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Production of Solid Sustainable Energy Carriers from Biomass by Means of Torrefaction

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Report on optimisation opportunities by integrating torrefaction into existing industries

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1 Summary

The objective of task 3.4 in the Work Package 3 is to optimise the efficiency and economic feasibility of the torrefaction process by integrating the torrefaction step to existing forestry operations or biomass power and heat production. Benefits are foreseen not only in energy (power and heat) integration, especially in the drying process, but also in feedstock logistics and biomass handling and preparation, as well as other common infrastructure benefits.

This report includes a stream-lined mass and energy balance calculation of three stand-alone torrefaction processes based mainly on data provided by the partners of WP3. Several integration cases were considered and an economic assessment has been carried out. A stand-alone TOP-pellets (Torrefaction and Pelletisation) production plant with a capacity of about 72 000 t/a, foreseen as a typical European commercial plant, was chosen as bench mark. A saw mill, a CHP plant, a Nordic pulp mill and a combined pulp and paper mill were chosen as parent process in the integration cases.

A mass and energy balance calculation was carried out on three stand-alone torrefaction concepts based on information provided by Topell Energy, ECN and CENER on their respective processes. These assessments served as bases for the integration of the torrefaction process to the selected industrial plants. The mass and energy balance calculations of all stand-alone processes are streamlined to a certain extent. A belt dryer is incorporated in all process schemes. The low temperature dryer is considered the most flexible and favourable alternative when elaborating on the integration options. The energy needed for drying is 4.0 MJ/kg evaporated H_2O for a belt dryer in all cases. The product of all processes is TOP-pellets from wood. The net calorific value (LHV) of wood is 19.2 MJ/kg on dry basis in all cases, equal to net calorific value as received 8.4 MJ/kg at 50 wt% moisture content. The amount wood fed into the system is the same in all cases (53.5 MW). The net calorific value (LHV) of TOP-pellets is 22.0 MJ/kg on dry basis.

Two stand-alone plants are included in this study. A large scale European torrefaction plant is compared to an overseas option utilising local wood. The evaluation is carried out using the same cost factors, expect that the feedstock cost applied is 25% lower than in the European cases. The feedstock price for wood has stabilised in the Nordic countries to a level of 18-25 €/MWh. In overseas regions the price variation is significantly larger, range from 10 to 20 €/MWh.

Altogether seven different integration options were assessed, reflecting the three chosen parent processes operating in slightly different context. The production capacity of the torrefied pellets in the wood industry integrates are considerably higher than in the chosen base case stand-alone plant. This reflects significantly on the calculated production costs.

The economic assessment was carried out mainly based on VTT and Pöyry Management Consulting Ltd in-house information. The assessment of investment costs is based on a number of feasibility studies and budget offers of commercially available equipment and components. The operation costs mainly reflect a Scandinavian price level. A feedstock price of 18-20 €/MWh (15 €/MWh in the overseas case study) and a operation time of 8 000 hours of the torrefaction plant are used in the assessment.

According to this assessment, the production price of TOP-pellets in integrated alternatives is 76-95% of that in the stand-alone base case plant. Part of the lower production price is due to the larger production capacities of most of the integrated plants. The price of the feedstock is the single parameter with the most significant influence on the production costs of torrefied pellets.

Production costs in a medium scale stand-alone torrefaction plant of 72 800 t/a are over 40 €/MWh, and integration to an existing CHP plant does not reduce the costs substantially. The integration of torrefaction to wood industry plants results in clear savings. A production price level of 34-38 €/MWh is reached. The integration to a saw mill is especially favourable if a new combined plant is constructed. In this case the energy for the timber dryer and the drying of the wood chips for the torrefaction plant can be produced with a single boiler, sized and fitted for both operations. In this case there is also the possibility to increase the capacity of the torrefaction island using excess forest residue as feedstock. Taking into account the medium scale stand-alone torrefaction plant chosen as bench mark, the actual cost savings gained by integrating the torrefaction process seem to be relatively limited. However, there are certainly benefits especially on wood procurement, logistics and transportation costs, storage and handling at the plant, and savings in other commodities that may not have been fully implemented in this assessment.

The estimated production costs of torrefied pellets at a large scale stand-alone overseas are 29 €/MWh for a 500 000 t/a plant, assuming a feedstock price of 15 €/MWh. The fixed operating costs and other variable costs were maintained at European/Nordic level for the sake of comparison. The latter is expected to reduce the production costs with 4-5 €/MWh, thereby off-setting the estimated overseas transportation cost of 3.2 €/MWh.

Torrefied pellets production cost in Spain has been evaluated using beech wood and straw as raw materials for comparison purposes. Straw is more reactive than beech, although the inherently lower bulk density requires 3 production lines compared to 2 production lines for beech, to reach the same production capacity. The higher investment, maintenance, electricity and consumables costs are compensated by the lower feedstock cost and the higher production efficiency. The final production costs are the same in both cases.

2 Introduction

Commercial development of torrefaction is currently in its early phase. Several technology companies and their industrial partners are moving towards commercial market introduction. An overview of reactor technologies that are applied for torrefaction is presented in [1] and [2]. Several torrefaction technology providers in Europe claim to have reached commercial production. In North America there are also some interesting initiatives under development, which claim that they are in a commercial demonstration phase. These first European commercial demonstration plants are usually stand-alone production sites of a capacity around 40 to 70 000 t/a. This plant size seems to fit both the technical scale up of the pilot and demo projects as well as the estimated future potential feedstock availability.

In particular in the Nordic countries, with a traditionally large utilisation of woody biomass both in the mechanical and chemical wood processing industry as well as in power and heat production, significant synergy effects could be obtained by integrating the torrefaction process to existing wood based industries. There are synergies for bioenergy carrier integration due to favourable procurement and logistics, energy and labour benefits. However, considering the huge potential of torrefied pellets in replacing coal in co-firing the plant production capacity could be 100 000 to 500 000 t/a in the future. This trend is clearly seen in the wood pellet industry.

The objective of task 3.4 in the Work Package 3 is to optimise the efficiency and economic feasibility of the torrefaction process by integrating the torrefaction step to existing forestry operations or biomass power and heat production. Benefits are foreseen not only in energy (power and heat) integration, especially in the drying process, but also in feedstock logistics and biomass handling and preparation, as well as other common infrastructure benefits.

This report includes a stream-lined mass and energy balance calculation of three stand-alone torrefaction processes based mainly on data provided by the partners of WP3. Several integration cases are considered and an economic assessment is carried out mainly based on VTT and Pöyry Management Consulting Ltd in-house information.

3 Stand-alone plants

3.1 Plant presentations

Three different torrefaction technologies in terms of process design and scale of present applications are briefly described below. These are all developed (or modified) by the partners involved in the SECTOR project. Topell Energy’s fluid bed technology is the only one that has reach commercial scale operation. The moving bed technology developed by ECN is in demonstration phase at the Andritz demo plant in Denmark. CENER has modified an indirectly heated rotating shaft technology to fit torrefied wood and straw production in a pilot scale plant. All technologies are designed to operate in a stand-alone mode, but this does not exclude the option of integrating the technologies to existing industrial plants.

3.2 Topell Energy

3.2.1 Process description

Topell Energy applies a TORBED reactor designed for effective gas/solid contact in various industrial applications. Topell started the construction of their first commercial torrefaction plant in Duiven, the Netherlands, in 2010. With a production capacity of 60 000 t/a, the plant started to producing torrefied fuel pellets from biomass in early 2011 [3]. Torrefied biomass has been produced for milling and co-combustion tests for various customers. The plant is still in the commissioning phase and a new combustion unit will be operational in mid-2013.

The core of the Topell Torrefaction System (TTS) consists of several TORBED reactors, Figure 1 and 2, which have a short retention time and high heat transfer efficiency. During the torrefaction process volatiles are produced (“torgas”). The thermal energy needed for the pre-drying and the torrefaction process is provided by a dual fuel combustor, which burns the torgas and natural gas as a support fuel.

The exiting gas from the combustor (the “flue gas”) is cooled with several heat exchangers before it is sent to the pre-dryer and torrefaction reactors. The heat exchangers are chosen in such a way that a range of operating conditions (flow and temperature) in the reactors can be chosen. Transport of the various gas streams is done by fans.

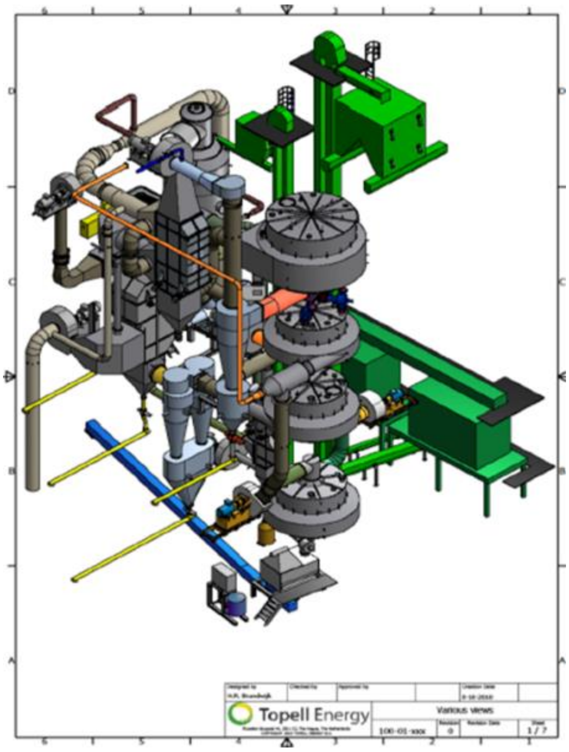


Figure 1. Topell Energy torrefaction reactor [3].

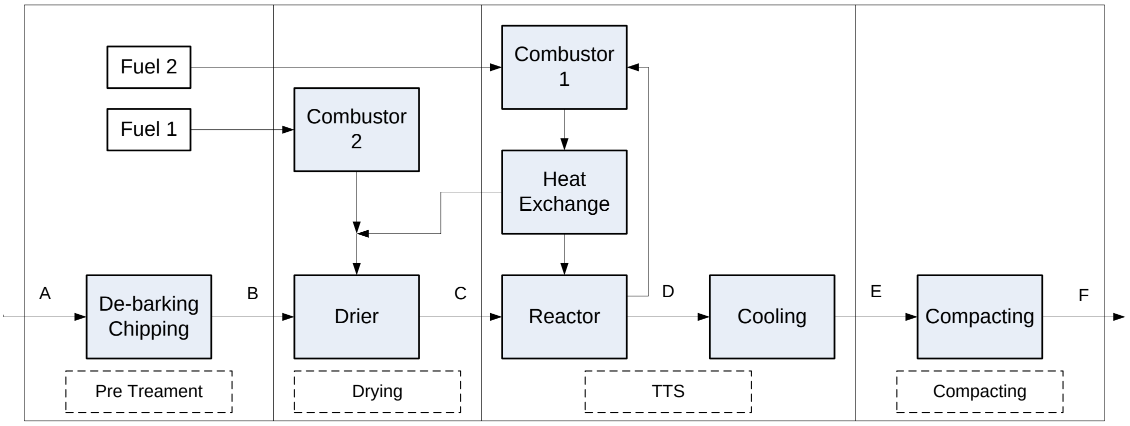


Figure 2. Flow diagram of torrefaction plant

In the torrefaction process, product characteristics evolve per the various island limits (A to F), Figure 2:

A. Incoming raw biomass: e.g. logs;
B. Wet chips with max size: 25 x 30 x 8 mm, moisture content of chips is 40-50 wt%;
C. Dried chips, moisture content of chips 10 wt%;
D. Torrefied biomass chips approx. 22 GJ/ton, 250-300 °C (depending on feedstock and torrefaction process parameters);
E. Cooled torrefied biomass chips suitable for compacting;
F. Densified pellets or briquettes.

3.2.2 Energy consumption

The thermal energy demand of the plant is driven by the energy needs of:

1. Drying of biomass: water evaporation;
2. Heating of biomass for torrefaction: this energy is lost at the product cooling step;
3. Heat loss through stack;
4. Heat loss to surroundings.

Table 1. Energy (thermal) consumption for 7.5 ton/h production of torrefied pellets

	Energy (MW_{th})	**Assumed breakdown ($\% MW_{th}$)**
Drying biomass	6.37	64
Heating of biomass	1.20	12
Stack loss	1.90	19
Heat loss	0.47	5
Total	**9.93**	**100**

The energy needed is provided by two combustors fired by the torgas and natural gas. The main fuel input is the torgas which is produced by the torrefaction process. Natural gas is used as a support fuel to heat up the plant, and to control fluctuations in the process. The control with natural gas is far more responsive resulting in a more stable process when compared to a solid fuel, which was earlier used as support fuel. The expected mass and energy yields of the TTS process are 78% and 90% on dry base, respectively.

3.3 ECN/Andritz

ANDRITZ has introduced two main torrefaction technology platforms focusing on small to medium-sized plants of 50 000–250 000 t/a, and large plants of up to 700 000 t/a [4]. The smaller concept is based on an indirectly heated rotary drum reactor and briquetting of the torrefied biomass. Pre-drying of the biomass is done in a belt dryer. Flue gas for the torrefaction process and the dryer is produced by a grate-fired biomass combustor.

ANDRITZ is developing the vertical reactor technology together with ECN and commissioned a demonstration plant in Denmark in 2012, Figures 3 and 4. The process is a pressurised, directly heated co-current moving bed reactor utilising conventional drying and pelletisation. The pilot plant incorporates biomass receiving, drying, torrefaction, and pelletising in an integrated system. The torrefaction process blends ECN and ANDRITZ technologies and has been patented. Fresh wood chips are first dried in a rotary drum drying unit to reach the desired moisture content for the reactor. The heart of the process is a vertical pressurized reactor. Inside the reactor there are trays (beds) stacked vertically. Dried wood chips enter the reactor at the top, are torrefied by the hot gases passing through the biomass and perforated trays which rotate to ensure even distribution, and then drop to the tray below for another stage of torrefaction. The torrefied material is discharged at the bottom of the reactor vessel. From the reactor, the torrefied material passes through a cooling screw to a storage silo. For the densification process, the material passes through a hammer mill for crushing to uniform size before entering the pellet press, resulting in an energy-dense torrefied pellet that can be stored and shipped. The production capacity of the demonstration plant amounts approximately 1 ton per hour, while focus for commercial plants is on plants with a capacity in excess of 250 000 tons per year.

