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Evaluation of a pilot-scale wood torrefcaction plant based on pellet properties and Finnish market economics

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Abstract
In this study torrefaction was demonstrated at a Torrec Ltd. pilot plant located in Mikkeli, eastern Finland. The pilot plant with a nominal capacity of 10,000 tonnes/year began operation in August 2014. The torrefaction solution was a batch type process based on a vertical reactor, where biomass material flows by gravity without drives or actuators and torrefaction happens by steam inertization and accurate process control. Steam was supplied from the local biomass combined heat and power (CHP) plant next to the pilot plant. The product quality of torrefied pellets was analysed by testing alternative local woody biomass sources, such as forest chips made from coniferous trees (spruce, pine) and broadleaf (birch), as well as by-products such as veneer chips. Lower heating value as dry basis varied 18.47–20.53 MJ/kg with a moisture content of 4.41-8.60% for torrefied pellets. All raw materials were suitable for torrefied pellet production without binder addition. Noteworthy was good results also with hardwood species. The potential Finnish customers are CHP plants aiming to replace coal with pellets. In 2013 coal use was 31.2 TWh, where condensing was 15.3 TWh, CHP 14.2 TWh, and separate heat 1.6 TWh in Finland. If half of the current coal use in CHP would be replaced by biocoal, then Finnish potential bio-coal markets would be 7 TWh or 1.2 million tonnes of pellets/year. Aided by the results of this demonstration study and modelling of logistics it is possible to evaluate the competitiveness of torrefied pellets based on the local circumstances.

Keywords: Torrefaction; Demonstration; Wood chips; Cost analysis.

1. Introduction
1.1 Torrefaction technologies
Torrefaction technology is near the commercialization phase at the moment and there are some 60 companies with technology development and testing programs in process. However, most of the demonstration plants have had technical problems that have delayed their commercial operation [1]. Torrefaction developers are typically small enterprises which are strongly dependent on private investors and public subsidies, but some large process technology companies also have activities in this sector. Several thermal treatment technologies for wood with high-temperature (200–300 ºC) absence of oxygen have been developed and piloted especially in Central Europe. Every reactor technology has specific advantages and disadvantages [2]. There are some 10 demo units and first commercial units, and units in operation and under construction [3]. Thermal treatment of biomass will be executed either by direct or indirect heating. Overall efficiency also depends on heat integration design, in which different options

are possible. The nearest commercialization stage among thermal treatment methods are torrefaction and steam explosion processes. Torrefaction can be done either by batch or continuous method, according to torrefaction volumes and space solutions.

Torrefaction technologies vary according to the demands for raw material characteristics, heat transfer, process control, investment and operating costs, and possibilities for dimensioning [4]. Therefore, direct technology commercialization without a piloting stage may be problematic, when the selected method should be adopted and applied to local circumstances and needs. Piloting periods with varying technologies have proven how the feedstock characteristics affect the maintenance of the process control and end-product quality [5]. Naturally, homogenous feedstock with uniform particle size distribution is desirable with most technologies. Feedstock of different type particle size distribution and volume weight needs varying residence times and temperatures in processing and thus customized technology choices [6].

The essential part of the process is pelletizing of torrefied material, since the potential customers are mostly far away and transport economy and material handling efficiency can be optimized [7]. Therefore, torrefied material must be crushed and pelletized immediately after torrefaction. Transport cost will not become such a dominant cost component for pelletized material as with forest chips or other biomass fuels. So far, there are few reports of handling and end-use experiments with torrefied pellets in the public, since there is only a limited amount of material available on the market and operators have not reported all results. However, thousand tonnes of torrefied pellets have been tested and demonstrated by US and European companies, mainly for large scale co-firing with coal. Experiments in Finland have been based on pellet shipments (pellet sacks) abroad or small-scale laboratory testing.

Vattenfall has reported experiments at Reuter's power plant (2x300 MW_e) in Berlin in 2011 and at Buggaeum's power plant (253 MW_e) in The Netherlands in 2013. In addition, pellets made via steam explosion method have been tested at several plants but not reported in public. Experiments with torrefied pellets indicated the challenges of dust during handling, potential problems with smell, durability (non-hydrophobic) and leachate problems (COD) with open storages. Combustion experiments have succeeded very well with high co-combustion shares with coal [8-11]. Additionally, Andriz has reported experiments performed at demo plants in Denmark and Austria (1 t/h), and called for additional research needed to verify pellets as fully marketable [12]. However, uncertainty still exists regarding large-scale production costs, durability, and the necessity of external binding agents.

