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Combined torrefaction and pelletisation

The TOP process

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Colophon

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Acknowledgement/Preface

This report describes the results of a project that was carried from June 2003 until January 2005 at ECN. The work was co-financed by SenterNovem. The ECN project number is 7.5224 and the corresponding SenterNovem project number is 2020-02-12-14-013. Jasper Lensselink, Lex Bos, Peter Heere, Ruud Wilberink and Ben van Egmond are greatly acknowledged for their contributions to the experimental work carried out during this project.

Abstract

The presented work describes a new technology for the production of biopellets from various biomass feedstock. This new technology combines **to**rrefaction and **p**elletisation (*viz.* densification) and is called the TOP process. The pellets produced by this technology are called TOP pellets and have high fuel quality. Proof-of-principle experiments revealed that TOP pellets have a typical bulk density of 750 to 850 kg/m^3, a net calorific value of 19 to 22 MJ/kg (as received) and a volumetric density of 14 to 18.5 GJ/m^3 (bulk). Analysis of the mechanical strength and water uptake revealed that the durability of TOP pellets is higher than the durability of conventionally produced biopellets.

The modelling of the TOP process based on experimentally derived design data revealed that the process can be operated at a net energy efficiency of typically 92%, which is typically 4%-points higher than conventional pelletisation. Although the inclusion of torrefaction in the pelletisation process increases the capital investment of a production plant, the total production costs are decreased due to decreased operational costs. The profitability of a biomass to electricity chain based on co-firing of biopellets in existing coal-fired power station is expected to increase dramatically when using TOP technology instead of conventional pelletisation.

Keywords

Biopellets, pellets, TOP process, TOP pellets, biomass, torrefaction, pelletisation, densification, pre-treatment, grindability, co-firing, economic evaluation, conceptual design, economic analysis.

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Summary

Densification by means of pelletisation is considered to be a proven technology to improve biomass properties for its conversion into heat and power. The current production volumes (world wide) that exceed 5 Mton/a, indicate that the biopellets (or wood pellets) market is becoming quite mature with serious outlets in the domestic market (heating) and the energy market (heat and power). Although a relatively small volume of biopellets is produced in the Netherlands, the Dutch energy sector is consuming a considerable amount through co-firing in coal-fired power stations. In fact, biopellets are the state-of-the-art sustainable fuel to replace coal, which must be roughly 6 Mton/a of coal in 2008-2012, according to the policy agreement between the Dutch government and the Dutch energy sector.

However, biopellets are expensive, require special treatment at the power station and cannot be produced from a wide variety of biomass feedstock. ECN has introduced an alternative process for the production of biopellets. This process is based on a combination of **to**rrefaction with **p**elletisation and is called the TOP process for the production of TOP pellets. The TOP process integrates the advantages of both processes with respect to the quality of the biopellet. Since the earlier development of the TOP process involved only initial desk studies, this work aimed for the proof-of-principle phase of its development and involved experimental evaluation of torrefaction combined with densification (pelletisation), conceptual design, and an economic analysis of a biomass to electricity production chain based on the TOP process.

The experimental work revealed that TOP pellets may have a bulk density of 750 to 850 kg/m^3 and a net calorific value of 19 to 22 MJ/kg as received. This results in an energy density of 14 to 18.5 GJ/m^3. The energy density is significantly higher than conventional biopellets produced from softwood (sawdust: 7.8 to 10.5 GJ/m^3). In contrast to conventional biopellets, the experimental tests revealed as well that TOP pellets can be produced from a wide variety of feedstock (sawdust, willow, larch, verge grass, demolition wood and straw) yielding similar physical properties. From tests on the water uptake and mechanical strength of both TOP pellets and conventional pellets, it is concluded that TOP pellets have a largely improved durability.

It is expected that the TOP production process can be operated with a thermal efficiency of typically 96% or a net efficiency of 92% on LHV basis. The TOP process requires a higher total capital investment compared to the conventional pelletisation process, respectively 5.6 M€ against 3.9 M€ for a capacity of 170 kton/a of sawdust feedstock with 57% moisture content. However, the total production costs of the TOP process expected to be lower, 2.2 €/GJ against 2.6 €/GJ for conventional pelletisation. Furthermore, the costs advantages of TOP pellets amount approximately 30% in logistic operations using the same infrastructure as used for conventional biopellets. This is the result of the higher bulk density of TOP pellets and the lower tonnage that needs to be transported (per GJ). For a market price of 7.3 €/GJ of biopellets the internal rate of return of the TOP process is 30% against 13% for conventional pelletisation. Under these conditions the payout periods are respectively 3 and 6 years.

From the above it is concluded that a high economic potential exists for the TOP process. The major possible savings in biomass-to-energy chains are of such nature that the economics of this new technology are attractive for the pellet producers, pellet consumers, but also the governmental organisations to stimulate sustainable energy production. The ECN TOP technology enables the production of biopellets from biomass that is more expensive or from biomass for which it is currently infeasible. On the longer term, TOP technology can contribute to a considerable and justified reduction of subsidies on green electricity, but this must be considered in close relation to the biomass feedstock prices, costs of logistics (especially sea transportation) and the general trends in energy market prices. It is recommended to continue the development of ECN TOP technology through pilot scale testing of the identified technology.

1. Introduction

1.1 Background

Densification by means of pelletisation is considered to be a proven technology to improve biomass properties for its conversion into heat and power. Over the last few years the installed pellet production capacity in Europe has increased significantly and currently amounts 4.5 to 5 Mton annually. The pellet production in Northern America was approximately 1.2 Mton in 2004 and is expected to increase to 1.5 Mton in 2005 (Bioenergy, 2004). Such numbers indicate that the biopellets market is becoming quite mature with serious outlets in the domestic market (heating) and the energy market (heat and power). Although a relatively small volume of biopellets (or wood pellets) is produced in the Netherlands, the Dutch energy sector is consuming a considerable amount through co-firing in coal-fired power stations. In fact, biopellets are a major sustainable fuel to replace coal. This must be approximately 6 Mton/a of coal in 2008-2010, according to the policy agreement between the Dutch government and the Dutch energy sector.

Biopellets are mainly attractive for power stations since they are composed of small particles. Therefore they can be readily crushed in coal mills and the resulting particles can be conveyed to the pulverised fuel burners just like coal powder. This is not the case for biomass of larger particle size (>1 mm) so that additional pretreatment is required. Nevertheless, biopellets are not free of drawbacks: (1) high production costs are involved (2) power stations still need to make serious investments in their logistic infrastructure (especially because biopellets are vulnerable to water) and (3) they only are produced economically from a narrow feedstock range.

ECN has introduced an alternative process for the production of biopellets from a wide range of biomass feedstock to yield a superior product against lower overall costs. The process is based on a combination of **to**rrefaction and **p**elletisation and is called the TOP process for the production of TOP pellets. The TOP process integrates the advantages of both processes with respect to the fuel quality of the biopellet. This is mainly the high calorific value, hydrophobic nature and good grindability through torrefaction and the high density through pelletisation. But not only the product quality is improved, also synergy effects in production are foreseen when both processes are combined. Adding torrefaction technology to conventional pelletisation leads to additional investments, but it also decreases the operational and investment costs of the unit operations involved with pelletisation. Initial desk studies done on the TOP process revealed that the total production costs do not increase necessarily, whilst the superior biopellets quality reduces the costs of transportation and processing at the power station.

