ECN TORREFACTION TECHNOLOGY HEADING FOR DEMONSTRATION

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ABSTRACT: The Energy research Centre of the Netherlands (ECN) has executed an extensive research and development programme in which the most important aspects of torrefaction and pelletisation were investigated. In this paper, some results of these investigations with different types of biomass (deciduous, herbaceous and coniferous) and interesting waste streams are outlined. ECN's torrefaction technology comprises of a dedicated (moving-bed) reactor and process design. In the framework of the R&D programme, a 50–100 kg/h pilot plant "PATRIG" was commissioned and several 10–100 hour test runs with various types of biomass were executed to validate the design. The produced tonnes of torrefied material were used in semi-industrial milling and pelletisation trials. Results of these torrefaction, milling and pelletisation trials are highlighted as well. In general, a well-controlled torrefaction temperature proves essential for a good torrefied product quality control, which is crucial for a proper pelletisation performance. The extensive torrefaction and pelletisation test work up to pilot-plant scale forms a solid base for the scale-up and demonstration of the ECN technology. ECN has teamed up with industrial partners (e.g., Vattenfall) to first demonstrate the technology at a scale of several tonnes per hour and then pursue global commercial market introduction.

Keywords: biomass pre-treatment, biomass/coal co-firing, costs, logistics, market implementation, pellets, pilot plant, solid biofuels, torrefaction

1 INTRODUCTION

Biomass is expected to play a major role in the transition to sustainable energy production. It is anticipated that in 2030 biomass can supply 30% of the total energy consumption. Most of it will be produced in thermal conversion processes (combustion, gasification). The biomass used will be a combination of biomass residues, mixtures of biomass, waste and specially grown woody materials.

Biomass and wastes are difficult fuels and most thermal conversion processes have very stringent fuel specifications which are difficult to fulfil with biomass (residue) streams. For co-firing in coal-fired power plants and gasifiers, a very small particle size is required. Woody biomass is tenacious and fibrous, which makes it difficult and expensive to grind. The limited grindability of biomass is one of the limiting factors for the introduction of biomass on a large scale. Further, the characteristics with regard to handling, storage, degradability and energy density are not favourable for biomass.

Conventional pelletisation offers several advantages. At present, conventional biomass pellets are amongst the most desirable solid fuels to be used in biomass to energy conversion chains. Their uniform shape and relatively high volumetric energy density is advantageous in transport and logistics and in their conversion into energy products such as electricity and heat. However, they require dedicated, closed storage and direct co-milling and co-feeding with coal is limited to a few percent share only. Moreover, the production is costly and energy consuming, particularly so for biomass feedstock other than clean sawdust.

Torrefaction is a promising biomass upgrading technology that can be applied to further enhance pellet quality by addressing these issues. Torrefaction is a mild thermo-chemical treatment used for the upgrading of biomass into a high-quality solid fuel. It is performed at a temperature between 200-300°C and carried out in the absence of oxygen.

Initial bench-scale testing with various woody biomass feedstocks has resulted in a detailed understanding of the torrefaction principles [1-5]. In this specific paper, the follow-up work performed by ECN in the framework of the TorTech project [6-7] is presented. This project resulted the characterisation of the torrefaction behaviour of a wide variety of biomass and interesting waste streams (as illustrated in Figure 1) and in ECN's torrefaction technology having been proven at pilot scale.

Figure 1: Tested types of biomass (bagasse[i], grass seed hay[ii], road side grass[iii], straw[iv], pine[v-vii] and spruce[viii-ix]) and waste streams (RDF[x] and Trockenstabilat[xi])

The TorTech project also helped in forming a solid base for the scheduled scale-up and demonstration of the technology, to which purpose ECN has teamed up with Vattenfall and is finalising discussions with a major equipment supplier.

2 TORREFACTION OF DIFFERENT TYPES OF WOOD AND INTERESTING WASTE STREAMS

2.1 Basic principles

In studies aiming at a better understanding of the decomposition mechanisms of woody and herbaceous biomass, three polymeric structures are mainly considered: cellulose, hemicelluloses and lignin. The structures form the foundation of cell walls and their mutual coherence, and as such provide mechanical strength and tenacity (toughness) to plant structures and so provide body and opportunity to grow in height for optimal photosynthesis.

