Index - Final Report

1.1 Project details

Project title	Torrefaction of Biomass
Project identification	Energinet.dk project no.10202
Name of the programme which has funded the project (ForskVE, ForskNG or ForskEL)	ForskEL
Name and address of the enterprises/institution responsible for the project	Danish Technological Institute
CVR (central business register)	DK 5697 6116
Date for submission	210513

1.2 Executive summary

The transition from coal to wood pellets in pulverised coal power plants requires special care and in most cases costly reconstruction of storage and handling facilities as well as of milling-, feeding- and firing equipment. However by pre-treatment of the biomass with torrefaction some of these reconstructions could potentially be avoided. Torrefaction, which is a mild pyrolysis at 200-300 °C changes properties of biomass into product which is claimed to have a higher density and could be handled and transported as coal.

The objective of this project was to investigate and understand some of the basics of the process of torrefaction and explore the true characteristics of this new type of solid biomass fuel. Tests with torrefaction of different biomass have thus been conducted in both laboratory scale as well as bench scale investigating samples from milligram up to >100 kg.

Test in TGA-FTIR and a lab scale pyro-ofen was used to understand the basic chemistry of the influence of torrefaction temperature on the kinetics of the process as well as the condensable gases leaving the process. The results reveal a process that above 250 °C is exothermic and that the major condensable gases consist mainly of methanol, acetic acid and water. Significant amounts of methyl-chloride were detected in the condensable gases and do thereby suggest that a certain amount of corrosive Cl could be reduced from the fuel by means of torrefaction. It was also concluded that great care has to be taken during and after production as the torrefied material was seen to self-ignite in an air environment at temperatures above 200 °C.

The characteristics of the biomass are indeed altered by the torrefaction. The effect is found to be a direct function of the torrefaction temperature used and the residence time in function of particle size, but also the type and species of the biomass has a significant impact on the result. Kinetics of these reactions The wanted effects are a material that is easy to grind, hydrophobic enough to be stored outdoors and has a high energy density for costs effective transport and handling.

The grindability of the material (energy consumption during milling) is indeed significantly improved by torrefaction and can be reduced up to 6 times compared to raw biomass. The results from test in bench scale as well as in lab scale mills suggested that in order to reach grindability similar to coal a torrefaction temperature above 240 °C is required for wood chips and above 290 °C for wood pellets. These figures will however differ with the type of biomass torrefied and the particle size of the material torrefied and milled.

Moisture uptake in torrefied materials is decreased compared to raw biomass. However, due to formation of cavities in the material during torrefaction, the full effect is met first after densification. The hydrophobicity of the material increases with higher torrefaction temperature, but still a rather significant moisture uptake is occurring even at biomass torrefied at 300 °C. Thus it cannot be concluded if pellets of torrefied materials can be stored outside or not. Due to the fact that the densification process will also have big influence on this property and full scale testing with more materials is required before this can be concluded.

Densification of torrefied material was tested in both bench scale as well as lab scale pellet presses and revealed larger challenges than expected. Torrefied material reveals a much higher friction, internal between particles as well as external with the die surface, than untreated biomass does and requires thus higher amounts of energy to compress and push through the dies. Moreover, due to that the chemistry of the binding agents in the biomass is altered by the heat treatment, it is also more challenging to produce pellets with high quality. Elevated die temperatures of above ~190 °C and usage of lubricating additives such as rape seed oil was shown to clearly improve the pelletisation properties, but more research and optimisation is necessary in the future.

While grindability and moisture uptake are important for the usage and storage at the power plants, the densification of torrefied is important for the transport to the plant as it is necessary for increasing the energy density. Due to that devolatilization creates cavities in the material the energy density on a volume bases (GJ/m3) is actually lowered during torrefaction. But the remaining torrefied biomass material does have a higher energy density on a mass basis (GJ/kg), and therefore subsequent densification by pelletisation will significantly increase it energy density above that of not treated biomass also on a volume bases.
Due to the fact that transport of solid fuels on ships is limited by volume rather that mass, this property is important for the economics of the supply chain.

A techno economic evaluation of the supply chain implementing torrefaction and densification did also reveal that the cost effective oversea transport by ship is the most important benefit of torrefaction, if costs avoided for reconstructing power plants from coal to biomass are not considered. The costs for reconstructing storage, feeding and firing systems at power plants were not included in the evaluations as it is typically specific for each plant but most likely significant. There is also a value in being able to quickly be able to change back and forward between coal and biomass if this is allowed.

The presented project has investigated many aspects and the process of torrefaction, but still more work has to be done before torrefied biomass will be a commodity fuel on the market. Torrefied biomass has a range of new properties compared to the solid biomass fuels used today and there is still a need for being able to describe and analyse these new properties such as eg. hydrophobicity and grindability and in a standardised way that is commonly accepted. From the test and analyses made in this project it can be concluded that although properties of biomass are changed by torrefaction the final statement of creating a more homogenous fuel with less dispersed properties is questionable.
The properties of the torrefied material will depend on what biomass is torrefied, but even more on how it is torrefied and finally on what densification process is applied to produce the final product. Thus more research on the combination of these influencing factors is required in order to get the full spectra of the potential properties of torrefied biomass. This project has only had the capacity to cover a fraction of the potential combination of these possibilities so far.

As consequence of this the greatest results that can be drawn from the presented project are the analyses methods and methodologies developed for analysing and characterising this new type of solid biomass fuel, but more work on standardisation and general alignment of these methods will be necessary in the future.

1.3 Project results

1.3.1 Background and conditions for the project

Replacing fossil coal with renewable biomass in large power plants is currently found to be one of the most energy efficient ways to use biomass for mitigating greenhouse gas emissions from the energy sector. Consequently, Denmark's power producers have already, and are still converting power plants from using pulverised coal into biomass. The absolute main part of this biomass is today consisting of imported wood pellets.
The transition from coal to wood pellets in power plants requires reconstruction and special care of storage and handling facilities at the ports and the plant itself as well such as milling-, feeding- and firing equipment.
Some of the major concerns with wood pellets are that they are sensitive to moisture and have to be stored and handle under dry conditions (i.e. indoor storage), while coal is stored and handled in open air. Secondly, milling of wood pellets and biomass requires more energy than milling coal and the particle size distribution becomes different. Moreover, due to relatively high content of volatile matter in biomass compared to coal, biomass burns differently, is a fire hazard in the mills and has a lower energy density than coal which effect the feeding and the combustion efficiency in the boilers.

A number of previous and current research have point at that by pre-treat the biomass at temperatures around 220- 300 C in an inert atmosphere, the properties of the biomass will change in favour of the disadvantages described above and a product behaving similar to coal can be obtained. The process is called torrefaction and has due to its claimed advantages been projected to be one of the major technical steps for converting coal plants to biomass. By using torrefaction it is claimed that less reconstructions of existing coal power plants will be necessary and that torrefied biomass will be one of the new large solid biofuel commodities on the world market.

Although, the process of torrefaction is known since the 1930's, it is only recently, with the political focus on using biomass in power plants that it has reached renewed focus. A quick survey at sciencedirect.com of the annual number of scientific papers published on torrefaction has increased from 1 in 2004, 28 in 2008, 40 in 2010, and 134 in 2012. Several patents and also a great number of different technologies has been presented and pilot plants has seen the light during these years, but still only very few commercial operating plants are operating. There are still some hurdles in both the production of and the standardisation of describing the quality of this new type of fuel before it has convinced the market.

1.3.2 Objective

According to previous research torrefaction could fulfil several tasks of upgrading biomass for improved utilization in power plants. The most promising effects and their relevance for power plants would be:

- Torrefaction changes the fibrous and typically more tenacious and less friable structure of biomass into a more brittle structure. This effect would increase the capacity on coal mills and lower the energy demand during size reduction of the biomass prior to the combustion. Ideally existing coal mill and feeding systems would not have to be changed in a change from coal to torrefied biomass

- Torrefaction increases the energy density per mass unit and also per volume unit when the torrefied biomass is densified (pelletized). This would significantly improve storage and transport efficiency and costs.

- Torrefaction change of the biomass from being a hygroscopic material to more hydrophobic. Thereby there is much less moisture bound in the material structure and would thus be inert to biological degrade. Consequently, less demanding storage, maybe even outside would be possible, without risking degradation or self-ignition of the fuel.
- Torrefaction would create of more homogenous biobased fuel from greater variety of biomass. This effect would enhance the possibility of using a wider range of biomass with less quality in the same fuel handling systems.

Considering this, the general objective of this project has thus been to investigate and evaluate the basic claims of torrefaction and try to understand some of the chemistry going on and evaluate its strength and weaknesses in a context of its utilisation in relation to Danish power plants converting from coal to biomass. In order to achieve this task, the work has been divided into 4 work packages, each with its own objectives. These objectives are described together with the description of work in the following section.

1.3.3 Implementation and organisation of the work conducted

The content of the work in the project was divided into 4 main work packages (WP) with interdepending work. WP 1 was focusing on laboratory scale torrefaction investigations, WP2 on up-scaled test in a bench scale torrefaction, WP3 on characterising the torrefied materials and finally a techno-economic evaluation of the torrefaction process potential impact on the transport to and use at power plants in Denmark.

WP1 laboratory scale experiments and analyses

In order to get better understanding of the torrefaction process, its underlying chemistry and what is the effect on different biomass types, studies were conducted in laboratory scale with a variety of smaller biomass samples. The work was initiated by making a study of biomasses that could be available as unused waste in Denmark or in great abundance abroad and therefore potential sources for torrefaction in the future (se report M1 in appendix for more details on this investigation).

Samples of these identified biomasses were obtained and tests with their behaviour during torrefaction conditions were conducted in a TGA (10 mg) and in a Pyro-oven (250 g) and in bench scale unit (300 kg). The original plan was also to use a Macro-TGA, but this equipment was damaged due to movement of the laboratory facilities at DTU/Risø and was repaired first at the end of the project thus no results from this method could thus obtained.

During the testing, it became clear that torrefaction is more complex than originally expected several parameters affect the process. Due to this not all biomass samples could be investigated and instead focus on parametric test of some chosen samples (Danish wood and straw) got more focus. Consequently it was only in the TGA investigation more than these biomasses were tested.

A NETZSCH STA 409 (Simultaneous Thermal Analysis) was used for the TGA test runs. Approximately 10 mg of the sample were placed in the microbalance and heated at rate of 10 k/min under 50 ml/min Nitrogen or Argon, to the final temperature of 300 ℃ and keep at this temperature for 1 h. Meanwhile evolved gas was analyzed online by two coupling systems connected to the TGA, which are quadruple mass spectrometer QMS 403 C from NETZSCH and Fourier transform infrared (FTIR) spectrometer Vertex 70 from Bruker, the setup is shown in Figure 1. In order to prevent condensation of evolved gas, the transfer line and gas cell for TG-FTIR was maintained at about 200 °C, while the transfer line and inlet system of

QMS was kept at about 300 ℃. A small portion of the evolved gas (together with the purge gas) was led to the ion source of mass spectrometer, since the pressure drops from atmospheric pressure in TGA down to high vacuum in the QMS; while the rest of the evolved gas was swept by the purge gas to the FTIR gas cell with no pressure change.

