raw materials, torrefaction degree and densification on logistics, milling and feeding were determined. The impacts of process temperature, load, λ and relative oxygen content (ROC) on gas quality, gasification process behaviour and efficiencies were also determined. The co-gasification of torrefied biomass and coal were carried out at different facilities including a full-scale 240 MW coal-fired Entrained Flow Gasifier in the Netherlands.

The entire work has been reported in Deliverables D7.2, D7.6 and D7.11. A summary of findings are as follows:

- 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 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 content in the syngas was reported.

- Syngas composition and quality remained approximately the same as for the reference fuel, and very close to chemical equilibrium values.
- Tar (polycyclic aromatic hydrocarbons) fingerprints in the syngas were documented to be in low concentrations and approximately the same for gasification of white and black pellets.

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

Fundamental investigations of the combustion behavior of torrefied biomass pellets were performed in a lab-scale reactor as well as utilizing thermo-gravimetric analysis. A particle layer model was adapted while CFD simulations of the selected combustion trials was also performed. Additionally, combustion technology screening and fuel assessment trials were performed in state-of-the-art pellet heating systems such as understoker, grate and overfed boilers up to $50kW_{th}$. The tests were performed under continuous as well as under variable power output conditions.

Detailed reporting of the experiences and research highlights have been done in Deliverables D7.3, D7.4 and D7.7. The main highlights are as follows:

- Torrefied wood pellets have the potential to provide at least the same or even a higher combustion efficiency as is achievable with wood pellets, however it has to be considered that higher char contents in torrefied fuels lead to increased need for burnout time (adaptations of the grate and the burnout zone are therefore possibly required).
- 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 level of pollutant emissions is largely similar to that of wood pellets, given that similar wood resources are used. This was observed for CO, NO_x and PM emissions. However, due to the higher expected fuel bed temperatures of torrefied fuels fine particle emissions may increase.
- The use of torrefied pellets may be associated with a higher share of slag formed during combustion due to the higher fuel bed temperatures expected. Measures to inhibit slagging are therefore of major relevance.

Utilization of torrefaction condensates

The quantity and quality of condensates produced from different biomass fuels during torrefaction were studied at VTT Technical Research Centre of Finland Ltd. and Energy Research Centre (ECN), Holland in order to assess the utilization routes for these condensates.

The findings (reported in Deliverable D7.1) indicate differences in the amounts and compositions of condensates between the feedstock and the temperature phases during test runs in a slow pyrolysis reactor. Mass yields and compositions of torrefaction condensates differed between softwood, hardwood, and herbaceous feedstocks and temperature ranges. At a higher final temperature (above 290 °C) strong exothermic reactions occurred, which decreased the yield of torrefied material considerably and produced tar containing condensates. The total condensates formed at ≤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 product. Due the low heat transfer in the slow pyrolysis reactor, the reactor may not be representative of all torrefaction plants. At a pilot scale torrefaction plant (ECN, Holland), torrefaction condensates at different torrefaction temperatures using the slowly moving bed pilot reactor was demonstrated.

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 an economical way for utilizing the condensates.

3.7 WP 8 Fuel specification, lab analysis and quality assurance

The work package aimed at verification, development and application of analysis methods to access fuel properties of torrefied biomass. Moreover, a material safety data sheet (MSDS) was developed and all the gained information and data of torrefied biomass is used as input for international standardization work.

Parameters like moisture content, bulk density, ash content, carbon content, hydrogen content, nitrogen content, major and minor elements, chlorine content, sulphur content, volatile matter etc., are optimised for solid biofuels but not for torrefied biomass. Since torrefied biomass gains increasing interest, a proper characterisation of these new fuels seems reasonable. Extending the applicability of methods for solid biofuel to torrefied materials was determined as a first step. For the applicability of the methods and a respective validation an international round robin was performed. The validation of existing methods was reported in D8.1 Round Robin I - Validation of “standard” test methods. A total of 43 laboratories of 17 countries participated in the round robin test of 11 different test methods. These “standard” test methods worked very well for torrefied material. However torrefied material showed a significant different behavior concerning some fuel properties (e.g. hydrophobicity), which could not ascertained with these standard test methods.

For a better description different new analysis methods were developed. For a validation of the newly developed methods a second round robin test (D8.4 Round robin report 2 – Validation of “new” test methods) was organized. Overall 31 testing laboratory from 15 countries participated in 6 different test methods. Within WP8 it was decided that only the methods “Water absorption” (OFI) and the “Grinding energy” (DBFZ) are part of the second round robin test. For various reasons the other methods were not being offered. For some methods most laboratories did not have the equipment (e.g. TGA) or a test in round robin was not necessary (e.g. degree of torrefaction). However the methods “Water absorption” (OFI) and “Grinding energy” (DBFZ) should give a better overall description of torrefied biomass for the end-user as well as the producers. Hence, this could also lead to possible new standards for torrefied materials, which could increase the quality of torrefied biomass. To support the use of torrefied biomass (pellets), a proposal for a new product standard in Europe and a worldwide standard was drafted in the SECTOR project. The development of a material safety data sheet (MSDS) for torrefied material as fuel was an additional objective of the work package.

The developed methods for an extensive description of torrefied material included hydrophobicity/water absorption, degree of torrefaction, grindability & hardness, particle size, size distribution & flowability properties, NIR spectroscopy, leaching behaviour, and a TGA method.

