MUSIC

Market Uptake Support for Intermediate Bioenergy Carriers

D5.3: Set of four Advanced Case Studies

(Public Edition)

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Executive summary

MUSIC aims to improve logistics and trade of biomass and intermediate bioenergy carriers (IBCs). IBCs are formed when biomass is processed to energetically denser, storable, and transportable intermediary products analogous to coal, oil and gaseous fossil energy carriers. They can be used directly for heat or power generation or further refined to final bioenergy or bio-based products. IBCs contribute to energy security, reduce greenhouse gas emissions, and provide a sustainable alternative to fossil fuels in Europe.

The MUSIC project will support market uptake of three types of IBCs by developing feedstock mobilisation strategies, improved cost-effective logistics and trade centres. The investigated IBCs include pyrolysis oil, torrefied biomass, and microbial oil.

In MUSIC, four case studies (CS) will be developed. These involve preparation of business plans for four case study regions (Sweden/Finland, Italy, Greece, and International). In this report the results of the advanced case studies are detailed. These advanced case studies are targeted to the shorter term, and are typically focused on the current settings, and scales that are appropriate for implementation in the near future.

In the **Sweden/Finland** case study, presented in Chapter 2, the logistics and feasibility of a long-distance value chain starting with pyrolysis oil production at various sites in Sweden and Finland and ending with pyrolysis oil upgrading to advanced marine biofuels at a site in the Netherlands was investigated. Both Sweden and Finland have large quantities of woody biomass available in the form of sawmill residues and fresh forest residues that can be used for production of pyrolysis oil. This pyrolysis oil is transported by ship to the Netherlands, were upgrading to marine biofuel can take place, using a process that is currently being developed by BTG, one of the consortium members.

In the advanced case study, the minimum quantity of pyrolysis oil that could realistically be upgraded in an upgrading plant was determined to be 72,000 tonne/year, which is the equivalent of the yearly production of 3 standard-sized biomass pyrolysis plants. The financial feasibility of these three plants was determined, and a choice was made for 2 plants in Finland and 1 in Sweden. Minimum costs for pyrolysis oil at the factory gate were determined to lie between 300 and 350 Euro/tonne.

International transport can take place in various ways and volumes. An option involving monthly transport is considered technically feasible. Total costs for international transport are about 61-62 Euro/tonne.

Upgrading of the pyrolysis oil requires substantial amounts of hydrogen. To ensure that the GHG emission reduction of the entire value chain is above 80% (to comply with RED II requirements), hydrogen production should be combined with carbon capture and storage (CCS) or hydrogen should be produced from renewable sources. A pyrolysis oil upgrading plant situated in the Netherlands will only be economically viable if current support levels for advanced transportation fuels are increased.

The Italian advanced case study analyses the overall feasibility of integrating a slow pyrolysis plant with the steel-making plant of ArcelorMittal in Taranto (Apulia), where biochar is to be used in a blast furnace for iron production as a replacement of pulverized injection coal, while the pyrogas co-product could be used for internal energy use.

Through a GIS-based biomass mobilisation tool – the INFER-NRG model – it was assessed that in the considered Southern Italy areas there is enough agricultural biomass available to fulfil the needs of the modelled slow pyrolysis plant, year-round. The price of dry biomass for use in the IBC plant was assessed for each crop type, with an average value ranging from 82.5€/t to 93.4 €/t.

The IBC plant operations and the possible integrations with the steel-making plant have been carefully evaluated and translated into a techno-economic model. The biochar would partially replace pulverised coal and would be mixed with raw coal before entering the grinding units. The use of the by-product - pyrogas – to replace fossil resources in the steel-making plant is less straightforward. It could be that additional cleaning is required.

Overall, the case study shows quite favourable results. The *Baseline* meta-scenario reports a Net Present Value (NPV) of 39,188,690 €, a 15 years Pay-Back Time (PBT)and an Internal Rate of Return (IRR) of 11.1%. All but two of the alternative scenarios showed economically viable results.

Essential for the business case is the timely securing of low-cost biomass. Another parameter with high-impact on the business case is the amount of pyrogas used to power the slow pyrolysis process. In the case study it is shown that use of the pyrogas is key to the viability of the business case. This means in practice that the IBC plant needs to be located at the steelmaking plant site, to ensure full usage of the pyrogas.