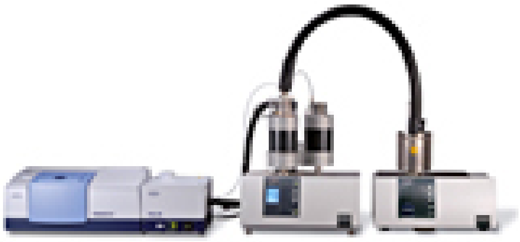


Figure 1: TG-MS/FTIR apparatus

These investigations allowed for development of kinetic expressions for the torrefaction. 9 of the identified kinds of biomass (Aspen, Norway spruce, red spruce, wheat straw, EFB, beech, willow, shea, barley) were investigated, but due to limitation of resources only the evaluation of the straw was completed before the end of the project. Data of the others biomasses are collected at DTU but need further processing for conclusive results.

The set-up of the Pyro-oven was used to torrefy batches of 250 g biomass for investigating the basic influence of different torrefaction temperatures and residence time. Wheat straw, wood chips and wood pellets were torrefied in the Pyro-oven.

Prior to each test the sample was dried at 104°C for 24 hours. The dried sample was then placed in a closed metal container (15×31×10cm) inside the pyro-oven before the heat was raised to torrefaction temperatures. During the test, 0.5 l/min N2 flows through the metal container to create an inert atmosphere. Temperatures were measured closed to the centre of the oven outside the metal container, inside the metal container and in the centre of the biomass samples placed inside the metal container.

Figure 2: The pyro-oven (Lyngbyovnen of type S 90, 3 × 380 V, 9 kW)

Moreover, heat transfer was studied during torrefaction by recording temperatures at different places in the Pyro-oven and in the sample. Temperature gradients and heat transfer dynamics of heating operations in the applied pyrolysis oven were conducted by a series of tests with full and empty pyrolysis reactor under different heating rates and maximum temperature settings. The influence of various sweep gas flow settings was also examined. During the tests 3-6 thermocouples logged the temperature in different places of the reactor – usually corner and center positions, and the variations were determined. The results were used to calculate average sample temperatures at different regulator settings, to determine efficient heating rates and maximum temperature periods and to estimate sample treatment deviations.
Samples produced in the pyro-oven were also used for a large part of the characterisation of torrefied material which was conducted as part of the subsequent WP3. The reason for this was the controlled conditions these samples could be produced and thereby the effect of different conditions on the characteristics of the torrefied materials could be investigated.

I.e. it was an important tool for correlating heating value and weight loss caused by torrefaction. In order to be able to compare biomasses with different moisture and ash content the Anhydrous weight loss was utilised for these investigations.

Anhydrous weight loss (AWL %) is the weight loss of a sample excluding moisture and ash and is calculated cording to equation 1- 3. AWL is indirectly revealing the decomposition and volatilisation of some of the organic part of the biomass and was at this used as a potential parameter to indicate the degree of torrefaction.

$$AWL\% = 100 \times \left(1 - \frac{m_{after\ torrefaction}}{m_{before\ torrefaction}}\right) \tag{1}$$

$$AWL\%_{\ (daf)} = \frac{AWL\%}{100 - ash\%_{(r.b.)}} \times 100 \tag{2}$$

$$ash\%_{\ (r.b.)} = ash\%_{(t.b.)} \times \frac{100 - AWL\%}{100} \tag{3}$$

Where $m_{\text{before torrefaction}}$ *was recorded right after the drying, making AWL% already dry based.* $\text{ash\%}_{(\text{r.b.})}$ *denotes ash percent in the raw material (untorrefied), whereas* $\text{ash\%}_{(\text{t.b.})}$ *is the ash percent in the torrefied material. Both parameters are dry material based.*

WP2 Bench scale tests, set up and experiments

Based on experience with pyrolysis of biomass as well as the introductory results from WP1 in the pyro oven a bench scale auger type torrefaction unit was constructed at DTU/Risø.
The torrefaction unit is an externally heated reactor and is supplied with biomass through an electrical powered screw conveyor (auger reactor). The unit is made of heat resistant steel and the inner diameter of the reactor is 0.355 meters and 2.5 meters in length.
The torrefaction unit is heated by a LPG burner (Liquefied Petroleum Gas) flowing in a thermo shell outside pyrolysis tube. The pyrolysis tube is constructed with a screw. The flue gas shell is constructed of heat-resistant steel has a total of six baffles. The temperature of flue gas is controlled by adjusting the gas and air volume. The thermo shell is insulated with 150 mm kaolin wool and then 100 mm rock wool. There is located 6 thermocouple in the pyrolysis tube, 4 in the exhaust shell and 1 at the feed entrance (se Figure 2 and 3). The thermocouple was data logged to a monitor to control the torrefaction experiment. Undesired com-

pounds in the exhaust from the reactor are burned with LPG before exhausted to the atmosphere.

Figure 3: Picture of the torrefaction test unit at Risø/DTU

Tests were conducted with spruce chips at 2 different temperatures (250 and 280) and different retention times (40 min at 250 C and 60 min at 280 C). The main aim was to produce larger batches of material for subsequent characterisation test such as milling, moisture uptake and pelletisation in the WP3. A secondary aim was to get experience with a continuous torrefaction process as well as safety issues of handling the hot reactive material leaving the reactor, which was challenging at first. E.g. cooling of the torrefied material in an inert atmosphere (N2) after the torrefaction to below ~200 C is crucial in order to avoid the material from self-ignite with air.

During the tests at 280 C, gases and condensate were samples for analyses. The sampling was performed by passing the the exhaust from the reactor through a distilled water bath and gas pipettes before let out to the surroundings (see Figure 3). The purpose of water bath and the gas pipettes was to collect all the potential condensable generated from the torrefaction reaction. To insure a constant gas flow through the water bath and gas pipettes a pump with a gas meter was added fig (1). The chemical composition of the condensates was analyzed using gas chromatography-mass spectrometry at 250 (GC-MS). The samples were spiked with D3-guaiacol and extracted with diethylether. The extracts were analyzed by a Hewlett Pachard HP6890 gas chromatograph interfaced to a HP5973 Mass Selective Detector (Agilent, Denmark). 1µl samples were injected by a HP 7683 auto sampler (Agilent, Denmark) and introduced in split mode (1:20) at 250 °C. The ion source and quadrupole rod temperature was 230 °C and 150 °C, respectively. The products were separated using a 0.32 mm i.d. x 30 m WCOT fused silica column coated with VF-23ms at a thickness of 0.25 µm (Analytical, Denmark). The carrier gas was He at a flow rate of 1.2 mL/min. Separation of a wide range of products was achieved by using a temperature program from 70 °C to 250 °C.

Full mass spectra were recorded every 0.5 s (mass range m/z 40 - m/z 450). Products were identified using a NIST search engine, version 2.0 f. Gas analysis was performed by using a Varian 3400 gas chromatograph interfaced to a Saturn II ion trap mass spectrometer.

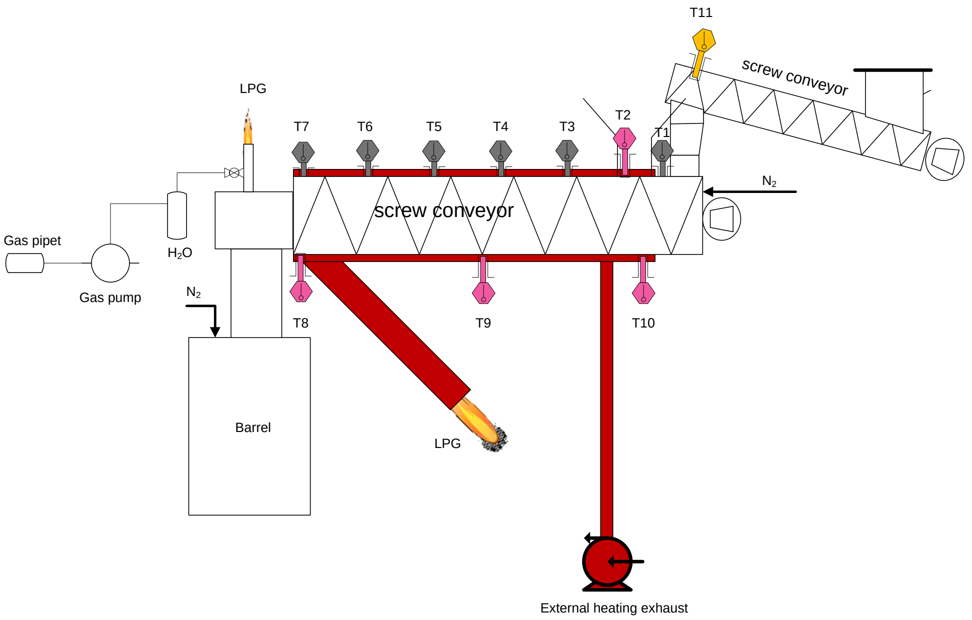


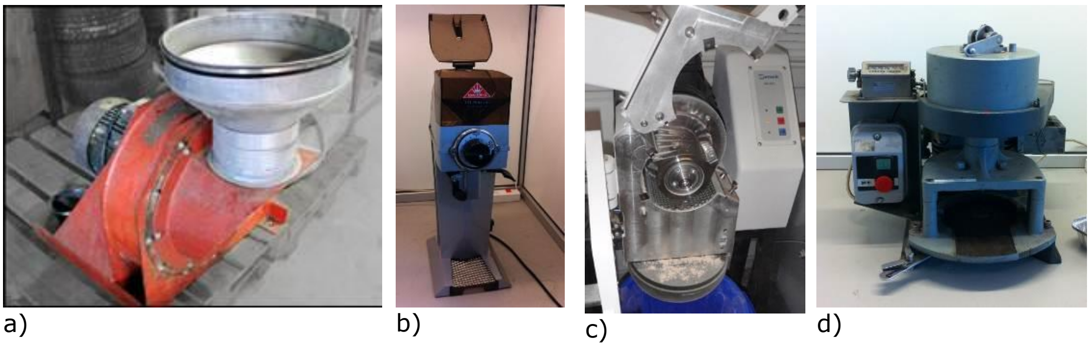
Figure 4: *Torrefaction unit. Thermocouples in the pyrolysis tube: grey (T1, T3, T4, T5, T6, T7), thermo shell: pink (T2, T8, T9, T10) and feeding screw conveyor: yellow (T11). Nitrogen is supplied to the pyrolysis unit and end product to avoid oxidation and ignition. Before the pyrolysis exhaust tube, a ball valve is placed to enable sample taking of the exhaust gas*

WP3 Processing and Characterisation of torrefied biomass

In WP3, torrefied biomass from the lab scale (batch) and continuous bench (continuous) production in WP1 and WP2 were characterized and analysed for application in processes relevant to fuel storage, handling and processing. The study was set up to focus on evaluating the main changes of torrefied biomass in terms of: chemical properties, mechanical strength, densification and storage properties.