The method water absorption is based on an immersion method of torrefied pellets in combination with a determination of mechanical durability before and after the water absorption test. The two parameters of the method are the water absorption (%) and the loss of mechanical durability (%). For a seamless application of torrefied pellets in e.g. a co-combustion plant an adjustment of the mills will be required. Therefore the method grindability was developed for a standardized measurement of the grinding energy required during the milling process of torrefied biomass pellets. The main parameter of this method is the specific grinding energy (Wh/kg). The degree of torrefaction was defined as the anhydrous weight loss during production of the torrefied material. Another parameter, which could describe the torrefied material, is the loss of volatile matter in dependence on the raw material. The particle size distribution and the share of fine particles as well as the particle length methods apply for torrefied and non-torrefied pellets. Therefore the method was improved by a novel image analysis method allowing for the measurement of large sample sizes within a short period time. Because of various reasons it was not reasonable to create a method for the measuring itself but it was deemed more useful to ensure the image analysis method would provide meaningful results by defining a procedure for testing and calibrating the instrument. The results of the measured bridging tendency and the angle of repose of torrefied pellets are comparable to non-torrefied pellets results and no further adjustment is necessary. The NIR spectroscopy method combined with multivariate calibration modelling is a technique for on-line prediction of various parameters e.g. grosses calorific vale, volatile matter or fixed carbon content of torrefied materials. The laboratory leaching test was developed to assess the possible environmental effects of torrefied pellet storage in open area fuel storage areas. The method is based on an immersion test of torrefied pellets in a filtration bag and the leachate is analysed for various parameters such as suspended solids, pH, nutrients, COD/TOC, DOC, etc. Thermogravimetric analysis (TGA) is a simple, fast and very informative method for assessing the torrefaction behaviour of different raw materials in small scale. After different pre-test a defined heating program was developed which was used by all partners within the SECTOR project to ensure comparable results.

Additionally different properties of torrefied material were investigated and evaluated. The control analysis of all produced torrefied material and corresponding raw material was conducted for a complete description of all materials within the project as well as a creation of a data pool of different torrefied materials. The influence of the torrefaction temperature, torrefaction time on parameters like carbon content, net calorific value, ash melting behavior, etc. was assessed for an overall statement about torrefied biomass.

The round robin I results showed an applicability of the existing biomass standards for torrefied material. The methods bulk density, mechanical durability, moisture content, ash, calorific value, chlorine content, sulphur content, volatile matter, carbon content, hydrogen content, nitrogen content, ash melting behaviour and major and minor elements were tested and evaluated with existing data of biomass round robin tests which showed a large concordance.

For Round Robin II two newly developed methods were chosen due to their importance for the end-user and major difference to non-torrefied biomass properties. Also other methods, like carbon content, gross calorific value, ash melting behaviour and diameter and length of pellets, were offered in this round robin test, to check and extend the data from SECTOR Round Robin I. This validation round robin was one goal of the SECTOR project. It furthermore should address doubts if the methods deliver reasonable accurate results for torrefied biofuels.

Due to the fact of the different water behaviour of torrefied and non-torrefied biomass materials the assessment of the water absorption gives an insight on the possible diverse storage condition and handling conditions for torrefied biomass materials. For the round robin II the method water absorption was divided into two parts to ensure a high participation of different laboratories. First part was the immersion test, to describe the water absorption ability of torrefied material. Second part was the determination of mechanical durability loss after the water absorption in order to make a clear statement about the influence of water contact on the mechanical quality of the torrefied pellets. The other method, grinding energy, should be a possibility, to determine the hardness of compressed materials and the comminution properties. Thereby a specified amount of pellets was grinded in a lab mill and the energy consumption was measured and so the specific grinding energy could be determined.

Both new methods showed promising results and valuable data and comments from participants were gained. With slight changes in the method description those methods could be adopted for standards.

Concerning safety and handling of torrefied biomass materials for the end-users, the material data and safety sheet is crucial. The outcome of the development of a MSDS is a MSDS-template for torrefied biomass referring to the EU regulation EU 1907/2006 (REACH). This document provides a template for a specific MSDS which has to be modified to the users' product properties. Companies can use the template, but will have to modify it according to their own specific product. It shall ensure a safe and secure handling of torrefied biomass on the market. A MSDS should ensure a free trade between countries and business partners.

Concerning the standardization work required in WP 8, a standard will be published in Europe as EN ISO 17225-8 "Graded thermally treated and densified biomass fuels". Thermal treatment includes processes such as torrefaction, steam treatment (explosion pulping), hydrothermal carbonization and charing, all of which represent different exposure to heat, oxygen, steam and water. The already published EN ISO 17225-1:2014 has also property classes for thermally treated pellets and briquettes, charcoal and thermally treated biomass (undensified).

International Organisation for Standardisation (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. This document includes quality tables, which will be presented as a draft international standard (DIS) for next ISO and CEN balloting in the beginning of 2016.

The most important impacts of WP8 can be summed up as following:

- Round robin I showed the applicability of existing biomass standards for torrefied biomass
- Development of a product standard which supports trading and market launch as well as comparability and reliability of the product torrefied material
- Development of a template for a MSDS which shall ensure a safe and secure handling of torrefied biomass
- Broad data set of torrefied material analysis results and the corresponding raw material, which gives an overview of the properties of various torrefied biomass materials
- Development of additional methods for an extensive description of torrefied biomass, which were partly test in round robin II and could be used for further standard development.

The main results of WP 8 can be used by the end-user as well helps the producer to provide the desired product quality. The standards and MSDS supports trading and market launch of torrefied biomass.

3.8 WP 9 Value chains and sustainability

The objective of this work package was the description and assessment of illustrative biomass-to-end-use-chains based on torrefaction as well as scenarios up to 2030 with regard to economic, social and environmental criteria. Subsequently, conclusions and recommendations about cost-efficient and environmentally sound deployment strategies for torrefied material rather than torrefaction technologies were derived.

