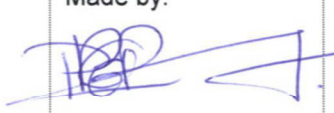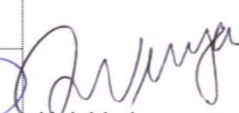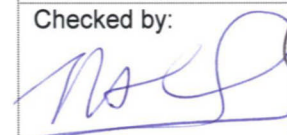# Torrefaction for biomass co-firing in existing coal-fired power stations

"BIOCOAL"

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Colophon

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Acknowledgement/Preface

Abstract

Torrefaction is considered to be a pre-treatment technology to make biomass more suitable for co-firing applications. Especially, the improved grindability of biomass after torrefaction may enable higher co-firing rates in the near future. Torrefaction is, however, a technology that is not commercially available yet. This work contributed to the development of torrefaction by means of extensive parametric research, process simulations and process design. Experimental work has revealed that torrefied biomass can be produced with a grindability comparable to coal and with a combustion reactivity comparable to wood. The process can be operated at high process energy efficiency; typically 96% thermal efficiency and 92% net process efficiency (including the internal electricity consumption). Reactor technology based on moving-bed principles is identified very promising reactor for torrefaction. A production plant of 60-kton/a product requires a capital investment of 5.2 to 6.3 M€. The total production costs amount in the range of 40 to 56 €/ton product (excluding feedstock costs), which is 2 to 2.8 €/GJ. It is recommended to further develop moving-bed technology for torrefaction by means of pilot-scale testing (prototype) and to investigate other important product properties such as hydrophobic nature and leeching behaviour in relation to operating conditions.

Keywords

Biomass, torrefaction, technology, pre-treatment, grindability, combustibility, co-firing, economic evaluation, process design, process concepts, parametric research, moving-bed, rotating drum, indirectly-heated screw reactor.

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Summary

It is stated in the policy agreement of the Dutch government with the Dutch energy sector that 6 Mton/a of fossil CO_2 reduction needs to be accomplished in 2008-2012 by the coal-fired power stations in the Netherlands. Half of this reduction is to be accomplished through the co-firing of biomass in these existing power stations, which comes down to 475 MW_e or approximately 13% coal replacement. However, at present the co-firing percentages are still limited, as problems are faced that are caused by differences in the nature of coal and biomass. Especially the size reduction of biomass to produce a powder that can be burned in a coal-fired power station has been identified to be problematic. Torrefaction is a technique known to improve the biomass fuel properties amongst which its grindability. Torrefaction is a thermal process operated at 200 °C to 300 °C in absence of oxygen and at relatively long residence times, typically 1 hour. The properties of the biomass are improved through limited devolatilisation that occurs under these conditions. The process is however not commercially available and considered to be in the "proof-of-concept" phase. The main objective of the presented work was to contribute to this "proof-of-concept" phase of the torrefaction development for co-firing of biomass in existing power stations. This was done through bench-scale characterisation of the torrefaction process, optimisation of process conditions, identification and evaluation of torrefaction concepts, process and reactor design, development of measurement techniques and techno-economic evaluation.

From this work it is concluded that the grindability of biomass (woodcuttings, willow and demolition wood) can be improved to the level of coal in the temperature range of 260 °C to 300 °C, whilst applying a reaction time of 30 min down to 7.5 min. In this range also good combustibility properties of the torrefied biomass are observed and a dry and high-calorific fuel can be obtained (19-22 MJ/kg ar). Under the favoured conditions, a thermal process efficiency of typically 96% is to be expected and a net process efficiency of 92% (including penalties for power consumption). As long as the liberated torrefaction gas can be combusted to produce heat for the process itself, these efficiency characteristics can be obtained. The moisture content is the most important property with respect to the process energy efficiency. Only for very dry biomass feedstock (<10-15% wt.), lower efficiencies are to be expected. Therewith, a wide range of biomass feedstock can be upgraded with high-energy efficiency by means of torrefaction.

A torrefaction process typically consists of pre-drying, torrefaction, product cooling and combustion of the torrefaction gas to generate heat for drying and torrefaction. The typical full-scale production capacity is estimated to range 50-60 kton/a (or 100-130 kton/a feedstock input with 50% moisture content). From the evaluated reactor technologies, a reactor based on moving-bed principles results in the most attractive process. The total capital investment of a 60 kton/a production plant are estimated 5 to 7.5 M€ and the total production costs in the range from 40 to 56 €/ton product (excluding feedstock costs).

Based on the above, it is concluded that torrefaction can be an efficient technology for upgrading biomass to facilitate high levels of biomass co-firing. It is recommended to continue the development of torrefaction technology by means of pilot-scale testing of the favoured (reactor) technology. It is also recommended to further address aspects that belong to the current phase of development. This includes dust formation (dust explosions), hydrophobic nature, leeching characteristics, which need to be investigated to see whether measures need to be taken with respect to handling, logistics, and safety. Evaluation of these aspects can be done following the approach applied in this work. Furthermore, it is recommended to further evaluate the potential of torrefaction in combination with densification (pelletisation), in order to minimise dust formation and to benefit from the high volumetric energy density that possibly can be achieved (with respect to e.g. handling and logistics).

1. Introduction

1.1 General background

It is stated in the policy agreement of the Dutch government with the Dutch energy sector that 6 Mton/a of fossil CO_2 reduction needs to be accomplished in 2008-2012 by the coal-fired power stations in the Netherlands. Half of this reduction is to be accomplished through the co-firing of biomass in these existing power stations. This comes down to 475 MW_e or approximately 13% coal replacement. However, at present the co-firing percentages are still limited, as problems are encountered due to the differences between the nature of coal and biomass. Especially the size reduction of biomass to produce a powder that can be burned in a coal-fired power station has been identified to be problematic. This is caused by the biomass its tenacious and fibrous structure so that the coal mills at the power station cannot be effectively utilised. Currently, the most appropriate fuel to be utilised in the power stations are biomass derived fuel pellets, but these are expensive, require expensive storage facilities, and still need modifications in the processing infrastructure of the power plant. Moreover, availability of biomass fuel pellets is limited, as they cannot be produced from a wide variety of biomass feedstock.

New techniques are searched for to increase the co-firing rates to desired levels. These can roughly be classified as modifications implemented on-site the power station, or off-site, which means that the biomass is pre-treated before it is delivered. Torrefaction is a technique that may be applied in both ways. Traditionally, torrefaction is a thermal process operated at 200 °C to 300 °C at relatively long residence time, typically 1 hour. The properties of the biomass are improved through limited devolatilisation that occurs under these conditions. It has been stated that this technique is capable of improving the grindability properties, but it also improves the calorific value, hydrophobic nature, and the energy density of the biomass.

1.2 Problem definition

Although the principles of torrefaction are known since 1930, currently no commercial process is available at the market. Torrefaction technology has been developed during the eighties of the last century to the phase of technical demonstration, but this was for a different market requiring different product specifications. Knowledge was gained with respect to this application, but the choices made with respect to technology and process conditions resulted in an expensive and an energy inefficient process, so that it is infeasible for biomass co-firing.

On the basis of the principles of torrefaction it is strongly believed that it has high potential to become a leading technology, but the current knowledge base provides insufficient design data with respect to operating conditions and their relation to (1) decisive process performance characteristics (such as process energy efficiency), (2) relevant product properties such as grindability and (3) the composition of the volatiles liberated during torrefaction and their treatment. The latter is important with respect to how the gas can be utilised so that waste streams are prevented. In addition, sampling and measurement techniques to quantify the properties of the torrefied biomass and the composition of the torrefaction gas are not available or existing techniques need to be modified. Therefore, development of torrefaction for co-firing of biomass in existing coal-fired power stations is to be considered in the phase of "proof-of-concept". Its development first needs to be concentrated on characterisation of the process and the produced products and the demonstration of its technological and economical viability. This implies that further research and development should aim for conceptual design and experimental exploration of the process resulting in appropriate technology that meets the demands of the pertinent product end-users.

1.3 Objectives and general approach

The main objective of the presented work was to contribute to the "proof-of-concept" phase of the torrefaction development for biomass co-firing in existing power stations. Sub objectives of this work were defined as:

· Characterisation of the torrefaction process. This included coupling of the main torrefaction parameters (temperature and reaction time) to product properties such as grindability and combustibility and to process parameters such as energy efficiency. Especially the minimisation of the reactor residence time to increase the reactor capacity and so minimise the involved capital investment was an important aspect.

· The identification and evaluation of torrefaction concepts. The identification of suitable reactor technology was therein an important aspect in relation to required solids residence time and scale of operation.

· Development of measurement techniques to quantify the difference in the properties of feedstock and product in relation to the requirements of a power station, but also the development of measurement methods to quantify the composition of the torrefaction gas liberated during the process.

· Assessment of the technical and economic feasibility through process design and economic evaluation.

To achieve these objectives, an extensive experimental programme was conducted using two bench-scale reactor facilities for which modifications to hardware, experimental procedures and sampling methods were made, so that they could serve as torrefaction reactors. Experimental data were used in process simulations to evaluate the main process characteristics such as the process energy efficiency. In striving for attractive process concepts, important design and operational aspects of torrefaction were identified and parameters to evaluate them were defined. Eventually, the obtained data from experiments, simulation and design were bundled to come to an economic evaluation, which was based on the capital investment and total production costs (€/ton product). The level of detail that could be added to process design and economic evaluation in this phase of development results in an accuracy of costing estimations that is known for study estimates (±30% accuracy in capital investment).

This work intended to provide more insight in the torrefaction technology as a pre-treatment technology for upgrading biomass. It does not intensively focus what its optimal position in the overall production chain from biomass to electricity would be; neither does this work focus on the life cycle analysis. The discussion on whether torrefaction should be performed on-site or off-site the power station is however discussed. Additionally, the combination of torrefaction and pelletisation is also not addressed in this work, although this may be attractive from the viewpoint of transportation and logistics, as the combination of the both may lead to an attractive fuel pellet. The combination of torrefaction and pelletisation has been addressed by Bergman (2005).

2. Background torrefaction

2.1 Introduction to the process

Torrefaction is a thermochemical treatment method in the first place earmarked by an operating temperature within the range of 200 to 280-300 °C. It is carried out under atmospheric conditions and in absence of oxygen. In addition, the process is characterised traditionally by low particle heating rates (< 50 °C/min) and by a relatively long reactor residence time (typically 1 hour). During the process, the biomass partly decomposes giving off various types of volatiles. The final product is the remaining solid, which is often referred to as torrefied biomass or char.

In open literature, torrefaction can be found under several synonyms. Some examples are roasting, slow- and mild pyrolysis, wood cooking and high-temperature drying. Especially the link with pyrolysis is easy to make since torrefaction comprises the very first decomposition reactions of pyrolysis, although process conditions are different. The name torrefaction is adopted from the roasting of coffee beans, which is however performed at lower temperature while using air (oxygen). Nevertheless, an important mechanical effect of torrefaction on biomass is supposed to be similar to its effect on coffee beans, which is the resulting brittle structure.

In the 1930's the principles of torrefaction were first reported in relation to woody biomass and in France research was carried out on its application to produce a gasifier fuel (Bioenergy, 2000). Since then, the process received only attention again, when it was recognised that torrefied wood could be used as a reducing agent in metallurgic applications. This led to a demonstration plant in 1980's, which was dismantled in the beginning of the 1990's of the last century. During the last five years, again torrefaction received attention, but now as pre-treatment option to upgrade biomass for energy production chains (co-combustion and gasification).

Figure 2.1 provides a typical mass and energy balance of torrefaction. Typically, 70% of the mass is retained as a solid product, containing 90% of the initial energy content (Bioenergy, 2000). 30% of the mass is converted into torrefaction gases, but containing only 10% of the energy content of the biomass. Hence, a considerable energy densification can be achieved, typically by a factor of 1.3 on mass basis. This example points out one of the fundamental advantages of the process, which is the high transition of the chemical energy from the feedstock to the torrefied product, whilst fuel properties are improved. This is in contrast to the classical pyrolysis process that is characterised by an energy yield of 55-65% in advanced concepts down to 20% in traditional ones (Pentananunt *et. al.,* 1990).
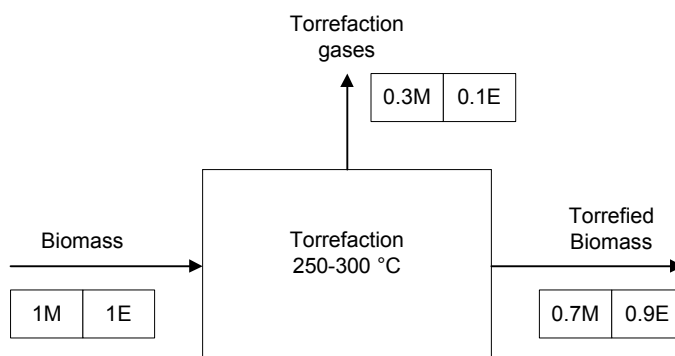
Figure 2.1 *Typical mass and energy balance of the torrefaction process. Symbols: E = energy unit, M = mass unit*

2.1.1 Torrefaction decomposition mechanisms

Woody and herbaceous biomass consists of three main polymeric structures: cellulose, hemicellulose and lignin; together called lignocellulose. The thermal decomposition of biomass is in general explained thereon. During torrefaction numerous reactions occur and different reaction pathways can be defined. All these reaction pathways can be grouped to a few main reaction regimes, as is shown in Figure 2.2.
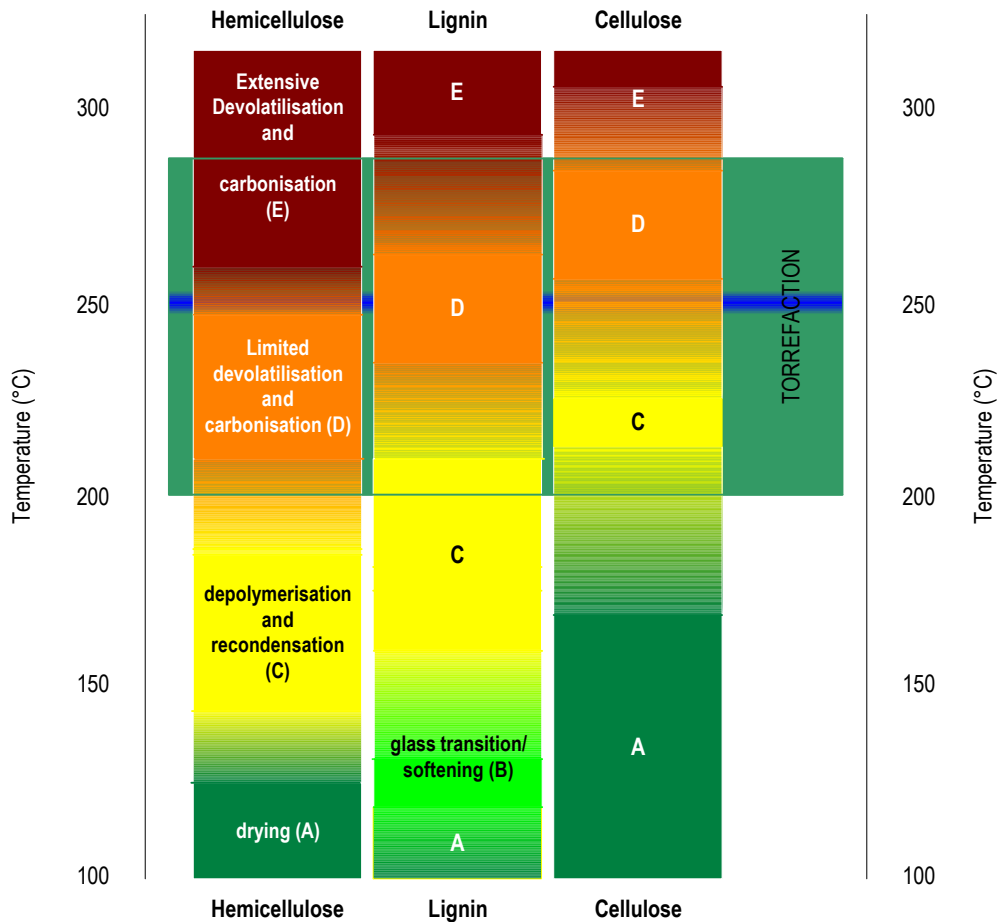
Figure 2.2 *Main physico-chemical phenomena during heating of lignocellulosic materials at pre-pyrolytic conditions (torrefaction). Main decomposition regimes are based on Koukios et al. (1982)*

For each polymer similar decomposition regimes can be defined. In temperature regime A, physical drying of biomass occurs. When the temperature is increased to regime C, depolymerisation occurs and the shortened polymers condense within the solid structure. A further increase of temperature to regime D leads to limited devolatilisation and carbonisation of the intact polymers and the solid structures formed in the temperature regimes C. Again a further increase of temperature to regime E leads to extensive devolatilisation and carbonisation of the polymers, and, of the solid products that were formed in regime D. For lignin also a temperature regime B is defined in which softening of this biomass constituent occurs, a phenomenon very beneficial in the densification of biomass, as softened lignin is a good binder. Figure 2.2 also includes the torrefaction temperature regime and the blue line splits it into a low (<250 °C) and high temperature regime (>250 °C). In general hemicellulose is the most reactive polymer followed by lignin and cellulose is most thermostable. In the lower torrefaction temperature regime the main biomass decomposition comes from the limited devolatilisation and carbonisation of hemicellulose. Minor decomposition is to be expected for lignin and cellulose except for chemical changes in their structure, which however do not lead to a significant mass loss. In the higher torrefaction temperature regime, decomposition becomes

more vigorous as hemicellulose extensively decomposes into volatiles and a char-like solid product and also lignin and cellulose show limited devolatilisation and carbonisation.

The transitions from one to another decomposition regime are rather gradual. For hemicellulose the transitions are rather strong (narrow temperature range), but for lignin and cellulose the transitions occur over a wider temperature range. Exact temperature transitions depend on the type and properties of the biomass. In addition, also the use of "limited" and "extensive" in regimes D and E are proportional to each other and need to be placed in the context of each polymer individually. In torrefaction, extensive devolatilisation and carbonisation must still be understood as processes occurring at a slow rate. The reactivity of hemicellulose very much depends on its molecular structure. A large difference exists between the structures of hemicellulose of deciduous (willow, beech) and coniferous (spruce, larch) wood. Due to these differences deciduous wood is much more reactive and results in significantly more devolatilisation (and carbonisation). More details can be found in the study of Bergman *et al.* (2005). The transitions between the reaction regimes of hemicellulose in Figure 2.2 represent hemicellulose of deciduous wood.

2.1.2 Product distribution

During torrefaction, numerous reaction products are formed. Their yield strongly depends on the torrefaction conditions (temperature and time) and on the biomass properties. Figure 2.3 gives an overview of the torrefaction products, classified based on their state at room temperature, which can be solid, liquid or gas. This classification has been developed in this work on the basis of experimental results (analysis and observations) and has proven to be useful in the further evaluation of the process.

The solid phase consists of a chaotic structure of the original sugar structures and reaction products. The reaction products that remain solid are large modified sugar structures, newly formed polymeric structures with possibly a certain degree of aromatic rings, typical carbon-rich char structures and the ash fraction. The gas phase includes the gases that are to be considered permanent gases. In general, these are compounds with a boiling point below –33 °C, but also light aromatic components such as benzene and toluene.
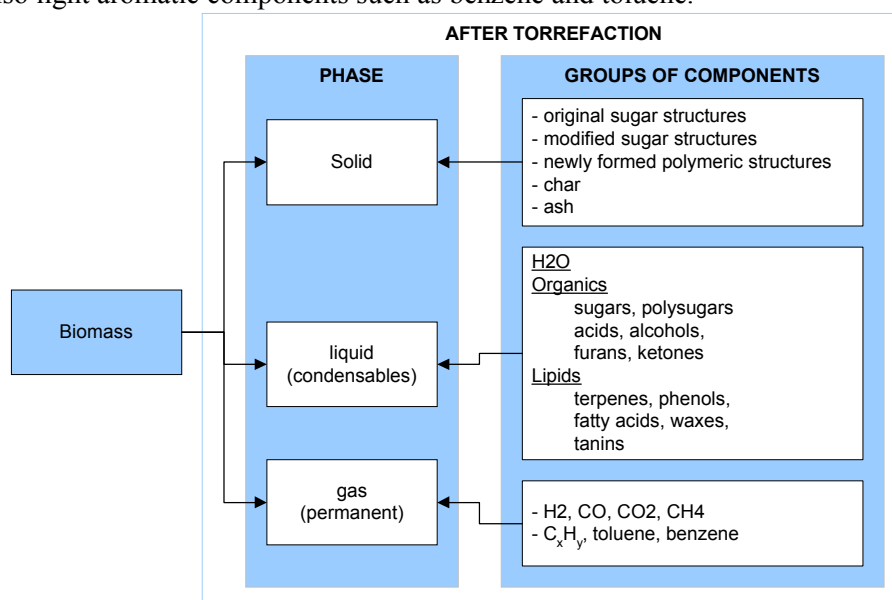
Figure 2.3 *Products formed during torrefaction of biomass*

The condensables or liquids can be divided into three sub-groups. One sub-group is reaction water as a product from the thermal decomposition (in addition to the freely bound water that has been released from the biomass by evaporation). The organics sub-group consists of organics that are mainly produced during devolatilisation and carbonisation (see Figure 2.2).

Finally, the lipids are a group of compounds that are present in the original biomass. They are not really reaction products, but inert compounds that may evaporate under torrefaction conditions. This sub-group contains compounds such as waxes and fatty acids. Although these compounds are mainly liquids, some can be solid at room temperature.