Each type of biomass has its own typical combination of polymeric structures. Coniferous wood, for example, typically is high in lignin, compared to deciduous wood and especially compared to herbaceous species. A big difference between deciduous and coniferous wood is found in the composition of the hemicellulose fraction. Whereas deciduous wood and herbaceous biomass predominantly consist of xylan-based hemicellulose, coniferous wood predominantly consists of mannan-based hemicelluloses [8].

From the main polymeric constituents, cellulose has received most attention considering the thermal decomposition of biomass. However, as Figure 2 illustrates, cellulose decomposition is not the main reaction in the temperature range of torrefaction (200-300°C).

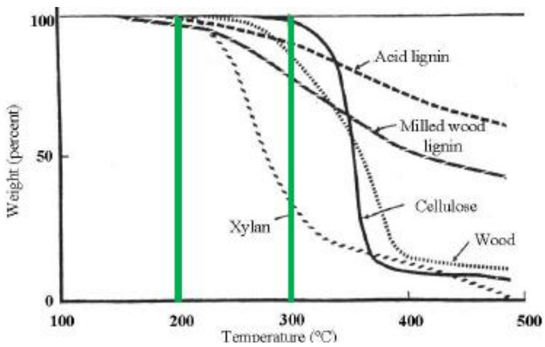

Figure 2: Thermogravimetry of cotton wood and its constituents [9]

During torrefaction, mass loss not related to the loss of water comes predominantly from decomposition (devolatilisation) of hemicellulose, and to a lesser extent from decomposition of lignin and extractives (resins, fats and fatty acids, phenolic compounds, phytosterols, salts and other compounds). Xylan-based hemicellulose generally has its peaking rate in decomposition around 250 to 280°C. Lignin decomposition proceeds slower, but shows a gradual increase of decomposition rate starting from temperatures of about 200°C or even lower. The thermal decomposition behaviour of the individual polymers of biomass may, however, be different from their strongly interacted structure in wood itself. Indications for this can be extracted from Figure 2 [9].

As such, there is not a singular optimal torrefaction (and/or densification) condition; each feedstock will require a different approach and finding the optimal torrefaction condition means compromising between overall energy efficiency, heating value, pellet durability and density, grindability and hydrophobicity.

2.2 Selection of feedstocks

Feedstocks torrefied in the TorTech project [6-7] were selected on the basis of diversity as well as of suggestions by the members of the industrial steering group of the project. The feedstocks tested included various herbaceous and woody (both coniferous and deciduous) biomass streams (*i.e.* bagasse, grass seed hay, road side grass, straw, pine, willow, poplar, larch and spruce) as well as organic-fraction containing waste streams (refuse derived fuel (RDF), solid recovered fuel (SRF) and Trockenstabilat). For some of these feedstocks, the shape was varied as well (as illustrated in Figure 1).

2.3 Experimental results

To determine the influence of torrefaction on fuel properties, an experimental plan was set up as shown in Figure 3, consisting of a series of bench- and lab-scale tests and associated analyses. Tests started with small scale Thermo Gravimetric Analysis (TGA) experiments (typically 1-2g feedstock per experiment), to get a first impression of the reaction behaviour and mass yields at different torrefaction temperatures.

The outcome of these TGA tests then acted as the input for directly-heated fixed-bed torrefaction experiments (batch experiments, typically 1-2 kg feedstock per experiment). The larger batch size allows for the determination of properties like elemental composition, proximate/ ultimate analysis, mass and energy yield, and carbohydrate composition, but also milling and pelleting behaviour.