The chemical properties investigated included measurements of the higher heating value (HHV) of torrefied material and chemical analysis of cell wall composition with regard to the content of hemicelluloses, cellulose and lignin in biomass samples before and after torrefaction. Considering this, the energy density increase caused by torrefaction could be investigated and determined.

The highest power production efficiency firing or co-firing biomass is achieved in large scale pulverized combustion systems designed for coal combustion. However, a major challenge of using biomass in these systems is that biomass is more tenacious and less brittle than coal and hence more difficult and energy intensive to grind into the necessary fine particles. By torrefying biomass the tenacious structure is destroyed and the biomass should be more brittle. This effect was therefore analyses by measuring mechanical strength (compression and tensile strength) and the energy consumption of grinding biomass materials before and after torrefaction in different mils (se figure 4). In addition, scanning electron microscopy was applied for analysis of chosen samples and pelletized materials where submitted to standard pellet durability test in (DS/EN 15210-1) as well as compression test of single pellets.



a) b) c) d)

Figure 5: Mills used for characterizing a) bench scale hammer mill, b) coffea mill, c) knife mill, d) Hardgrove ball mill for measuring Hardgrove index (HGI

Coal is in opposite to biomass hydrophobic in its character and can as such be handled and stored outdoor facilities. Torrefaction changes the properties of biomass into a more hydrophobic material, but could it be stored and handled outdoors? Considering this the storage properties of biomass samples torrefied in WP1 and WP2 were tested through investigation of moisture and water uptake ability under controlled environment (temp, humidity), water uptake ability during real outdoor climate, and drying rate experiments. By measuring these properties, a comparison of untreated and torrefied biomass under real storage condition could be made. Moreover, leachate from a potential storage is thus should thus be investigated in the future in order to evaluate potential run off from outdoor storage of torrefied material.

Figure 6: Experimental setup for long term outdoor test of water uptake. Picture was taken top down.

During the torrefaction process biomass losses about 20 % of its weight but only 10 of its energy content and as a consequence the energy density of the material increases on a mass basis. However, on a volume basis it has decreased. Thus, in order to tap the true potential of the higher energy density of torrefied materials it has to be densified after the torrefaction. The densification properties of the torrefied material is therefore a vital part for the chain of supply and has to be able to produce a high quality product using as little energy as possible and that can be handle with ease at the receiving power plants. Considering this densification test in both laboratory single pelletisation (~1 g pellets) investigations as well as in a bench scale pellet press (5kg/h) were conducted with materials from WP1 and WP2.

Energy consumption and quality of the pellets as well as parametric test including usage of additives were investigated.

Figure 7: The flat die bench scale pellet mill (~5-10 kg/h)

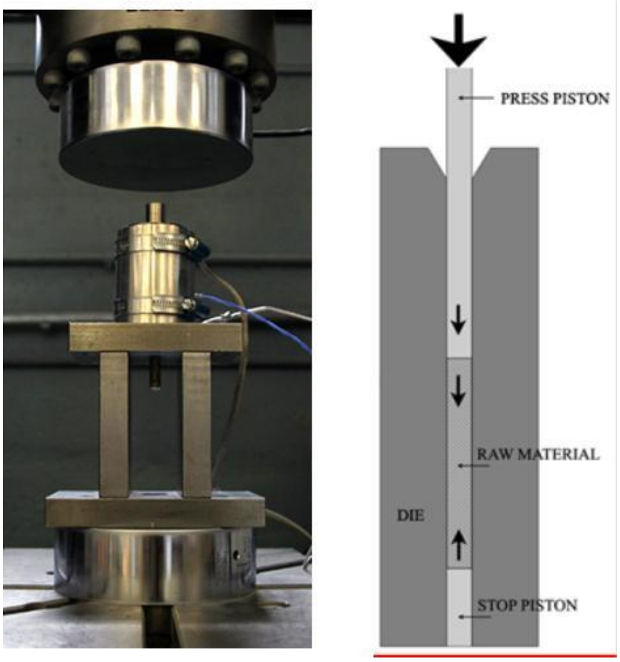


Figure 8: The laboratory singel pellet press for measurement of compression, density and force needed for pressing and pushing through a pellet through the die (1 g/pellets)

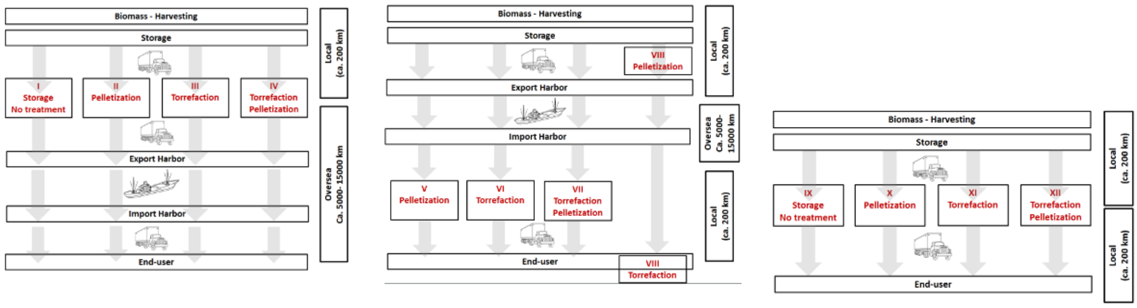
<u>WP4 Techno economic and sustainable evaluation</u>

As described above the reasons for upgrading biomass with the torrefaction process can be several, but does this extra processing actually pay off? In WP4 a techno-economic approach on the torrefaction process was conducted, investigating chosen scenarios relevant for transport to and utilisation in Danish power plants. While there are a vast amount of papers investigating different technical and scientific aspects of torrefaction, there are very little published on its potential economic impact. Moreover, due to the fact that there is less than a hand full of industrial scale operating plants using torrefaction operating and that these existing “first mover” plants are typically very keen on not revealing actual cost, mass and energy balances of these plants, there is a lack of available data for this. Consequently the current techno-economic evaluation had to be based on at the present of conducting the investigation best available literature data and is focusing on 12different cases combining transport and production of torrefied material in different types of logistic chains and compares the effect of torrefaction on these.

The 12 different scenarios discussed are:

1) Scenario I is reference case on import of untreated wood chips
2) Scenario II to IV cover oversee import where the biomass is either pelletised, torrefied or both prior to shipment
3) Scenario V and VII cover import of wood chips which are pre-treated in Denmark after import
4) Scenario VIII covers import of pelletised wood which is torrefied locally at user facility in order to improve characteristics

5) Scenario IX cover use of untreated Danish wood chips
6) Scenario X to XII covers use of Danish wood chips which are either pelletized, torrefied or both at some regional facility and transported to end user



Scenario I - V Scenario V - VIII Scenario IX - XII

Figure 9: Outline of scenarios investigated in the techno economic evaluation

Torrefied pellets will be compared and measured against wood pellets, also called white pellets, at first on economic feasibility and first thereafter on environmental and sustainability. Due to the fact that there are still discussions concerning how evaluate the sustainability of white pellets, it was decided at the end of the project that it still too early to be able to evaluate the sustainability of black pellets. It was decided that as long as these cannot be standardised it was decided to keep the evaluations study to the economic evaluations. The work will however continue in collaboration with the on-going work in IEA Task 40.

1.3.4 Main results and conclusions

The following summarises the main findings and conclusions drawn from the work described in the previous section.

1.3.4.1 Review of biomasses potentially suitable and available for torrefaction

There is a vast amount and various biomass resources available in the world. By utilizing the potential advantages of torrefaction such as more cost effective storage and more efficient transport larger volumes of biomass resources from all over the world could be available for Danish power plants. At the same time there could be great advantage of torrefying biomass from close distance due to energy savings and handling advantages during the milling and storage at the power plant. Thus torrefaction of Danish biomasses could be of potential interest as well. After a survey of potential national (Danish) biomass resources as well as potential large resources available elsewhere in the world following biomass were concluded to be investigated further in the project; 1) Norwegian spruce and beech were chosen as these are the two most common species in Denmark, 2) With the same logic straw from wheat and barley were chosen as these are the dominating species in Denmark, 3) Denmark does yet not have extensive amounts of energy crops. Willow was thus chosen for its potential and the availability of samples. 4) Industrial by-products such as mash from breweries and Shea nut residues were chosen as samples which are relatively abundant unused resources but also due to their very different composition compared to other biomasses.

The non-Danish biomass resources chosen for the tests were: 1) Aspen wood which represent an abundant hard wood (especially in Russia) that could be torrefied, pelletised and exported to Denmark. 2) Empty fruit bunches (EFB) from palm oil industry which represent a very abundant rest product in south east Asia which could have a great potential for being converted into a commodity fuel if torrefied. 3) Bagasse from sugar cane plantation due to fact that this is one of the largest biomass residues in the world. Bagasse has already many uses, but torrefaction and creation of a solid commodity biomass fuel could be another way for utilising this waste product. Samples of these biomasses were collected, but not all were used for the extensive experimental work. The reason for this was unexpected results from while testing the first Danish materials tested (Norwegian spruce and Wheat straw), and thus most of the following experimental results has thus focused on parametric test of these two biomasses. In the bench scale test only Norwegian spruce was tested due to lack of control of the process.

It is only in the TGA analyses were 9 of the different samples and pyro-oven were actually tested through. However, due to time consuming evaluation processes, only wheat straw was fully evaluated at the writing of this report.

Due to limiting data of real scale torrefaction and also the economic evaluation was limited to one biomass. In this case it was wood as it is the currently the only biomass torrefied on a commercial basis today.

1.3.4.2 Lab scale torrefaction tests

Test with samples of Aspen, Norway spruce, wheat straw, EFB, beech, willow, shea and Bar were conducted in a A NETZSCH STA 409 (Simultaneous Thermal Analysis). Approximately 10 mg of the sample were placed in the microbalance and heated at rate of 10 k/min under 50 ml/min Nitrogen or Argon, to the final temperature of 300 °C and kept at this temperature for 1 h. Meanwhile evolved gas was analyzed online by two coupling systems connected to the TGA, which are quadrupole mass spectrometer QMS 403 C from NETZSCH and Fourier transform infrared (FTIR) spectrometer Vertex 70 from Bruker.

By coupling the result from the weight loss in the TGA with the in-situ analysed gases, kinetic expressions for the de-volatilisation and heat transfer during the torrefaction process up to 300 °C was obtained. Theoretically the type of gases released gives an indication on what basic components of the biomass is reacting or falling apart at what temperature.

9 of the chosen biomass samples were investigated in the TGA tests. First the ash content was measured by heating the samples to 850 °C in the air atmosphere (Table 1). Shea and empty fruit bunches (EFB) have the highest ash content, wood chips and beech have the lowest ash content.