Figure 2.4 shows the product yields and composition of the permanent gases and organics of a torrefaction experiment that was carried out during this work. This example shows the high preservation of mass, but especially energy in the solid product. It can be seen that besides the solids mostly water is produced during torrefaction and that the energy content of the volatiles is mainly preserved in the lipids and organics. The group of permanent gases consists mainly of CO_2 and some CO and other components are only found in trace amounts. The organics composition is dominated by acetic acid, methanol and 2-furaldehyde. As a general remark to these data, it must be emphasised that the yields and type of products are strongly dependent on the torrefaction operating conditions and the biomass properties.

Product group yields (wt% biomass feedstock)

Composition permanent gas

Composition organics
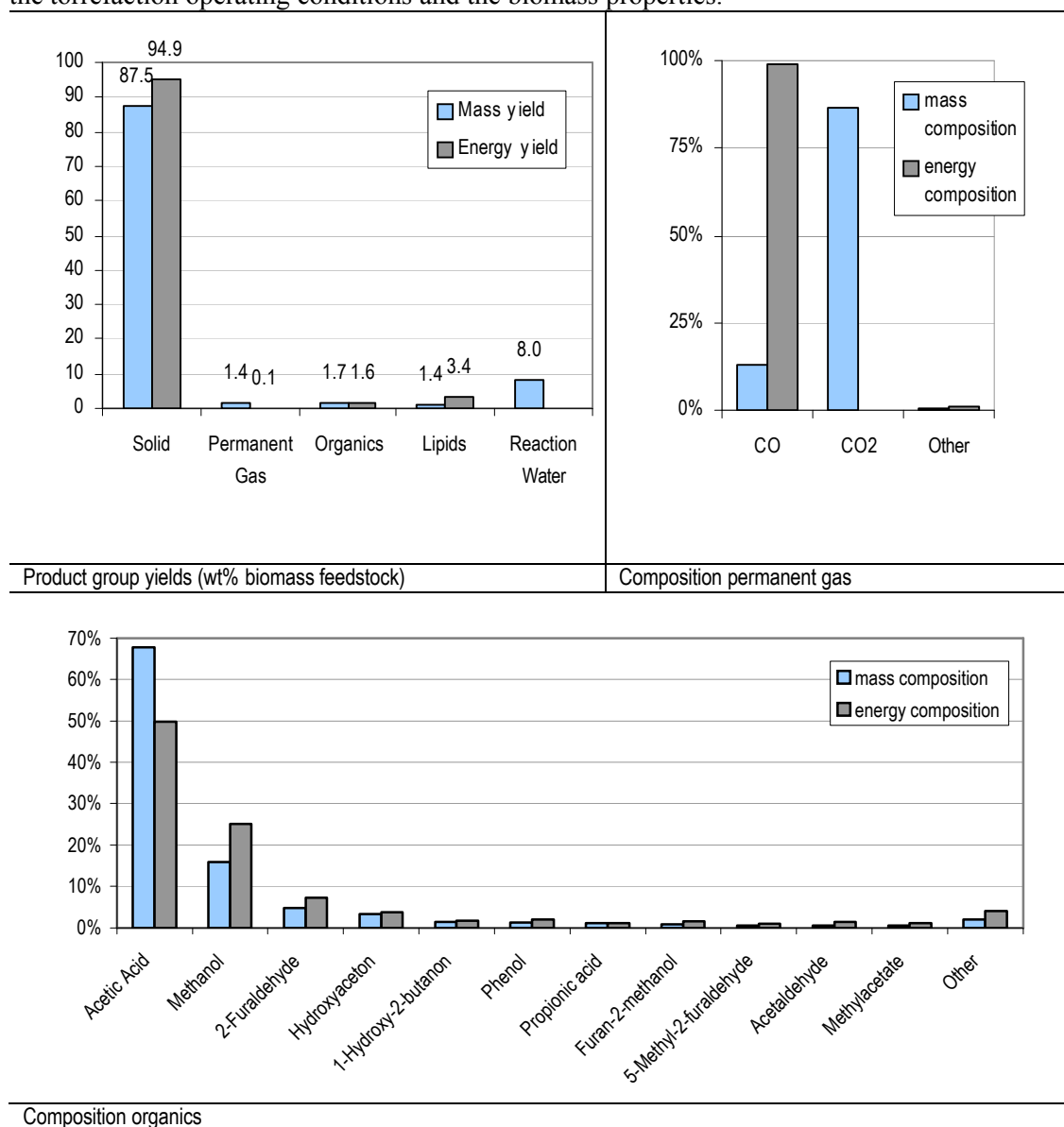
Figure 2.4 *Yields and composition of the different product groups. Data corresponds with the torrefaction of woodcuttings at 280 °C and 17.5 min reaction time. Data is obtained from the experimental programme conducted in this work*

2.1.3 Definition of the mass and energy yield

The mass and energy yield are main parameters in the evaluation of the torrefaction process. They describe the transition of mass and chemical energy from the biomass to the solid product. Analogous to Bergman *et. al.* (2005), the following definitions of mass and energy yield have been applied:

$$y_M = \left(\frac{m_{char}}{m_{feed}} \right)_{daf} \tag{1}$$

and

$$y_E = y_M \left(\frac{LHV_{char}}{LHV_{feed}} \right)_{daf} \tag{2}$$

The mass and energy yield of torrefaction are based on the reactive part of the biomass and therefore the ash and free water content are excluded in the definition. Hence, the yields are expressed on dry- and ash-free basis. In addition, use is made of the lower heating value of the (torrefied) biomass to have the yield expressed on the basis of the energy that can effectively be retrieved from the feed and product after its combustion. The higher heating value (HHV) would include the energy needed to evaporate the water (during combustion) as available energy, which is only true through effective condensation of water from the flue gas. This is uncommon in the Netherlands.

2.1.4 Definition of reaction time and torrefaction temperature

Bergman *et al.* (2005) discussed the importance of the definition of reaction time (instead of reactor residence time). Because biomass needs to be heated through several stages before the real torrefaction regime is reached, the residence time of solids in a (industrial) torrefaction reactor is practically never equal to the time that the biomass particles are exposed to torrefaction. The definitions provided by Bergman *et al.* (2005) have been used as a basis to further define the temperature-time stages in torrefaction. This takes into account the changes in moisture content, mass loss (*viz.* mass yield or devolatilisation) and the required heat duties of these stages. Figure 2.5 illustrates these temperature-time stages for a batch-wise operated torrefaction reactor, but the stages are basically the same for continuous operation. Five main stages have been defined:

· **Initial heating**. The biomass is initially heated until the stage of drying of the biomass is reached. In this stage, the temperature of the biomass is increased, while at the end of this stage moisture starts to evaporate.

· **Pre-drying**. Free water is evaporated from the biomass at constant rate. Its temperature remains practically constant, until the critical moisture content[1] is reached and the rate of water evaporation starts to decrease.

· **Post-drying and intermediate heating**. The temperature of the biomass is increased to 200 °C. Physically bound water is released, while the resistance against mass and heat transfer is within the biomass particles. The biomass is practically free of moisture after this stage. Although not shown, during this stage some mass loss can be expected, as light organic compounds (like terpenes) can evaporate.

· **Torrefaction**. During this stage the biomass is actually torrefied. This stage is entered as soon as the temperature exceeds 200 °C and is ends as soon the temperature becomes below 200 °C again. The stage of torrefaction is contains a heating period and a cooling period, besides a period of constant temperature. The torrefaction temperature is this constant temperature, which may also be a peak temperature. Devolatilisation (mass loss) starts

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[1] The moisture content at which the drying kinetics change from constant rate of evaporation to falling rate of evaporation is called the critical moisture content. At that point pore diffusion becomes the rate limiting step. For biomass the critical moisture content is generally in the range of 5 to 10% wt.

during the heating period, continues during the period of constant temperature and stops during or after the period of cooling.

· **Solids cooling**. The solid product is further cooled from 200 °C to the desired final temperature. During this period no further mass release occurs, but some evaporation of adsorbed reaction products may occur.

Figure 2.5 illustrates that the largest heat duty is encountered during the drying of the biomass. This, however, depends on the initial moisture content, so that the stage of drying may not be present for seriously dry biomass. The second-largest heat duty is encountered during the post-drying and intermediate heating and the smallest heat duty is concerned with torrefaction itself. The required heat during the period of constant torrefaction temperature reflects the endothermic nature of decomposition reactions. However, it can also be a cooling duty, as torrefaction can be exothermic as well. This depends on the type of biomass and the decomposition regime (see Section 2.1.1).

The reaction time is defined as $t_{tor,h}+t_{tor}$. The period of cooling the biomass down to 200 °C is considered to be irrelevant, as the torrefaction reactions are supposed to "freeze" below this temperature. Note that Figure 2.5 clarifies what kind of error could be faced when the reactor residence time is mistaken for the reaction time of torrefaction.
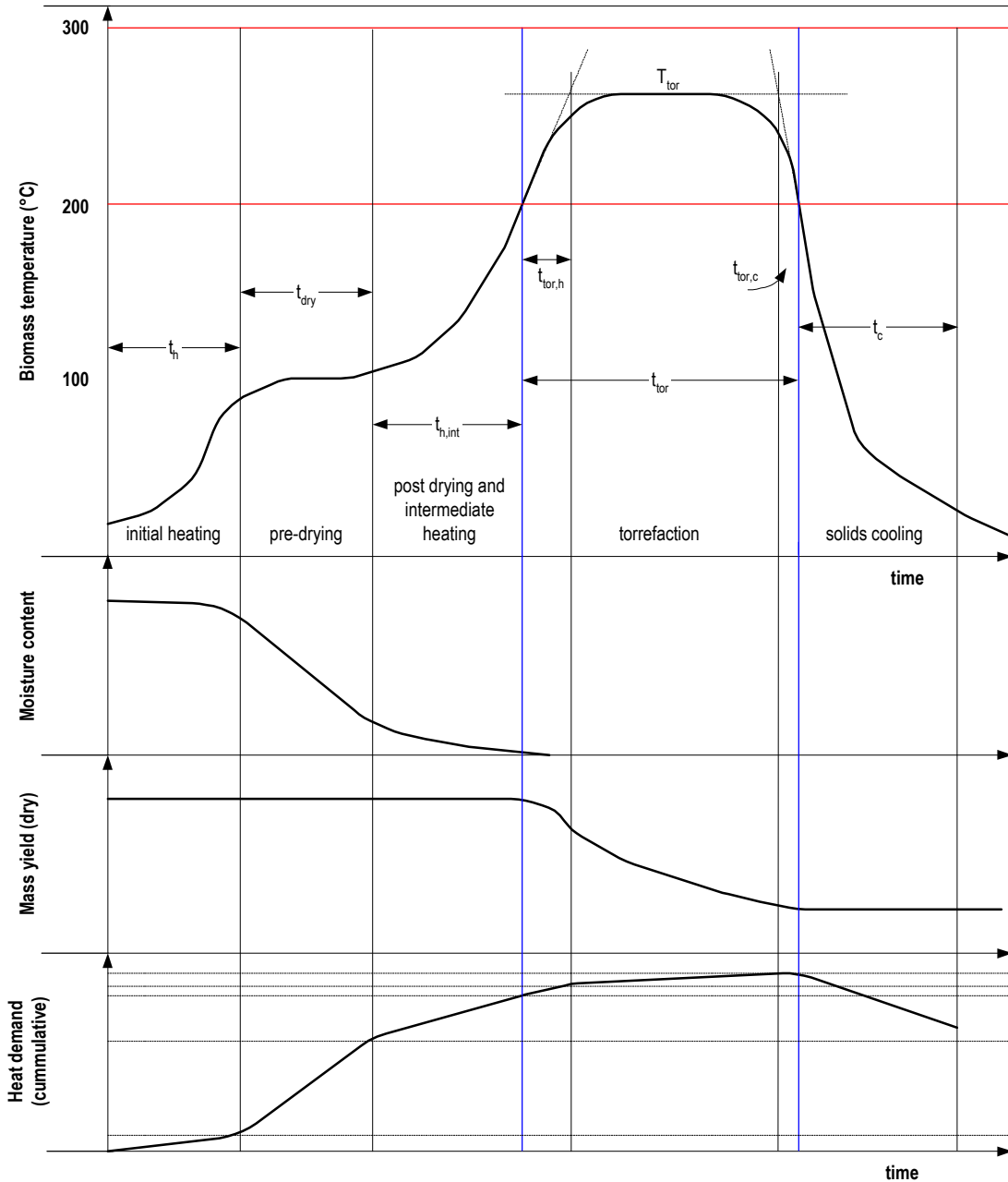
Figure 2.5 *Stages in the heating of moist biomass from "ambient" temperature to the desired torrefaction temperature and the subsequent cooling of the torrefied product. Temperature-time profile is considered to be typical for a batch-wise operated reactor. Explanation: t_h = heating time to drying, t_{dry} = drying time, $t_{h,int}$ = intermediate heating time from drying to torrefaction, t_{tor} = reaction time at desired torrefaction temperature, $t_{tor,h}$ = heating time torrefaction from 200°C to desired torrefaction temperature (T_{tor}), $t_{tor,c}$ = cooling time from the desired T_{tor} to 200 °C, t_c = cooling time to ambient temperature*

2.2 Properties of torrefied biomass (fuel quality)

Figure 2.6 represents the Van Krevelen diagram for various (torrefied) wood, (char) coal and peat samples and provides insight in the differences in their elemental composition (C,H,O). It can be seen that the highest H/C and O/C ratios belong to wood and the lowest belong to coal. Torrefied wood is in the middle and the higher the torrefaction temperature, the more the composition moves from wood to coal. The same goes for an increase of the time that wood is exposed to torrefaction. Apparently, during torrefaction the changes in elemental composition follow a similar pathway regardless of the type of biomass. The elemental composition of charcoal (produced at temperatures exceeding 350 °C) is following the same pathway of torrefied wood, but its composition is more comparable to that of coal. The elemental composition of torrefied wood produced in the higher temperature region is closed to that of peat.
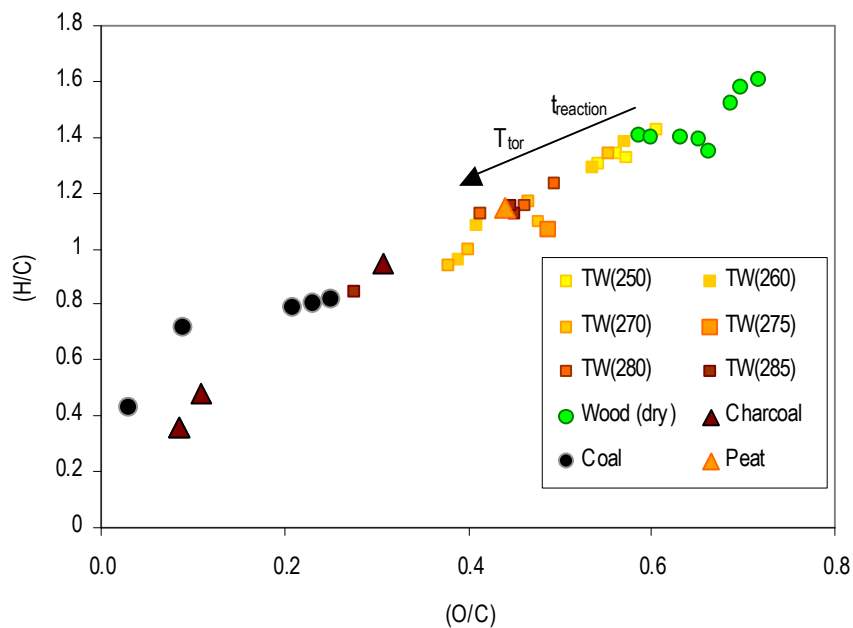
Figure 2.6 *Van Krevelen diagram for torrefied wood (TW) produced at different conditions, untreated wood, coal, charcoal and peat samples. Coal and peat data is taken from Ullmann (1999). Wood and torrefied wood from Bourgois and Doat (1984), Girard and Shah (1989) and Pentananunt et al. (1990)*

From Figure 2.6 it can be seen that biomass loses relatively more oxygen and hydrogen compared to carbon. The main consequence of this is an increase of the calorific value. Depending on the torrefaction conditions, the net calorific value (LHV) is in the range from 18 to 23 MJ/kg or 20 to 24 MJ/kg when the HHV is concerned (dry basis). For comparison, the LHV_{dry} of coal is typically in the range from 25 to 30 MJ/kg and is typically 30 MJ/kg in the case of charcoal. The LHV_{dry} of untreated wood is typically 17-19 MJ/kg.

Biomass is completely dried during torrefaction and after torrefaction the uptake of moisture is very limited. Depending on the torrefaction conditions this varies from 1-6% wt. The main explanation for this is, that by the destruction of many OH groups in the biomass through dehydration reactions, torrefied biomass has lost the capability to form hydrogen bonds with water. In addition, more unsaturated structures are formed which are non-polar and hence it has become hydrophobic to a certain extend. It is likely that this property is also the main reason that torrefied biomass is practically preserved and rotting, which is often observed for untreated biomass, does not occur anymore.

The volumetric density of the biomass changes in a similar way as can be observed for the drying of biomass. It shrinks as a consequence of de-watering. However, shrinkage of torrefied biomass is comparable to that of dried biomass, despite the higher degree of de-watering and the loss of mass to volatiles. As a result, the volumetric density of torrefied biomass ranges from 180 to 300 kg/m^3 (depending on initial biomass density and on torrefaction conditions), which is in the range of 250 to 400 kg/m^3 of (partly) dried biomass and 400 to 800 kg/m^3 for wet biomass.

2.3   Foreseen applications

Due to the advantageous properties of torrefied biomass over untreated biomass, Dryer (1989) mentioned the suitability of torrefied wood as a reducing agent in electrometallurgy (in particular its worth in the production of silicon metal), as fuel for domestic uses (barbeque grill), and as a standard fuel in developing countries. Especially torrefied wood as a reducing agent has been a major driving force for the development of torrefaction, which ultimately resulted in a demonstration plant in La val de Cere (France, mid 1980's). A description of this plant is given in Section 2.4.1.

An important advantage of torrefied biomass is the increased uniformity in product quality. According to Encotec (2001), woodcuttings, demolition wood, waste wood have quite similar physical and chemical properties after torrefaction. Also seasonal influences on these properties are expunged to a large extend (Girard and Shah, 1991). This is a very attractive feature in the light of process optimisation, control, and standardisation in general (governmental-, economic-, and technical processes involved in the biomass energy production chain).

Encotec (2001) mentioned the advantages of torrefied wood in transportation and logistics. As the energy density of torrefied wood is significantly higher compared to untreated wood, larger transportation distances can be allowed. This increases the cultivation area (quadratic) by which more biomass can be exploited without increased production costs (only when the biomass is evenly spread over the cultivation area). The combination with densification to produce pellets or briquettes will make these advantages even more attractive. Another advantage torrefied biomass is the ease of (intermediate) storage, because of the rotting behaviour and hygroscopic nature. This enables uncoupling of production and consumption of torrefied biomass on large scale and the seasonal dependency of biomass availability (harvest periods versus periods of growth).

The improved properties of biomass after torrefaction make it an attractive solid fuel for (energy) conversion processes as combustion and gasification. Serious attention has been paid to its application as a fuel for co-combustion in coal-fired power stations within the last few years. The most important incentive for this is the improved grindability, but also the promising on-site handling properties of torrefied biomass discussed above. As expected, all the advantages offer the possibility to process torrefied biomass in the existing coal infrastructure (see Figure 2.7), without needing significant additional investments.
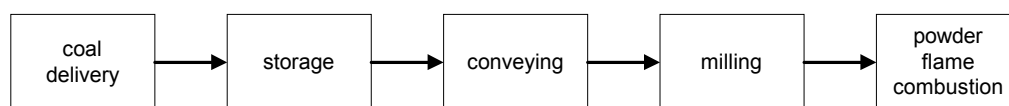
Figure 2.7 *General steps involved in on-site processing of coal at the power station*

Girard and Shah (1991) addressed advantages of torrefied biomass as a fuel for gasification. Experiments using a fixed-bed gasifier demonstrated that a higher calorific gas can be produced against a higher thermal efficiency. Especially the very low moisture content of torrefied biomass contributes to these improvements. According to Girard and Shah (1991), torrefied biomass gasification allows higher gasification temperatures, yields a cleaner gas of constant quality, increases the fixed-bed capacity and decreases the dust content of the gas when substituting charcoal. Bergman *et al.* (2004) demonstrated the applicability of torrefaction as a pre-treatment for the entrained-flow gasification of biomass. For this application, biomass has to

be pulverised to very small particles of sufficient spherical shape to be charged to the gasifier by means of a fluidised bed operated in the smooth regime. This is found to be difficult for fresh (woody) biomass to do in an economic manner.

2.4 Status of production technology

Up till now, no commercially operated torrefaction production plant has ever existed. During the eighties of the last century a demonstration plant was built and operated by the company Pechiney (France), but it was dismantled in the beginning of the 1990's for economic reasons. Since the interest in torrefaction as a pre-treatment technology of biomass for combustion and gasification, new concepts for torrefaction have been proposed, but none have been developed to commercial status or to the stage of technical demonstration. Examples are SHST process (Arcate, 2002), the concept of airless drying, which is under development at CDS (Bioenergy, 2003), and a concept based on rotating drum technology (Duijn, 2004). However, the Pechiney demonstration plant was operated for a few years continuously with a production capacity of approximately 12,000 ton/a, so that this technology is in this work considered as state-of-the art torrefaction technology.

2.4.1 Description of the Pechiney process

Figure 2.8 schematically represents the Pechiney demonstration plant. The process used wood from the forestry in the near surroundings (location La Val de Cere, France) and was designed to produce 12,000-ton/a torrefied wood. The main product by mass was torrefied wood for the metallurgic industry (cokes substitute). The leisure market (e.g. barbeque, cooking) was seen as another market to exploit the produced torrefied wood.