1.2 Problem definition and objectives

The initial exploration of the TOP process involved desk studies based on only a poor knowledge base and design data without experimental proof. Therefore, the process was to be considered in the “proof-of-principle” phase of development. Furthermore, it was not known how both processes combined optimally and what the optimum torrefaction and densification conditions would be. Furthermore, it was unknown what the possible improvement in pellet quality are.

The main objective of this work has been to contribute to the proof-of-principle phase of the TOP process development by means of:
1. Experimental evaluation of torrefaction combined with densification (pelletisation) and the determination of the properties of the TOP pellets in relation to torrefaction conditions and pelletisation conditions.
2. Conceptual design of the TOP process (process synthesis).
3. Economic evaluation of the TOP process as part of a biomass-to-electricity production chain.

1.3 Approach

This project was carried out parallel to another SenterNovem project called BIOCOAL known under project number 2020-02-12-14-013 (Bergman *et al.*, 2005[b]). This project particularly focussed on the experimental evaluation, process synthesis and economic evaluation of torrefaction, but without densification. The required torrefaction experiments for the present work were to a large extent combined with those of the BIOCOAL project. Also, the design and process evaluation done in the BIOCOAL project were of direct use, so that the experimental work of this project could be focussed mainly on the pelletisation of torrefied biomass.

During the experimental work, the emphasis was on determining the effect of torrefaction on the pelletisation process. This was done by using different biomass feedstock, which were torrefied under different conditions (temperature and time). Subsequently, for a certain torrefied biomass several densification experiments were carried out to also determine the effect of the main densification conditions (temperature and pressure) on the produced TOP pellets. With respect to product characterisation, the produced pellets were evaluated on the most important properties, which are the pellet density, calorific value and durability (mechanical strength and water resistance). As a laboratory press was used (a modified Pronto-Press), also pellets of untreated biomass feedstock were made (reference pellets) to see the effect of torrefaction on pelletisation.

Before the experimental programme was conducted, the conceptual design of the TOP process was largely performed to match the experimental programme optimally (experimental design) to the structure of the TOP process. The conceptual design was then completed on the basis of the experimental results. The design data on torrefaction already available at ECN was combined with the design data obtained from the experimental results of the presented work to evaluate the technical feasibility of the process. This included the design of selected unit operations and the estimation of the net process energy efficiency.

The economic evaluation comprised the estimation of the required total capital investment and the total production costs. Furthermore, a production analysis was performed to have an indication of the possible advantages of TOP pellets with respect to transportation and co-firing at existing coal-fired power stations. This part of the work was conducted in collaboration with a pellet producer in the field. The techno-economic evaluation of the TOP process was done using conventional pelletisation as the (state-of-the-art) reference.

2. The TOP process

2.1 The combination of torrefaction and pelletisation

2.1.1 Background biopellets

Biopellets (or wood pellets) offer many more attractive properties in comparison to untreated biomass. With respect to heating value, grindability, combustion nature, storage, transport and handling, biopellets are in many cases the superior fuel. Particularly their high (energy) density and uniformity has proven to be the basis for a relatively new and boosting pellet market. Their usage as heating fuel in the domestic market has increased strongly, especially in scattered areas such as the Nordic countries and Austria. Compared to untreated biomass, biopellets have a relatively high heating value and in combination with the high bulk density this allows small combustion units (domestic application: pellet stoves) and cost savings in handling and transportation. Biopellets are less vulnerable to biological degradation as they are dry, so that periods of storage can be longer (Lehtikangas, 1999). But also large volumes of pellets are nowadays produced for the large-scale generation of heat and power, in order to replace coal with sustainable energy resources.

With respect to large-scale biomass co-firing in coal-fired power stations, biopellets proved to offer a solution to grinding issues existing for untreated biomass (e.g. wood chips). Large-particle biomass feedstock are difficult to grind in the existing coal mills due to their tenacious and fibrous nature. Biopellets are already composed of small particles and in a coal mill they are readily disintegrated (crushed) to these original particles. In countries such as the Netherlands, the large-scale production of power from biomass in existing coal-fired power stations can only be established though the import of biomass. This requires transportation of large volumes of biomass to the Dutch harbours from all over the world (e.g. Canada, Brazil, South Africa). Here, biopellets with their high (volumetric) energy density are an interesting fuel.

Despite the strong development of the biopellet market over the last decade, research is still ongoing to improve the biopellet properties. This mostly concerns their durability and biological degradation. The durability of biopellets can be interpreted as resistance against water and moisture uptake and the mechanical resistance against crushing and dust formation. Generally, when exposed to water, snow, moisture or condensed water, biopellets rapidly swell and disintegrate to the original feed particles (and volume: original mass density). To prevent this they need to be stored in a dry and possibly conditioned place. Additionally, special precautions to the handling and transportation need to be taken (Alakangas and Paju, 2002).

Biological degradation of biomass is decreased after pelletisation, but can still occur. The biopellets are dry and that inhibits degradation processes, such as fungal growth and microbial activity. The effect of these phenomena on the biopellet properties can be dramatic. Especially a decrease of the mechanical durability and variations in uniformity can be the result after changes of the biological, physical, and chemical properties (Lehtikangas, 1999). Besides, storage can become hazardous due to temperature development.

As pelletisation mainly consists of physical operations, the feedstock quality is crucial in meeting the desired biopellet quality standards. Pellet uniformity is difficult to establish as the sources for quality variations are numerous. There are large differences between softwoods, hardwoods, between different tree species, and between different parts of the trees. Moreover, climatic and seasonal variations affect feedstock properties, as well as the length of the storage period and the type of storage (Lehtikangas, 1999).

Sawdust and planer shavings (cutter shavings) are the most favoured feedstock for pelletisation. These are often uniform and are low in mineral content so that high combustion quality can be established. This especially concerns domestic applications, which do not include advanced technology for emission reduction. Softwood is preferred over hardwood, since the lignin content of softwood is higher. Lignin is one of the main biomass polymers and acts as binding agent. The more lignin, the higher quality of the pellet and the milder the densification conditions can be. Also bark is a good feedstock for biopellets. It gives a high calorific value pellet, but it contains more pollutants. Therefore, it is mainly suitable for large-scale applications that typically comprise gas clean up, such as power stations. Pelletisation of fresh biomass is more difficult and, according to Alakangas and Paju (2002), pellets produced thereof are not available commercially. Their durability is poorer and they are much more vulnerable to biological degradation. It is one of the threats of pelletisation that it is practically limited to sawdust and cutter shavings as economical feedstock. With that in mind, the pellet market is closely related to the wood-processing industry and coupled to its economic nature. This may lead to future feedstock shortages when the pellet market continues to boost.