Table 1: Ash content of biomass samples investigated by TGA (850 C)

biomass	ash% (w.b.)
Wood chips	2,44
Asp	4,4
Norwegian Spruce	4,54
Shea	11,13
Barly	7,88
Wheat	5,98
Willow	6,42
EFB	8,87
Beech	2,93

Secondly, the mass loses during torrefaction conditions up to 300 C using the TGA for the same 9 different biomass. The results in Figure 9 reveal that torrefaction is occurring in two stages, an initial stage where the weight loss is fast followed by a second stage with a more moderate weight loss. Following this fact, and using the kinetic data obtained from the TGA it was successfully attempted to describe the torrefaction a two-step first order reaction model.

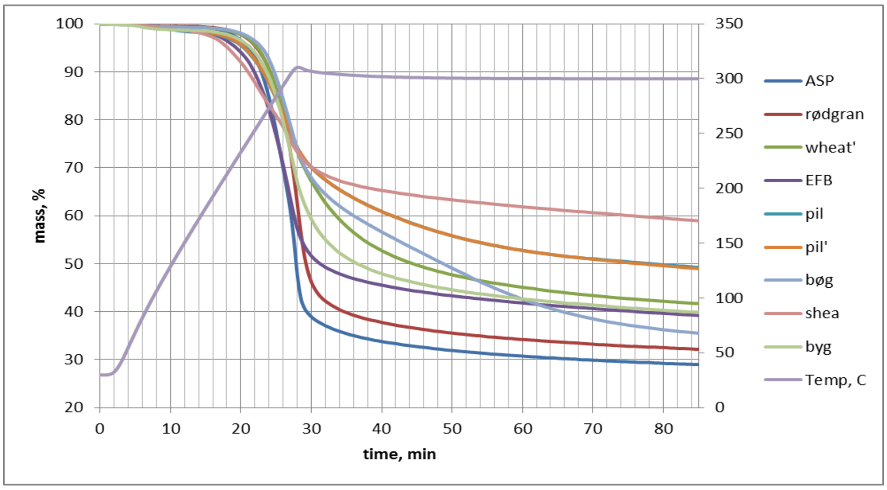


Figure 10: Mass loss curves and temperature curve of the different biomass samples during torrefaction conditions

In Paper IV, wheat straw sample (< 0.09 mm) was tested on TGA at heating rates of 10 and 50 °C min^{-1} to obtain intrinsic kinetic parameters. Different from other researchers approach (se paper IV), weight loss during the heating stage has been taken into account when deriving the kinetic parameters from the isothermal stage. Afterwards this model and parameters were examined by comparing the residual mass predicted by the model and experimental data from a batch scale reactor. Secondly, devolatilization of wheat straw during torrefaction (at 250 and 300 °C) was studied by coupling a mass spectrometer with the TGA and detecting the gas products in situ. The relative quantity of each gas product from the two torrefaction temperatures was also compared. The result is a kinetic expression that can predict the mass loss and gas evolution during torrefaction of wheat straw under real production conditions.

This kinetic study was only performed in full for wheat straw (se attached paper IV) due to the late development of the method and time running out. But due to the similarities of the TGA the developed methodology could be applied for the rest of the biomass samples tested, too.

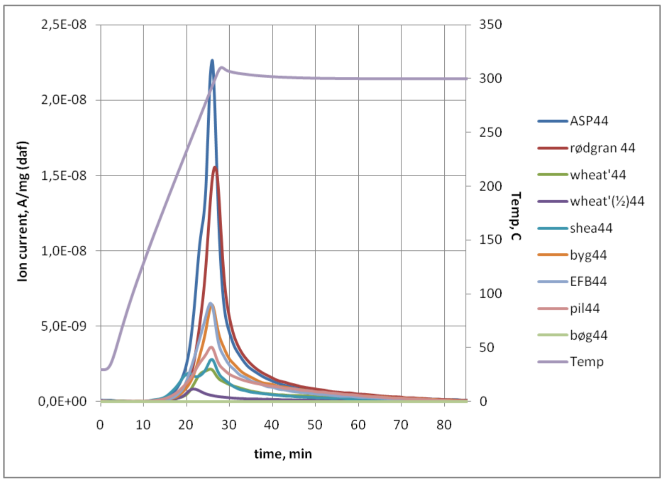


Figure 11: MS curves of CO2 development for different biomass samples during torrefaction conditions

The gases evolved during torrefaction were analyzed by TGA coupled with MS for 9 of the different biomasses samples chosen in WP1. Data were collected for all, but only wheat straw was studied in detail (paper IV) at the writing of this report.

Figure 20 shows an example of the CO_2 release during torrefaction at 300 °C from different biomass samples. It can be seen that ASP released most CO_2, and most of CO2 were released in the first 30 min.

The main gases formed during torrefaction are: water, carbon monoxide, formic acid, formaldehyde, methanol, acetic acid, carbon dioxide for all samples. Methyl chloride, and traces of hydrogen sulphide, carbonyl sulphide were found at both 250 and 300 °C for wheat straw. At 300 °C, evolution of water accounts for almost half of the overall mass loss.

Methyl chloride was observed in torrefaction of wheat straw, at both 250 and 300 °C, which is of special interest as it means torrefaction can reduce some of the chlorine content of the solid products.

In order to produce larger samples of material that could be used for further characterisation, torrefaction test in a 9 kW pyro-oven with batches of around 250 g each were conducted at different torrefaction temperatures and residence times for wheat straw, wood chips, wood pellets. The results of these screening tests are illustrated by the pictures in Figure 11.

Figure 12: Samples from torrefaction test in the pyro oven (wood pellets, wood and straw)

By analyzing the weight (AWL) and the higher heating value (HHV) of the samples after different torrefaction temperatures and residence times in the pyro-oven, correlation curves between AWL and HHV could be obtained (figure 12). Wood pellets and wood chips showed similar heating values and weight loss characteristics during torrefaction. For wheat straw, the HHV was always about 0.8 MJ kg-1 lower than the values for the other two fuels. The correlation between weight loss and energy loss is very similar for the three tested biomass fuels and could thus potentially be used as defining a degree of torrefaction which takes into account the temperature history of the samples torrefied. I.e. the same torrefaction degree can be obtained at short residence time and high torrefaction temperature as by a longer residence time at a lower torrefaction temperature.

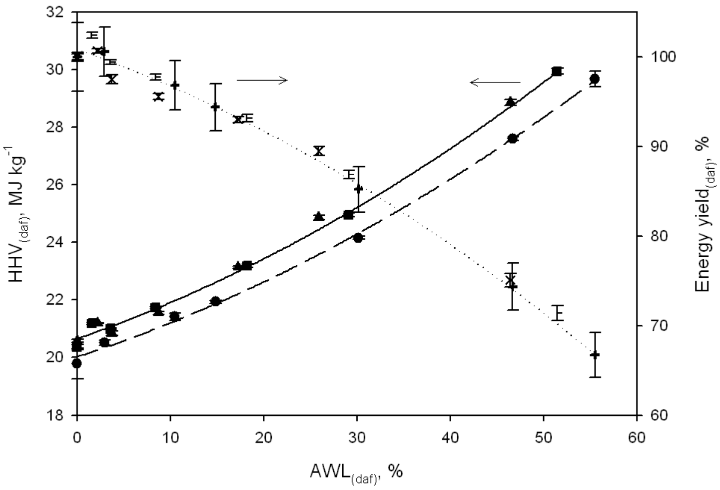


Figure 13: Higher heating value for wheat straw (●), wood pellets (■) wood chips (▲), and energy yield for wheat straw (+), wood pellets (-), wood chips (×) vs. anhydrous weight loss (0% AWL represents oven dried samples) on dry and ash free basis. [3]

Moreover, by comparing temperature measurements within the biomass with temperatures of the surrounding (inside the metal container and the pyro oven control temperature), it was observed that at about 250 °C the temperature of the biomass suddenly raises above the surrounding. This indicates that an exothermic reaction occurs when the torrefaction temperature reaches about 250 °C and means that in order to keep a constant torrefaction temperature heating is only required at lower temperatures but at above 250 °C cooling would be necessary in order to keep a even temperature. Due to this the energy balance of the torrefaction process is more complicated than thought of starting these investigations.

More details and results can be found in the attached milestone report M3 and the papers I-IV.

1.3.4.3 Bench scale torrefaction and milling test

A bench scale torrefaction unit was constructed and tests with pine chips and nitrogen as a carrier gas preventing oxidation and ignition of the torrefied material was carried out. The torrefaction unit is of auger type and has a capacity of 10 kg/h of torrefied material. Test were conducted at three different torrefaction temperatures 250, 270 and 280 C and the produced material was compared with the same material produced at the same torrefaction temperature in the pyro-oven. However, in order to ensure homogeneity of the product in the continuous bench scale reactor, the retention time was enhanced to (40 min at 250 °C and 60 min at 280 °C) in order to make sure that the heat transfer was ideal for the more massive wood chips. This assumption was confirmed by correlating the higher heating value of the torrefied wood materials from the pyro-oven and the auger reactor, torrefied under similar conditions (se fig 13).

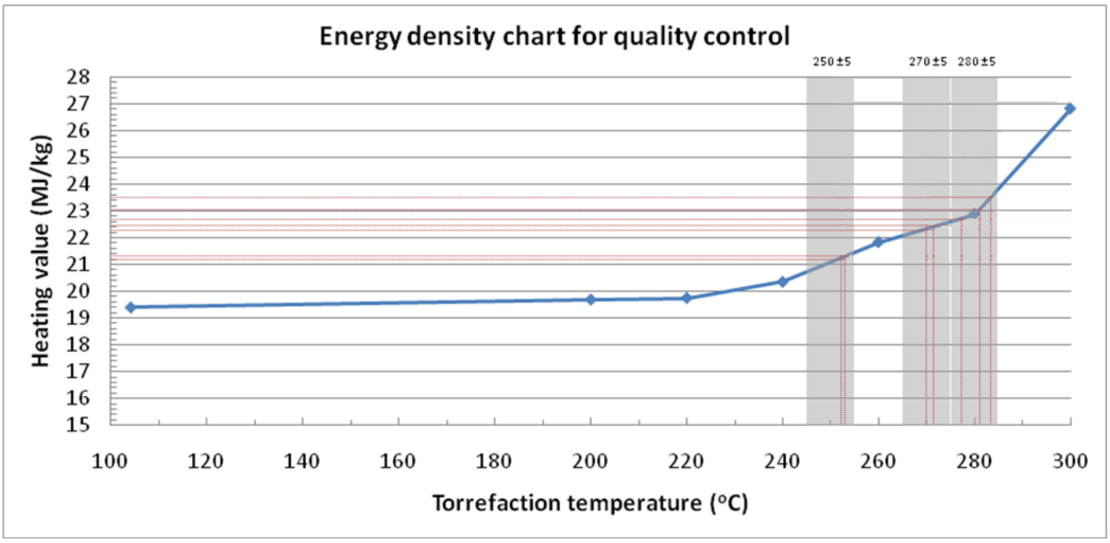


Figure 14: Energy density chart. Heating value versus set temperature for torrefaction confirm comparable results between Bench scale and lab scale results.