About 60% of the calculated income is generated by the EU carbon allowance prices that are earned because of CO_2 emission reduction and a Green Steel premium that is to be paid by the customers of the steel mill. The Green Steel premium accounts for 15% of the revenues.

In the **Greek** Advanced Case Study, the logistics and feasibility of a torrefied biomass value chain supplying the DETEPA-owned 30 MW_{th} Amyntaion district heating plant was examined. Currently, DETEPA utilizes a fuel mix of wood-chips and lignite and they plan to gradually replace the lignite part of the fuel mix, potentially with torrefied material produced from locally available biomass, in particular agricultural residues.

The advance case study has shown that enough biomass is available in the vicinity of the torrefaction unit. Investment cost are primarily linked to the torrefaction reactor size (70% of the CAPEX). Torrefaction doubles the operational cost in comparison with the utilization of the energy-equivalent raw biomass.

In the short term the currently used fuel mix of lignite and wood chips is financially the most attractive option, as long as lignite can be procured at a price not exceeding 46 €/ton. It is realistic to assume that the lignite price will increase because of the Greek coal phase-out that is to be completed by 2028. DETEPA, and other actors in the energy sector, should anticipate significant increases in energy production costs because of this coal-phase out, even when it offers substantial environmental benefits.

The **International** advanced case study is based on the ArcelorMittal steel plant in Ghent, Belgium. At that facility, the Torero torrefaction demonstration plant is under development. Based on its long track record as biomass user and on early Torero findings, AM anticipates good opportunities and a substantial potential to expand the use of torrefied biomass (including the biogenic fraction of solid recovered fuel - SRF and refuse derived fuel - RDF). The advanced case study has assessed a value chain broadening the range of biomass feedstocks to be torrefied at AM's Ghent facility.

Value chain analyses have taken place, and various feedstocks have been tested and assessed. The main conclusion is that when taking into account availability and business economics, shredded used treated wood (B-wood) and SRF or blends from both are the most promising feedstocks. However, the presence of ash, chlorine, sulphur and heavy metals In these feedstocks need proper attention and consideration, and have an impact on the possible applications of the torrefied product.

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Abbreviations

AM	Arcelor Mittal
BF(G)	Blast Furnace (Gas)
CAPEX	Capital Expenditure
COG	Coke Oven Gas
CCS	Carbon Capture and Storage
CS	Case study
CSR	Coke Strength after Reaction
Daf	Dry, ash-free
Db	Dry basis
DR	Discount Rate
Dx.x	Deliverable
EC	European Commission
EGD	European Green Deal
EU	European Union
EUA	EU Allowances
EU ETS	European Union Emission Trading Scheme
EU-27	Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain and Sweden
EU-28	EU-27 and United Kingdom
GHG	Greenhouse gases
GIS	Geographical Information System
HR	Heat Rate
HRSG	Heat Recovery Steam Generator
HVRT	Hot Vapour Retention Time
IBC	Intermediate bioenergy carrier
IRR	Internal Return Rate
ktoe	kilo tonnes oil equivalent

LHV	Low Heating Value
LRF	Linear Reduction Factor
MC	Moisture Content
MDF	Medium-Density Fibreboard
MSR	Market Stability Reserve
NCF	Net Cash Flow
NECP	National Energy and Climate Plan
NG	Natural Gas
NPV	Net Present Value
OPEX	Operational Expenditure
OSB	Oriented Strand Board
PBT	Pay Back Time
PC	Pulverized Coal
PCI	Pulverized Coal Injection
PP	Power Plant
PPC	Public Power Corporation (large power company in Greece).
RDF	Refuse Derived Fuel
RED	Renewable Energy Directive
SRF	Solid Recovered Fuel
TB	Torrefied Biomass
Thm	Tons of hot metal
TJ	Tera Joule
TR	Tax Rate
TRL	Technology readiness level
TTCR	Total Tax and Contribution Rate
Tx.x	Task
WP	Work Package
Wt%	Weight percent
BFG	Blast Furnace Gas
CAPEX	Capital Expenditure
COG	Coke Oven Gas
CS	Case study