2.1.2 The added value of torrefaction

Torrefaction is a thermochemical treatment of biomass at 200 to 300 °C. It is carried out under atmospheric conditions and in the absence of oxygen. In addition, the process is characterised by low particle heating rates (< 50 °C/min). 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 torrefied wood when produced from woody biomass.
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 contains 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).

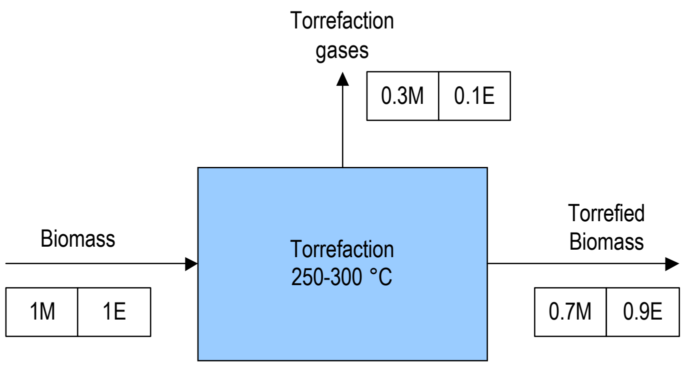


Figure 2.1 *A typical mass- and energy balance of the torrefaction process on as received basis. Symbols: E = energy unit, M = mass unit*

In the 1930's, the principles of torrefaction were first reported in relation to woody biomass and in France research was done on its application to produce a gasifier fuel (Bioenergy, 2000). Since then the process received only attention again when it was discovered that torrefied wood could be used as a reducing agent in metallurgic applications. This led to a demonstration plant, which was operated during the eighties, but was dismantled again in the beginning of the nineties of the last century (see also Bergman *et al.*, 2005[b]). During the last five years, torrefaction has received attention again, but now as pretreatment technology to upgrade biomass for energy production chains (co-combustion and gasification). During this recent period new process concepts have been proposed and are under development. No commercial torrefaction production plant is operated at the moment and its development is to be considered in the pilot-phase (Bergman *et al.*, 2005[b]).
The key-property that makes torrefied biomass attractive for co-firing in existing coal-fired power stations is its superior grindability compared to untreated or fresh biomass. After torrefaction biomass has lost its tenacious nature and partly its fibrous structure (Bergman *et al,*

2005[a]). Through torrefaction, biomass becomes more alike coal and so its size reduction characteristics. Besides, the devolatilisation during torrefaction results in an increase of the calorific value on mass basis, as the reaction products are rich in oxygen (e.g. H_2O, CO_2, acetic acid).

Biomass is completely dried during torrefaction and after torrefaction the uptake of moisture is very limited. This varies from 1-6% depending on the torrefaction conditions and the treatment of the product afterwards. The main explanation of the hydrophobic nature of the biomass after torrefaction is that through the destruction of OH groups the biomass loses its capability of hydrogen bonding. Moreover, unsaturated structures are formed which are non-polar. It is likely that this property is also the main reason that torrefied biomass is practically preserved and biological degradation, as often observed for untreated biomass, does not occur anymore. The most reactive biomass polymer during torrefaction is hemicellulose. After torrefaction it has reacted completely to alternative char structures and volatiles. Most of the weight loss can be contributed to hemicellulose with the effect that torrefied biomass mainly consists of cellulose and lignin. Hence the lignin content has increased.

Although torrefaction leads to increased energy density on mass basis, during torrefaction only little shrinkage can be expected so that the volume of produced torrefied biomass is decreased only slightly. From experimental analysis (reported in Bergman *et al.* 2005[b]) the density of torrefied biomass is ranging from 180 to 300 kg/m^3 or generally 10-20% lower than the used feedstock (when dried). Despite the higher calorific value, the volumetric energy density is not improved (typically 5 GJ/m^3). Torrefied biomass is more brittle of nature compared the biomass it was derived from. This is crucial for establishing the desired grindability, but has the drawback of decreased mechanical strength and increased dust formation.

Consequently, torrefaction and pelletisation can be very complementary when considering the pros and cons of their resulting products. From the pelletisation viewpoint, the implementation of torrefaction within the pelletisation process offers theoretically solutions to the problems encountered with the durability and biological degradation of biopellets. Torrefaction can potentially be applied to a wide variety of biomass (softwood, hardwood, herbaceous, wastes) so that the range of biomass feedstock for biopellets can be enlarged seriously. From the torrefaction viewpoint, the implementation of pelletisation within the torrefaction process subsequently offers solutions to the drawbacks of torrefied biomass, such as the low volumetric energy density and dust formation.

Synergy effects through the combination of torrefaction with pelletisation have earlier been recognised by Reed and Bryant (1978). They researched simultaneous torrefaction and densification at a temperature up to 225 °C and found that the densification process was enhanced. The compaction pressure required for densification could be reduced with a factor of 2 to achieve the same pellet quality as if produced under typical pelletisation conditions. Also the energy consumption needed for densification could be reduced by a factor of 2, whilst the pellet density and the calorific value increased significantly. Importantly, they also explored temperatures in the range of 250-300 °C, but encountered heavy devolatilisation during compression. Koukios (1993) also investigated the effect of simultaneous torrefaction and densification of biomass. Apparent biomass densities exceeding 20 GJ/m^3 were observed for straw, olive kernels and waste wood (softwood). Also, Koukios (1993) observed slight devolatilisation during densification, but this was limited probably due to the low temperatures applied. In Japan, where biomass resources are far away from the urban areas, the combination of torrefaction and densification (again simultaneous) is under investigation to reduce transport volumes of biomass (Honjo *et al.*, 2002).

2.2 The basic TOP process concept

A biomass pelletisation process typically consists of drying and size reduction prior to the densification itself. After densification the hot biopellets are cooled. Steam conditioning of the biomass is commonly applied to enhance the densification process through softening of the fibres. Torrefaction typically consist of pre-drying of the biomass, torrefaction and product cooling. Hence great similarity is present between the basic structure of both processes. The TOP process combines torrefaction and pelletisation according to Figure 2.2.