1.2 Market situation in Finland

So far Finnish biocoal business models are targeted on local markets, not on export on global markets [13]. The primary market for biocoal in Finland is comprised of combined heat and power (CHP) plants aiming to replace coal with pellets. Only this kind of biocoal produced either by torrefaction or steam explosion process offers the possibility to use high mixing percentages (< 50%) with minor investments. Conventional wood pellets can be mixed with 5–7% shares [14]. The readiness to pay from biocoal is dependent on the market price of coal, price of emission allowances, fuel taxes (must be paid only for heating) and other potential incentives such as feed-in tariffs or production subsidies. The incentives vary greatly between countries and there are many exemptions and temporal variation with them. The coal price has decreased during the last years because of recession and decreased energy demand. At the moment, coal is the cheapest fuel in power production (Figure 1).

At the moment only wood fuel used with large-scale CHP-boilers is forest chips. They receive an energy subsidy for power production which is dependent on the price of emission allowances and excise tax on peat. When the price of emission allowances is lower than 10 €/t CO_2, the subsidy is at the maximum of 16 €//MWh and 0 €/MWh when they are higher than 22.7 €/t CO_2. The effect of the energy subsidy on the readiness to pay from fuels depends on boiler efficiency and power-to-heat ratio. Due to this subsidy system the readiness to pay for milled peat and forest chips are slightly better than for coal. But this is targeted at CHP plants (fluidized bed boilers suitable for co-combustion) where all these fuels can be used. At the moment there is no such subsidy system for coal plants (pulverized fuel boilers), because so far there has not been a biocoal market in Finland. This system could resemble the system made for forest chips, but including the excise tax for coal instead of peat in the calculation formula.

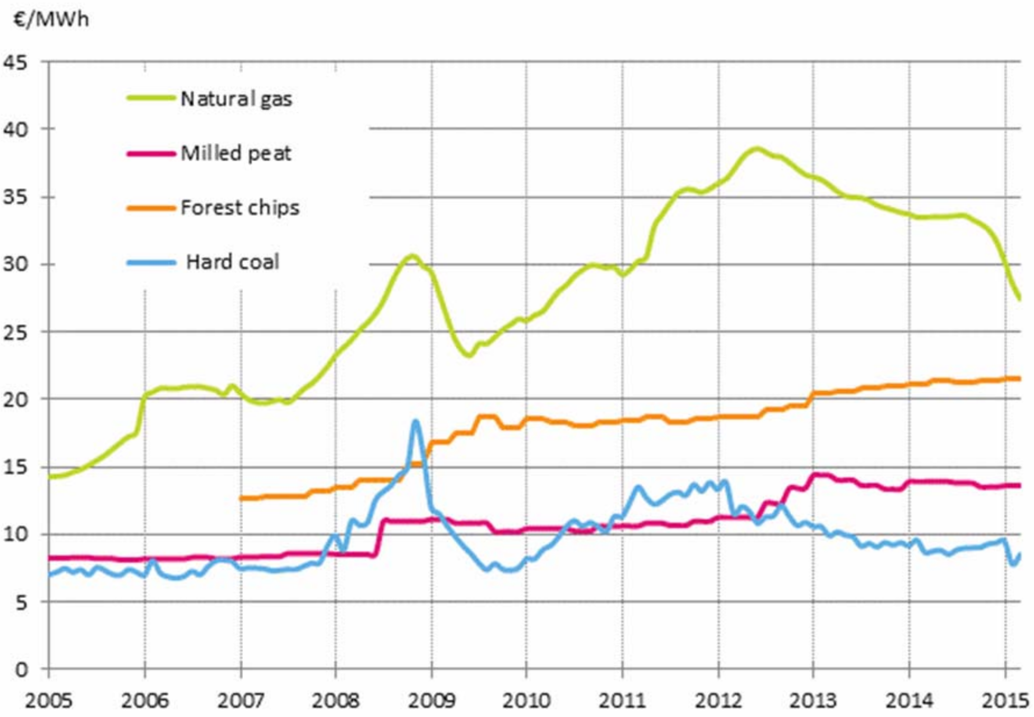

Figure 1. Fuel prices in electricity production in Finland, fuels labelled in descending order (Statistics Finland)