The process consisted of three main sections: chopping, drying and torrefaction (roasting). After chopping, the biomass with typically 40% moisture content was first dried to 10% moisture content before charged to the roaster (torrefaction reactor). Hot air was used for this purpose and this was produced by the combustion of the torrefaction gas. Torrefaction was performed in an indirectly heated reactor. The operating temperature was in the range of 240 °C to 280 °C and the residence time 60 to 90 min. Heat for torrefaction was put in the reactor by means of thermal oil, which circulated between the reactor and the boiler. The boiler was fuelled with wood fines from the chopping section. Product cooling was performed by bringing the hot product in direct contact with water, directly after exiting the roaster. It was cooled to at least below 150 °C to prevent spontaneous combustion. Operation of the process was done such that the desired product quality of the torrefied wood was established. The most important specifications were fixed carbon content and moisture content.

The torrefaction reactor that was applied in the Pechiney process was an indirectly heated screw reactor manufactured by the Swiss company LIST, see Appendix A for a scheme of the reactor. The reactor was especially developed by LIST to serve as a post-dryer of solids with high-added value or products requiring very homogeneous product moisture content. Heat is put in the biomass by means of conductive heat transfer through the shell and screw. The size of the reactor is typically determined by the required heat duty, as the area for heat exchange is limiting. Therefore, the allowed moisture content of the feed is usually limited to 15% maximum and the reactor throughput is limited to about 2 ton/h. A higher moisture content would drop the reactor throughput capacity. Other important characteristics of the reactor are plug-flow characteristics, accurate temperature control (because of the limited heat transfer rates) and long residence time. The reactor requires free-flowing feed particles.

On the basis of technical data that was obtained from interviews with researchers involved with the demonstration plant the energy efficiency was estimated to be in the range of 65% to 75% including feedstock and utility usage (propane as support fuel and electricity). Serious energy losses were encountered due to fines production during cutting and sieving of the biomass feedstock. Without these losses the energy efficiency would have been 82%. The total production costs were estimated in the range of 150 to 180 €/ton product. Without the costs for

biomass feedstock (31 €/ton a.r.), the production costs amounted approximately 100 €/ton product. The investment costs amounted approximately 2.9 M€ in 1985, which is a specific investment of 240 €/ton of installed capacity (annual), or about 25 €/ton product. The investment costs were dominated by the costs of the reactor.
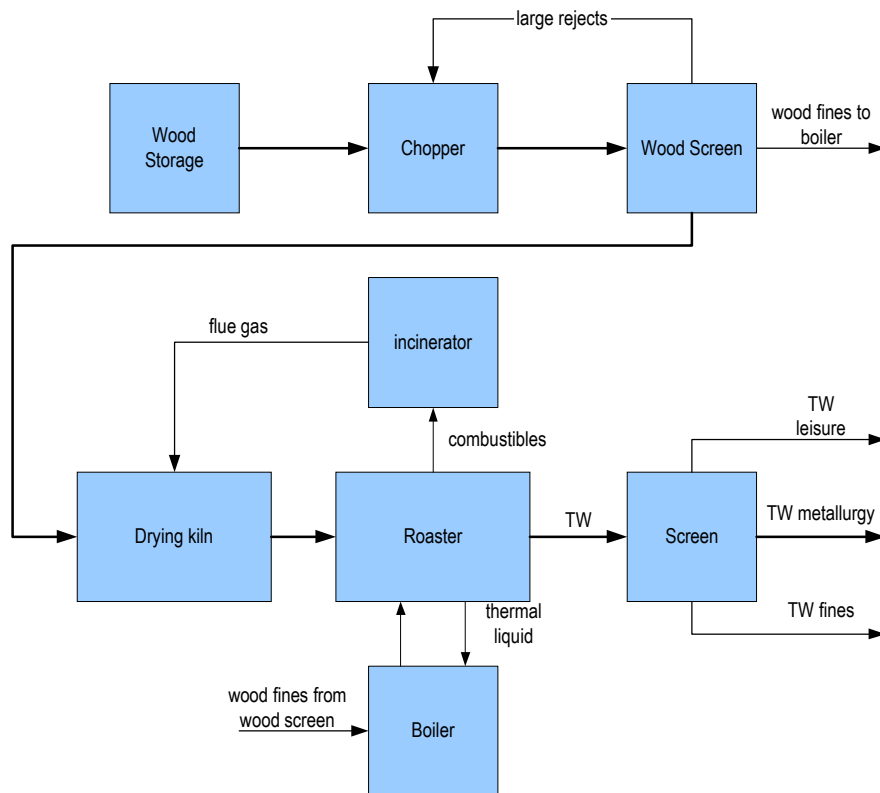
Figure 2.8 *Conceptual scheme of the Pechiney Process*

2.5   Evaluation

Although the Pechiney demonstration plant can be considered as state-of-the art technology and is to be judged technically feasible as it was operated for a few years, its feasibility for large-scale production of torrefied biomass for co-combustion in existing power stations is questioned. Its process its energy efficiency of 82% maximum is insufficient. Partly this may be caused by scale effects (demonstration plant), but may also be caused by the applied torrefaction conditions (especially large residence time). The Pechiney demonstration plant was designed to produce torrefied wood suitable as a reduction agent in the production of aluminium. This required other product specifications (fixed carbon content and moisture content) than relevant to co-firing (predominantly grindability with maximum energy efficiency of production). It is likely that the maintained torrefaction conditions were optimised towards the fixed carbon content, while accepting loss of energy efficiency due to increased devolatilisation.

The current market price (Netherlands) of fuel pellets for co-firing amounts to approximately 100-120 €/ton. When comparing this value to the production costs of the Pechiney demonstration plant (ranging from 100 €/ton to 150 €/ton depending on the biomass feedstock price), it is very likely that this torrefaction based on Pechiney technology cannot compete. The production costs will drop when the process is scaled to more industrial capacities. It is however expected that this will not be sufficient, since the applied reactor technology is expensive and has poor scale-up characteristics. Hence the statement that torrefaction to upgrade biomass for large-scale co-firing purposes is still in the phase of "proof-of-concept" phase, which first needs to be advanced following the objectives formulated in Chapter 1.

3. Considered aspects in the design and operation of a torrefaction production plant

Before presenting the results of the experimental work and process simulations (Chapter 4), and of process design and economic evaluation (Chapters 5 and 6), first the considered aspects in the design and operation of a future torrefaction plant are discussed. Figure 3.1 schematically provides an overview of the considered aspects. Roughly these aspects deal with the process structure, product quality, feedstock properties and performance characteristics of the production plant. These aspects are considered to be crucial in the demonstration of the feasibility of torrefaction and thus the first to be evaluated.
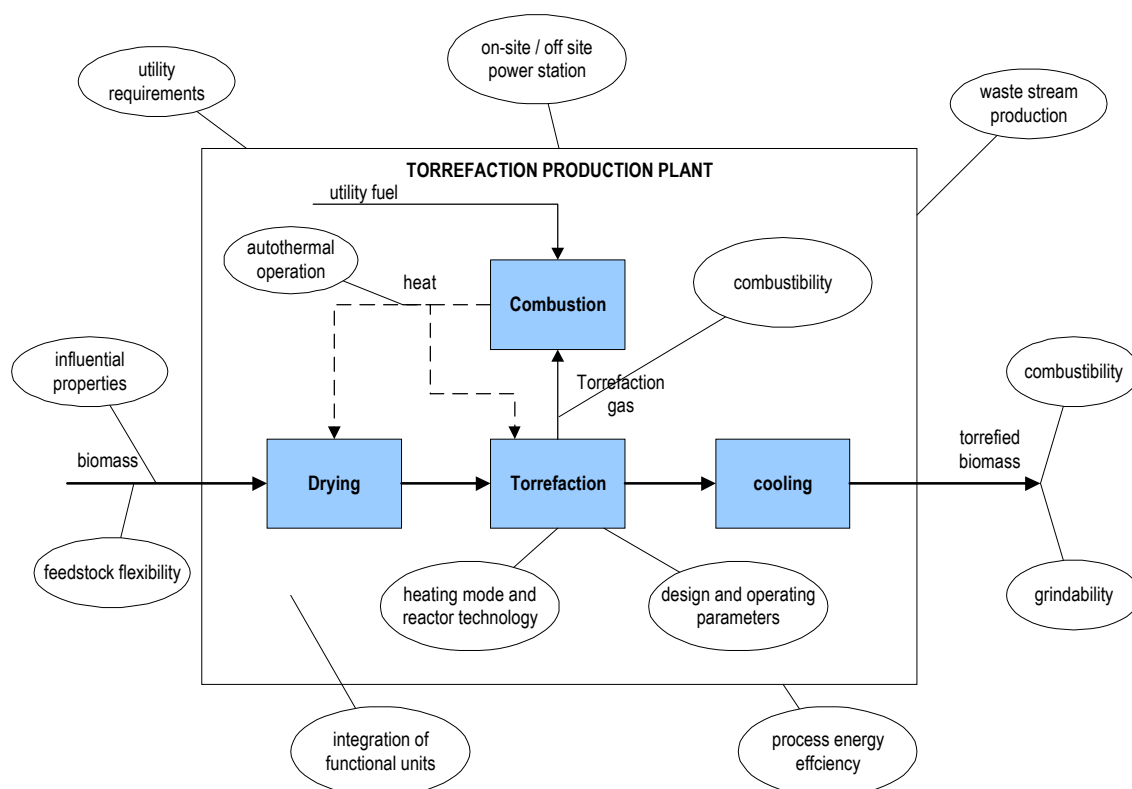
Figure 3.1 *Design aspects considered during this work*

Figure 3.1 reflects the basic conceptual structure of a torrefaction plant, which was taken as a start for further development. It exhibits great analogy with the Pechiney process (see Figure 2.8). A typical torrefaction process is presumed to comprise drying of the biomass feedstock to have a biomass feed of constant moisture content to torrefaction, which also implies a more or less constant heat duty to be delivered to the torrefaction reactor. Furthermore it is expected that the best destiny for the liberated torrefaction gas is to combust it to generate heat for the drying and torrefaction processes, which requires a combustible torrefaction gas.

The torrefaction process organised in this way is considered to reflect an off-site situated production plant, meaning that the process is self-supporting when it comes down to the heat demand and is not integrated with the power station. The discussion on possible advantages of integrating torrefaction with the power station is held later on in this Chapter (Section 3.1.3).

3.1 Process layout and technology related aspects

3.1.1 Combustibility of the torrefaction gas

The torrefaction gas consists of a wide variety of combustible organic components. However the components that dominate its composition are incombustible (water and CO_2). From the given product distribution in Figure 2.4 it can be observed that the torrefaction gas is rather wet. Even when completely dry biomass is torrefied, it must be expected that the torrefaction gas has a water content of over 50% wt and a CO_2 content of about 10% wt. Hence in total the torrefaction gas will at least consist of about 60% wt of incombustible components. The exact amount will be determined by the applied conditions, but also significantly by the moisture content of biomass feed. It is thus questionable if the torrefaction gas can be combusted.

When the torrefaction gas is to be used as a fuel, it is important to evaluate what the adiabatic flame temperature will be and whether at this temperature a stable combustion process can be expected. This adiabatic flame temperature needs to be higher than the temperature of auto ignition of those components present in the gas that are most difficult to combust. A typical value of 400°C difference between the adiabatic temperature rise and the ignition temperature of these components is at least required to speak of a combustible gas. Analysis of the experimentally derived composition of the torrefaction gas revealed that CO and phenol have the highest ignition temperature, which for both components is approximately 600 °C. Hence an adiabatic flame temperature of ± 1000 °C is required to have a fully combustible torrefaction gas.

3.1.2 Autothermal operation

In case of autothermal operation, the energy content of the torrefaction gas balances the heat duty of drying and torrefaction and heat losses encountered elsewhere in the process (e.g. during product cooling and to the environment). Two other scenarios than autothermal operation are possible:

(1) the process is operated below the point of autothermal operation. This is the case when the torrefaction gas does not contain sufficient energy so that an additional fuel is required to operate the process.

(2) The process is operated above the point of autothermal operation. This is the case when the torrefaction gas contains too much energy, energy needs to be withdrawn by some utility or by-product (e.g., cooling water or by-production of steam).

Especially scenario (2) is important to the (energy) efficiency of the process. When the torrefaction gas contains too much energy, torrefaction has been carried out under too extreme conditions resulting in loss of product. Hence the process energy efficiency of the process is harmed as energy is "thrown away", but this can be necessary when only then the desired properties of the torrefied biomass are obtained.

3.1.3 Off-site or on-site torrefaction and co-production of heat and power

Two typical plant configurations have been identified; the off-site and on-site production plant. In the case of an off-site production plant, it is not integrated in any way with the power station, which is the case when torrefied biomass is produced at a location rich of biomass and transported to the power station. This is in contrast to an on-site production facility where torrefaction and the actual power production may be coupled through heat integration. In that case the untreated biomass is delivered to the power station. Next to the production of torrefied wood, the process may also be configured to produce other products such as heat and power. This can be attractive in scattered areas to co-produce heat and power for the surroundings or district heating. Examples of this can be found in the field of biomass pellets production, as for instance the combined pellet and heat production plant at Norberg in Sweden (Mared, 2002).

Possible benefits of the on-site variant must come from the possibilities to use heat from the power station for the drying and torrefaction operations in the torrefaction production plant.

Depending on the configuration of the torrefaction process, this would require heat, likely steam, of about 300 °C. Such heat is not directly available and requires modifications in the set-up of the existing power station. It will influence the point of operation of the power station (steam capacity) and hence its electrical power output and electrical efficiency. Heat integration would require transport of heat from the power station itself to the torrefaction plant with only little losses allowable to the environment. By the heat integration the operation of torrefaction and the power station become highly dependent on each other and perturbations in the operation of one will influence the operation of the other. These aspects will likely make the costs of heat integration or the heat itself very expensive and complicated so that the on-site variant is not most attractive for an existing power station. In the case of a new power station, however, this may not be the case as the design can be optimised to both processes. Nevertheless, it is also recognised that the on-site variant cannot benefit from the advantages torrefied wood may offer in transport and logistics (see also Section 2.3).

3.1.4 Reactor technology (heating mode) and process concepts

A typical torrefaction reactor needs to combine two main process tasks. These are heating the biomass to the desired torrefaction temperature and holding it at this temperature for a specific period of time. In the case the biomass is pre-dried, this corresponds with the "Post-drying and intermediate heating" and "torrefaction" time-temperature stages defined in Section 2.1.4 (see also Figure 2.5). Without pre-drying also the stages of "initial heating" and "pre-drying" are housed in the torrefaction reactor.

The basis for suitable torrefaction reactor technology may come from three main fields known for biomass: drying, pyrolysis (carbonisation), and gasification. The (reactor) technology applied in these areas can roughly be divided in two main categories:

·   **Indirectly-heated**. The biomass is in indirect contact (by means of a wall) with the heat carrier. The indirectly heated (with oil) screw reactor applied in the Pechiney process is a good example. Most of the carbonisation and slow pyrolysis processes are based on this principle (rotary kilns, indirectly-heated screw reactor), but also some drying technology is based on this technology (e.g. steam tube dryer, superheated steam dryers).

·   **Directly-heated**. The biomass is brought in direct contact with a gaseous heat carrier. The reactor proposed in the superheated steam torrefaction concept is such a reactor. Most of the drying technology (conductive dryers) is based on this technology; louvre and rotary drum dryers, tunnel dryers, fluidised bed dryers. Also many gasification technologies are based on this principle (moving-bed, fluidised bed, entrained-flow), but with the remark that in gasification the biomass is partly oxidised.

Both these two reactor types were taken as a basis to develop an integral torrefaction process; The main process structure of the indirectly heated process turned out to have great similarity with the Pechniney process, see Figure 3.2. The directly heated torrefaction process turned out to have a rather different process structure due to different principle of charging heat to the reactor, see Figure 3.3. With respect to the objective to identify process concepts superior to that of the Pechiney process, most is to be expected from directly heated process.

The proposed indirectly heated process differs from the Pechiney process with respect to heat integration. In the Pechiney process two combustion processes took care of the heat supply. Furthermore, the concept comprises one combustion unit in which the torrefaction gas is combusted, possibly in combination with a utility fuel when the energy content of the torrefaction gas is insufficient for autothermal operation. Part of the heat present in the flue gas is used to heat up circulating thermal oil that provides the torrefaction unit with heat. Subsequently, the same flue gas is used to provide heat to the drying process.
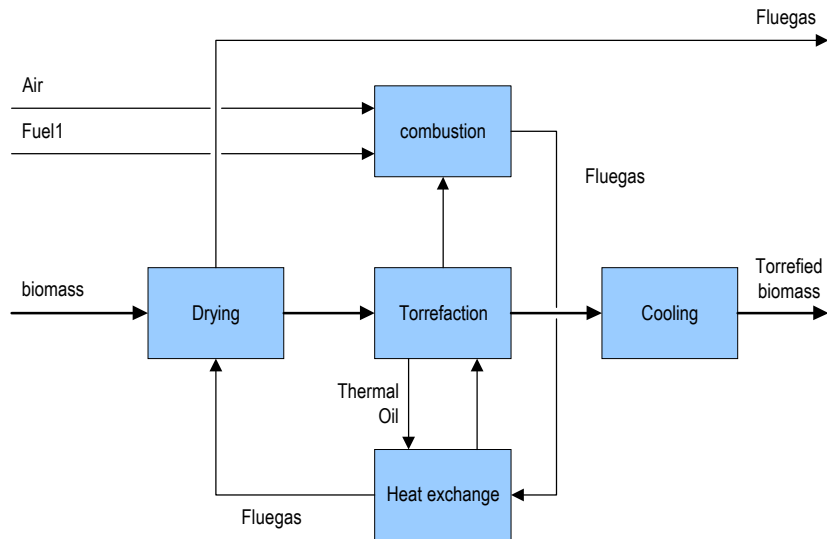
Figure 3.2 *Simplified basic concept for indirectly heated torrefaction*

In directly heated torrefaction, the required heat for torrefaction also comes from the combustion of the torrefaction gas, possibly together with a utility fuel, though gas instead of a thermal oil is used as a heat carrier. The hot gas gives off heat in the torrefaction reactor by which it is cooled. During its pass through the reactor it is mixed up with the produced torrefaction gases. Part of the reactor exit gases is charged to combustion and its flow rate equals the rate of torrefaction gas produced in the reactor. The remainder re-pressurised (step DP in Figure 3.3), heated and returned to torrefaction. As no use is made of a utility gas, the gas recycle consist of torrefaction gas with a composition similar to the gases produced during torrefaction.
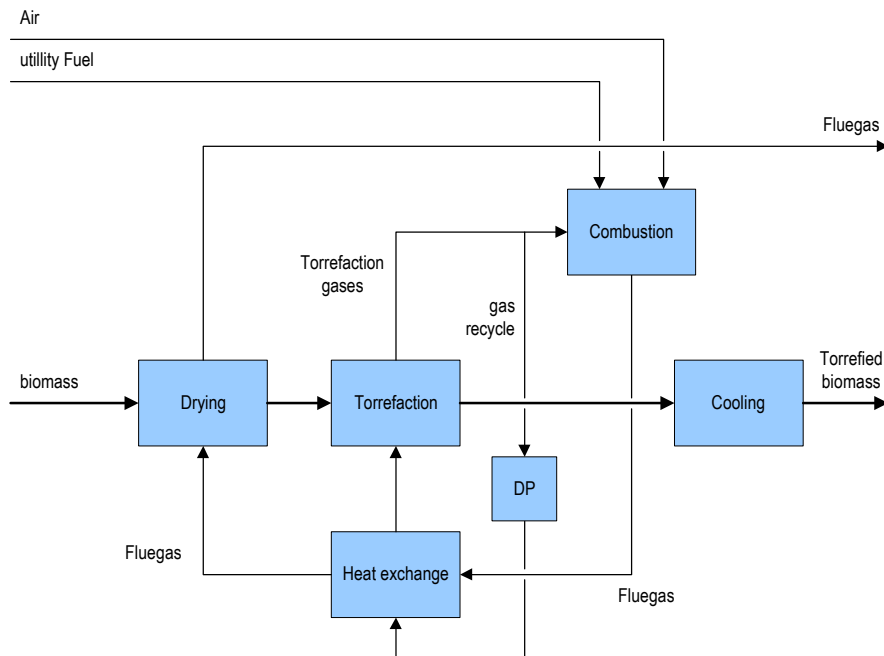
Figure 3.3 *Basic concept directly heated torrefaction*

In comparing the directly heated process to the indirectly heated process, the main differences are caused by the gas recycle requiring a gas re-pressuring operation to enable the recycling of the gas, and the heat exchange is between two gases instead of between gas and oil. Problems that can be of influence on the operation of the gas recycle are related to the nature of the

torrefaction gas. Dust may lead to complications and heavier volatile components can condensate on cold surfaces and so foul equipment (similar to tar in biomass gasification). In addition, the heat exchange between two gases is less effective and more difficult compared to heat exchange between gas and oil. However, the directly heated concept has the major advantage that the direct heat exchange between gas and the solids is much faster. This will contribute to the minimisation of the required reactor volume and complexity so that the capital costs of torrefaction can still be reduced, despite the possible penalties discussed above.

3.2 Performance related aspects

3.2.1 Process energy efficiency

One of the most important aspects to evaluate pre-treatment techniques on is their process energy efficiency. The energy efficiency is in direct relation to the feedstock demands and since the prices of biomass feedstock is often the main cost-driver (or even showstopper), significant energy losses during biomass pre-treatment are unacceptable. In addition, the lower the energy efficiency, the lesser its sustainable nature.