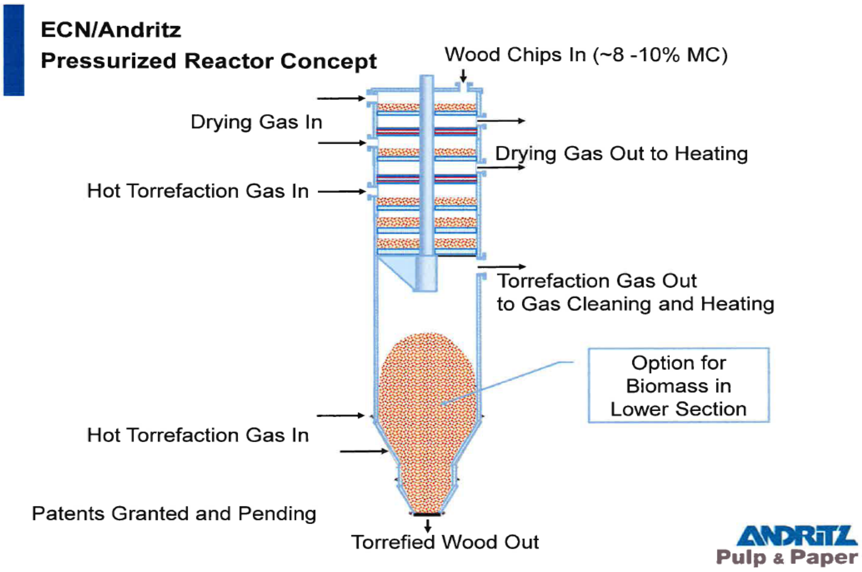
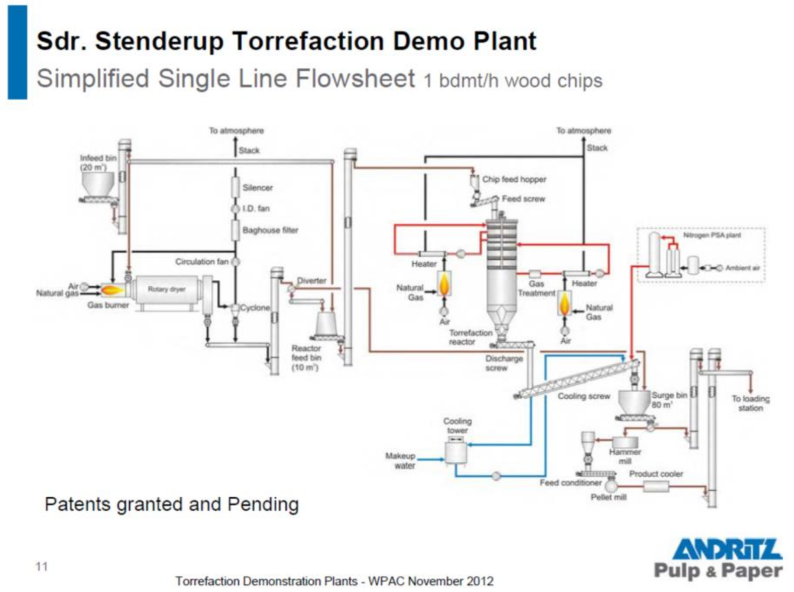


Figure 3. Moving bed reactor.

The demonstration plant is partially funded by the Danish EUDP (Energy Technology Development and Demonstration Program), but the majority of capital funding comes from ANDRITZ. The Danish Technology Institute (DTI), Danish energy company Dong, and British energy company, Drax are also part of the EUDP team. ECN is acting as a consultant to ANDRITZ on the design of the torrefaction technology and is assisting in optimizing the demonstration plant. ANDRITZ signed a cooperation agreement with ECN in 2011 to license its technology for co-current drying and counter current torrefaction of biomass.



Sdr. Stenderup Torrefaction Demo Plant

Simplified Single Line Flowsheet 1 bdmt/h wood chips

Patents granted and Pending

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Torrefaction Demonstration Plants - WPAC November 2012

ANDRITZ Pulp & Paper

Figure 4. ECN/Andritz torrefaction demo plant in Stenderup, Denmark

3.4 CENER

3.4.1 Biomass pre-treatment

Regarding biomass pre-treatment, CENER has a pilot plant divided into two units: Chipping and chopping, and drying. In chipping and chopping unit, the particle size of biomass feedstock is reduced below 20-40 mm. This is required to increase reactor throughput, improve heat transfer rate and guarantee homogeneous product characteristics. In the rotary drum type drying unit, the biomass is dried down to 5-10 wt% moisture content before torrefaction. A hammer mill is also available if particle size reduction below 10 mm screen size is required.

3.4.2 Torrefaction

In torrefaction unit, an indirectly heated reactor using thermal fluid at temperatures between 250 and 300 ºC converts raw biomass into torrefied product. The combustible vapours from torrefaction reaction are burned in a thermal oxidiser. The core of the process equipment is the torrefaction reactor. It is a cylindrical horizontal reactor with an agitator shaft and attached elements of special design procuring axial transport characteristic for all kind of biomass, radial product homogenisation inside the reactor and excellent heat transfer conditions (Figure 5).

Figure 5. Torrefaction reactor in CENER facilities

Reactor heating is carried out indirectly through the hot reactor walls, the actively heated shaft tube and the actively heated internal shaft elements using thermal oil as heat transfer fluid.

3.4.3 Pelletisation

The pelletisation plant consists of a pilot-scale pellet mill of 30 kW, using ring die. Torrefied material is reduced below 4-12 mm screen size according to required particle size for pelletisation. Then milled torrefied material is humidified as required and fed to the pellet mill.

3.4.4 Biomass properties

With regards to raw material selection CENER takes into account some properties of biomass as shown below (Table 2). Some of them are still under revision, as more experience is gained with pilot plant operation, and they should still be considered as indicative. New biomass material is tested first at cold conditions with opened inspection windows to check the flowability behaviour.

Table 2. Biomass acceptance criteria for torrefaction at CENER pilot plant.

Parameter	Torrefaction reactor	Pilot plant
Dimension /nominal size, mm	< 40 mm	Woody < 150 x 2500 mm Bales < 110 x 240 cm
Bulk density, kg/m ^{3}	>50 (1)	
Moisture, %	5-15%	<50 wt%
Amount of fines, % (≤ 3,15 mm)	< 89% (1)	
Dust content (250 < microns)	<62%	

(1) Tested feedstock. Limits could depend case by case on other feedstock characteristics and process conditions

4 Integration of torrefaction processes

4.1 Assessment of stand-alone plants

A mass and energy balance calculation was carried out on three torrefaction concepts based on information provided by Topell Energy, ECN and CENER on their respective processes. These assessments served as bases for the integration of the torrefaction process to the selected industrial plants. The calculations are detailed in Appendices 1-3.

The mass and energy balance calculations of all stand-alone processes are streamlined to a certain extent. A belt dryer is incorporated in all process schemes. The low temperature dryer is considered the most flexible and favourable alternative when elaborating on the integration options. Energy need in drying for all cases is 4.0 MJ/kg evaporated H_2O for belt dryer [5].

The product of all processes is TOP-pellets from wood. The net calorific value (LHV) of wood is in all cases 19.2 MJ/kg, dry basis, equal to net calorific value as received 8.4 MJ/kg at 50 wt% moisture content. The amount wood feed into the system is same in all cases (53.5 MW). The net calorific value (LHV) of TOP-pellets is 22.0 MJ/kg, dry basis. The additional energy needed is generated in ECN case with natural gas and in Topell Energy and CENER cases with biomass. In CENER case the torrefaction gas is burned in a separate combustion chamber by using a small methane flow as a support fuel. Torrefied wood is cooled down with steam (directly) and water (indirectly) in all cases. Power need for grinding is 18 kWh_e/t TOP-pellet and pelletisation 64 kWh_e/t TOP-pellet, respectively. Thermal efficiencies without electricity use are practically almost the same in ECN, Topell and CENER cases, based on the assumptions above, 91%, 90% and 89%, respectively. In the Topell and CENER cases the calculation results are to some extent influenced by the change of raw material data to the same as used in the ECN case. This leads some inaccuracy to the mass and energy balances. Thermal efficiencies are lower than in process concepts based on the flue gas dryers. Energy need in drying is normally about 3.5 MJ/kg evaporated H_2O for flue gas dryer [5]. On the other hand belt drier is a more flexible solution in integrated cases than flue gas drying with regard to the fact that low grade heat sources are usually available in the chemical and mechanical wood industry.

4.2 Integration

Integration of torrefaction plant into existing CHP (Combined Heat and Power) plants (heat integration), pulp and paper mills and saw mills (feedstock as well as heat integration) is explored in the following chapters. The main mass and energy flows of stand-alone plant used in evaluations are given in Figure 6. The difference of mass and energy flows of different techniques (ECN BO_2 process based on moving bed or shaft furnace; CENER process based on indirectly oil heated rotating shaft reactor and Topell Energy process based on special fluid bed or vortex reactor) is small. The main advantages of integrates are economical and can lower the production price of TOP-pellets as well as use energy more efficiently compared to stand alone plants.

Benefits are also gained in feedstock logistics and preparation, as well as other common infrastructure benefits.

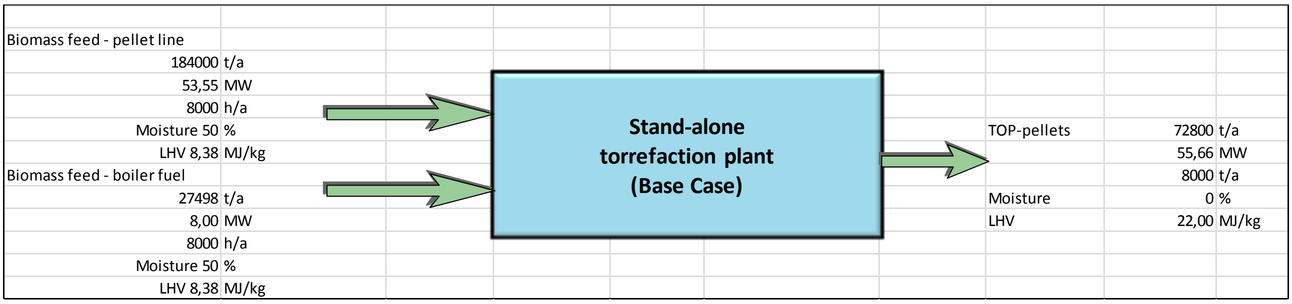

Figure 6. Main mass and energy flows of stand-alone torrefaction plant calculated against annual operating time 8000 h and biomass is used as a boiler fuel.

The parent process in integration cases are:

- Saw mill
- CHP plant
- Nordic pulp mill
- Pulp and paper integrate

4.2.1 Saw mill – definition of parent process and integrates

Torrefaction processes are integrated into 250 000 solid m^3/a (timber product) modern saw mill. Annual operating time of parent process is 8 000 t/a. Saw mill is producing exported dried timber products from soft wood with a moisture content of 15-20 wt% and mill has progressive kiln for timber drying. A stand-alone saw mill produces hot water mainly for timber drying from side products, bark or sawdust with a separate boiler (10 MW_{th}, LHV basis). Surplus sawdust and bark is available still at a market price 16 €/MWh (LHV basis as received) and can be used as a fuel for an extra hot water boiler needed for operation when the torrefaction process is integrated into an existing sawmill. In the case of a new investment in a torrefaction plant - sawmill combination, an integrate can have a bigger hot water boiler and have a scale up profit of that. Therefore two alternatives are considered, described in more details below: a new saw mill and torrefaction integrate, and integrating a new torrefaction plant in an existing saw mill.

The wood chips produced as a by-product in sawmilling is used as raw material in torrefaction. This is considered a favourable option especially when the transportation distance from the saw mill to pulp mill is long (above 100 km). The bark and sawdust is assumed not to be applicable raw materials for TOP-pellets. The market price of wood chips is 18 €/MWh (LHV basis), the price of forest fuels in Finland is used as a reference. Integration enables savings in raw material logistics, personnel costs (assumption 75% of stand-alone plant costs), maintenance costs (assumption 75% of stand-alone plant costs) as well as savings in common equipment use. These alternatives are based on purchased electricity (60 €/MWh_e), which is used mainly for grinding and pelletising operations of the torrefaction plant.

Main mass and energy flows of 250 000 m^3/a timber producing sawmill are shown in Figure 7. The amount of wood chips is enough for about 40 MW_{th} torrefied pellet (TOP) production. The surplus energy in sawdust and barks is 204 GWh/a (LHV basis as received). This is enough for 35 MW_{th} boiler use enabling timber drying and TOP-pellet production of about 231 600 t/a, 177 MW_{th}. In this case 136 MW_{th} (LHV basis) forest biomass e.g. whole tree chips or forest residue chips with 50 wt% moisture content in addition to by-product wood chips from sawmill is needed. Wood residues can be delivered to plant gate in most alternatives in Finland with the price of about 18 €/MWh (LHV basis as received, including the cutting, chipping and delivering chips to the torrefaction plant), when the raw material needed is less than 150 MW_{th}.

There is also low value energy in timber drying exhaust gases. The economic part of heat is already utilized for preheating the drying air at saw mill. The heat price for the rest part of the heat is too high because of low heat transfer coefficient in a heat exchanger and so the heat transfer area needed for utilization is high.

