ECN

Energy research Centre of the Netherlands

TorTech

Torrefaction Technology for the production of solid bioenergy carriers from biomass and waste

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Acknowledgement/Preface

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The project was executed by Energy research Centre of the Netherlands (ECN, coordinator), Technical University of Eindhoven (TU/e) and GF Energy. This report describes the work conducted by ECN and GF Energy. The work of TU/e is reported in the PhD thesis of Michiel van der Stelt (published March 15, 2011). The work was conducted under the guidance of an industrial mirror group consisting of:

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Abstract

Biomass is expected to play a major role in the transition to sustainable energy production. However, biomass is a difficult fuel and most thermal conversion processes have very stringent fuel specifications. Torrefaction offers the potential to convert biomass into attractive solid biofuels. It involves heating in the absence of oxygen to a temperature of 200 to 300 °C. As a result, biomass becomes easy to grind and water resistant, reducing the risk of spontaneous biological degradation and heating, and permitting outdoor storage. By combining torrefaction with pelletisation, biomass is converted into a high-energy-density solid bioenergy carrier with superior properties in view of (long-distance) transport, handling and storage, and in many major end-use applications (e.g., co-firing in coal-fired power stations and gasification-based biofuels and biochemicals production).

The Tortech project has been focussed on the further development torrefaction for a broad of biomass and mixed biomass/waste feedstocks. The project comprised basic research, in which important aspects of torrefaction and pelletisation were investigated, the design, construction and initial operation of a pilot-plant incorporating ECN’s torrefaction technology concept, small and semi-industrial scale pelletisation and an economic and environmental evaluation of the biomass-to-end-use value chain including torrefaction and co-firing.

The basic research yielded valuable insights into the torrefaction characteristics of the 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 an attractive option for certain mixed biomass/waste streams as well. The pilot-plant torrefaction test work confirmed the validity and strength of the ECN torrefaction technology. During over 800 hours of operation, a range of feedstocks, including poplar, pine, forestry residues and palm oil residues, was torrefied successfully. For this range of feedstocks, it was proven that ECN’s torrefaction concept allows for smooth operation, good process control and product quality control, and high energy efficiency. With the torrefied materials produced, it appeared to be possible to produce high quality pellets without the need for a binder. However, there appears to be a trade-off between proper pelletisation behaviour and pellet quality in terms of strength, grindability, energy density and hydrophobicity.

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.

Finally, the location where the pellets are produced has a large impact on the total value chain CO_2 emissions. Not only the transportation distance but also the CO_2 emissions related to the local electricity mix are relevant. The difference in overall CO_2 emission reduction between wood and torrefied wood pellets is slightly in favour of the latter technology, with CO_2 emission reductions in the range of 80-90% compared to firing coal in a coal-fired power plant.

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 to first demonstrate the technology at a scale of several tonnes/h and then pursue global commercial market introduction.

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Summary

Biomass is expected to play a major role in the transition to sustainable energy production. 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. As a result, biomass becomes easy to grind, providing the potential of direct co-milling and co-feeding, and water resistant, reducing the risk of spontaneous biological degradation and heating, and permitting outdoor storage. By combining torrefaction with pelletisation, biomass is converted into a high-energy-density solid bioenergy carrier with superior properties in view of (long-distance) transport, handling and storage, and in many major end-use applications (e.g., co-firing in coal-fired power stations, gasification-based biofuels production and production of bio-based chemicals).

This report describes the results of the work conducted by ECN and GF Energy in the framework of the so-called TorTech project. The TorTech project has been focussed on the development of commodity solid biofuels from biomass by means of torrefaction. The project comprised basic research, in which important aspects of torrefaction and pelletisation were investigated, the design, construction and initial operation of a pilot-plant incorporating ECN's torrefaction technology concept, small and semi-industrial scale pelletisation and an economic and environmental (in terms of CO_2 emissions) evaluation of the biomass-to-end-use value chain. The Tortech project also included a PhD project at the Technical University of Eindhoven on the fundamentals of torrefaction, but this will be reported separately.

The basic research at ECN 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. Torrefaction experiments were conducted in different small-scale reactors, viz. a Thermo Gravimetric Analyser, a batch reactor and a continuous Auger or screw reactor. The experiments were supported by various analysis and performance characterisation techniques to determine properties and behaviour of the solid and gaseous products, e.g. chemical composition, mass and energy yields, lignocellulose composition and milling behaviour. The work yielded valuable insights into the torrefaction characteristics of the 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.

In general, energy densification during torrefaction was demonstrated. Herbaceous materials and waste streams showed the highest energy densification, while the lowest densification was found for the coniferous materials. Small-scale milling experiments were performed on a number of raw and torrefied materials to evaluate the impact of torrefaction on grindability. It was demonstrated for all biomass feedstocks, that after torrefaction the milling power consumption was significantly lower. As expected, the torrefied materials were found to be much more brittle than the original materials. Raw waste materials could not be milled at room temperature, as the fraction of plastic caused blockage of the milling device. Torrefied waste materials could be milled, showing lower power consumption at higher torrefaction temperatures. The torrefaction gas contains reaction water, CO_2, organics and, to a lesser extent, CO. Straw and woody materials showed the highest ratios of $(CO+organics)/CO_2$, indicating a higher energy content of the torrefaction gas. A closer look into the organic fraction revealed that the main components were acetic acid and methanol. Furfurals were also found for all the feedstocks. For deciduous woods larger amounts of phenolic compounds were detected indicating lignin degradation. For the waste streams, the release of Cl appeared to be directly proportional to the torrefaction temperature. Ash concentrations and compositions were determined as well. As most of the mineral matter is not released during torrefaction, ash concentrations in the torrefied feedstock were found to increase proportional to the decrease in mass.

Parallel to the basic research work, the design of a 50 - 100 kg/hr pilot plant was put into effect. After a literature survey it was decided to develop a novel torrefaction concept based on the principles of moving bed technology. The design of the pilot plant (named PATRIG) started in June 2006 and erection and commissioning of PATRIG were completed in September 2007. During commissioning some modifications had to be implemented, which took place in December 2007 and January 2008. The first torrefied material was produced batch wise in February 2008. On March 5, 2008, PATRIG was in full continuous operation for the first time, with all the systems running automatically. Subsequently, many tests were conducted in the framework of the Tortech project but also in a range of industrial contracts with various biomass feedstocks, including poplar chips, pine chips, forestry residues and residues from the palm oil industry. By the end of 2010, PATRIG had been in operation for more than 800 hours. More than 30 tons of torrefied materials were produced during short, 8 hour tests and several duration trials ranging from 40 up to 100 continuous operating hours. In general, the trials confirmed the validity and strength of the original reactor and process design. For the range of feedstocks tested, it was proven that ECN's torrefaction 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 pelletisation 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.

In close cooperation, ECN and GF Energy conducted an economic evaluation of torrefaction as a retrofit option for existing wood pellet plants. The study 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 location where the pellets are produced appears to have a large impact on the total CO_2 emissions over the entire biomass-to-end-use value chain. Not only the transportation distance but also the CO_2 emissions related to the local electricity mix are relevant (coal / gas / nuclear / biomass generated power). The difference in overall CO_2 emission reduction between wood and torrefied wood pellets is slightly in favour of the latter technology, with CO_2 emission reductions in the range of 80-90% compared to firing coal in a coal-fired power plant.

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 to first demonstrate the technology at a scale of several tonnes/h and then pursue global commercial market introduction.

1. Introduction

1.1 Background and objectives

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. Figure 1.1 shows a typical torrefaction mass and energy balance for dry biomass. From 1 unit of dry biomass fed into the process, typically 0.7 units are retained as a solid product, representing 0.9 units of energy processed. 0.3 units of mass are converted into torrefaction gases representing typically 0.1 units of energy. This example illustrates one of the main characteristics of the process, being the high retention of the chemical energy from the feedstock in the torrefied product, whilst fuel properties are improved.

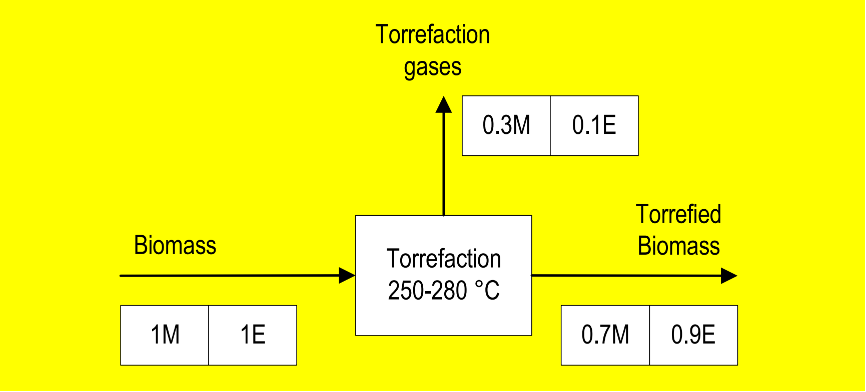


Figure 1.1 *Typical mass and energy balance for torrefaction (M = mass unit, E = energy unit)*

Upon torrefaction, the hygroscopic and tenacious nature of the biomass is largely destroyed, with the degree of destruction depending on operating temperature and residence time. Further, the torrefied biomass has become more resistant against biological degradation and more easily grindable. These properties make torrefied biomass an attractive feedstock for fuel pellets. From the main constituents of biomass, mainly hemicellulose is decomposed during torrefaction, leaving cellulose and lignin virtually intact (considering mass loss). Hence the lignin content of torrefied biomass is significantly higher (5 to 10 %-points). This potentially enables the production of high quality fuel pellets from raw materials other than currently economical feedstock, such as sawdust, without the use of an additional binder.

The destruction of the tenacious behaviour of the biomass is a very welcome improvement when considering size reduction. Loss of the tenacious nature of the biomass is mainly coupled to the breakdown of the hemicellulose matrix, which bonds the cellulose fibres in biomass. Depolymerisation of cellulose decreases the length of the fibres.

At the start of the TorTech project the mechanisms and technical possibilities of torrefaction for clean, woody biomass streams were reasonably well understood. For more difficult biomass streams and residues, the mechanisms were less clear. The aim of the TorTech project was to get more insight in the torrefaction and pelletisation behaviour of more complicated biomass streams and to demonstrate ECN's torrefaction process concept on pilot scale.

1.2 Approach

The project builds on the development of torrefaction technology for woody biomass streams as executed by ECN and TU/e in three preceding research projects [1-5]. Thanks to this, the required experimental infrastructure on lab-scale was largely available at the start of the project.

The project is divided into six interlinked work packages:

WP1 Basic research
WP2 Design and construction of a torrefaction pilot plant
WP3 Pilot plant torrefaction tests
WP4 Torrefaction and pelletisation
WP5 Economic and sustainability evaluations
WP6 Project management, reporting and communication.

The same subdivision in work packages (except for WP6) has been used to structure this report.

2. Basic research

2.1 Introduction

In this chapter, basic torrefaction research results are reported for a large number of biomass (residue) streams, including clean woody biomass (willow, birch, larch), straw, road-side grass, demolition wood, bagasse, RDF/SRF and Trockenstabilat. In order to characterise the torrefaction behaviour of these biomass streams, lab- and bench-scale tests were executed. The characterisation of the product quality includes grinding behaviour, combustion behaviour, hygroscopic behaviour, leaching behaviour and the amount of dust formation and biological degradation. The results presented relate specifically to the experimental activities that have been carried out by ECN. The results obtained in the parallel research programme of TU/e are reported in the PhD thesis of Michiel van der Stelt [6].

The work was aimed to generate new insight into the following topics:

- The torrefaction behaviour of a range of feedstocks, paying special attention to hemicellulose degradation, as this carbohydrate is the main component responsible for the tenacity and hydrophilicity of these materials.
- The torrefaction enthalpy and the influence of heat and mass transfer.
- The relationship between the properties of biomass/waste and the resulting quality of the solid product as well as the composition of the torrefaction gas or torgas.

This information is vital for judging the viability of using torrefaction for upgrading the difficult biomass and biogenic waste streams considered. Next to that, this information is also important for the development of cost effective reactor and process concepts.

2.2 Torrefaction principles

Torrefaction is a thermochemical treatment at an operating temperature of typically 200 to 300 °C in the absence of oxygen. The name torrefaction is adopted from the roasting of coffee beans, which is, however, done at lower temperature and does allow the presence of oxygen.

The main torrefaction product is the solid phase. Similar to pyrolysis, during torrefaction the chemical structure of biomass is altered. This leads to the formation of a variety of volatile (decomposition) products of which some are liquids at room temperature (condensables). On mass basis, important reaction products other than the char or torrefied biomass are carbon dioxide, carbon monoxide, water, acetic acid and methanol. After condensation, liquid products manifest themselves as a yellowish/black liquid. All these non-solid reaction products contain relatively more oxygen compared to the untreated biomass. Hence the O/C ratio of torrefied biomass is lower than untreated biomass, resulting in an increase of the calorific value of the solid product [2,7].

2.2.1 Cell structure of lignocellulosic biomass

Lignocellulose refers to the three dominant polymeric structures in plants, viz. cellulose, hemicellulose 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.

A typical plant cell is structured as shown schematically inFigure 2.1. A single cell typically contains a primary and a secondary wall. The secondary wall consists of three layers. Individual cells are connected through a gluey layer called the middle lamella.

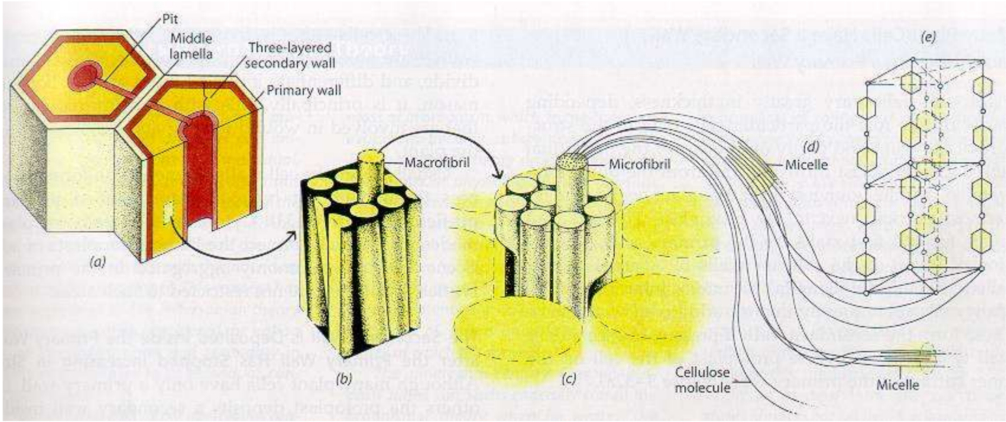


Figure 2.1 *Detailed impression of the structure of a cell wall*
(a) part of the cell wall and middle lamella, primary wall and secondary cell wall
(b) macrofibril mutual structure, (c) microfibrill structure, (d) individual cellulose polymers including micelles, and (e) mutual coherence of individual cellulose polymers on a micro level.[8]

The second layer of the secondary wall is the thickest one and is built from vertically oriented macrofibrils. The macrofibril is on its turn composed from microfibrils, which predominantly consist of evenly oriented cellulose molecules of certain length. The cellulose chains comprise amorphous parts, but also crystalline parts whereby subsequent cellulose molecules are connected.

The polymeric composition of the different walls and layers varies strongly and each wall has different tasks. Figure 2.2 illustrates how the polymeric composition varies throughout the cell wall. The middle lamella predominantly contains the lignin. Lignin acts as a binding agent and can be considered a glue to bind adjacent cells. Whilst the lignin fraction decreases cell inwards, the fraction of (hemi)cellulose increases. Cellulose meets a maximum content in the S_2 of the secondary layer and hemicellulose in S_3.

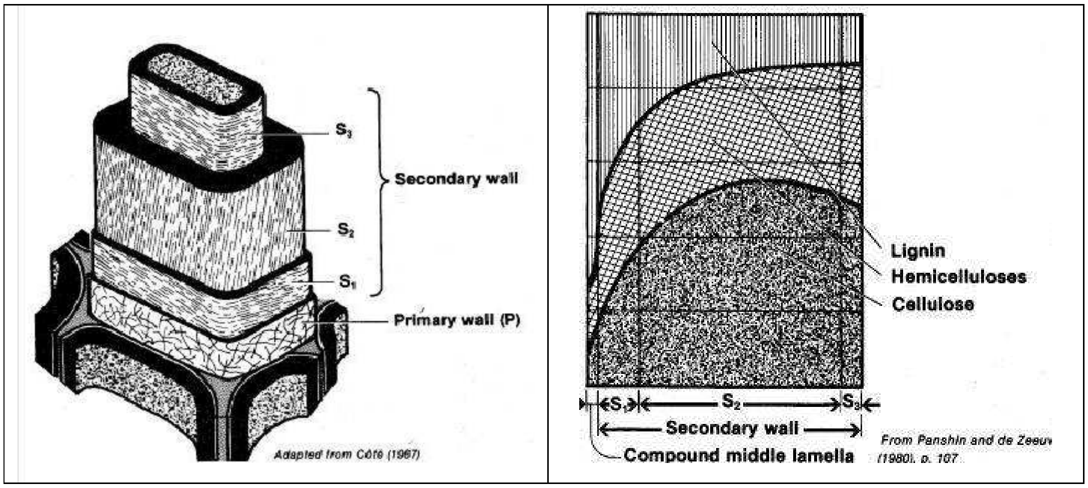


Figure 2.2 *Distribution of lignocelluloses within the three layered secondary wall [9]*

The three-layered secondary cell wall mainly consists of cellulose and is very well organised by nature. The cellulose macrofibrils are embedded in a matrix of (disoriented) hemicellulose that bonds the macrofibrils mechanically, but also through hydrogen bonding. The cell wall has a repetitive pattern in which hemicellulose binds macrofibrils of a cell wall and lignin binds adjacent cells. The function of hemicellulose is often well illustrated by comparing its function to concrete in reinforced concrete. Without the concrete the iron rods lose their mutual coherence and orientation.

Each layer of the three-layered cell wall has a different fibre orientation. The main body of the cells (S_2) is a vertical oriented structure of fibres kept in a compact form by an outer husk (S_1) and annular (inner) husk (S_3) both with near perpendicular fibre orientation. The wood structure consists of many of these cellular units 'glued' together by the lignin-rich primary walls. The anisotropic nature of wood, the fibrous structure, is caused due to the differences in thickness and orientation of the different layers. The way cell walls are mechanically organised is copied multiple times from nature because of the high strength and tenacity it provides.

Every type of green biomass has its own typical lignocellulose composition. Table 2.1 summarises the lignocellulose composition of biomass species used in the experimental programme of this work. Woody types of biomass are commonly divided into coniferous (larch, spruce, pine) and deciduous (beech, poplar, willow) categories. Next to that a group of herbaceous species (straw, grass seed hay) is commonly defined.

Table 2.1 *Lignocellulose composition of different biomass types [10]*

Polymer (wt%)	**Deciduous**	**Coniferous**	**Herbaceous**
Lignin	18-25	25-35	15-25
Cellulose	40-44	40-44	30-50
Hemicellulose	15-35	20-32	20-40
Composition Hemicellulose (wt%)			
4-0 methyl glucuronoxylan	80-90	5-15	
4-0 methyl glucuronoarabinocyxylan	<1	15-30	
Glucomannan	1-5	60-70	
Galactoflucomannan	<1	1-5	
Arabinogalactan	<1	15-30	
Other galactose polysaccharides	<1	<1	
Pectin	1-5	1-5	

Coniferous wood typically is high in lignin, compared to deciduous wood and especially compared to herbaceous species. Deciduous and coniferous wood differ 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 hemicellulose [11].

Another difference between deciduous and coniferous species is in the content of crystalline cellulose, which is thermally more stable. According to Wikberg [12], coniferous wood contains a higher proportion of crystalline cellulose than deciduous wood. She also found that lignin of coniferous wood is mainly composed of guaiacyl units whereas in deciduous wood it is based on guaiacyl and syringyl units and that this will have an influence on condensation reactions and gas emissions when applying thermal treatments.

2.2.2 Decomposition during torrefaction

From the three main polymeric constituents of biomass, cellulose has received most attention considering the thermal decomposition of biomass. However, as Figure 2.3 illustrates, cellulose decomposition is not the main reaction in the temperature range of torrefaction (200 – 300 °C).
During torrefaction, mass loss not related to the loss of water comes predominantly from the 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 biomass itself. Indications for this can be extracted from Figure 2-3.

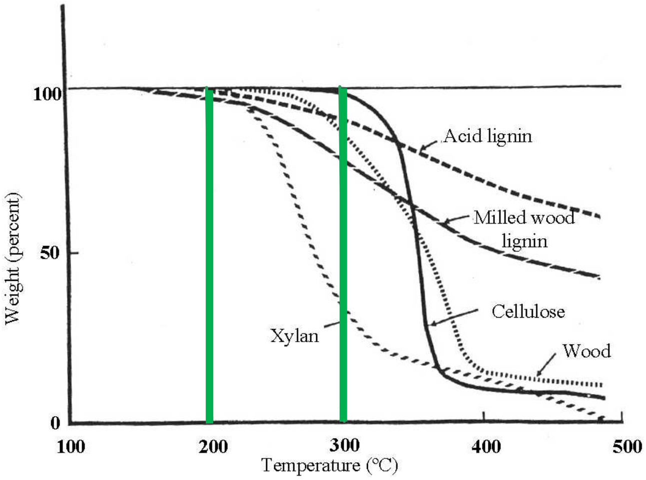


Figure 2.3 *Thermogravimetry of cotton wood and its constituents*
([13] The green lines are added to indicate the torrefaction temperature regime)

2.3 Experimental approach

2.3.1 Introduction

To determine the influence of torrefaction on fuel properties, an experimental programme was set up as shown in Figure 2.4. It was decided to start with small scale (<2g) Thermo Gravimetric Analysis (TGA) experiments, to get a first impression of reaction behaviour and mass yield at different torrefaction temperatures. The outcome of these TGA tests was then used as input for batch experiments (1-2 kg), where larger amounts of torrefied materials could be produced. With these materials, properties like proximate/ ultimate analysis, mass and energy yield, lignocellulose composition and milling behaviour could be determined.

Based on the results of the batch experiments, the optimum temperature for continuous screw reactor experiments (1-10 kg) was selected. From these continuous tests, material properties like proximate/ ultimate analysis data, mass and energy yield, lignocellulose composition and milling behaviour were determined. Furthermore, the continuous nature of the tests allowed extensive characterisation of the gases produced.

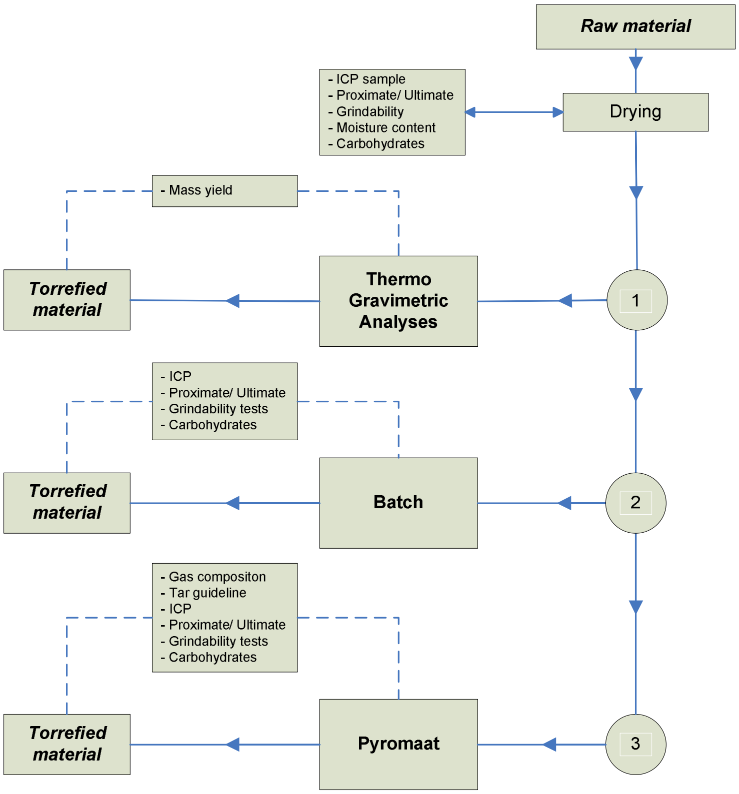


Figure 2.4 *Set-up of the experimental programme*

2.3.2 Experimental facilities

In this section, a description is given of the experimental facilities applied.

TGA

TGA stands for “Thermo Gravimetric Analysis”, a small-scale experiment to determine the mass loss and reactivity of a material under well-controlled conditions. The TGA experiments were performed by using a TGA850 from Mettler Toledo. This TGA850 has a temperature range of room temperature to 1100°C and is equipped with water cooling. It has a heating rate of 0.1 – 50 °C/min and a measuring range from 0 – 2g. An automated temperature programme allows different time-temperature profiles.