The following paragraphs summarise the main findings and results from the environmental assessment (WP 9) in SECTOR. For this assessment, a huge number of (torrefied)-biomass-to-end-use-chains considering various feedstocks, locations and technological configurations as well as end uses have been assessed with regards to their economic and environmental implications. The results of this assessment have been discussed and compared to both fossil energy carriers and white pellets as references. The techno-economic assessment in WP 9 showed that optimisation of pelletisation through torrefaction can lead – depending on the proper adjustment of the key process parameters – to considerable cost savings in comparison to white pellets in scenarios where higher amounts of solid bioenergy carriers are deployed. Production cost differences for torrefaction are mainly outweighed in these scenarios by better unit scaling effects and thus higher optimal plant sizes as well as through the positive effect of higher heating values of the final product for longer transport distances and import from third countries. Torrefaction can lead to considerable cost savings especially for large scale torrefaction plants due to higher scaling effects for a more expensive technology but especially for lower quality woody feedstock. The economic profitability of torrefaction is highly sensitive on the different key parameters of the entire biomass-to-end-use chain. This can be explained by the example that the average supply distance depends on a combination of feedstock yield, availabilities and accessibilities and (also) size dependent mass and energy balance of the plant which should be optimised. Furthermore not only competitiveness to white pellets but also general economic viability has to be ensured. Therefore, if the final product price is still in an affordable range for the end user, increased transport distances can be favourable for torrefaction. According to our analyses the argument regarding a diversification of the biomass for energy portfolio through torrefaction can be supported only to a certain extent at this stage of the research. Production costs of torrefied pellets depend on the density of the used feedstock. Here the utilisation for higher cost woody biomass can be beneficial if costs stay in an affordable range. For recycled wood cost savings can be expected but for herbaceous biomass no clear advantage for torrefaction can be outlined yet. Cost reduction for herbaceous biomass can be reached through pre-pelletisation. The following figure shows average simulated costs for torrefied pellets based on saw dust for selected biomass-to-end-use chain constellations compared to white pellets.

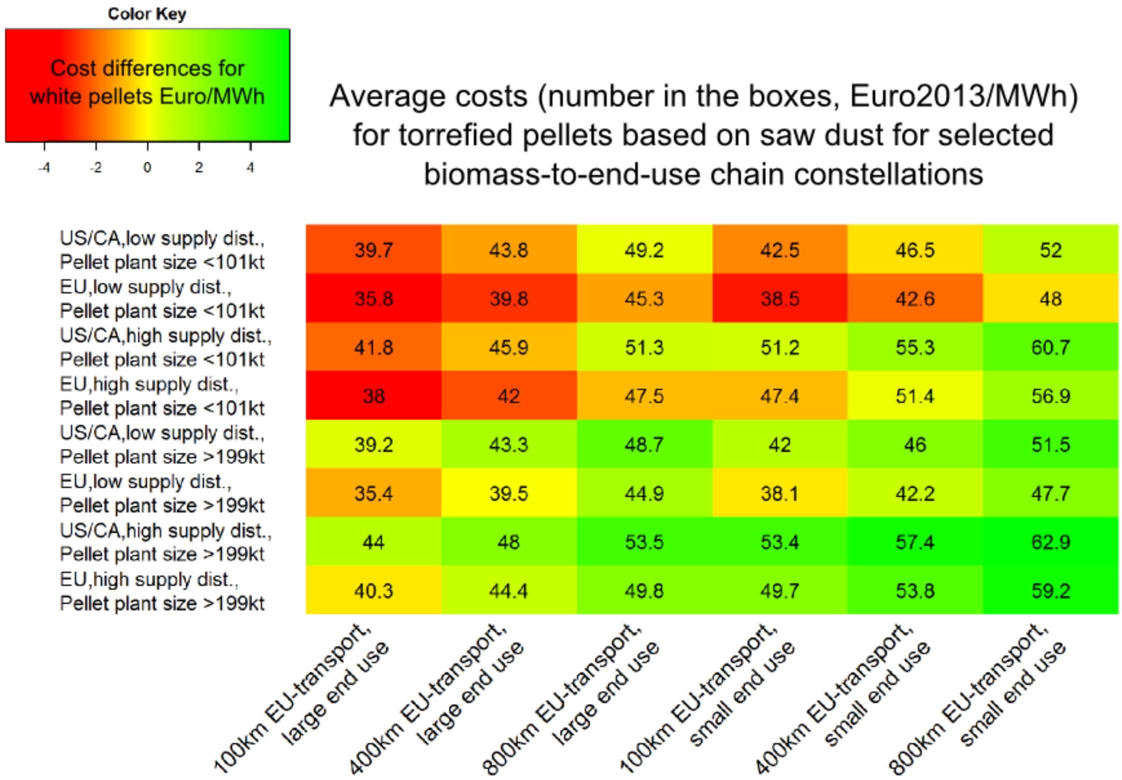


Figure 8: Average simulated costs for torrefied pellets based on saw dust for selected biomass-to-end-use chain constellations (see x- and y-axis). The difference for same constellations but without torrefaction step (white pellets) are indicated with colours from dark red (cheaper white pellets) to dark green (torrefied pellets are cheaper).

The assessment of GHG-emissions has shown advantages for torrefied pellet supply chains compared to conventional pellet production in those cases where the heat supply of the torrefaction and densification process was supplied from biomass. As expected the results also showed that, due to the higher energy density, the transportation of the torrefied pellets leads to lower GHG-emissions compared to the transportation of conventional pellets. Another important factor was the use of electricity for the process of torrefaction/densification. Depending on the location specific mixture of energy carriers for electricity supply, the emission factor for electricity differs between the four considered locations. Together with the different distribution scenarios this explains the main differences between the results of the various locations. Figure 9 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 GHG-emissions compared to the transportation of conventional pellets (e.g. 11.5 gCO_2-Eq. from Canadian straw white pellet distribution compared to 9 gCO_2-Eq. for torrefied Canadian straw pellets).