The bench scale tests also observed that torrefied material leaving the reactor at temperatures above 200 °C and in air could suddenly self-ignition or start smoldering. It was thus concluded that the product has thus to be cooled down to below 200 °C in an inert atmosphere (N2) before it can be safely stored. At lower temperature no reactions was observed even when stored in air.

Condensable gaseous from the gaseous side streams of the reactor was collected in a water bath with distilled water subsequently analyzed by means of GC-MS. The results revealed acetic acid, methanol and 2-furaldehyd as the dominating gaseous species. Traces of methyl chloride were also detected. These results were in good agreement with the test previously conducted in the TGA with in-situ gas measurements.

The test rig design was laid out to produce up to 10 kg/h in a continuous production. However, although tests were conducted for several hours with production rates of 6-10 kg/h and about 300 kg of wood chips at each of the three temperatures tested were torrefied no real steady state conditions could be obtained. Accordingly, mass and energy balances turned out to be impossible to establish from this set up. Due to these difficulties and also lack of resources only test with spruce wood chips was carried out although tests with additional 2 other biomass samples (straw and biomass waste) were in the original plan.

One reason for setting up the bench scale torrefaction unit was the possibility to produce large amount of torrefied material for further characterization and processing tests. Some of this material was also used for the characterization test in the subsequent laboratory testing (se next section) but the major part was used for test in a bench scale hammer (7.5 kW) and a pellet mill (3 kW).

The test in the hammer mill was performed with a 4 mm screen while energy consumption and particle size distribution was measured. All torrefied materials were tested and the results compared to milling of non torrefied pine wood chips. The results revealed that the energy consumption for grinding pine chips was about halved for chips torrefied at 250°C and up to six times for chips torrefied at 280°C compared to that of untreated chips. (se table 4)

Table 2: Energy consumption for grinding untreated and torrefied wood chips. The values from untreated and torrefied wood chips are subtracted the hammer mill own consumption where no material are present.

Pine chips	Energy consumption [kW]	Feeding speed [kg/h]	Hammer mill Own consumption [kW]†	Net energy consumption [kWh/t]*	Net energy reduction [%]
Untreated	6,49	60	2,61	64,67	-
Torrefied at 250 °C	4,15	52	2,61	29,61	55
Torrefied at 280 °C	3,71	52	2,61	10,76	85
Dry coal	7	804	3,56	4,29	

† No material is present

* Hammer mill own consumption are subtracted

The particle size distribution is also altered by the torrefaction and milling of torrefied material using the same screen produces smaller particles. The results showed that using a 4 mm screen in the hammer mill 40% of the particles leaving the mill are less than 1 mm in diameter when milling untreated pine chips while for torrefied pine chips the distribution are 75% and 80% less than 1 mm (250 °C and 280°C, respectfully).

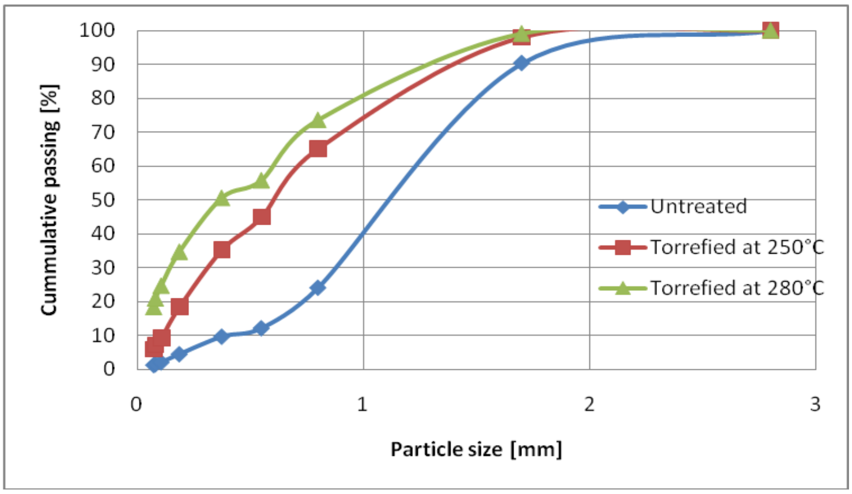


Figure 15: Cumulative passing graph of ground untreated and torrefied pine chips using 4 mm screen in a hammer mill.

Finally, the torrefication of wood chips has not only effect on the size distribution, but also on the shape of the particles after milling. Torrefaction makes the wood less fibre rich and more smooth which diminish cavities. This is clearly revealed by the micrographs shown in Figure 15 & 16.

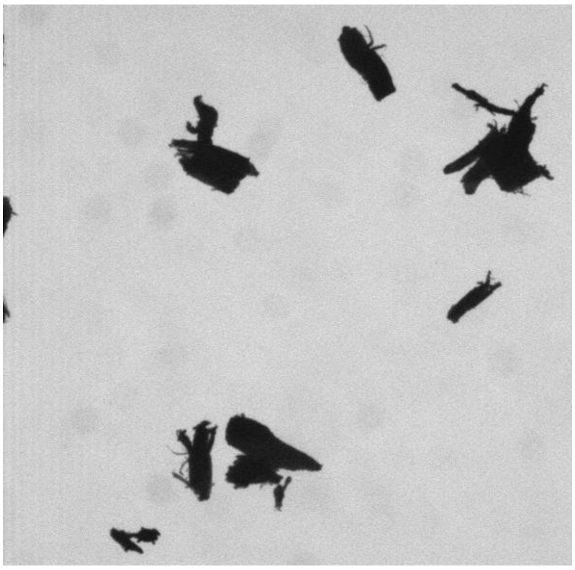


Figure 16: Milled Raw wood chips

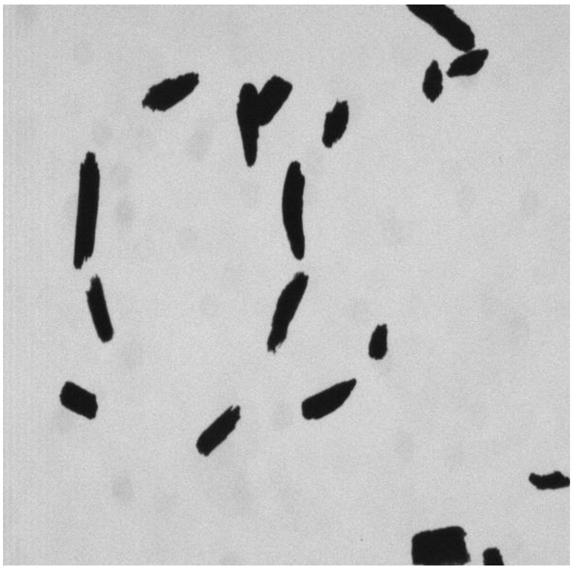


Figure 17: Milled torrefied wood chips (280°C)

The trials in the bench scale pellet mill (Kahl 14-175 flat die pellet mill) revealed problems caused by extremely high frictions caused by the torrefied material (Figure 17). The energy consumption became extremely high and the temperature of the dies quickly rose to temperatures well above normal operation and could not be stabilized for a steady state production (se figure 18). Addition of water could not solve this problem as the friction was still too high. By adding 2% rape seed oil as a lubricant a steady state production could be obtained and about 10 kilo was produced, but the quality of the produced pellets was relatively poor with low durability and quite short pellets.

Figure 18: The Kahl Pellet mill during pelletisation of torrefied wood (a) the mill , (b) pellets from torrefied beech wood, (c) short pellets from torrefied pine with addition of 2 % rape seed oil

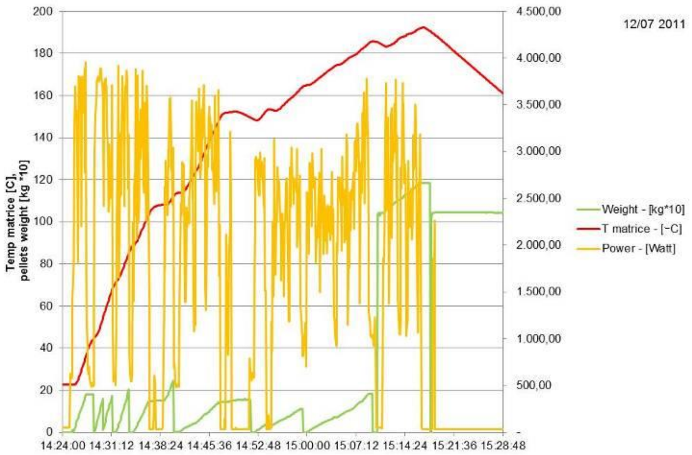


Figure 19: Data collection from pelletising torrefied material in bench scale pellet mill (die temperature –red curve, power usage –yellow curve, pellet mass flow –green curve)

It was therefore decided to continue test in single pellet test equipment where the influence of die, temperature, moisture and the amount of lubricating additive could be separately evaluated in more detail. (se next section about characteristics of torrefied materials for details on the single pellet test)

More details and results from the bench scale tests are also found in the appendix (report M4 and M5.)

1.3.4.4 Characteristics of torrefied biomass

A major aim of the project was to confirm or reject the previous claimed improvement torrefaction could have on the characteristics of solid biomass fuels. The results from both bench scale and lab scale test in the project do indeed prove that most of these are correct and can be replicated.
The energy density (weight basis), grindability, and hygroscopicity of biomass fuels are indeed improved by means of torrefaction, but that pelletisation becomes more challenging.

Moreover, the correlation between these properties and degree of torrefaction was also established. By analyzing the chemical changes of both non-torrefied biomass and biomass torrefied at 300°C and 2 h, it can be seen that hemicellulose is totally degraded and that the cellulose is also strongly altered under such torrefaction conditions.

Results from the bench scale hammer mill (se bench scale test section) and the test in the lab scale coffee mill show agreeing results and confirms that grindability can be significantly improved by torrefaction.
The results revealed that in order to achieve a grindability of biomass samples similar to that of coal, a torrefaction temperature of above 240 °C would be needed for wheat straw and wood chips, while for wood pellets 290 °C is required.