Batch torrefaction reactor

Batch torrefaction tests were performed in a fixed-bed or batch reactor, see Figure 2.5. The reactor consists of a vertical cylinder with an internal diameter of 16.5 cm and an effective length of 100 cm. The reactor is directly heated by supplying preheated nitrogen through a distributor plate at the bottom. Trace heating is applied to minimise heat losses. Off gases are transported to an incinerator.

The reactor is divided into three zones, separated by perforated plates. To measure the bed temperatures in the reactor, 7 thermocouples are placed inside the reactor at different axial positions. Pressure sensors are placed in the bottom and top of the reactor. All temperatures, gas flows and pressures are logged, allowing for off-line data analysis. For all the experiments, the residence time was fixed at 30 minutes. The nitrogen flow rate was 650 l_n/min.

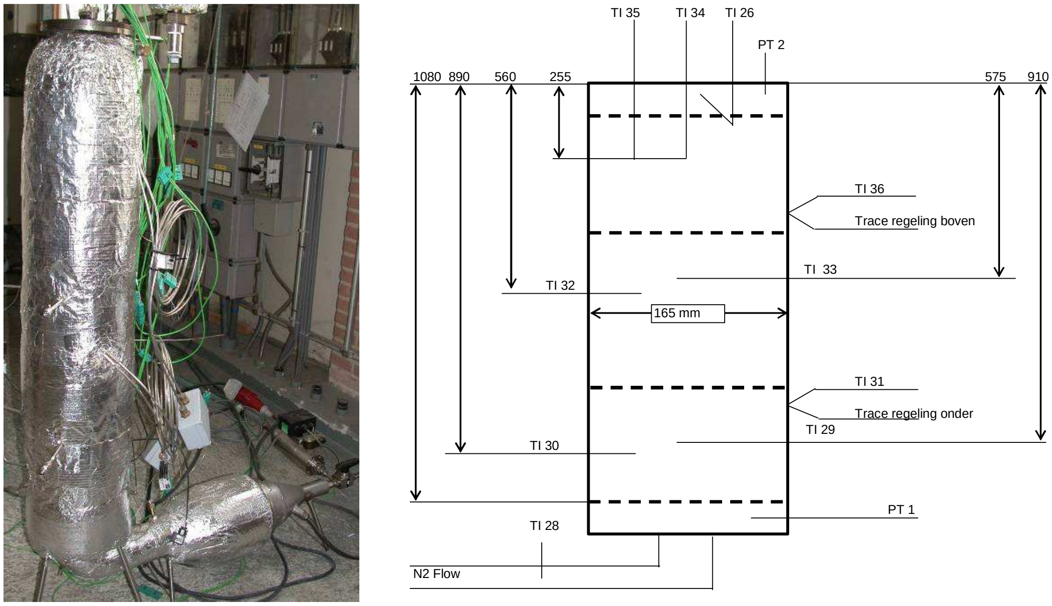


Figure 2.5 *Picture and schematic of the batch torrefaction reactor*

Pyromaat

The pyromaat is an auger or screw reactor with an internal diameter of 15 cm and an effective length of 120 cm. The reactor wall is electrically heated and the feeding system has a capacity of 1 – 10 kg/h. The maximum particle size allowed by the feeding system is 3 cm. The off gases are sent via a high temperature cracker and a gas cleaning unit to an after burner. The installation is equipped with thermocouples for measuring temperatures inside the reactor and along its wall. The torrefaction gas composition is measured on-line with a μGC to quantify the permanent gases (Ar/O_2, CO, CO_2, CH_4). By applying the CEN-certified tar measurement standard for sampling biomass gasification tars, organic compounds and reaction water are trapped in isopropanol for off-line analysis [14]. The organics are analysed off-line by a gas chromatograph equipped with an FID detector. The reaction water is analysed by Karl-Fisher. The chlorine content in the torrefaction gas is determined by trapping it in isopropanol and water and analysing the residue obtained after some extractions by EOX (Extractable organic halogens). To determine the ionic Cl trapped in water, an ion chromatograph is used.

In the torrefaction experiments, the residence time was set at 30 minutes and argon was used as inertisation gas. The pyromaat is shown schematically in Figure 2.6.

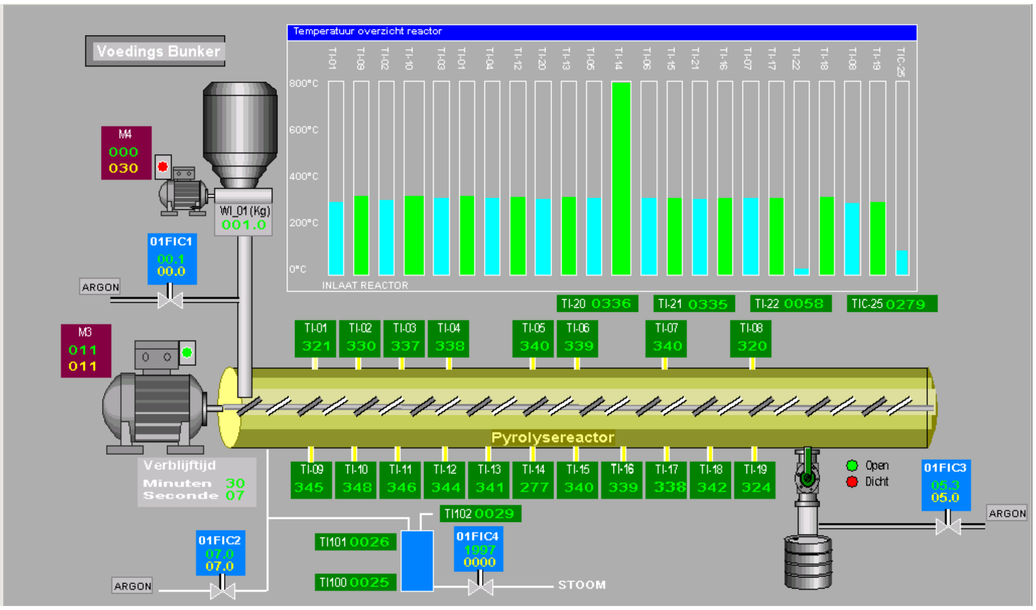


Figure 2.6 *Schematic of the pyromaat screw reactor*

Cutting mill

A schematic of the cutting mill facility is given in Figure 2.7. The core of this facility is a RETSCH SM 2000 heavy duty cutting mill powered by a 2.0 kW$_e$ electrical motor. This motor runs at constant speed. Disturbances that occur in feed rate and feed properties which influence the speed of the motor are compensated by alterations in the power rate of the motor. Hence, the power rate at which the motor operates is a measure for the energy duty done on the milled feed. The power rate of the motor is registered by the monitoring system.

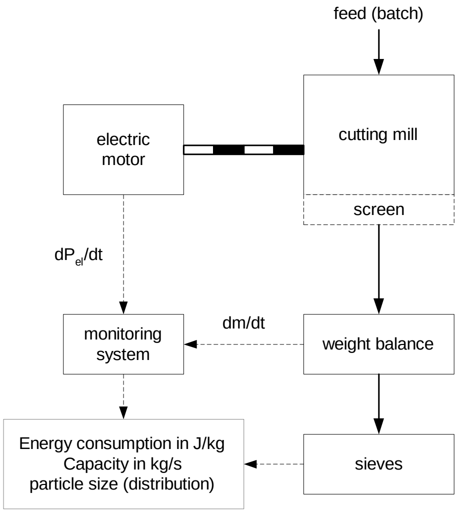


Figure 2.7 *Schematic representation of the cutting mill facility*

The RETSCH SM 2000 heavy cutting mill is a batch-wise operated mill. The feeding system is a funnel through which the biomass is fed into the grinding chamber of the mill. In the milling chamber four cutting bars are mounted. Furthermore, four series of hammers are mounted on the axis that is driven by the electrical motor. Each series comprises eight individual hammers which are lined up in jumped position from each other. The free distance between the bars and the hammers when passing the bars is 2 mm. In operation, the biomass falls into the milling chamber and is circulated by the hammers. In one rotation, the biomass passes the four cutting bars. It then either gets blocked between the hammers and the bars and is cut, or it is pressed backwards in the open space between a bar and the hammers. The hammers have an off-set in relation to each other. The resulting particle size of the biomass is regulated by changing the bottom sieve of the mill (manually).

2.3.3 Materials

For the torrefaction experiments, the following types of biomass/ waste streams have been selected:

- Bagasse
- Road side grass
- Beech
- Willow
- Pine
- RDF/SRF
- Grass seed hay
- Straw
- Poplar
- Larch
- Spruce
- Trockenstabilat

In previous work [2], a complete set of experiments and analysis for willow, beech and waste wood was already performed. These results are not reported in detail in this document, but used as a reference to show experimental consistency.

Prior to the experiments, samples were collected, dried at 105°C and sent for ICP, proximate, ultimate and lignocelluloses composition analysis. If required, the samples were milled to meet the specifications of the different experimental facilities and analyses.

2.4 Experimental results and discussion

2.4.1 TGA experiments

For the TGA measurements, the materials were dried at 105°C and milled to a diameter of 65 – 180 µm. The sample size was in the range of 10-20 mg. To get insight in the decomposition behaviour of the fuels, 3-4 torrefaction temperatures were selected based on previous experience with woody biomass. The temperature-time profile was set according to a standard procedure, shown in Figure 2.8.

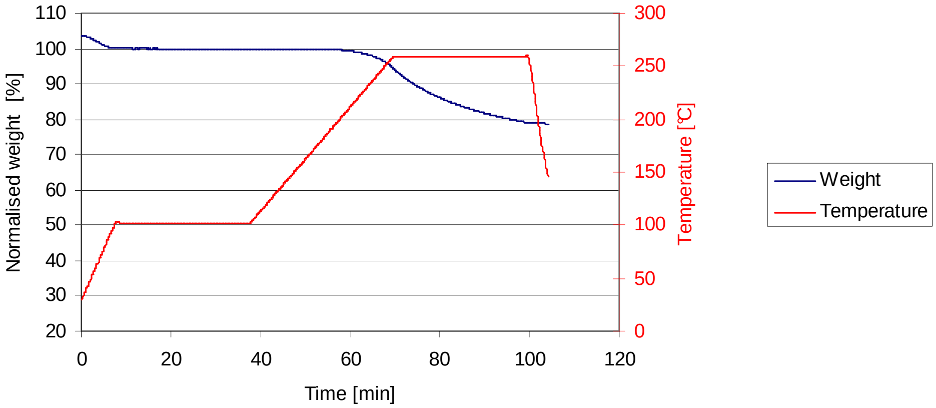


Figure 2.8 *Typical TGA temperature-time profile and weight loss curve (Bagasse, 260°C torrefaction temperature)*

According to this procedure, the temperature is first increased from 25°C to 100°C with a heating rate of 10°C/min. To make sure that all the materials are thoroughly dried, the samples are kept at 100°C for 30 minutes. After drying, the sample is heated to the desired torrefaction temperature with a heating rate of 5°C/ min. The residence time at the torrefaction temperature is set to 30 minutes.

The TGA experiments result in weight loss and reaction rate versus time curves. An example is shown in Figure 2.9. Weight loss and reaction rate versus time curves of all the tested materials can be found in Appendix A.1.

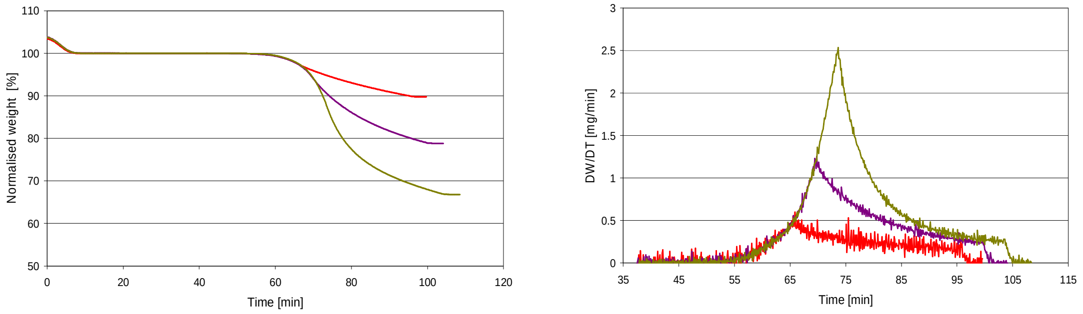


Figure 2.9 *TGA weight loss and reaction rate versus time curves for bagasse at different temperatures*
(Red = Torrefaction at 240°C, Purple = Torrefaction at 260°C, Green = Torrefaction at 280°C)

From the curves, mass yields were derived, as presented in Table 2.2.

From the TGA results, the following can be concluded:

- The highest reaction rate is observed when arriving at the desired torrefaction temperature.
- Different biomass types show a different behaviour. Herbaceous materials are most reactive and decompose at the lowest temperatures. The woody materials need a higher temperature to decompose. The highest temperatures are needed for RDF, probably due to the low biogenic fraction and high content of plastics.
- The difference in reactivity between the different biomass types can be related to their typical lignocellulosic composition, given in Table 2.1. Especially the composition and concentration of the hemicellulose differs between the deciduous/ herbaceous species and the coniferous species. The hemicellulose of the deciduous and herbaceous species is mainly xylan-based, while for coniferous wood it is glucomannan-based. From xylan-based hemicellulose, it is known that it is more reactive than glucomannan-based hemicellulose. The difference in mass loss between the herbaceous and deciduous species may be explained by the larger concentration of hemicellulose present in the herbaceous species.

Table 2.2 *TGA mass yields for different materials and torrefaction temperatures*

	Temperature [°C]	**Residence time [min]**	**Mass yield [% d.a.f.]**
Bagasse	240	30	90
	260	30	78
	280	30	66
Grass seed hay	240	30	79
	260	30	68
	280	30	57
Road side grass	240	30	84
	260	30	74
	280	30	61
	300	30	51
Straw	240	30	87
	260	30	75
	280	30	57
Poplar	240	30	89
	260	30	80
	280	30	69
Pine chips	260	30	86
	280	30	75
	300	30	59
Spruce chips	240	30	94
	260	30	87
	280	30	76
	300	30	60
RDF	240	30	93
	260	30	88
	280	30	81
	300	30	68
Trockenstabilat	260	30	82
	270	30	76
	280	30	67
	300	30	50

2.4.2 Batch experiments

To generate more information about the selected biomasses, batch experiments were performed resulting in larger amounts of torrefied material produced under different torrefaction conditions. With these torrefied materials, properties like proximate/ultimate analysis data, mass and energy yield, lignocellulose composition and milling behaviour were determined.

For the batch experiments, the material was first dried at 105°C and crushed to a particle size smaller than 100 mm. For Trockenstabilat, a sieved fraction was used, as there was a lot of sand and even stones in the material.

In the batch reactor, heat is supplied from the bottom of the reactor upwards. This gives that the material located at the bottom of the reactor is heated up faster than the material at the top of the reactor. To obtain samples prepared under well-defined uniform conditions, the reactor is separated into 3 sections. After running the experiment, the samples from the 3 sections were stored separately. Torrefied material recovered from the section that experienced the conditions closest to the selected ones was used for further analyses and tests.

Figure 2.10 shows typical temperature profiles during a batch experiment. The figure also illustrates how the reaction time and the torrefaction temperature are defined.

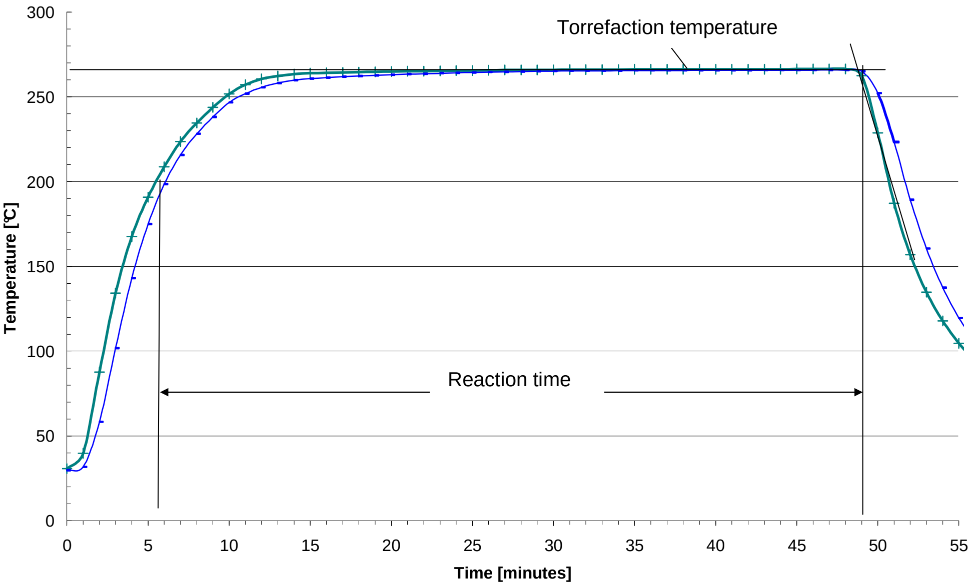


Figure 2.10 *Typical temperature profiles at two locations in one section during a batch experiment*

An important finding during the batch experiments is that, overall, torrefaction generally is exothermic. In view of this finding, attempts were made to determine the enthalpy of reaction of grass seed hay and wood chips with a DSC (differential scanning calorimetry). However, these tests did not reveal a significant exothermic behaviour. A probable explanation lies in the difference in particle size, which has an impact on the extent to which exothermic secondary reactions can occur.

An overview of the results of the torrefaction experiments in the batch reactor is given in Appendix A.2.

Pressure drop

Although the pressure drop across the bed is an important parameter for scale-up of the torrefaction process (in case of applying a moving-bed type torrefaction reactor), the data obtained from the batch experiments should be used only qualitatively. In the batch reactor the materials are manually compressed in order to minimize the voidage and as such generating a different pressure drop than in an industrial plant, where the material falls freely on the rest of the bed.

During a batch reactor test, the pressure was measured at the bottom and at the top of the reactor by using digital pressure differential sensors with a range of 0 – 400 mbar. Appendix A.2 shows the maximum pressure drop measured during the test. All values higher than 400 mbar are not reliable. From these results, the following observations were made:

- Eight materials have a pressure drop higher than 150 mbar and fourteen have a lower pressure drop.
- In case of torrefied pine, the particle size of the raw material was very small (0.075 and 0.3 cm) resulting in a really high pressure drop.
- Bagasse showed a high amount of dust due to its extreme brittleness after drying. Next to that, the material may have been pressed too much whilst filling the reactor, leading to a high pressure drop.

- In case of RDF, the high pressure drop was caused by an internal “explosion”. This “explosion” was caused by the fact that under elevated temperatures the RDF expanded and started to get sticky. This stickiness formed a impermeable layer.

Mass yield

The solid mass yield on a dry and ash-free basis (daf), was determined as a function of torrefaction temperature by measuring the total batch weight before and after each experiment. The results are shown in Figure 2.11, with results from earlier ECN batch experiments with deciduous (willow and beech) and coniferous wood (larch) included as a reference.

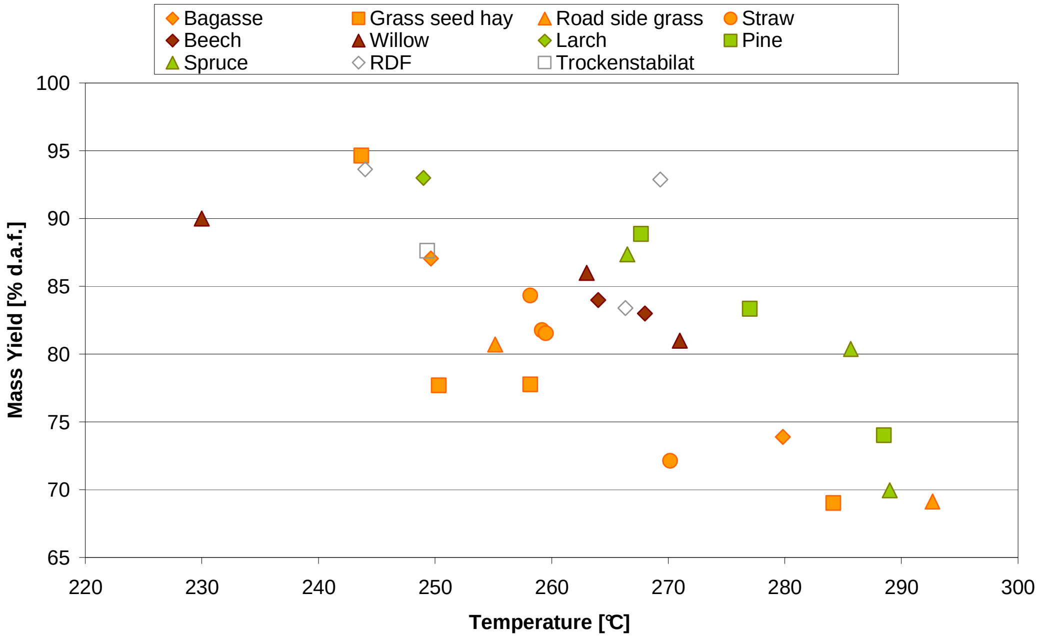


Figure 2.11 *Mass yield versus temperature for the biomass types tested in the batch reactor (Mass yields and temperatures averaged over the three sections in the reactor)*

Figure 2.11 reveals the same trends for reactivity between the different biomass types as observed in the TGA experiments:

- 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 probably their high ash content that catalyses the reaction.
- Deciduous wood (beech and willow) shows a more reactive behaviour than coniferous wood. Its hemicellulose is based on xylan polysugars.
- Coniferous wood (larch, pine and spruce) shows the lowest reactive behaviour as its hemicellulose is based on glucomannan polysugars.

The results for Trockenstabilat and RDF suffer heavily from the inhomogeneity of these streams and, as a consequence, the varying composition of the samples. This makes it impossible to draw firm conclusions for these materials.

Whilst the trends of the mass yields found in the TGA tests are similar to the trends found in the batch tests, the TGA mass yields are up to 15% lower. The difference is mainly attributed to a difference in reaction time between the two experiments.

Proximate/ultimate analysis

The C, H, N, O and ash content for all the raw and torrefied materials, together with the calorific values are presented in Table 2.3. 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.

Table 2.3 *Proximate/ultimate analysis data*
(The values are the averages of all the different batches of the same material analysed. Unless indicated otherwise, all values are on dry basis)

Material/Parameter	**Ash 550 (wt%)**	**C (wt%)**	**H (wt%)**	**N (wt%)**	**O (wt%)**	**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

In Appendix A.2 it can be observed that 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, since for these materials a decrease in N and O content is observed. The lower heating value (LHV) can be estimated from the higher heating value (HHV). The HHV is determined using an adiabatic bomb calorimeter. Figure 2.12 shows the LHV of the derived torrefied materials.

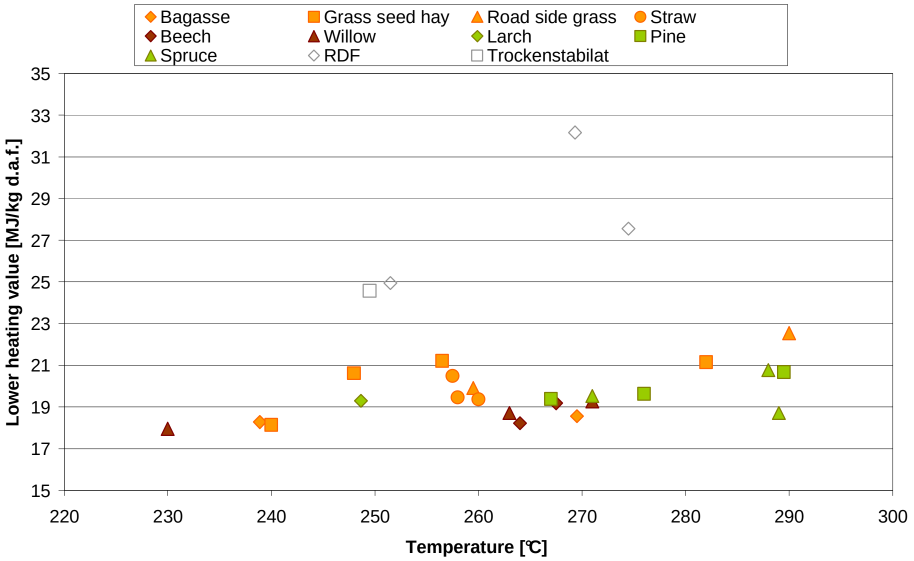


Figure 2.12 *Lower heating values of the torrefied materials produced during batch experiments*
(LHV and temperatures refer to the section of the reactor with actual conditions closest to the selected ones)

From Figure 2.12, in combination with the values given in Table 2.3, it is observed that the herbaceous materials (grass seed hay and straw) have a higher increase of LHV than the coniferous and deciduous wood species. This increase is already observed within the lower temperature range. The waste streams show higher LHV's than the biomass materials as their main fraction consists of plastics, which are (in general) higher in energy content than biomass.

Energy yield

The energy yield is defined according to the next formula:

$$E_y = m_y * \frac{E_{tor}}{E_{raw}}$$

where: E_y is the energy yield (referred to the LHV)
m_y is the mass yield (m_{tor}/m_{raw})
E_{tor} is the LHV of the torrefied material
E_{raw} is the LHV of the raw material.