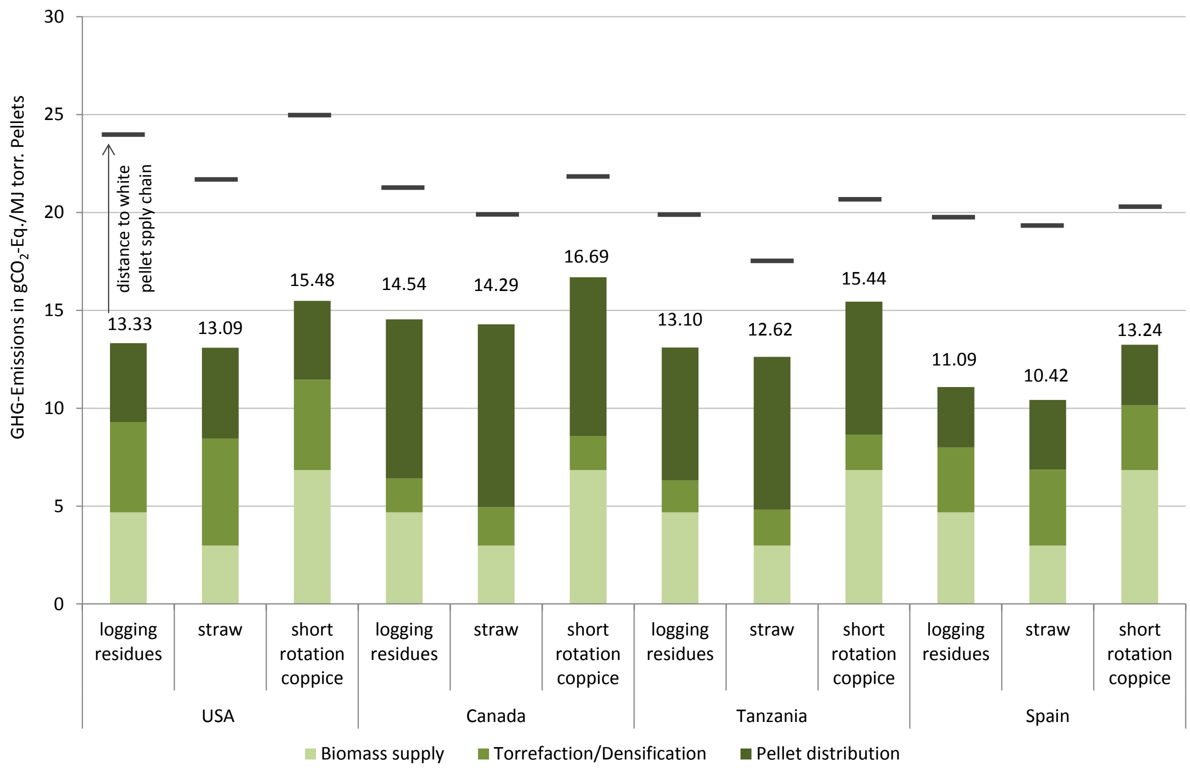


Figure 9: GHG-emissions from the supply of torrefied pellets from different feedstock types and locations compared to white pellets.

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. The results are summarized in Table 6 and can be found in detail in: Majer S, Gawor M, Nebel E. LCA of torrefied biomass chains in comparison to reference pathways. 2015.

Table 6: GHG-emissions of the conventional fuel, and from the use of conventional and torrefied pellets from different supply chains per MJ of product

Application[2]	Conventional pellets	Torrefied biomass
Co-firing with hard coal	0.06-0.08 kg CO_2 eq/MJ_e	0.03-0.06 kg CO_2 eq/MJ_e

[2] The reference levels for the three applications are: 1: hard coal: 0.3 kg CO_2 eq/MJ_e; nat. gas: 0,07 kg CO_2 eq/MJ_{th}; MeOH: 2.15 kg CO_2 eq/MJ

	72-80% reduction	80-87% reduction
Replacing natural gas in 15 kW boiler	0.022-0.031 kg CO_2 eq/MJ_{th} 58-70% reduction	0.015-0.021 kg CO_2 eq/MJ_{th} 71-79% reduction
Production and combustion of methanol	1.25-2.01 kg CO_2 eq/MJ_e 5-42% reduction	0.95-1.55 kg CO_2 eq/MJ_e 28-55% reduction

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.

CO_2 emissions of torrefied pellets are in most of the investigated pathways lower than for white pellets. It has to be considered that advantages for torrefied to white pellet mitigation costs for co-firing cannot be determined in all cases in the investigated scenarios. Increasing coal and energy prices (also for production and transportation of pellets) but also increasing average mitigation costs between the two commodities in most cases result in lower mitigation costs for torrefied pellets.

4 Impact

The impacts of the numerous results described in the preceding chapters are elaborated here according to the target sectors industry, science and policy. In the chapters describing the results of the WPs, their impact is explained in the individual context. The following paragraphs give an overview from the greater perspective.

As this project aimed to shorten the time to market, industry has been one of its major target groups – foremost torrefaction developers and end users. Partner belonging to the first group, namely Topell, ECN, UmU and CENER, improved their technologies and offer now better services to the industry. In the case of Topell, they were able to accomplish the final step towards commercial scale, which they can now offer to the market. The standardisation work (esp. ISO standardisation, REACH recommendations, MSDS template) provided prerequisites for the torrefaction business from technology producers, torrefiers down to end users. The identification of feasible value chains gives orientation for interested parties to establish business cases, which is the next step to implement torrefaction. The end users within the project, namely EON, Vattenfall and RWE, gained valuable experience in handling, transport and storage as well as in co-firing and co-gasification. These increased the confidence lacking in the energy sector regarding the fitness of torrefied material in these areas. Unfortunately, the companies in question reduced or even stopped their bioenergy activities due to market conditions but nevertheless stated the expertise gained in SECTOR will be valuable once bioenergy fits into their corporate strategies again. The tests done at their sites, complemented by the tests of Helen Ltd., will spur confidence of other end users as the results cemented the fact that torrefied pellets are now fit for major application without showing any major game stoppers. As a considerable side effect, the long running SECTOR project supported some market players to carry the engagement through a significant recession in interest and hence R&D expenditures in the field of torrefaction. Now, with torrefaction at the brink of commercialisation, technologies and services can be provided based on the work in SECTOR.