There are no excise taxes for fuels in electricity production, whereas in heat production they have excise taxes which are divided into energy content tax, carbon dioxide tax, and strategic stockpile fee, which is used for imported fuels as coal. The carbon dioxide tax is half for CHP production (Table 1). In 3/2015 the coal price for heat production was 30.31 €/MWh, while the price in power production was 8.50 €/MWh (see Figure 1). It is assumed that the coal market price will decrease to some extent according to futures set on coming months in 2015. The price of emission allowances was 7.50 €/t CO_2 (EUA Spot December 2015, EEX). The emission factor for coal is 94.6 gCO_2/MJ (0.34056 tCO_2/MWh). Thus, the current price of emission allowances constitutes 2.55 €/MWh of additional cost for coal combustion. At CHP plants the magnitude of excise taxes depends on the share of heat produced, since only that part of each fuel from the whole fuel consumption is liable to taxation. Therefore, the higher the share of power is the lower the energy taxation.

Table 1. Energy taxes and stockpile fees for coal (Statistics Finland, Energy prices)

Production mode	Energy content [€/MWh]		Carbon dioxide [€/MWh]		Stockpile fee [€/MWh]		In total [€/MWh]	
	2014	2015	2014	2015	2014	2015	2014	2015
Condensing power	0	0	0	0	0.00	0.00	0.00	0.00
CHP	6.65	6.65	5.96	7.50	0.17	0.17	12.78	14.31
Heat	6.65	6.65	11.93	14.99	0.17	0.17	18.74	21.81

The import of coal depends on rainfall and potential hydro power in Nordic countries, since a lot of rainfall means more electricity import instead of own condensing with coal power plants. Coal consumption has varied during the last decade, being at the maximum level of 9 million tonnes in the dry year of 2003 and lowest in the rainy year of 1999. However, there is a decreasing trend. Almost half of the coal is imported from Russia, while other export countries are South Africa, Indonesia, China, Colombia, Poland and United States.

In 2013 coal use was 31.2 TWh (4.4 million ton), where condensing 15.3 TWh, CHP 14.3 TWh, and separate heat 1.6 TWh in Finland. If half of the current coal use in CHP were replaced by torrefied pellets, the potential annual market would be 7 TWh or 1.2 million tonnes. There are 8 CHP plants, where the biggest user, Helen (energy company of Helsinki), could use 0.5 million tonnes of torrefied pellets on its own, comprising about 40% of the company's current coal use. In 2014 the coal use in Finland was dropped till 26.9 TWh (3.8 million ton).

2. Materials and methods

The target of this study was to evaluate the quality and characteristics of torrefied pellets produced at the Torrec pilot plant. The idea of the pilot plant was that the technologies and operations could be tested before launching the large-scale unit. This information is valuable for the latter stages in the supply chain (storing, handling, transporting, and milling). Co-combustion is beyond the scope in this study. The potential co-combustion market in Finland was also evaluated, as well as preliminary production cost level at full-scale production.

2.1 Pilot plant

Torrec Ltd constructed a pilot plant for torrefaction technology in Mikkeli, eastern Finland, in 2014 (Figure 2). This pilot site contains the whole process, including drying, torrefaction, and pelletizing. The nominal capacity is 10,000 t/a. In practice, the units utilize some 9–10 bulk-m³ of woodchips (approx. >300 kg/bulk-m³) to produce 1.5–2.0 tonnes of torrefied pellets allowing small scale testing by laboratories, and the actual capacity is lower. The torrefaction solution is based on a vertical reactor, where biomass material flows by gravity without drives or actuators and torrefaction occurs by steam inertization and accurate process control. Steam was supplied from the local biomass combined heat and power (CHP) plant next to the pilot plant.

Wood chips were conveyed from chip silo to the torrefaction unit, in which all the phases of torrefaction took place: pre-drying, post-drying, torrefaction, and cooling of solids. The pre-drying stage was performed between 100 °C and 200 °C, eliminating the need for a separate drying unit in the process. The torrefaction unit was dense when in progress in order to keep up the anoxic conditions, but it can be opened when maintaining the equipment. Both processes were run by electricity, and the anoxic conditions were achieved by introducing water vapor into the process to replace oxygen. Water vapor was also used in cooling the biomass after torrefaction to 100° C. After the torrefaction process, the torrefied mass was conveyed to the pelletizing unit, in which water vapor was taken into process in order to control the flammability and explosion risks. It also constrained the dusting of the material. There was a storage silo between the torrefaction and pelletizing unit. In the pelletizing process, torrefied material was crushed, and some moistening with tar liquid obtained from the torrefaction process were injected before pelletizing. After pelletizing, the pellets were packed into flexible intermediate bulk containers, which were big bags (1m^3). At the commercial scale the process is intended to be continuous, with separate drying and torrefaction units.