A summary of the energy yields for the materials tested is given in Figure 2.13.

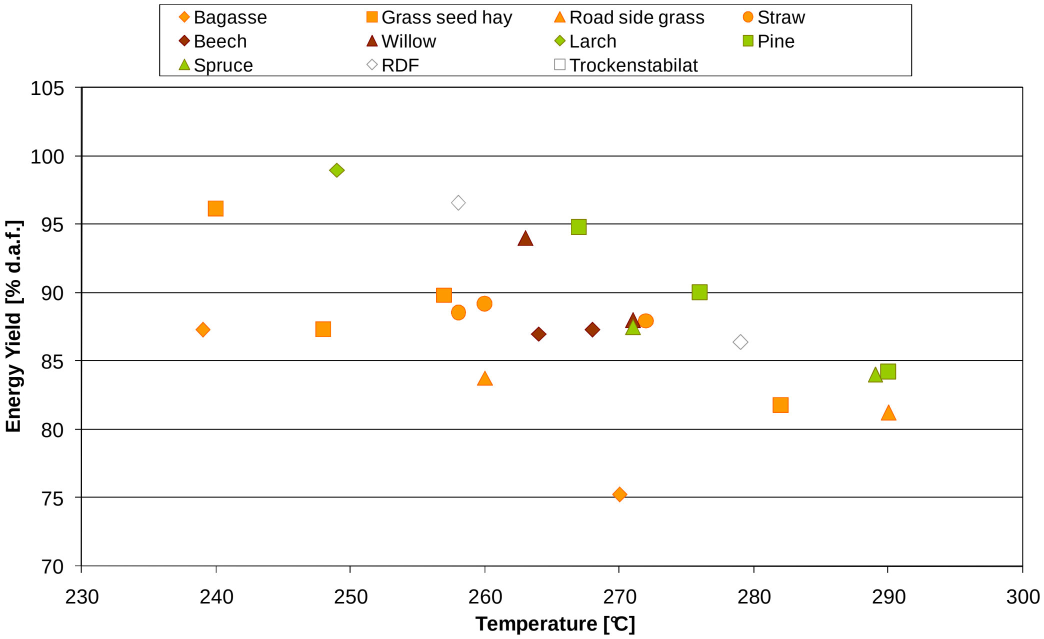


Figure 2.13 *Energy yields obtained from the batch experiments (Energy yields and temperatures refer to the section of the reactor with actual conditions closest to the selected ones)*

In Figure 2.13, it can be observed that the energy yield decreases at higher torrefaction temperatures. All the values are higher than 80% except for bagasse (270,30). Values for Trockenstabilat could not be given. The composition of the material was too inhomogeneous to come to accurate results.

Lignocellulose composition

Lignocellulosic feedstocks are composed primarily of carbohydrates (cellulose and hemicellulose) and phenolic polymers (lignin). Lower concentrations of various compounds, such as proteins, acids, salts, and minerals, are also present. To determine the concentrations of hemicellulose, cellulose and lignin, the methods of NDF (Neutral Detergent Fibre), ADF (Acid Detergent Fibre) and ADL (Acid Detergent Lignin) have been used (see Appendix A.4).

Figure 2.14 represents the different concentrations of hemicellulose, cellulose and lignin for the different feedstocks. For the waste streams the lignocellulose composition has not been determined as the major fraction of these materials are plastics.

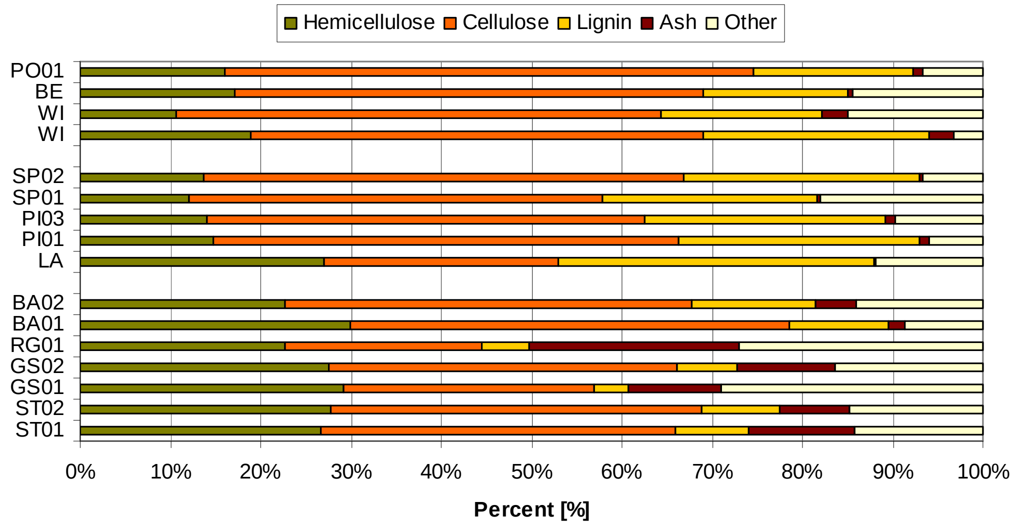


Figure 2.14 *Lignocellulose composition of the biomass feedstocks tested*
(The codes stand for:
BE --- beech *LA --- larch* *BA --- bagasse*
PO --- poplar *SP --- spruce* *RG --- road side grass*
WI --- willow *PI --- pine* *GS --- grass seed hay*
ST --- straw
The numbers indicate different batches of the same type of material.)

From the results, the following observations can be made:

- The herbaceous materials show a higher concentration of hemicellulose than the coniferous and deciduous materials.
- The herbaceous materials show the lowest concentration of lignin.
- Coniferous materials show the highest concentration of cellulose and lignin.
- A fraction of the feedstock, varying from 3% for willow to almost 30% for road side grass, could not be identified with the method applied as it was not suitable for determining components like xylose, mannose, galactose, rhamnose, and arabinose.

The main reason to apply torrefaction is the degradation of the hemicellulose, as this carbohydrate is the main cause of the tenacity and the hydrophilicity of lignocellulosic biomass. Figure 2.15 shows the influence of torrefaction on the hemicellulose, cellulose and lignin content for the investigated feedstocks.

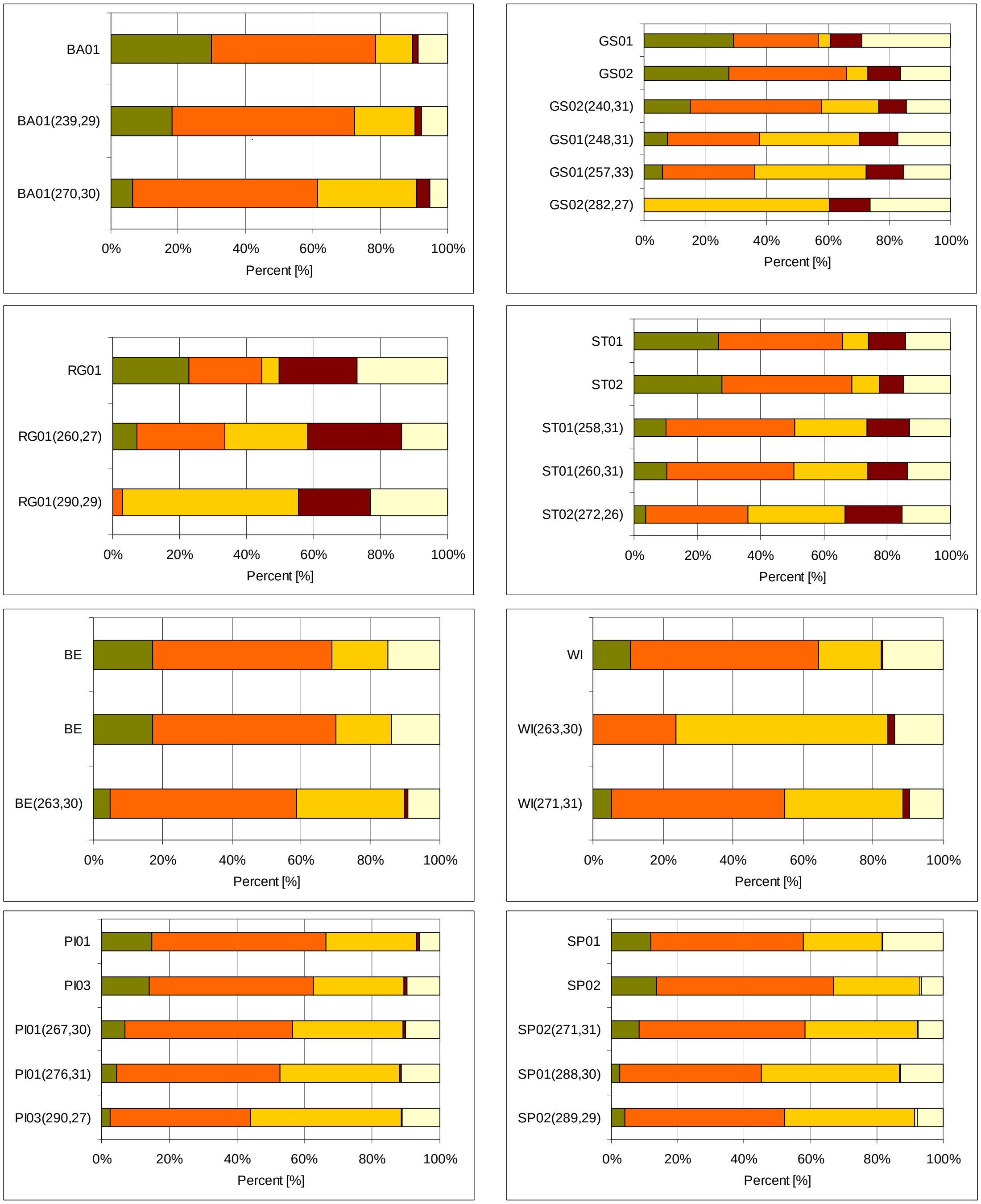


Figure 2.15 *Influence of torrefaction on lignocellulose composition (The values between brackets are the temperature and residence time during torrefaction and Green = Hemicellulose, Orange = Cellulose, Yellow = Lignin, Brown = Ash, White = Other)*

From Figure 2-15, the following observations can be made:

- For all the samples, the hemicellulose content decreases with increasing torrefaction temperature.
- Herbaceous materials show a higher reactivity than the deciduous and coniferous materials. 260°C seems to be a good torrefaction temperature for them.

- Coniferous materials show the lowest reactivity. Their optimum torrefaction temperature appears to be between 290°C and 300°C, which is slightly higher than for deciduous biomass (around 280°C).
- Willow (263,30) shows a somewhat unexpected value, as the hemicellulose should not be totally degraded under these conditions. This unexpected result can be caused by improper handling or deterioration of the material as it was analysed 5 years after the experiment was done.
- Cellulose of grass seed hay and road side grass appears to degrade rapidly at higher temperatures, after the hemicellulose has degraded.

Morphology

After torrefaction, the material has been visually inspected, mainly to check the degree of torrefaction of the different components and materials. As expected, the colour of all the feedstocks becomes darker brown and the material becomes more brittle when applying more severe torrefaction conditions. For the waste streams, formation of agglomerates is observed due to molten plastics covering the less torrefied organic materials. Pictures of the different torrefied materials from the batch experiments can be found in the Appendix A.3.

Particle size reduction

Grinding experiments were executed with several materials to investigate the power consumption during grinding. Figure 2.16 shows the results of these size reduction experiments carried out on coal, dried biomass and torrefied biomass.

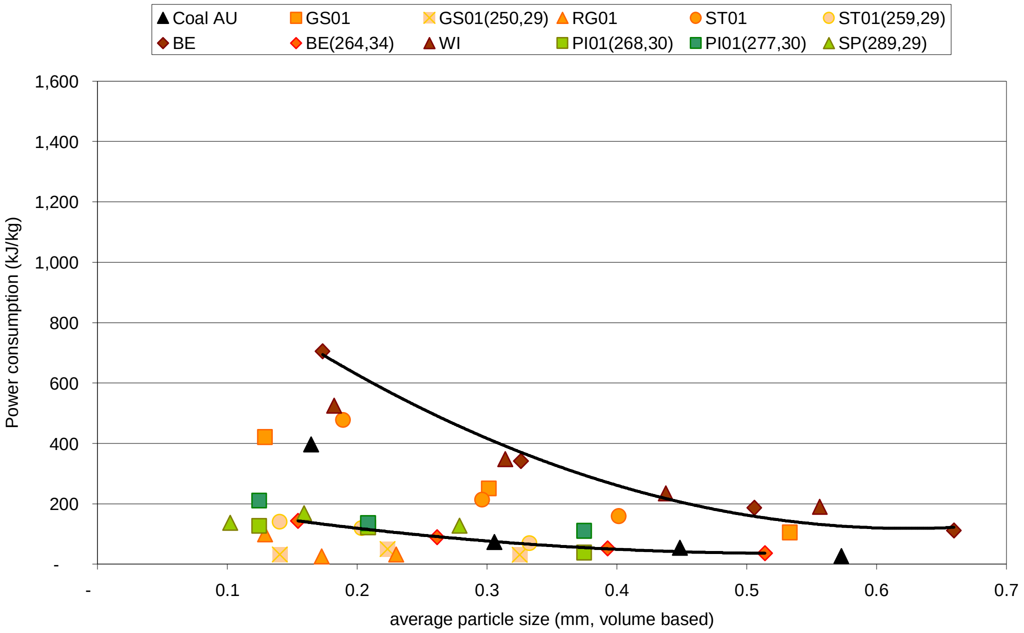


Figure 2.16 *Relation between power consumption and particle size for coal, dried biomass and torrefied biomass*
(Torrefaction temperature and residence time are given between brackets)

The following observations can be made:

- The power consumption of the cutting mill reduces dramatically when the biomass is torrefied.
- The power consumption for dried biomass strongly increases when decreasing the particle size selected as the output.
- Herbaceous biomass like road side grass and straw show lower power consumption than the deciduous and coniferous biomass.

The measurements are dependent on the initial shape and particle size of the materials so comparisons between feedstocks should be made with care.

Untreated RDF and Trockenstabilat could only be milled cryogenically. On the contrary, torrefied RDF and Trockenstabilat could be milled at room temperature. However, the required power consumption was significantly higher than for torrefied biomass. This is attributed to the fact that a fraction of the material appeared to be not completely torrefied leading to blockages in the mill.

2.4.3 Pyromaat experiments

For a number of materials, pyromaat experiments were conducted. For the lignocellulosic biomass materials, the experiments were performed at the "optimum" temperature with respect to hemicellulose degradation. For the waste streams, three different temperatures were selected to get more knowledge about the behaviour of these materials. Since the pyromaat is equipped with a micro-GC and a wet sampling system (according to the tar measurement standard), information could be collected about the release of permanent gases (CO, CO_2, CH_4, Ar, O_2), condensables (organic matter), water and chlorine. In addition, the same set of analyses as in case of the batch reactor tests were executed with the torrefied materials produced. For the pyromaat experiments, all materials were dried at 105°C and milled to a particle diameter smaller than 3 cm. An overview of the results can be found in Appendix A.5.

Mass yield and lignocellulose composition
Table 2.4 shows the selected conditions for each material tested.

Table 2.4 *Selected pyromaat operating conditions for each material*

Material	**Temperature (ºC)**
Bagasse	270
Grass seed hay	260
Road side grass	265
Straw	260
Beech	280
Poplar	280
Pine	290
Spruce	290
Trockenstabilat	240 260 280
RDF	240 260 280

Figure 2.17 shows the resulting mass yields and Figure 2.18 summarises the lignocellulose composition of the torrefied materials produced. For the waste streams the lignocellulose composition has not been determined, since the major fraction of these materials is plastics. As can be seen, the hemicellulose of most of the materials has been totally degraded. In addition, a fast degradation of cellulose can be seen for grass seed hay and road side grass, where more than half of the cellulose in the raw material has been eliminated (compare Figure 2.15 and Figure 2.18). Pine, spruce and poplar also show a significant decrease in their cellulose content. In conclusion it can be said that for most materials the selected torrefaction temperature might be too high. The results for Trockenstabilat and RDF again are not very accurate, due to the inhomogeneity of the feedstock.

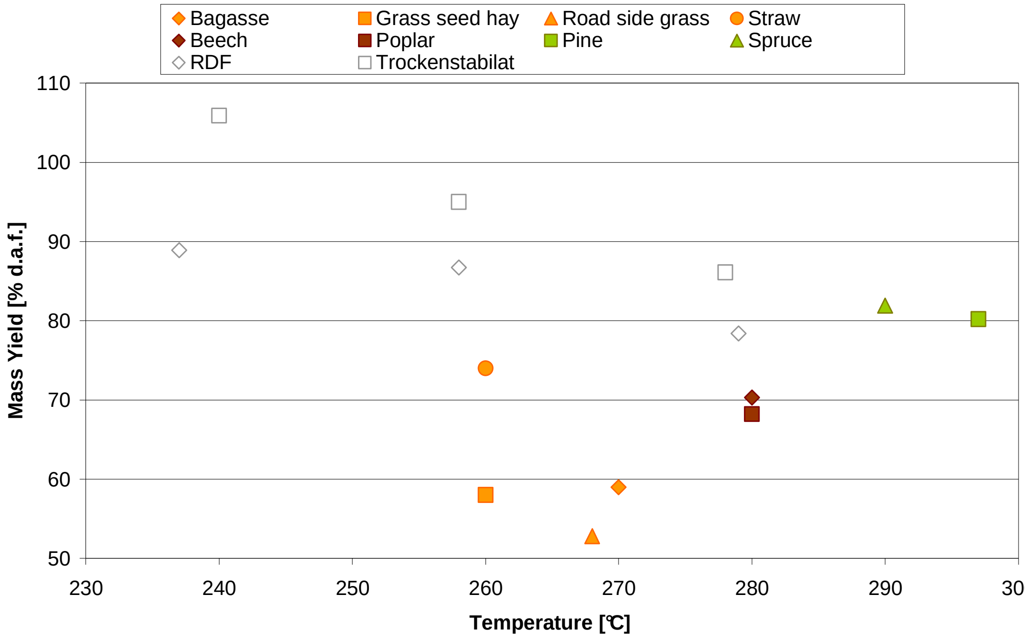


Figure 2.17 *Mass yield of torrefied materials produced in the pyromaat (Mass yields > 100% are not possible. This finding must be inaccurate. RDF and Trockenstabilat are very inhomogeneous. Determination of the mass yield becomes questionable)*

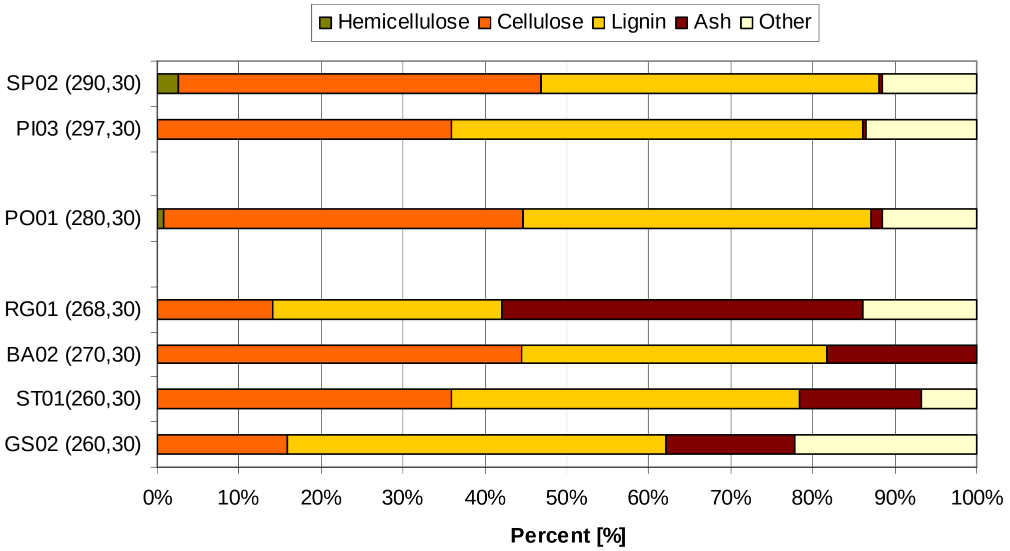


Figure 2.18 *Lignocellulose compostion of torrefied materials produced in the pyromaat*

Torrefaction gas
During torrefaction, gas is produced and gas production increases with increasing torrefaction temperature. In this section, the composition of the torrefaction gas will be discussed. A distinction will be made between the permanent gases (CO, CO_2 and CH_4), including (reaction) water, and the organic compounds (“condensables”). Moreover, for RDF and Trockenstabilat, particular attention will be paid to the fate of chlorine.

The results for the permanent gases, reaction water and chlorine are shown in Figure 2.19 to Figure 2.21.

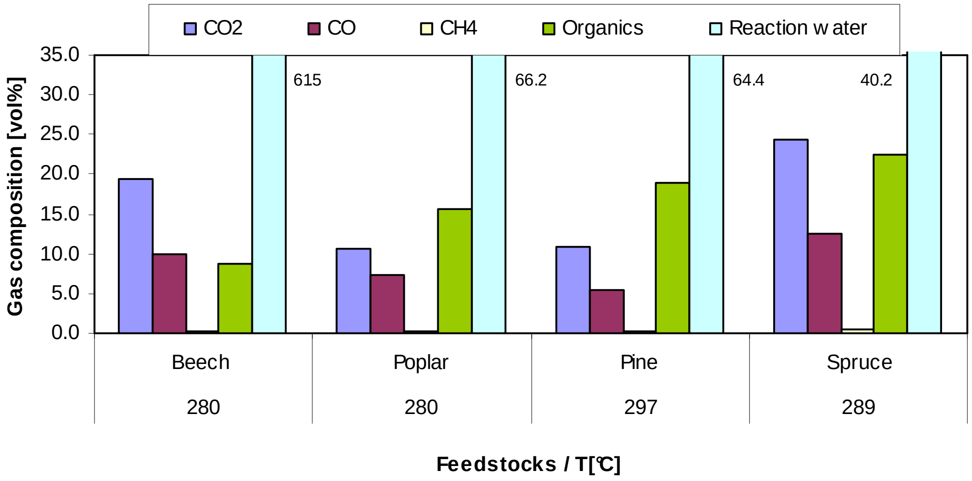


Figure 2.19 *Gas composition for the deciduous and coniferous woods*

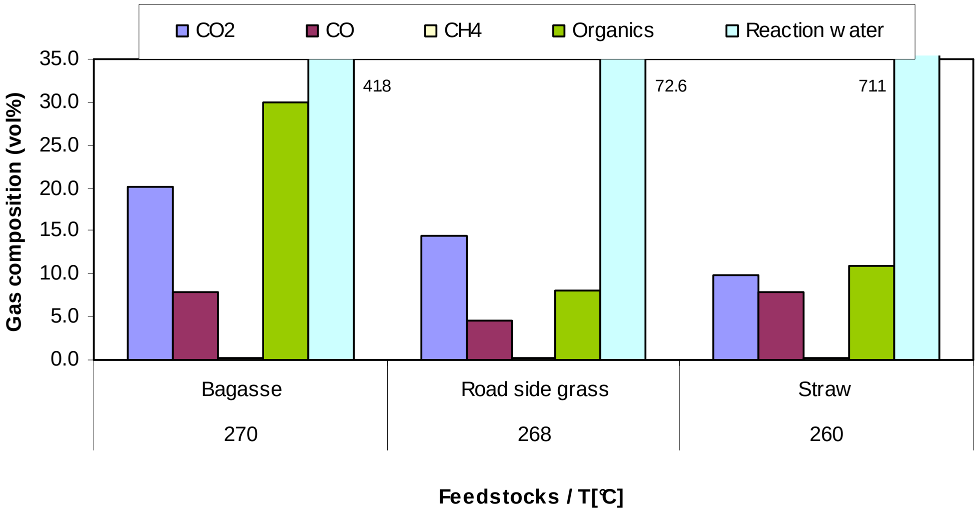


Figure 2.20 *Gas composition for the herbaceous materials*

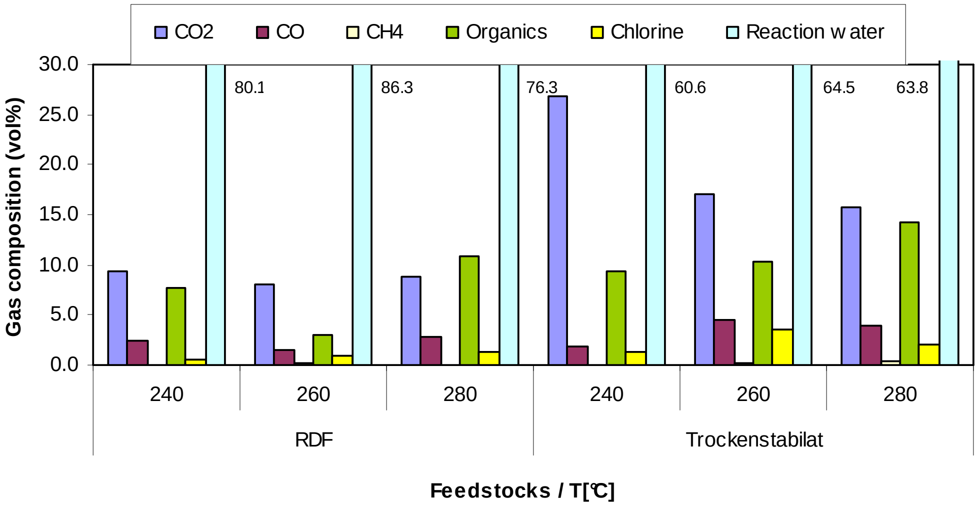


Figure 2.21 *Gas composition for the waste streams*

It can be concluded that for woody biomass, straw and bagasse, the torrefaction gas is most suitable for combustion due to the higher content of CO and organics.