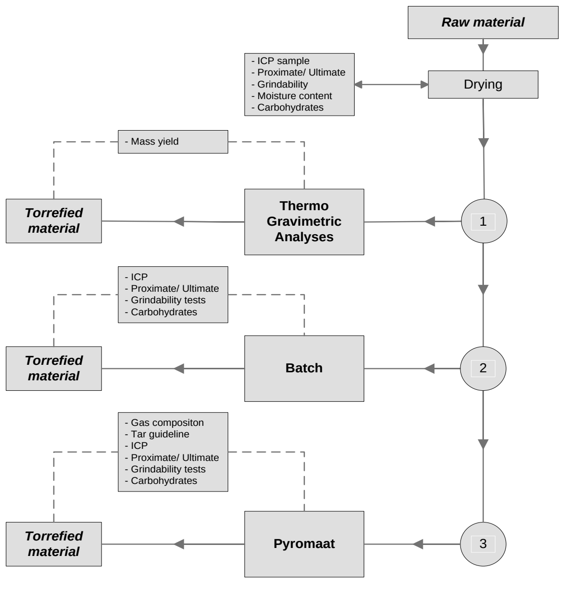

Figure 3: Set-up of the experimental programme

Based on the results of the batch experiments, the optimum temperature for indirectly-heated continuous screw-reactor experiments (so-called pyromaat reactor, feedstock typically 5 kg/hr) was determined. For the waste materials (RDF and Trockenstabilat), more experiments with a broader range of temperatures were carried out in the pyromaat, as this device allows continuous analysis of the gas fraction produced.

To link the material properties to the degree of torrefaction, the raw and torrefied materials produced were characterised in terms of morphology, milling behaviour, mass and energy yield, chemical composition and carbohydrate composition.

2.3.1 Morphology

The torrefied material from the batch and pyromaat experiments was inspected visually to identify differences in torrefaction degree between different particles or inside particles. No clear colour differences were identified indicating a rather uniform degree of torrefaction in all experiments. Generally, the colour was (dark) brown, not black, indicating that conversion was not as extreme as in charcoal production. For the waste streams, formation of agglomerates was observed due to molten plastics covering the less torrefied organic fraction. Pictures of the torrefied material resulting from the different batch experiments can be found in the TorTech report [6].

2.3.2 Milling behaviour

The milling behaviour was determined by grinding the different materials to various particle sizes in a lab-scale cutter mill, while investigating the power consumption during grinding. Figure 4 shows some of the results of these size reduction experiments carried out on dried and torrefied grass seed hay (GS), road side grass (RG), straw (ST), beech (BE), willow (WI), pine (PI) and spruce (SP) as well as coal.

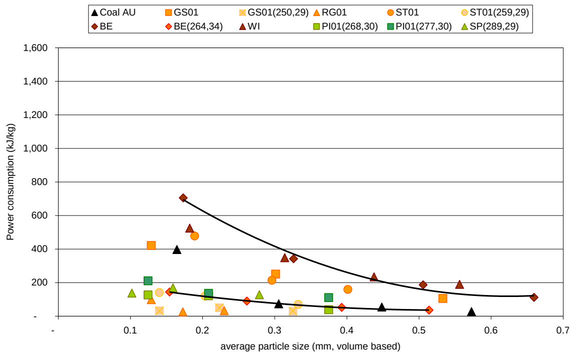

Figure 4: Power consumption as a function of final particle size (torrefaction conditions in brackets, temperature in °C, residence time in minutes)

It can be concluded that for all the materials tested, it is very beneficial to torrefy the material before grinding. In all cases the power consumption is reduced drastically when the material is torrefied.

2.3.3 Mass and energy yield

The mass and energy yields for the different kinds of materials are presented in Figures 5 and 6. The solid mass yield on dry and ash free basis as a function of torrefaction temperature was determined by measuring the total batch weight before and after the experiment. In the figure, results from earlier ECN batch experiments with deciduous (willow and beech) and coniferous woods (larch) are shown as a reference.

The energy yield has been defined according to the formula $E_y = m_y \times E_{tor} / E_{raw}$, where Ey is the energy yield (referring to the lower heating value LHV), m_y the mass yield (m_{tor}/m_{raw}), E_{tor} the LHV of the torrefied material and E_{raw} the LHV of the raw material.