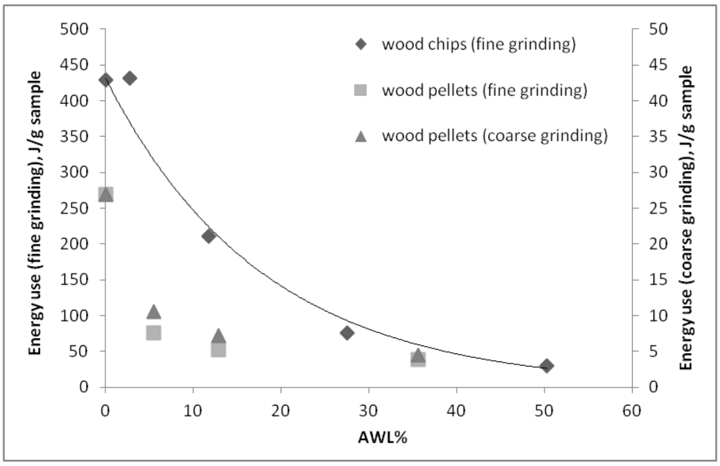


Figure 20: specific energy required for grinding pellets and wood chips (J/g) vs. Anhydrous weight loss (AWL %)

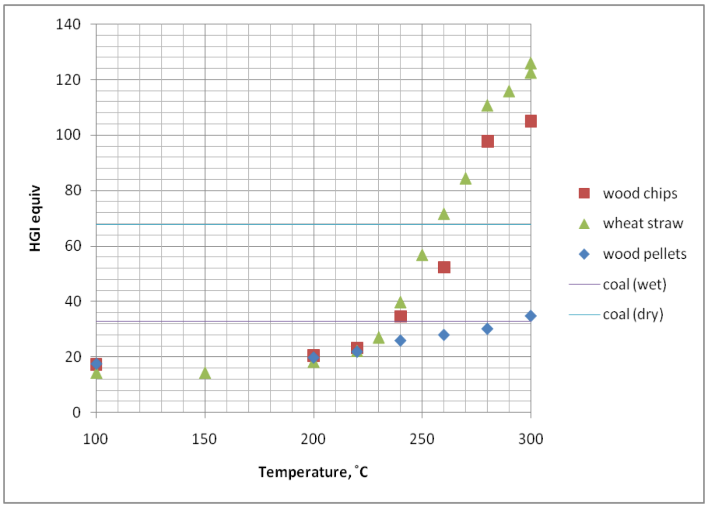


Figure 21: Results of Hardgrove Grindability test for biomass torrefied at different temperatures (for 2 h), coal in wet (9% moisture content) and dry (dried at 104 °C for 24 h) conditions were also tested as reference

However, it was also concluded that the traditional Hardgrove Grindability Index method, developed for roll milling of coal, is not suitable for predicting the level of energy consumption during grinding of torrefied biomass particles larger than 1,18 mm in a hammer or disc mill.

Moisture uptake of biomass from humid air was found to be considerably reduced by torrefaction, and the reduction increases with torrefaction temperature for all applied humidity levels (see Figure 21).

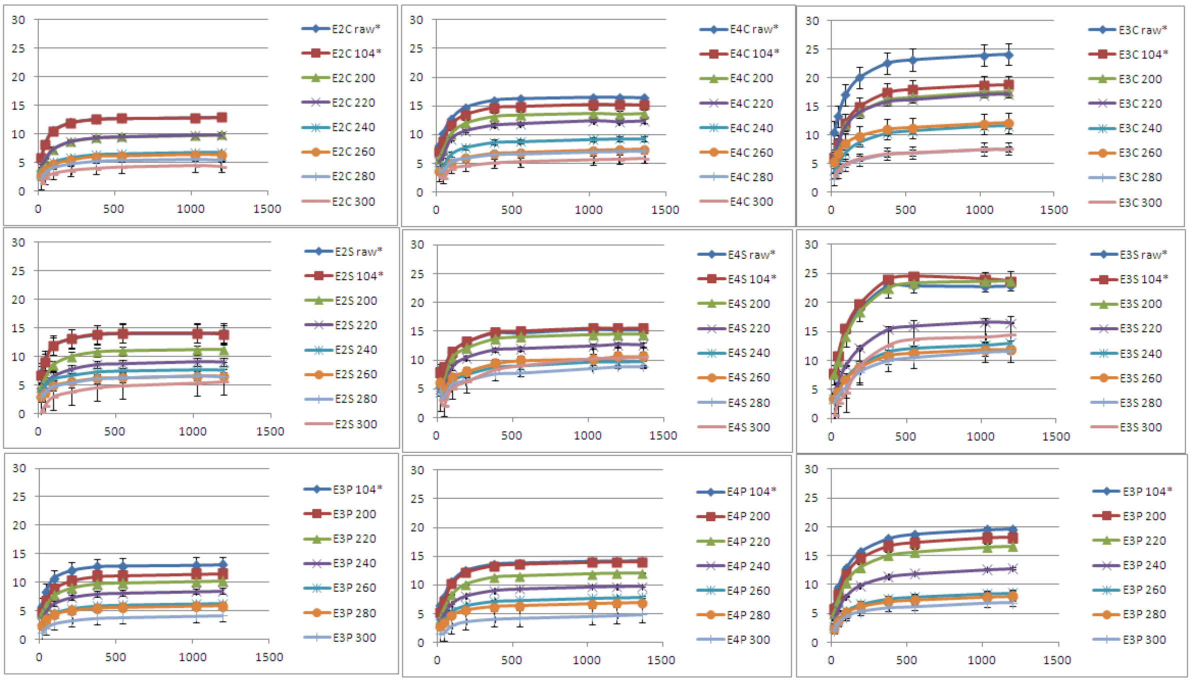


Figure 22: Changes of samples' equilibrium moisture content (on dry basis, as y-axis) with time (in hour, as x-axis) under 3 relative humidity levels (E2: 75.5%, E4: 85%, and E3: 92.5%) for original samples (denoted as 'raw'), oven dried biomass samples (denoted as '104', which means dried at 104 °C for 24 hours) and samples torrefied at different temperatures (S: straw, C: wood chips, P: pellet).

Water uptake in submerged biomass was also reduced by torrefaction (figure 22), but the pattern was less straight forward than it was for the moisture experiments as it was observed that the most severely torrefied sample (300 °C) took up more water than the 200 and 250 °C samples. In a natural environment with combined exposure to water (outdoor rain test) and moisture, a straight forward pattern was observed in the first month. In this period, the level of moisture in the biomass samples decreased with increasing torrefaction temperature. After approximately 1 month this pattern changed and the most severely torrefied sample (300 °C) began to take up most water. The reason for this is not known but most likely it is an effect of the increased amount of cavities in this material created from the devolatilization during torrefaction. These cavities are destroyed when the material I densified (e.g. pelletised) but test were only made with torrefied chips due to the unexpected problematic issue of making high quality pellets for the test.

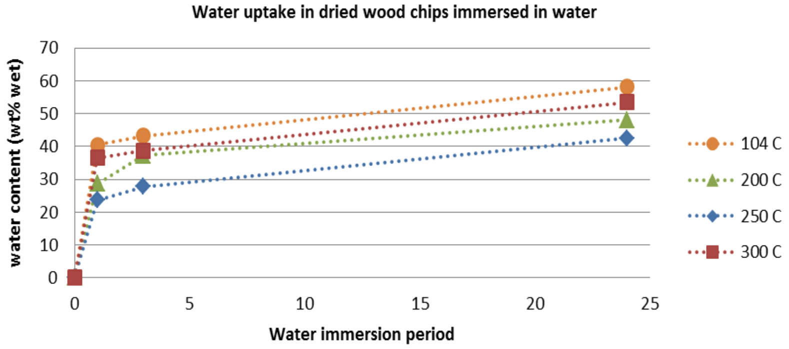


Figure 23: Water uptake in submersion test of dry and torrefied pine wood chips.

The reason for the lack of high quality pellets was that pelletisation of torrefied material proved to be more challenging than pelletising untorrefied biomass. The main reason for this challenge is the unexpected high frictions torrefied material creates in the process and the changed chemistry of the natural binders (e.g. lignin) in the biomass. However, by combining die or material temperature, additives and moisture this could most likely be overcome in the future. Test in a single pellet press revealed that addition of lubricating additives such as rape seed oil can overcome the increased friction but the quality of the pellets are suffering. The same effect is seen by increasing moisture, although less effective. An increased die temperature (190C) did however improve both quality (strength) of the pellets and lowered the friction in the dies. This approach do however implicates other potential challenges such as risks for potential fires during the production. Torrefied pine chips from the bench scale torrefaction reactor showed sign of self-ignition at temperatures above 200 °C.

More optimization and test are required and will most likely have to be optimized on a case by case basis depending on the material that has to be pelletized.

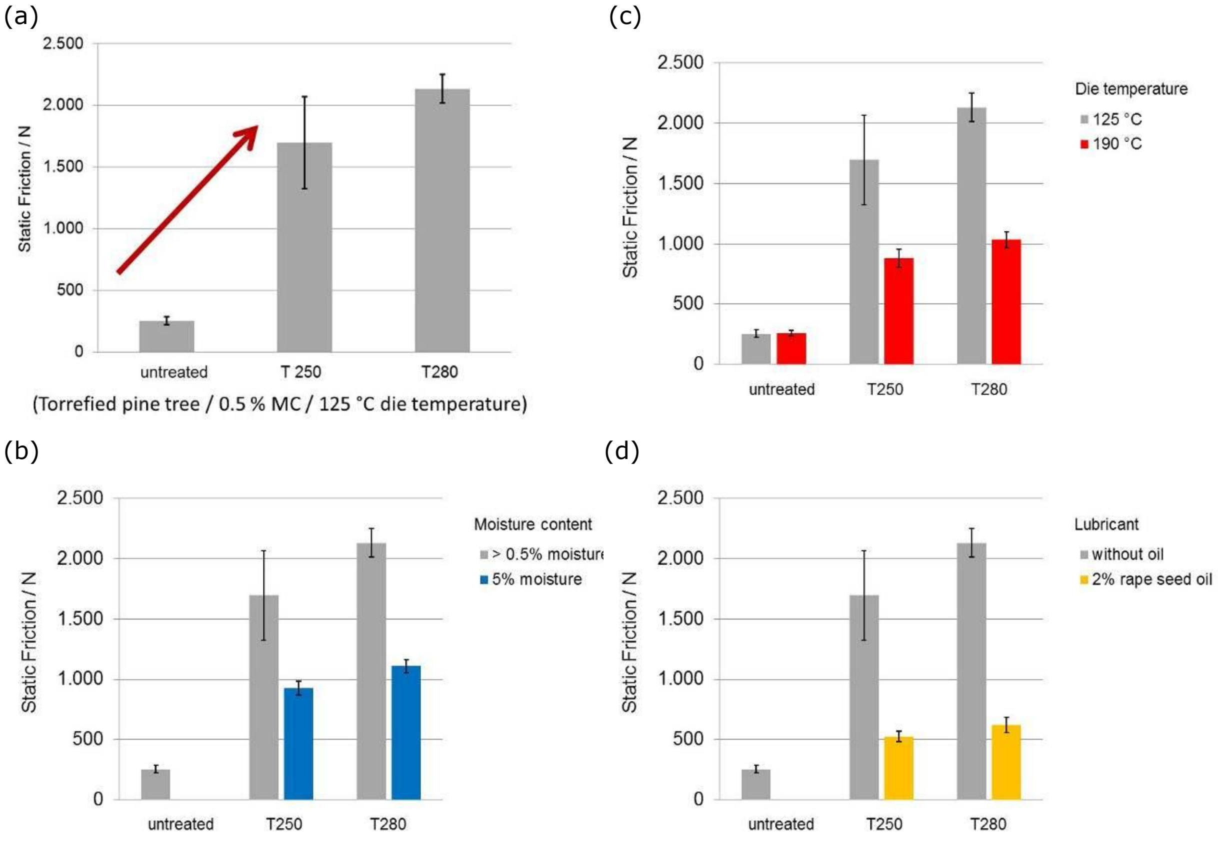


Figure 24: Parametric test in single pellet test influencing static friction between pellets and die revealing influence from (a) degree of torrefaction (temp),(b) moisture content,(c) die temperature and (d) addition of lubricant (rape seed oil