The results for the waste materials RDF and Trockenstabilat must be used carefully due to the unhomogeneity of the feedstocks that can lead to wrong conclusions. Nevertheless, the gaseous chlorine emissions appear to be significant, contrary to what is generally found for biomass feedstocks. Probably, these emissions originate from the plastics fraction.

Organic fraction
The composition of the organic fraction of the torrefaction gas is given in Figure 2.22 to Figure 2.24.

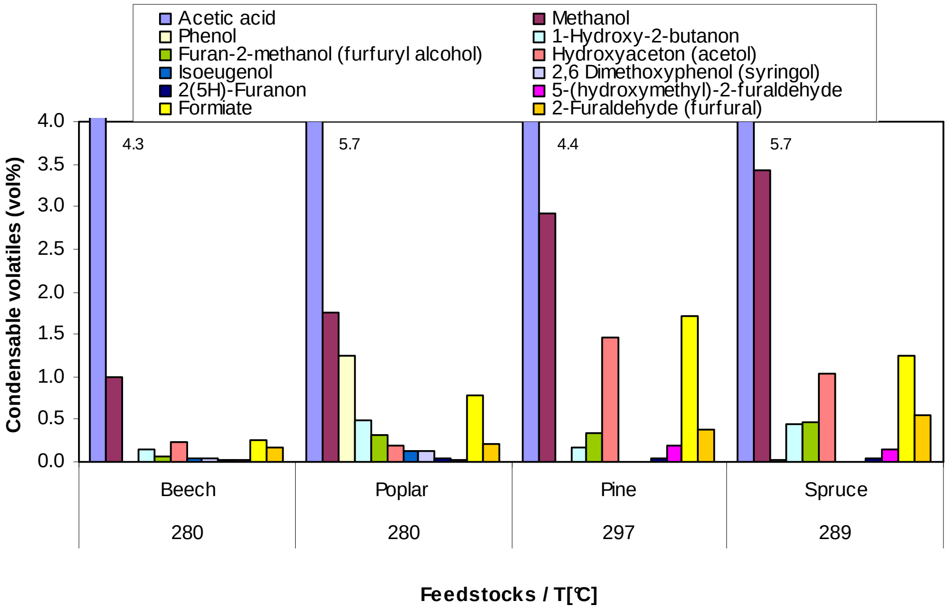


Figure 2.22 *Production of organic compounds for deciduous and coniferous wood (as percentage of the total gas production)*

For deciduous and coniferous wood, the main products in the gas are acetic acid and methanol. According Bergman et al. [2] and Prins [15], it was expected to find more acetic acid and methanol in the torrefied deciduous wood samples than in the torrefied coniferous wood samples, since the hemicellulose of deciduous woods has acetoxy- and methoxy- groups attached to the polysugars (mainly xylan) and these groups are released at temperatures above 200°C. However, this is not confirmed by the data generated during this investigation. Possibly, this is caused by the differences in torrefaction temperature, which might have an effect on the degradation of cellulose, lignin and other minor compounds (extractives) as well.

This seems to be supported by the data for poplar as large quantities of phenolic (phenol, isoeugenol, syringol) compounds, typical from lignin degradation, are found and also in the high quantities of methanol and lower quantities of phenol released by coniferous materials. Lignin from coniferous wood is thought to be more stable than from deciduous wood.

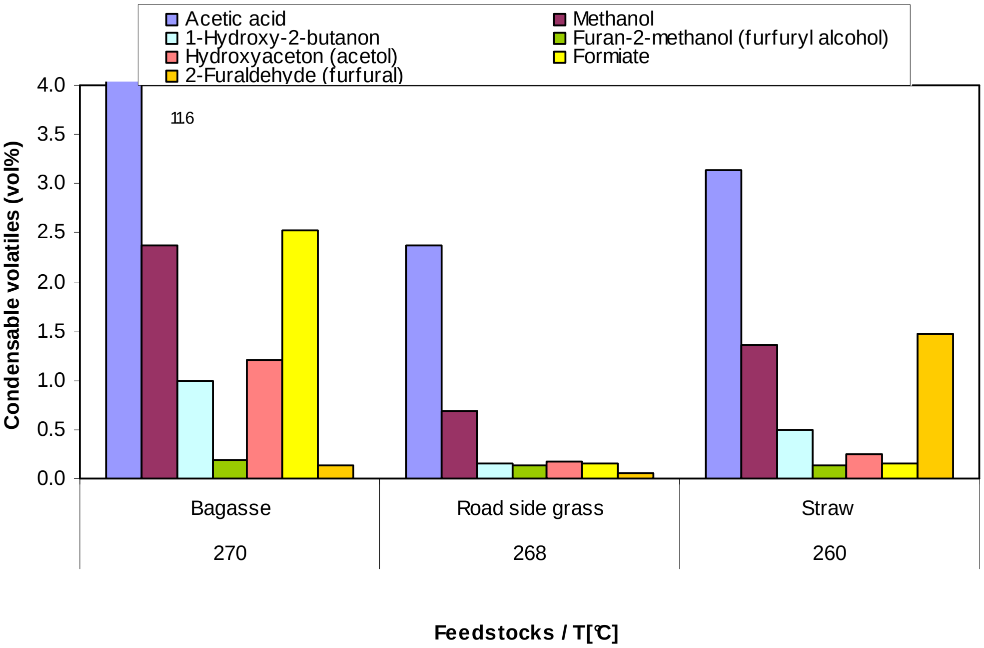


Figure 2.23 *Production of organic compounds for herbaceous materials (as percentage of the total gas production)*

For the herbaceous materials the range of components with significant values (set at >0.1%) is not as broad as for the woody material. The dominant components are acetic acid, methanol, 1-hydroxy-2-butanon, acetol and furan-2-methanol. Only traces of phenolic compound were found in the torrefaction gas released by any of the herbaceous materials suggesting cracking activity by the mineral matter. Furan-based substances are found due to hemicellulose degradation of C2-C4 oxygenates (acetol, 1-hydroxy-2-butanon). In road side grass, the percentage in furan-based species is much lower and could be related to the high degree of degradation of its cellulose diluting the hemicellulose typical components.

The gases produced by thermal treatment of the waste streams have a lower concentration of organic compounds than the other materials tested, see Figure 2.24. The organic fraction of RDF has a completely different composition than Trockenstabilat. The inhomogeneity of the materials, however, plays an important role. It makes the interpretation of the results difficult.
At the lowest temperature tested, acetic acid and methanol are the main products due to early stages of degradation of the plastic and organic fractions in the materials. Whilst increasing the

temperature the amount of different species increases. Typical pyrolysis products of carbon based materials like levoglucosan becomes the main product for RDF at 280°C, indicating advanced degradation of some of the polymers in the feedstocks.

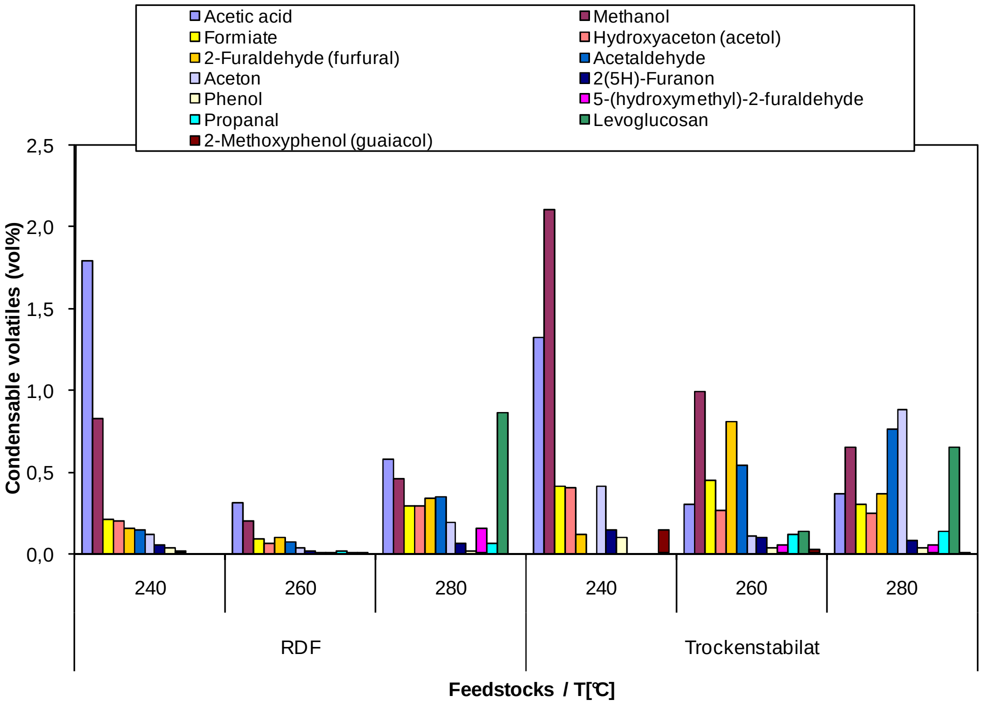


Figure 2.24 *Production of organic compounds for waste streams (as percentage of the total gas production)*

A common phenomenon for all the experiments was the blockage of the filter in the cold trap before the micro-GC. The deposit was collected from one experiment with straw. To study the composition of this sticky material, GC/MS analysis, C, H, N, O determination and TGA tests at 270°C (torrefaction temperature for the experiment) and at 1000°C (to assure complete carbonization of the material) were performed. From this, it could be concluded that in the data presented, the amount of phenolic compounds released due to lignin degradation is underestimated.

3. Pilot-plant design, construction and commissioning

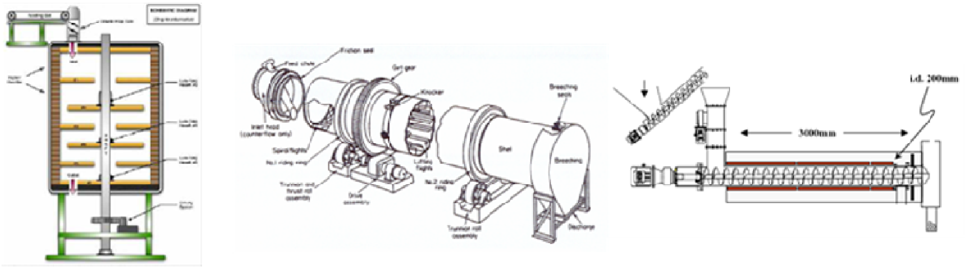
3.1 Introduction

An important part of the TorTech project was the design, construction and commissioning of a pilot-scale torrefaction test installation, named PATRIG.

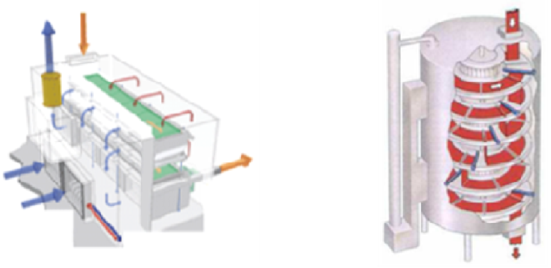
The design is based on moving bed technology with direct heating of the biomass materials by recycled product gas (torgas). No pre-drying of the fresh biomass is incorporated in the design. If pre-drying is needed, then this will be done externally. The design is based on the knowledge generated in three earlier projects executed by ECN and TU/e. The detailed design and the erection of the plant were executed by ECN personnel, but for special components external expertise and component suppliers were involved. The scale of the pilot plant has been set to be 50 - 100 kg/hour biomass input.

3.2 Background

Before the design of the pilot plant started, a literature search was done to see what concepts were already available. A selection of pre-existing torrefaction technologies is given in Figure 3.1.



Multiple hearth furnace Rotary drum reactor Screw conveyor reactor



Oscillating belt reactor TurboDryer

Figure 3.1 *Impression of pre-existing torrefaction technologies*

All the existing technologies were evaluated. It appears that most technologies were derived from existing drying or pyrolysis technology. It was concluded that most of the existing technologies had serious limitations in terms of:

- not being fuel flexible / robust
- having limited scale-up possibilities
- having high investment cost
- having a limited energy efficiency
- allowing limited control of process parameters

Therefore it was decided to develop a novel torrefaction concept based on moving bed technology with direct heating of the biomass materials by recycled product gas (torgas). Based on thorough knowledge of the torrefaction process a cost effective and flexible moving bed concept was designed with special features concerning the gas-solids contacting enabling a good temperature control in the reactor.

3.3 PATRIG pilot-plant design, construction and commissioning

The design of the pilot plant started in June 2006 with the definition of the "Programme of Demands". With this document the first drafts of the "Process Flow Diagram" and the "Process and Instrumentation Diagram" were made and the process data for all the necessary equipment was determined. With these documents all the auxiliary equipment was specified and ordered from the equipment suppliers. The reactor itself, including the complete process safety and control system of the plant, was designed and constructed by ECN Engineering and Services.

In order to come to a reliable reactor design a cold flow model of the reactor was fabricated. Gas flow tests were conducted in order to develop proper designs for the gas inlets and outlets. A generalised flow scheme of the PATRIG torrefaction pilot-plant (with additional facilities in yellow) is given in Figure 3.2.

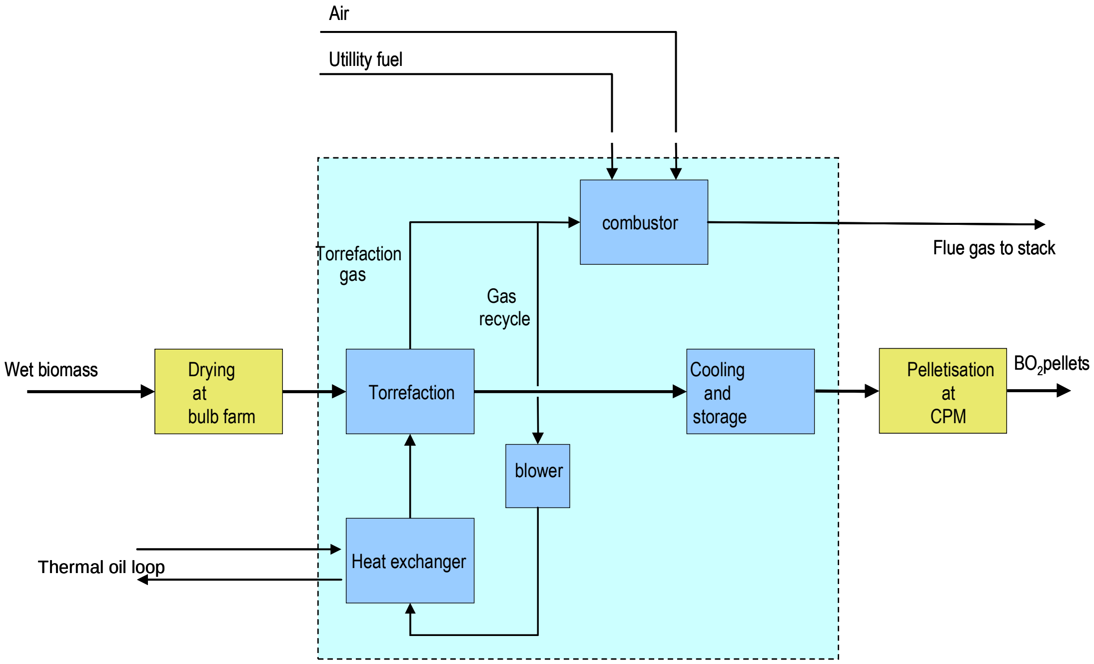


Figure 3.2 *General flow scheme of the ECN PATRIG pilot-plant (BO$_2$ pellets = torrefied biomass pellets produced according to the ECN torrefaction-based BO$_2$-technology)*

If required, the biomass is pre-dried at a bulb farm near ECN to a moisture content of <20%. After drying the biomass is torrefied in the moving bed torrefier which is flushed with circulating gas. This gas is the torrefaction gas (torgas) released during the torrefaction process. The gas is circulated, using a blower, and heated in a heat exchanger with an electrically heated thermal oil system. The surplus torrefaction gas is burnt in a combustor and vented to the stack. The torrefied material is extracted from the reactor via screw conveyors and stored in storage vessels were it cools down. In case densification (pelletisation or briquetting) of the torrefied material is required, the torrefied material is transported to a pelletising/briquetting facility; e.g. to the test facility of California Pellet Mill (CPM, one of the large pellet mill producers) in

Amsterdam. At CPM, the torrefied material can be grinded and pelletised in a semi-industrial size pellet mill.

For the capacity of the pilot plant, 50 to 100 kg biomass input was chosen, depending on the characteristics of the biomass. The maximum design temperature in the reactor is 350°C, but normally the torrefaction temperature will be between 220 and 300°C.

Figure 3.3 shows the three stories high pilot plant after erection. On the top floor the biomass is fed to the torrefaction reactor via conveyor belts and a sluicing system. On the first floor the directly heated moving bed torrefaction reactor is situated. Here the biomass is heated, using the recycled torrefaction gas (torgas). On the ground floor, the torrefied material is extracted and stored in storage bins.

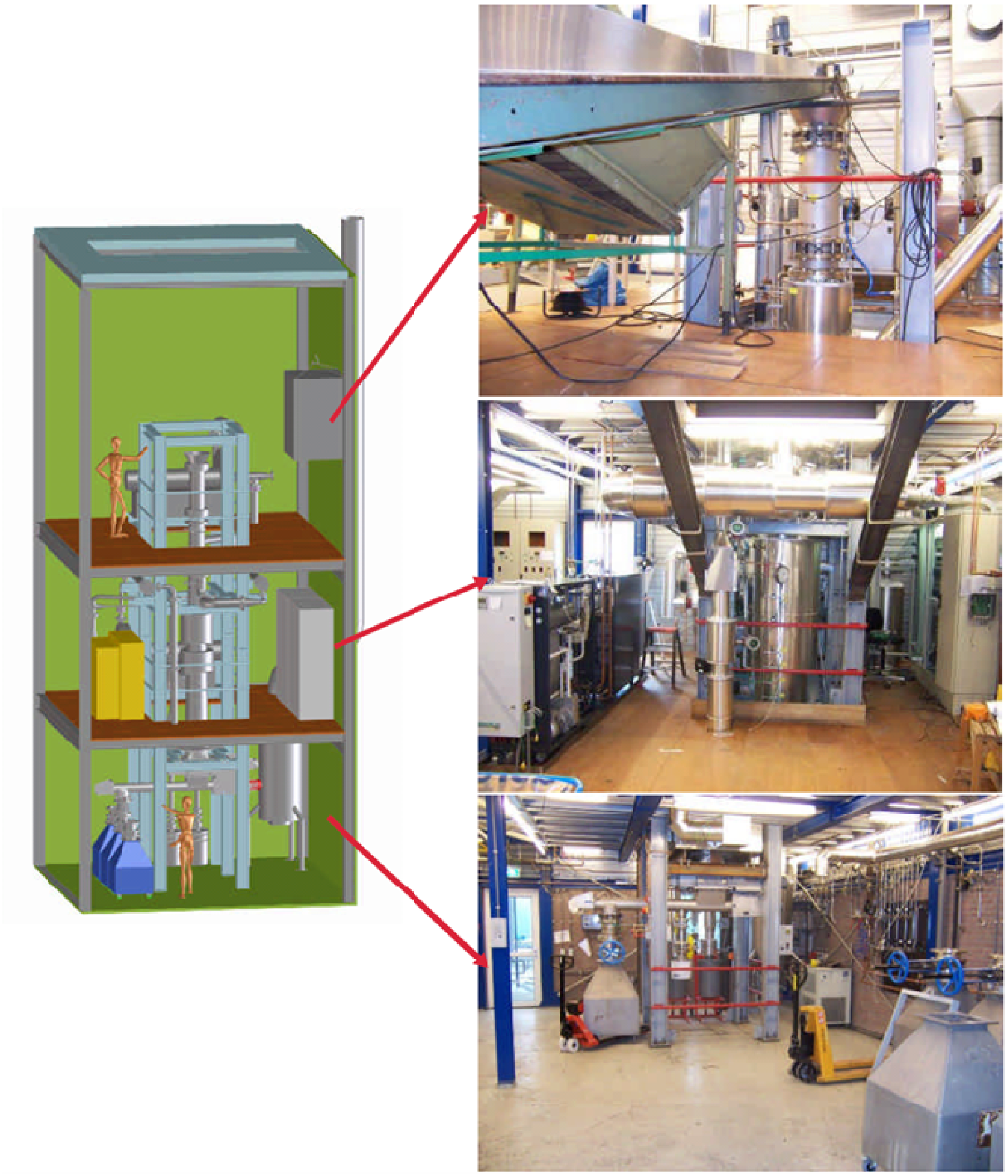


Figure 3.3 *PATRIG torrefaction pilot plant at ECN*

The construction and assembly of PATRIG were completed in September 2007. Cold and hot testing started with wood pellets to mechanically test the feeding and extraction systems. Wood pellets were chosen for the first tests, because they are dry and easy to handle.

During cold testing, the reactor could not be brought to working pressure. In- and outlet valves and expansion joints were leaking and had to be replaced or modified. A gland of a blower had to be replaced by a labyrinth gland with nitrogen seal. Further, it was discovered that there was a high pressure resistance in some pipe work. These heat traced pipes had to be replaced by pipes with a bigger internal diameter. The torrefied biomass extraction mechanism had to be modified as well. The capacity was to large, jeopardising proper control of the throughput.

All the necessary modifications were executed in December 2007 and January 2008. Subsequently, the first torrefied material was produced batch-wise in February 2008. It was planned to execute the first series of torrefaction tests with wood pellets and that wood chips would be used after that. However, it was noticed during the first tests that the wood pellets disintegrated during torrefaction. Therefore, the decision was made to stop with wood pellets and continue the tests with wood trimmings. These wood trimmings were wet when delivered and had to be dried. Drying was done at the nearby flower-bulb farmer, see Figure 3.4. A high percentage of dust, sand and needles was detected and screened out after drying. The wood trimmings were delivered in big bags and stored, see Figure 3.5.

Figure 3.4 *Screening of the Dutch "wood trimmings"*

Figure 3.5 *Storage of woodchips*

During drying and handling of the biomass, it was concluded that big bags were not very practical. Bulb drying is done in wooden cube boxes with a steel grid as bottom plate. Following that example, it was decided to use the same cube boxes as well for drying, storage and handling of the biomass. Especially during storage, the cube boxes proved to be practical, since they can be stacked.

On Wednesday March 5th 2008, PATRIG was in full operation for the first time, with all the systems running automatically. The pictures in Figure 3.6 show the fresh biomass trimmings that are used and the first batch of torrefied wood trimmings, as they leave the reactor.

Biomass on feeding system

Fresh biomass

Fresh biomass

Torrefied biomass in full product collection vessel

Biomass sample

Torrefied biomass sample

Figure 3.6 *Pictures of fresh biomass to the reactor and torrefied biomass leaving the reactor*

After a number of tests, including duration tests, it was concluded that the product vessel was too small. The vessel was full within one hour and in order to change the vessel the extraction of torrefied materials had to be stopped for 15 minutes. This gave big disturbances in the process. Therefore the small vessel was removed and replaced by two big product vessels and an automatic switching system, see Figure 3.7. As soon as one vessel is full, the product flow is switched over to the other vessel and the full vessel is replaced by an empty one. In this way no process interruptions occur anymore.

Figure 3.7 *New torrefied product collection system*

During commissioning, the torgas combustor needed extra attention as well. The combustible gas produced during torrefaction was burned in a combustor. In this combustor, an ignition burner was placed to ignite the torgas. The temperature in the combustor is limited to 950°C. When the temperature rose above this value, the ignition burner was switched off. This method of controlling the temperature in the combustor gave irregularities in the process. After modifications, the temperature in the combustor is now controlled via extra excess air.

After these modifications the pilot-plant appeared to run smoothly and a lot of valuable operating experience could generated. An overview of this experience generated is given in the next chapter.

4. Pilot-plant torrefaction trials

The commissioning of PATRIG ended after the installation was in full operation and the first torrefied material was produced in March 2008. After commissioning, trials started to generate a better understanding of the behaviour of the pilot plant. In this chapter, the results of the torrefaction trials in PATRIG are summarised. The trials were directed to validation of the results and findings in the small-scale experiments and to optimise pilot-plant operation. During the trials, both solid and gaseous products were sampled and analysed.