The process energy efficiency can be expressed in two ways; on the basis of the higher heating value (HHV) or on the lower heating value (LHV). The higher heating value represents the absolute amount of energy and the lower heating value represents the retrievable amount of energy from the biomass without flue gas condensation. In practice efficiencies expressed on LHV basis provide a better impression of the efficiency of a process, since they show how efficient the usable part of the energy content of biomass is converted into products. This gives the following definition:

$$\eta_P = \left(\frac{F_{prod} LHV_{prod}}{F_{feed} LHV_{feed} + E_{util}} \right)_{ar} \tag{4}$$

Hence it is defined as the ratio of energy flow of product over the sum of energy input through the feedstock and utilities (E_{util}). Utilities can either be sensible/latent heat carriers (e.g. steam), chemical energy (fuels like propane or natural gas), or electricity. The process energy efficiency is also called the net energy efficiency of the process when the effect of electricity consumption is included. This can only be determined when it is known which technology is to be used and what power requirements are. In this work also the thermal energy efficiency is used, which represents the energy efficiency excluding electricity consumption, but including other (energy) utilities.

The process energy efficiency is not similar to the energy yield of torrefaction. The energy yield of torrefaction describes the transfer of chemical energy from the biomass to the solid reaction product (torrefied biomass), but it does not quantify how efficient the utilisation of the torrefaction gas proceeds and how much energy is charged to the process by means of utilities. The energy yield of torrefaction can be low, whilst the process efficiency is high (or opposite). It is considered important to be aware of the difference between the energy yield of torrefaction and the process energy efficiency, as many in publications the high energy yield is emphasised to be a key parameter. This must, however, always be related to the process energy efficiency corresponding with operational conditions under which the torrefied biomass is produced.

3.2.2 Feedstock flexibility

Depending on the availability of possible biomass feedstock (type and amount), a certain degree of flexibility of the production plant is necessary. The principles of torrefaction can theoretically be used to upgrade practically all woody and herbaceous biomass, and even biomass containing mixed streams (waste streams, including plastics and other). However, the applied technology will strongly limit the allowable variation in feedstock properties of which size and shape characteristics are the most important ones. Furthermore contaminated streams such as demolition wood or dry industrial wastes containing amounts of for instance paint (organics)

synthetic polymers may influence the composition of the torrefaction gas. Hence, different combustion characteristics including stack emissions can be expected and they may set more stringent specifications to the applied technology (used materials and principles) and may require specific gas cleaning technology. Besides the technical aspects, also the product quality is depending on these possible contaminations.

When the torrefaction production plant is based on a single type of feedstock, its design can be specific. However, when the plant needs to produce torrefied biomass from a variety of feedstock, the torrefaction technology requires a MISO approach (Multiple Input, Specific Output), meaning that especially the reactor technology must be flexible in processing different types of feedstock regarding hydrodynamics, solids transportation and operating conditions.

3.2.3 Utility consumption

From the viewpoint of utilities consumption, two main aspects need to be considered; type and availability. When the torrefaction production plant is located at a well-developed industrial site comprising utility production, various utilities are available and delivery is more or less guaranteed. When the torrefaction plant is located in areas of low industrial activity this is not the directly the case. Furthermore, the use of the amount of type utilities fuels (such as propane, natural gas, or steam generated with fossil fuels), must be carefully considered, as fossil fuels decrease the sustainable nature of torrefaction. Sustainable utility fuels may be preferred, like part of the feedstock, dried feedstock, or even part of the produced torrefied biomass, or another source that is available.

3.2.4 Production of waste streams and emissions

As in any production process, the production of waste streams needs to be avoided or minimised as much as possible. The torrefaction processes represented by Figure 3.2 and Figure 3.3 are closed systems and thus waste streams are avoided through the process structure. Nevertheless, a waste stream may occur from the treatment of the torrefaction gas when it cannot be combusted (as proposed in the presented concepts) or through the way the hot product discharged from the torrefaction reactor is cooled. For instance, in the Pechiney process cooling of the hot product was conducted by direct contact with water, which resulted in a wastewater stream. Emissions to air can be encountered as a consequence of drying of the biomass. They can also be a consequence of the combustion of the torrefaction gas (e.g., NO_x and VOCs). This will depend on the quality of the converted feedstock and the applied torrefaction conditions.

3.3 Product quality related aspects (and design and operating conditions)

Eventually, torrefaction is only attractive when the produced torrefied wood meets the required fuel specifications. All torrefied wood properties discussed in Section 2.2 are relevant in this respect, but the in the first place focus is set to the grindability and combustion characteristics. Especially the grindability of torrefied biomass is considered to be crucial in whether torrefaction is useful for biomass co-firing in existing power plants. The properties of torrefied biomass are mainly dependent on the torrefaction conditions (except some geometrical properties and/or density related properties) under which it is produced so that product quality and applied operating conditions are in direct relationship. The effect of torrefaction conditions on the grindability was considered the most important relationship to reveal from the experimental programme.

Useful work done by Bergman *et al.* (2005) was performed parallel to this work. They investigated the influence of torrefaction on the grindability for different biomass and developed a measurement method of the grindability (based on a cutting mill). Torrefaction conditions were varied in the range of 230 °C to 280 °C and 8 to 45 min reaction time. A dramatic

improvement of grindability was observed above 250 °C. Maximum improvements were found for a reaction time typically of 30 min, but a considerable improvement in grindability was observed also for a reaction time as low as 8 min. The improvement involved both the power consumption and capacity of the applied cutting mill. Torrefaction resulted in a reduction of the power consumption of 50-85% and the capacity of the used cutting mill increased with a factor 2-6.5 compared to untreated biomass with 10-15% moisture content.

Based on the findings of Bergman *et al.* (2005), the operating window of torrefaction was narrowed from the general range of 200 °C to 300 °C and a typical time scope of 1 hr, to 250 °C to 280 °C with a typical time scope of <30 min reaction time. Figure 3.4 includes these ranges, as they are incorporated in an artist impression of the operating window of torrefaction. On the axis the torrefaction temperature and reaction time are depicted and they are related to product quality and energy efficiency. The boundaries of the given areas are indicative and serve to illustrate the operating window of torrefaction.
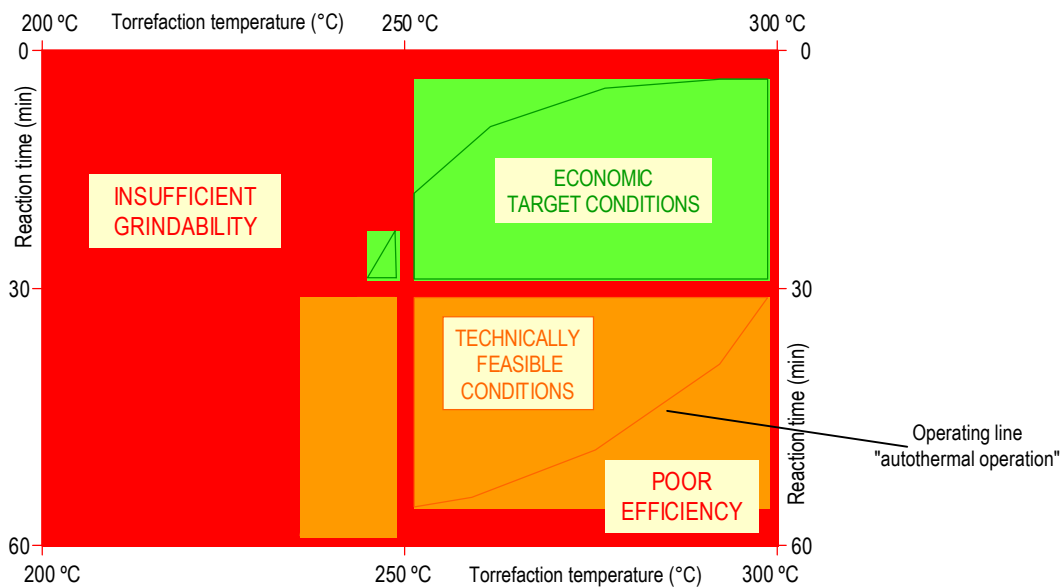
Figure 3.4 *Artist impression of the operating window of torrefaction*

The operating window comprises four different areas in which the torrefaction reactor can be operated. In the area of "insufficient grindability", the conditions are not vigorous enough to produce torrefied biomass with sufficient grindability. At too vigorous conditions (high temperature and long reaction time), however, the grindability will be sufficient. But then the devolatilisation will be too severe, so that the process will be operated above the point of autothermal operation (see Section 3.1.2). In between these areas, operation leads to torrefied biomass with sufficient grindability, whilst maximal (optimal) energy efficiency is obtained. As minimisation of the reaction time is one of the targets to optimise the process (economically) the area of "economic target conditions" is favoured. The best operating conditions are expected to be near 300 °C and an as short as possible reaction time (upper right corner).

Figure 3.4 includes the transitions in grindability and autothermal operation, but can be extended with transitions in other important fuel properties (e.g. combustibility) or important operational aspects such as combustibility of the torrefaction gas. The depicted boundaries need to be experimentally explored, which is discussed in chapter 4.

4. Experimental work and process simulations

4.1 Approach

The previous chapter explained various aspects of torrefaction that need to be addressed. Some of these aspects could be further examined (quantified) experimentally (e.g. mass and energy yield, product distribution, grindability and combustibility of torrefied biomass). Others were only examinable by means of process simulations (e.g. mass and energy balance of the integral process, thermal process efficiency, autothermal operation and combustibility torrefaction gas). Therefore, an approach was chosen in which experiments and process simulations were combined. Figure 4.1 illustrates this approach. The parameters called the critical moisture content (MCA) and the biomass usage factor (BUF) were defined to evaluate the autothermal operation of the process. Both are explained in Section (4.3).
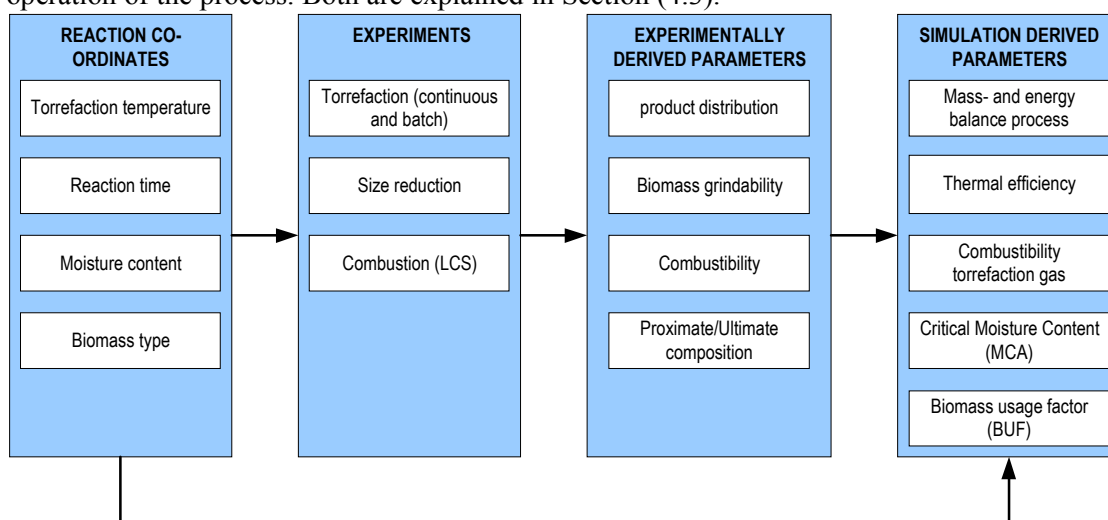
Figure 4.1 *Experimental approach of combining experiments with process simulation*

Experimental procedures were developed and facilities optimised to carry out torrefaction experiments, batch-wise and continuous-wise using a batch reactor and an indirectly heated screw reactor. With respect to analysis methods special attention was paid to the sampling and analysis of the torrefaction gas (to yield the product distribution), and to the quantification of the grindability. With respect to the latter, the applicability of the Hardgrove Grindability Index (HGI) measurement technique was considered. This technique is widely used to quantify the grindability of coal, but it was found to be difficult to translate the results obtained from it for (torrefied) biomass, see Appendix B.2.2. Though it is believed that the technique can be used, the modifications and evaluation thereof were considered to be outside the scope of this work. Instead, an alternative method developed by Bergman *et al*. (2005) has been applied and is based on size reduction experiments using a cutting mill. This method quantifies the grindability on the basis of the power consumption of the mill, see appendix B.2.2. Standard analyses were applied to determine the proximate and ultimate composition of feedstock and product and to determine the combustibility of the (torrefied) biomass. The combustibility of the (torrefied) biomass was determined in the lab-scale combustion simulator (LCS) available at ECN. An overview of the used experimental facilities and (developed) analysis methods is given in Appendix B.

4.2 Conducted experimental programme

The conducted torrefaction experiments focussed on the torrefaction operating window that is described in Section 3.3 as the "economic target conditions" (Figure 3.4). Hence, the torrefaction temperature was varied in the range of 250 °C to 300 °C and the reaction time was varied from ±7.5 min to 30 min. Three different biomass were used: willow, woodcuttings and demolition wood. Willow and woodcuttings represented typical green wood that has a high moisture content (35% to 50%). In contrast, demolition wood generally consists of old wood with low moisture content (15%-25%). Both were typically chip-size (typical size: 10x20x40 mm)[2]. Figure 4.2 explains the torrefaction conditions that were applied.
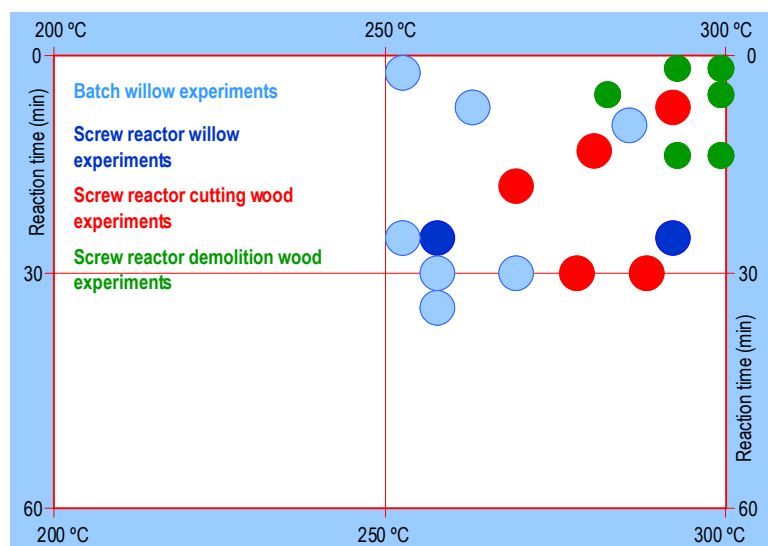
Figure 4.2 *Representation of conducted experiments with respect to the torrefaction-operating matrix*

Three experimental campaigns were conducted with in between evaluations of the experimental procedures and results obtained from the experiments and process simulations. Experiments using the batch reactor were done on willow and served as pinpoint experiments. Subsequently, in a second campaign willow and woodcutting torrefaction experiments were carried out to further explore the desired operational area. In a third campaign screw reactor experiments were carried out to examine conditions of (extremely) short reaction time and high temperature, for which optimal economics were to be expected.

4.3 ASPEN simulations

ASPEN simulations were performed to obtain the simulation-derived parameters. For this a dedicated property set of the involved components was generated. A database structure was developed to process the data produced during the different steps of Figure 4.1 to eventually produce integrated results. The integral results of each experiment were put together in a so-called design matrix to provide an integral overview of the most important parameters of the process and to evaluate the torrefaction process, see Figure 4.3. Using ASPEN, a template simulation tool was constructed on the basis of the scheme given in Table 4.1, which also summarises the main input data of the simulation. The flow sheet is based on stand-alone torrefaction wherein part of the biomass feedstock may be co-combusted with the torrefaction gas to meet autothermal operation in the case the torrefaction gas does not contain sufficient energy. To track the autothermal nature of the process, a parameter called the biomass usage

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[2] size in diameter x width x length (mm).

factor (BUF) was introduced. This parameter is defined as the ratio of stream 2a over stream 1 and so expresses the amount of biomass that is charged to drying. A BUF smaller than 100% means that part of the biomass is co-combusted (100%-BUF), a BUF of 100% means autothermal operation. The simulations are performed primarily on the basis of the mass and energy yields of torrefaction that were determined experimentally. The flow sheet calculates the mass and energy balances of the process while accounting for heat losses to the environment and the balances are solved for a production rate of 150 MW_{th} of torrefied biomass. This capacity corresponds with a typical co-firing rate of 10% on energy basis for an existing 600 MW_e power station.

Generally, the simulations have been conducted for biomass with a default moisture content of 50% wt. However, a standard sensitivity analysis was performed to see the influence of moisture content on the main process characteristics, in particular the thermal energy efficiency. An evaluation parameter MCA was introduced, which stands for the (virtual) Moisture Content corresponding with Autothermal operation. At this moisture content of the biomass feedstock (stream 1 of the flow sheet, see Table 4.1) the process can be operated at maximum thermal energy efficiency whilst only the energy content of the torrefaction is utilised (no additional utility fuel: BUF = 100%). In the case the biomass feedstock has lower moisture content than the MCA, the torrefaction conditions were too severe so that too much energy is driven off the biomass into the torrefaction gas. When the biomass feedstock has higher moisture content, the process is operated below the point of autothermal operation and a utility fuel is needed (BUF < 100%).

Table 4.1   *Simplified representation of the Aspen flow sheet and used standard settings to evaluate the torrefaction conditions (experimentally derived) on important process characteristics*
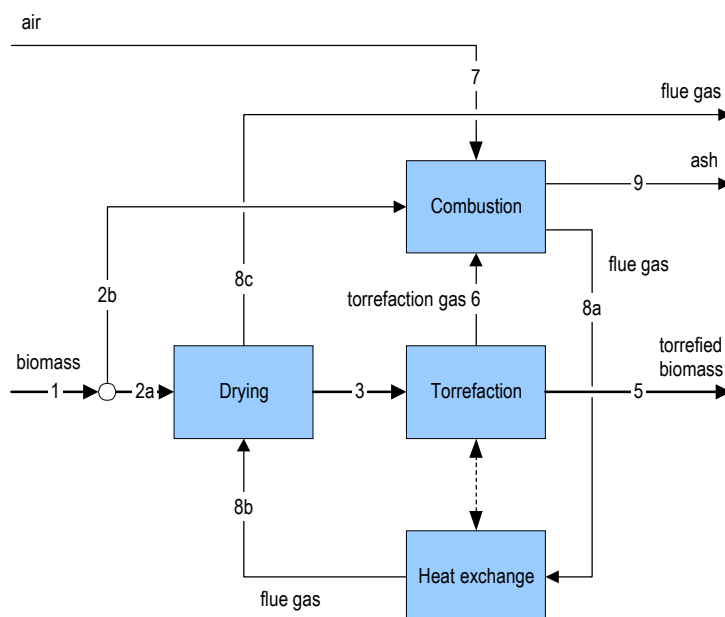
Parameter	Unit	Value	Remark
Energy production rate process (**5**)	MW$_{th}$	150	Output rate is on as received basis and corresponds with a possible co-firing rate of 10% in a coal-fired power station.
Moisture content biomass feedstock (**1**)	% wt.	50	Corresponds with typical value for "green" biomass.
Ambient temperature	°C	20	Inlet temperature of input streams (combustion air, biomass) are set to this temperature
Flue gas stack temperature (**8c**)	°C	140	Set to this value to ensure absence of water condensation
Biomass exit temperature drying (**3**)	°C	110	
Heat loss drying	%	0.5% HHV biomass feedstock	Represents losses to the environment
Heat loss torrefaction	%	0.5% HHV biomass feed to torrefaction	Represents losses to the environment
Heat loss combustion	%	1% HHV fuel input	Based on the average calorific value of the torrefaction gas and biomass feedstock

4.4   Results (Design matrix)

Figure 4.3 represents the main design matrix that combines the most important torrefaction process parameters and process characteristics as a function of torrefaction temperature and reaction time. The main torrefaction parameters are calorific value and the mass and energy yield. The included process parameters are the adiabatic flame temperature (T_{ad}), the biomass grindability index (BGI), the BUF, the MCA, and the thermal energy efficiency.

Figure 4.3 *Torrefaction design matrix combining mass and energy yield with important process characteristics (combustibility torrefaction gas, grindability and process efficiency)*

The blue areas represent the expected areas of insufficient grindability (left area) and the area of insufficient grindability (right area). Both areas were interpolated on the basis of the points of operation (in grey) that were evaluated experimentally. The experiment carried out for woodcuttings is shown in detail and was torrefied at 280 °C and 17.5 min reaction time.

4.4.1 Thermal energy efficiency and autothermal operation

When considering the thermal efficiency of the process, values ranging from 90% to 103% and typical value would be 95% on LHV basis. No structural trends with torrefaction temperature and reaction time were observed; the thermal energy efficiency is more or less constant within the examined operating window. The observed spread is mainly contributed to the inaccuracy of measurement method used for the determination of the higher calorific value analysis, see Appendix B.2.1. By this method a relative error of ±3% is produced[3], which nearly explains the observed variations. In addition, the applied demolition wood was found to be heterogeneous in composition (spread in ash content and some plastics have been observed) so that the biomass sampling method also can be of influence.

A few phenomena form the basis for the high thermal efficiency. These are explained on the basis of Figure 4.4 representing the net energy flows of one of the points of operation. The first important phenomenon is the LHV efficiency of drying. Although this process is very energy intensive, it has the advantage that it increases the calorific value of the biomass (LHV basis). In Figure 4.4, 22.2 MW$_{th}$ is used for drying of the biomass from 50% to 15%. This increases the calorific value resulting in an energy flow from 135.7 MW$_{th}$ before and 152.8 MW$_{th}$ after drying. The corresponding thermal energy efficiency of drying is 96.7%.

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[3] The spread in process efficiency for 95% yield would range from 92.2% to 97.9%, which is considered fairly large with respect to the observed variations in process efficiency.