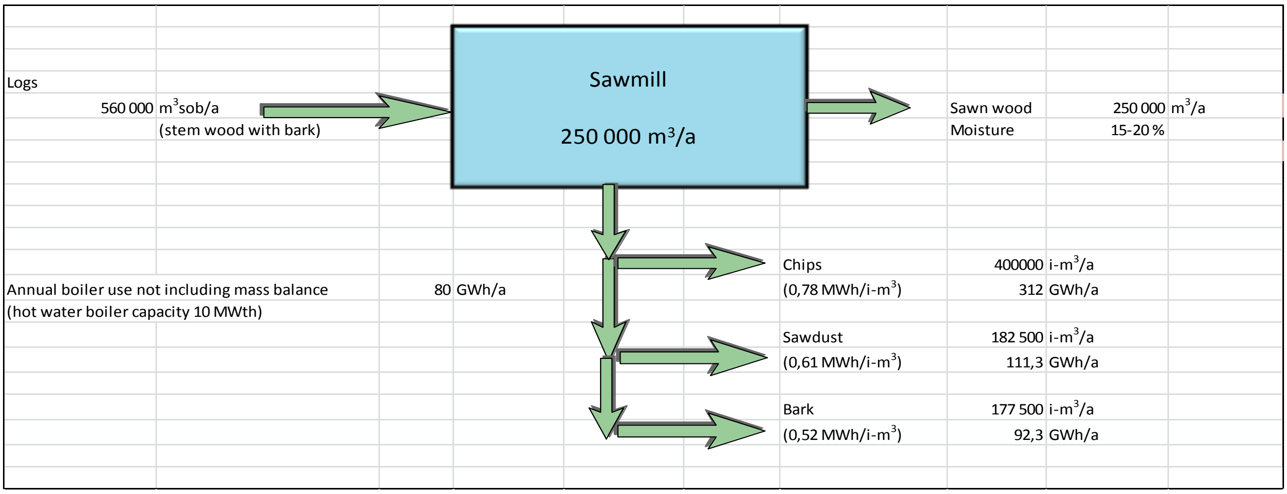

Figure 7. Main mass and energy flows in modern saw mill.

The structure of the two saw mill integration options are shown detailed below:

Saw mill Alternative 1 (main mass and energy flows in Appendix 4.1):

- New saw mill and torrefaction plant integrate, 231 600 t/a TOP-pellets
- One biomass (bark, sawdust) boiler for hot water generation (35 MW_{th})
- Wood chips are utilized as a raw material in torrefaction plant (39 MW_{th})
- Additional forest fuels are also utilized as a raw material for torrefaction plant (136 MW_{th})

Saw mill Alternative 2 (main mass and energy flows in Appendix 4.2):

- Existing sawmill with a new torrefaction plant integrate, 101 100 t/a TOP-pellets
- New biomass boiler (bark) for torrefaction plant (about 12 MW_{th})
- Wood chips and sawdust are not utilized as a raw material in torrefaction plant or boiler fuel
- Forest fuels are utilized as a raw material for torrefaction plant (77 MW_{th})

4.2.2 CHP plant – definition of parent process and integrates

Integration of torrefaction into 80 MW_{th} CHP plant is presented below and the main energy flows of the parent process are given in Figure 8. The CHP plant uses forest fuels. Two alternative operation modes are considered: A typical Nordic case with an operating time of the CHP boiler of 5 000 h/a (Alternative 3), and a Central European case with operating time of 3 500 h/a (Alternative 4). Annual operating time varies due to the climate conditions and heat load, the effective operating time in Central Europe being shorter than in Nordic countries. The annual operating time of torrefaction plant is, however, 8 000 h/a to have a reasonable production cost of the TOP-pellets. Therefore the torrefaction plant (72 800 t/a, 56 MW_{th}) needs a separate boiler with a capacity of about 8 MW_{th}.

Another option would be to assume that the torrefaction plant would use surplus heat for drying from the CHP plant during the summer season, when mainly power is produced. Heat demand during the cold season may, however, constitute a problem if a separate boiler is not available. The modern CHP plants are usually design to a given heat load and deflection from the production mode may cause losses in power production.

The CHP plant serves local electricity for torrefaction plant at a market price (50 €/MWh_e) mainly for grinding of torrefied biomass and for pelletising operations. Transfer costs of the electricity used in the integrated plant can be avoided. The torrefaction plant uses district heat (hot water) in a biomass belt dryer, when the demand of heat is low. Integration enables the savings in raw material logistics (wood price 18 €/MWh), personnel costs (assumption 75% of stand-alone plant costs), maintenance costs (assumption 75% of stand-alone plant costs) as well as savings in common equipment use. The average price of hot water from the CHP-plant is 20 €/MWh and 10% of heat produced can be utilized. The main mass and energy flows of integrates are given in Appendix 5.

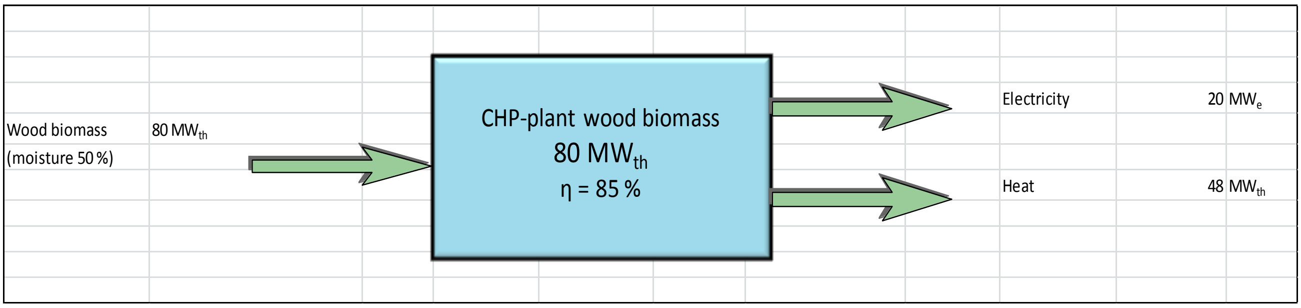

Figure 8. Block flow diagram of CHP-plant.

4.2.3 Nordic pulp mill - definition of parent process and integrates

In this case study the torrefaction process is integrated into a 600 000 dry t/a (pulp product) modern Nordic pulp mill. In this mill part of the bark is gasified to fuel gas for the lime kiln. Black liquor is processed by recovery boiler (3 400 ton dry matter/day). The mill is equipped with a back-pressure turbine and a condensing turbine. Annual operating time of the parent process and torrefaction plant is 8,000 t/a. The pulp mill produces surplus bark and electricity. The main mass and energy flows are shown in Figure 9.

The torrefaction process (407 200 t/a, 311 MW_{th}) can use the extra bark as a boiler fuel (45 MW_{th}). The market price of bark is 16 €/MWh (LHV basis). The TOP-pellet price is estimated based on the feedstock price of forest fuel of 20 €/MWh. The pulp mill serves local electricity (50 €/MWh_e) for the torrefaction plant at a market price mainly for grinding of torrefied biomass and for pelletising operation. The same integration savings concerning logistics, personnel and maintenance costs as in the saw mill case are assumed.

It is assumed that extra heat is not available for drying of biomass in the torrefaction process at the pulp mill. In this respect a market pulp mill differs from a combined pulp and paper mill. The main mass and energy flows of this integrate is given in Appendix 6 (Alternative 5).

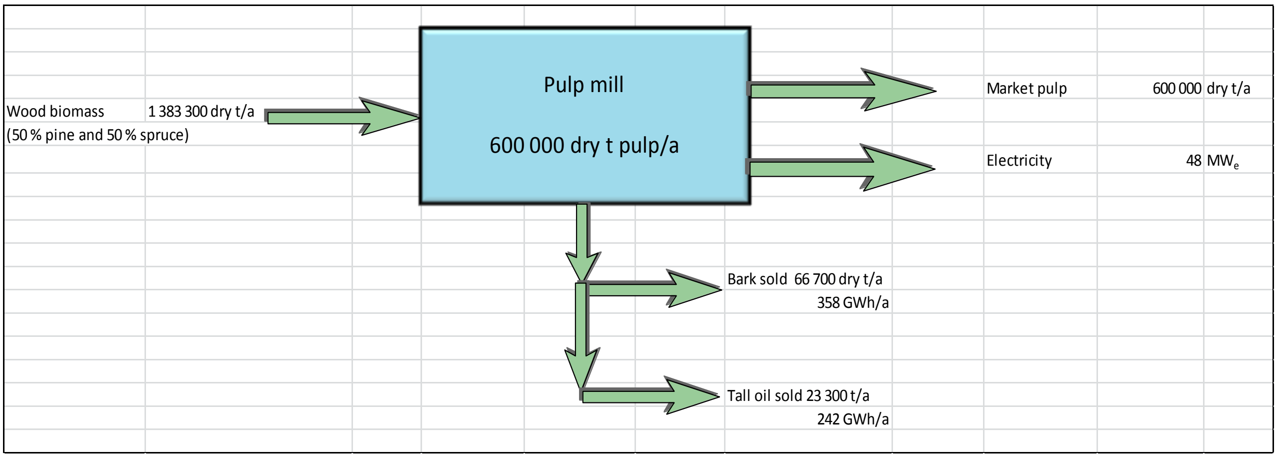

Figure 9. Mass and energy flows in modern Nordic pulp mill.

4.2.4 Pulp and paper integrate - definition of parent process and integrates

In this case the structure (virgin or recycled fibre and paper grade) of pulp and paper integrates can vary a lot. As a consequence of this the energy flows can vary case by case. Integrates based on recovered paper are mainly concentrated to Central Europe and integrates utilizing virgin wood pulp are concentrated to Nordic countries. In this case study a Nordic pulp and paper integrate is considered.

Extra heat (low pressure steam) is normally available in integrates based on virgin wood pulp. Annual operating time is 8 000 h/a. The availability of steam varies seasonally. The price of steam varies from 10 to 40 €/MWh (average price 25 €/MWh). The biomass feedstock price is 18 €/MWh, and savings in personnel and maintenance costs (75% of stand-alone plant costs) are the same as in previous case studies. Two different torrefaction capacities are studied: 91 600 t/a (Alternative 6) and 183 300 t/a (Alternative 7). Main mass and energy flows are given in Appendix 7.

The structure of the two integrates are:

Pulp and paper integrate, Alternative 6:

- No need for own boiler. All heat for torrefaction comes from the parent process at a price of 25 €/MWh
- Fuel gas from torrefaction can be utilized in existing pulp and paper integrate boilers
- Forest fuels are utilized as a raw material for torrefaction plant (67 MW_{th})

Pulp and paper integrate, Alternative 7:

- No need for own boiler. All heat for torrefaction comes from the parent process at a price of 25 €/MWh
- Fuel gas from torrefaction can be utilized in existing pulp and paper integrate boilers
- Forest fuels are utilized as a raw material for torrefaction plant (135 MW_{th})

4.2.5 Large scale production utilising European and overseas biomasses

The price of feedstock is the most significant variable influencing the production costs of TOP-pellets. The Figure 10 presents the current pulpwood prices delivered at plant in a global perspective. There is a significant difference between biomass costs in European and Nordic countries and overseas plantation wood from for instance North America or Russia. In large scale plants the economy of scale is evident, especially concerning stand-alone plants. In recent years the capacity of new wood pellet plants have increased to 500 000 t/a and beyond.

Eventually, two stand-alone plants are included in this study. A large scale European torrefaction plant (Alternative 8) is compared to an overseas production option, utilising local wood and transporting the torrefied pellets to a European port (Alternative 9). The evaluation is carried out using the same cost factors, expect that the feedstock cost in the European case is 20 €/MWh and in the overseas case 15 €/MWh. The price of wood fuels has stabilised in the Nordic countries to level of 18-25 €/MWh. In overseas regions the price variation is significantly larger, range from 10 to 20 €/MWh. In a 10 year perspective the prices are expected to rise due to increasing demand from other wood industry sectors.

Figure 10. Pulpwood costs, delivered at plant, in selected regions 2013, in m^3 sob (solid over bark) [6].

4.3 Economic evaluation of integrates

4.3.1 Basis for evaluation

The 9 case studies used in the economic evaluation are summarised in Table 3. The main mass and energy flows of base case (stand-alone plant) and integrated alternatives described in the previous chapter are shown in Table 4.

Table 3. Summary of the evaluated case studies.

Base case	Stand-alone torrefaction plant, 72 800 t/a
Alternative 1	New sawmill and torrefaction integrate, 231 600 t/a
Alternative 2	Existing sawmill and new torrefaction plant, 101 100 t/a
Alternative 3	CHP-plant (5 000 h/a) and new torrefaction plant 72 800 t/a
Alternative 4	CHP-plant (3 500 h/a) and new torrefaction plant 72 800 t/a
Alternative 5	Pulp mill and new torrefaction plant, 407 200 t/a
Alternative 6	Pulp and paper mill and new torrefaction plant, 91 600 t/a
Alternative 7	Pulp and paper mill and new torrefaction plant, 183 300 t/a
Alternative 8	Large scale stand-alone production utilising European biomasses, 500 000 t/a
Alternative 9	Large scale stand-alone production utilising overseas biomasses, 500 000 t/a

Table 4. Main mass and energy flows of the base case and integrated alternatives.