In the original TorTech test programme, trials were scheduled with a wide variety of biomasses including Trockenstabilat and other RDF or SRF fractions, demolition wood, clean wood, road side grass and straw. However, since the costs for the commissioning of PATRIG were much higher than originally anticipated, the remaining TorTech budget for torrefaction trials was limited. Furthermore, after extensive test work performed in the batch reactor reported in Chapter 2, it was concluded that testing Trockenstabilat and other RDF or SRF fractions, demolition wood, road side grass and straw in PATRIG would give permitting problems and/or would require special precautions. Therefore NL Agency agreed to limit the test work to trials with clean wood chips and wood trimmings. However, outside the TorTech project many other trials were executed by the end of 2010, for instance with agro residues from the palm oil industry, poplar chips, mixtures of clean wood chips, aspen chips, pine chips etcetera. By the end of 2010, PATRIG had been in operation for more than 800 hours. More than 30 tons of torrefied materials were produced during short, 8 hour trials and several longer-duration trials ranging from 40 up to 100 hours of continuous operation.

In all the trials, the torrefaction temperature was between 220 and 280°C inlet temperature. The capacity ranged from 40 to 60 kg/hr input. Smooth operation and straightforward start/stop procedures were developed and demonstrated.

During the runs, the influence of the gas flow rate and the torrefaction temperature on the torrefaction process was studied. In general, the modestly exothermic nature of the torrefaction process was confirmed, leading to locally higher temperatures in the reactor than the gas inlet temperature. By using proper gas velocities, good temperature control can be ensured. Higher torrefaction temperatures enhance the exothermicity of the process. By choosing proper gas velocities in combination with a proper inlet temperature of the circulating gas, the desired torrefaction temperature can be maintained. During the trials, it was demonstrated that the mass and energy yield found in the batch reactor can be reproduced in PATRIG. From this, it was concluded that with the results obtained in the batch reactor it is very well possible to predict the torrefaction behaviour in the pilot plant.

After the tests with gas flow and temperature variation, the attention shifted to optimisation of the product quality. The torrefaction conditions influence the grindability and the pelletisation behaviour of the torrefied material. In general, heavily torrefied material is brittle and easy to grind, but is more difficult to pelletise. Tests were conducted to better understand this relation and to find optimum conditions (see Chapter 5, "Torrefaction and pelletisation"). The first lab-scale pellet of torrefied material produced on a continuous basis in PATRIG was made in week 13, 2008. A picture of the first two pellets is given in Figure 4.1.

Figure 4.1 *Picture of the first lab-scale pellets from biomass, torrefied in PATRIG*

Later, much more pellets were produced on a semi-industrial scale as is illustrated in Figure 4.2.

Figure 4.2 *Pellets produced from wood torrefied in PATRIG*

By performing longer-duration trials, the behaviour of the installation during longer operating periods was studied. It was demonstrated that the installation operates reliable over longer periods of time. The installation shows high feedstock flexibility and the pressure drop in the system can be kept to a low level. Since the reactor has a relatively small diameter, bridging can occur when oversized particles are fed. Bridging can be prevented effectively by removing all oversized particles.

Additional research focussed on the composition and properties of the torrefaction gas (torgas). This torgas is a mixture of (reaction) water, CO, CO_2 and organics. The organics are a complex mixture of organic compounds like acetic acid, methanol and many other compounds, as described in Chapter 2. These compounds will condensate at certain temperature levels. Tests were conducted to generate better understanding of the behaviour of these compounds when changing the temperature of the torgas. The torgas is combusted in a combustor. The flue gasses of the combustor are analysed on-line. The emissions measured were low and comparable with natural gas combustion (0-50 ppmv CO and 20-70 ppmv NO_x).

When the torrefied material leaves the reactor it is stored in air tight storage bins where it cools down to nearly the temperature of the environment. After disconnecting the storage bin, air enters the storage bin. This admittance of air must be done with caution, so that the material gets the time to "get used" to the oxygen. Otherwise, under certain circumstances, the product can heat up spontaneously and start to smoke. Extinguishing this spontaneous combustion can be difficult.

5. Torrefaction and pelletisation

5.1 Objectives

Despite proof that torrefaction in combination with pelletisation leads to a better pellet quality, no industrial production recipes were available at the start of this research programme. The first exploratory investigations by ECN showed good perspectives for torrefied pellets. However, some of the benefits were based on assumptions that can only be validated by research. In particular the relationship between torrefaction and pelletisation conditions and their influence on the pellet quality is an area which needs further research. Therefore, the following research objectives were formulated:

- Determination whether it is possible to produce good quality pellets from torrefied material.
- Research on the relationship between torrefaction and pelletisation conditions and the resulting pellet quality.

5.2 Approach

The research work started with small-scale tests and extensive analysis of the pellet quality (e.g., strength, water uptake, shape stability and biological resistance). Selected batches produced in the batch reactor were used to conduct pelletisation tests in a single-pellet piston press at ECN and in a continuous bench-scale pelletisation mill (10 - 50 kg/h) of CPM in Amsterdam. On the basis of these results, selected batches of torrefied product produced in PATRIG were taken to conduct 100 - 500 kg/h pelletisation tests with the CPM semi-industrial pellet mill. The experimental pelletisation facilities applied are described in the following sections.

5.2.1 Single-pellet piston press

Experiments at ECN were carried out in a single-pellet Struers Prontopress (lab-scale piston press) with a piston diameter of 17 mm. A picture is given in Figure 5.1. The feed is batch by batch and 3-6 grams of material can be pelletised, depending on the specific weight of the input material. Around the piston is an oven, which allows the piston to be heated to 300°C, so pelletisation at high temperatures is possible. With the help of the available cooling system, the pellets can quickly be cooled after the experiment. The pressure of the piston press is adjustable between 0 and ~ 1700 barg.

Figure 5.1 *Struers Prontopress for pelletisation at higher temperatures*

5.2.2 Bench-scale pellet mill

Experiments at CPM were carried out in a continuous CPM bench-scale pellet mill (see Figure 5-2), with a regulated feeding screw. The throughput of this mill is 10 kg/hour at full capacity. The pellet mill warms up by the heat generated by friction in the die. Steam conditioning is not possible in this pellet press, but it is possible to manually add moisture to improve the lubrication in the die.

Figure 5.2 *CPM bench-scale pellet mill*

Prior to pelletisation, it is important that the raw material meets the specifications, being a Dp50 of 1 mm. The raw material is stored in a bunker, and is transported to the pellet mill by a vibrating gutter. Figure 5.3 (left) shows the principle of the CPM pellet mill.

In this type of pellet mills, the die rotates around the roller and the material inside the pellet press is forced against the inside of the die by centrifugal forces. The quality of the pellet will largely depend on the resistance in the die. This resistance is determined by factors such as die length, diameter and particle matrix. To reduce the resistance in the die, extra moisture addition to the raw material is needed, that acts as a lubricant. The resistance in the die will also create frictional heat, which can be beneficial. Because this method of pelletisation is a continuous process, a knife at the outlet of the die cuts the pellets at the desired length. Figure 5.3 (right) shows how the pellets exit the die.

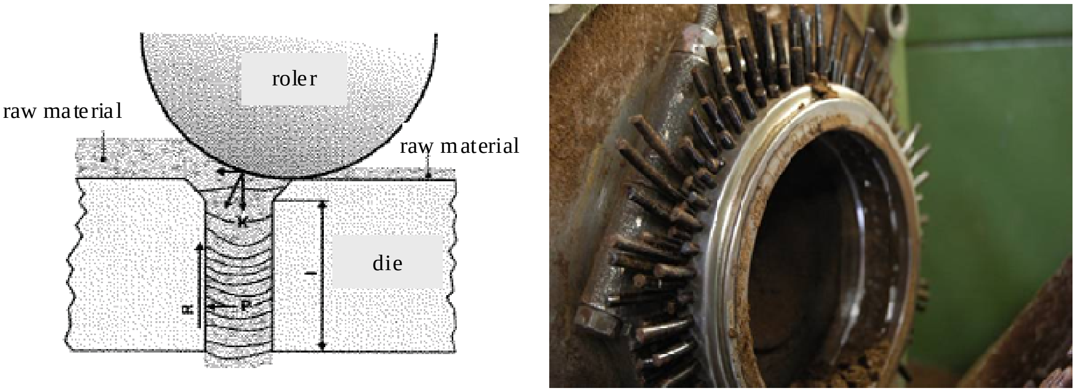


Figure 5.3 *Principle of pelletisation (left) and exit of the CPM die with torrefied pellets (right)*

5.2.3 Semi-industrial pellet mill

CPM's pelletisation unit named HYFLO (Figure 5.4) is a semi-industrial pellet mill with a capacity of approximately 200-300 kg/h. CPM offers a variation of dies that can be used in this pellet mill. The feeding rate can be adjusted manually and the moisture supply is manually as well, mostly by pre-mixing the material with water. This pellet mill offers the possibility to supply extra moisture by two manually driven spray units. The temperature of the die is around 80-100°C after continuous operation for a small period of time. There is no possibility to (pre)heat the die. The machine's maximum amperage is 50 Amp.

Figure 5.4 *CPM semi-industrial HYFLO pelletisation unit*

5.3 Experimental results and discussion

5.3.1 Single-pellet piston press tests

In this paragraph a summary of the basic work carried out in the Struers piston press at ECN is presented. Research carried out by Reed and Bryant [16] showed a positive influence of thermal treatment of materials on the density of a pellet. The experiments carried out by ECN also showed that thermal treatment has a positive effect on the density of a pellet. Figure 5.5 represents the experimental values of Reed and Bryant, and the experimental values of the ECN experiments. The left Y-axis represents the values for the density and the right Y-axis represents the percentage of weight loss.

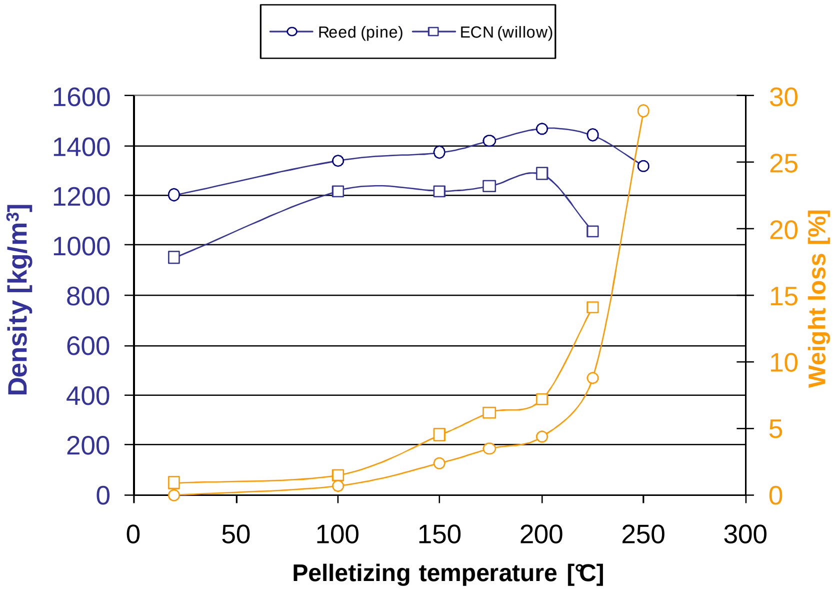


Figure 5.5 *Influence of pelletizing temperature on pellet density*

From Figure 5.5, it is observed that for both the values of Reed (and Bryant), and the values of the ECN, the density of the pellet increases with increasing temperature. Pellet density reaches a maximum around 200°C;. At higher temperatures, the weight loss increases and the pellet density decreases again. This trend can be explained by the fact that around 200°C decomposition of the material is initiated. This decomposition results in an increased weight loss. During the ECN experiments not only clean willow was pelletised at higher temperatures, also torrefied willow was tested. Table 5.1 shows the results of density measurements with torrefied willow, pelletised at different piston temperatures. Torrefied willow showed similar results in terms of density, but it is remarkable that these densities can only be obtained at higher temperatures.

Table 5.1 *Pellet density in kg/m^3 for torrefied willow, pelletised at elevated temperatures (TW 260-24 = Willow, torrefied at 260°C for 24 minutes, X = No good quality pellet could be produced, nt = not tested)*

Piston temperature / Material	20°C	100°C	150°C	175°C	200°C	225°C	260°C
Willow	947	1220	1219	1239	1285	1056	nt
TW 260-24	X	X	X	X	1275	1306	825
TW 280-60	X	X	X	X	X	1198	1268
TW 280-120	X	X	X	X	X	1171	1244
TW 290-24	X	X	X	X	X	1202	1282

The observed shift in temperature between the fresh and torrefied material may be caused by the fact that torrefied material was already torrefied in an external reactor. With this, the weight loss in the initial decomposition step is not visible for the torrefied materials.

The results show that the highest density for torrefied materials can be obtained by pelletising 20-30°C below the applied torrefaction temperature. If the temperature in the piston gets closer to the torrefaction temperature, the material starts to decompose and the temperature can increase further by exothermal reactions, giving hot spots and further decomposition in the pellet (Figure 5.6). The formation of hot spots seems dependent on the pellet diameter. With small diameter pellets (6 mm) it seems that extra heat can be transported via the wall of the piston, while with bigger diameter pellets (> 10 mm) this occurs to a lesser extent, which results in hot spots within the pellet itself.

Figure 5.6 *Hot spot on the inside of the pellet after high temperature pelletisation*

Pellet strength

The strength of a pellet is determined by means of a compressive test. A pellet is placed between compressive plates parallel to the surface. The specimen is then compressed at a uniform rate. The maximum load is recorded along with stress-strain data. In this case the results are normalized with a ”standard pellet” produced from willow at 100°C piston temperature. A value of 1.7 indicates that the pellet under investigation is 1.7 times as strong as the ”standard pellet”.

Table 5.2 shows the results of the strength of torrefied willow pellets.

Table 5.2 *Normalised strength of torrefied willow pellets (TW 260-24 = Willow, torrefied at 260°C for 24 minutes, X = Not tested)*

Piston temperature / Material	200°C	225°C	260°C
Willow	X	X	X
TW 260-24	1.70	2.06	1.16
TW 280-60	X	1.29	2.03
TW 280-120	X	1.01	1.52
TW 290-24	X	1.63	1.99

The results of the 1st experimental series show that torrefaction has a positive effect on the strength of the pellets. In addition, the density of the pellets is larger, which means that the porosity of the pellet has decreased, allowing less moisture and air within the pellet. With the higher density, there is better contact between particles, leading to stronger pellets.

Hygroscopic behaviour

During torrefaction, depolymerisation of the polymers occurs. The hemicellulose is largely destroyed, disabling the biggest moisture absorption capacity. Further, many oxygen groups such as hydroxyl, carbonyl and carboxyl are removed from the cell wall polymers during torrefaction, making room for furan-aromatic, aliphatic structures. With this change in structure, the hydrophilic groups are replaced by hydrophobic groups, so water is rather rejected from than attracted to the pellet.

Torrefied willow pellets were tested on their hygroscopic behaviour. Table 5.3 summarises the results. The values given in the table are percentage increase in moisture content. Values > 50 indicate that the pellet was not sufficiently hydrophobic to measure an accurate moisture accumulation (they fall apart). It should be mentioned that this test of the hygroscopic nature of a pellet is not a standard test. Therefore this method can only be used in a comparative way.

Table 5.3 *Normalised moisture assimilation in % for torrefied willow pellets (TW 260-24 = Willow, torrefied at 260°C for 24 minutes, X = Not tested)*

Piston temperature / Material	200°C	225°C	260°C
Willow	X	X	X.
TW 260-24	>50	>50	30
TW 280-60	X	40	11
TW 280-120	X	32	13
TW 290-24	X	>50	18

The results clearly show that a higher degree of torrefaction (higher temperature and longer torrefaction time) has a positive effect on the hydrophobic behaviour, as the higher degree torrefied willow pellets show a smaller amount of water assimilation. Striking is the difference in hygroscopic behaviour when pelletisation is done at different temperatures. This difference can either be explained by the lower density of the pellets at lower piston temperatures which creates open space were moisture can enter, or by the influence of fatty's and lignin at elevated temperatures.

5.3.2 Bench-scale pellet mill tests

Results in this paragraph represent a summary of the experimental work carried out in the bench-scale pellet mill at CPM. Experiments were carried out with various types of torrefied biomass, torrefied under different conditions, as shown in Table 5.4.

Table 5.4 *Materials used in the bench-scale continuous pellet mill tests*

Test number	*Material*	*Torrefaction conditions (Temperature, reaction time)*	*Dp_{50}*
1	Various	Orientation	
2	Various	Orientation	
3	Various	Orientation	
4	Willow	230,60	N.A.
5	Willow	250,60	N.A.
6	Willow	260,24	N.A.
7	Willow	260,60	N.A.
8	Willow	270,60	N.A.
9	Willow	280,60	N.A.
10	Willow	290,24	N.A.
11	Willow	290,60	N.A.
12	Willow	280,120	N.A.
13	Cutting wood	270,22	0.70
14	Cutting wood	270,31	1.00
15	Cutting wood	280,20	0.65
16	Cutting wood	290,12	N.A.
17	Demolition wood	280,11	0.70
18	Demolition wood	300,11	0.65
19	Straw	240,30	N.A.
20	Grass seed hay	240,30	N.A.

Twenty experiments were carried out at CPM, with varying materials and pelletizing parameters. The first 3 tests were short exploratory experiments with various materials. Within these tests, several settings like die length, die thickness and moisture content were varied. An important criterion to judge the quality of pelletisation was dust production. During a number of tests with grinded particles with a cut-off diameter <1mm, apart from of pellets, dust was produced in the pelletiser. The die emptied before a proper pellet was formed. Using longer dies and more moisture did solve the problem. The pellets produced during the initial experiments showed a large variation in quality, but sometimes good quality pellets were produced.

In the tests 4-8, the cut-off of the grinded material was <4mm. This avoided dust formation. The die filled itself properly with biomass. It was noticed that for proper lubrication of the die, 15 wt% extra moisture had to be added to the raw material (with less moisture addition, the material got stuck in the die). The pellets looked good and showed a shining black skin. The original moisture content of the material was 3 wt%. With 15 wt% extra moisture, the moisture content of the ingoing material is approximately 18 wt%. After pelletisation and cooling, the moisture content of the pellet was 9 wt%. The rest of the moisture evaporated during pelletisation and cooling.

For the tests 9-11, the cut-off of the material was < 4 mm. The purpose of these tests was to investigate the possibilities of reducing the extra moisture addition, whilst maintaining quality. An important variable influencing the required extra moisture addition is de dimensions of the die. During these tests a shorter die was used, giving better results than in the first 3 tests. By applying the shorter die it appeared possible to reduce the addition of extra moisture in the raw material to 10 wt%, the moisture content of the pellets produced was around 7 wt%.

Tests 12-20, finally, were mainly carried out to investigate the hygroscopic behaviour of the heavier torrefied materials. For the heavier torrefied materials 15 wt% extra moisture was added. It was observed that heavier torrefied product produced poor quality pellets (brittle and short).

Density
The particle density of the produced pellets was between 1200 and 1300 kg/m^3. The highest densities were obtained by pelletizing relatively lightly torrefied material with an extra moisture addition of 10 wt%. The lowest densities were obtained with pelletizing heavy torrefied wood, which in most cases needed 15 wt% extra moisture addition.

Abrasion resistance
To investigate the abrasion resistance of the pellets, tumbling tests were performed. The results of the standard tumbler test show that the percentage of fines was for all the pellets between 3-6 wt%.

Moisture content
In all cases moisture was added to the raw torrefied materials to reduce friction in the die and to improve the throughput. At the end of the experiments the equilibrium moisture content of the pellets was determined by applying the ASTM D3201-94 (2003) standard "Standard test method for hygroscopic properties of fire-Retardant wood and wood-based products."

In general terms, there is a difference between the torrefied and non torrefied wood. The hydrophobic nature of torrefied wood is significantly better than that of non torrefied wood. At *full saturation* the torrefied wood has a moisture content of ~9 wt% vs. 15 wt% for non torrefied wood. This difference in moisture content can be explained by the fact that within the torrefaction process the hydrophilic oxygen groups are replaced for the hydrophobic groups. At ambient conditions, the average moisture content of the torrefied pellets is around 7 wt%, compared to an equilibrium moisture content of 3 wt% of the torrefied starting material. This difference of moisture content at ambient conditions (partly saturated) can be explained by the fact that moisture is added within the pelletizing process to reduce friction in the die. The heavier torrefied materials cause more friction (naturally possess less lubricant), making it necessary for such materials to add extra moisture so the friction in the die is acceptable.

Looking to the total saturation, it is observed that heavier torrefied materials absorb less moisture than lighter torrefied materials. It is also observed that the percentage of increase of the moisture content is lower for the heavier torrefied materials compared to lightly torrefied materials. With this it can be argued that heavier torrefied materials show a more hydrophobic behaviour than lightly torrefied materials.

5.3.3 Semi-industrial pellet mill tests

For the large-scale tests, the semi-industrial pellet mill of CPM was transferred to ECN, together with a roller mill, in which the torrefied material was reduced in size. As this was the first test series on a semi-industrial mill, this test series was envisaged to be of a trial and error nature.

There are a limited number of parameters to vary:
Before the test run:

- diameter of the holes in the die
- length of the holes in the die
- distance between the rollers and the die
- input power/rotation speed

During operation:

- feeding speed of material to the pellet mill
- amount of water added in the mixing chamber

Parameters of the material to be pelletised:

- particle size
- moisture content
- binder, either mixed beforehand or in the mixing chamber

By using different die-hole diameters, different materials and different input power/rotation speeds, it was expected that insight could be obtained in the possibilities of pelletizing torrefied materials. Some findings:

Feed rate
During pelletisation, the only parameter which is good to control is the feed rate. The feed rate is determined by the speed of the screw feeder above the pellet mill. Too high feed rates overload the machine and lead to blockages in the mixer, the chute or in the grinding zone. Applying too low feed rates can lead to too high temperatures in the grinding zone.

Resistance
The die determines the resistance during the extrusion of the particles in the holes. This is a combination of diameter and length of the holes. On the one hand the resistance must not be too high to prevent blockages, on the other hand sufficient pressure must be generated in order to compress the material to generate binding. Therefore the design of the die is crucial for the production of good quality pellets.

Temperature and heat
The temperature in the pelletizing zone increases automatically. All the electric energy supplied to the pellet press is transferred to heat. The heat is used to make the material softer and to activate the binding components in the material. The heat is dissipated via the product and by evaporation of water. Due to this water evaporation the temperature cannot rise much higher than 100°C. If the temperature increases too much, decomposition reactions will start.

Blockages
Blockages are always caused by a too high resistance in the die. In that case the throughput through the die is lower than the feed rate and the feed material is overloading the grinding zone.

After a whole series of trial and error tests it can be concluded that pelletizing is a delicate balance between material quality, particle size, water and binder admission, die thickness and hole size. If the recipe is wrong, either blocking or emptying of the die will occur, resulting in either extremely high power consumption of the pellet press (and sometimes very good quality pellets), or large quantities of dust and hardly any pellet production. Finding the proper settings to produce good quality pellets is not a straightforward thing, but is based on practical experience. Some rules can be specified, but pelletizing is more an art than a science. At the end of the trials a good combination of die thickness and hole diameter was found and larger quantities of good quality pellets were produced as shown in Figure 4.2.

6. Economic evaluation and CO_2-emissions

A comparison between wood pellet and torrefied wood pellet production in case of a retrofit

6.1 Introduction

Torrefaction is a technology which may be applied in the wood pellet industry. Wood pellets are currently being used as a carbon emission reducing fuel to replace coal in power plants. They consist of grinded, dried and compressed wood. The major cost component of wood pellets, besides the wood costs itself, is logistics. These costs can be reduced by applying torrefaction technology in the process: it increases the density (in terms of volume and energy) and the product becomes water resistant, where wood pellets must at all times be kept dry. This, in the end, can result in a lower cost per unit of energy delivered to the customer.

In the original TorTech programme, it was planned that, with the knowledge gained in the other work packages, GF Energy and ECN would evaluate the economic potential of torrefaction, on the basis of the ECN torrefaction technology, for three concrete cases: a Trockenstabilat case, a demolition wood case and an import case. The evaluation would include an estimate of the investment- and operational costs, leading to production costs and an estimate of the return on investment. However, during the course of the project it became clear that due to developments outside ECN it became less important to execute this programme. A demo project for the torrefaction of Trockenstabilat was under construction, making the economic evaluations out-dated. Therefore NL Agency gave permission to change the content of the evaluation and to limit the study to the import case in the course of which:

- much attention would be given to the (costs of) the whole logistic chain and
- the economic evaluation would be extended with a CO_2 balance over the whole logistic chain in relation to a comparable chain based on conventional wood pellets. This because the net CO_2 reduction is an important durability criterion and this criterion was not yet determined for the torrefaction route.

In the course of this study, a detailed model has been developed for calculating the full-supply chain costs of the two fuels. As a case study, a comparison has been made between these wood pellets and torrefied wood (TW) pellets in terms of economics and CO_2-emissions during the production chain until delivery at the power plant gate. Claimed cost advantages at the site of the end user, like cheaper handling and storage, have not been taken into consideration as they are very site-specific. The assumption is that the products have the same sales price expressed in EUR/GJ product as the power plant gate. Thus, this study presents *conservative results* for production of TW pellets. In this report, specific cost information is omitted due to the confidential nature of this data.