The second group impacted by SECTOR is science, research and development. The desk research, broad testing activities from lab to demonstration scale as well as the modelling, LCA and socio-economic calculation provided a first-of-a-kind, consistent data sets along the value chains. The data along with the underlying methodologies have been published (e.g. Phyllis2 database) and announced through numerous conference, papers and other dissemination activities. Parties active in research and development can use the information and the developed tools and facilities in their own research complementing or taking forward the work done in SECTOR. The scientific partners of the project gained excessive experience which they use in their own research projects succeeding SECTOR.

The third group which was very important to involve in the project has been policy. Torrefaction, being not only a renewable energy but also a young one, heavily relies on the political framework to be successfully implemented in the (European) market. The first of the two main distinguishable fields of policy is the integration of torrefaction value chains into the regulatory framework to allow their rollout and establishment. Policy stakeholders have to be addressed on the interlinked European and national level. The second policy field is the placing of incentives to foster development and market implementation of torrefaction value chains. The funding of SECTOR has been one of the taken measures. The impact of SECTOR on policy consisted in feeding back relevant information on the potentials and status of development to evaluate and adopt the political instruments. This was achieved through intensive exchange with the DG Research, the institution within the EU responsible for SECTOR. Also the general dissemination activities addressed alongside industry and science the political scene. Several dedicated publication were placed in policy related journals. The interaction with the policy makers peaked in a policy workshop held in Brussels together with the project BioBoost were intense discussion took place on the status and way ahead for torrefied materials and other advanced biofuels. The future specification of political instruments in these fields will show the impact SECTOR was able to induce.

The following charts give an overview of the properties of torrefied pellets compared to other relevant energy carriers and their costs in different scenarios.

Table 7: Overview of properties of torrefied pellets in relation to other fuels

	Wood chips	Wood pellets	Torrefied wood pellets	Charcoal	Coal
Moisture content (wt%)	30 – 55	7 – 10	**1 – 5**	1 – 5	10 – 15
Calorific value (LHV, MJ/kg)	7 – 12	15 – 17	**18 – 22**	30 – 32	23 – 28
Volatile matter (wt% db)	75 – 84	75 – 84	**55 – 80**	10 – 12	15 – 30
Fixed carbon (wt% db)	16 – 25	16 – 25	**22 – 35**	85 – 87	50 – 55
Bulk density (kg/l)	0.20 – 0.30	0.55 – 0.65	**0.65 – 0.80**	0.18 – 0.24	0.80 – 0.85
Vol. energy density (GJ/m^3)	1.4 – 3.6	8 – 11	**12 – 19**	5.4 – 7.7	18 – 24
Hygroscopic properties	Hydrophilic	Hydrophilic	**(Moderately) Hydrophobic**	Hydrophobic	Hydrophobic
Biological degradation	Fast	Moderate	**Slow**	None	None
Milling requirements	Special	Special	**Standard**	Standard	Standard
Product consistency	Limited	High	**High**	High	High
Transport cost	High	Medium	**Low**	Medium	Low
					

Abbreviations:
db = dry basis
LVH =Lower Heating Value

sources: ECN (table, fig.1, 3), Pixelio (fig. 2, 5), OFI (fig. 4)

4.1 Plan for use and dissemination

A great share of the dissemination activities and implementation of foreground has already been performed during the project as it timespan of 4 years allowed, and demanded, according measures. The past and future work is based on the plan for use and dissemination, which is described in the subsequent chapter.

4.1.1 Target groups

A wide spectrum of specific target groups within the above described target sectors are addressed by specific measures each:

Members of Advisory Board as Multipliers
The members of the Advisory Board have been chosen because they play a very important role in the bioenergy sector. They are not only contributing their knowledge to assure the success of the project, but also have the function of multipliers of the project's results.

Scientific experts
Since SECTOR was the first large research project concerning the subject of torrefied densified bioenergy carriers, the results ARE of importance for researchers in the bioenergy sector to continue and accelerate the research work in this field. Members of the SECTOR-consortium are working in many different relevant research groups, e.g. European Biofuels Technology Platform (EBTP), EERA Bioenergy, European Industrial Bioenergy Initiative (EIBI), Renewable Heating- and Cooling Platform (RHC-ETP, now ETIP), IEA Bioenergy Tasks 32 (combustion and co-firing), 33 (gasification) and 40 (sustainable bioenergy trade).

Relevant stakeholders
Another major aim of the project is to inform interested stakeholders along the whole supply chain. This includes providers of raw material, producers of torrefaction-based bioenergy carriers, providers of combustion/gasification technology and relevant equipment, biofuel traders and logisticians and end users (energetic as well as material use). Since there is currently no existing industrial-scale production of torrefied fuels, the information is of great importance to foster confidence and support the stakeholder's economic decisions.

Technical standardisation committees on solid biofuels
Currently a wide range of standards concerning the sustainability of biomass sources, test methods for the determination of material properties as well as product specifications are under construction on European (CEN) and international (ISO) level. Torrefied fuels have not been subject of these standards before the project. Several beneficiaries of SECTOR are members in various standardisation committees and play a major role in shaping the standards (esp. ISO 17225-8).