Figure 4.4 *Energy flows (in MW$_{th}$, red = LHV, black = enthalpy, Q = duty) corresponding with torrefaction of woodcuttings at 280 °C and 17.5 min reaction time (see Figure 4.3)*

Although torrefaction itself has an energy yield of 95.8% at the applied conditions, no energy is lost as the energy of the torrefaction gas is fully utilised through combustion. This brings the torrefaction efficiency at practically 100% when neglecting heat losses to the environment. Therewith, the thermal energy efficiency of the whole process is basically determined by the thermal efficiency of drying and is in practice a little lower due to heat losses to the environment during torrefaction and combustion (*viz.* 96.7% for drying and 96.1% for the whole process).

Since the thermal efficiency torrefaction is mainly determined by drying and not by the energy yield of torrefaction, it is also explained why the thermal energy efficiency is practically constant within the examined operating window; as long the energy content of the torrefaction gas can be utilised completely, which is the case for all points of operation that were explored. All examined operating conditions turn out to be below the point of autothermal operation. Note that this holds for a feedstock moisture content of 50%, which was used as default in the ASPEN simulations. When comparing the heat duties of drying and torrefaction in Figure 4.4, it can be observed that the heat duty of the process mainly depends on heat duty of drying and hence the moisture content of the biomass feedstock is a decisive parameter in this respect.
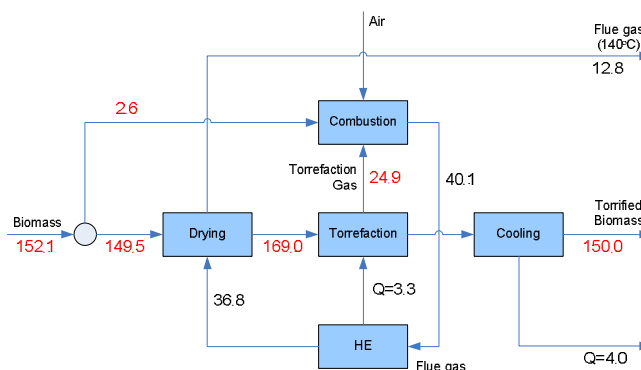
Figure 4.5 *Energy flows (in MW$_{th}$, red = LHV, black = enthalpy, Q = duty) for torrefaction of demolition wood at 300 °C and 10 min reaction time (see Figure 4.3)*

More insight in the autothermal operation of the process can be obtained through the process parameters MCA and the BUF. These indicate how close torrefaction is operated to the point of autothermal operation. At the point of autothermal operation the MCA equals a moisture content of 50% and the BUF equals 100% (*viz.* no biomass is used as a utility fuel). Both these parameters vary with the torrefaction temperature, reaction time and biomass type. It could be concluded that the point of autothermal operation is approached when torrefaction is carried out above 270 °C and a reaction time longer than 20 min, or above 280 °C at short reaction times (5 to 20 min). Under these torrefaction conditions the MCA exceeds 40%. For illustration, Figure

4.5 shows the LHV energy balance of demolition wood torrefied at 300 °C and 10 min reaction time. It points out, that under these conditions torrefaction occurs at such high decomposition rates, that the torrefaction gas becomes the main fuel for combustion.

The energy content of the torrefaction gas is directly related to the mass and energy yield of torrefaction and, for torrefaction conditions of Figure 4.5, an energy yield of 89% almost meets autothermal operation for 50% moisture content of the biomass feedstock.

4.4.2 Product distribution and combustibility of the torrefaction gas

Figure 4.6 represents the mass and energy yields of the different groups of products (permanent gases, organics, lipids and water, see also Section 2.1.2) expressed as unit of mass/energy per unit of mass/energy of biomass feedstock on daf basis). Also the calculated calorific value of the torrefaction gas is given together with the water concentration of the torrefaction gas (% wt.). The water yield and its concentration in the torrefaction gas do not include the moisture from the biomass feedstock.

Figure 4.6 *Torrefaction design matrix combining product yields and the calorific value of the torrefaction gas to torrefaction temperature and reaction time*

The general trend is that all yields (excluding mass yield) increase with increasing temperature and reaction time. This also goes for the energy yield of the different groups. The order in mass yield and energy yield is respectively:

Reaction water >> permanent gases and lipids > organics

Lipids >> organics >> permanent gases (>∞ reaction water)

The yield of reaction water varies between 5 and 15% wt. resulting in a concentration of 50% to 80% wt. in the torrefaction gas (excluding free water from the feedstock). The reaction water yield increases with reaction time and temperature, whilst its concentration decreases. Consequently, the relative contribution of combustible products increases with increased temperature and reaction time. Hence, the calorific value of the gas increases with increased temperature and reaction time. The calorific value ranges from 5.3 to 16.2 MJ/Nm^3. Despite the high water content of the torrefaction gas, the calorific value is relatively high. It can be compared to producer gas from air blown biomass gasification (4 to 7 MJ/Nm^3) and to syngas produced in indirectly heated gasification processes (15 to 20 MJ/Nm^3). On the basis of this comparison, the torrefaction gas should be combustible.

The torrefaction design matrix (Figure 4.3) includes T_{ad} on the basis of 15% wt. moisture content of the biomass feedstock before torrefaction. It ranges from 986 °C to 1473 °C and the highest values are found for demolition wood. Increasing reaction time and torrefaction

temperature increases the adiabatic flame temperature. The minimum temperature of 1000 °C for stable combustion is nearly always achieved, but the margin is not always comfortable. The lowest adiabatic flame temperature is found for conditions corresponding with a high water yield and/or high-energy yield.

Figure 4.7 relates T_{ad} to the moisture content of the biomass feedstock before torrefaction for three points of operation in the design matrix with different energy yields. Point of operation (D,300,10) has a relatively low energy yield (87%) and hence the biomass feedstock can be as wet as approximately 45% wt. to yield a combustible gas. In contrast, point of operation (C,280,17.5) results in a relatively high-energy yield (97%) so that a relatively dry feed is required (< 18% wt.) for a combustible gas.
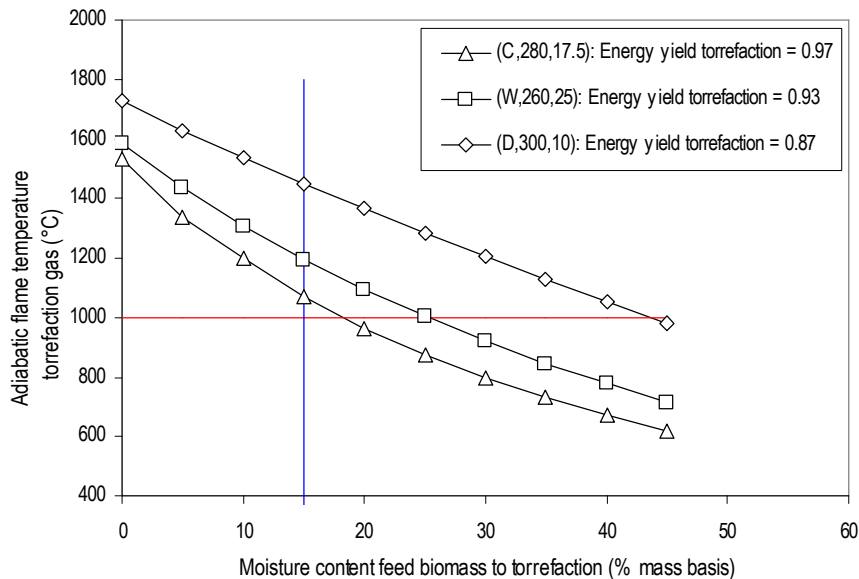
Figure 4.7 *Relationship between the biomass feed moisture content to torrefaction and the adiabatic flame temperature (stand alone) on the basis of ASPEN simulations. Blue vertical curve: moisture content of the biomass feedstock to torrefaction corresponding with Figure 4.6. Red vertical line: minimum required adiabatic flame temperature of the flue gas after combustion of the torrefaction gas. Legend: (biomass type, torrefaction temperature [°C], reaction time [min]), biomass type: C=woodcuttings, W=willow, D=demolition wood)*

As long as the energy content of the torrefaction gas is insufficient for autothermal operation of the process, part of the biomass feedstock is co-fired with the torrefaction gas (BUF < 100%). Therefore, the adiabatic flame temperature corresponding with co-combustion of feedstock and torrefaction gas is dealt with, which is higher compared to only torrefaction gas combustion. This is illustrated in Figure 4.8 for the point of operation (C,280,17.5). Below 15% moisture content of the feedstock, the process is operated above the point of autothermal operation and hence no biomass feedstock is combusted (BUF = 100%) and the flue gas temperature results from solely torrefaction gas combustion. A temperature increase can be observed starting at about a moisture content of 15-20% of the biomass feedstock. This is the point where the BUF starts to drop from 100% and the process becomes operated below the point of autothermal operation. From thereon the temperature increase is caused by co-combusting biomass feedstock of higher calorific value compared to the torrefaction gas. As the moisture content of the biomass feedstock increases further its calorific value decreases so that the flue gas temperature, passes a maximum, and starts to decrease again when the net calorific value of the biomass feedstock drops below that of the torrefaction gas.
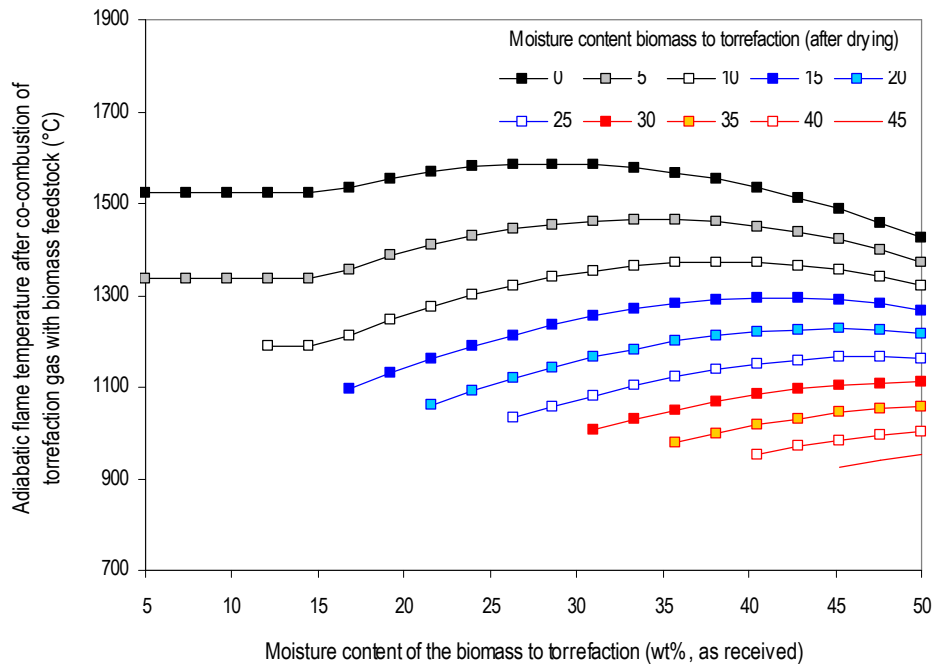
Figure 4.8 *Predicted adiabatic temperature rise after the co-combustion of torrefaction gas with biomass feedstock in relation to the feedstock moisture content and the moisture content before torrefaction (after drying). This plot holds for torrefaction of woodcuttings at 280 °C and 17.5 min reaction time (C,280,17.5)*

In the case of 15% moisture content of the feed to torrefaction, it can be observed that the flue gas temperature is increased due to the co-combustion of 50% moist biomass feedstock. Hence the moisture content of the feed to torrefaction can be as wet as 35% to meet the required flue gas temperature of 1000 °C, instead of 17% for solely combustion of the torrefaction gas. When adding another utility fuel such as natural gas, the gas will normally be combustible at any chosen co-firing rate and for any point of operation in the design matrix (Figure 4.3), since the calorific value of natural gas is much higher compared to biomass.

4.4.3 Grindability

The design matrix represented by Figure 4.3 comprises values for the Biomass Grindability Index (BGI), which were obtained from size reduction experiments carried out on the produced torrefied biomass. The BGI represents the net electricity consumption (in kW_e/MW_{th} of processed (torrefied) biomass) required to produce a powder of 0.2 mm average size. The BGI values were obtained from the so-called power curves, which are shown in Figure 4.9 for several conducted experiments (left graph). Similar plots, but in different units (kWe/kg) can be found in Appendix C.

It becomes clear from Figure 4.9 that the influence of torrefaction on the size reduction of biomass is substantial. From the comparison with untreated willow and woodcuttings it can be observed that a reduction in power consumption up to 80-90% can be established through torrefaction. In addition, the right graph of Figure 4.9 reveals that at the same time a capacity increase up to 10 times that of untreated biomass is possible. It is also noticeable that variations in power consumption within the examined operating window are quite small, which indicates that the influence of the torrefaction operating conditions (reaction time and torrefaction temperature) within the examined operating window is limited. The obtainable capacity increase (right graph) does much more depend on the applied conditions. In general an increase is observed with an increase in torrefaction temperature. This is in line with observations done by

Bergman *et al.* (2004), who also proposed an explanation for the observed effects (see this reference for more details).

Net power consumption curves   Capacity curves
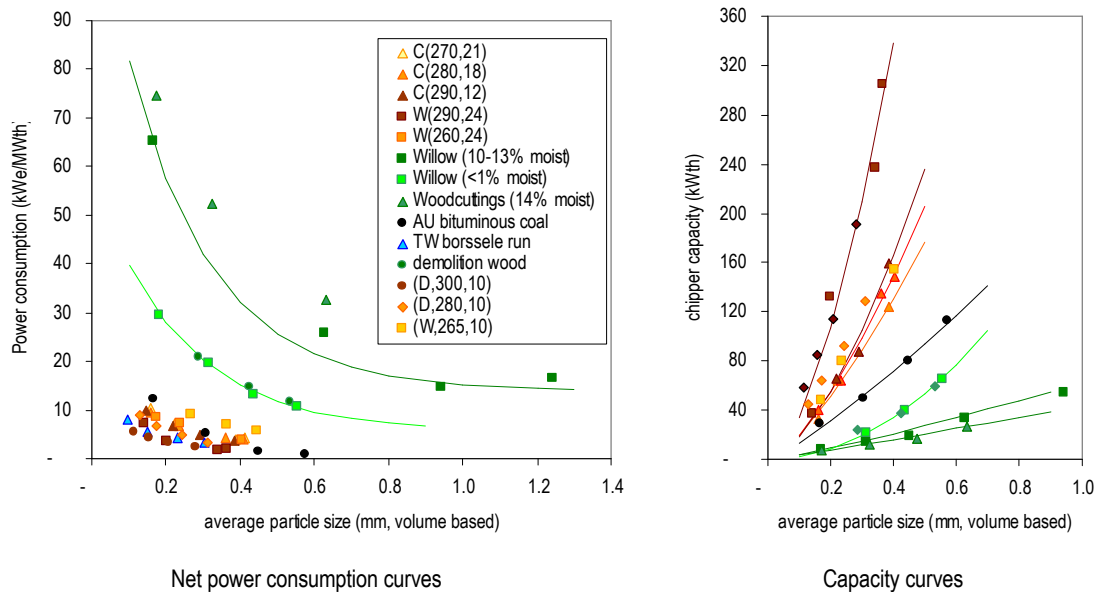
Figure 4.9   *Size reduction results of coal, biomass feedstock, and various torrefied biomass samples*

When considering demolition wood, it can be observed that the power consumption is lower compared to both other biomass types and is comparable to the power requirements of dried willow. This may be related to the low moisture content of untreated demolition wood and that it is aged wood. Also, demolition wood consist of wallboard, which consists of pressed (relatively small) biomass particles.

For comparative reasons, size reduction experiments were also carried out for coal (Australian bituminous coal). It can be observed that the power curves of torrefied biomass and this coal are fairly comparable, Moreover, from the capacity curves it can be seen that torrefied biomass is easier processed. It is expected that the applied method of the grindability quantification (power consumption as parameter) is therefore quite useful to evaluate the process conditions. The grindability method was also evaluated by applying it to a torrefied wood sample obtained from Weststeijn (2004). The sample came from a larger batch of torrefied wood produced for a field test in the Borssele power station in the Netherlands. The main objective of this field test was to determine whether problems would occur in the processing line from coal-mills to the burners when torrefied wood was co-fired. The test was successful. From Figure 4.9 it can be observed that the sample (Borssele run) shows a grindability behaviour comparable to the torrefied biomass samples obtained from the ECN experiments.

On the basis of these results, the BGI was defined as the power consumption of torrefied biomass or coal to produce a powder of 0.2 mm mean particle size. For the examined coal this is 8.5 kW_e/MW_{th}. When comparing this value to the values given in the design matrix (Figure 4.3), it appears that the BGI is lower for most examined points of operation. Although the differences are not very distinct within the examined operating window, the BGI decreases with increasing torrefaction temperature and increasing reaction time. Only for the mildest examined conditions (*viz.* low torrefaction temperature and/or short reaction time), the BGI value is higher compared to that of the examined coal.

Legend (as shown in table key):

biom	size	exp
ash	vol.	FC
C	H	O
Δash	Δvol	ΔFC

	250 °C	255 °C	260 °C	265 °C	270 °C	275 °C	280 °C	285 °C	290 °C	295 °C	300 °C
5 min											
7.5 min	W 5 1.76 80.0 18.3 45.71 5.48 44.8 -11% -1% 7%			W 5 3.08 77.0 19.91 49.5 5.79 41.2 10% -4% 14%					D 5 2.59 69.0 28.4 52.4 5.639 38.1 15% -12% 45%		D 5 2.90 67.3 29.8 53.23 5.295 37.3 -25% -11% 47%
10 min							D 5 3.99 70.6 25.4 51.27 5.631 37.9 77% -10% 30%		C 7 2.49 74.1 23.4 51.08 5.49 40.5 32% -7% 27%		D 5 3.92 65.3 30.8 53.71 5.493 35.5 75% -16% 57%
12.5 min								W 5 3.41 74.0 22.6 51.5 5.66 38.9 22% -7% 29% **2.8 79.8 17.5**			
15 min									D 5 5.53 66.0 28.5 52.05 5.313 35.9 28% -13% 45%		D 5 4.86 63.6 31.5 54.83 5.264 34.0 -23% -14% 61%
17.5 min					C 7 2.28 75.0 22.7 51.34 5.558 40.5 21% -6% 23%		C 7 2.28 74.9 22.9 51.74 5.449 40.2 21% -6% 24%				
20 min											
22.5 min		W 20 1.81 78.0 20.3 49.1 5.62 43.2 63% -5% 21%									
25 min			W 5 4.33 73.4 22.3 51.2 5.55 38.3 55% -8% 27%						W 5 4.80 67.7 27.5 53.25 5.266 36.1 71% -15% 57%		
27.5 min											
30 min			W 5 2.84 74.6 22.5 50.74 5.63 40.3 1% -6% 29%		C 5 2.31 74.35 23.34 51.8 5.523 40.0 22% -7% 27%		C 5 2.55 70.3 27.1 53.42 5.43 38.2 34% -10% 37%				
32.5 min											
35 min											

Figure 4.10 *Experimental matrix on the proximate and ultimate composition of torrefied biomass*

4.5 Combustion and gasification characteristics

4.5.1 Proximate and ultimate analysis

Figure 4.10 represents the proximate and ultimate analysis results as a function of torrefaction temperature and reaction time. The proximate and ultimate analyses of the biomass feedstock are given in Table 4.2 and can be used for comparative purposes.

In general, torrefaction decreases the volatile matter content and increases the ash and fixed carbon content due to devolatilisation of the biomass. In addition, the carbon content is increased and both the hydrogen and oxygen content are decreased. At the mildest conditions evaluated (*viz.* lowest temperature and shortest reaction time), the changes are limited. At more vigorous conditions (*viz.* high temperature and short to long residence time), the changes in proximate and ultimate composition are significant. Especially above 280 °C, the proximate/ultimate composition is sensitive to temperature and reaction time. Under these conditions, the relative decrease in volatile content ranges 10-15% and the increase in fixed carbon content ranges ± 25-60%.

Table 4.2   *Proximate and ultimate analysis of the biomass feedstock*

#	Fuel	Proximate			Ultimate				
		Ash	Volatile	Fixed Carbon	C	H	N	O	HHV
		% (db)	% (db)	% (db)	% (daf)	% (daf)	% (daf)	% (daf)	kJ/kg (db)
1	Woodcuttings	1.89	79.7	18.4	47.1	5.78	0.33	44.9	18,709
2	Woodcuttings	1.85	78.8	19.4	47.7	5.91	0.33	44.2	19,021
3	Woodcuttings	1.90	78.3	19.8	48.1	5.88	0.37	43.8	18,896
4	Demolition wood	4.31	76.1	19.6	47.1	5.87	1.40	41.3	18,620
5	Demolition wood	6.34	74.1	19.6	46.4	5.82	1.55	39.9	18,129
6	Demolition wood	2.25	78.2	19.6	48.2	5.88	1.40	42.2	19,122
7	Demolition wood	3.85	75.9	20.2	46.8	5.71	1.53	42.1	18,988
8	Willow	3.41	74.0	22.6	51.5	5.66	0.49	38.9	20,620
9	Willow	3.08	77.0	19.9	49.5	5.79	0.45	41.2	19,711
10	Willow	1.76	80.0	18.3	45.7	5.48	0.25	44.8	19,534

The observed trends for the ash content are inconsistent with temperature and residence time. Ash is inert in the torrefaction process and thus the ash must remain in the solid phase, but a decrease of the ash content can frequently be observed in Figure 4.10. This is the result of a wide spread in ash content found for the biomass feedstock, see Table 4.2, and will be encountered in the torrefied biomass as well.

4.5.2 Combustion and gasification reactivity

The combustion reactivity of torrefied wood was evaluated for three different samples; woodcuttings (C,280,17.5), and demolition wood (D,280,10) and (D,300,10)[4]. These were selected as they represent a wide variation in fixed carbon content (see Figure 4.10) and the fixed carbon content usually is an indicator of the reactivity. Figure 4.11 represents the combustion reactivity (conversion) after 1000 ms residence time under typical combustion conditions applied in coal fired boilers (typical residence time in coal fired boilers is 6000 ms).