Figure 2. The pilot plant of Torrec Ltd. in Mikkeli, eastern Finland, which is a batch process where drying and torrefaction occurs inside the same reactor

2.2 Quality analysis of raw material

Forest chips were made of pulp-wood-sized trees felled in March, two months before torrefaction period. The trees were chipped at the roadside by a drum chipper with a sieve (50x60 mm). Each truck shipment consisted of 30 bulk-m^3 assorted wood selection (pine, spruce, birch). The characteristics of chipped and sieved material are presented in table 2. By-products were from the local plywood mills consisting both birch and spruce veneer chips (marked ve in Table 2). The trees were stored to some extent during spring, but still the moisture content was high, especially for pine. The mixed lot were imported from Russia, and consisted mainly of broadleaves such as birch and aspen, but the exact mixture of them was unknown. The ash content was low for spruce veneer and birch veneer chips, because they did not contain any bark. The energy content as a dry and wet basis of both birch assortment were the highest.

Table 2. Properties of chipped feedstock material

Tree assortment	Moisture content (%)	Ash content (%)	Bulk density (kg m^3)	Heating value (MJ kg $_{dry}$)	Heating value (MJ kg $_{ar}$)
Birch	42.7	1.53	312	19.8	10.3
Spruce	51.3	1.79	310	18.8	7.9
Pine	60.5	1.37	371	18.5	5.8
Mixed	52.2	1.44	327	15.5	na
Birch ve	45.9	0.45	322	18.9	9.1
Spruce ve	57.4	0.29	348	18.9	6.7

The particle size distribution was calculated as an average value from three sieving tests (EN ISO 17827-1). The main fraction was classed in P16, when the main fraction was $3.15<P \leq 16$. The fine fraction (< 3.15) was rather high, F15-F25, without separate sieving. There was no difference between tree assortments, since they all were chipped with the same chipper. The reason for a higher fine fraction might be blunt edges. This share of fines was too high for this torrefaction process and all lots were sieved separately after chipping. After sieving the fine fraction dropped to F5-F15 and the share of the main fraction P16 was 90–95% (Table 3).

Table 3. Particle size distribution of raw materials after separate sieving, the size of chips is the median value of the whole fraction.

Tree assortment	Fines	Main	Coarse	Size, mm
Birch	F10	P16	-	6.3
Spruce	F5	P16	P16	7.1
Pine	F10	P16	-	5.5
Mixed	F15	P16	-	5.3
Birch ve	F5	P16	P16	10.3
Spruce ve	F5	P16	P16	7.6

2.3 Quality analysis of torrefied pellets

The product quality of torrefied pellets was analyzed by testing alternative local woody biomass sources, such as forest chips made from coniferous trees (spruce, pine) and broadleaf (birch) and local by-products as birch and spruce veneer chips. The effect of particle-size distribution before torrefaction was analyzed by testing normally drum chipped material versus separately sieved material (EN 15149-1). Energy density, moisture and ash content, and alkalis were verified. In addition, the durability of pellets was verified by means of laboratory tests (EN 15210-1). All tests were done without any additional binder, which provides additional interest as many previous challenges are reported with torrefied pellet quality without binder [1]. Measured quality properties were evaluated according to the EN 17225-8 standards for “Graded thermally treated and densified biomass fuels” [15].