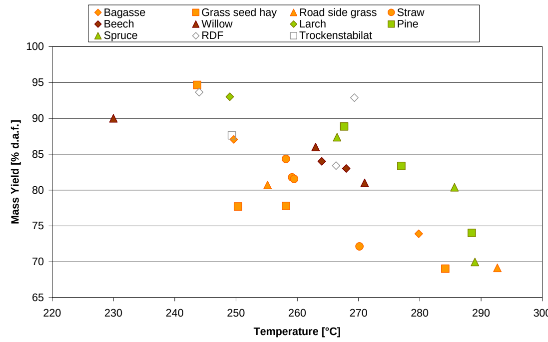

Figure 5: Mass yield of the different kinds of materials

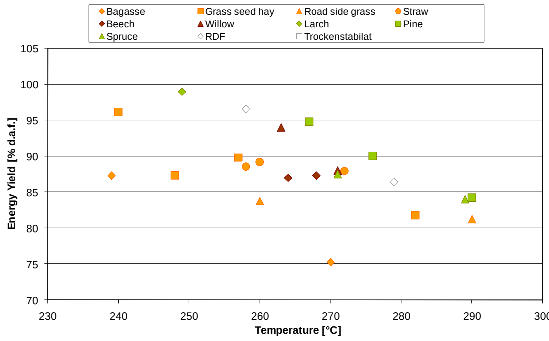

Figure 6: Energy yield of the different kinds of materials

Figure 5 reveals that the herbaceous species (bagasse, grass seed hay, road side grass and straw) show a more reactive behaviour than the other materials due to their higher content of (xylan based) hemicellulose and high ash content that could catalyse the reaction.

The deciduous woods (beech and willow) show a more reactive behaviour than coniferous woods. Their hemicellulose is based on xylan polysugars, wheras for coniferous materials (larch, pine and spruce) the hemicellulose is based on glucomannan polysugars.

Whilst analysing the results for the Trockenstabilat and the RDF, the poor homogeneity of the waste streams and the varying composition of the different batches should be taken under consideration.

This poor homogeneity is reflected in the varying content of organic material and the plastic fraction. Different plastics lead to different results in mass yield and emissions. Concerning the mass losses, a guide as the hemicellulose content for the biomass streams is not valid for the waste streams.

Figure 6 reveals that the energy yield, based on the LHV_{daf}, decreases while applying higher torrefaction temperatures. All the values are higher than 80% with the only exceptions of bagasse torrefied at 270°C for 30 minutes. Accurate values for Trockenstabilat could not be given, as the material was too inhomogeneous.

2.3.4 Chemical composition

The proximate and ultimate analysis for all the raw materials, together with the calorific values are summarised in Table 1. In general, the feedstocks with a higher calorific value are the ones with a higher carbon content and a lower oxygen content, giving a lower O/C ratio. It is also noticeable, in agreement with Obernberger et al. [10], that for clean coniferous woods and clean deciduous woods the content of N is almost always below or close to the detection limit, minimizing the problems with NO_x emissions while combusting or gasifying these materials later on.

Table 1: Mean values from proximate/ultimate analysis.

Material	Ash (%)	C (%)	H (%)	N (%)	O (%)	O/C (-)	LHV (MJ/kg_{daf})
Bagasse	3.1	46.6	5.7	0.2	44.5	0.95	18.24
Grass seed hay	10.6	42.4	5.8	1.6	39.6	0.93	18.10
Road side grass	23.2	38.4	5.3	2.0	31.1	0.81	19.19
Straw	10.6	42.2	5.7	0.4	41.0	0.97	17.30
Beech	0.3	45.9	6.2	0.4	47.3	1.03	17.72
Poplar	1.1	47.2	6.0	0.0	45.7	0.97	17.68
Willow	1.7	47.7	6.0	0.4	44.3	0.93	17.43
Larch	0.1	47.4	6.1	0.6	45.9	0.97	18.20
Pine	0.5	48.7	6.3	0.1	44.4	0.91	18.53
Spruce	0.3	50.4	6.4	0.0	42.9	0.85	19.67
RDF	15.8	53.8	7.5	0.5	22.4	0.42	27.20
Trockenstabilat	23.2	41.3	5.4	1.3	28.8	0.70	20.40

Due to torrefaction, the C and N content increases in almost all the experiments for all the woody and herbaceous materials while the concentrations of H and O decreases. This is mainly due to the release of bounded water and acid groups during the depolymerisation of the hemicellulose. Exceptions are Trockenstabilat and RDF, for these materials a decrease in N and O content is observed. Full analysis can be found in the TorTech report [6].