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[4] Coding represents (biomass type, torrefaction temperature [°C], reaction time [min]), with for biomass type C=woodcuttings, D=demolition wood. Coding adopted from Bergman *et al.* (2005).
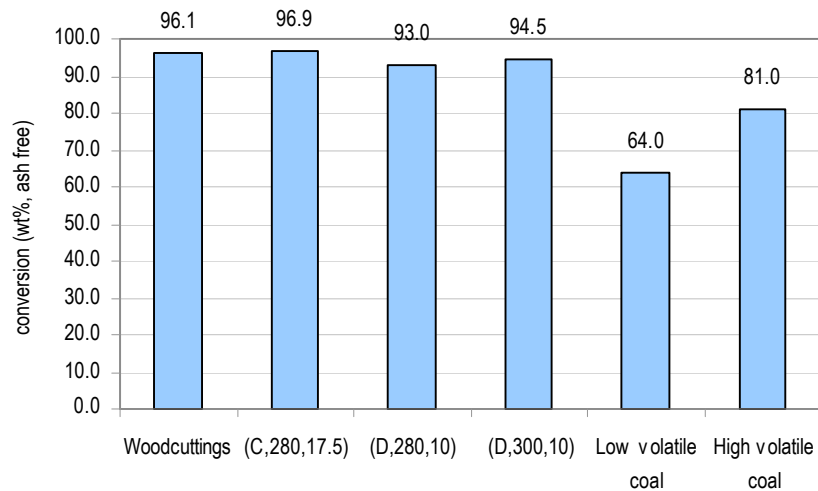
Figure 4.11 *Conversion of coal and (torrefied) biomass after 1000 ms residence time at pulverised-fuel combustion conditions. Results obtained from the LCS experiments*

It can be observed that the carbon conversion of torrefied biomass is fairly comparable to that of woodcuttings (untreated) and significantly higher compared to low- or high volatile bituminous coal. From this it can be expected that complete conversion can be reached for torrefied biomass, as in practice is found for untreated biomass. The gasification reactivity was studied by gasifying beech and torrefied beech under entrained-flow gasification conditions (1450 °C to 1950 °C) in the LCS facility. Whereas the carbon conversion of beech reached 97-98% after 0.3 s residence time, this was 92% for torrefied beech. Apparently, the gasification reactivity decreased after torrefaction.

4.6   Discussion and conclusions

The desired operating window of "economic target conditions" (Figure 3.4 in Section 3.3 of the previous chapter) implying a short reaction time (<30 min) and a torrefaction temperature in the range of 250 °C to 300 °C was examined using an integrated approach of experimental validation and process simulations. The results from this approach is the design matrix Figure 4.3) Within a temperature range of about approximately 260 °C to 300 °C and a reaction time in the range of 7.5 to 30 min, the technical process objectives can be achieved:
·   Torrefied biomass with a grindability comparable to bituminous coal.
·   Good combustibility, *viz*., a reactivity comparable to the original biomass.
·   A high thermal efficiency, *viz*., typically 96% on LHV basis.
·   A combustible torrefaction gas, despite its high moisture content. It can be applied as a fuel for drying and torrefaction and does not lead to waste streams.
With respect to operating conditions, the results have shown that the long reactor residence times that have been reported in the open literature and which were applied in the Pechiney process (see section 2.4), are not needed to meet the desired fuel properties for co-firing purposes. In addition, a reaction time in the order of 10 min offers the possibility to design the torrefaction reactor smaller so that economics can be improved from the viewpoint capital investment and throughput capacity. These aspects are further addressed in the next two chapters. The Pechiney process was operated with a net efficiency of maximal 82% and thus the predicted values for the thermal efficiency of 96% of this work are very promising, although the energy losses due to power consumption are not included yet. This is covered in the next chapter.

5. Process design

5.1 Approach

The performed design activities served to evaluate the integral torrefaction concepts that were proposed in Section 3.1.4 and to evaluate the applicability of different reactor technologies. In total, three torrefaction concepts have been designed; one indirectly heated process and two directly heated processes. The indirectly heated process is based on the technology of the Pechiney production plant (see also Section 2.4). The directly heated concepts were based on rotating drum and moving-bed technology.

The level of detail and subsequent accuracy of the generated designs are expected to be in line with that of a study-estimate design (see Peters and Timmerhaus, 1991). This only included limited information according to the site. The generated equipment lists are based on preliminary sizing of the main plant items and approximate sizes of electrical equipment (e.g. blowers, motors). With respect to utilities, rough quantities have been determined. The design activities did not include the derivation of a control strategy, HAZOP analysis or detailed design.

The processes were evaluated on the basis of one point of operation for which the mass and energy balance were derived on the basis of ASPEN simulations. Subsequently, the selected main plant items were designed on the basis of short-cut design methods to determine typical size characteristics. More advanced models were used to design the different reactors. Special attention was paid to the reactor residence time characteristics to see whether the desired short reaction time also could lead to a short solids residence time to decrease reactor volumes and achieve high capacity. The process design activities were also performed to evaluate the scalability of the process and the net process energy efficiency (*viz.,* including electricity consumption).

5.1.1 General input data

Table 5.1 provides the applied general input data The production capacity was set at 150 MW_{th} fuel output using woodcuttings chips as feedstock. The torrefaction conditions were based on the experimental design basis. A torrefaction temperature of 280 °C and 17.5 min reaction time were selected, as being a feasible point of operation (sufficient grindability, combustible gas, high thermal efficiency, etc). To meet the desired production capacity, an annual feedstock intake of 517 kton/a is required, which corresponds with a fuel output rate of 227 kton/a. The difference is caused by nearly complete moisture removal (50% to <1%) and volatiles production (mass yield for selected point of operation is 88%).

Table 5.1   *General input data process design*

Production capacity	10% co-firing rate, 150 MW_{th} fuel
On stream time	8000 hr
Plant type	Stand-alone
Location	Netherlands (Western Europe)
Feedstock	Woodcuttings (chips), 50% moisture content, Typical size (10 x 30 x 50 mm)
Torrefaction conditions	Reaction time: 17.5 min Torrefaction temperature: 280 °C
Production rates	517 kton/a of biomass feedstock 227 kton/a of production
Available utilities	Natural gas Water, Air (No limitations to amounts)

The Netherlands was chosen as the geographic location for the plant, having various highly developed industrial areas with good infrastructure. With respect to utilities, it has been assumed that the basic ones are available without serious limitations. Therefore, natural gas was applied as utility fuel to thermal balance the process.

5.2 Technology selection

5.2.1 Reactor technology

The indirectly heated screw reactor of the Pechiney Process (*viz*. Discotherm reactor) was selected for the indirectly heated torrefaction concept. Several other indirectly heated reactor technology originating from pyrolysis technology could have been used as well. This reactor was chosen as it proved to be technically feasible for torrefaction so that a proper reference for the indirectly heated concept could be obtained. The design of this reactor was based on performance characteristics that were derived from the reactor applied in the Pechiney process and communication with the manufacturer (LIST, Switzerland). Scale-up from the Pechiney production (12,000 ton/a) to the desired scale of 227 kton/a was done on the basis of required surface area for heat exchange.

Rotating drum technology and moving-bed technology were selected for the directly heated torrefaction concepts. The rotating drum technology has received serious attention for its application as a torrefaction reactor and was therefore selected. The design of the rotating drum technology was based on a design model available at ECN to design rotary drum technology for drying applications. This model was modified to predict heat transfer rates during the time-temperature stages of "Post-drying and intermediate heating" and "torrefaction", which were discussed in Section 2.1.4.

Moving-bed technology was selected since this reactor is compact (high fill percentage), is simpler in construction compared to both other selected reactor types and high heat transfer rates are possible, so that in combination with optimal torrefaction conditions (short reaction time) a compact reactor can be obtained. However, the reactor is not a typical moving bed, but has unique features for optimal heating and temperature control with minimal pressure drop. It is optimised towards heat integration, and is suitable for non-free flowing biomass and waste (for which both other options are not suitable). The design of the moving-bed reactor was done using a design model available at ECN. This model estimates the size of the reactor on the basis of heat transfer rates from gas to the biomass particles. Special attention was paid to the pressure-drop over the moving-bed, since this is a critical parameter for the blower present in the gas recycle supplying hot gas to the reactor.

5.2.2 Other technology

Directly heated rotary drum technology was selected to dry the biomass from the initial 50% moisture content to the desired 15% before the biomass is charged to the torrefaction reactor. The design of the rotary drum was done using the design model developed at ECN and was based on flue gas recirculation.

Indirectly heated rotating drum technology was selected to cool the torrefied biomass from the reactor temperature to below 50 °C. Water was chosen as a coolant. In the case of the indirectly heated torrefaction concept, a typical fired heater was selected to heat the heat carrier (thermal oil) using the hot flue gas. In the case of the directly heated concepts, a burner was applied in combination with a heat exchanger to heat the recycle gas using the hot flue gases.

5.3 Process design results

5.3.1 Equipment list and reactor performance

Table 5.2 represents the equipment list of the three evaluated torrefaction concepts. It can be observed that multiple production lines are required to meet the desired capacity. In each concept 4 rotary drum dryers are required, which need to be operated parallel. In the case of concept A 4 indirectly heated screw reactors of equal capacity are required. This is 5 rotating drums when considering concept B and 8 moving-bed reactors when considering concept C. In the case of concept A and B, each reactor has its own combustion and heat exchange equipment and in the case of concept C, this is per two moving-bed reactors. Consequently, to meet the desired capacity four parallel operated production lines are required (concepts A and C) or five lines in the case of concept B. With respect to concepts A and B, the limiting factor for reactor scale up is the limited heat transfer rate. The size of the moving-bed reactor (concept C) is limited by the pressure drop. Although 8 moving-bed reactors are required, it can be observed that their total volume is significantly less compared to both other reactors.

Table 5.2 *Equipment list*

Functional unit	A. Indirectly-heated - screw reactor		B. Directly-heated – Rotating Drum		C. Directly-heated – Moving bed	
Rotary Drum Dryer	#4, Duty = 7 MW$_{th}$, Drum size = 5 m x 20 m, Drum volume 410 m^3					
Torrefaction Reactor	4	45 m^3	5	D = 3 m, L = 32 m, V = 230 m^3	8	D = 1.3 m, L = 6.7 m, V = 9 m^3
Fired heater / Heat exchanger	4	8 MWth	5	6.4 MWth	4	8 MWth
Indirectly water cooled rotary drum product coolers	#5: D = 2.7 m, L = 13 m					
Air turbo blower	4	100 kWe	4	100 kWe	4	100 kWe

Table 5.3 compares time-temperature stage characteristics of the three reactor types (as was discussed in Section 2.1.4) to explain the large differences in size. One cause is the difference in solids hold-up (fill percentages), which is 100% for a moving-bed reactor, 60-70% for the screw reactor (Discotherm) and 10-15% for a rotating drum. The other cause is the difference in heat transfer rates, which are represented by the overall heat transfer coefficient.

Table 5.3 *Comparison of time-stage characteristics (estimations) of the three evaluated reactor types. Note that the estimated heat transfer coefficient, U, is based on m^2 exchange area for the screw reactor, on m^3 reactor volume for the rotating drum and on m^2 particle surface area for the moving-bed*

Reactor	Fill (%)	U	Heating 100-200 °C (min)	Heating 200-280 °C (min)	Hold-time Torrefaction temperature (min)	residence time (min)
Indirectly-heated Screw reactor	60-70	30 (W/m^2/K)	16	15	3	34
Rotating Drum	10-15	41 (W/m^3/K)	26	29	0	55
Moving-bed	100	200 (W/m^2/K)	1	2	18	21

The differences in heat transfer rates clearly lead to differences in the required residence time. The solids temperature in a moving-bed is fast increases rapidly to the desired torrefaction temperature so that the solids residence time approaches the reaction time. Consequently, torrefaction is carried out practically almost at the desired torrefaction temperature (holding time ≈ reaction time). For both other reactors it can be observed that the heating to the

torrefaction temperature takes significantly more time, so that a longer solids residence time is required. In the case of the rotating drum, it is estimated that a time of 29 min is required to heat the biomass from 200 to 280°C. Hence the desired reaction time of 17.5 min is surpassed, whilst the final torrefaction temperature is only tipped after 55 min. The indirectly heated screw reactor shows a better performance, but it can be seen that for shorter desired reaction times the same phenomenon will appear.

5.3.2 Unit ratios

Table 5.4 summarises the unit ratios estimated for the three evaluated concepts. As all three-process concepts where simulated with similar losses of heat per functional unit (see Table 4.1), the thermal efficiencies of all three concepts are equal. Hence the unit ratios estimated for feedstock, air, cooling water and natural gas are equal as well. For 1 ton of product 2.17 ton of woodcuttings chips of 50% moisture is required. This relatively large ratio is due to the high moisture content and to the devolatilisation during torrefaction (mass yield = 88%). When natural gas is used as utility fuel, a consumption of nearly 43 Nm^3 per ton product is estimated. When feedstock is used as utility fuel, this is 0.36 ton of feedstock per ton of product. In the case biomass feedstock is used, the total biomass feedstock consumption becomes 2.53 ton per ton of product, which would increase the feedstock requirements from 517 kton/a to 574 kton/a.

Table 5.4 *Unit ratios*

Utility	Unit per ton product	A. Indirectly-heated – Screw reactor	B. Directly-heated – Rotating Drum	C. Directly-heated – Moving bed
Feedstock	ton	2.17	2.17	2.17
Air	nm^3	1159	1159	1159
Cooling water	m3	16.7	16.7	16.7
Natural gas	nm^3	42.8	42.8	42.8
Feedstock as fuel	ton	0.36	0.36	0.36
Electricity	kWh	90 (2.55 MWe installed)	106 (3.0 MWe installed)	92 (2.61 MWe installed)

With respect to electricity consumption different values are found. For all concepts the rotary drum dryer installation consumes approximately 1000 kWe and the solids cooler 340 kWe. The differences are due to the technology applied. The power consumption of the screw reactor is estimated at 1200 kWe, the rotating drum including recycle blower (concept B) at 1600 kWe, and the moving-bed including recycle blower (concept C) at 1260 kWe.

5.4   Process efficiencies

Table 5.5 provides an overview of the process efficiencies of the three evaluated concepts. The net efficiency, which includes the electricity consumption of the process, is calculated on the basis of the electricity consumption reported in Table 5.4 using a 40% efficiency to generate electricity. It can be observed that the net efficiency is approximately 92% and the differences between the concepts are not significant. About 8% of the energy input of the process is lost, which is about 50% due to power consumption and the remainder due to heat losses (mainly stack losses).

Table 5.5 *Process efficiencies of the three evaluated concepts*

Utility	Unit	A. Indirectly-heated - screw reactor	B. Directly-heated – Rotating Drum	C. Directly-heated – Moving bed
Thermal output	MW_{th}	150	150	150

Thermal input	MW_{th}	156	156	156
Electrical input	MW_e	2.55	3.0	2.61
Thermal equivalent	MW_{th}	6.38	7.50	6.63
Thermal efficiency	%	96.1	96.1	96.1
Net efficiency	%	92.4	91.7	92.3

5.5   Discussion and conclusions

The results of the process design activities reveal that 4 to 5 production lines are needed to meet the desired output capacity of 230 kton/a. Hence the maximum capacity of a single production line is estimated at about 50-60 kton/a production capacity, corresponding with a fuel production of 30 to 40 MW_{th}. In the case of the rotating drum technology, the reactor limits the maximum scale of operation. This is also true for the moving-bed reactor, which in the proposed design has a maximum capacity of 30 kton/a. Nevertheless, this limitation has a much smaller impact, since the required reactor volumes are very small. Two reactors are needed to meet the capacity of the indirectly heated screw reactor for less than half its reactor volume. The maximum production scale estimated corresponds with a feedstock requirement of 100 to 130 kton/a (50% moisture content). This is a typical capacity that is also applied in a commercial wood pellets production plant, but significantly higher compared to charcoal production plants. Charcoal production capacities are typically in the range of 10-20 kton/a (Ullmann, 1999).

With respect to reactor technology, from the three evaluated options the moving-bed reactor shows the most attractive residence time characteristics. The solids residence time is in this reactor most effectively used, as only little time (and thus reactor volume) is required to heat the biomass to the desired torrefaction temperature. A decrease of the reaction time with 50% (appr. 10 min) would then require 4 reactors instead of 8. In this respect, both other reactor types suffer from slower heating rates and fill percentages, which makes minimisation of reactor volume a difficult task. Although the reactors are not fully optimised, reactor operation in the area of "economic target conditions" described in section 3.3 is expected to be unrealistic in these reactors. In reducing the capital investment, the reaction time is expected to be a major design variable so that the moving-bed reactor seems to be the most attractive reactor technology, although the economy must support this conclusion.

The net energy efficiency of the evaluated process concepts is approximately 92% with only minor differences between the concepts. Compared to the thermal efficiency, which is approximately 96% for the evaluated point of operation, half of the total energy loss is thus due to the consumption of electricity.

6. Economic evaluation

6.1 Approach

The economic evaluation of the three process concepts has been conducted on the basis of the total production costs (€/ton product). The applied methods that were used are based on factorial methods in general described by Peters and Timmerhaus (1991) to estimate first the total capital investment and subsequently the total production costs. The spreadsheet used for this purpose has been developed at ECN. This method of costing corresponds with a study estimate design and provides a general impression of the economic performance of the three studied torrefaction concepts. It does not include detailed data of a particular plant location and neither does it include the opportunities for quantity rebates. The latter may be relevant, as the torrefaction plants consists of parallel operated equipment of same size, type and capacity. The accuracy of the total production costs estimation is mainly dependent on the accuracy of the estimation of the total capital investment. For a study estimate design this is typically ±30%, which roughly yields an accuracy of ±20-25% in total production costs. For comparative purposes, the accuracy is higher as many inaccuracies of the estimation methods are expected to be similar for each evaluated concept.

The total capital investment of the concepts was estimated using a combination of capacity factored, equipment-based estimates and vendor quotes of the main plant items (Table 5.2). Capacity factored estimates utilise the ratio of the capacity (flow rate, heat duty, power requirements, etc) of an existing piece of equipment to the required equipment using a typical power law equation (Douglas, 1988). The equipment-based estimates were determined from more detailed equipment design calculations based on process conditions and simulation results (ASPEN and spreadsheet simulation tools). Where necessary, costs were corrected to 2004 using the M&S index or other cost indices. For most main plant items the purchased costs (*viz.* the delivered equipment costs) were estimated using these methods. Subsequently, a factorial method described by Brennan (1998) was applied to come to the installed costs (*viz.* total direct costs). Following the procedure described by Peters and Timmerhaus (1991), costs were added to the installed costs for items such as engineering and process contingencies to come to the total capital investment.

The total production costs were estimated using the factorial method of Peters and Timmerhaus (1991), which uses a typical breakdown of cost items categorised to manufacturing costs (variable and fixed), plant overhead and general expenses. With respect to variable manufacturing costs, the operating labour required per shift was estimated from the nature of the main plant items. The costs of feedstock and utilities were based on the determined unit ratios (Table 5.4) and costs for maintenance and repairs was related to the fixed capital investment. With respect to fixed manufacturing costs, charges for depreciation, insurance, and local taxes were related to the fixed capital investment. With respect to general expenses, administrative costs were related to the operating labour and financing of the required capital was based on the fixed capital investment.

6.2 General input data

Table 6.1 provides a summary of general economic data used in the evaluation. The depreciation period was set to 10 years (linear in time), corresponding with the expected lifetime of the drying and reactor equipment, which are expected to dominate the investment costs. Financing of the investment is set to 5% of the fixed capital investment, which is a common value for a financing structure in which a possible plant owner takes care of about 50% of the investment. The remainder would be a loan from venture capitalists.

Table 6.1   *Summary of general input data used for the economic evaluation*

Item	Unit	Value
Depreciation period	Year	10
Depreciation method	-	Linear
Financing	% of investment	5
Feedstock (gate delivered)	€/ton (wet)	0
Utilities		
Electricity	*€/kWh*	0.065
Natural gas (NG)	*€/nm³*	0.14
Cooling Water	*€/m³*	0.04
Air		
Labour		
Costs	*€/a per operator*	50,000
Operator shifts	*# / day*	5

The feedstock price (woodcuttings) is set to 0 €/ton (wet). This means that the production costs are not influenced by the cost for feedstock, which may not be true in many cases. Therefore the sensitivity for feedstock costs will be evaluated up to 25 €/ton. The prices for utilities correspond with current prices (2004) for the Dutch economic situation. The yearly overall costs for operating labour were set to € 50,000. An 8-hour shift was assumed and hence 3 shifts per day for continuous operation. 2 additional shifts were included to compensate for the availability of the operating labour (holidays, sick leave).

6.3   Total capital investment

Table 6.2 provides a detailed breakdown of the estimation of the total capital investment of the three process concepts. The total required investment of concepts A, B and C are respectively M€ 50, M€ 36, and M€ 26. The overall installation factors to come from purchased costs (A1) to the total direct costs of concepts A, B and C are respectively 2, 2.4, and 2.4. The differences are mainly caused by the purchased costs of the different reactors applied. It can be observed that several cost items are estimated similarly for each concept, as these are expected to be independent of the reactor technology. Examples are service facilities and instrumentation and control. Other cost items are expected to depend on the applied reactor technology (e.g. main plant items erection, piping/ducting/chutes and yard improvements). These depend strongly on the size of the equipment (large footprint, larger distances between main plant items).