2.4 Production cost analysis
Cost calculation was based on a torrefaction plant annual capacity of 50,000 t. This was a scale-up form the existing pilot-plant. The production and distribution costs of torrefied pellets were divided into three sections: raw material, torrefaction and pelletizing, and storing and transportation to the power plant. Fixed cost parameters to torrefaction comprised investment and annual maintenance and variable cost parameters such as electricity consumption, heat consumption, work load, and binder consumption, if needed. The plant was a stand-alone plant where the biomass boiler was fuelled with the same raw material base as used for torrefaction. The fine and coarse fraction were sieved out and used for heating. Plant location dictated the transport costs of raw material to the torrefaction site and torrefied pellet material to the end-users. It also dictated possible transport modes (road, rail, and waterway) and storing needs between supply and demand sites. Here the potential plant was located inland and the potential pellet customer (co-combustion with coal at a CHP plant) was located in a coastal area and transportation was based on trucks.
Torrefied biomass must be pelletized and pellets are intended for bulk delivery by trucks, reducing the handling, packaging, and consumables utilization in the facility. Storage as torrefied pellets should be less vulnerable to wetting, but outdoor storage should be avoided so the logistics was based on covered solutions during the whole supply chain.
The initial values for calculations were listed in Table 4 and were based on demonstrated torrefaction technology and local circumstances and price levels. Since there were many uncertainties among cost parameters, there was a need for cost sensitivity analysis (raw material price, investment, electricity, heat, workforce, freight). Each parameter was varied using the range of ±10–20–30%. Additionally, the energy content of torrefied pellet was varied from the base value of 5.1 MWh/t using the target value of 5.7 MWh/t.

Table 4. Cost parameters for torrefcaction

Raw material, R_p	20 €/MWh
Raw material economy, η	90 %
Investment, I	6.7 Million €
Maintenance, m	4 %
Electricity, E_c	240 kWh/t
Electricity price, E_p	100 €/MWh
Heat, H_c	615 kWh/t
Heat cost, H_p	25 €/MWh
Work load, L_c	8 person year
Labor cost, L_p	25 €/h
Freight, F_p	20 €/t

Production cost (€/MWh), was calculated by using the equation 1, where costs were divided into above mentioned feedstock, fixed and variable torrefcaction and freight costs. Annuity factor $c_{n/i}$ was defined using lifetime of 20 years and interest rate of 10%.

$$P_{cost} = \left(R_p/\eta + (c_{n/i} * I + m * I + L_p * L_c)/C + (E_p * E_c + H_p * H_c + F_p)/Q_{net}\right. \quad (1)$$

where annuity factor, $c_{20/10}$ = 0.1175 and annual production capacity, C = 50 000 t x 5.1 MWh/t

3. Results
3.1 Torrefied pellet quality analysis
According to results of torrefaction test runs done during 28.4-9.6 2015 the lower heating value (as received) varied 17.57–18.77 MJ/kg (4.87–5.12 kWh/kg) with a moisture content of 4.41-8.60%. Lower heating value as dry basis varied 18.47–20.53 MJ/kg (5.13–5.54 kWh/kg) (Table 5). The heating value was a result of raw material characteristic, the torrefaction reactor max temperature, 249-259 °C where max temperature of raw material mattress varied 240-250 °C and residence time 1h36min–2h13min,

which typically contained 2-3 separate torrefaction period. Even the weather conditions had an effect to the torrefaction process which was possible only outside the winter period with this pilot facility construction. Now the temperatures varied between 5-9 °C with a windy weather in May and 13-18 °C with a windy and rainy weather in June. Additionally, moistening of the pelletizing process had an effect on torrefied pellet moisture content and heating value. There was no specific differences in heating values between local woody biomass sources used in this study. All raw materials were suitable for torrefied pellet production without binder addition. Noteworthy was good results also with hardwood species like birch and aspen, which offer vast unused resources in Russia. They also offered best mechanical durability among tested samples. The delivered steam from the near-site power plant defined the maximum torrefaction temperature.

According to EN 17225-8, these pellets should belong to property class TW1. Origin and source are stemwood, moisture M8≤8, Ash A2.0 ≤2.0, net calorific value dry Q19≥19, and bulk density BD BD650≥650, diameter D08, (8±1), length L (3.15≤L≤40), fines F1.0≤1.0, mechanical durability DU97.5≥97.5, where numbers define threshold values [15]. Fines and mechanical durability (DU) were measured as w-%. Only the mechanical durability was lower than threshold value. The mechanical durability according to EN 15210-1 was tested also for conventional wood pellets made from pine and spruce sawdust, being 97.9.