The O to C ratio of the torrefied materials decreases significantly for all the torrefied materials. Due to the increased carbon content, an increase in caloric value can be expected, although the ash content will be higher as well due to densification. This is also revealed in Figure 7, presenting the lower heating values of the materials produced by torrefaction at different temperatures.

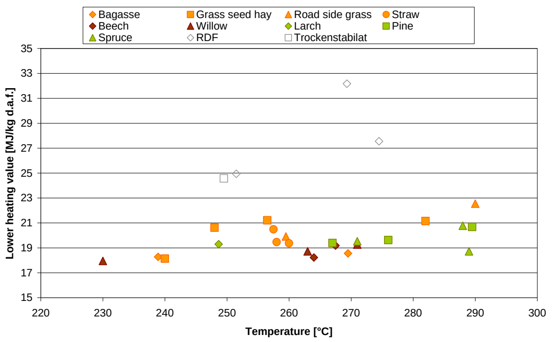

Figure 7: LHV of the materials produced by torrefaction at different temperatures.

3 PILOT-SCALE PRODUCTION OF BO_2 PELLETS

3.1 The BO_2-technology

ECN's BO_2-technology consists of three main process steps, viz. drying, torrefaction and pelletisation. Drying and pelletisation are considered to be conventional steps, for which commercially available technology can be applied. The innovative part in the technology is the torrefaction step. The applied torrefaction technology concept is aimed at achieving high energy efficiency at low cost. The central element in this step is a directly heated moving bed torrefaction reactor in which biomass is heated using recycled torrefaction gases (torgas). The recycle consists of re-pressurization of the torgas to compensate for the pressure drop in the recycle-loop and of the heating of the recycle gas to deliver the required heat demand in the torrefaction reactor. A generalized process flow diagram of the BO_2-technology process is presented in Figure 4.

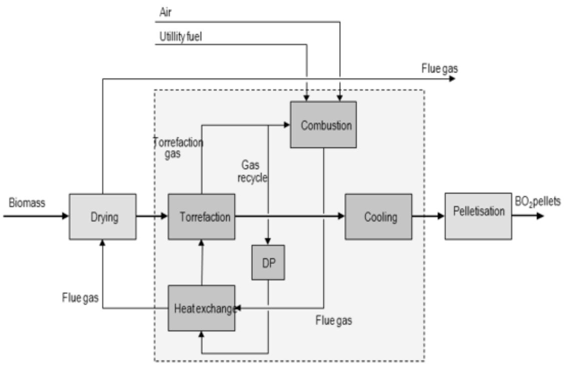

Figure 4: Process flow diagram of BO_2-technology.

For biomass feedstock wetter than 15-20% moisture content, an external dryer is required. This lowers the heat requirement of the torrefaction process, reduces the recycle flow rate, and permits the direct combustion of the torgas that otherwise would be too wet. The heat generated by combustion of the torgas is used for both torrefaction and drying of the biomass. A support fuel is employed as a start-up fuel, to balance the process thermally and to provide stability and control of the combustion process.

The moving bed reactor has been selected for the torrefaction unit as it provides a low cost option, as well as high heating rates and a high filling degree. Consequently, it is also very compact. The reactor has several innovative aspects to allow for feedstock flexibility, good temperature control and to make the integral process feasible. The reactor design enables the use of state-of-the-art technology for all other operations than torrefaction. This minimises both the investment costs and the technological risks.

Typical commercial scale of operation is expected to be initially at 60-100 ktonne/a of product, which is comparable on energy basis to the typical production scale of pelletisation (80-130 ktonne/a). Modifications to the BO_2 technology and its operating conditions to allow for even further upscaling are currently being evaluated.