6.2 Process description and assumptions

In this study, the performance of a wood pellet plant is compared with the same pellet plant equipped with an additional torrefaction facility. Wood chips (45 $wt\%_{wet}$) are used as a feedstock for both fuels. Most pellet plants are currently operating on wood residues like sawdust and shavings. However, the availability of sawdust in the future is expected not to be sufficient for the global wood pellet demand. To make a direct comparison of the two technologies possible, wood chips have been used as feedstock in all cases.

Furthermore, a production capacity of 100,000 tonne wood pellets per year is assumed, a typical size for a pellet mill, with an availability of 6,000 hrs/yr (= 65%). The torrefaction unit is considered as an add-on to this plant.

Figure 6.1 shows the process elements of a typical TW pellet plant where the torrefaction unit operations are incorporated in the pellet process chain.

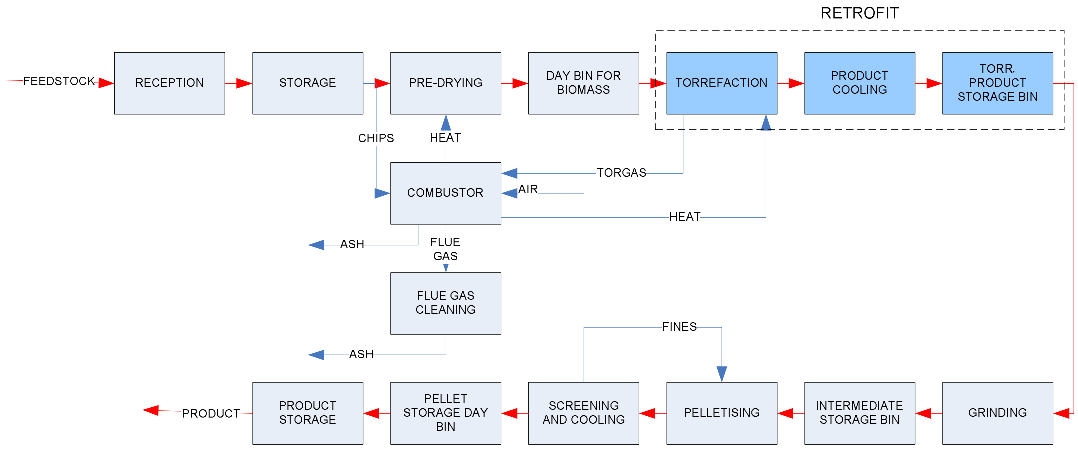


Figure 6.1 *Typical value chain of a torrefied wood pellet plant*

As a feedstock, softwood chips are assumed, delivered to the plant in a shape and size suitable to feed into the dryer and torrefaction unit. The feedstock is debarked and chipped before further processing. The moisture content of the chips entering the dryer is 45 wt%$_{wet}$. For the wood case, the wood chips have to be dried to a moisture content of 10 wt%$_{wet}$ before the grinding step before entering the pellet mill. For the torrefaction case, the chips are dried to 20 wt%$_{wet}$ moisture content before the torrefaction reactor. The heat needed for drying is supplied by combusting wet wood chips for wood pellets and for torrefaction by wood chips and torgas (this is the combustible gas produced during torrefaction), although application of secondary auxiliary fuels (natural gas, diesel) also would be possible. The assumption is that 16 wt%$_{dry}$ of the material is converted into torgas. For the production of TW pellets, the amount of chips needed for drying is much lower than for the wood pellet case, as a large part of the required heat (around 65%) is supplied by combustion of the produced torgas. The properties of the products are summarized in Table 6.1.

Table 6.1 *Product properties of wood pellets and TW pellets*

Property	**Unit**	**Wood pellets**	**TW pellets**
Bulk density	kg/m$^3_{wet}$	650	750
Lower heating value	MJ$_{LHV}$/kg$_{wet}$	17.3	19.3
Energy density	MJ$_{LHV}$/m^3	11.3	14.25
Moisture content	wt%$_{wet}$	10	3

Two cases are defined for the torrefaction process:
1. the pellet mills are limiting in throughput (in tonne dry product per yr) or
2. the evaporative capacity (in tonne moisture per year) of the dryer is limiting.

The cost data for torrefaction are based on available study estimates for the ECN torrefaction technology (accuracy ± 40%). A depreciation and project time of ten years is assumed.

Table 6.2 *Comparison of key characteristics of wood and TW pellet processes*

	Unit	Wood pellets	TW pellets Pellet mill limiting	TW pellets Dryer limiting
Wood chips input				
For drying	ktonne$_{wet}$/a	27	9.0	9.5
For pellet production	ktonne$_{wet}$/a	164	194	203
For pellet production	1,000 m^3/a	656	776	812
Total input	ktonne$_{wet}$/a	191	203	213
Dryer				
Moisture content chips in	wt%$_{wet}$	45	45	45
Moisture content chips out	wt%$_{wet}$	10	20	20
Amount of water evaporated	ktonne/a	64	61	64
Availability	hours/a	6,000	6,000	6,000
Product capacity				
Mass flow	ktonne$_{wet}$/a	100	93	97
Energy flow (output)	GJ$_{LHV}$/a	1,730,000	1,800,000	1,900,000
Thermal Capacity	MW$_{th,LHV}$	80	83	87
Investment (study estimate)	million Euro	12.0	17.1	17.2
Investment per thermal capacity	Euro/MW$_{th,LHV}$	150,000	206,000	198,000

6.3 Economic evaluation

6.3.1 Introduction

To compare the economics of wood pellet production vs. TW pellet production, three cases have been considered to evaluate the benefits of a torrefaction unit, retrofitted into an existing wood pellet plant. The costs and carbon emissions are considered from raw material purchasing (wood chips) until delivery by river barge to the customer (assumed to be a power plant) DDU (Delivered Duty Unpaid), Incoterms. The plants for all cases are assumed identical.

6.3.2 Case description and assumptions

Key assumptions:

- An equal Euro/GJ market value for wood and TW pellets, which is a conservative estimate. In reality, for TW pellets a premium is expected due to their superior quality.
- The ship capacity, taking into account the actual bulk densities of the products, is limited by volume not weight for both products.
- Logistic handling has the same price per tonne.
- Ship prices are based on time charter.
- The cost of capital, cost of working capital and tax not incorporated.
- The loss of income due to shut-down for retrofit not incorporated.
- The study is performed from the point of view of a pellet mill owner who has to make a decision whether or not to invest in a retrofit with a torrefaction unit.

The three cases studied are:

A. Intercontinental
B. Intra-Europe

C. Regional
The three cases are further described below.

Ad A. Intercontinental
The intercontinental case assumes a plant (as described in Section 6.2) in Southern Africa, 250 km from the ocean port, where pellets are transported from the plant to the storage in the loading port by rail, with a capacity of 1,200 tonne per train. It assumes Handysize vessels carrying 19,000 tonne of wood pellets, the *MV WHITE MIST* is used as reference. The distance to the port of discharge is 7,245 nautical miles and an additional "ballast" distance of 750 nautical miles is included. This is the distance the ship needs to travel to get to the load port, which is charged to the charterer. At the port of discharge, half the cargo is directly trans-shipped into river barges, and then delivered to the customer's site. The distance from the port of discharge to the customer's site is 100 km. The average storage time for the remaining 50% of product is 60 days; it is eventually also delivered by river barge to the customer.

Ad B. Intra-Europe
In this case, the pellet plant is assumed to be located within one of the Baltic states, 100 km from the loading port, where the pellets are transported to the port by truck. Pellets are then shipped by coaster vessel containing 2,500 tonne of pellets, transported over a distance of 1,800 nautical miles; no ballast distance (prior to voyage) included. All cargo is assumed to be directly trans-shipped into river barges at the port of discharge (board-board trans-shipment) and again transported by river barge over a distance of 100 km.

Ad C. Regional
The third case describes a pellet plant in Germany, supplying the pellets to a Dutch customer. The distance from pellet plant to river port is 50 km, transported by trucks, where the pellets are loaded into 1,000 tonne river barges with direct delivery to the customer, total distance by barge is 500 km.

Table 6.3 gives an overview of key parameters and assumptions for each case.

Table 6.3 *Key case parameters*

Parameter	**A: Intercontinental**	**B: Intra-Europe**	**C: Regional**
Distance to load port	250 km	100 km	50 km
Type of transport to deliver to load port	Train (1,200 tonne)	Truck	Truck
Cargo size per shipment (wood pellets)	19,000 tonne	2,500 tonne	n/a
Cargo size per shipment (TW-pellets)	21,923 tonne	2,885 tonne	n/a
Distance to discharge port	7,245 nautical miles + 750 nautical miles ballast	1,800 nautical miles	n/a
60 days storage @ discharge port	9,500 tonne	n/a	n/a
Cargo size river barge shipment	2,000 tonne	2,000 tonne	1,000 tonne
Distance to customer by barge	100 km	100 km	500 km

All cost parameters are based on actual market data and on real cost prices provided by freight forward companies, shipbrokers and actual prices as encountered by GF Energy in the past.

6.3.3 Cost scenarios

Besides the three cases described in the previous paragraph, three scenarios have been considered to evaluate the effects of key cost components which may fluctuate outside of the control of the producer. This provides for an economic evaluation, in which significant parameters have been varied to obtain an insight in the cost ranges.

Three scenarios have been considered: worst, base and best case. It is important to note that "worst" in this case means worst for TW pellets compared to wood pellets and best means, the best outcome to be expected (i.e. most benefits over wood pellets).

Cost of wood chips has been assumed to be the same for all cases. The key values of these three cost scenarios are depicted in Table 6.4. It should be noted that the feedstock costs for all location scenario's are assumed to be the same. In practice there can be regional price differences, e.g. that wood chips can be more expensive in Europe than in South-Africa.

Table 6.4 *Key cost component values*

Cost component	**Unit**	**Worst**	**Base case**	**Best Case**
Wood chips (@45 wt% MC)	Euro/ton_{wet} 1)	20	15	10
Ship time charter				
Oceanic	US$/day 2)	9,000	15,000	25,000
Regional (coaster)	US$/day 2)	2,000	2,500	3,200
Bunkers IFO 180	US$/tonne 2) 3)	200	300	500
Bunkers MGO	US$/tonne 2) 3)	400	600	1,000
Sales price	EUR/tonne 4)	140	150	160

1) Delivered to pellet plant

2) Used exchange rate: 1.25 US$ = 1 Euro

3) It is assumed that the price of bunker MGO is twice the price of IFO 180

4) This depicts the sales price for wood pellets, the sales price for TW pellets is determined by assuming the same price per GJ delivered, which translates into comparable pro rata per tonne prices for TW pellets

6.3.4 Results and discussion

The largest cost savings for TW pellets are in logistics: higher energy density and water resistance lead to lower logistic costs. Because the density is higher, one can actually fit more product in the same cargo space. Although at certain densities, the actual mass becomes more important than the volume, bulk densities of the products considered are still causing the volumetric advantage. As vessels are commonly chartered on a per day basis, if one can fit more product into the same ship, the transport cost per GJ is reduced. Handling cost in bulk logistics are a key component of the overall supply chain. One of the disadvantages of wood pellets is that they must be kept dry at all times. Therefore loading, storage and transportation must all be covered (or in the case of loading, must be stopped when it rains).

However, feedstock costs are higher than those of wood pellets as the process requires more feedstock per GJ of produced pellets than wood pellets. This additional feedstock is needed to fuel a part of the torrefaction process. In the production process, the higher feedstock costs are partially offset by a lower power consumption in the grinding step and possibly also in the pelletizing step. Also the operating and maintenance costs of these steps may be lower in the BO_2 pellets case. However, because of the still existing uncertainties, these effects have not been taken into account. Again, this is a conservative approach. In this sense, this study is different than previous studies, where these advantages have been taken into consideration. Combining the above, the higher the logistic costs along the supply chain and the cheaper the feedstock, the more favourable TW pellets become. So in effect, torrefaction is suitable and more attractive for plants that are located far away from its customers and have relatively cheap feedstock costs.

Still, the margin between TW pellets vs. wood pellets for the pellet producer must be sufficient to justify the additional investment in the torrefaction unit. In this study, an additional investment for the torrefaction unit of 5.1 million EUR and 5.2 million EUR is assumed (for the pellet mill limiting case and the dryer limiting case respectively).

The cost saving per cost element along the supply chain in the three cases A (Southern Africa), B (Baltic States) and C (Regional) are shown in Figure 6.2 (total) and Figure 6.3 (specified per cost element) respectively (base case only). The figures show the cost savings per GJ, in other words: the cost savings per unit of energy delivered. This is a more relevant number than cost savings per tonne (which is commonly used in the business) as in the end the customer is buying energy, not tonnes.

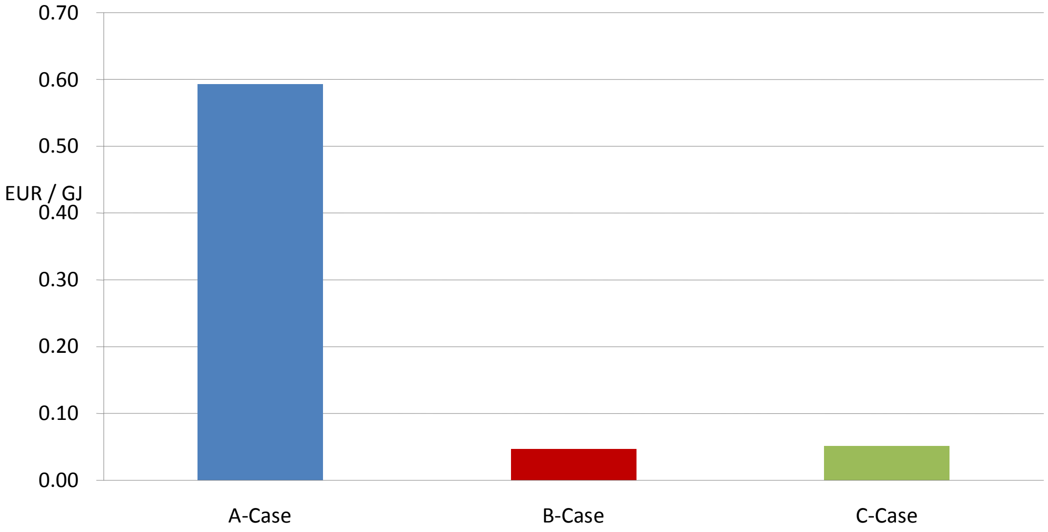


Figure 6.2 *Overall net cost savings per GJ of TW pellets over wood pellets Case A (Southern Africa), B (Baltic States) and C (Regional)*

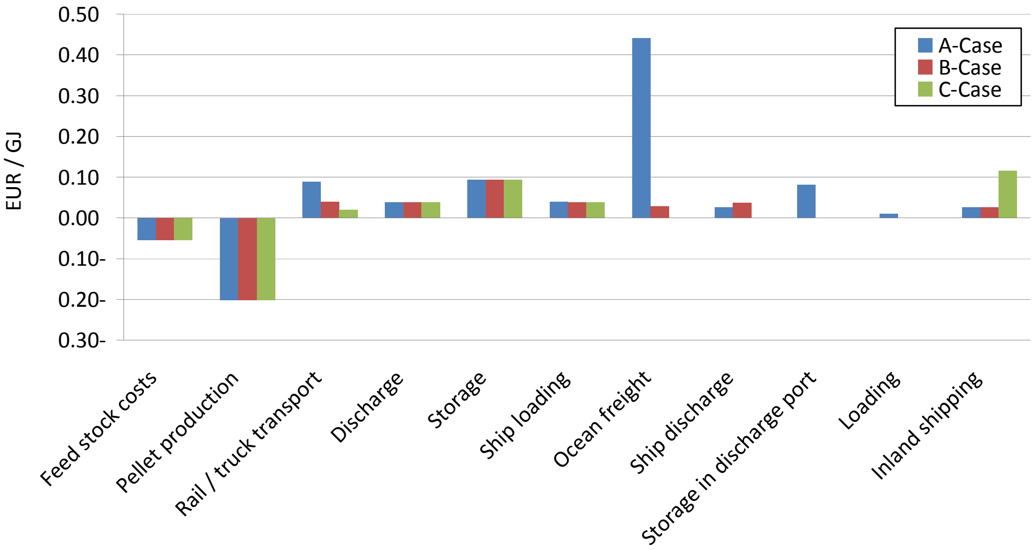


Figure 6.3 *Detailed net cost savings along the value chain*

The Project Internal Rate of Return (Project IRR) has been used as the relevant parameter determining the viability of an investment hence economic evaluation. The Project IRR is defined as the rate of interest that equates the initial investment (excluding working capital) with the present value of future free cash flows. Free cash flow in this case is EBITDA (Earnings Before Interest Tax Depreciation and Amortization). Cash flows are taken over 10 years of operation, with one year of construction time, i.e. a total lifetime of 11 years and no salvage value. As mentioned before, the sales price for TW pellets and wood pellets is assumed to be the same per unit of energy, which is a conservative estimate. See also Table 6.4.

This economic evaluation has been developed for existing wood pellet plant owners to decide whether they should invest in a torrefaction unit or not. Many factors in such a decision play a role, but a key element is the return on investment. That valuation is shown in this study. When calculating the Project IRR's of the three cases, this study found that the Project IRR's of the B and the C case for TW pellets were actually lower than that of wood pellets. In other words, the cost savings were not large enough to sustain the additional investment required, under the conservative assumptions in this study. In effect, only the A case (Southern Africa) indicated substantial cost savings that could validate an additional investment in a torrefaction unit. The economic evaluation is, therefore, only shown for the A case.

The Project IRR's are shown in three scenarios: worst, base and best case as defined in Table 6.4. The results are specific for this case. In order to assess the viability of other business cases, specific calculations must be performed. For each scenario, three situations are compared. Each case and each scenario is shown for the base case investment of the torrefaction unit itself and for investments of 20% less and 20% more. Investment of the wood pellet plant itself is not changed, only the torrefaction unit investment. The project internal rate of returns are shown below in Figure 6.4.

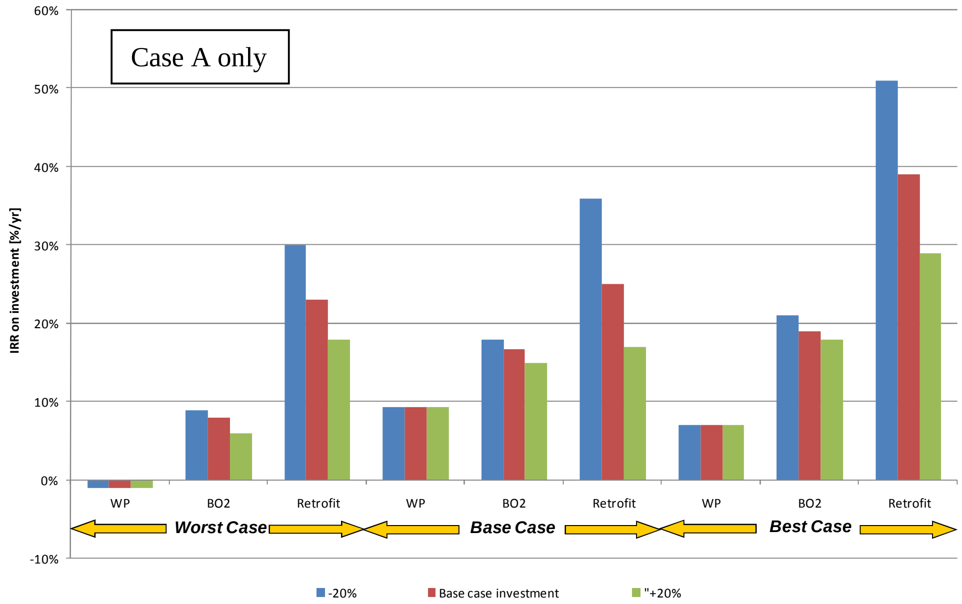


Figure 6.4 *Comparison of case A Project IRR's*

Some remarks regarding Figure 6.4 above:

- The label 'WP' in the above figure stands for wood pellets. This is a stand-alone wood pellet factory, however without optimization of the overall process towards torrefaction
- The label 'BO2' in the above figure is a green field TW pellet plant, based on wood pellet production optimization, not torrefied wood pellet production.
- The label 'Retrofit' is an existing wood pellet factory, which has later invested in a torrefaction unit and hence makes TW pellets instead of wood pellets. The IRR indicated for this specific category above, represents the return on the *additional* investment of the torrefaction unit only. It does not represent the overall return of the complete retrofitted factory.
- All three elements described above are shown in three cost scenarios: worst case, base case and best case. These scenarios are described earlier. The scenarios are shown in the figure in

three groups indicated by the yellow arrows. Left is worst case, middle is base case and right is best case.

- As the torrefaction unit is still under development (investment cost may still vary substantially) three additional scenario are shown: the base case of 5.1 million EUR investment for a torrefaction unit; worst case when investment is actually 20% higher; best case when the investment is 20% lower. These effects are shown in the figure by means of colour-coding. The red bars show the base case, the blue bars show the 20% lower investment cost returns and the green bars show the returns for a 20% more expensive torrefaction unit.

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.

Table 6.5 shows the difference in cost price per GJ for the A-case (Southern Africa supplying to Europe) of TW pellets versus wood pellets. Positive numbers (shown in red) indicate higher costs, negative numbers (shown in green) show cost reductions of TW pellets compared to wood pellets. This table illustrates the importance of having low cost feedstock (to limit the effect of needing more raw materials per GJ of product than wood pellets) and to travel long distances to take full advantages of lower logistic costs of TW pellets . The worst, best and base case again refer to the cases described in Table 6.4.

Table 6.5 *Cost differences of TW pellets vs. wood pellets (in EURct/GJ)*

In EUROct/GJ	**Worst Case**		**Base Case**		**Best Case**	
	dryer lim	**pellet lim**	**dryer lim**	**pellet lim**	**dryer lim**	**pellet lim**
Feed stock costs	**7**	**7**	**5**	**5**	**4**	**4**
Pellet production	**20**	**17**	**20**	**17**	**20**	**17**
Rail transport	**9-**	**9-**	**9-**	**9-**	**9-**	**9-**
Discharge	**4-**	**4-**	**4-**	**4-**	**4-**	**4-**
Storage	**9-**	**9-**	**9-**	**9-**	**9-**	**9-**
Ship loading	**4-**	**4-**	**4-**	**4-**	**4-**	**4-**
Ocean freight	**29-**	**29-**	**44-**	**44-**	**71-**	**71-**
Ship discharge	**3-**	**3-**	**3-**	**3-**	**3-**	**3-**
Storage in discharge port	**8-**	**8-**	**8-**	**8-**	**8-**	**8-**
Loading	**1-**	**1-**	**1-**	**1-**	**1-**	**1-**
Inland shipping	**3-**	**3-**	**3-**	**3-**	**3-**	**3-**
Total	**42-**	**46-**	**59-**	**63-**	**88-**	**92-**

6.4 CO_2-balance

6.4.1 Introduction

To determine the overall CO_2-emissions and to identify if there is a significant difference in CO_2-balance between the production of wood pellets versus TW pellets, the CO_2-emissions from both production chains have been estimated. The 'CO_2 Tool', as developed for NL Agency [17], has been used as a starting point for this assessment. The 'CO_2 Tool' assumes for the production of wood pellets sawdust as feedstock. This sawdust is considered as a waste material from wood processing, and thus CO_2-emissions before pellet production are allocated to the wood product, not to the sawdust and the fuel pellets produced there from. The associated CO_2-

emissions are thus zero. Furthermore, the assumption in the 'CO_2 tool' is that no return trips of transportation means are taken into consideration, in contrast to this study. The found CO_2-emissions in the 'CO_2 Tool' are therefore relatively low, and range from 0.008 to 0.020 kg CO_2-eq per MJ_e for wood pellets. In contrast to the "CO_2 Tool", within this TorTech study, the CO_2 emissions before pellet production (tree cultivation, harvesting and chipping) and partially empty return trips are incorporated.