6.4   Total production costs

Table 6.3 provides a breakdown of the estimation of the total production costs (TPC) of the three evaluated torrefaction concepts. Respectively, the TPC are estimated at 77, 72 and 56 €/ton product for concept A, B and C. Divide by 2.17 to come to the production costs per ton biomass feedstock (respectively 35, 33, and 26 €/ton feedstock). The largest costs items are natural gas, depreciation, and financing. Other important items are costs of labour and electricity. In case of concepts A and B, also maintenance and repairs are substantial.

Differences between the concepts with respect to depreciation and financing are the result of the differences in fixed capital investment. Differences between the concepts with respect to labour costs and maintenance and repairs are based on differences in the nature and size of the reactor technology.

Table 6.2 *Total Capital Investment (TCI) of the three concepts*

COST ITEM	A: Screw reactor		B: Rotating Drum		C: Moving Bed	
	MEURO	Breakdown	MEURO	Breakdown	MEURO	Breakdown
I. Direct Costs						
Purchased costs equipment						
Dryers	2.5	5%	2.5	7%	2.5	10%
Reactors	13.4	27%	5.6	15%	2.2	9%
Other	2.7	5%	3.0	8%	3.1	12%
TOTAL	18.5	37%	11.0	30%	7.7	31%
Equipment installation	11.0	22%	8.8	24%	5.2	21%
Other direct costs	7.5	15%	7.1	20%	5.2	21%
TOTAL	**37**	75%	**27**	74%	**18**	73%
II. Indirect Costs						
Engineering & Supervision	4.4	9%	4.2	12%	3.1	13%
Construction expense/contractor fee	1.8	4%	1.3	4%	0.9	4%
Contigency	4.3	9%	3.2	9%	2.1	9%
TOTAL	**10**	21%	**8.7**	24%	**6.1**	25%
III. FIXED CAPITAL INVESTMENT	**48**	97%	**35**	97%	**24**	95%
IV. Working capital	1.24	3%	1.24	3%	1.24	5%
V. TOTAL CAPITAL INVESTMENT	**49**	100%	**36**	100%	**25**	100%
Specific investment (EUR/ton)	**22**		**16**		**11**	

Table 6.3 *Total production costs of the three concepts*

COST ITEM	A: Screw reactor		B: Rotating Drum		C: Moving Bed	
	EURO/ton	Breakdown	MEURO	Breakdown	MEURO	Breakdown
I. MANUFACTURING COSTS						
A. Direct Product Cost						
Operating Labour	5.42	7%	6.50	9%	5.42	10%
Utilities						
Electricity	5.75	7%	6.77	9%	5.88	11%
Natural Gas	13.44	17%	13.44	19%	13.44	24%
Maintenance and Repairs	6.10	8%	6.10	9%	2.04	4%
Other	3.80	5%	4.07	6%	3.19	6%
TOTAL	**34.5**	**45%**	**36.9**	**52%**	**30.0**	**54%**
B. Fixed Charges						
Depreciation	20.38	27%	15.24	21%	10.20	18%
Other	3.06	4%	2.29	3%	1.53	3%
TOTAL	**23.4**	**31%**	**17.5**	**25%**	**11.7**	**21%**
C. Plant Overhead	**3.25**	**4%**	**3.90**	**5%**	**3.25**	**6%**
II. GENERAL EXPENSES						
Financing	10.46	14%	7.89	11%	5.37	10%
Other	5.15	7%	5.31	7%	5.15	9%
TOTAL	**15.6**	**20%**	**13.2**	**18%**	**10.5**	**19%**
TOTAL PRODUCTION COSTS	77	100%	71	100%	55	100%
EUR/GJ	3.8		3.5		2.7	

Table 6.3 was generated while applying 0 €/ton feedstock costs. When the feedstock costs are 25 €/ton (a.r.), the production costs increase to respectively 131, 126 and 110 €/ton product (using the unit ratio of 2.17 ton of feedstock per ton product). For a feedstock price of 10 €/ton this is 98, 93 and 78 €/ton respectively.

The most dominant cost item is natural gas, amounting approximately 13.5 €/ton and is mainly needed for drying of the biomass feedstock. When instead feedstock or in general biomass is used of 10 €/ton, fuel costs decrease to 3.6 €/ton. Subsequently, the TPC of concept C drops to approximately 43 €/ton (concept C), neglecting however that investment costs will likely increase when needing a biomass burner (including solid fuel infrastructure) instead of a gas burner. Cost will also reduce when drier biomass feedstock can be used. When for instance demolition wood is used of 20% moisture content, the estimated TPC is 42 €/ton product while using natural gas.

6.5   Discussion and conclusions

In this chapter the three process concepts for which the main design results were given in the previous chapter where evaluated economically. Concept A, based on the indirectly-heated screw reactor as used in the Pechiney process, turns out to be the most expensive option both in investment and total production costs. The total production costs are estimated at 77 €/ton (in 2004) against 100 €/ton (in 1988) for the Pechiney process as built originally. The estimated costs are thus lower, which is expected to be caused mainly by scale differences; 60 kton/a of product per production line versus 12 kton/a of product for the Pechiney production plant.

The directly heated process concepts were generated to see whether production costs could be decreased further. As the results have shown, only the concept based on moving-bed reactor technology substantially reduces the capital investment and the total production costs. The required fixed capital investment of the moving-bed based concept is only half of that of the indirectly heated screw reactor concept and the total production costs amount 56 €/ton; a reduction of nearly 30%. Therewith moving-bed technology is considered the most attractive reactor technology of the three evaluated options.

Taking the total production costs of the moving-bed technology as a basis, further reduction of costs can be established by minimising the use of natural gas. This can be done by optimisation of torrefaction conditions and by using biomass feedstock as utility fuel. It is expected that this can decrease the total production costs from 56 €/ton to approximately 45 €/ton product (or 20 €/ton of feedstock for a biomass feedstock with 50% moisture content), but will depend on the costs and availability of the biomass feedstock and on additional investments required for a biomass fuelled burner. Other possibilities to reduce the costs can be found in minimisation of the reaction time, which was only found to be possible for the moving-bed reactor technology. The given estimation of the fixed capital investment (25 M€, production rate 230 kton/a) is based on a solids residence time of 20 min. At only half this solids residence time, it is expected that this can be decreased to 21 M€. The resulting total production costs would then be 53 €/ton product. Consequently, the required capital investment is decreased significantly with 4 M€ (16% reduction), but the production costs only with 3 €/ton (5% reduction).

Under optimised conditions it is expected that a torrefaction production plant of 230 kton/a product consists of four parallel operated production lines, requires an investment of 21 M€ and results in total production costs of about 40 €/ton (or 18 €/ton feedstock). The required investment of each line (60 kton/a production rate) is then 5.2 M€. When drier feedstock can be used, cost may be further reduced, as the drying operation will be cheaper or even not necessary (saving another 5 M€ in total investment costs). The total production costs can then even decrease to below 40 €/ton product.

7.   Conclusions and recommendations

This work aimed for the development of torrefaction as a pre-treatment technology for the co-firing of biomass in existing power stations. The poor grindability of biomass limits the co-firing percentages, but this can be improved by torrefaction. The main objective of the present work was to contribute to the "proof-of-concept" phase.

Torrefaction is known as a process that is operated at 200 °C to 300 °C and a rather long residence time of typically 1 hour. From this work it is concluded that the grindability of biomass (woodcuttings, willow and demolition wood) can be improved to the level of coal in the temperature range of 260 °C to 300 °C, whilst applying a reaction time of 30 min down to 7.5 min. In this range also good combustibility properties of the torrefied biomass are observed and a dry and high calorific fuel can be obtained (>19 MJ/kg ar). Under the favoured conditions a thermal process efficiency of typically 96% is to be expected and a net process efficiency of 92% (including electricity consumption). As long as the liberated torrefaction gas can be combusted to produce heat for the process itself, these efficiency characteristics can be obtained. The moisture content is the most important property with respect to the process energy efficiency. Only or very dry biomass feedstock (<10-15% wt.), a decreased efficiency is to be expected. Therewith a wide range of potential biomass feedstock can be upgraded with a high-energy efficiency by means of torrefaction.

With respect to technology, two main process concepts were evaluated. These are the indirectly heated process and the directly heated process concept. The biggest difference between both is the way heat is charged to the torrefaction reactor. The indirectly heated process avoids direct contact between the heat carrier and the biomass. The directly heated process is based on direct contact between the biomass and a gaseous heat carrier. Both concepts consist of pre-drying, torrefaction and product cooling, and combustion of the torrefaction gas (heat integration). Process design and economic evaluation of these concepts was performed on the basis of three selected reactor types: indirectly-heated screw reactor, a directly heated rotating drum, and a directly heated moving-bed reactor. The maximum output capacity of the three processes is estimated 50-60 kton/a (100-130 kton/a feedstock input, 50% moisture content).

Moving-bed technology appeared to be the most attractive technology offering the possibility to apply short residence times to enable large-scale production against lowest capital costs. The capital investment of a 60-kton/a production rate is estimated at 5.2 to 7.5 M€. The total production costs are estimated in the range of 40 to 56 €/ton product (excluding feedstock costs), which is 18 to 26 €/ton of feedstock (50% moisture content). In contrast to the Pechiney process, this identified technology is believed to be economically attractive.

Based on the above, it is concluded that torrefaction can become an attractive technology to upgrade biomass to contribute to the increase of biomass co-firing rates in the existing coal fired power stations. It is recommended to continue with the development of torrefaction technology by means of pilot-scale testing of the favoured moving-bed technology. It is also recommended to further analyse the most optimal position of torrefaction in the chain of biomass to electricity for which this work provides a good basis. This should also include comparison with alternative production chains based on for instance wood pellets or routes wherein the biomass is prepared by solely size reduction.

This work focussed on the most crucial properties of torrefied biomass (grindability, combustibility). However, properties of concern in relation to dust formation (dust explosions), hydrophobic nature, leeching characteristics, need to be investigated to see whether measures need to be taken with respect to handling, logistics, and safety. This may change the economic perspectives. Evaluation of these properties can be done following the approach applied in this work (design matrix).

The phase of pilot scale testing must demonstrate the technical and economical feasibility at a larger capacity and needs to take a way all technical uncertainties for (commercial) demonstration. From this work it is concluded that this phase should be based on a directly-

heated process using moving-bed technology. Important aspects in this phase are the experimental validation of the combustibility of the torrefaction gas, which is crucial in achieving a high process energy efficiency and prevention of waste streams. In this work this has been evaluated on the adiabatic flame temperature, which however under some condition just above the minimum value of 1000 °C. This value is based on a simple heuristic of which the practical value should be evaluated. In addition, the torrefaction gas consists of condensables that may be of concern for the operation of the burner and all equipment present in the gas recycle. In addition, research on emissions to air resulting from the combustion of the torrefaction gas is recommended. Especially when contaminated biomass feedstock is to be used.

In addition, it is recommended to further address torrefaction in combination with pelletisation. Initial work performed on this combination has been carried out parallel to this work (the TOP process; Bergman, 2005) and revealed that superior fuel pellet quality can be obtained with respect to transportation, handling and storage.

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9. Used symbols and abbreviations

Symbol or Abbreviation	Unit	Description
ar		As received
AU		Australian
BGI	kW_e/MW_{th}	Biomass Grindability Index
BUF	% wt.	Biomass Usage Factor
C		Woodcuttings
D		Demolition wood
daf		Dry and ash free
DP		Re pressuring operation
Exp		Experiment
FC	% wt.	Fixed Carbon Content
FCI	€	Fixed Capital Investment
HHV	MJ/kg	Higher Heating value
LCS		Lab-scale Combustion and Gasification Simulator
LHV	MJ/kg	Lower Heating Value
M&S index		Marschall and Swift cost index to relate value of money to time
MC	% wt.	Moisture content
MCA	% wt.	Moisture content of the biomass feedstock corresponding with autothermal operation of the torrefaction process under the maintained operating conditions (reaction time and temperature)
M_{char}	kg	Mass flow of char from torrefaction
M_{feed}	kg	Mass flow of biomass feedstock to torrefaction
NG		Natural Gas
SHST		Super Heated Steam Torrefaction
T_{ad}	°C	Adiabatic temperature rise
t_c	min	Cooling time to ambient temperature
TCI	€	Total Capital Investment
t_{dry}	min	Drying time
t_h	min	Heating time to drying
$t_{h,int}$	min	Intermediate heating time from drying to torrefaction
TPC	€/ton product or feedstock	Total Production Costs
$t_{reaction}$	Min	Torrefaction reaction time or reaction time
t_{tor}	min	Reaction time at desired torrefaction temperature
T_{tor}	°C	Desired torrefaction temperature
T_{tor}	°C	Torrefaction temperature
$t_{tor,c}$	min	Cooling time from the desired T_{tor} to 200 °C
$t_{tor,h}$	min	Heating time torrefaction from 200°C to desired torrefaction temperature
TW		Torrefied wood
W		Willow
y_e	% energy basis LHV daf	Energy yield or solids energy yield torrefaction
y_m	% mass basis, daf	mass yield, solid mass yield torrefaction
η_p	% (LHV, as received)	Net process energy efficiency
$\eta_{p,th}$	% (LHV ar)	Thermal process energy efficiency based on lower heating value, as received

Appendix A LIST Indirectly-heated screw reactor
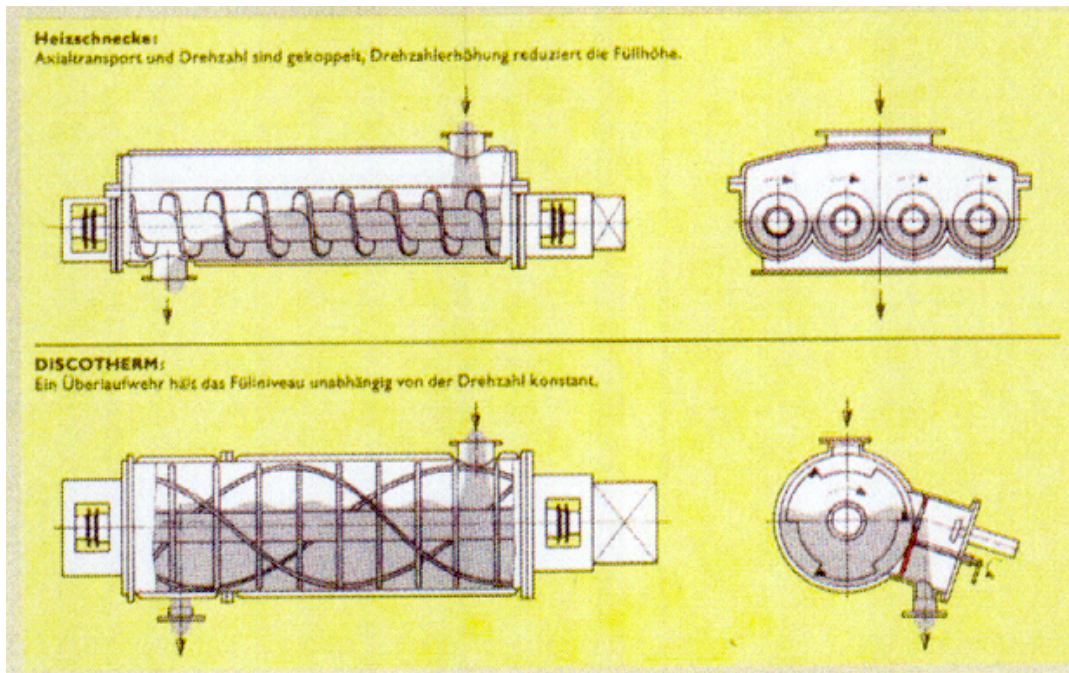

Side and front view of the DISCOTHERM reactor
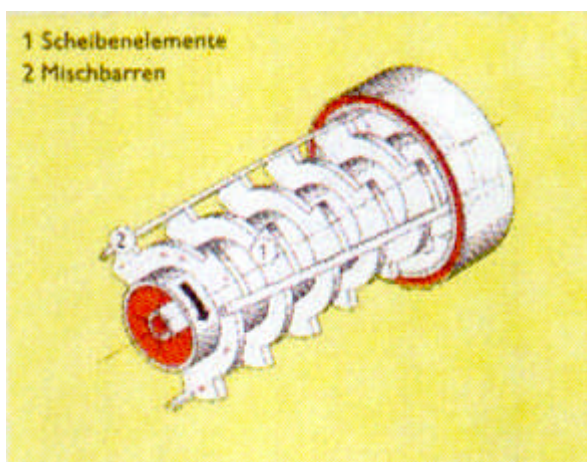
Schematic of the internals of the reactor. (Source: www.list.ch)

Appendix B Facilities, experimental procedures and measurement techniques

B.1 Experimental torrefaction facilities

B.1.1 Batch reactor

The torrefaction batch reactor consists of a vertically placed steel tube. A schematic and photo of the reactor is given in Figure B.1. The reactor is made from stainless steel (AISI 316) and has a diameter of 0.16 m and a length of 100 cm, resulting in a reactor volume of $\pm$ 20 ltr.
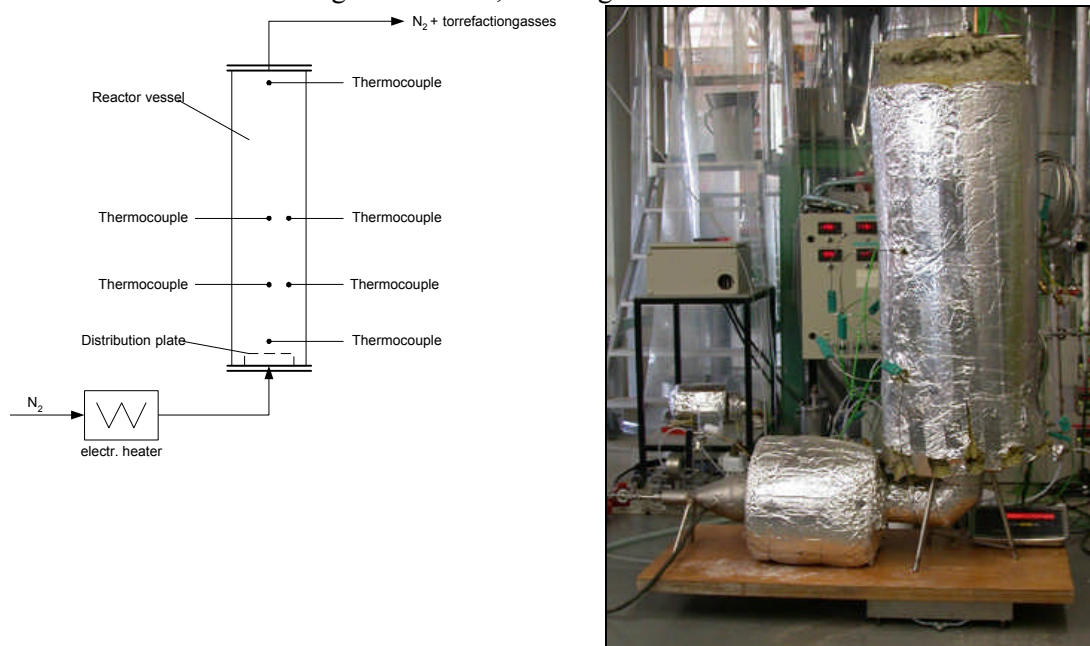
Schematic of the batch reactor   Picture of the Batch reactor

Figure B.1. *The ECN batch reactor for torrefaction*

The reactor is filled from above with biomass or waste and operated as a fixed-bed reactor. Heating of the biomass is primarily conducted by bringing it into direct contact with a gaseous heat carrier (Nitrogen) via a distribution plate at the bottom of the reactor. Tracer ribbons are wrapped around the reactor to minimize heat losses to the surroundings. The content of the reactor is heated until the desired temperature and reaction time is reached. For that purpose the reactor is equipped with thermocouples at several radial and axial positions. An example of the recorded profiles is given in Figure B.2. Cooling of the (torrefied) biomass is done by switching from hot to cold carrier gas and switching off the tracer ribbons simultaneously. The reactor is coupled to a gas treating facility where the gas is combusted and the produced flue gas is charged to a stack.
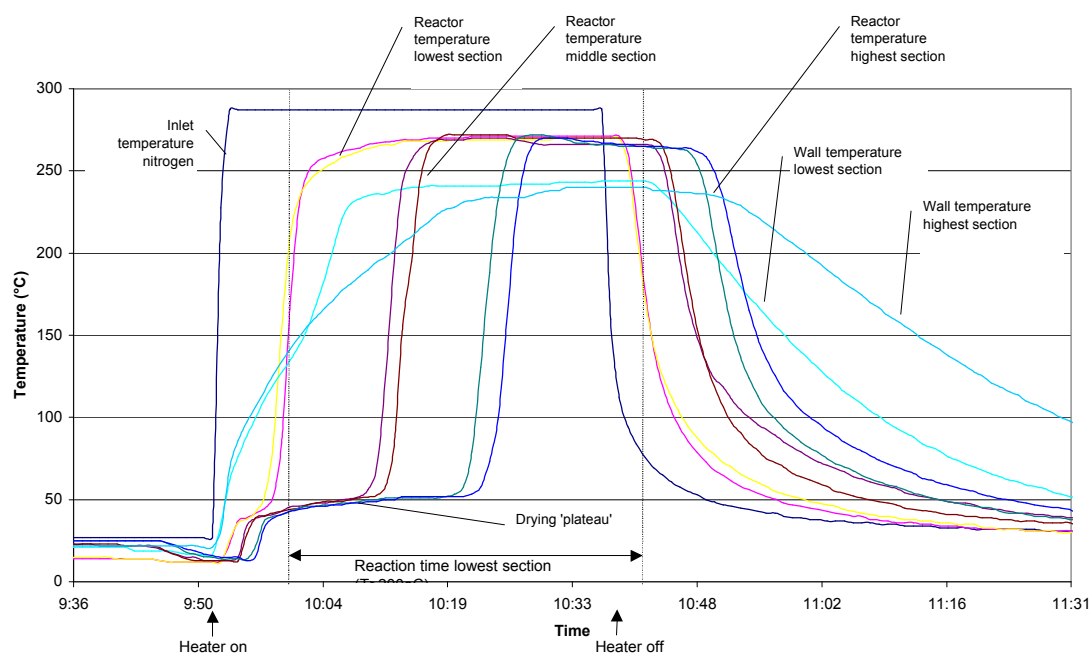
Figure B.2. *Example of the reactor temperature profiles reactor during a torrefaction experiment*

B.1.2 Continuous reactor (Pyromaat)

Since 1999 the 25 kW$_{th}$ Pyromaat facility (see Figure B.3.) is operational. This facility was developed for the pyrolysis of waste materials and consist of a pyrolysis reactor, thermal cracker and a gas scrubber operated in continuous mode. The pyrolysis reactor was deployed as a torrefaction reactor. It is an indirectly-heated screw with a capacity of 1-10 kg/hr and can be operated up to 550 °C. Heat is charged to the reactor by means of electrical heating elements wrapped around the reactor tube, which can be controlled independently. Along the axis of the reactor, gas and solids temperatures are registered and gas samples can be taken for analyses (see Figure B.4.). Experiments using the Pyromaat are more extensive compared to experiments using the batch reactor, but its accuracy is higher, because of more accurate temperature control and due to its continuous operation. Especially the latter is important to sampling and analysis of the liberated torrefaction gas.