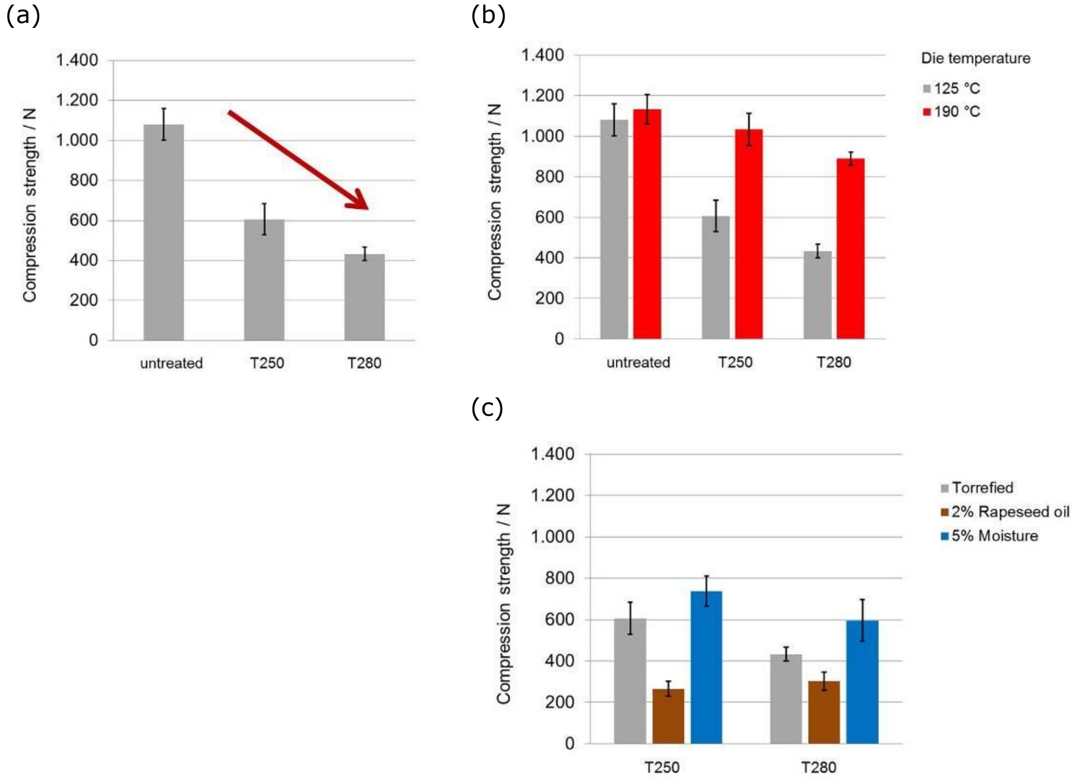


Figure 25: Parametric test influencing strength of pellets revealing influence of a) degree of torrefaction, b) die temperature and c) moisture and addition of rape seed oil

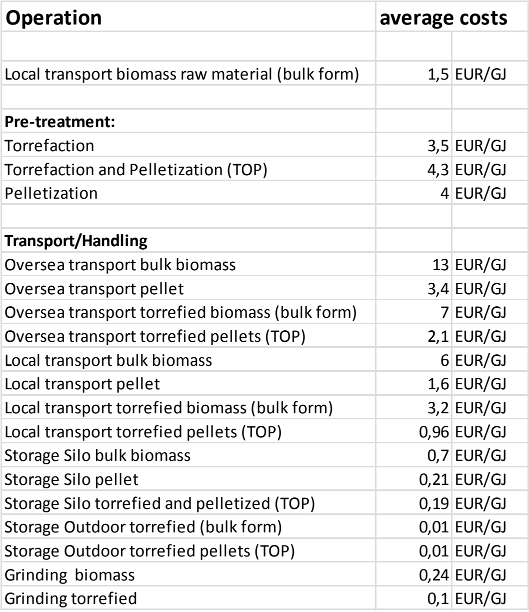
Moreover, the original plan of the project was to also investigate the leaching of ash components after torrefaction as an additional process step for upgrading the biomass. This idee was based on the assumption that torrefied biomass would be so hydrophobic that water would simply run of the material taking dissolved ash components (salt) with the runoff water without the need for further drying of the biomass. However, after realizing that the torrefied material does still absorb quite some amounts of water, especially in the undensified form like the torrefied wood chips which is the needed for efficient leaching, a subsequent energy consuming drying step would be needed.
Thus, if reduction of ash forming elements is a goal of the process, it is thus better to use wet torrefaction were the torrefaction and the leaching are obtained in one step. The efficiency of this process has been shown by others in laboratory scale wet torrefaction processes and the ash content can be significantly reduced. This project did only have access to dry torrefaction and thus the step leaching ash consistent was not further pursued, but is recommended to be tested in the future projects. It should be added that off gases from the torrefaction of straw did contain substantial amounts of methyl chloride and the amount of Cl is reduced also by dry torrefaction.

More details on tests and results from the work characterising torrefied materials are revealed in the attached appendix (report M5) and the peer review papers I-IV.

1.3.4.5 Techno-economic evaluation

The techno economic part of this report is based on data from earlier studies such as scientific publications and technical reports as well as personal communication with pellets industry and power producers. It has to be noted that there was a wide spread when comparing data from different resources especially regarding costs and energy for biomass processing. The differences originate in different frame work conditions for different countries and often also in the presentation of "very optimistic" best case scenarios where energy losses and costs have been minimized by integration and combination of processes. Especially techno economic data of torrefaction processes found in literature are, although written by different authors, often based on the same original data (the most cited and work referred to is the one by Bergman [8] that was one of the first studies published about biomass torrefaction processes). This makes it difficult to compare data for different processes and to estimate the spread of processing costs that can likely be expected when operating in different countries and biomass resources. Based on the data from earlier publications an average price for different operations in the value chain of biofuel production and logistics has been set up as shown in Table 2 and been used to calculate different processing scenarios (Scenario I to XII) as shown in Table 3 and visualized in Figure 13.

Table 3. Average costs for solid biofuel supply chain. The data is calculated/based on literature findings and represents average values. For more informarion see Figures 3,5,7,8,9 and Table 1 and references [7-30].



Operation	**average costs**	
Local transport biomass raw material (bulk form)	1,5	EUR/GJ
Pre-treatment:		
Torrefaction	3,5	EUR/GJ
Torrefaction and Pelletization (TOP)	4,3	EUR/GJ
Pelletization	4	EUR/GJ
Transport/Handling		
Oversea transport bulk biomass	13	EUR/GJ
Oversea transport pellet	3,4	EUR/GJ
Oversea transport torrefied biomass (bulk form)	7	EUR/GJ
Oversea transport torrefied pellets (TOP)	2,1	EUR/GJ
Local transport bulk biomass	6	EUR/GJ
Local transport pellet	1,6	EUR/GJ
Local transport torrefied biomass (bulk form)	3,2	EUR/GJ
Local transport torrefied pellets (TOP)	0,96	EUR/GJ
Storage Silo bulk biomass	0,7	EUR/GJ
Storage Silo pellet	0,21	EUR/GJ
Storage Silo torrefied and pelletized (TOP)	0,19	EUR/GJ
Storage Outdoor torrefied (bulk form)	0,01	EUR/GJ
Storage Outdoor torrefied pellets (TOP)	0,01	EUR/GJ
Grinding biomass	0,24	EUR/GJ
Grinding torrefied	0,1	EUR/GJ

Under the price assumptions made it can be seen that pre-treatment operations are costly and pay off when transporting the biomass over long distance. The Figures presented in Table 2 and 3 can however only be seen as price indications. The data presented earlier in this report indicates how volatile the cost calculations are (wide spread of data) and depend to great extent on single factors i.e shipping costs of biomass. The raw materials price which is not included into the scenarios because of its high uncertainty has a big impact too. High value biomass resources such as wood chips cost a lot of money per GJ compared to waste products such as fruit bunches, straws or pulps that are available for little or no costs.

Table 4. Different supply chain scenarios

Scenario	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	
Local transport raw material	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	EUR/GJ
Pre-treatment	0	4	3,5	4,3	4	3,5	4,3	4,3	0	4	3,5	4,3	EUR/GJ
Oversea transport	13	3,4	7	2,1	13	13	13	3,4	0	0	0	0	EUR/GJ
Local transport	6	1,6	3,2	0,96	1,6	3,2	0,96	1,6	6	1,6	3,2	0,96	EUR/GJ
Storage	0,7	0,21	0,01	0,01	0,21	0,01	0,01	0,21	0,7	0,21	0,01	0,01	EUR/GJ
Grinding biomass	0,24	0,24	0,1	0,1	0,24	0,1	0,1	0,1	0,24	0,24	0,1	0,1	EUR/GJ
sum	**21,44**	**11**	**15,31**	**8,97**	**20,55**	**21,31**	**19,87**	**11,1**	**8,44**	**7,55**	**8,31**	**6,87**	**EUR/GJ**

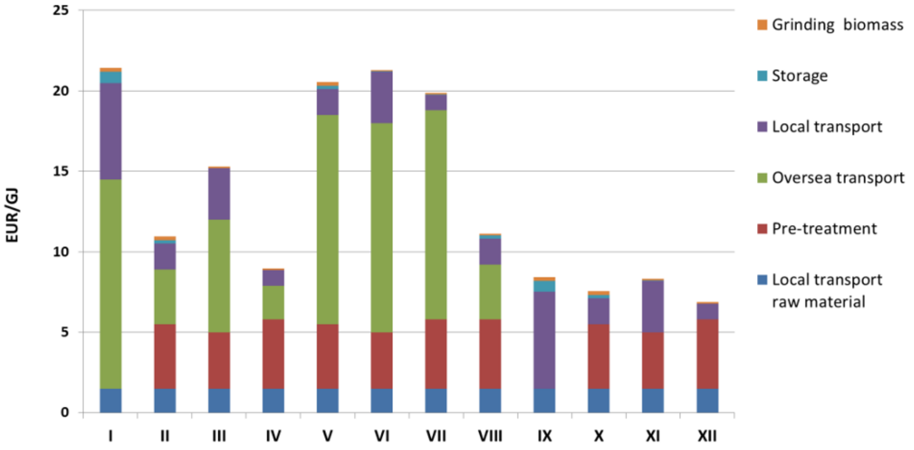


Figure 26: Illustration of results of applying different biomass supply chain scenarios

Looking at the long distance oversea transportation of pre-treated biomass (Scenarios I to IV) it is obvious that Pre-treatment and transportation are the major cost factors. Pre-treatment reduces the cost for shipping to a fraction. The bulk density is increased up to factor 10 which means that the same amount (weight) of biomass can be transported with fewer vessels. The longer the transportation distance and the higher the density of the biomass carrier the greater is the effect on the overall supply chain. The highest energy density can be obtained by combing torrefaction and pelletization (Scenario IV) and thus this energy carrier is least expensive to ship over long distance. Pelletization of biomass increases the density sufficiently to reduce the overall price for the whole supply chain while torrefaction alone results in a product of relatively low bulk density that still is expensive to transport. The torrefied biomass is cheaper to store at power plant sites and requires less energy to grind but compared to transport and processing costs they can be seen as minor cost factors having only little influence for the whole supply chain.