Alternative/Utility	Base case	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5	Alternative 6	Alternative 7	Alternative 8	Alternative 9
Forest fuel for TOP-pellets, MW	54	136	77	54	54	299	67	135	368	368
Chips, MW	0	39	0	0	0	0	0	0	0	0
Total, MW	54	175	77	54	54	299	67	135	368	368
TOP- pellet production, MW	56	177	80	56	56	311	70	140	382	382
TOP- pellet production, t/a	72 800	231 600	101 100	72 800	72 800	407 200	91 600	183 300	500 000	500 000
Boiler fuels , MW	8	25	12	4	5	45	0	0	55	55
Forest fuel, MW	8	0	0	4	5	0	0	0	55	55
Bark, MW	0	12	12	0	0	45	0	0	0	0
Sawdust, MW	0	14	0	0	0	0	0	0	0	0
Purchased heat, MW	0	0	0	3	2	0	8	16	0	0
Hot water, MW	0	0	0	3	2	0	0	0	0	0
Low pressure steam, MW	0	0	0	0	0	0	8	16	0	0
Purchased electricity, MW_e	2	6	2	2	2	10	2	3	12	12
Without transfer costs, MW_e	0	0	0	1	1	10	0	0	0	0
With transfer costs, MW_e	2	6	2	1	1	0	2	3	12	12

4.3.2 The economic default values

The economic assessment is carried out mainly based in VTT and Pöyry Management Consulting Ltd in-house information. The assessment of investment costs is based on a number of feasibility studies and budget offers of commercially available equipment and components. The operation costs reflect mainly a Scandinavian price level.

The estimated investment of a 100 000 t/a torrefaction plant is presented in Table 5. The VTT-Pöyry estimate is clearly higher than the recently published IEA Task 32 estimate [2]. If an accuracy of ± 30% is anticipated, the difference can be considered acceptable, especially as the extent of costs included in these studies (buildings, installation, auxiliary machinery, instrumentation etc.) may not be comparable. Anyway, the deviation of the commercial dryer and pelleting investments is noteworthy.

Some observations are, however, justified:

- The belt dryer used in this integration assessment is usually considered more expensive than a flue gas rotary dryer used in the IEA Bioenergy study. The investment in the VTT-Pöyry case includes also installation, dust and VOC removal from drying gas.
- The pelletisation island of the VTT-Pöyry case includes three pellet presses with a capacity of 5-6 t/a, buildings and installation.

Table 5. Comparison of estimated investment costs.

	IEA Bioenergy Task32, M€	%	VTT-Pöyry, M€	%
Wood yard	5.0	17	4.2	10
Dryer	3.6	12	6.7	16
Torrefaction	13.0	45	17.6	43
Pelleting	3.1	11	7.3	18
Others	4.3	15	5.5	13
Total	29.0	100	41.3	100

Key input data and bases for calculating production costs are presented in Table 6. These figures reflect mainly costs applied in a Nordic context.

Table 6. Key bases of the estimate of production costs.

Cost factor	Value
Feedstock costs	
Forest residues 1 up to 150 MW_{th}	18 €/MWh
Forest residues 2 (alternatives 5 an	20 €/MWh
Bark	16 €/MWh
Sawdust	16 €/MWh
Wood chips (sawmill)	18 €/MWh
Plantation wood in South	15 €/MWh
Heat	
Hot water	20 €/MWh
Low pressure steam	25 €/MWh
Electricity	
Without transfer costs	50 €/MWh
With transfer costs	60 €/MWh
Labour	
Cost, including payroll overheads	55 €/manhour
Cost factors	
Annual capital charges factor	0,1175 (10 % interest, 20 a)
Costs for startup, interest during co	21 % of plant investment
Scale-up exponent	0,7
Maintenance, insurance, taxes	4 % of total investment
Operational times	
Stand-alone plant	8 000 h/a
Torrefaction integrates	8 000 h/a
Parent processes	
Sawmill, pulp mill, pulp and paper i	8 000 h/a
CHP plant	3 500 or 5 000 h/a
Time	
2012	CEPI-index 584,6

4.3.3 Results and discussion

The estimated costs of stand-alone torrefaction base case as well as integrated torrefaction alternatives are shown in Table 7. Fixed operating costs consist of operating labour, maintenance labour, maintenance materials, overheads, insurances and taxes. Variable operating costs consists of raw materials, boiler fuels, electricity and other utilities. The estimation is based on the use of final Chemical Plant Cost Index value 2012 (1.6.2012). No subsidies are included in these calculations.

Table 7. Summary of the production costs.

	Base case	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5	Alternative 6	Alternative 7	Alternative 8	Alternative 9
Plant capacity, t TOP-pellets/a	72 800	231 600	101 100	72 800	72 800	407 200	91 600	183 300	500 000	500 000
Production costs, M€/a										
Fixed operating costs	3,99	5,39	3,47	3,15	3,15	6,71	3,31	4,80	8,70	8,70
Variable operating costs	9,87	31,73	14,00	9,65	9,69	58,50	12,36	24,73	74,56	57,66
Capital costs	5,44	11,68	6,84	5,44	5,44	17,34	5,74	9,33	20,95	21,23
Total Costs	19,30	48,80	24,31	18,24	18,28	82,54	21,41	38,85	104,20	87,58
Production cost of TOP-pellets, €/t	265	211	240	251	251	203	234	212	208	175
Production cost of TOP-pellets, €/MWh	43	34	38	41	41	33	38	35	34	29
Market price of wood pellets, €/MWh (PIX Pellet Nordic Index)	30	30	30	30	30	30	30	30	30	30
Price compared to base case, %	100	79	91	94	95	76	88	80	79	66
Price compared to market price, %	145	115	126	137	137	111	127	116	114	96

The production costs of torrefied pellets are expressed as plant gate values. The PIX Index for wood pellets (FOEX Indexes Ltd.), currently about 30 €/MWh (industrial pellets) is used as a comparison for the TOP-pellets production costs. The production costs of Alternatives 1-9 are also compared to the stand-alone base case. According to this assessment, the production price of TOP-pellets in integrated alternatives is 76-95% of that in the stand-alone base case plant. Part of the lower production price is due to the bigger production capacities of most of the integrated plants.

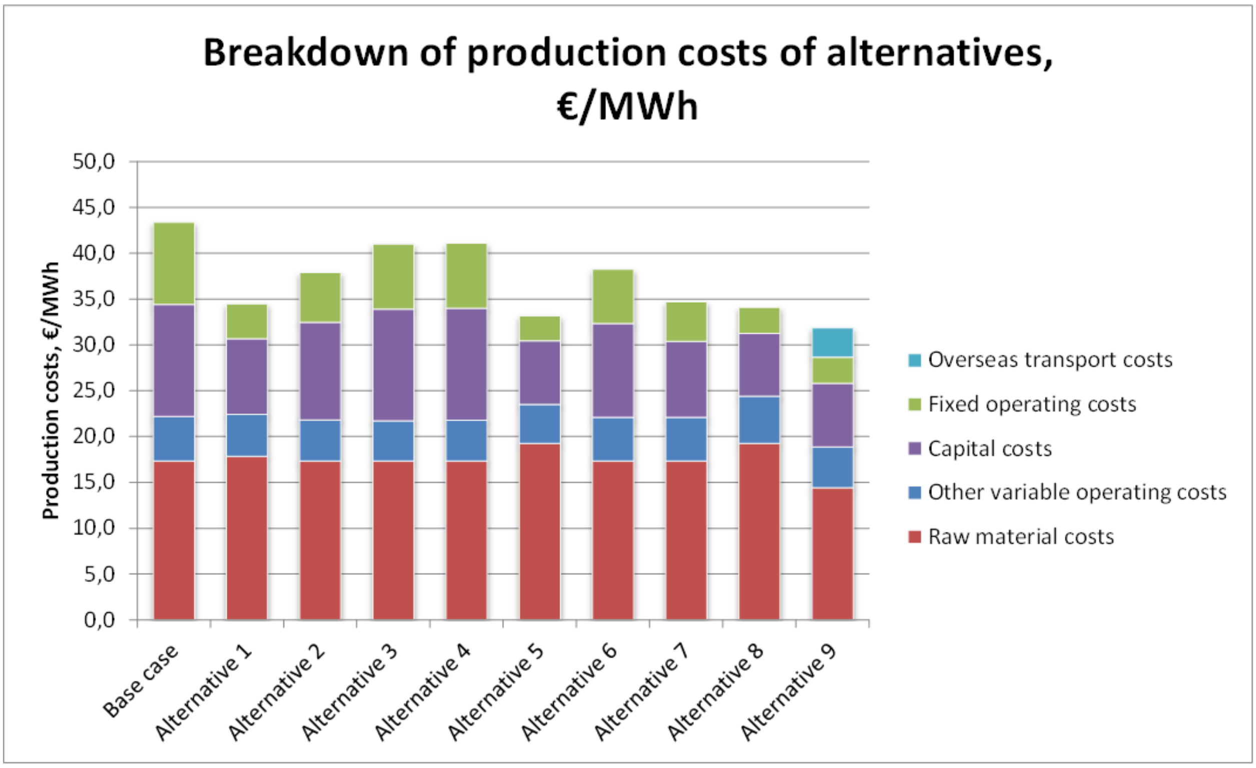

Figure 11. Breakdown of the production costs.

A breakdown of the torrefied pellets production costs is presented in Figure 11. Regarding the overseas large scale stand-alone plant an estimated transportation cost of 3.2 €/MWh [2] is added to make this case study reasonably comparable to the other European/Nordic alternatives (no inland transportation or loading costs are included).

The price of the feedstock is the single parameter with the most significant influence on the production price of torrefied pellets. This is clearly seen in Figure 11 and further elaborated in Figure 12. The economy of scale is also obvious when comparing the medium and large scale operations described in Table 7 and Figure 11.

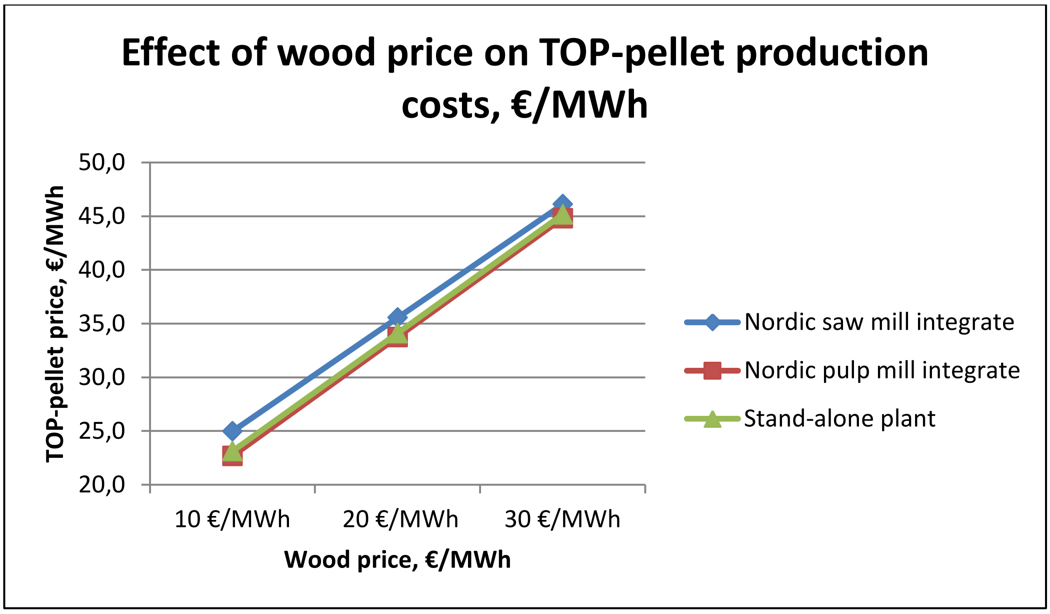

Figure 12. Effect of wood price on the production costs of torrefied pellets (Alternatives 1, 5 and 8).

The influence of the investment is depicted in Figure 13. The calculated investment costs can of course be debated, especially concerning the torrefaction island, because no commercial cost information of this part of the process was available for this study. The accuracy of the assessment at its best is considered to be within the ± 30% range. The influence on the production costs is about ± 2-4 €/MWh.

Concerning the stand-alone plants, the largest uncertainties in this study relate to the calculated investment costs. Comparison to available investment data is questionable, because the exact extent of included cost items is not known. One of the significant factors influencing the operation costs is the energy consumption of the dryer, which affects the process efficiency. If the water evaporation energy is lowered from 4.0 MJ/kg (this study) to 2.9 MJ/kg (requires probably heat recovery), the process efficiency is estimated to increase from 90% to 96%. In this respect the moisture content of the feedstock (in this study 50%) is also of considerable importance.

The production costs of torrefied pellets at a large scale overseas plant is estimated to be slightly below 30 €/MWh if the feedstock price is 15 €/MWh. However, the calculation is based on the same European/Nordic level of fixed operation costs (salaries etc.) and other variable costs (power, steam etc.) used in all case studies. An adjustment of these cost items to half of those presented in Table 7 and Figure 11 would decrease the production costs by 4-5 €/MWh.

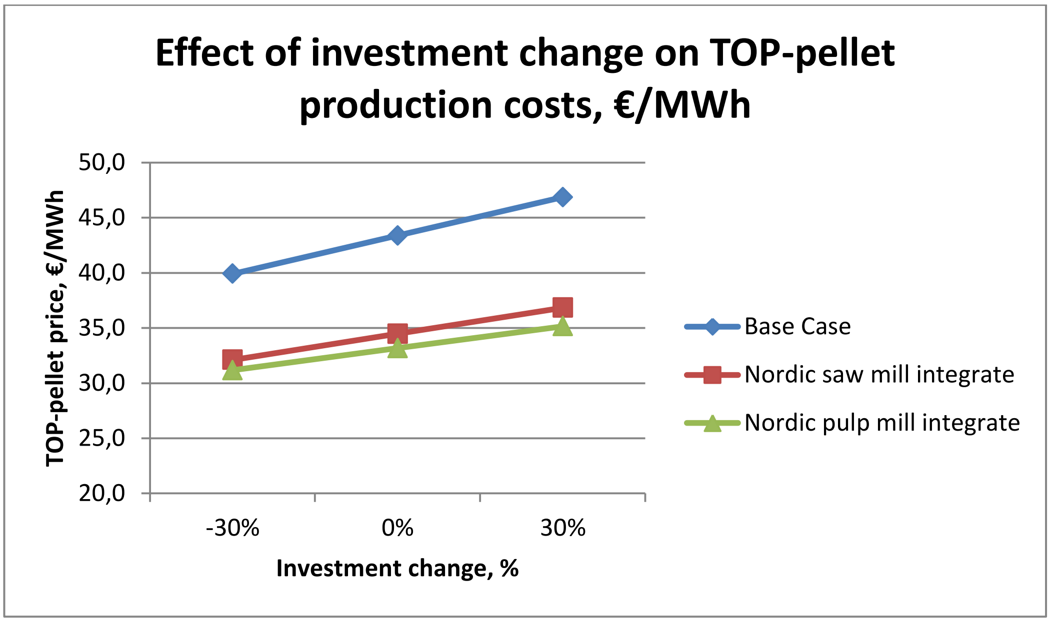

Figure 13. Effect of change in investment costs on the production costs of torrefied pellets (Alternatives Base case, 1 and 5).