3.2 PATRIG pilot plant

The pilot plant at ECN, illustrated in Figure 6, has been built to demonstrate the torrefaction step of the BO_2-technology, including the innovative moving bed reactor, the torgas recycle loop and the accompanying heat integration.

Figure 6: Top, middle and bottom section of the PATRIG torrefaction pilot plant

Over 1,000 hours of operation have now been accumulated with recycle torgas temperatures varied between 220 and 280 °C, recycle flows varied by a factor three, and a throughput of 50-100 kg/h (input basis). Test runs typically last 10–100 hours and are performed with various types of biomass, both for ECN itself (dedicated development of the technology) as well as for third parties (specific production for different end-use applications).

In general, the plant shows smooth operation. Due to the modestly exothermic nature of the process, the temperature in the reactor is slightly elevated over the recycle torgas inlet temperature. The temperature control of the process is clearly vital, as otherwise a thermal runaway towards 400-500 °C with charcoal production and, consequently, low product yields would result, as was proven in some initial testing in batch mode.

3.3 Quality of torrefaction pellets

The torrefied material from the pilot plant has been subjected to bench-scale and semi-industrial scale pelletisation tests making use of the facilities of California Pellet Mill (CPM) in the Netherlands. Despite the very heterogeneous nature of the biomass feedstock and the preliminary nature of the torrefaction tests, good quality pellets could be produced without the need to add a binder. Pellet quality, however, is clearly influenced by the torrefaction conditions as well as the feedstock applied. At too extreme conditions, pelletisation without binder addition becomes more difficult. This relates to degradation of the lignin fraction in the biomass.

3.3.1 Pellet strength

Tests on the mechanical strength of conventional and torrefied pellets reveal that pellets produced from torrefied wood can be twice as strong compared to those produced from untreated wood. It is expected that the relatively high lignin content of torrefied biomass is responsible for this increase.

3.3.2 Hygroscopic character

As during torrefaction the hydrophilic oxygen groups (e.g. hydroxyl, carbonyl and carboxyl) are removed from the cell wall, making room for hydrophobic furan-aromatic aliphatic structures, the torrefied materials will become more water repellent. The torrefied pellets were also tested on their hygroscopic nature, by immersing pellets for long periods (*viz.* 15 hours) in water. A higher degree of torrefaction (higher temperature and longer torrefaction time) has a positive effect on the hydrophobic behaviour, as the higher degree torrefied materials show a smaller amount of water assimilation.

3.3.3 Density

Regarding the density of the pellets, particle densities of the produced pellets can be achieved of 1200 and 1300 kg/m³. The highest densities are obtained by pelletizing relatively lightly torrefied material. The lowest densities were obtained with pelletizing heavy torrefied wood. When torrefying at mild conditions, for some materials there is no need for binders during pelletisation. When the torrefaction conditions are more severe (i.e. longer residence times but in particular higher temperatures), the utilisation of a binder seems to be inevitable.

3.3.4 Abrasion resistance

To investigate the abrasion resistance of the pellets, tumbling tests were performed. Regarding the abrasion resistance, the results of these tumbler tests show that the released fines was for all the pellets between 3-6 wt%.

3.4 Available test facilities and production quantities

The available torrefaction facilities at ECN, in combination with the test facilities at CPM, allow for the production of one kilogram up to several tonnes of torrefied materials in pelletized and non-pelletized form.

Following the initial testing with pelletisation and optimising torrefaction operation, in combination with subsequent pelletisation, focus at ECN is now also on briquetting as densification. For certain types of biomass feedstocks and/or end-use applications briquetting may be more attractive.

4 ECONOMICS

A model was developed to compare the economics of conventional wood pellet production with torrefied wood pellet production. On the basis of this model, the performance of an existing wood pellet plant with a capacity of 100 ktonne/a wood pellets was compared with the same wood pellet plant retrofitted with a torrefaction unit. Wood chips (45 $wt\%_{wet}$) were assumed to be the feedstock in both cases and in case of BO_2-pellets production, it was assumed that existing equipment of the wood pellet mill is used. Thus, the overall process was not optimized for BO_2-pellet production as is possible for green field plants. The costs of the entire supply chain until delivery at a power plant gate were considered and the Internal Rate of Return (IRR) was used as the relevant parameter determining the viability of the investment.