Administration and Public
There is large public interest in the sustainable production and use of energy carriers. Results about the economy as well as about the sustainability of torrefaction-based bioenergy carriers will be provided to relevant groups (e.g. European and national administration, policy makers, interest groups, NGOs) of the society to enable a corporative discussion about chances and risks of the technology.

The following table summarizes the memberships of beneficiaries in relevant committees and platforms:

Table 8: memberships of beneficiaries in committees and platforms

committee/ board	No. of partners involved
IEA (International Energy Agency)	7
CEN (European Committee for Standardisation)	9
ISO (International Organization for Standardisation)	5
RHC-Platform (European Technology and Innovation Platform on Renewable Heating & Cooling)	5
EERA Bioenergy (European Energy Research Alliance)	4
European Pellet Council	1
Dutch Torrefaction Association	2
Spanish Biomass Technology Platform	1
VGB Powertech	2
N.ERGHY	1
World Energy Council	1
NKGCF (National Committee for Global Change Research)	1
PEER (Partnership for European Environmental Research)	1

4.1.2 Dissemination Tools and Measures

The dissemination of results towards the above mentioned target groups are accomplished by using a large number of specific communication tools and measures:

- Project homepage: All public deliverables as well as publications, presentations and general information about torrefaction and the project are available via the project homepage (www.sector-project.eu).
- Dissemination via the channels of existing committees: Beneficiaries of the project are members in numerous committees and organisations. They take care of the inclusion of the results in the committees' work. This is done e.g. by providing project publications and by giving presentations at workshops organised by the corresponding Technical Committees of CEN and ISO, IEA Bioenergy Tasks 32, 33 and 40, EERA Bioenergy and others.
- Presentations on international conferences: Presentations are be held at international conferences on bioenergy, sustainability, renewable energies etc.
- Scientific papers: To reach scientific institutions and experts working in the field of torrefaction but which are not included in the consortium, scientific articles about several aspects of the project are published in relevant journals.

- Press releases: Press releases concerning the development of the project as well as singular results are drafted and communicated to relevant trade magazines in several countries.
- Phyllis2 database: Data about the physical and chemical properties of torrefaction-based bioenergy carriers will be incorporated into the publicly accessible internet database Phyllis2.
- Workshops: During the project duration 3-4 international workshops were arranged on specific topics around the status quo of the torrefaction of biomass and its impacts on global bioenergy use.
- Knowledge exchange with other relevant projects within the EU R&D projects (especially related to logistics and LCA analysis with other linked projects, e.g. the BioBoost project)

Table 9: project results and addressed target groups

Project results	Addressed target groups
General information about the opportunities of torrefied bioenergy carriers and SECTOR	All target groups
Profiles of the most suitable raw materials	Raw material suppliers and producers, administration and public
Information about torrefaction fundamentals	Scientific experts, producers
Fundamental densification characteristics of torrefied materials	Scientific experts, producers
Report on Torrefaction Technology and Market Strategy	Producers
Optimisation opportunities by integrating torrefaction into existing industries	Scientific experts, producers
Optimisation potential of torrefaction towards the quality of the solid energy carriers	Scientific experts, producers, standardisation committees
Optimisation potential towards (co-) production of bio-chemicals and bio-materials	Scientific experts, producers, end users (material use)
Compilation of quality analyses from the different production sites	Standardisation Committees
Requirements of end users on densified and torrefied materials	Scientific experts, Producers
Analysis reports on self-ignition, exothermal behaviour, dust explosion and emission risks	Scientific experts, producers, traders, Logisticians, end users
Report on biodegradation behaviour in different climate conditions and consequences on pellet characteristics	Scientific experts, producers, traders, logisticians, end users, standardisation committees
Report on (co-)/milling and feeding characteristics in co-firing and co-gasification	Scientific experts, end users, technology providers
Report on torrefied biomass co-firing tests with lignite/hard coal	Scientific experts, end users, technology providers
Report on torrefied biomass gasification tests	Scientific experts, end users, technology providers
Reports on the combustion behaviour in small scale applications (incl. CFD-simulations)	Scientific experts, end users, technology providers
Report on the production of chemicals and biomaterials	Scientific experts, end users, technology providers

Project results	Addressed target groups
Round robin reports on validation of “standard” test methods and new test methods	Scientific experts, standardisation committees
Drafts for EN 14961-X and ISO 17225-8	Standardisation committees
Description of the relevant biomass-to-end-use chains	Stakeholders, administration and public
Deployment scenarios and corresponding socio-economic assessment	Stakeholders, administration and public
LCA-analysis and assessment of additional sustainability indicators	Stakeholders, administration and public
New methodology requirements for Sustainability evaluation	Standardisation committees

4.1.3 Summary of completed Dissemination Activities

The dissemination activities were extensively and are summarized in the following list:

- 69 presentations incl. multiple plenaries
- 25 papers in conference proceedings
- 65 deliverables (28 of them are public, more will be made public later)
- 18 posters
- 11 peer-reviewed papers 6 more in review or under preparation
- 3 workshops plus one side event
- 1 exhibition
- BIOMAP/Phyllis2 database entries
- BioBoost cooperation

4.2 Exploitation of Project Results

Next to the extensive dissemination of project results, the results are exploited directly by the project partners themselves. SECTOR creates avenues for academic and private partners to transfer or exploit directly technology being developed during the course of this project for commercialisation. Once potentially exploitable technology has been appropriately protected by the partners involved, technology transfer actions and implementation are undertaken.

This holds foremost for the partners involved in the experimental activities. The torrefaction (and densification) technology providers, e.g., CENER, ECN, UmU, Topell and VTT, use the project results to improve their technologies, prepare/optimise demo-plant operation of the Topell technology as well as the other demonstration plants related to the partners UmU, ECN and CENER, and pave the way for market implementation and commercialisation of the technologies by (partially already associated) industries.