The integration of the torrefaction process to a saw mill is especially favourable if a new combined plant is constructed. In this case the energy for the timber dryer and the drying of the wood chips for the torrefaction plant can be produced with a single boiler, sized and fitted for both operations. In this case there is also the possibility to increase the capacity of the torrefaction island using excess forest residue as feedstock.

The CHP plant integration options are less favourable, mainly due to the restricted operation time of the CHP plant (5 000 h (Nordic case) and 3 500 h (European case)). If the torrefaction plant is to operate in 8,000 hours, it needs a separate boiler to produce the drying energy. Operation only in the time space of low/no heat demand would increase the production costs of the torrefied pellets due to the considerable investment to an unacceptable level.

It is also possible to integrate the production of torrefied biomass directly to a co-fired pulverised coal (PC) power (or CHP) plant, an option which has not been assessed in this study. This would enable the feeding of torrefied wood chips directly to the coal mills, and therefore to eliminate an expensive pelletising step. A prerequisite is available space and possibilities to store, dry and process the wood chips on site. The logistic costs of transporting the feedstock are also a major concern.

The wood industry based integration options are more feasible than the CHP alternatives. The economy of scale is evident in the pulp mill integrate. In the combined pulp and paper mills the integration of the torrefaction process provides several benefits regarding feedstock and energy flows. Low price steam and electricity is available for drying and pelletisation and a separate boiler is not needed. A reasonable production cost is achieved at medium capacity.

5 Economical evaluation of straw and beech wood torrefaction

To secure a competitive price and availability of feedstock increased torrefaction process flexibility has been proposed [2] with regard to the quality of the biomass. Agricultural residue like straw is a potential resource readily available in Central and Southern Europe. A Spanish case study by CENER on straw and beech wood torrefaction compares the processes and economics of two stand-alone torrefaction plants.

Torrefied pellets production cost has been evaluated, considering that production is located in Spain, using beech and straw as raw materials for comparison purposes between woody and herbaceous biomass. Similar conditions have been considered in both cases:

- Production capacity: 56-59 kt/a
- Weight loss: 14.5 % daf
- Product moisture content: 5 %
- Product LHV: 5.0-5.1 kwh/kg

Other conditions used for production cost calculation are listed in the following Table 8.

Table 8. Basis for calculation of the production costs

	Parameter	Value	Units	Reference
General conditions	Electricity price	94,4	€/MWh	Spanish National Energy Commission (CNE). Report on the electricity retail market (April 2013) + 6% due to new electricity tax
	Price N_2/CO_2	87	€/t	supply cost to CENER (PRAXAIR)
	Natural gas price	36,11	€/MWh PCS	Eurostat Industrial consumer S1 2012
	Interest rate	6,79	% annual	Statistical Bulletin Spanish Central Bank. Preferential loans from banks (March 2012) + 1,5%
	Life time	15	years	50 years for civil works
	Maintenance	1.7	%/a of investment	
	Other cost	0,5	%/a of investment	
	Plant availability	91	% annual	8000 h
	Simultaneity factor (electricity consumption)	85	% of installed power	
Man power	Daily shifts	3	shifts	
	Working dayº	7	days /week	
	Man power cost	2.907	€/man-month	Spanish National Statistical Institute (INE). Period January - March 2013,
	Operator per shift	2		
	Number of shifts	5		
	Assistance and maintenance	3		
	Managing, administration and marketing	104.652	€/year	
	Administration and marketing	1		
	Managing	1		

Due to the nature of the feedstock some particular conditions are considered in each case which is shown in the Table 9.

Table 9. Operating conditions.

	STRAW	BEECH
Feedstock moisture content	12%	40%
Feedstock price	12 €/MWh	15 €/MWh
Number of production lines	3	2
Installed power capacity	1.7 MWe	1,4 MWe
Investment	18 M€	13.9 M€

Although straw is more reactive, due to the much lower bulk density 3 production lines are needed in comparison with beech where 2 production lines with the same torrefaction reactor size are need for a similar production capacity.

Investment costs are based on vendor bids for equipment of similar capacity for the following sub-systems:

- Biomass handling and feeding systems (only for woody biomass; for straw case estimation has been carried out)
- Drying
- Torrefaction
- Thermal oxidizer
- Boiler and thermal fluid circuit
- Screw coolers

This equipment represents 2/3 of the investment. The costs evaluation for the following sub-systems are based on knowledge and experience in the construction of the torrefaction pilot plant at CENER: civil works, metal structures and benches, auxiliary systems (cooling circuit and air coolers, air compression and distribution, nitrogen supply, sprays circuit, electrical wiring and control system). Reference to the costs assessment is given in Appendix 8.

The simplify flow diagrams for each case are shown in Figure 14.

Because it's lower moisture content straw torrefaction has a higher thermal efficiency since it is not necessary to dry the straw before it is fed to the torrefaction reactors saving energy in this way.

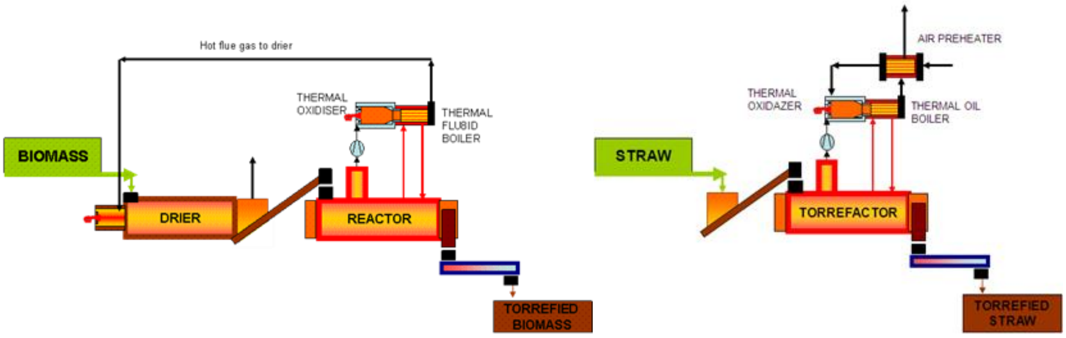

Figure 14. Beech wood and straw torrefaction (CENER).

In the case of straw torrefaction hot flue gas from the thermal oil boiler is used to preheat the combustion air to the thermal oxidizer. In the case of wet feedstock hot flue gases are used in the dryer. According to these process integrations mass and energy balances for both cases are shown in Figure 15.

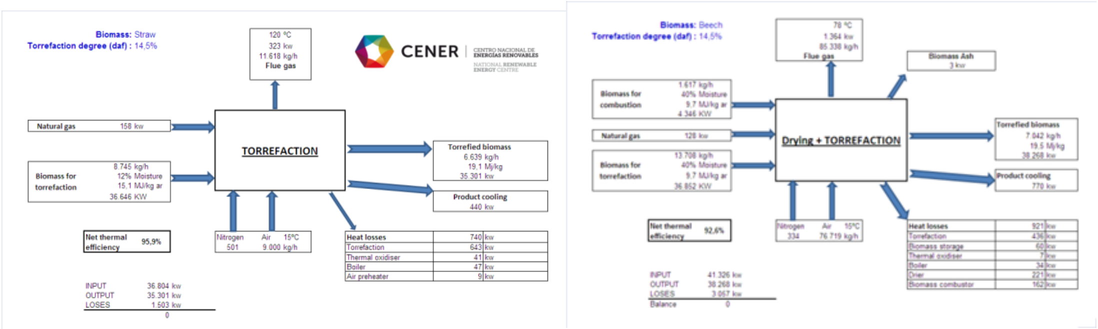

Figure 15. Mass and energy balances of the straw and beech wood torrefaction.

Information from mass and energy balance is used to calculate operating costs which include:

- Cost of staff
- Auxiliary fuel (drying)
- Electricity and consumables
- Maintenance
- Other general and insurance costs

The annual maintenance cost of different equipment is calculated as a percentage of the investment cost. This percentage is estimated for each piece of equipment based on their characteristics. Other general and insurance costs are also estimated as a percentage of the investment. The power consumption is calculated by estimating a ratio of simultaneity relative to the installed capacity.

In Table 10 the production cost breakdown for both cases are compared.

Table 10. Production costs of torrefied straw and beech wood pellets.

	Torrefied straw pellets		**Torrefied beech pellets**	
	€/t	€/MWh	€/t	€/MWh
Investment	32.88	6.58	24.69	4.83
Maintenance	5.01	1.00	4.42	0.87
Electricity	19.59	3.92	14.63	2.86
Consumables	6.96	1.39	3.96	0.77
Biomass	63.09	12.62	83.65	16.37
Man power	9.97	1.99	9.40	1.84
Other costs	1.54	0.31	1.17	0.23
	139.03	**27.81**	**141.91**	**27.77**

Although torrefied straw pellets production has a lower feedstock cost and a higher efficiency on the other hand, because of the lower bulk density of the feedstock, investment, maintenance, electricity and consumables costs are higher. The final production cost is the same in both cases.

6 Conclusions

The aim of this study is to assess possible benefits in terms of production costs of producing torrefied biomass pellets by integrating the production to wood industry operations or combined heat and power production. A stand-alone TOP-pellets production plant with a capacity foreseen in a typical European commercial plant was chosen as bench mark. Mass and energy balances provided by the partners in the concerned work package are used as basis for the calculations.

The investment, operation and feedstock costs used in this assessment are mainly based in VTT and Pöyry Management Consulting Ltd in-house information and reflect a Scandinavian price level. Production costs in a medium scale stand-alone torrefaction plant is over 40 €/MWh, and integration to an existing CHP plant does not reduce the costs substantially. According to other in-house assessments, increasing the capacity of a stand-alone plant should bring down the production cost to about 35-37 €/MWh for a 200 000 t/a plant.

The direct conclusion of the assessed production costs compared to the chosen base case stand-alone plant is, that in terms of production costs the integration of torrefaction to wood industry plants results in clear savings. A production price level of 34-38 €/MWh is reached. The production capacity of the torrefied pellets has, however, a significant influence the costs. Considering this fact and taking into account the medium scale stand-alone torrefaction plant chosen as bench mark, the actual cost savings gained by integrating the torrefaction process seem to be relatively limited. However, there are certainly benefits especially on wood procurement, logistics and transportation costs, storage and handling at the plant, and savings in other commodities that have not been fully implemented in this assessment.

The largest single cost item regarding the production costs of torrefied pellets is the cost of feedstock. The present price range wood fuels varies from 15 €/MWh to 30 €/MWh. In overseas regions (Brazil, Chile, South Africa, Russia) a price level of 10 €/MWh has been used in various assessments. Considering the increased competition for wood feedstocks from other industry sectors this price level is not realistic, and a level of 15 €/MWh was used during this assessment. In case of the stand-alone overseas plant the latter figure leads to an production price level of 29 €/MWh for a 500 000 t/a plant (fixed operating costs and other variable costs were maintained at European/Nordic level for the sake of comparison).

Torrefied pellets production costs in Spain have been evaluated using beech and straw as raw materials for comparison purposes. Similar conditions have been considered in terms of production capacity, weight loss, product LHV and main parameters used in cost calculation. Selected parameters are representative for average Spanish conditions.

Straw is more reactive than beech, although the inherently lower bulk density requires 3 production lines compared to 2 production lines for beech, to reach the same production capacity. The higher investment, maintenance, electricity and consumables costs are compensated by the lower feedstock cost and the higher production efficiency. The final production cost is the same in both cases.

The common understanding is that the largest potential use of the torrefied pellets is in co-combustion in PC-boilers replacing fossil coal. The current exceptional low price of coal and CO_2 emissions requires substantial national subsidies in terms of e.g. feed-in tariffs to create a market for biomass fuels in general. Especially in co-combustion torrefied wood pellets are considered to have favourable properties compared to white wood pellets. Due to their brittle nature torrefied pellets are easier to grind together with coal in the roller or ball type coal mills. Thus larger shares of torrefied wood pellets, up to 50% or higher, can be co-fired in PC-boilers. The enhanced hydrophobicity results in better and cheaper storage possibilities. Altogether, the on-site costs for utilities are lower in case of torrefied pellets in comparison to the use of other solid biomass fuels, such as white wood pellets.