The economic evaluation revealed that in the pellet production itself, BO_2-pellets require approx. 3.6 wt%/GJ more feedstock than wood pellets, increasing the feedstock cost with the same percentage. Furthermore, the actual cost of pellet production (sum of depreciation and operational expenditures) is 6-7% higher per GJ product. These additional cost at the production plant have to be compensated by cost benefits further downstream in the supply chain and in end-use.

When considering entire supply chains up to the gate of an end-user, it appeared that even without taking into account cost benefits in end-use (same sales price per GJ at the gate of an end-user), attractive business cases can be identified already. For example, a feedstock price of 15 EUR/tonne of wet woodchips, almost 14,000 km travel distance and an additional investment of 5.1 million EUR for a torrefaction unit retrofitted into an existing 100,000 tonne/a wood pellet plant resulted in an overall IRR of 25% for the stand alone investment of the torrefaction unit only.

Moreover, the cost benefits in end-use may be considerable. For example, in the case of biomass co-firing BO_2-pellets offer the potential of outside storage in the coal yard and direct co-milling and co-feeding with coal using the existing equipment. This avoids the need for additional investments in seperate handling and storage and seperate milling and feeding lines. On this basis, a significant premium on the price per GJ delivered at the gate of an end-user would be justified.

5 CONCLUSION AND OUTLOOK

In the TorTech project, a wide variety of activities with respect to the development of torrefaction was executed by ECN and partners. These activities included basic research investigating the most important aspects of torrefaction, the commissioning and operation of a pilot-plant incorporating ECN's torrefaction concept, small and semi-industrial scale pelletisation and an economic evaluation of the supply chain from the biomass source to the gate of an end-user.

The basic research was done with a wide variety of biomass and waste feedstocks including bagasse, grass seed hay, road side grass, straw, beech, poplar, willow, larch, pine, spruce, RDF/SRF and Trockenstabilat. It yielded valuable insights into the torrefaction characteristics of these feedstocks and the properties of the torrefied material produced. From a technical point of view, torrefaction appeared to have a similar impact for all relatively dry lignocellulosic biomass feedstock and it may be attractive for the upgrading of certain mixed waste streams as well.

The pilot-plant torrefaction test work confirmed the validity and strength of the original reactor and process design. During over 1,000 hours of operation, a range of feedstocks, including poplar, pine, forestry residues and residues from the palm oil industry, was torrefied successfully. For this range of feedstocks, it was proven that ECN's concept allows for smooth operation, good process control, and as a consequence good product quality control, and high energy efficiency.

With the materials produced in the different experiments, it appeared to be possible to produce high quality pellets without the need for a binder. However, the results of the pelletising tests show that often there is a trade-off between proper pelletisation behaviour and pellet quality in terms of strength, grindability, energy density and hydrophobicity. High torrefaction temperatures in combination with long torrefaction times give very water resistant pellets, but these pellets are difficult to make. Low temperature/short time torrefaction reduces the water resistance and the grindability, but the pellet is easier to produce and stronger.

Finally, an economic evaluation of torrefaction as a retrofit option for existing wood pellet plants revealed that attractive business cases can be identified already, when considered the supply chain from biomass source to the gate of an end-user, without taking into account cost benefits for the end-user. For woody biomass, this is particularly valid in case of long distance transport. However, knowing that these latter cost benefits can be considerable, torrefaction is expected to be an attractive upgrading option for many biomass feedstocks and biomass supply chains.

The extensive torrefaction and pelletisation test work up to pilot-plant scale now forms a solid base for the scale-up and demonstration of the ECN technology. ECN has teamed up with industrial partners (e.g., Vattenfall) to first demonstrate the technology at a scale of several tonnes/h and then pursue global commercial market introduction.

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