CSR	Coke Strength after Reaction
DR	Discount Rate
Dx.x	Deliverable
EC	European Commission
EGD	European Green Deal
EU	European Union
EUA	EU Allowances
EU ETS	European Union Emission Trading Scheme
EU-27	Austria, Belgium, Bulgaria, Croatia, Cyprus, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain and Sweden
EU-28	EU-27 and United Kingdom
GHG	Greenhouse gases
GIS	Geographical Information System
HR	Heat Rate
HRSG	Heat Recovery Steam Generator
HVRT	Hot Vapour Retention Time
IBC	Intermediate bioenergy carrier
IRR	Internal Return Rate
ktoe	kilo tonnes oil equivalent
LHV	Low Heating Value
LRF	Linear Reduction Factor
MC	Moisture Content
MSR	Market Stability Reserve
NECP	National Energy and Climate Plan
NG	Natural Gas
NPV	Net Present Value
OPEX	Operational Expenditure
PBT	Pay Back Time
PC	Pulverized Coal
PCI	Pulverized Coal Injection
PP	Power Plant

RED	Renewable Energy Directive
thm	Tons of hot metal
TJ	Tera Joule
TR	Tax Rate
TRL	Technology readiness level
TTCR	Total Tax and Contribution Rate
Tx.x	Task
WP	Work Package

1 Introduction

The MUSIC project

Intermediate bioenergy carriers (IBCs) are biomass that is processed to energetically denser materials, analogous to oil, coal, and gaseous fossil energy carriers. This means they are easier to transport, store and use.

The MUSIC project will support market uptake of three types of Intermediate Bioenergy Carriers (IBCs) by developing feedstock mobilisation strategies, improved cost-effective logistics and trade centres. IBCs covered in MUSIC include pyrolysis oil, torrefied biomass, and microbial oil.

IBCs are formed when biomass is processed to energetically denser, storable, and transportable intermediary products analogous to coal, oil and gaseous fossil energy carriers. They can be used directly for heat or power generation or further refined to final bioenergy or bio-based products. IBCs contribute to energy security, reduce greenhouse gas emissions, and provide a sustainable alternative to fossil fuels in Europe.

Industry-led case studies on supply chain logistics

WP5 covers industry-led case studies (CS) on supply chain logistics in four case study regions (Sweden/Finland, Italy, Greece and International) where intermediate bioenergy carriers are not yet (fully) introduced and where the objective is to introduce their large-scale production.

In each case study region both a concrete advanced case study and a more strategic case study for the market up-take of intermediate bioenergy carriers will be developed. Advanced and strategic case studies will take a holistic look and broad view at cost-effective logistics, feedstock mobilisation strategies and trade-centres) at the broadest sense.

Scope of the current document

This document presents the results of the four advanced case study reports. It is the result of the work of four case study teams that were formed early in the project. These case study teams consisted of:

- Sweden/Finland: Case Study Lead: Biofuel Region (BFR). Other members: Green Fuel Nordic (GFN), BTG Bioliquids (BTL), BTG and Goodfuels
- Italy: Case study Lead: Renewable Energy Consortium for R&D (RE-CORD). Other members: ENI
- Greece: Case study Lead: Centre for Renewable Energy Sources and Saving (CRES) and Chemical Process and Energy Resources Institute, Centre for Research and Technology (CERTH). Other members: Cluster of Bioeconomy and Environment of Western Macedonia (CLUBE)
- International: Case study Lead: ArcelorMittal (AM). Other members: TorrCoal (TCT) and Renewi

In this report, one chapter is dedicated to each of the four advanced case studies.

The purpose of this document is:

- To provide a structured overview of the studied IBC value chains, thereby taking into account regional aspects and technical and economic aspects of the IBC value chains, whereby the aim was to identify and characterise economically viable value chains.
- To provide technical and economic information on the advanced case studies so that the consortium partners can use this as a basis to further develop their IBC value chains.
- To provide a sound basis for the later work on the strategic case studies

This deliverable (D5.2) is confidential, intended only for the relevant Commission services and for the Consortium. A similar deliverable (D5.3) will be completed at the same time and will contain basically the same information, except those parts that are of commercial interest to consortium partners.

2 Pyrolysis production and upgrading: the Nordic case study.

2.1 Technology

2.1.1 Pyrolysis process

Fast pyrolysis is a process in which organic materials are rapidly (≈2 sec) heated to 450 - 600 °C in the absence of air. Under these conditions, the structure is broken down and organic vapours, pyrolysis gases and charcoal are produced. In a next step, the vapours are condensed, and pyrolysis oil is formed. For a good oil quality quick condensation of the formed vapours is also important. Typically, 60-75 wt.% of the feedstock is converted into oil (see Figure 1).