7 References

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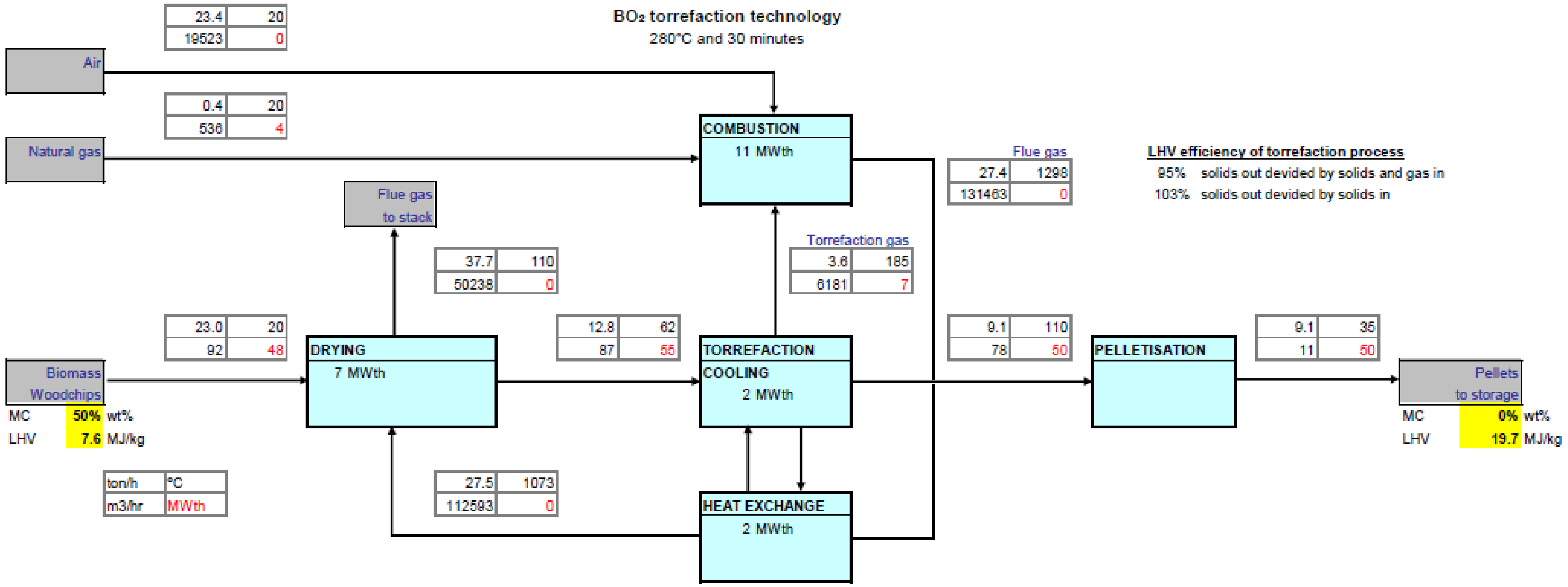
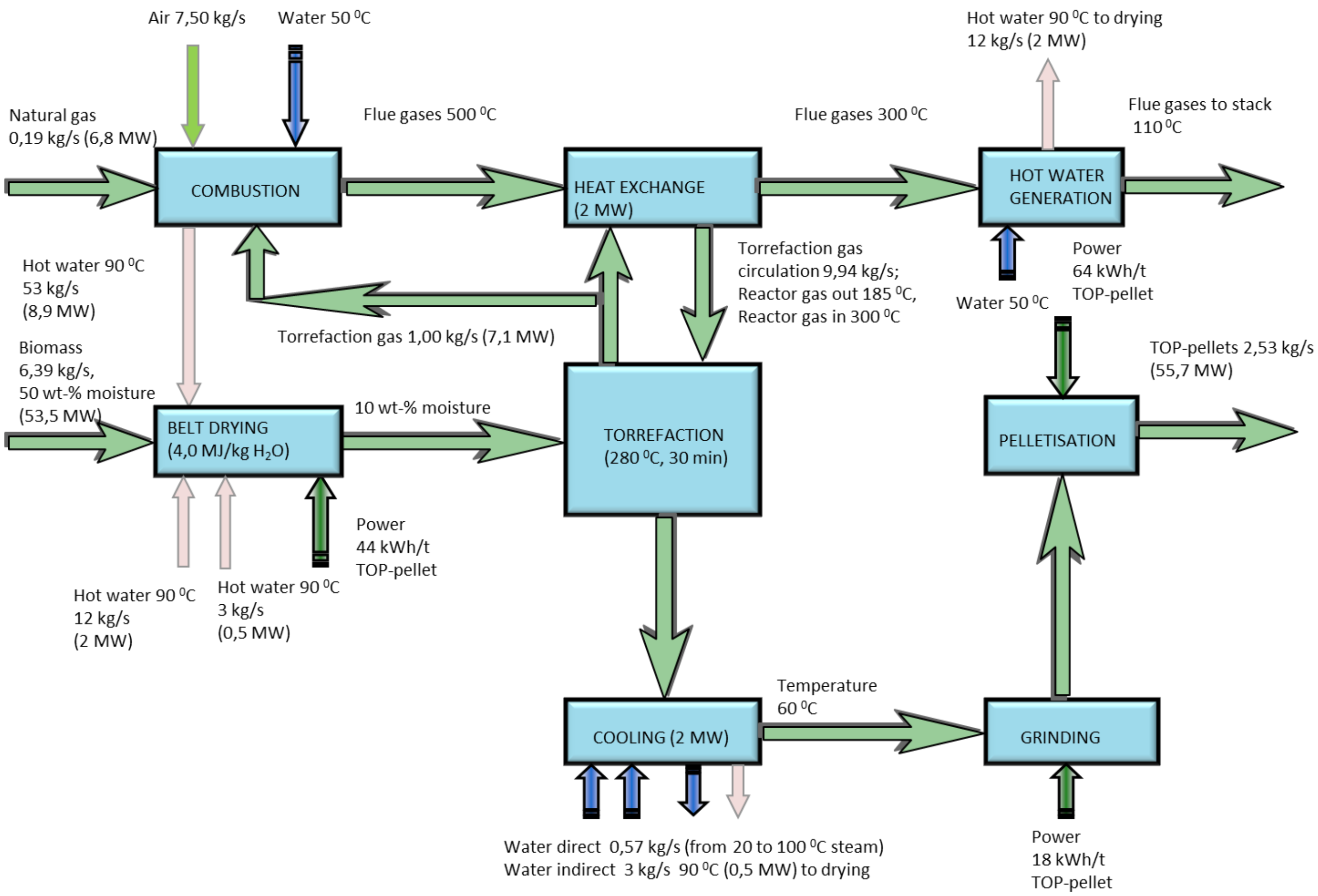
8 Appendices

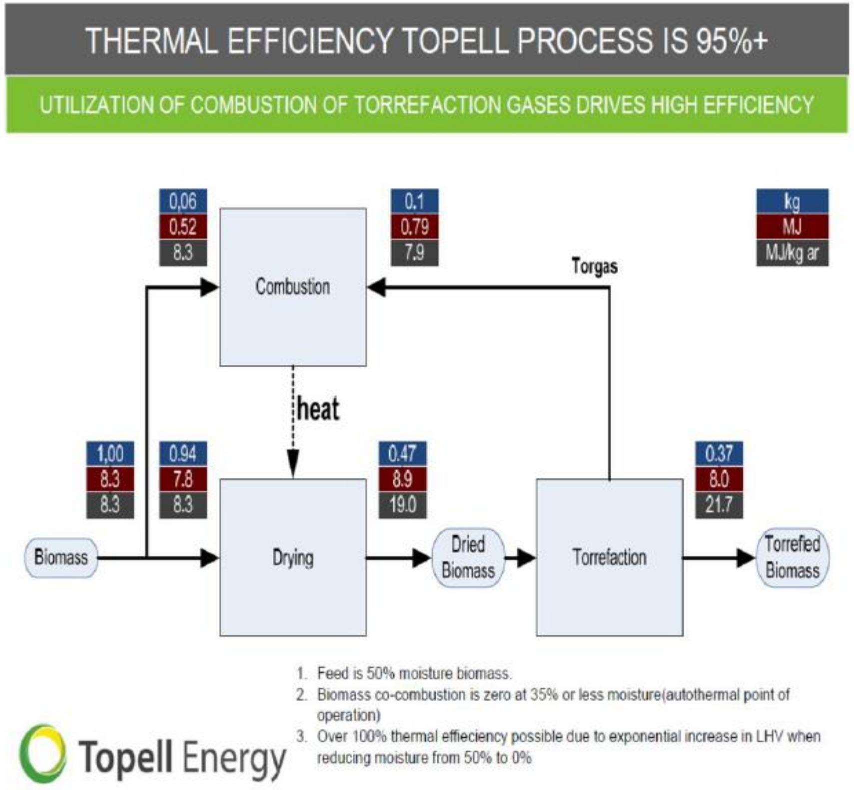
8.1 Appendix 1 Stand-alone plant - Black box data of ECN



8.2 Appendix 1 Stand-alone plant –BASE CASE A (BO$_2$ torrefaction technology)



8.3 Appendix 2 Stand-alone plant - Black box data of Topell Energy from the literature



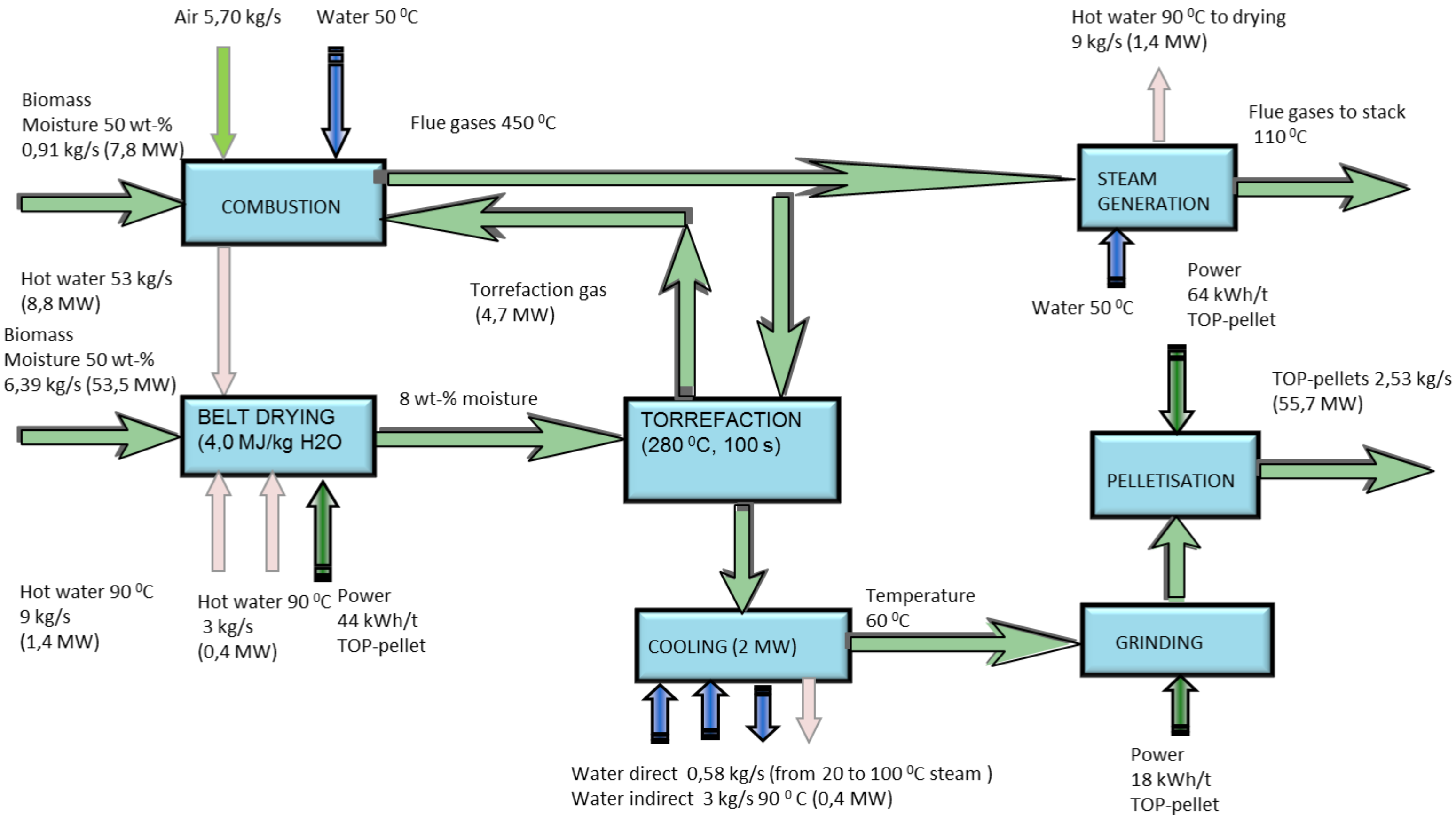
THERMAL EFFICIENCY TOPELL PROCESS IS 95%+

UTILIZATION OF COMBUSTION OF TORREFACTION GASES DRIVES HIGH EFFICIENCY

1. Feed is 50% moisture biomass.
2. Biomass co-combustion is zero at 35% or less moisture(autothermal point of operation)
3. Over 100% thermal effieciency possible due to exponential increase in LHV when reducing moisture from 50% to 0%

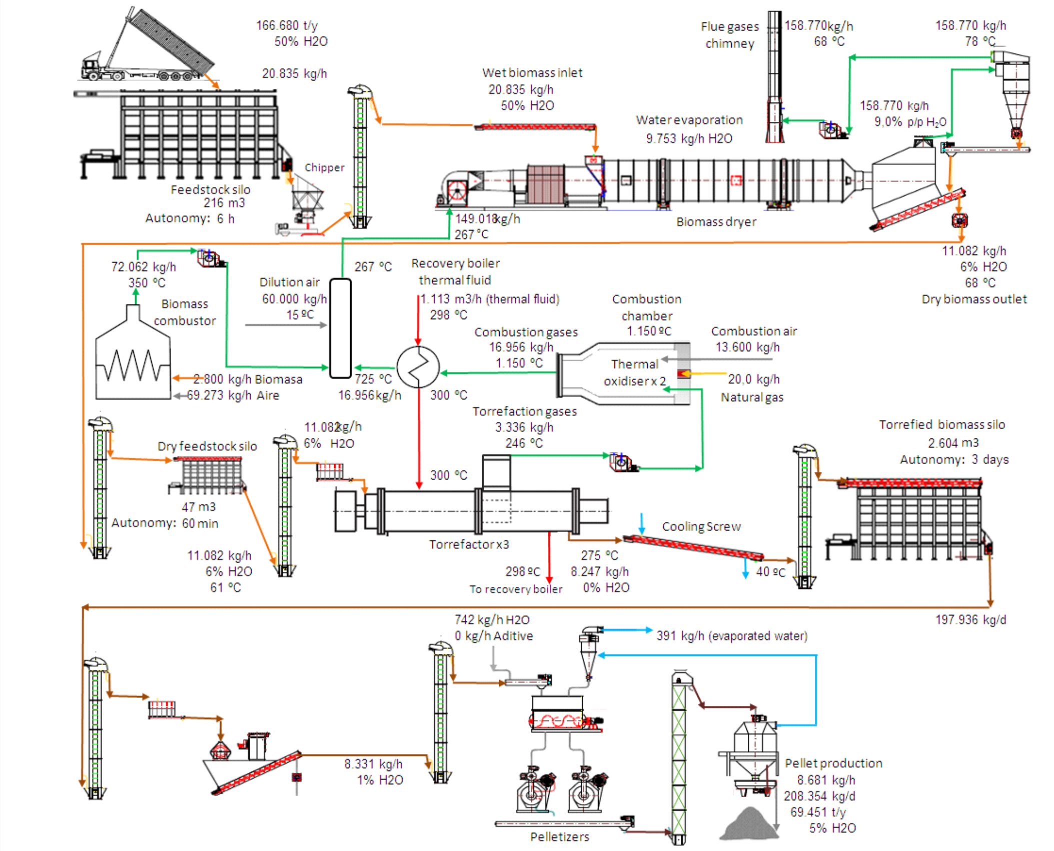
Post-van-der-Burg_Topell_torrefaction 21 6 2012