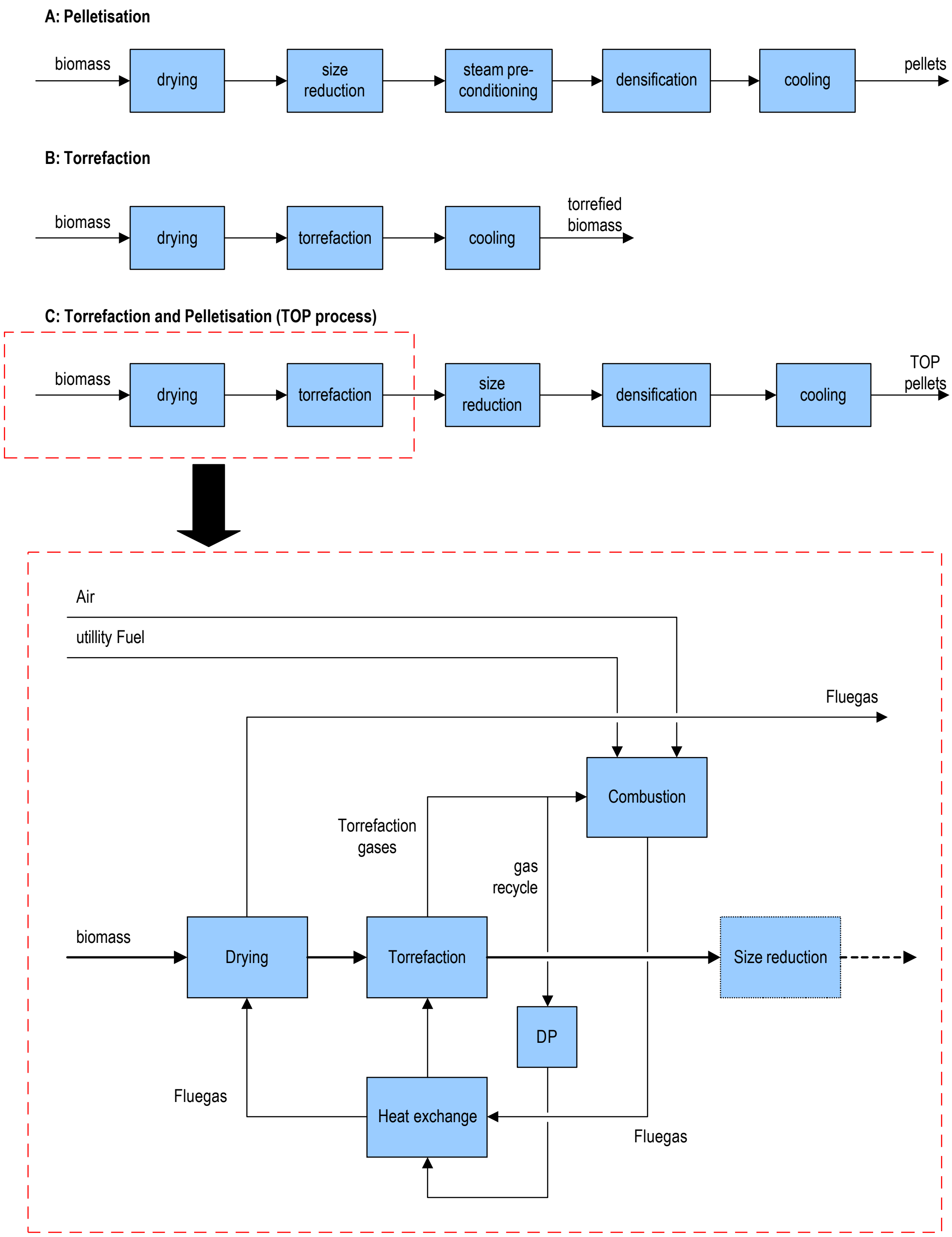


Figure 2.2 *Basic process structures of pelletisation, torrefaction and the TOP process. The lower part depicts the envisaged conceptual structure of the torrefaction process including pre-drying of the biomass (Bergman et al. (2005[b]). (DP: pressure drop recovery)*

Torrefaction is introduced as a functional unit after drying and before size reduction. In contrast to the ideas of Reed *et al.* (1978) and Koukios (1993), the TOP process does not combine torrefaction and densification in one step. A number of arguments have led to this configuration, of which the main is to prevent devolatilisation of the biomass during the densification process. Furthermore, it is believed to be complex to charge the necessary thermal heat for torrefaction to a reactor in which torrefaction and densification are integrated.

The lower part of Figure 2.2 represents the conceptual process structure of torrefaction. The depicted process layout is based on direct heating of the biomass during torrefaction by means of hot gas that is recycled. The hot gas consists of the torrefaction gas itself and is re-pressurised and heated after each cycle. The necessary heat for torrefaction and pre-drying is produced by the combustion of the liberated torrefaction gas. Possibly a utility fuel is used when the energy content of the torrefaction gas is insufficient to thermally balance the torrefaction process. Bergman *et al.* (2005[b]) identified this process concept being most promising for torrefaction. Use is made of a dedicated torrefaction reactor that is based on moving bed principles, but with 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. Currently, this torrefaction reactor is under development at ECN. The typical scale of operation is expected to be 60 kton/a of product, which is on energy basis comparable to the typical production scale of pelletisation (80 kton/a). Scale-up is in practice limited by the scale-up characteristics of the drying unit.

The thermal efficiency of the torrefaction process, according to Figure 2.2 (lower part), is typically 96% on LHV basis (net process efficiency typically 92%). Pre-drying of the biomass mainly causes the encountered loss of efficiency, as long as the torrefaction gas can be used as dryer fuel and does not contain more energy than needed. A potential loss of efficiency is when the devolatilisation of the biomass during torrefaction is too severe. Then too much energy is lost through the torrefaction gas. Bergman *et al.* (2005[b]) introduced the concept of autothermal operation, which is achieved when the total heat demand of the process (drying and torrefaction) is balanced by the energy content of the torrefaction gas. When the process is balanced below the point of autothermal operation, the energy content of the torrefaction gas is insufficient and a utility fuel is needed. When the process is operated above the point of autothermal operation, the torrefaction gas contains a surplus of energy, which in practice will result in a higher flue gas temperature after drying (hence higher stack losses). Only when the process is operated at or below the point of autothermal operation, the high thermal efficiency can be obtained. The torrefaction conditions (temperature and reaction time) are the crucial variables to tune the thermal balance (viz. the energy yield of torrefaction and hence the energy content of the torrefaction gas).

The moisture content of the biomass feedstock is very important to the thermal balance of the process, since this feedstock property mainly determines the total required heat demand. Figure 2.3 shows the relationship between autothermal operation of the process in relation to the energy yield of torrefaction and the moisture content of the biomass feedstock. Bergman *et al.* (2005[b]) derived this relationship on the basis of experimental work and process simulations. It can be observed that dry feedstock requires a high energy yield during torrefaction to avoid energy losses. The wetter the biomass feedstock, the lower the energy yield is allowed to be. It is argued by Bergman *et al*. (2005[b]) that a high thermal energy efficiency is most difficult to obtain for dry biomass, since then the energy yield must be maximal. The torrefaction gas that is produced at high energy yields has the lowest calorific value and it can be problematic to combust.

Next to synergetic effects found in the fuel quality when torrefaction and densification are combined, they also occur at the level of the unit operations involved with pelletisation. After torrefaction, size reduction and densification of biomass are significantly enhanced with respect to power consumption, capacity characteristics and equipment wear. The storage of the produced pellets can be simplified since biological degradation and water uptake is minimised. Another advantage is found in the fuelling of the drying operation. In the conventional pelletisation process, natural gas, propane or part of the feedstock is used. The use of fossil utility fuel is to be avoided because it harms the sustainable nature of the produced biopellets.