A series of partners, including Bioenergy 2020+, BIOS, Doosan Babcock, DTI, IEN, USTUTT, OFI, Procede, TFZ and VTT, make use of the project results in providing equipment or technical consultancy and R&D services with respect to the application of torrefaction-based bioenergy carriers. Development of product and quality standards, as well as analysis of the safety issues increases the likelihood of this application.

End-users, like EON, RWE and Vattenfall apply the project results to prepare and optimise future large-scale (commercial) implementation of torrefaction-based bioenergy carriers and potentially in biomass upstream projects of torrefaction plants, once bioenergy fits into their corporate strategies. These potential users also identify the potential issues and guided the optimization of the production process of the torrefaction-based bioenergy carriers, increasing the market acceptability of these carriers.

Finally, TU Wien and DBFZ exploit the project results in their future techno-economic and sustainability assessment studies and their advisory activities.

At any appropriate stage of the implementation, the consortium endeavours to make best use of the exploitable results of the project, in particular those with a commercial potential, through its own resources or external services.

This may include proof of concept outside the laboratory; the identification of market potential and opportunities; the evaluation of competing technologies; the assessment of the cost for upscaling from lab scale to industrial application; the development of a business plan; protection of intellectual property rights; etc.

Activities that have been performed to meet the objectives are:

1. Torrefaction process optimisation and integration (WP3 task 4)
2. Development of optimised torrefaction and densification recipes (WP4 task 4)
3. Development of a material safety data sheet (WP8 task 2)
4. Preparation of CEN and ISO product and quality assurance standards (WP8 task 3)
5. Installation and running of the Advisory Board and workshops with members of this Advisory Board as well as other stakeholders for maximising the exploitation and benefits for the industry (WP10 task 1)

Special exploitation activities as of the end of the project are represented in the following list.

Exploitation in Industry

- Topell/Blackwood: offering market ready, industrial scale torrefaction technology
- ECN: close cooperation with Andritz for potential industrial scale application
- DTI: close cooperation and sharing of results with C.F. Nielsen (compacting)
- E.ON, Vattenfall and RWE might use results from logistics and co-firing/co-gasification in the future
- Project partners offer improved (research) services to industry (e.g. CENER, ECN, DB, Procede, IEN, BIOS, VTT)
- Standardisation/MSDS/REACH is driven forward (VTT, OFI)
- Customer confidence increased through showcasing production, combined with assessment of the environmental, economic and sustainability
- Publication of D10.2 “Torrefaction Technology and Strategy Report” and the IEA Bioenergy “Status overview of torrefaction technologies”

Exploitation in Science

- Provision of knowledge through peer reviewed papers and other publications to the scientific community
- Development of new methodologies and software (e.g. BioChainS) to be used in future projects

- Provision of consistent and up-to-date data along the value chains to the scientific community
- Results will be used in future research on further improving woody biomass torrefaction, expanding the feedstock base and diversifying the end use.

Exploitation in Policy

- Policy and Technology Workshop on improved bioenergy carriers of the EU-projects BioBoost and SECTOR
- Publications in “The Parliament Magazine” and “International Innovation”
- Publication of D10.2 “Torrefaction Technology and Strategy Report” and the IEA Bioenergy “Status overview of torrefaction technologies”

4.3 Knowledge and IPR Management

The management of knowledge and IPR was formally arranged in the consortium agreement. This included the regulation of access to foreground and background and also the exclusion of certain intellectual properties as some of the project partners were direct or indirect competitors. The partners have been regularly informed about the definitions and regulations of the funding programme. They have also been advised in matters of protection.

For the general exchange of data, an internet based file management system was employed, following strict access rules for each WP. The IP needed to implement the project was organized between the respective partners. In a few cases, the coordinating team was involved in cases that concerned a greater part of the consortium.

The deliverables and scientific publications have been elaborated by the according partners in mutual consensus to make the contained information public. Presentations and other material were based on the already public material.

The project partners choose not to file any patents and disclosed IP as needed for implementation and use. A great share of information has been made public (see dissemination activities).

No major IPR problems occurred during the project.

4.4 Further R&D requirements

In the light of the COP21 climate talks in Paris, Dec. 2015, and the agreed upon 2°C goal, an exit strategy for the use of coal is a pressing matter. Torrefied fuels can play a crucial role here as they can replace coal easily. Torrefied fuels are eventually not competing with coal as it exits the market but with other renewable energies in general and for replacing coal specifically. The question to be answered is the layout of the future (power) energy system based on renewables. In Europe, solar and wind systems are foreseen to build the main pillars of power provision but, being volatile, they need a set of complementing measures to balance power demand and supply (implemented in a renewable energy market design). Biomass and especially torrefied fuels can provide a flexible power source here, delivering relevant system functions through which they enable higher shares of volatile and cheaper power sources. In this special area, torrefied fuels are competing for example with other biomass resources such as conventional white pellets. SECTOR has shown that in a significant range of scenarios, torrefied fuels are already today price competitive with white pellets. Nevertheless, their large scale implementation depends upon the general energy market conditions, aiming for high shares of renewables, including adequate prices for emissions certificates.

Torrefaction technology has been improved significantly for woody biomass and is now commercially available. Torrefaction of non-woody biomass has been investigated as well but still needs further research to fulfil market requirements in terms of quality and price. The process has the potential to convert often inhomogeneous feedstock, which is difficult to use in most existing bioenergy technologies, into a homogeneous bioenergy carrier, thus enlarging the feedstock base. Non-woody biomass has additionally the potential to reduce logistic costs as it will increase the overall biomass availability in certain areas resulting in less long distance transport (and potentially imports).