6.4.2 Assumptions

For calculation of the total CO_2-emissions during the production chain, the following assumptions are made:

- For CO_2-emissions associated with the production of wood logs, a rotation age of 30 years has been assumed. The available data are based on large-scale forestry in the North West of the United States, and includes the whole production chain, including seedlings, fertilizer and harvesting [18]. It is assumed that all emitted CO_2-emissions are allocated to the pellets. The value in the reference corresponds to 30 kg CO_2-eq per tonne wet wood (assuming wood with a 710 kg/m^3 bulk density with $45wt\%_{wet}$ moisture).
- For the drying process of the feedstock, flue gas generated by the combustion of biomass (wet wood chips and torgas) is used. No additional fossil fuel use is assumed.
- Power required for the fuel production is supplied from the public grid and assumed to be the national electricity mix of the relevant countries where pellet production is taking place (South Africa, the average from Baltic States, Germany) and is ranging from 0.40 kg/kWh_e to 0.87 kg/kWh_e [19].
- Fuels used for transportation are assumed to be from a fossil origin. For emissions associated with transportation general data has been used, originating from life cycle analysis (LCA) databases [20], and the same as used as a reference in the NL Agency 'CO_2 tool'.
- For the wood log transport (assumed to be 50 km single trip distance) empty return trips are assumed. For sea transport 10% empty return trips are taken into consideration. For other transport means 50% empty returns trips are assumed.
- The used distance cases (intercontinental, intra-Europe and regional) are the same as used in the economic evaluation in the previous section.
- The emissions associated with storage and trans-shipment are considered very low compared to the overall emissions and neglected.
- Power consumption data with respect to the pellet production is supplied by GF Energy and is based on 60 wt% softwood and 40 wt% hardwood. It has been assumed that the overall power consumption of the torrefaction process is around 10% lower than for wood pellets, due to better grinding behaviour of the torrefied material.
- Firing coal in coal-fired power plants in the Netherlands is chosen as a reference case. The produced renewable fuels are substituting this coal. The CO_2-emission factor for electricity at the consumer from coal is 0.76 kg CO_2/kWh_e (or 0.33 kg/MJ_e). It has been assumed that energy losses from power station to end user are 4% [17].

Table 6.6 displays the applied specific CO_2-emissions in this study.

Table 6.6 *Specific CO_2-emissions used in this study*

Process step	Value	Unit	Reference
Wood logs, at road side	2.2	tonne CO_2-eq/100 m^3 wood	[18]
Pellet production			
Wood pellets	180	$kWh_e/tonne_{wet}$ product	Estimate
Torrefaction pellets	175	$kWh_e/tonne_{wet}$ product	Estimate
Transport			
Road (32 tonne lorry)	0.164	kg CO_2-eq./tonne km	[20]
Freight train	0.013	kg CO_2-eq./tonne km	[20]
Barge (inland)	0.046	kg CO_2-eq./tonne km	[20]
Seagoing vessel (oceanic)	0.011	kg CO_2-eq./tonne km	[20]
Power			
South Africa	0.87	kg CO_2/kWh_e	[19]
Baltic states	0.34	kg CO_2/kWh_e	[19]
Germany	0.40	kg CO_2/kWh_e	[19]
Netherlands (coal)	0.79	kg CO_2/kWh_e	[19]
Netherlands (energy mix)	0.39	kg CO_2/kWh_e	[19]

6.4.3 Results and discussion

Table 6.7 displays the results of the calculations for the different cases.

Table 6.7 *Results CO_2-emission calculations in g CO_2-eq/MJ electric power at consumer*

Process step/Case	Inter continental	Inter continental	Inter continental	Inter continental	Intra-Europe	Intra-Europe	Regional	Regional
Product	Wood pellets	TW pellets	Wood pellets	TW pellets	Woodpellets	TW pellets	Wood pellets	TW pellets
Country	South Africa	South Africa	South Africa	South Africa	Baltic States	Baltic States	Germany	Germany
Transport to harbour	train	train	truck	truck	truck	truck	truck	truck
Production wood logs	0.0084	0.0087	0.0084	0.0087	0.0084	0.0087	0.0084	0.0087
Transport wood logs	0.0022	0.0023	0.0022	0.0023	0.0022	0.0023	0.0022	0.0023
Transport wood logs, return trip	0.0022	0.0023	0.0022	0.0023	0.0022	0.0023	0.0022	0.0023
Pellet production	0.0228	0.0214	0.0228	0.0214	0.0089	0.0084	0.0105	0.0099
Truck transport pellets to harbour	-	-	0.0059	0.0053	0.0023	0.0021	0.0012	0.0011
Truck transport pellets to harbour, return trip	-	-	0.0029	0.0026	0.0012	0.0011	0.0006	0.0005
Rail transport to harbour	0.0005	0.0004	-	-	-	-	-	-
Rail transport to harbour, return trip	0.0002	0.0002	-	-	-	-	-	-
Sea transport (oceanic)	0.0203	0.0182	0.0203	0.0182	-	-	-	-
Sea transport (oceanic), return trip	0.0021	0.0019	0.0021	0.0019	-	-	-	-
Sea transport (regional)	-	-	-	-	0.0051	0.0045	-	-
Sea transport (regional), return trip	-	-	-	-	0.0005	0.0005	-	-
Barge transport (inland)	0.0007	0.0006	0.0007	0.0006	0.0007	0.0006	0.0033	0.0029
Barge transport (inland), return trip	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0003	0.0003
Total	**0.060**	**0.056**	**0.068**	**0.063**	**0.032**	**0.031**	**0.029**	**0.028**
Savings [%]	**82%**	**83%**	**80%**	**81%**	**90%**	**91%**	**91%**	**92%**

The overall CO_2-savings compared to power originating for coal fired power stations range from around 80% for the large distance cases to 90% for the shorter distances for both cases. This is significantly lower compared to the wood pellets case used in the NL Agency ‘CO_2 Tool’, and is caused by the difference in the selected feedstock: wood chips instead of saw dust and their associated emissions. The difference between wood pellets and TW pellets are minor. The results are depicted graphically in Figure 6.5 and Figure 6.6.

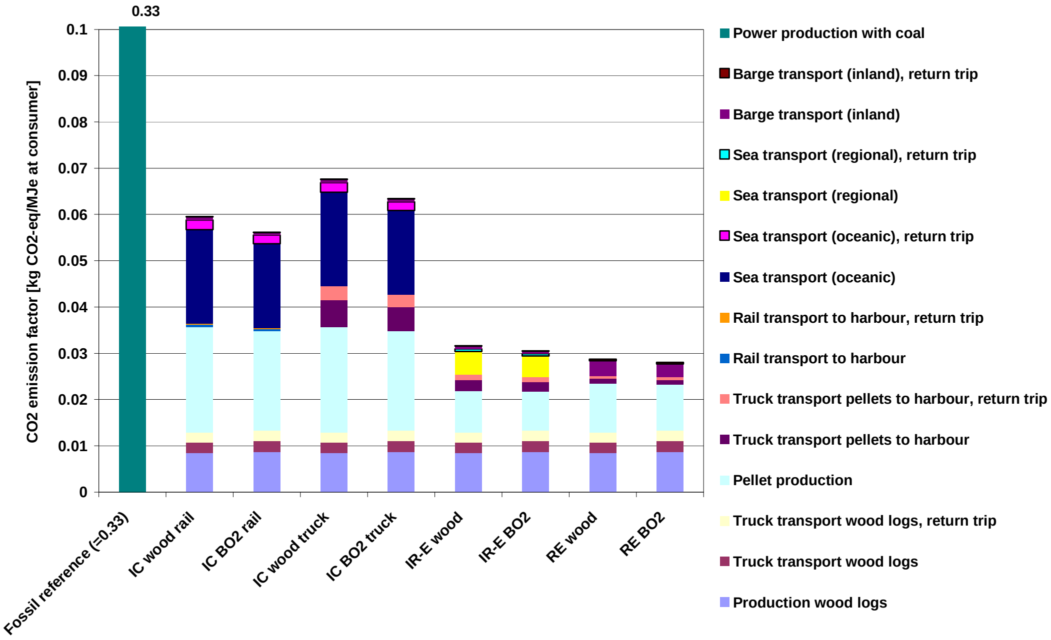


Figure 6.5 *Results CO_2-emission calculations in kg CO_2-eq/MJ electric power at consumer (IC = intercontinental, IR-E = intra-Europe, RE = regional, wood = wood pellets, BO2 = TW pellets, rail/truck = transport to harbour for intercontinental cases)*

For the long distance (intercontinental) case, the pellet production and sea transport are the largest contributors to the overall CO_2 emissions. The CO_2 contribution of the pellet production is also relatively high compared to the other cases, as the power production sector in South Africa heavily depends on coal with a high specific CO_2-emission. For the shorter distances (the Baltic states, Germany), the overall chain emissions are comparable, caused by lower emissions during pellet production by local lower specific emission during power production, and lower emissions during transport, finding its origin in lower transport distances. Further reductions in CO_2 emissions are be achieved when green (or nuclear) power is used for pellet production or biomass waste as a feedstock.

Figure 6.6 depicts the savings for each case compared the fossil reference, firing coal in a pulverized coal power plant. It indicates that all the cases have a significant reduction in CO_2-emission, ranging from 80-90% compared to the fossil reference coal.

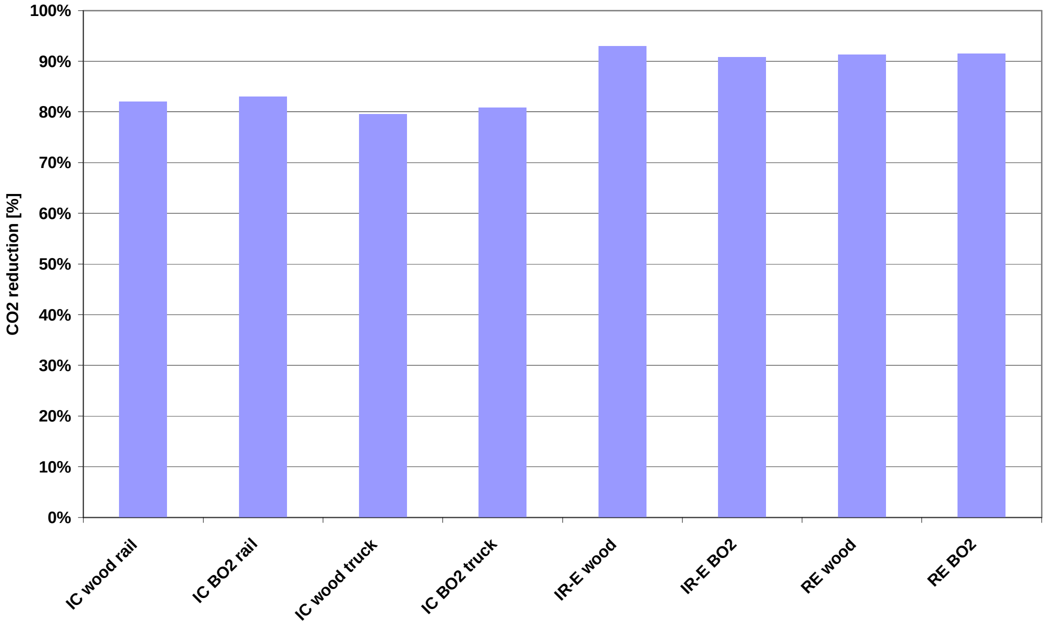


Figure 6.6 *CO_2-savings compared to fossil reference coal*
(IC = intercontinental, IR-E = intra-Europe, RE = regional, wood = wood pellets, BO2 = TW pellets, rail/truck = transport to harbour for intercontinental cases)

7. Contribution to the goals of the EOS-LT programme

The TorTech project has been directly focused on two main goals of the Dutch Long-Term Energy Research Strategy programme (EOS-LT) - research topic “Electricity and Heat from Biomass”, i.e. to raise the percentage of electricity production from biomass and waste to 40% and to raise the co-firing percentage to 40%. These ambitious targets demand the use of a wide range of biomass residual streams, biomass/waste mixtures and energy crops. However, at the moment many of these streams cannot be co-fired as such, whilst other can only be co-fired in small quantities. By means of torrefaction, developed further in this project, a wide variety of biomasses and waste/mixtures are potentially opened up for co-firing in coal fired power plants. On top of that, for many streams higher percentages of co-firing are possible after torrefaction, due to a better grindability and a higher energy density of the torrefied products. This applies for the present pulverised-coal combustion technologies as well as for advanced clean coal technologies under development, like Ultra Super Critical (USC) boilers, oxy-fuel combustion and entrained-flow gasification. Moreover, the conversion of biomass into commodity solid biofuel through torrefaction and densification provides large advantages in logistics and trading.

Therefore, torrefaction has the potential to become a key technology for the upgrading of a wide variety of biomass streams and waste/mixtures to commodity, high energy-density solid biofuels for multiple use.

7.1 Contribution to a more sustainable energy production

The objective of the EOS-LT research programme is to realise a more sustainable energy production. Biomass co-firing will play an important role in this objective. The state of art with respect to co-firing at the moment is that co-firing biomass or waste streams in coal fired boilers is only possible for a selected number of streams. Via the application of torrefaction a much wider range of biomasses can be co-fired. The results of the TorTech project show that a large variety of biomasses can be torrefied, that the co-firing properties of these biomasses improve significantly and that it is possible to make pellets from torrefied biomass. Due to these improvements, demonstrated in TorTech, the possibilities to use these biomasses for co-firing are improved. Therefore torrefaction is an important technology for the large scale use of biomass co-firing in the future.

It is expected that the total contribution of biomass in the Netherlands in 2040 will be 600 – 1000 PJ/yr. From this, roughly 50% will be imported clean biomass (300 – 500 PJ/yr), for which torrefaction is relevant in the country of origin. This in view of the lower transportation- and storage costs. Roughly 25% of the supply will be covered by lower quality biomasses and waste streams (150 – 250 PJ/yr) for which torrefaction plays a key role as well. The remaining 25% will partly consist of wet biomass fractions; here so-called wet torrefaction (a combination of torrefaction, washing and drying) may play a role. On European scale and globally the expected market for torrefaction is many times larger. The TorTech project contributes to the realization of torrefaction technology and with that to the realization of the above mentioned ambitious expectations.

7.2 Contribution to the reinforcement of the Dutch knowledge position

At the start of the project both ECN and TU/e already had (also internationally) a prominent knowledge position in the field of torrefaction. An extensive lab/bench scale research infrastructure was already built in previous years. Thanks to the TorTech project, this knowledge position and research infra structure at ECN and TU/e has been further extended.

The strengthening of the knowledge position concerns a.o.:

- An even better understanding of the underlying mechanisms of torrefaction.
- Knowledge with respect to the torrefaction behaviour of a wide range of non-woody biomasses and waste/mixed streams and of the relation between torrefaction conditions and product quality.
- Optimised reactor- and process concepts for torrefaction, validated on pilot scale.
- Insight in how to optimise the integration between (pre)drying and torrefaction.
- Insight in how to come to an optimal combination of torrefaction and pelletisation and to proper recipes for the pellet production.

The extension of the lab/bench scale research infrastructure includes new techniques and methods for the characterisation of the torrefaction behaviour and the analysis and evaluation of the gaseous and solid products. This concerns amongst others the determination of the reaction enthalpy, the characterisation of the lignocelluloses composition of the torrefaction products, the analysis of organic components in the torrefaction gas and the characterisation of the hygroscopic behaviour of the materials.

And last but not least, the research infrastructure of ECN has been extended with the 50 – 100 kg/hr PATRIG pilot plant, in which the torrefaction of biomass and residual streams can be tested on a representative scale. PATRIG is very well instrumented, giving reliable data with respect to the relation between torrefaction conditions (temperature, residence time), torrefied product quality and torrefaction gas composition.

7.3 Spinoff inside and outside the sector

Spinoff of the project research findings is realised along three lines:

- *Via the industrial parties involved in the project*
  Different industrial parties in the TorTech project are involved in separate (confidential) development routes with regard to the application of torrefaction. The knowledge and insights generated within the project are, or are going to be, directly applied within these developments by these industrial partners.
- *Via commercial services to market parties*
  ECN is assisting market parties in the development and market introduction of torrefaction for specific applications. On demand of interested parties, ECN produces smaller and larger quantities of torrefied biomass and torrefied biomass pellets for further testing in-house or by the industrial parties with respect to their logistics and end-use behaviour. With respect to the logistics and end-use testing, ECN is equipped with an extensive set of smaller-scale testing and analysis facilities.
- *Within the further development and market implementation of ECN's own torrefaction technology*
  The results of the TorTech project are an important asset in the further development of ECN's own torrefaction technology. The PATRIG facility has allowed pilot-scale validation and optimisation of the reactor- and process concepts. The next step will be the demonstration of the technology on an industrial scale. For the execution of this phase negotiations with relevant industrial partners (end users and technology suppliers) are in the final stage. It is expected that in 2011 the erection will start of an industrial size demonstration unit designed according to ECN's torrefaction technology.

8. Conclusions and outlook

This report describes the results of the work conducted by ECN and GF Energy in the framework of the TorTech project. The TorTech project has been focussed on the development of commodity solid biofuels from biomass by means of torrefaction. The project comprised basic research, in which important aspects of torrefaction and pelletisation were investigated, the design, construction and initial operation of a pilot-plant incorporating ECN's torrefaction technology concept, small and semi-industrial scale pelletisation and an economic and environmental (in terms of CO_2 emissions) evaluation of the biomass-to-end-use value chain.

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 800 hours of operation, a range of feedstocks, including poplar, pine, forestry residues and residues from the palm oil industry, was torrefied successfully. More than 30 tons of torrefied materials were produced during short, 8 hour tests and several duration trials ranging from 40 up to 100 continuous operating hours. For the range of feedstocks tested, it was proven that ECN's torrefaction 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 pelletisation 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.

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 location where the pellets are produced has a large impact on the total CO_2 emissions over the entire biomass-to-end-use value chain. Not only the transportation distance but also the CO_2 emissions related to the local electricity mix are relevant (coal/gas/nuclear/biomass generated power). The difference in overall CO_2 emission reduction between wood and torrefied wood pellets is slightly in favour of the latter technology, with CO_2 emission reductions in the range of 80-90% compared to firing coal in a coal-fired power plant.

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 to first demonstrate the technology at a scale of several tonnes/h and then pursue global commercial market introduction.

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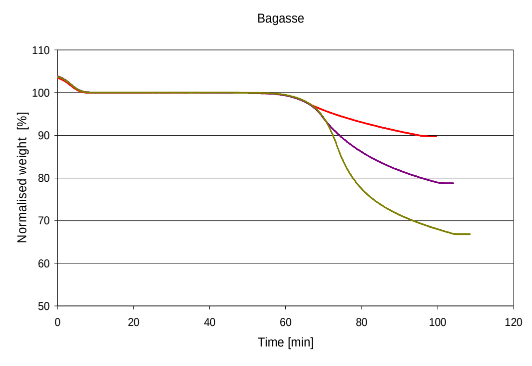
10. Acronyms and abbreviations

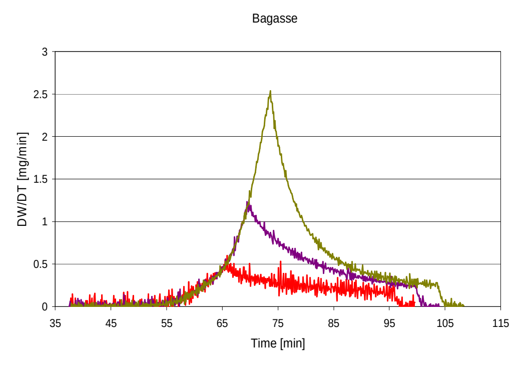
Acronyms or abbreviations	**Unit**	**Explanation**
a.r.		As received
ADF		Acid detergent fibre
ADL		Acid detergent lignin
AISI		American Iron and Steel Institute
BA		Bagasse
BE		Beech
BO_2-technology		ECN torrefaction technology
BR		Batch reactor
CAPEX		Capital expenditures
CEN/TS		Comité Européen de Normalisation/Technical specification
CrI		Crystallinity index
d.a.f		Dry and ash free
d.b.		Dry basis
DSC		Differential scanning calorimetry
ECN		Energy research Centre of the Netherlands
EOX		Extractable organic halogens
GC		Gas chromatograph
GS		Grass seed hay
HHV	MJ/kgK	High heating value
IC		Ion chromatograph
ICP		Inductively coupled plasma
IRR		Internal rate of return
LA		Larch
PATRIG		Pilot scale torrefaction unit at ECN
LHV	MJ/kgK	Low heating value
MS		Mass spectrometer
NDF		Neutral detergent fibre
OPEX		Operational expenditures
PI		Pine
PO		Poplar
PY		Pyromaat reactor
RD / RDF		Residue derived fuel
RG		Road side grass
RVS		Roestvrijstaal --- Stainless steel
SP		Spruce
SR / SRF		Solid recovered fuel
ST		Straw
T	°C	Temperature
t	min	Reaction time
TGA		Thermo gravimetric analysis
tor		Material already torrefied
TS		Trockenstabilat
TU/e		Technical University of Eindhoven
vol	%	Percentage in volume
WI		Willow
wt	%	Percentage in weight
Y_e		Mass yield
Y_m		Energy yield

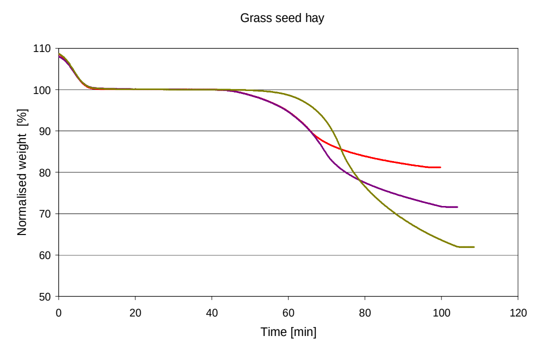
Appendix A Appendices

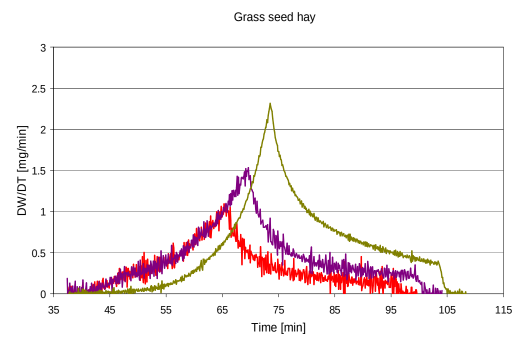
A.1 TGA weight loss and reaction rate versus time curves

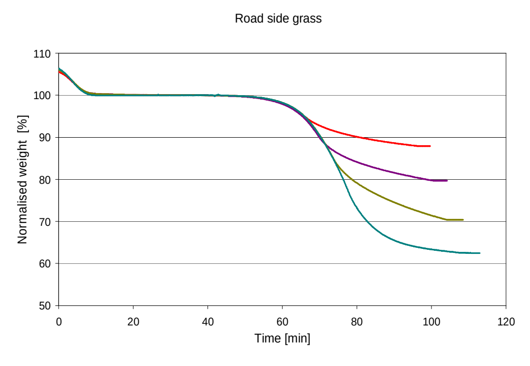
Each colour represents a different torrefaction temperature: Red = Torrefaction at 240°C, Purple = Torrefaction at 260°C, Pink = Torrefaction at 270°C, Green = Torrefaction at 280°C, Blue = Torrefaction at 300°C.