The use of biomass (e.g., feedstock), however, increases the burner complexity and so the investment costs of drying (Reesinck, 2005). In the TOP process, the torrefaction conditions can be optimised to operate it near or at the point of autothermal operation. Under such conditions drying is fuelled practically by the torrefaction gas, see also Figure 2.2 (lower part). This eliminates the need for a complex and expensive drying unit.

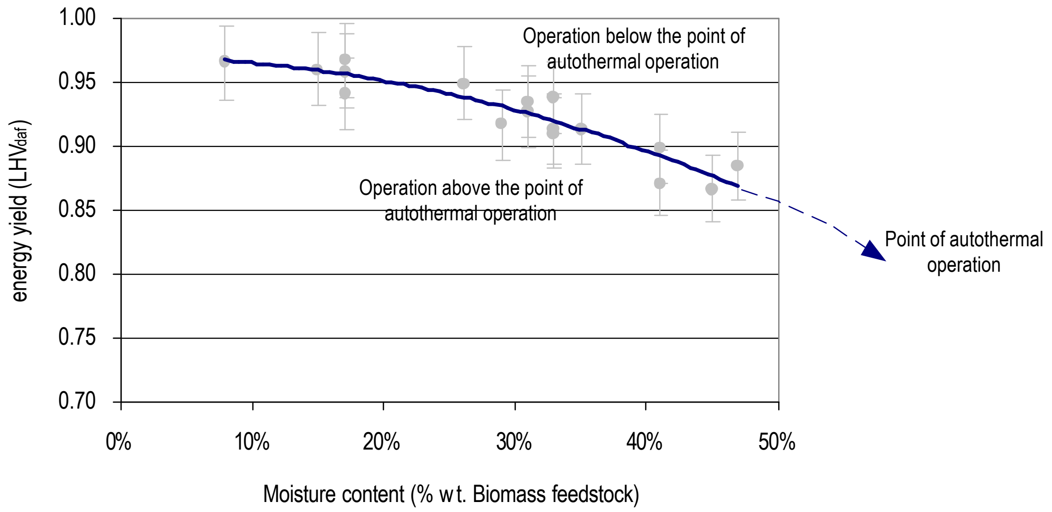


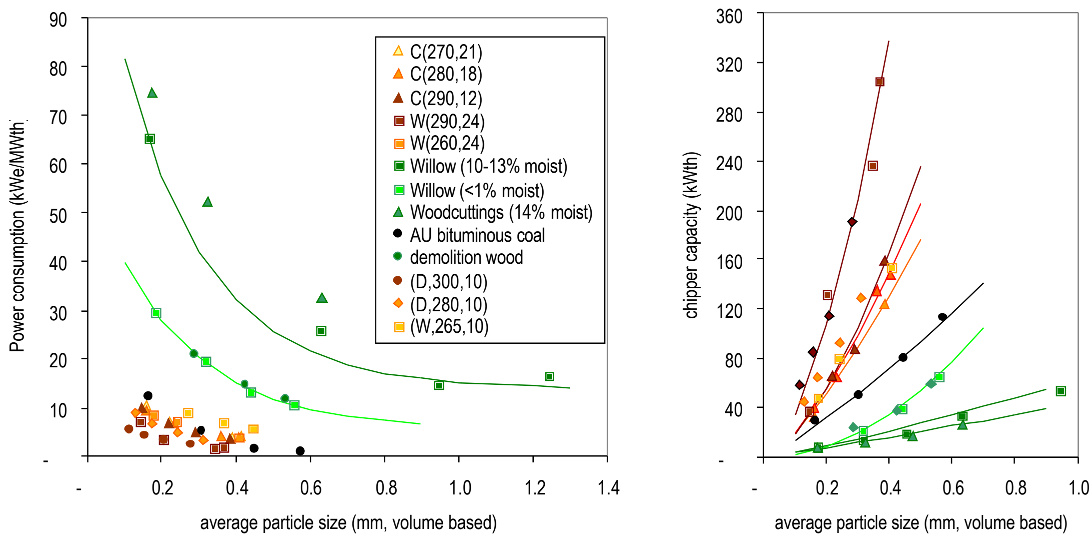
Figure 2.3 *Relation between energy yield of torrefaction and moisture content of the biomass feedstock with respect to autothermal operation of the torrefaction process (based on Bergman et al., 2005[b])*

2.3 Experimental validation of the TOP process concept

The experimental work aimed for the demonstration of the added value of torrefaction to pelletisation according to the TOP process concept. The main focus was set to important product properties, which are the calorific value, density, resistance to water, mechanical strength of the TOP pellets. In addition, the effect of torrefaction on the process of size reduction and pelletisation was explored. Torrefaction experiments were carried out under different operating conditions (temperature and reaction time) to produce the required torrefied biomass. To demonstrate the feedstock range, different feedstocks were applied: larch (softwood), willow (hardwood), demolition wood (mixed), straw and verge grass (herbaceous biomass). A description of the used torrefaction facilities and procedures can be found in Bergman *et al.* (2005[a,b]).

2.3.1 Size reduction of torrefied biomass

Figure 2.4 represents the results of size reduction experiments carried out on untreated biomass (15% moisture content), torrefied biomass and coal. The results were obtained using a heavy duty cutting mill equipped with a monitoring system to determine its capacity and the net power consumption needed for the size reduction of the biomass. It can be observed that the power consumption of the cutting mill reduces dramatically when the biomass is first torrefied. Depending on the applied torrefaction conditions, the reduction in power consumption ranges from 70% to 90%. Simultaneously, the production capacity increases dramatically after torrefaction. Depending on the applied torrefaction conditions, the capacity increase is a factor of 7.5 to 15.



Net power consumption curves Capacity curves

Figure 2.4 *Size reduction results of coal, biomass and various torrefied biomass. Coding: biomass (torrefaction temperature, reaction time). See Bergman et al. (2005[a,b]) for explanation on torrefaction temperature and reaction time*

Size reduction of biomass is known as an energy consuming process and suffers from excessive wear of the equipment involved. As in the TOP process size reduction takes place after torrefaction, a high-energy consumption is avoided and the desired production capacity can be established with much smaller equipment. Hence the energy efficiency is improved; lower operational costs are possible against a lower capital investment. In the conventional pelletisation production process use is made of hammer mills, whilst in the TOP process a simpler type of equipment can be applied (e.g. cutting mill, jaw crusher) or size reduction is established during densification.