8.4 Appendix 2 Stand-alone plant –BASE CASE B (Topell Energy Technology)



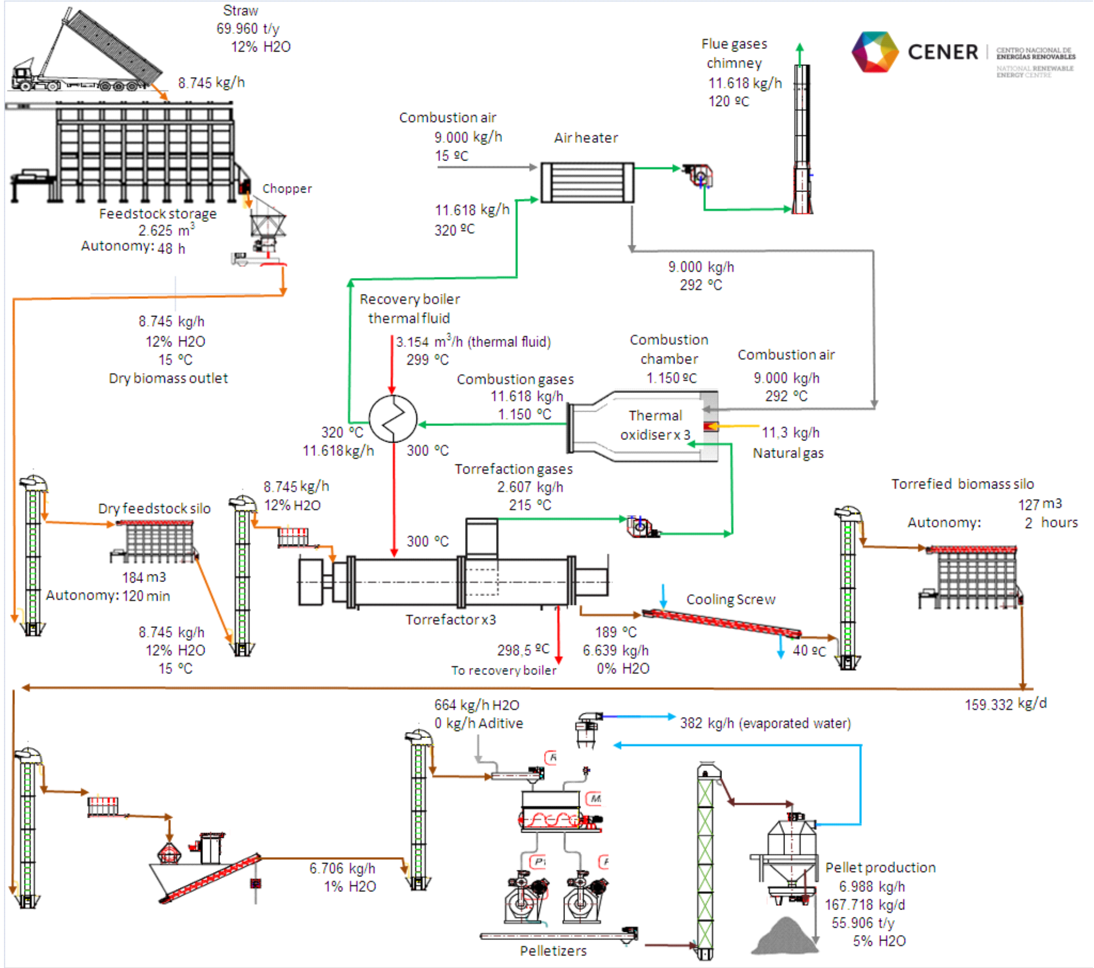
8.5 Appendix 3 Stand-alone plant of beech wood- Black box data of CENER

Flow diagram of drying, torrefaction and pelletization process at CENER

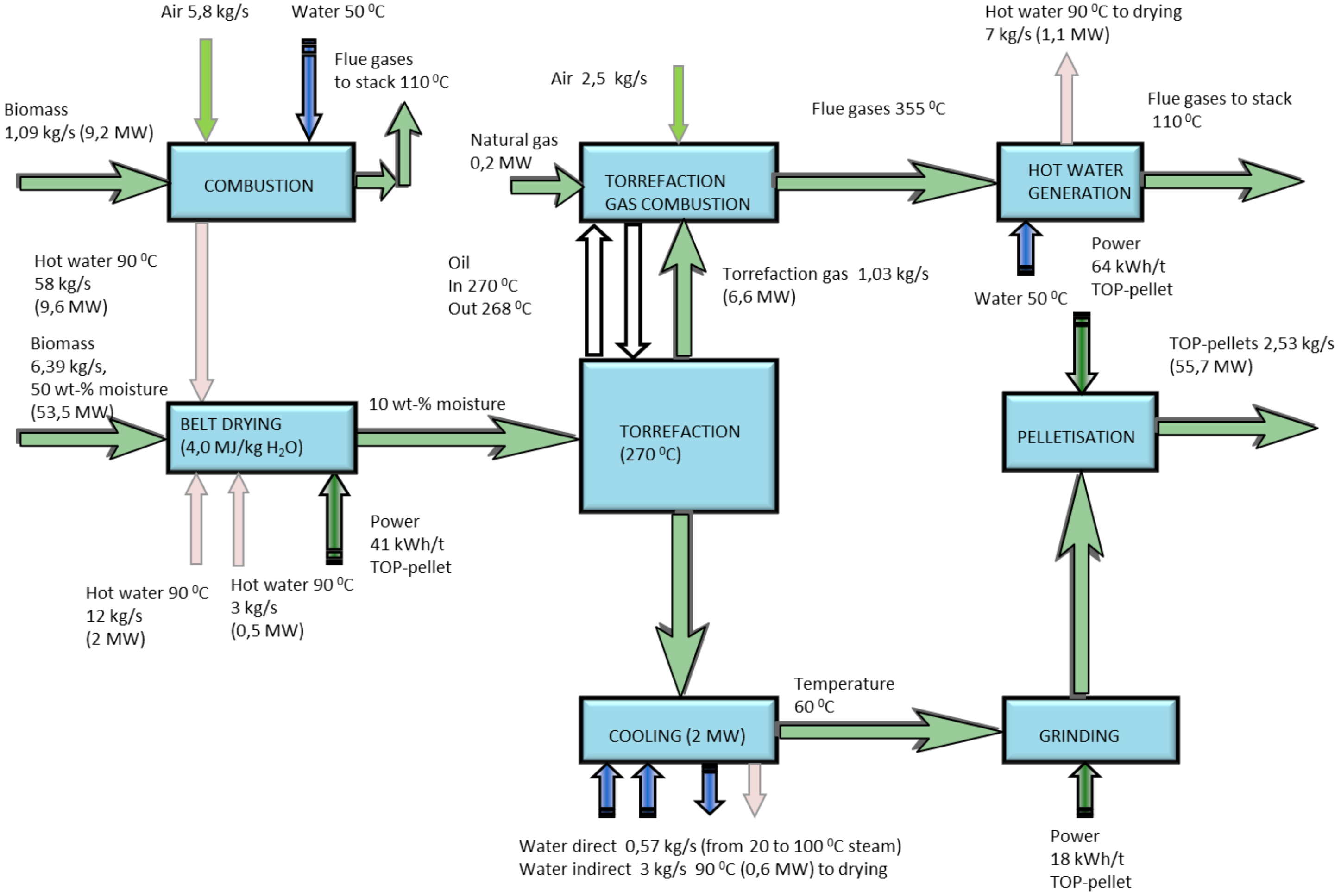


8.6 Appendix 3 Stand-alone plant of straw- Black box data of CENER

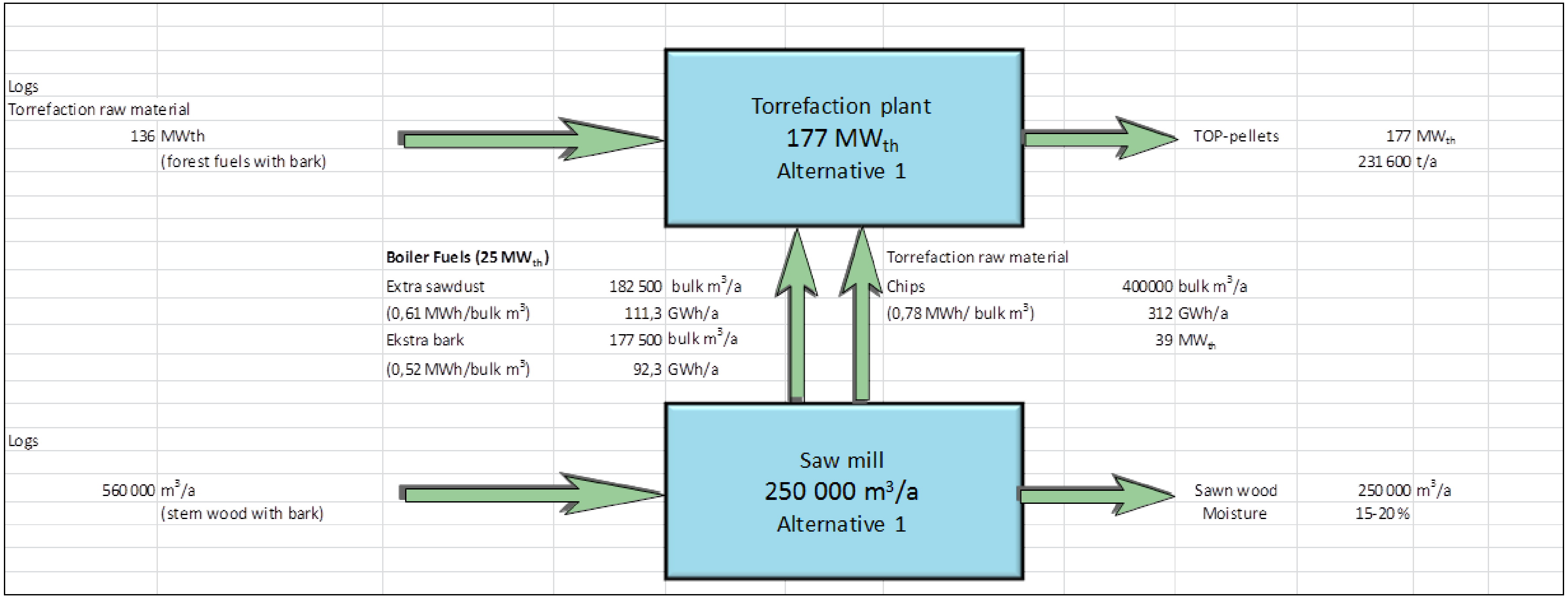
Flow diagram of straw torrefaction and pelletization process at CENER



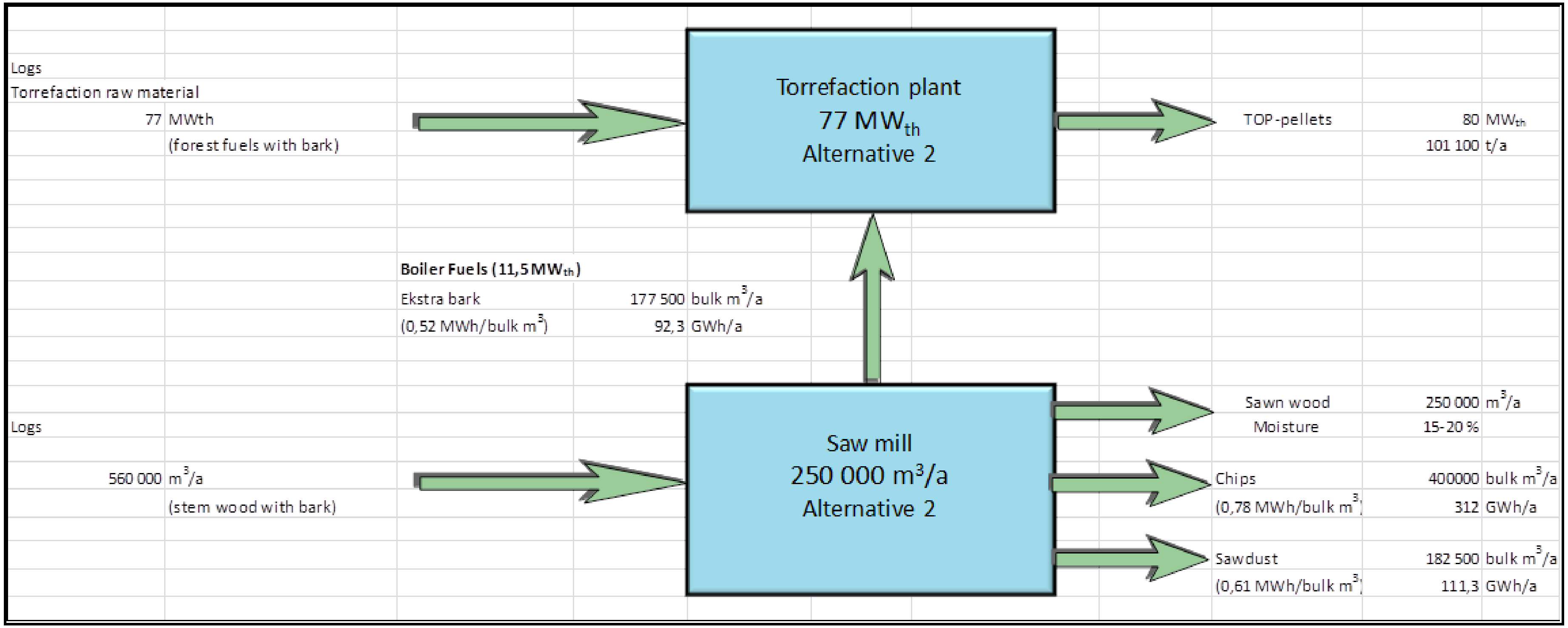
8.7 Appendix 3 Stand-alone plant of wood –BASE CASE C (CENER technology)