Table 5. Characteristics of torrefied pellets

Sample	MC-%	Ash-%	kg/m^3	MJ/kg d	MJ/kg ar	MWh/m^3	L, mm	D, mm	Fines, %	DU, %
Birch	6.40	1.23	678	19.37	17.96	3.38	10.79	7.95	0.57	97.4
Spruce	4.41	1.43	699	18.47	17.53	3.40	10.33	7.99	0.10	96.8
Pine	6.80	1.30	682	19.96	18.43	3.49	9.07	7.93	0.85	91.8
Mixed	6.52	1.41	696	19.15	17.80	3.44	17.06	7.99	0.16	96.6
Birch ve.	4.98	1.16	699	19.88	18.77	3.64	13.11	8.08	0.24	96.8
Spruce ve.	8.60	0.87	649	20.53	18.56	3.34	7.97	7.99	0.81	92.6

3.2 Torrefied pellet production cost analysis

Raw material was the main cost component, at 56%, variable torrefaction 20%, fixed torrefaction cost 14%, and outbound logistics 10% (Figure 3). The average cost level was 202 €/t and 39.5 €/MWh with the energy content of 5.1 MWh/t. The price level was clearly higher compared to the current coal price for heating part in CHP production, 25 €/MWh. If the price of emission allowances were 20 €/t CO_2 instead of the current 7.5 €/t CO_2, then the coal price would rise to 30 €/MWh.

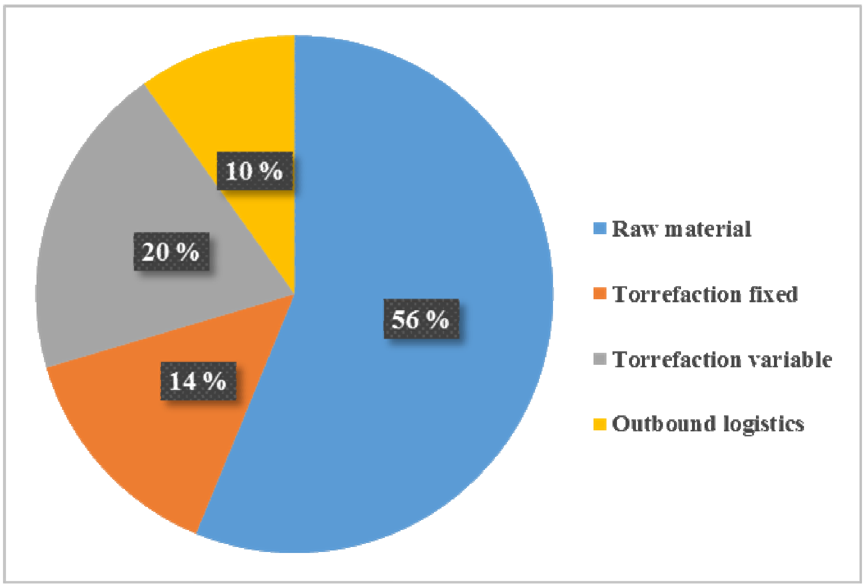

Figure 3. Cost structure of torrefied pellets, %

According to the sensitivity analysis, the raw material price had the highest effect on cost competitiveness. The torrefied pellet price varied ±17% in relation to raw material cost at ±30%, whereas with other parameters the variation was ±3% (Figure 4). The cost range was 32.9-46.2 €/MWh according to the raw material prize. In simultaneous variation with all cost parameters the range was 27.7-51.5 €/MWh.