2.3.2 Densification of torrefied biomass

Densification experiments have been carried out on untreated and torrefied biomass. The applied experimental facility comprised a piston press (Pronto-Press) that can be operated at different pressures and temperatures. The press was modified to press pellets of various diameters. Using this facility, the densification behaviour of different torrefied biomass produced under different torrefaction conditions was evaluated, whilst also variations in operating conditions of densification were applied (die-temperature and pressure). In all experiments, first the temperature was raised to the desired level before the densification was started, according to the TOP concept. The facility did not allow evaluation of the effect of torrefaction on the capacity and power consumption characteristics of densification.
Table 2.1 provides an overview of the properties of TOP pellets in comparison with wood, torrefied biomass and conventional wood pellets. The given ranges in properties of the TOP pellets were found after optimisation of the densification conditions in relation to the torrefaction conditions for each biomass type. The bulk densities obtained for TOP pellets vary in the range of 750 to 850 kg/m^3. In combination with the relatively high calorific value (LHV basis) of torrefied biomass (generally 19 to 22 MJ/kg (ar) and for the examined types of biomass 19.9 to 21.5 MJ/kg (ar), see also (Bergman *et al.*, 2005[b]), the energy density of TOP pellets ranges from approximately 15 to 18.5 GJ/m^3. Conventional wood pellets have a bulk density of 520 to 640 kg/m^3 (Obernberger and Thek, 2002) and a net calorific value of 15 to 17 MJ/kg (Lehtikangas, 1999). Therefore, the energy density of conventional pellets ranges from 8 to 11 GJ/m^3 and hence TOP pellets can be about 70-80% more dense. The energy density of TOP

pellets is best compared to sub-bituminous coal, which has a typical value of 16-17 GJ/m^3 (Perry and Green, 1998). For bituminous coal this is typically 21-22 GJ/m^3.

Table 2.1 *Properties of wood, torrefied biomass, wood pellets and TOP pellets*

Properties	unit	Wood	Torrefied biomass	Wood pellets		TOP pellets	
				low	high	low	high
Moisture content	% wt.	35%	3%	10%	7%	5%	1%
Calorific value (LHV)							
as received	MJ/kg	10,5	19,9	15,6	16,2	19,9	21,6
dry	MJ/kg	17,7	20,4	17,7	17,7	20,4	22,7
Mass density (bulk)	kg/m^3	550	230	500	650	750	850
Energy density (bulk)	GJ/m^3	5,8	4,6	7,8	10,5	14,9	18,4
Pellet strength		-	-	good		very good	
Dust formation		moderate	high	limited		limited	
Hygroscopic nature		water uptake	hydrofobic	swelling / water uptake		poor swelling / hydrofobic	
Biological degradation		possible	impossible	possible		impossible	
Seasonal influences (noticable for end-user)		high	poor	moderate		poor	
Handling properties		normal	normal	good		good	

The mechanical strength of the TOP pellets was evaluated by means of crushing tests. The TOP pellets can withstand typically 1.5 to 2 times the force exerted on conventionally produced pellets before breakage. TOP pellets produced from larch could even withstand 2.5 times this pressure. It is believed that the higher mechanical strength is the result of the densification process at high temperature, which causes the biomass polymers to be in a weakened state (less fibrous, more plastic), but also the chemical modifications that have occurred during torrefaction lead to more fatty structures acting as binding agent. In addition, the lignin content has increased by typically 10-15% as the devolatilisation process predominantly concerns hemicellulose.
The hydrophobic nature of the produced pellets was determined by immersing them in water for a period of 15 hours. The hydrophobic nature was evaluated on the basis of the state of the pellet after this period (integrated or disintegrated) and by gravimetric measurement to determine the degree of water uptake. Whereas pellets from untreated biomass showed swelling rapidly followed by the disintegration of the pellet into the original particles, TOP pellets did not show this unfavourable behaviour. Under optimal production conditions the pellets did not disintegrate and showed little water uptake (7-20% on mass basis, depending on production conditions).

2.4 Technical process performance characteristics

Both the conventional pelletisation and the TOP production process were designed and modelled to provide insight in the important production characteristics such as process energy efficiency, production capacity and utility consumption. For this purpose several modelling tools were used that are available at ECN and useful technical information on the conventional pelletisation process was obtained from Zakrisson (2002). Table 2.2 provides an overview of the technical performance characteristics of the conventional pellet process and the TOP process. Two cases were analysed for both that differed in feedstock: sawdust and green wood (hardwood). The cases were based on a feedstock capacity of 170 kton/a with a moisture content of 57%. Both processes were thermally balanced by using natural gas for required heat input for drying.

Table 2.2 *Technical performance characteristics of conventional pelletisation process and the TOP process. The reported net efficiencies are based on electricity generated with an efficiency of 40%*

Item	Unit	Conventional pelletisation	TOP process	Conventional pelletisation	TOP process
Feedstock		Sawdust	Sawdust	Green wood chips	Green wood chips
Feedstock capacity	kton/a	170	170	170	170
Moisture content	wt.	57%	57%	57%	57%
LHV_{ar} feed (ar)	MJ/kg	6.2	6.2	6.2	6.2
Production capacity	kton/a	80	56	80	56
	Mm^3/a	133	70	133	70
	MW_{th} fuel	44	40	44	40
Moisture content	% wt.	9	3	9	3
LHV_{ar} product	MJ/kg	15.8	20.8	15.8	20.8
Cooling water	m^3/ton product	-	16.7	-	16.7
Steam	ton/ton product	0.025	-	0.025	-
Utility fuel	MW_{th}	10.4	3.9	11.3	4.7
Power consumption	MWe	1.26	0.83	1.84	1.01
Thermal efficiency	LHV(ar)	93.9%	98.5%	92.2%	96.5%
Net efficiency	LHV(ar)	88.0%	93.7%	84.0%	90.8%

The production capacity of the conventional pelletisation process is 80 kton/a of pellets, which is equivalent to 44 MW_{th} of fuel output. The TOP process produces 56 kton/a of pellets, which corresponds to 40 MW_{th}. The lower production capacity of the TOP process is caused by the devolatilisation reactions during torrefaction. However, the TOP process may produce less fuel-energy from the feedstock, but it also uses less utility fuel (natural gas), as it is replaced by the torrefaction gas. Whereas more than 10 MWth of utility fuel is required in case of conventional pelletisation, about 4 MWth is needed in the TOP process. Hence the TOP process is operated below the point of autothermal operation.

A big advantage of the TOP process is found in the volumetric production rate of pellets. Whereas the conventional pelletisation process produces 133 Mm^3/a for 44 MWth fuel output, the TOP process produces 70 Mm^3/a for 40 MWth output. This enormous reduction offers a big advantage in the logistic operations, see also Section 3.3. The volumetric reduction is caused by the very high energy density obtained for TOP pellets (high calorific value and bulk density).

The power consumption of the TOP process is lower compared to the conventional pelletisation process due to the decreased power consumption of size reduction (see also Figure 2.4) and pelletisation, despite the torrefaction operation that increases the power consumption. Overall, both the thermal and net process efficiency of the TOP process are significantly higher. The biggest loss of energy is encountered during the drying of the feedstock. In the case of sawdust, the net efficiency of the TOP process is estimated at 93.7%, compared to 88% for conventional pelletisation.

The results for the production of biopellets from green wood (chips) show the impact of increased energy consumption of drying, size reduction and densification on the process energy efficiencies (conventional pelletisation). Because chips are more difficult to dry, increased thermal losses and higher power consumption are encountered. Also size reduction of chips is more complicated and needs to be performed in two steps in series. In case of the TOP process comparable energy losses are encountered with respect to drying, but the size reduction and densification operations remain with similar performance characteristics as are expected for sawdust. Hence the higher efficiencies that can be obtained by the TOP process.