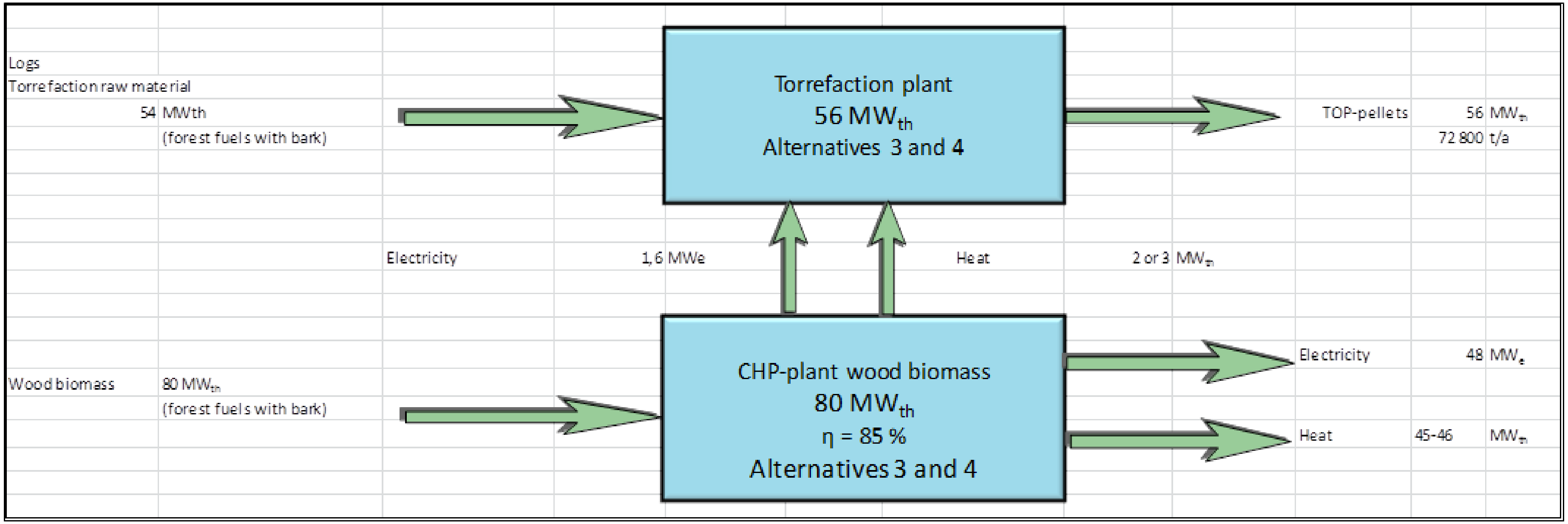
8.8 Appendix 4.1 Saw mill integrate - Alternative 1- Main mass and energy flows, new sawmill and torrefaction plant integrate with 25 MW$_{th}$ boiler



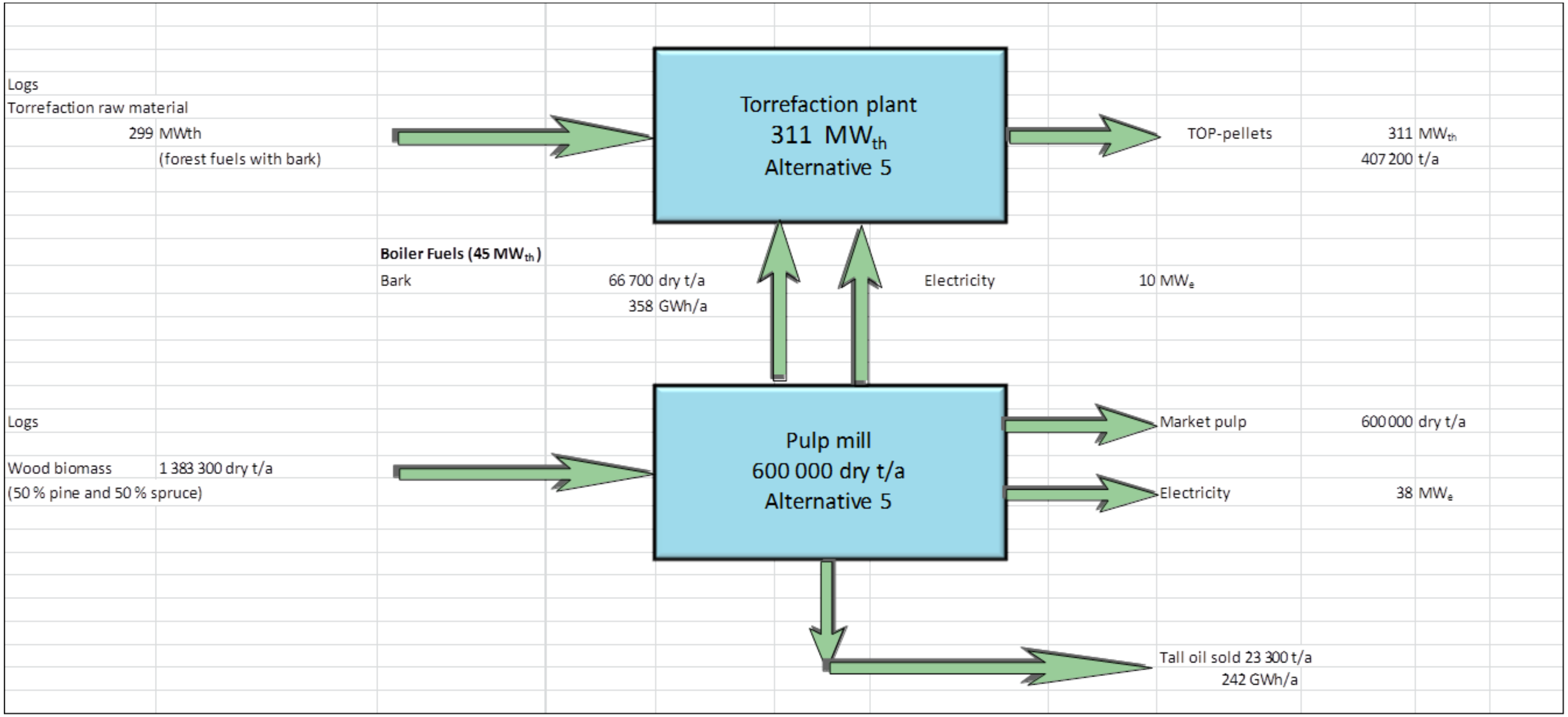
8.9 Appendix 4.2 Saw mill integrate - Alternative 2 - Main mass and energy flows, existing sawmill and new torrefaction plant



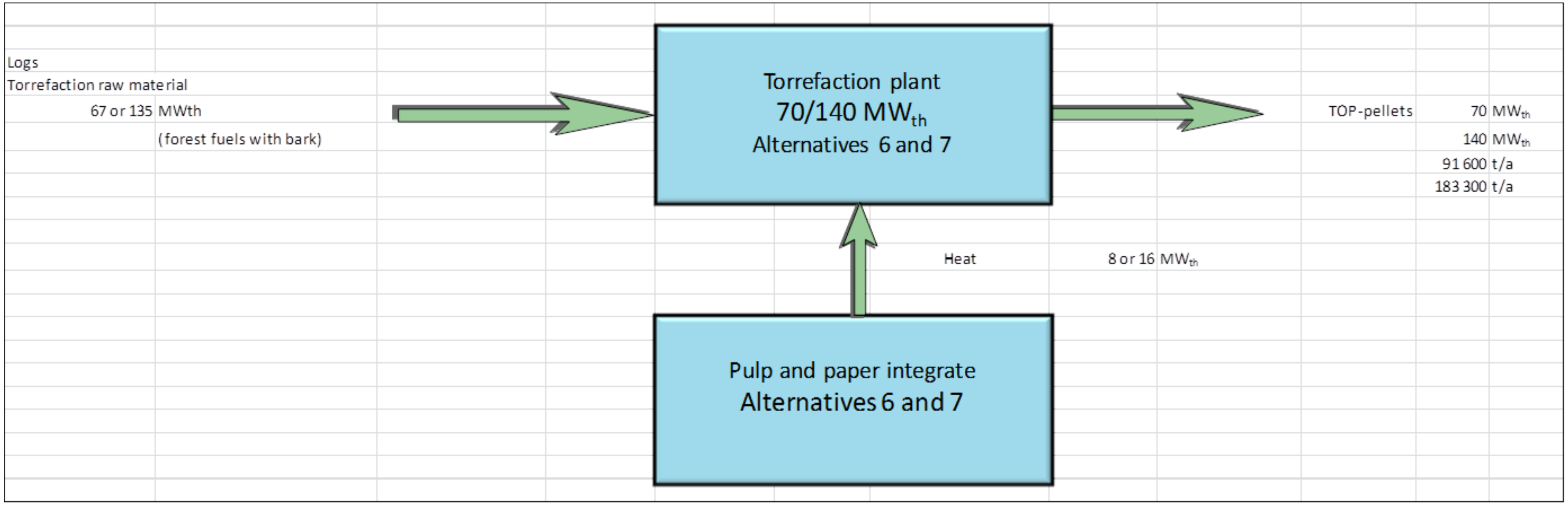
8.10 Appendix 5 CHP integrate – Alternatives 3 (5 000 h/a) and 4 (3 500 h/a) - Main mass and energy flows – existing CHP plant and new torrefaction plant



8.11 Appendix 6 Pulp mill integrate – Alternative 5 - Main mass and energy flows – existing pulp mill and new torrefaction plant



8.12 Appendix 7 Pulp and paper mill integrate – Alternatives 6 (70 MW$_{th}$) and 7 (140 MW$_{th}$) - Main mass and energy flows – existing pulp and paper mill and new torrefaction plant



8.13 Appendix 8 References to straw and beech wood torrefaction calculations by CENER

CASES	STRAW	BEECHWOOD CHIPS
PLANT SECTION	**Reference**	
Civil Works and buildings	Estimation based don CB2G construction	
Office equipment	Estimation	
Engineering	Estimation	
Permitting	Estimation based don CB2G construction	
Raw material storage and handling	Estimation. No data available.	Supplier quotation equipment for wood (APISA 2011) Updated with Equipment cost index (Spanish National Statistical Institute). Scaled-up with a power factor of N=0,6.
Chipping /chopping	Extrapolated from CB2G cost (APISA 2008) Updated with Equipment cost index (Spanish National Statistical Institute). Scaled-up with a power factor of N=0,6.	
Drying	-----	Supplier quotation equipment for wood (APISA 2011) Updated with Equipment cost index (Spanish National Statistical Institute). Scaled-up with a power factor of N=0,5.
Biomass combustor. Hot flue gas generator		Supplier quotation (ERATIC 2008) Updated with Equipment cost index (Spanish National Statistical Institute). Scaled-up with a power factor of N=0,6.
Milling	Supplier quotation equipment for wood (APISA 2011) Updated with Equipment cost index (Spanish National Statistical Institute). Scaled-up with a power factor of N=0,6.	
Torrefaction reactor feeding system	Supplier quotation equipment for wood (APISA 2011) Updated with Equipment cost index (Spanish National Statistical Institute). Scaled-up with a power factor of N=0,6.	
Torrefaction reactor and cooling screw	LIST(2011).	
Water cooling system	Extrapolated from CB2G cost (2009) Updated with Equipment cost index (Spanish National Statistical Institute). Scaled-up with a power factor of N=0,6.	
Thermal oxidiser and thermal oil boiler	Supplier quotation (KALFRISA 2012) Updated with Equipment cost index (Spanish National Statistical Institute). Scaled-up with a power factor of N=0,345	
Thermal oil circuit and air coolers	Extrapolated from CB2G cost (2009) Updated with Equipment cost index (Spanish National Statistical Institute). Scaled-up with a power factor of N=0,6.	
Pellet mill feeding system	Supplier quotation equipment for wood (APISA 2011) Updated with Equipment cost index (Spanish National Statistical Institute). Scaled-up with a power factor of N=0,6.	
Pellet mills	Supplier quotation equipment for wood (APISA 2011) Updated with Equipment cost index (Spanish National Statistical Institute). Scaled-up with a power factor of N=0,6.	
Auxiliaries, utilities and control system.	Extrapolated from CB2G cost (2009) .Updated with Equipment cost index (Spanish National Statistical Institute). Scaled-up with a power factor of N=0,6. Supplier quotation for some items (APISA 2011)	
Erection and start up	Extrapolated from CB2G cost (2009) .Updated with Equipment cost index (Spanish National Statistical Institute). Supplier quotation for some items (APISA 2011)	