R&D for woody biomass should also continue to further decrease costs and GHG emissions especially in the context of upscaling and market integration. As the research in SECTOR has shown, there is a large number of scenarios in which torrefied pellets are competitive in price to white pellets, which appears to be a reference used by mostly large scale end users despite the (cost) advantages of torrefied pellets in logistics, storage and handling (CAPEX). Also technical aspects need to be investigated for upscaling and continuous operation. For market implementation, standardisation, trade registration and legal permission also have to be advanced.

Another field of research emerges as the end use of torrefied material is diversified. In the past, mainly co-firing in coal-fired power plants has been seen as the main utilisation path but market conditions have moved the attention also to medium and small scale application. Here, the conversion technologies and the properties of the torrefied material need to be aligned in a first step (a range of promising tests was already performed in SECTOR) and the according regulation (e.g. certification) need to be adopted to allow market implementation.

The same measures need to be taken for the use of torrefied material in gasification plants as a first step to produce transportation biofuels and material for the bioeconomy.

Another large area of research has been opened up by identifying fractions of the torrefaction gas which could be used for bioeconomic products such as biopesticide or the production of plywood. This would be potentially beneficial both for the advancement of the bioeconomy and the production of torrefied material by establishing by-products which might also reduce the costs of the torrefied material.

As laid out in chapter 3.2 Torrefaction in more detail, the greatest share of costs is the feedstock, offering therefor the greatest potential for cost reduction. To use this, the choice of location of the plant is of greatest importance. The second major option to reduce costs is the integration of the torrefaction plant into existing industries, particularly saw mills and pulp mills. As both measures might prove contradictory, a case-by-case decision balancing the different options has to be made. This holds also true for the economies of scale; a large plant might prove more cost effective yet it depends on numerous other factors such as feedstock, yield, availability and accessibility. In case of co-firing, the strongest competitor for torrefied fuels are white pellets. Exemplary calculations indicate that the savings are increasing significantly with a rising share of torrefied pellets (see chapter 3.2).

Efforts should continue at a more local level to promote the general concept of torrefaction-based biomass-to-end-use chains so that they become embedded in development plans for local authorities, provinces etc. Public awareness should continue to be raised about the concept of using biomass in conversion technologies as sustainable alternatives to fossil fuels that give benefits to the community which outweigh any localised negative environmental impacts. Deliverable D10.2 “Torrefaction Technology and Strategy Report” and the IEA Bioenergy “Status overview of torrefaction technologies” describing opportunities and challenges for market implementation of torrefaction technologies can be distributed to all relevant sectors of the biomass to energy chain to further these goals.

5 List of project partners

Following is a list of all beneficiaries with the corresponding contact name and associated coordinates.

Table 10: List of beneficiaries

Beneficiary short name	Beneficiary	Contact Name	Contact Address
DBFZ	Deutsches Biomasseforschungszentrum gGmbH	Daniela Thrän	Torgauer Str. 116 04347 Leipzig, Germany E-Mail: daniela.thraen@dbfz.de
VTT	Technical Research Centre of Finland Ltd.	Eija Alakangas	Koivurannantie 1, Box 1603, FI-40101 Jyväskylä, Finland E-Mail: Eija.Alakangas@vtt.fi
ECN	Stichting Energieonderzoek Centrum Nederland	Jaap Kiel	Westerduinweg 3 1755 LE Petten, The Netherlands E-Mail: kiel@ecn.nl
DTI	Teknologisk Institut	Wolfgang Stelte	Gregersensvej 1 2630 Taastrup, Denmark E-Mail: wst@teknologisk.dk
EON	E.ON Technologies (Ratcliffe) Limited	Susan Weatherstone	Technology Centre, Ratcliffe-on-Soar, Nottingham, NG11 0EE, UK E-Mail: susan.weatherstone@eon.com
USTUTT	Universität Stuttgart	Jörg Maier	Pfaffenwaldring 23, 70569 Stuttgart, Germany E-Mail: Joerg.Maier@ifk.uni-stuttgart.de
OFI	Österreichisches Forschungsinstitut für Chemie und Technik	Ute Wolfesberger-Schwabl	Arsenal, Objekt 213, Franz-Grill-Str. 5, 1030 Vienna, Vienna E-Mail: ute.wolfesberger@ofi.at
UmU	Umeå Universitet	Anders Nordin	KBC-building, level 6, 90187 Umeå, Sweden E-Mail: anders.nordin@umu.se
CENER	FUNDACION CENER-CIEMAT	Javier Gil Barno	Avenida Ciudad de le Innovacion 7, 31621 Sarriguren, Spain E-Mail: jgil@cener.com
Topell	Topell Energy BV	Alex Adell	Siriusdreef 17-27, 2132WT Hoofddorp, The Netherlands E-Mail: A.Adell@topellenergy.com
Vattenfall	Vattenfall Research and Development AB	Nader Padban	Jämtlandsgatan 99 Stockholm 162 16, Sweden E-Mail: nader.padban@vattenfall.com
RWE (until 10.12.2013)	RWE Innogy GmbH	Kirsten Theobald	Gildehofstraße 1 45127 Essen, Germany E-Mail: Kirsten.Theobald@rwe.com

Beneficiary short name	Beneficiary	Contact Name	Contact Address
DB	Doosan Power Systems S.A.	Bill Livingston	Porterfield Road, Renfrew PA4 8DJ, UK E-Mail: bill.livingston@doosan.com
Procede	Procede Biomass BV	Jaap Koppejan	Vlierstraat 111 7544GG Enschede, The Netherlands E-Mail: JaapKoppejan@procede.nl
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6 Public website

The SECTOR project website, can be accessed via www.sector-project.eu or www.torrefied-fuels.eu.

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