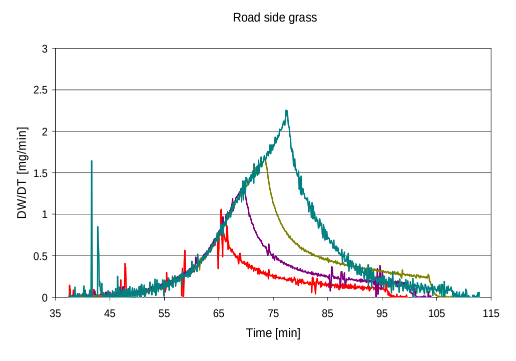


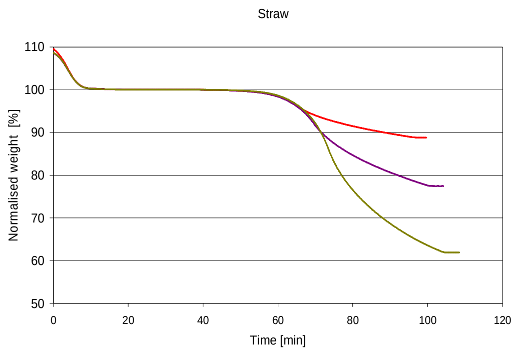








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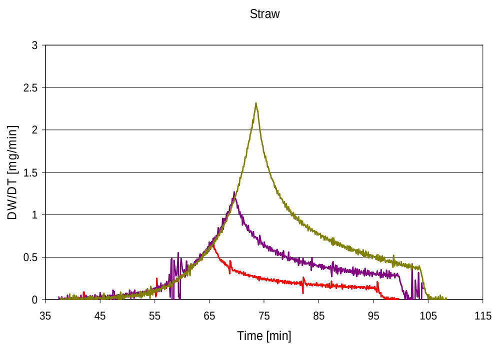
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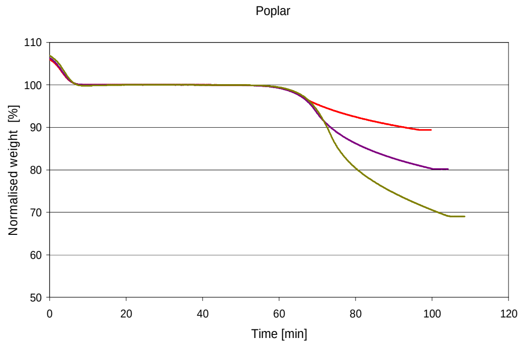
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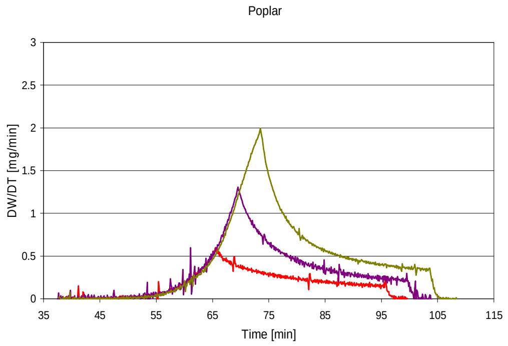
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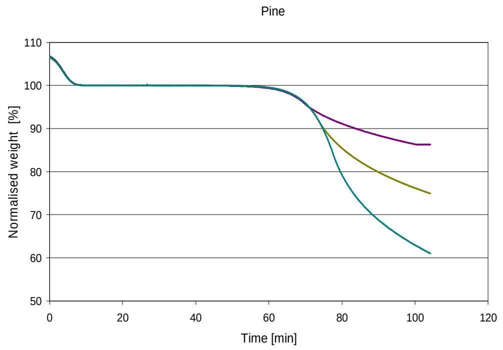
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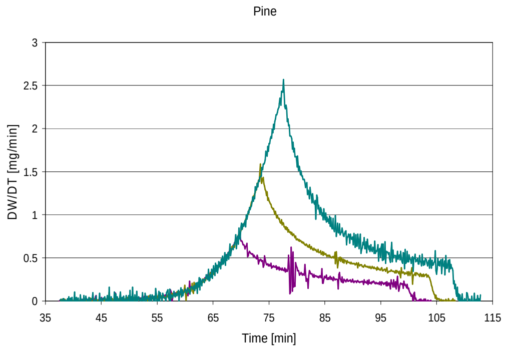
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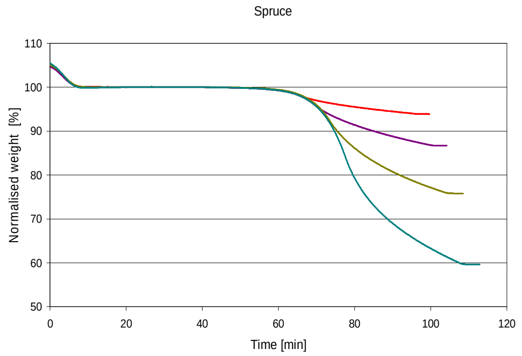
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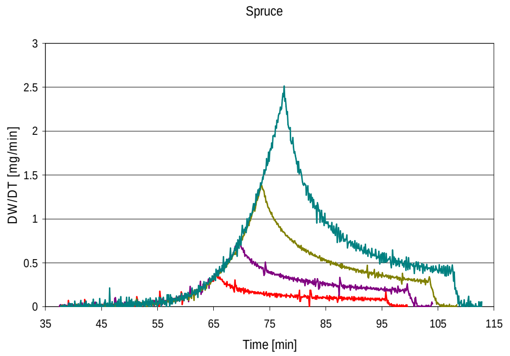
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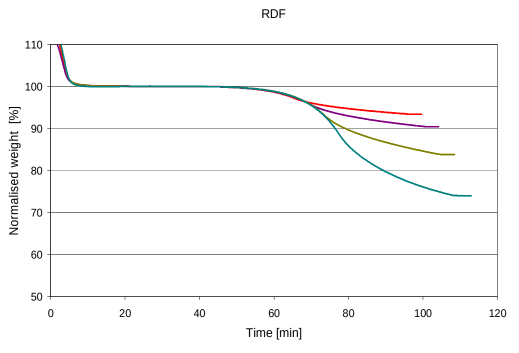
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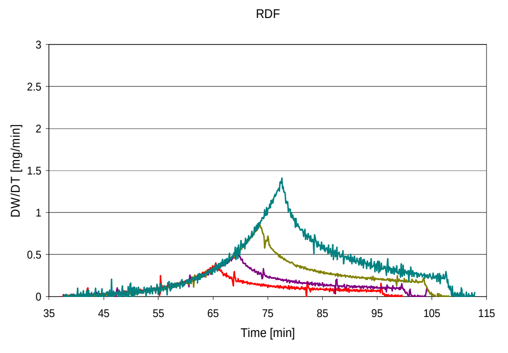
100
90
80
70
60
50
0
20
40
60
80
100
120
Time [min]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DW/DT [mg/min]
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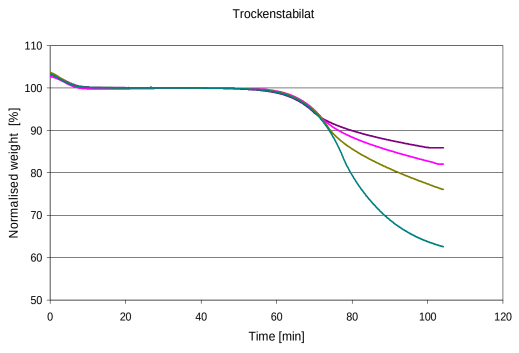
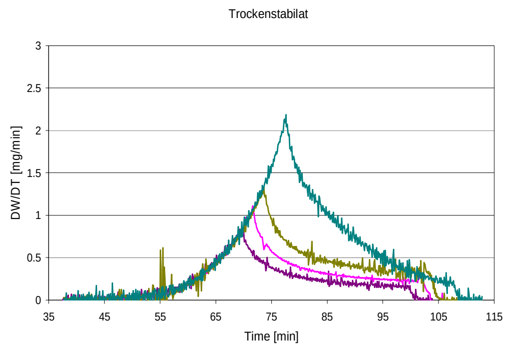
Time [min]


Trockenstabilat
Normalised weight [%]
110
100
90
80
70
60
50
0
20
40
60
80
100
120
Time [min]


Trockenstabilat
DW/DT [mg/min]
3
2.5
2
1.5
1
0.5
0
35
45
55
65
75
85
95
105
115
Time [min]

A.2 Results batch experiments

Material		**Bagasse**			**Grass seed hay**						**Road side grass**		
		BA01-RA	BA01-BR17	BA01-BR19	GS01-RA	GS01-BR12	GS01-BR09	GS02-RA	GS02-BR27	GS02-BR30	RG01-RA	RG01-BR26	RG01-BR24
Termperature average [℃]			250	280		250	258		244	284		255	293
Residence time average [min]			32	30		29	31		31	27		27	29
Temperature section for analysis [℃]			239	270		248	257		24 0	282		260	290
Residence time section for analysis [min]			29	30		31	33		31	27		27	29
Pressure drop [mbar]			395	187		143	106		14	24		38	4
C	m% (db)	47.43%	47.72%	48.09%	42.43%	45.49%	46.11%	42.36%	44.23%	48.65%	38.39%	36.93%	46.25%
H	m% (db)	5.71%	5.61%	5.88%	5.85%	5.11%	5.11%	5.73%	5.43%	4.86%	5.30%	4.49%	4.27%
N	m% (db)	0.14%	0.18%	0.19%	1.71%	1.98%	1.98%	1.52%	1.23%	1.50%	2.03%	1.64%	2.11%
O	m% (db)	44.91%	44.37%	41.83%	39.63%	34.89%	34.49%	39.62%	40.23%	31.60%	31.09%	28.76%	26.03%
Ash Calculated database	m% (db)	1.81%	2.11%	4.01%	10.38%	12.54%	12.30%	10.77%	8.89%	13.38%	23.19%	28.18%	21.34%
H20	m% (ar)	1.17%	1.03%	0.39%	0.23%	1.78%	2.81%	3.48%	1.41%	2.36%	5.56%	1.69%	1.68%
Volatile	m% (db)	83.30%	81.58%	75.23%	70.80%	63.70%	62.40%	68.70%	69.47%	55.50%	60.10%	54.74%	49.99%
HHV [db]	MJ/kg	19.14	19.11	19.09	17.73	19.15	19.71	17.18	17.71	19.38	15.89	15.28	18.67
LHV [ar]	MJ/kg	17.66	17.68	17.73	16.41	17.67	18.01	15.29	16.26	17.83	13.78	14.02	17.40
LHV [db]	MJ/kg	17.90	17.89	17.81	16.45	18.04	18.60	15.93	16.52	18.32	14.74	14.30	17.73
LHV [daf]	MJ/kg	18.23	18.27	18.55	18.36	20.62	21.21	17.85	18.13	21.15	19.19	19.92	22.54
Energy densification			1.00	1.02		1.12	1.16		1.02	1.18		1.04	1.17
Ym	m% (ar)		0.87	0.75		0.81	0.82		0.90	0.70		0.82	0.64
Ym	m% (daf)		0.87	0.74		0.78	0.78		0.95	0.69		0.81	0.69
Ye	LHV (daf)		0.87	0.75		0.87	0.90		0.96	0.82		0.84	0.81

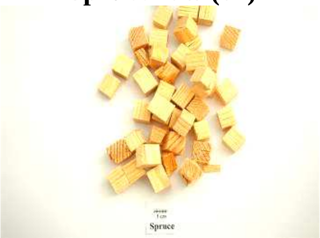
Material		**Straw**						**Beech**				**Willow**				
		ST01-RA	ST01-BR06	ST01-BR08	ST01-BR14	ST02-RA	ST02-BR34	BE-BA-OLD	BE-OLD034	BE-PAUL	Paul B06-1h	WI-BA-OLD	WI-OLD29	WI-OLD31	WI-PAUL	Paul-B06-05
Termperature average [℃]			258	259	260		270		268		264		230	271		263
Residence time average [min]			29	29	29		26		24		34		30	31		33
Temperature section for analysis [℃]			258	260	258		272		26 8		264		230	271		263
Residence time section for analysis [min]			32	31	31		26		24		34		30	31		33
Pressure drop [mbar]			11	109	751		758		na		na		na	na		na
C	m% (db)	41.33%	na	44.69%	42.97%	43.32%	43.77%	45.46%	49.54%	46.25%	50.06%	47.28%	48.64%	51.34%	48.11%	47.58%
H	m% (db)	5.66%	na	5.48%	5.07%	5.66%	4.94%	5.90%	5.81%	6.54%	6.25%	5.79%	5.89%	5.56%	6.26%	6.50%
N	m% (db)	0.50%	na	0.54%	0.55%	0.24%	0.72%	0.45%	0.61%	0.29%	0.18%	0.42%	0.64%	0.65%	0.30%	0.40%
O	m% (db)	40.77%	na	36.64%	37.87%	43.13%	32.45%	47.71%	43.35%	46.92%	42.33%	43.71%	42.93%	40.42%	44.83%	43.46%
Ash Calculated database	m% (db)	11.73%	na	12.65%	13.54%	7.67%	18.11%	0.49%	0.68%	0.00%	1.19%	2.80%	1.90%	2.02%	0.51%	2.06%
H20	m% (ar)	2.01%	na	2.71%	2.54%	1.32%	0.72%	8.80%	1.77%	0.00%	2.20%	9.60%	2.89%	1.21%	0.00%	1.30%
Volatile	m% (db)	69.80%	na	64.10%	63.80%	77.52%	57.90%	44.36%	78.93%	83.00%	78.00%	79.70%	80.76%	77.00%	82.00%	77.00%
HHV [db]	MJ/kg	16.99	na	18.20	17.85	16.74	17.85	19.40	20.32	18.66	19.37	18.46	18.89	20.09	18.44	19.75
LHV [ar]	MJ/kg	15.38	na	16.47	16.26	15.27	16.64	16.30	18.67	17.23	17.55	15.31	17.03	18.62	17.07	18.06
LHV [db]	MJ/kg	15.75	na	17.00	16.75	15.51	16.78	18.11	19.05	17.23	18.00	17.20	17.61	18.87	17.07	18.33
LHV [daf]	MJ/kg	17.84	na	19.46	19.37	16.80	20.49	18.20	19.18	17.23	18.22	17.70	17.95	19.26	17.16	18.72
Energy densification			na	1.09	1.09		1.22		1.05		1.06		1.01	1.09		1.09
Ym	m% (ar)		0.87	0.83	0.84		0.74		0.77		0.81		0.83	0.73		0.84
Ym	m% (daf)		0.84	0.82	0.82		0.72		0.83		0.78		0.90	0.81		0.82
Ye	LHV (daf)		na	0.89	0.89		0.88		0.87		0.82		0.91	0.88		0.89

Material		**Larch**		**Pine**					**Spruce**				
		LA-BA-OLD	LA-OLD33	PI01-RA	PI01-BR11	PI01-BR13	PI03-RA	PI03-BR35	SP01-RA	SP01-BR20	SP02-RA	SP02-BR29	SP02-BR28
Termperature average [℃]			249		268	277		289		289		267	286
Residence time average [min]			30		30	30		27		29		30	29
Temperature section for analysis [℃]			249		267	276		290		28 8		271	289
Residence time section for analysis [min]			30		30	31		27		30		30	29
Pressure drop [mbar]			na		195	216		17		13		138	158
C	m% (db)	47.41%	49.19%	47.86%	50.59%	50.91%	49.82%	54.36%	51.68%	53.51%	49.19%	50.64%	52.28%
H	m% (db)	6.08%	5.65%	6.16%	6.04%	6.08%	6.61%	5.90%	6.38%	5.97%	6.44%	6.19%	5.73%
N	m% (db)	0.57%	0.59%	0.13%	0.03%	0.03%	0.04%	0.02%	0.00%	0.00%	0.02%	0.00%	0.00%
O	m% (db)	45.90%	44.50%	44.87%	42.69%	42.50%	43.29%	39.39%	41.69%	40.31%	44.04%	42.83%	41.21%
Ash Calculated database	m% (db)	0.04%	0.07%	0.98%	0.64%	0.49%	0.24%	0.33%	0.25%	0.21%	0.31%	0.34%	0.79%
H20	m% (ar)	8.77%	0.90%	0.52%	1.66%	1.21%	1.32%	1.76%	0.48%	0.00%	2.18%	0.87%	0.39%
Volatile	m% (db)	84.12%	80.94%	82.70%	79.80%	78.70%	83.80%	75.10%	86.10%	78.79%	83.30%	81.00%	79.69%
HHV [db]	MJ/kg	19.52	20.52	19.34	20.58	20.86	20.27	21.90	21.99	22.03	20.04	20.00	20.63
LHV [ar]	MJ/kg	16.39	19.09	17.89	18.90	19.26	18.55	20.21	20.49	20.73	18.17	18.47	19.29
LHV [db]	MJ/kg	18.20	19.28	18.00	19.26	19.53	18.83	20.61	20.60	20.73	18.63	18.65	19.38
LHV [daf]	MJ/kg	18.20	19.29	18.18	19.39	19.63	18.88	20.68	20.65	20.77	18.69	18.72	19.53
Energy densification			1.06		1.07	1.08		1.10		1.01		1.00	1.04
Ym	m% (ar)		0.86		0.90	0.84		0.74		0.70		0.88	0.79
Ym	m% (daf)		0.93		0.89	0.83		0.74		0.70		0.87	0.80
Ye	LHV (daf)		0.99		0.95	0.90		0.81		0.70		0.87	0.84

Material		**RDF**					**Trocken stabilat**	
		RD01-RA	RD01-BR21	RD01-BR22	RD02-RA	RD02-BR36	TS01-RA	TS01-BR15
Termperature average [℃]			244	266		269		249
Residence time average [min]			31	31		24		29
Temperature section for analysis [℃]			252	275		269		250
Residence time section for analysis [min]			33	34		24		30
Pressure drop [mbar]			23	758		8		39
C	m% (db)	54.56%	53.62%	53.62%	53.07%	58.46%	42.71%	41.92%
H	m% (db)	7.64%	6.92%	7.10%	7.38%	7.81%	5.74%	5.55%
N	m% (db)	0.23%	0.34%	0.30%	0.79%	0.77%	1.16%	0.95%
O	m% (db)	23.48%	24.22%	20.25%	21.24%	17.66%	27.12%	25.39%
Ash Calculated database	m% (db)	14.09%	14.89%	18.74%	17.52%	15.30%	23.27%	26.19%
H20	m% (ar)	13.39%	0.03%	0.00%	0.00%	0.26%	0.75%	0.00%
Volatile	m% (db)	81.56%	76.21%	73.13%	78.08%	75.90%	64.60%	60.50%
HHV [db]	MJ/kg	24.31	22.74	23.94	24.74	28.95	17.49	19.35
LHV [ar]	MJ/kg	19.28	21.22	22.39	23.12	27.17	16.10	18.14
LHV [db]	MJ/kg	22.64	21.23	22.39	23.12	27.25	16.24	18.14
LHV [daf]	MJ/kg	26.36	24.94	27.55	28.04	32.17	21.16	24.57
Energy densification			0.95	1.05		1.15		1.16
Ym	m% (ar)		0.94	0.88		0.91		0.91
Ym	m% (daf)		0.94	0.83		0.93		0.88
Ye	LHV (daf)		0.89	0.87		1.07		1.02

A.3 Visual observations batch experiments

Bagasse raw	**BA01-BR17 (250,32)**	**BA01-BR19 (280,31)**
		
Grass seed hay raw	**GS01-BR12 (250,29)**	**GS01-BR09 (258,31)**
		
	GS02-BR27 (244,31)	**GS02-BR30 (284,27)**
		
Road side grass raw	**RG01-BR26 (255,27)**	**RG01-BR24 (293,29)**
		
Straw raw	**ST01-BR14 (260, 29)**	**ST02-BR34 (270,26)**
		
Pine raw (01)	**PI01-BR11 (268,30)**	**PI01-BR13 (277,30)**
		

Pine raw (02)  	**PI02-BR18 (320,30)** 	
Pine raw (03)  	**PI03-BR35 (289,27)**  	
Spruce raw (01)  	**SP01-BR20 (289,29)**  	
Spruce raw (02)  	**SP02-BR29 (267,30)**  	**SP02-BR28 (286,29)** 
RDF raw (01)  	**RD01-BR21 (244,31)**  	**RD01-BR22 (266,31)** 
Trockenstabilat raw  	**TS01-BR15 (249,29)** 	

A.4 Detergent fibre analysis

The concept behind the detergent fibre analysis is that plant cells can be divided into less digestible cell walls (contains hemicellulose, cellulose and lignin) and mostly digestible cell contents (contains starch and sugars). Van Soest separated these two components successfully by using two detergents: a neutral detergent (Na-lauryl sulphate, EDTA, pH =7.0) and an acid detergent (cetyl trimethyl ammonium bromide in 1 N H_2SO_4).

Neutral Detergent Fibre (NDF)
Neutral detergent fibre (NDF) is the residue, corrected for ash, after refluxing the sample for 1 hour in a neutral detergent solution (Na-lauryl sulphate, EDTA, pH =7.0). The anionic detergent solution contains sodium dodecyl sulphate which forms soluble complexes with the proteins; EDTA as a chelating agent to prevent interference from divalent ions; Triethylene glycol (Trigol) to aid in the solution of starches and borate and phosphate to buffer the system at neutral pH to prevent hydrolysis of hemicellulose. Neutral detergent fibre is considered to be the entire fibre fraction of the feed, but it is known to underestimate cell wall concentration because most of the pectic substances in the wall are solubilised. As a result, NDF is a poor estimate of cell wall concentration for the pectin-rich legumes. Heat-damaged proteins in processed feeds are also retained in NDF, which will overestimate fibre content. These shortcomings of NDF as a method to determine cell wall concentration may be a problem if one is interested in the plant cell wall as a biological structure.

Acid Detergent Fibre (ADF)
Acid detergent fibre (ADF) is the residue, corrected for ash, after refluxing the sample for 1 h in an acid detergent solution consisting of cetyl trimethyl ammonium bromide in sulphuric acid. Acid detergent fibre includes the cellulose and lignin from cell walls and variable amounts of xylans and other components.

Acid Detergent Lignin (ADL)
Acid Detergent Lignin (ADL) is determined gravimetrically by first obtaining the acid detergent residue, then treating it with 72 % sulphuric acid to solubilise cellulose and isolate crude lignin plus ash. There is some evidence to indicate that it underestimates lignin due to solubilisation of some lignin at the ADF step in the procedure.

Forage cellulose and hemicellulose concentrations are commonly estimated as ADF minus sulphuric acid detergent lignin (ADL) and as NDF minus ADF, respectively. Cellulose concentrations are overestimated by ADF minus ADL to the extent that xylans are present in ADF and underestimated by heat-damaged protein contamination of ADL. Similarly, hemicellulose estimates based on NDF minus ADF are overestimated by non-extracted protein in NDF, and residual xylans in ADF cause underestimates of hemicellulose.

A.5 Pyromaat data

Material		**Straw**		**Grass seed hay**		**Road Grass**		**Bagasse**		**Pine**		**Spruce**	
		ST01-RA	ST01-PY13	GS02-RA	GS02-PY03	RG01-RA	RG01-PY02	BA02-RA	BA02-PY12	PI03-RA	PI03-PY06	SP02-RA	SP02-PY01
Termperature average [℃]			260		260		268		270		297		289
Residence time average [min]			30		30		30		30		30		30
C	m% (db)	41.33%	45.16%	42.36%	49.19%	38.39%	31.88%	45.66%	43.68%	49.82%	56.71%	49.19%	53.70%
H	m% (db)	5.66%	4.84%	5.73%	4.89%	5.30%	3.49%	5.66%	4.55%	6.61%	5.57%	6.44%	5.86%
N	m% (db)	0.50%	0.55%	1.52%	1.82%	2.03%	1.80%	0.17%	0.22%	0.04%	0.00%	0.02%	0.03%
O	m% (db)	40.77%	34.36%	39.62%	28.04%	31.09%	18.39%	44.14%	33.18%	43.29%	37.28%	44.04%	39.97%
Ash Calculated database	m% (db)	11.73%	15.10%	10.77%	16.07%	23.19%	44.43%	4.37%	18.37%	0.24%	0.44%	0.31%	0.43%
H20	m% (ar)	2.01%	1.14%	3.48%	1.73%	5.56%	0.73%	2.05%	3.36%	1.32%	1.05%	2.18%	1.67%
Volatile	m% (db)	69.80%	61.22%	68.70%	52.50%	60.10%	38.20%	80.00%	60.70%	83.80%	72.10%	83.30%	75.90%
HHV [db]	MJ/kg	16.99	17.87	17.18	19.92	15.89	13.32	18.68	17.49	20.27	22.81	20.04	21.61
LHV [ar]	MJ/kg	15.38	16.59	15.29	18.49	13.78	12.45	17.04	15.87	18.55	21.34	18.17	19.95
LHV [db]	MJ/kg	15.75	16.81	15.93	18.86	14.74	12.56	17.45	16.50	18.83	21.59	18.63	20.33
LHV [daf]	MJ/kg	17.84	19.80	17.85	22.47	19.19	22.60	18.24	20.22	18.88	21.69	18.69	20.42
Energy densification			1.11		1.26		1.18		1.11		1.15		1.09
Ym	m% (ar)		0.77		0.68		0.68		0.64		0.80		0.82
Ym	m% (daf)		0.74		0.58		0.53		0.54		0.80		0.82
Ye	LHV (daf)		0.82		0.73		0.62		0.59		0.92		0.90

Material		**Poplar**		**Trocken stabilat**				**RDF**			
		PO01-RA	PO01-PY04	TS02-RA	TS02-PY11	TS02-PY09	TS02-PY10	RD02-RA	RD02-PY07	RD02-PY05	RD02-PY08
Termperature average [℃]			280		240	258	278		237	258	279
Residence time average [min]			30		30	30	30		30	30	30
C	m% (db)	47.24%	52.48%	39.86%	56.76%	57.83%	59.27%	53.07%	51.43%	56.82%	55.37%
H	m% (db)	6.04%	5.62%	5.10%	7.59%	7.31%	7.58%	7.38%	6.81%	7.31%	6.96%
N	m% (db)	0.00%	0.00%	1.46%	0.84%	0.81%	0.89%	0.79%	0.41%	0.95%	0.43%
O	m% (db)	45.67%	40.43%	30.46%	18.74%	17.04%	14.94%	21.24%	21.55%	18.39%	17.89%
Ash Calculated database	m% (db)	1.05%	1.47%	23.11%	16.06%	17.00%	17.31%	17.52%	19.79%	16.53%	19.35%
H20	m% (ar)	0.00%	0.04%	0.75%	0.34%	0.48%	0.25%	0.00%	0.95%	0.71%	0.44%
Volatile	m% (db)	83.99%	73.02%	64.60%	75.60%	74.10%	73.60%	78.08%	71.30%	74.60%	69.60%
HHV [db]	MJ/kg	18.82	21.14	16.22	27.47	27.87	29.06	24.74	24.69	27.67	26.44
LHV [ar]	MJ/kg	17.50	19.90	14.97	25.72	26.13	27.33	23.12	22.96	25.87	24.80
LHV [db]	MJ/kg	17.50	19.91	15.10	25.81	26.27	27.41	23.12	23.21	26.07	24.92
LHV [daf]	MJ/kg	17.68	20.20	19.64	30.75	31.65	33.15	28.04	28.93	31.23	30.90
Energy densification			1.14		1.57	1.61	1.69		1.03	1.11	1.10
Ym	m% (ar)		0.69		0.97	0.87	0.80		0.94	0.87	0.82
Ym	m% (daf)		0.68		1.06	0.95	0.86		0.89	0.87	0.78
Ye	LHV (daf)		0.78		1.66	1.53	1.45		0.92	0.97	0.86