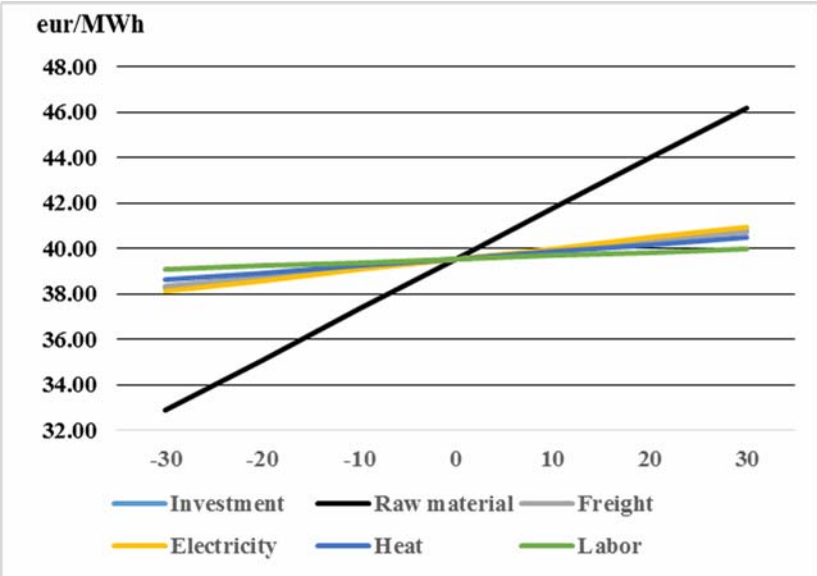

Figure 4. Sensitivity analysis of torrefaction cost parameters

4. Discussion and conclusion

Previous studies have proven higher energy content of torrefied pellets than in the preliminary results of this piloting unit [1]. The reasons for this might be the lower torrefaction temperature, 240-260 °C and torrefied wood moistening practice before pelletizing in the piloting unit. Energy research Centre Netherlands (ECN) reported MC 1–5% and LHV 18–24 MJ/kg [1]. Here the respective values were MC 4–9% and LHV 18–19 MJ/kg. In addition, this study pointed out that the quality of torrefied pellets depends to a large extent on the quality of raw material, and in this case the particle size distribution should be as homogenous as possible and fine particles avoided. The absence of binder was noteworthy, as it typically represents an additional cost with torrefaction. Here, conditioning by steam added to the biomass seemed more adequate for the rather mild torrefaction treatment. However, changes in torrefaction parameters (medium and/or dark torrefaction) may require the utilization of a different binder. Also technological solutions matters, for example the lower durability than expected might be result of the unoptimized feed screw for pellet press because of pilot facility construction and pelletizing without a binder like starch.

The production cost would decrease only to the level of 37 €/MWh with the target value on LHV 20 MJ/kg of torrefied pellets. In this study a sensitivity analysis was made, since torrefaction of biomass on a large scale is a recent concept; there is still a lack of reliable sources for cost estimates. Suppliers of this type of equipment are scarce, and the majority is still mostly in the pilot test stage for their technologies. Depending on the range (± 30%) of cost parameters, the cost can vary between 27–50 €/MWh, where the raw material costs were the most crucial cost parameter in the sensitivity analysis. In previous studies lower cost level has also been reported, e.g. for a 200, 000 t plant, the total supply cost accounts to 32 €/MWh [16]. There the economy of scale could lower the cost level whereas the stand alone plant capacity in this analysis was 50, 000 t. A drawback of higher capacity is the increasing raw material costs if supply areas and transport costs are increased. Another way to decrease cost level is the integration of torrefaction with the forest industry. There the benefits are related to by-product utilization at sawmills or plywood mills, but also to general wood procurement logistics at forest industry plants [17]. In the SECTOR programme the production cost of torrefied pellet was evaluated at the existing sawmill to 34 €/MWh, at a new sawmill 38 €/MWh or at modern pulp mill 33 €/MWh, compared to a stand-alone plant at 43 €/MWh [18].

The cost structure of torrefied pellets got in this study is a rather typical also with larger capacity, as in the 200,000 t study, in which the supply system accounts for 60%, the production cost 31%, and the distribution system 9% of the total cost [16]. With larger capacity the raw material supply costs will be emphasized if material supply is outsourced. It has been also shown that in spite of the fact that economy of scale plays an important role in costs of pre-treatment, there are capacity limits after it won't bring more economical advantage [17].

The main market for torrefied pellets would be pulverized coal-fired power plants, but also other markets as entrained flow gasification and small scale combustion using pellets have been reported [19]. In Finland the main market would be CHP plants, due to better readiness to pay and more even work load compared to condensing plants. The market potential of 1.2 million tonnes would need 6 large-scale 200, 000 t torrefaction units or several smaller ones. Pulverized coal-fired power plants are found in nearly all European countries, with a total capacity of around 200 GW_e or some 1,200 plants. The great majority of these plants are, however, located in Germany, the UK and Poland [17]. This European market is practically unlimited for torrefied pellets, since one 350 MW_e plant needs some 6 TWh of fuel annually when operating full-time at 40% efficiency.

The current fuel costs with coal at CHP plants is 25 €/MWh for heat and condensing plants 11 €/MWh in Finland. If the price of emission allowances rose to 20 €/t CO_2, then the fuel cost for heat would be 30 €/MWh at CHP plants. This is at the same level as the wood-pellet market price of 30 €/MWh, which represents the PIX index price of pellets in the Baltic Sea region. However, wood pellets need additional investments at power plants to be suitable for co-combustion. Due to the price difference, the attractiveness of co-firing torrefied pellets with coal is heavily dependent on national support schemes for renewable electricity generation. This could be a feed-in tariff or similar support mechanism for torrefied pellets to guarantee paying capability for coal-fired power plants above 35 €/MWh so as to make the investments viable. The level of feed-in tariff could be 40–50 €/MWh, depending on the price of emission allowances and excise tax for coal. However, problems with support schemes are posed by possible market disturbances between alternative end-users for the same raw material base.