Scenarios V-VII are scenarios where biomass is transported from oversea and pre-treated after arrival. Examples are wood pellets producers that ship wood residues from the Americas to Europe and dry and pelletize it after arrival. Figure 13 shows that the costs are relatively high since the advantage of saving money during transportation is lost. However since cases like these exist there have to be customers that are willing to pay the higher price, either due to lacking competition, subsidies or selling a high value product (i.e. wood pellets for the domestic market).

Scenario VIII is a special one were biomass pellets are imported from abroad and torrefied prior utilization in a power plant. The costs are relatively high but using torrefied biomass in the plant may save high investment costs at power plant site (change from coal to biomass lines) and might justify the greater costs. The off heat from the plant could be used for the torrefaction process so that there might be some additional synergy effects that have not been taken into account in the context of this study.

Scenarios IX to XII are based on local scenarios were biomass is transported short distance. It can be seen that at this short distance pre-treatment does not pay off. However the economic situation can change by increasing the distance above the 200 km. Pellets produced for use in private homes can be sold to a much higher price as pellets sold to industry customers. Local factors such as transport limitations, taxes and legislation may also change the outcome of the scenario justifying the pre-treatment.

The present study does not take into account other factors that improve the value of pre-treated biomass such as homogeneous size and composition (allowing standardization and process automation) and storage and combustion properties such as off-gas formation and self-heating of biomass and co-firing properties. Power producers may be willing to pay extra for those properties since they ease the handling and utilization of biomass within their facilities. Especially the savings (time and money) and flexibility that can be obtained when biomass can be run in existing coal lines have to be named as sales argument for torrefied pellets. Last but not least the green image and the relatively fast implementation of biomass firing (compared to other renewables) are influencing the marked price too. Aim of this report is not to present absolute values but more to show the correlation of the different processing and logistics steps and to show that scenarios are highly depending on the volatile prices of individual parts of the supply chain. Shipping prices depend for example to large extends on the global economy and in recession times shipping cost are a fraction of what they are in strong growth phases.

Further studies need to focus on storage properties of biofuels that have shown to be problematic, especially in large scale and the utilization of alternative raw materials such as residues from agriculture and food industry. Moreover, also process integration to reduce the costs of pre-treatment by maximizing synergy effects with existing processes, such as drying, milling and densification.

It is here of utter importance that gases from torrefaction process are utilized in some efficient way, either as gas for chemical extractions or at least as a heat source integrated in the process, as these gases will contain 10-25 % of the energy of the original biomass.

The full report with assumptions and literature review which these studies are based on is found in the attached Milestone report M6.

1.4 Utilization of project results

The development and research on torrefaction is currently quite extensive in several research organisations and companies all over the world and a number of demonstration plants are under construction or have been erected. E.g. one of the largest demonstration plants is the plant erected in Denmark (EUDP project 10-II Torrefaction Development and Demonstration Plant) where DTI, Andritz and DONG are involved. The existence of this torrefaction project was one of the reasons that the demonstration plant was erected in Denmark at the facilities of DTI in Sdr. Stendrup, but was build and is operated by Andritz Pulp & Paper.

However, although this large amount of on-going activity, there are still more work to be conducted in order to characterise and secure quality of this new type of fuel.

The work carried out in this project has provided significantly more insight into the challenges of analysing and characterising this of new type of solid fuel. The new properties of this fuel have forced the project to develop new methodologies for characterising its properties such as (hydrophobicity (moisture uptake), grindability, and degree of torrefaction and pelletisation properties. These new methods and methodologies are very important results which will be used further by DTI and DTU/Risø for future characterisation of torrefied biomass fuels and pellets that will for sure be commercial in one or other form in a near future. DONG will also use the knowledge from these results and analyses, which enable DONG as a purchaser of biomass, to define and to have more realistic quality demands on potential providers of torrefied materials for their power plants.

Moreover, the initial investigations carried on in this project has also formed one of the starting points for the European project SECTOR (www.sector-project.eu) which started jan 2012 and DTI is a project partner and especial focus on the further understanding of pelletising torrefied biomass . This project will further investigate torrefaction on several levels, including large scale tests and production at different sites in Europe, but will also focus heavily on the further development of methods for correct characterisation of torrefied materials. The methods and results from this project forms a god basis for these further developments

The results from the Lei Shangs thesis are directly incorporated in the teaching of the Biorefinery courses at DTU and finally results and knowledge of the project will be used as input for the work at IEA Task 40 (DTI is the Danish representative) on defining new standards for sustainable international trade of biomass.

1.4.1 PhD and dissemination

The results of the project has been disseminated in a number of peer review papers but also presented at a number of national and international conferences as oral and poster presentations. Furthermore, a major part of the published material has been and will be disseminated as part of the PhD thesis of Ms Lei Shang.

1.4.1.1 PhD Thesis

Author: Lei Shang
Title: Upgrading fuel properties of biomass by torrefaction
Defence: May 24, 2013

1.4.1.2 Peer review papers from the project:

I Changes of chemical and mechanical behavior of torrefied wheat straw,
Lei Shang*, Jesper Ahrenfeldt, Jens Kai Holm, Anand R. Sanadi, Søren Barsberg, Tobias Thomsen, Wolfgang Stelte, Ulrik B. Henriksen
Biomass and Bioenergy, (2012), 40: 63-70.

II Physical and chemical property changes of 3 biomass fuels caused by torrefaction,
Lei Shang*, Wolfgang Stelte, Jesper Ahrenfeldt, Jens Kai Holm, Rui-zhi Zhang, Yong-hao Luo, Helge Egsgaard, Søren Barsberg, Tobias Thomsen, Lars Stougaard Bach, Ulrik B. Henriksen
Biomass and Bioenergy, under review

III Quality effects caused by torrefaction of pellets made from Scots pine,
Lei Shang*, Niels Peter K. Nielsen, Jonas Dahl, Wolfgang Stelte, Jesper Ahrenfeldt, Jens Kai Holm, Tobias Thomsen, Ulrik B. Henriksen *Fuel Processing Technology*, (2012), 101: 23-28.

IV Intrinsic kinetics and devolatilization of wheat straw during torrefaction,
Lei Shang*, Jesper Ahrenfeldt, Jens Kai Holm, Søren Barsberg, Rui-zhi Zhang, Yong-hao Luo, Helge Egsgaard, Ulrik B. Henriksen
Journal of Analytical and Applied Pyrolysis, Available online 24 December 2012, ISSN 0165-2370

1.4.1.3 Peer review papers made in collaboration with other projects

A Pelletizing properties of torrefied spruce, Wolfgang Stelte, Craig Clemons, Jens K. Holm, Anand R. Sanadi, Jesper Ahrenfeldt, Lei Shang, Ulrik B. Henriksen, *Biomass and Bioenergy*, Volume 35, Issue 11, November 2011, Pages 4690-4698

B Pelletizing properties of torrefied wheat straw, Wolfgang Stelte, Niels Peter K. Nielsen, Hans Ove Hansen, Jonas Dahl, Lei Shang, Anand R. Sanadi, *Biomass and Bioenergy*, Volume 49, February 2013, Pages 214-221

1.4.1.4 Oral presentations disseminated from the project:

TORREFACTION-Fremstilling og brug af varmebandlede træpiller
J. Dahl.
Dansk Træpillekonference 2010, 27 april, 2010, Middelfart

TORREFACTION of BIOMASS, J. Dahl., Presented at EnergiForsk 2010, 21 Juni, 2010, København, Session: Bio-ressources

Shang L*, Stelte W, Ahrenfeldt J, Holm JK, Bach LS, Thomsen T, Zhang RZ, Luo YH, Henriksen UB. Physical and chemical property changes of 3 biomass fuels caused by torrefaction. Oral Presentation at: World Sustainable Energy Days – WSEDnext conference, Wels, Austria, 29 February - 2 March, 2012.

1.4.1.5 Posters disseminated from the project:

1 Grindability study of torrefied wheat straw
Lei Shang, Jesper Ahrenfeldt, Jens Kai Holm, Tobias Thomsen, and Ulrik B. Henriksen
Poster presented at the Central European Biomass Conference, Graz, 2011.

2 Linking pellet raw material properties to pellets mill capacity and pellet durability - pelletizing properties of torrefied material,
Dr. Niels Peter K. Nielsen, Dr. Jonas Dahl,
Poster was presented at the Central European Biomass Conference, Graz, 2011.

3 An Investigation of the Application Aspects of Torrefaction,
L Shang, Poster presented in Risø International Energy Conference 2011, Denmark.

4 Quality of pellets from torrefied biomass and pellets torrefied at different temperatures
Lei Shang, Jonas Dahl, Jesper Ahrenfeldt, Jens Kai Holm, Niels Peter K. Nielsen, Wolfgang Stelte, Tobias Thomsen*, Lars Stougaard Bach*, Ulrik B. Henriksen, Presented at the EU BC&E 2012, Milano, June 2012

5 Torrefaction of pine wood chips in a pilot-scale reactor, Tobias Thomsen, Lars Stougaard Bach, Lei Shang, Helge Egsgaard, Jesper Ahrenfeldt, Jens K. Holm, Ulrik B. Henriksen, Presented at the EU BC&E 2011, Berlin, June 2012

1.4.1.6 Other articles

Ristede biobrændsler,
J. Dahl, FiB nr. 32, juni 2010

1.5 Project conclusion and perspective

Torrefied biomass has been predicted to be the fuel that could replace fossil coal with renewable biomass in especially pulverised fuel fired power plants without the typically more challenging storage, handling, milling and combustion of the biomass. Moreover, it has been stated that by torrefying biomass it could more or less be used in these types of power plants almost without any reconstruction of the plants. It has also been stated that energy density of the biomass is increased and thereby improve cost effectiveness of biomass al long the supply chain.

The results from the investigations in this project do agree with those properties such as grindability and moisture uptake are indeed improved, although outdoor storage has still to be tested in larger scale before it can be confirmed. The results do also reveal that torrefaction does not by default improve all properties and in order to make use of the benefits of higher energy density the challenge of densification that become much more challenging after torrefaction has to be solved.

The project has investigated the general benefits that can be obtained from torrefaction, understand some of its basic chemistry and draw some conclusions about its limitations. However, the process of torrefaction is complex and there are still many things to solve in terms of technical solutions of optimising the combined process of torrefaction and densification as well as development of standardised methods for quality control before this can become a standard commodity fuel replacing coal and wood pellets.
Furthermore, issues about storage properties such as potential self-heating, off gassing, and potential organic contaminants in water run off from storage facilities with this new type of fuel are other questions that has to be looked into in the future.