3. Economic analysis

3.1 Approach

The economic analysis performed on the TOP process was based on estimations of the required capital investment and total production costs. In addition, the influence of the TOP process and product on a production chain from biomass to electricity via existing coal-fired power stations was evaluated on the basis of a discounted cash flow analysis to determine the internal rate of return and the payout period of the investment. This was also done for conventional pelletisation to serve as reference. Shortcut methods were used to estimate the installed costs of the main plant items. Based on the installed equipment costs, the fixed capital investment and total capital investments were estimated using the factorial method described by Peters and Timmerhaus (1991). The estimation of the total production costs were also based on the factorial method described by these authors, and by using the technical data obtained from the modelling activities (M&E balances and utility consumption, see also Table 2.2). A potential production chain was set up in close collaboration with GF Energy (Pellet producer) to estimate the costs of logistics. This production chain describes the involved costs of the production of pellets from sawdust in South Africa and consumption in North-West Europe.
Table 3.1 provides a summary of general economic data used in the economic 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.

Table 3.1 *Summary of general input data used for the economic evaluation*

Item	Unit	Value
Depreciation period	Year	10
Depreciation method	-	Linear
Financing	% of investment	5
Feestock (gate delivered)	€/ton (wet)	0
Utilities		
Electricity	*€/KWh*	0.065
Natural gas (NG)	*€/Nm^3*	0.14
Cooling Water	*€/m^3*	0.04
Air		
Labour		
Costs	€/a per operator	50,000
Operator shifts	# / day	5

The feedstock price (woodcuttings) is set to 0 €/ton (wet) to get a clear impression of the involved production costs. The prices for utilities correspond with current prices (2004) for the Dutch economic situation (thus not South Africa). 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 are included to compensate for the availability of the operating labour (holidays, sick leave).

3.2 Estimation of the total capital investment and total production costs

Table 3.2 summarises the main outcomes of the economic analysis done on the four cases described in the previous chapter. The main cost items shown are the total capital investment

(TCI) and the total production costs (TPC). Although depreciation and financing are items contributing to the TPC, they are also summarised individually, as these items may be treated differently in discounted cash flow analyses.

Table 3.2 *Economic performance characteristics of the pelletisation of sawdust and green wood (hardwood) for the conventional pelletisation process and the TOP process*

item	unit	Conventional Pelletisation	TOP process	Conventional Pelletisation	TOP process
Feedstock		Sawdust	Sawdust	Green wood	Green wood
Productionrate	kton/a	80	56	80	56
Total Capital Investment*	M€	3.9	5.6	5.9	7.4
Total production costs**	€/ton	41	45	54	50
	€/GJ	2.6	2.2	3.4	2.5
Financing	€/ton	2.0	4.4	3.2	5.9
Depreciation	€/ton	4.0	8.8	6.5	11.7

*: including working capital of about 0.5 to 0.7 MEURO

**: Including cost items financing and depreciation

Capacities and costs are related to tonnages of product

When considering only the sawdust cases, the TOP process requires a higher TCI compared to the conventional pelletisation process, which is due to the introduction of torrefaction, despite lower investments costs in size reduction, pelletisation, and product storage. The TPC of the TOP process per ton of product is higher than for conventional pelletisation, but a ton of TOP pellets contains more energy than a ton of conventional pellets. The best comparison between both processes is on the basis of €/GJ and it can be observed that the TPC of TOP pellets is estimated at 2.2 €/GJ against 2.6 €/GJ for conventional pelletisation. Due to the higher capital investment, the fixed charges of the TOP process are higher (+0.34 €/GJ), but the utility costs are significantly lower (-0.74 €/GJ). This is due to lower usage of natural gas and electricity. Less use of natural gas is the consequence of the partial replacement of it by the torrefaction gas. This originates from the feedstock and since the feedstock costs are taken at 0 €/ton, the produced torrefaction gas is very low in costs. It is estimated that the total production costs of both processes equal at feedstock costs (sawdust) of 25 €/ton. Note that this 'point of break-even' very much depends on the economic boundary conditions of Table 3.1, in particular the costs of natural gas.

From both evaluated cases on green wood, it can be observed that for both processes the TCI and the TPC are higher compared to pellet production from sawdust. Especially the investment costs involved with drying increased, as this is more expensive for green wood chips compared to the sawdust (lower drying temperatures, resulting in a significantly larger dryer). In case of conventional pelletisation, also the variable costs (electricity consumption) and investment costs of size reduction increase. The latter is not the case for the TOP process. The green wood cases indicate that TOP pellets production from this biomass can be established against similar production costs as for conventional sawdust pellets.

3.3 Analysis of logistical and transportation costs

The profitability of the TOP process was evaluated on the basis of a production chain of producing pellets in South Africa from sawdust (5 €/ton gate delivered) for co-firing in North-West Europe. The analysis included a cost analysis of the following logistic operations:

- Delivery of feedstock at the production site,
- Transportation and handling of the produced pellets to a harbour in South Africa,
- Intermediate storage and transfer operations in this harbour

· Sea transportation
· Transfer operations and intermediate storage in the European harbour
· Transportation to the end-user

The case was set-up and evaluated in close collaboration with GF Energy B.V., which is a biomass trading and (future) pellet production company. The cost analysis was also performed on conventional pelletisation to have an impression of the advantages of the TOP process over conventional pelletisation. The possible advantages of TOP pellets with respect to handling and logistics (e.g. simpler storage facilities) were not included in the analysis so that purely the influence of a higher energy density and smaller volumes to be transported become visible. Table 3.3 summarises the results of this analysis.

Table 3.3 *Costs analysis of TOP pellets and conventional pellets production and logistics. Production in South Africa and consumption in North-West Europe*

			TOP process		Conventional Process	
	Production capacity	ton/a	56,000		80,000	
		MWth	40		44	
		density	800		650	
			EUR/ton product	EUR/a	EUR/ton product	EUR/a
South Africa	Feedstock gate delivery		15	840,000	11	840,000
South Africa	Pellet production & product storage		45	2,520,000	41	3,280,000
South Africa	Road Transportation to harbour		4.4	245,000	4.4	350,000
South Africa	Storage in harbour		1.5	81,900	1.8	144,000
South Africa	Transfer & handling harbour		3.3	182,000	4.0	320,000
	Sea Transportation		28	1,575,000	35	2,769,231
NW Europe	Transfer & handling harbour		3.3	182,000	4.0	320,000
NW Europe	Storage in harbour		1.7	95,550	2.1	168,000
NW Europe	Water transportation to end-user		1.6	91,000	2.0	160,000
		TOTAL	104	5,812,450	104	8,351,231
		EUR/GJ	4.99		6.61	

The total costs per ton of product are similar of both processes (which is coincidence), but on absolute basis the costs involved in the production chain are significantly less (30%) for the TOP process, due to the lower production volumes (higher energy density) and higher bulk density. The most important savings are found in the production and in sea transportation.