Finnish new government has decided in 2015 to leave off coal use in energy production by 2030. One practical action would be higher excise taxes and also full carbon dioxide tax instead current half value for CHP production. This may lead to investment trend to pure heat capacity instead of more resource efficient CHP capacity and pure electricity capacity based on carbon free production based on nuclear, wind and solar. Helen (energy company of Helsinki) has already announced this kind of plan to invest pellet boilers and geothermal energy for heat production and solar panels for electricity production. This will increase the share of renewables in Helsinki from the current 7% till 20% by 2020 but still leave a high share of gas and coal based CHP capacity.

Due to promising market prospects in Finland, the next stage in the piloting would be a continuous process with a separate drying and torrefaction unit and own biomass boiler where the torrefaction temperature could be increased. The target value for the LHV would in this case be the before mentioned 20 MJ/kg, which would be nearer the reported literature values [1].

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References

[1] Acharya, B., Sule, I. & Dutta, A. A review on advances of torrefaction technologies for biomass processing. Biomass Conv. Bioref. 2012, 2:349–369.
[2] Kiel, J. Torrefaction – Product Quality Optimization in View of Logistics and End-use. World Biomass Power Markets. Amsterdam, the Netherlands. May 17th, 2013.
[3] Kleinschmidt, C. Overview of international developments in torrefaction. Central European Biomass Conference, 28.1. 2011.
[4] Meijer, R. Overview of European torrefaction landscape. EPRI Biomass Torrefaction Workshop. April 13-14, 2011, Pensacola, FL, US.
[5] Chew, J.J. & Doshi V. Recent advances in biomass pretreatment – Torrefaction fundamentals and technology. Renewable and Sustainable Energy Reviews 15, 2011, 4212–4222.
[6] Koppejan, J. et. al. Status overview of torrefcaction technologies. IEA Bioenergy Task 32 report. 2012. 52 p.

[7] Chen, W-H., Peng, J. & Bi, X.T. A state-of-the-art review of biomass torrefaction, densification and applications. Renewable and Sustainable Energy Reviews 44, 2015, 847–866.
[8] Hermes, H.D. The Role of Biomass in Large Scale Renewable Generation Ambitions. European Biomass Power Generation Conference. 10.1.2012.
[9] Hermes, H.D. What is the Future Role of Biomass in Coal Fired Power Plants. 3rd International BBE/VDMA Business and Export Forum for Bio Energy. 31.5.2011. Hannover.
[10] Khodayari, R. Vattenfall Strategy and Experiences on Co-firing of Biomass and Coal. IEA Clean Coal Conference 27 March 2012.
[11] Padban, N. First experiences from large scale co-gasification tests with refined biomass fuels. Central European Biomass Conference. 17th January 2014, Graz, Austria.
[12] Thamer, D. New challenges in Torrefaction biomass. AEBIOM, June 2013.
[13] Wang, L. Value chain analysis of bio-coal business in Finland: Perspectives from multiple value chain members. Biomass and bioenergy 78, 2015, 140-155.
[14] Flyktman, M. et al. Kivihiilen korvaaminen biomassoilla yhteistuotannon pölypolttokattiloissa. [Replacing coal with biomass in cogeneration using pulverised combustion boilers]. Espoo 2011. VTT Tiedotteita – Research Notes 2595. 65 p.
[15] Alakangas, E. Graded thermally and densified biomass fuels Development of the ISO 17225-8 standard. Deliverable No. D8.3, 2014.
[16] Svanberg, M. et al. Analysing biomass torrefaction supply chain costs. Bioresource Technology. Vo.142, Aug. 2013, 287–296.
[17] Wilen, C. et.al. Wood torrefaction – market prospects and integration with the forest and energy industry. VTT Technology 163. 2014, 55 p.
[18] Arpiainen, V. & Wilen, C. Report on optimisation opportunities by integrating torrefaction into existing industries. Deliverable No. D3.2, 2014.
[19] Stelt van der, M.J.C. et al. Biomass upgrading by torrefaction for the production of biofuels. Biomass and Bioenergy 35, 2011, 3748-3762.