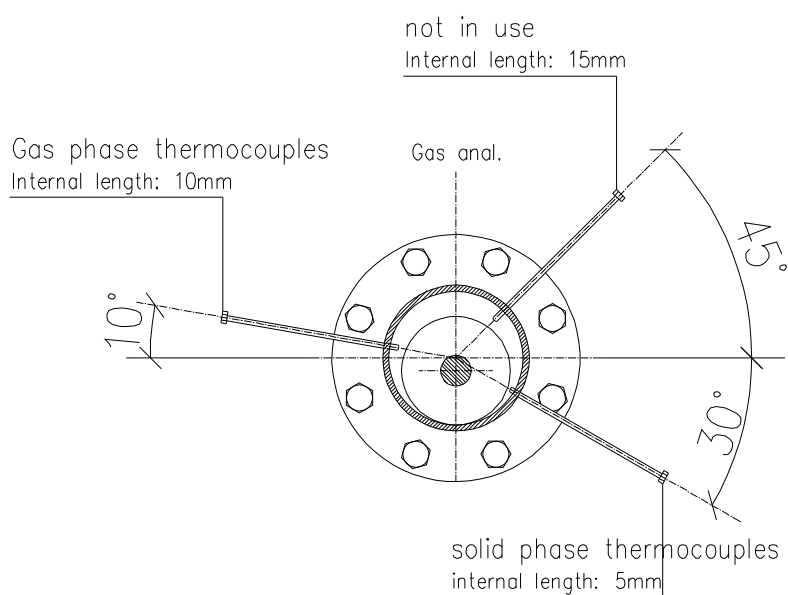Figure B.3. *The ECN pyromaat experimental facility*

Figure B.4. *Schematic representation of the spherical and radial location of the thermocouples and gas analysis points in the pyrolysis reactor*

B.2   Solid analysis methods

B.2.1 Proximate and ultimate analysis

The proximate and ultimate analysis comprises methods to determine the basic composition of solids that predominantly consists of organic structures (coal, biomass). By the proximate analysis the ash, volatile matter, moisture, and fixed carbon content is determined. The ultimate analysis provides the elemental composition of the solids (C,H,N,O) together with the Higher Heating Value (HHV), according to ECN standards. The Lower Heating Value (LHV) is derived From the HHV by using a standard estimation technique.

Bergman *et al.* (2004) denoted that the inaccuracy of the HHV analysis method cannot be neglected in torrefaction. The HHV is determined by an ASTM method using an adiabatic bomb

calorimeter. The inaccuracy of such measurement is approximately 240 J/g, which is up to 1.5% in HHV on relative basis (95% confidence) for (torrefied) biomass. These errors have to be summed in the case of the energy yield calculation (see for definition Section 2.1.3), meaning that the calculated energy yield has a relative inaccuracy of ±3%, only caused by the measurement of the calorific value. For an energy yield of 95% this means that the true value may range from 92.1% to 97.9%. As the calculated energy yields for practical applications vary in the range from 85% to 100%, such an inaccuracy inherently complicates the interpretation of results and an extensive number of experiments are needed to statistically justify trends.

B.2.2 Grindability

The quantification of the grindability of solids, in this case coal and (torrefied) biomass, is essential in evaluating the feasibility of the size reduction of (torrefied) biomass (together with coal) in the existing coal mills of coal-fired power stations. The Hardgrove Grindability Index (HGI) is a well-known analysis technique used to determine the grindability of coal. On the basis of the HGI, the capacity and the number of required coal mills for a certain coal is determined. It uses a strict procedure of pre-grinding the coal and only the coarsest particles from this step are used in a small ball-mill from which the grindability is evaluated. Consequently, the HGI is based on that part of the coal that is most difficult to grind. The applicability of this analysis technique was evaluated for (torrefied) biomass and results from this evaluation are given in Figure B.5.
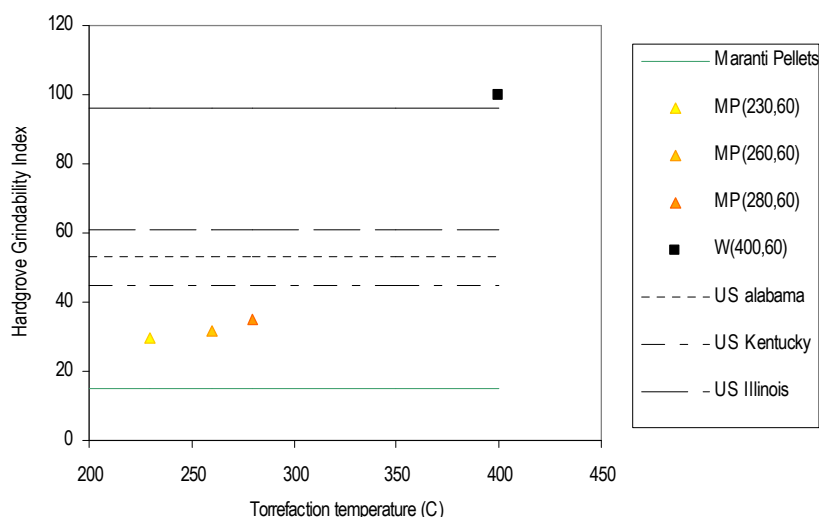

Figure B.5. *Results of HGI analysis for untreated and torrefied maranti pellets (MP), together with the HGI for charcoal willow (W) produced at 60 min reaction time and different temperatures*
The HGI values represented for different coals have been taken from Perry and Green (1999) and must not be interpreted towards temperature

The HGI for untreated maranti pellets is determined to be 17, which indicates their poor grindability. The HGI for torrefied maranti pellets varies from 30 to 35. The grindability in terms of the HGI is thus improved after torrefaction, but is lower than the various coals (and charcoal) presented in Figure B.5.

The problem, however, with the HGI method is that it is not a general technique. It has been observed that, from the initial amount of torrefied biomass used, only a very small fraction of coarse particles was produced, much smaller compared to coals. This implies that the largest fraction was grinded to a very small size, which would not limit the capacity of the coal mill. Hence, the HGI procedure produces very conservative results for torrefied biomass when compared to coal.

An alternative way to determine the grindability of (torrefied biomass) was developed by Bergman *et al.* (2004) and during this work. This method is based on evaluation of the net energy that is needed to break-up coarse particles to meet a certain particle size of the produced powder. When the required energy for breakage is low, the power consumption of the applied mill is low and its capacity will be relatively high. This method differs from the HGI method, as the grindability is determined on the basis of energy requirements, instead of simulating the grinding mechanisms of a coal mill on small scale (ball mill). However, the required energy to induce particle breakage by breaking up bonds is independent of the type of mill applied.

A conceptual scheme of the experimental facility to determine the grindability on the basis of the energy of breakage is given by Figure B.6. The core of this facility is a RETSCH SM 2000 heavy duty cutting mill powered by an approximately 2.0 kW$_e$ electrical motor. This motor runs at constant speed (number of revolutions). Perturbations that occur in feed rate and feed properties and 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.
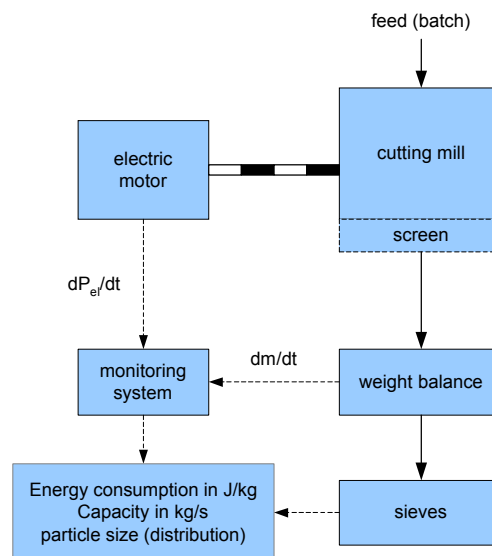

Figure B.6. *Schematic representation of the experimental facility to characterise grindability*

The mill is coupled to a data-acquisition (monitoring) system that registers the power consumption together with its capacity. Different screens can be applied to evaluate the power consumption and capacity characteristics as a function of the average particle size of the produced powder. Figure 4.9 represents typical results (power- and capacity curves) obtained from grindability experiments using this technique.

B.2.3 Combustion behaviour (combustibility)

Experimental investigation of the combustibility of torrefied biomass is done using the Lab-scale combustion simulator (LCS) present at ECN. The LCS is a flexible facility for the characterisation of solid fuel behaviour under typical pulverised fuel fired furnace conditions. A schematic of the core of the facility is given in Figure B.7.
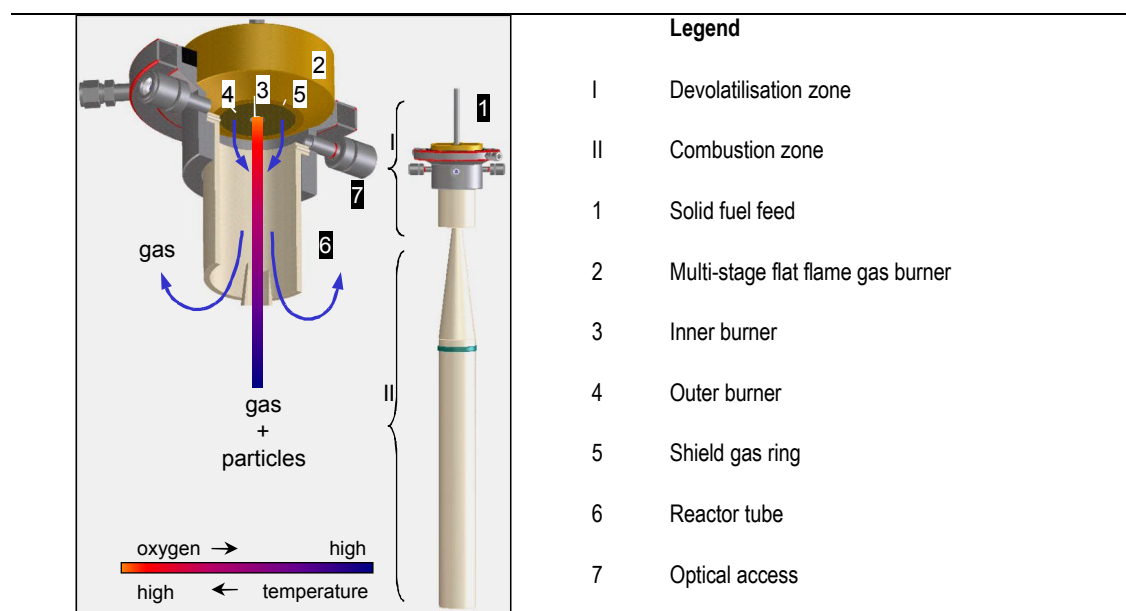

	Legend
I	Devolatilisation zone
II	Combustion zone
1	Solid fuel feed
2	Multi-stage flat flame gas burner
3	Inner burner
4	Outer burner
5	Shield gas ring
6	Reactor tube
7	Optical access

Figure B.7. *Staged flat flame gas burner and reactor tube of the ECN lab-scale combustion simulator (LCS)*

The facility comprises a drop tube reactor together with a primary/secondary gas burner to simulate a flame/flue gas environment in which the conversion behaviour of fuel particles can be studied as a function of time. An adequate simulation of heating rate, gas temperatures and composition can thus be obtained independent of the fuel tested. The approach is specifically suited to study secondary fuels under primary fuel conditions. Different properties of solid fuels may be characterised, as summarised in Table B.1.

Table B.1. *Summary of fuel properties that can be determined using the LCS facility*

combustible (organic) matter
- time & particle size dependent conversion, including burnout (C-in-ash, LOI)
- volatile matter yield under high heating rates
- fate of nitrogen, NO_x formation
- char reactivity (in combination with thermogravimetric analysis)

incombustible (inorganic or ash forming) matter
- slagging of near-burner zones or water walls
- fouling of heat exchanging surfaces in boiler convective areas
- fly ash composition and quality
- fine particle formation and emission, including related trace elements

B.2.4 Liquid (condensables) sampling and analysis methods

The sampling method used to collect the organic condensable constituents present in the torrefaction gas is based on methods developed for tar sampling in biomass gasification. Figure B.8. provides a schematic of the sampling system. It basically consists of two impinger bottles in which the reaction liquids are condensed/absorbed. The bottles are almost completely immersed in a cold bath to keep their temperature low (< 5 °C). The gas is sucked through bottles at a pre-specified rate so that the yields of the various condensables can be determined. A filter is situated upfront the pump to protect it against aerosols.
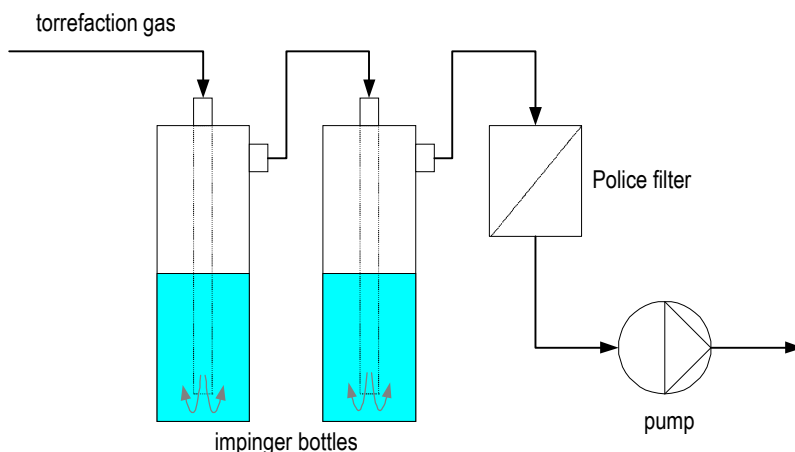
Figure B.8. *Sampling system for capture of torrefaction condensables*

The gas is fed to the first bottle preferably at the exit temperature of the torrefaction reactor to prevent condensation before the gas enters the bottles. Because most reaction products are polar components, a polar solvent is used in the bottles. Water has been used, but also tests with ethanol gave good results.

Tests in which the number of bottles was varied showed that two bottles are minimally needed to remove all liquids from the gas phase. Especially in the first bottle, aerosols are formed due to quenching of the gas from the reactor exit temperature (> 200 °C) to near 0 °C. Part of these aerosols are captured in the second bottle, but complete elimination of aerosol break-through could not be established.

From the three condensable subgroups, the organics are well collected using this sampling method. The quantification of water (by gravimetric measurement) was found to be unreliable due to aerosol formation and because the reaction water also mixes with physically bound water from the biomass feed. It is unclear whether lipids are collected efficiently using this method, also because the components belonging to this subgroup were not quantified afterwards.

The content of the bottles is off-line analysed using a combination of GC-FID, GC-MS and Ion Chromatography. An analysis method has been developed in which the compounds with highest yields are quantified. Table B.2. provides an overview of these compounds.

Table B.2. *Identified and quantified torrefaction reaction products (organics)*

2-furaldehyde	Furan-2-methanol	Phenol
5-methyl-2-furaldehyde	Furan-3-methanol	2-Methoxyphenol
Acetaldehyde	Methanol	3-methoxyphenol
2(5H)-Furanon	Methylacetate	4-methoxyphenol
Ethylene-glycol diacetate	Methylformiate	26 Dimethoxyphenol
Ethanol	Hydroaceton	Aceton
Pyrrole	Cyclohexanon	3-methoxypyridine
1-Hydroxy-2-butanon	Butanon	4-methoxypyridine
Eugenol	Propanal	2-methoxypyridine
Isoeugenol	Pyrrole-2-carboxaldehyde	Acetic acid
Propionic acid	2-butenal	Formic acid
345 Trimethoxytoluene		

B.2.5 Permanent gases analysis

The permanent gases are quantified using an on-line measurement procedure. This basically comprises micro-gas chromatography by which the composition of the dry gas is determined. Before the gas is charged to the micro GC, water is removed in a cold trap because water disturbs the measurement. Quantified gases are O_2, Ar, N_2, H_2, CO, CO_2, CH_4, C_2H_2, C_2H_4, C_2H_6, benzene, toluene and xylenes.

B.3 Experimentally derived mass and energy balance

Using the developed sampling and analysis procedures, the solid yield, permanent gas yield and organics yield can be determined[5]. Of the 6 main product groups discussed in Section 2.1.2 can be quantified. This leaves two unknowns and two equations, which is illustrated by Figure B.9.
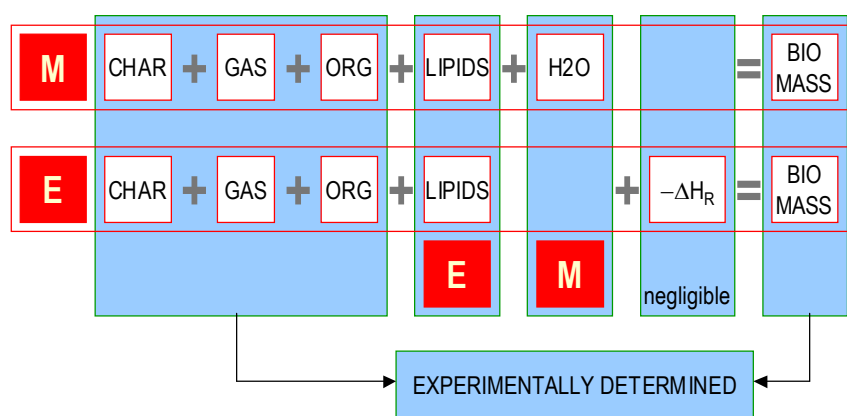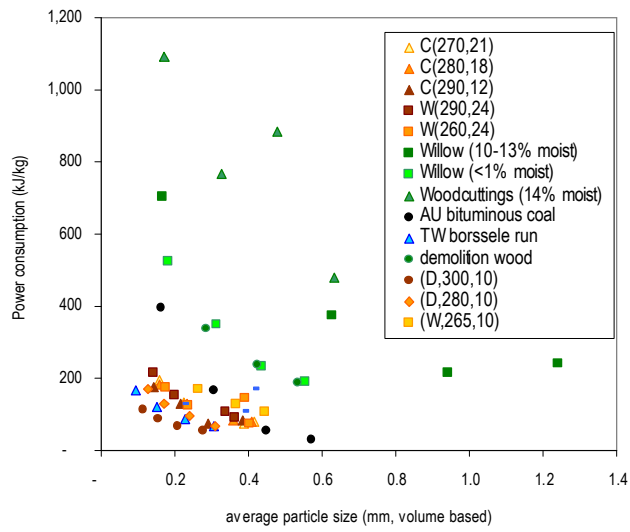
Figure B.9. *Mass (M) and energy balance (E) of torrefaction, corresponding with Figure 2.3*

The energy balance is closed by assuming that the difference between the energy content of the biomass feedstock and the quantified products is caused by the evaporation of lipids from biomass to the gas phase. This approach is valid under the assumption that the heat of reaction of torrefaction can be neglected. Van Dongen (2003) has shown that the heat of reaction indeed is very limited; about ±1% of the energy content of the biomass feedstock. It is, however, also known that the heat of reaction very much depends on the decomposition regime (see Figure 2.2), so that the operating conditions are of influence on the exothermic nature of torrefaction and its magnitude.
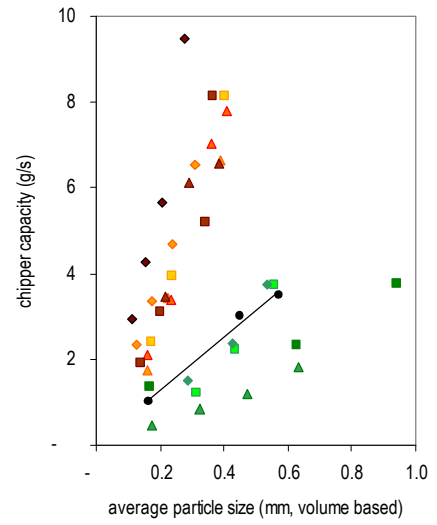
By closing the energy balance on the basis of the lipids, their mass yield can be determined on the basis of their calorific value (typically in the range of 45 to 50 MJ/kg for fatty organic structures). The mass balance is then closed by assuming that the difference in mass between the biomass feedstock and the measured product groups is due to the reaction water formed. This assumption implies that dust formation by solids attrition in the reactor can be neglected, which can be verified during the experiments.

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[5] The yields are defined as $y_i = \left(\dfrac{m_i}{m_{biomass}} \right)_{daf}$ with i the pertinent product group or individual component.

Appendix C   Grindability results in mass units

Net power consumption curves

Capacity curves