3.4 Market price of TOP pellets

The market price of biomass depends on all the properties discussed in Section 2.1.1. Generally, The more ideal the fuel is, the less costs will have to be made by the consumers and thus the higher the market value can be. A first indication of the market prices of TOP pellets has been obtained for the co-firing market and the domestic market (see Table 3.4, which is based on only the differences in net calorific value.

Table 3.4 *Estimation of market prices of TOP pellets. Values are derived from the market prices of conventional biopellets*

Item	Unit	Conventional pellets	TOP pellets	Conventional pellets	TOP pellets

		Co-firing market		Domestic market	
LHV (ar)	GJ/ton	16.5	20.4	16.5	20.4
Gate price	€/ton	120	148	150	185
	€/GJ	7.3	7.3	9.1	9.1

The estimated market price of TOP pellets is nearly 150 €/ton for the co-firing market and 185 €/ton for the domestic market. Please note that the market price is in close relation to the torrefaction conditions, as these determine the net calorific value of the product.

3.5 Profitability analysis

Table 3.5 represents the results of the cash-flow analysis of the TOP pellets- and conventional pellets production (SA), transportation and delivery at the power station (NW-Europe). The revenues are based on the market prices reported in Table 3.4. The tax-rate was set to 35% of the profit before tax (item E). The costs of financing were excluded from the total production costs and even so the depreciation, which is considered to be a different item in the DCF analysis (item D). The internal rate of return was estimated on a constant market price and based on a project lifetime of 10 years, equal to the depreciation period.

Table 3.5 *Results of the DCF analysis*

Item	Description	calculation	TOP pellets	Conv. Pellets
			EUR/a	EUR/a
A	Revenues		7,616,000	8,800,000
B	Costs		5,073,250	7,871,231
C	Operational Income	A-B	2,542,750	928,769
D	Depreciation		492,800	320,000
E	Profit before Tax	C-D	2,049,950	608,769
F	To state	Tax rate * E	717,483	213,069
G	Net Income	E-F	1,332,468	395,700
H	Cash Flow	G+D	1,825,268	715,700
	Internal rate of return		30%	13%
	Pay-out period	year	3	6

The TOP pellets case generates much more cash flow compared to the conventional pellets case. This is the consequence of the lower production and logistic costs, despite smaller revenues due to the lower thermal output capacity (40 MWth against 44 MWth for the conventional process). Consequently, whereas the IRR for conventional pelletisation is estimated at 13%, this is 30% in the case of TOP pellets. In addition, the payout period of the TOP process is only half the payout period of a conventional pelletisation process.

3.6 Advantages of TOP pellets at the power station

Co-firing of conventional biopellets in coal-fired power stations requires a dedicated storage system with its own handling and logistics together with a dedicated processing line comprising transportation, size reduction and feeding to dedicated burners. It the most ideal case, TOP pellets can be stored together with coal and processed using the existing infrastructure for coal. In that case the savings that can be established by the owners of the power stations are enormous. In the case the TOP pellets require similar technology as used currently for pellets, the additional investments and operational costs will be roughly 30% smaller due to lower volumes for the same thermal capacity. Thus the potential savings that can be made when power stations use TOP pellets instead of conventional biopellets are expected to be in between 30%-100%. In addition, it is expected that the efficiency of the power station is higher for TOP pellets compared to conventional pellets, as their higher calorific value and lower moisture content will lead to decreased stack losses.

4. Conclusions and outlook

4.1 Conclusions

This work aimed for demonstrating the synergy effects of combining torrefaction with densification (pelletisation) to produce a high quality biopellet (TOP pellet) with improved economics in comparison to conventional biopellets. This was done by proof-of-principle experiments and economic analysis so that this work must be placed in the phase of proof-of-principle / proof of concept. The work was focussed on the production of TOP pellets for co-firing applications in existing coal-fired power stations.

The experimental work revealed that TOP pellets may have a bulk density of 750 to 850 kg/m^3 and a net calorific value of 19 to 22 MJ/kg as received. This results in an energy density of 14 to 18.5 GJ/m^3, which is reasonably comparable to sub-bituminous coal (16-17 GJ/m^3). The energy density is significantly higher than conventional biopellets produced from softwood (sawdust: 7.8 to 10.5 GJ/m^3). In contrast to conventional biopellets, the experimental tests revealed as well that TOP pellets can be produced from a wide variety of feedstock (sawdust, willow, larch, verge grass, demolition wood and straw) yielding similar physical properties. From tests on the water uptake and mechanical strength of both TOP pellets and conventional pellets, it is concluded that TOP pellets have improved durability.

It is expected that the TOP production process can be operated with a thermal efficiency of typically 96% or a net efficiency of 92% on LHV basis. The TOP process requires a higher total capital investment compared to the conventional pelletisation process, respectively 5.6 M€ against 3.9 M€ for a capacity of 170 kton/a of sawdust feedstock, with 57% moisture content. However, due to significant cost reductions the drying, size reduction, densification and product storage, the total production costs of the TOP process are lower; 2.2 €/GJ against 2.6 €/GJ in the case of conventional pelletisation. It is emphasised that these results specifically belong to the cases that were evaluated.

The costs advantages of TOP pellets in logistic operations were evaluated on the basis of a specific production chain (production in South Africa and consumption in North-West Europe). For this case, the logistic costs involved with TOP pellets are estimated to be 2.1 €/GJ against 3.1 €/GJ for conventional pelletisation (using the similar logistic technology). This is the result of the higher bulk density of TOP pellets and the lower tonnage per GJ that needs to be transported. The total costs from feedstock delivery at the pellet production site to gate delivery of pellets at the power station are estimated at 5 €/GJ and 6.6 €/GJ for respectively the TOP- and the conventional pelletisation. For a market price of 7.3 €/GJ of biopellets the internal rate of return of the TOP process is 30% against 13% for conventional pelletisation. Under these conditions the payout periods are 3 and 6 years respectively. It is again emphasised that these results specifically belong to the cases that were evaluated.

From the above it is concluded that a high economic potential exists for the TOP process. The major possible savings in the biomass-to-electricity production chain are of such nature that the economics of this new technology are attractive for the pellet producers, pellet consumers, but also governmental organisations to stimulate sustainable energy production. The ECN TOP technology enables the production of biopellets from biomass that is more expensive or from biomass for which it is currently infeasible. It may also enable the production of biopellets economically from biomass that currently have a negative market value (e.g. verge grass). On the longer term, TOP technology can contribute to a considerable and justified reduction of subsidies on green electricity, but this must be considered in close relation to the biomass feedstock prices, costs of logistics (especially sea transportation) and the general trends in energy market prices.

4.2 Outlook

This work focussed on the proof-of-principle phase of the TOP process, but also the proof-of-concept phase of development was addressed by the conceptual design of the involved unit operations and economic analysis. Therefore it is believed that the next step in the development of TOP technology comprises the phase of pilot-scale testing by means of constructing a prototype of the identified technology. This is to expand the knowledge base on larger scale and to gain experience with TOP pellets with respect to production, logistics and conversion applications. Next to the development of the technology, the further, characterisation, registration and standardisation of TOP pellets as a new biofuel product will have to be addressed.

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