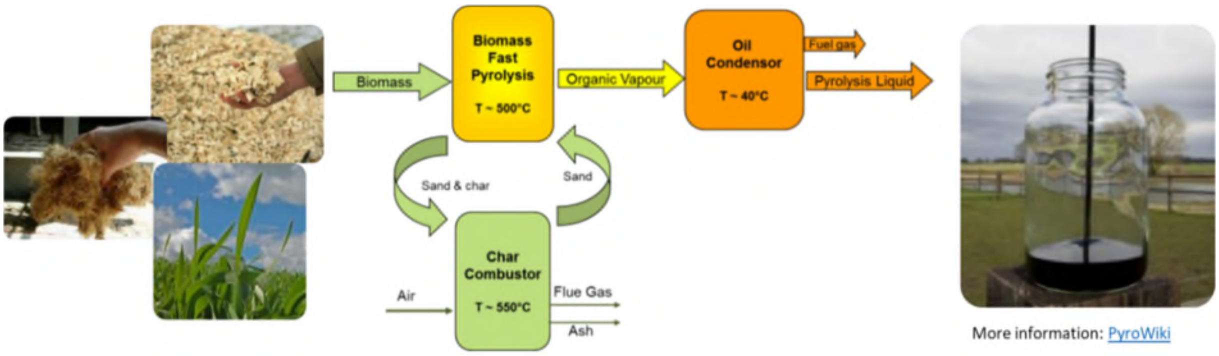

Figure 1: Fast pyrolysis process [1]

For achieving maximum yield and high quality of the oil rapid heat transfer is essential. This can be done by using small, homogeneous feedstock particles (approx. 3mm) with a moisture content of less than 10% and a carrier material for enhancing heat transfer (e.g. sand). The sand is heated during the combustion of char in a combustor. The energy generated during the combustion can be used to power the plant or to produce process heat for other applications. The quality of the pyrolysis oil is influenced by factors, such as type of reactor used, operating conditions and other feedstock properties, like ash content [1]. Some advantages of pyrolysis oil compared to raw biomass are the following:

- Pyrolysis oil is easier to store, transport and use than raw biomass
- Biomass residues becomes available in many forms. With pyrolysis these can be converted to a homogeneous liquid
- Energy density of pyrolysis oil is 4-20 times higher than of raw biomass
- Biomass contains minerals that are almost absent in the pyrolysis oil, this reduces the emissions during usage of the material
- Pyrolysis oil can be upgraded to transport fuels, chemicals, and materials [1].

The final product of the process is fast pyrolysis bio-oil (FPBO), a dark brown, acid and viscous liquid which can be used in different forms, e.g. as bioliquid for energy purposes, feedstock to be processed to advanced biofuels, feedstock for co-processing or as feedstock to produce chemicals and materials [2].

Pyrolysis oil may appear to be like fossil oil, but in properties there are quite some differences. Besides already mentioned aspects such as acidity and viscosity, the energy density of pyrolysis oil is roughly half of the energy density of fossil transport fuels like diesel and gasoline, and it is also not miscible with these fuels. To utilise pyrolysis oil as transport fuel, it is necessary to upgrade it. In the next chapter technologies to accomplish this are discussed.

2.1.2 Pyrolysis technology status

At this moment (2021) there are several pyrolysis oil production plants in operation or under development in Europe.

In Finland, Fortum has implemented a fast pyrolysis plant in Joensuu, next to its own combined heat and power (CHP) plant. The pyrolysis reactor is a circulating fluidized bed, using local forest residues, wood chips and saw dust. Heat is provided to the CHP plant. The reactor was designed and delivered by Valmet. The plant was commissioned in 2013.

The location for the plant was chosen based on the availability of the feedstock nearby and the high level of forestry knowledge in the region. Combining the CHP plant and the PO plant allows for better use of lower-quality biomass fuel (residues and sawdust) that would otherwise be used at lower efficiency in conventional CHP. Furthermore, biomass in the region can be converted to more valuable fuel when demand for heat and power are limited.

Figure 2: The Fortum pyrolysis plant in Joensuu, Finland. Capacity is 50,000 liters of pyrolysis oil per year.

In the Netherlands, a 24,000 liters/year pyrolysis plant (the Empyro plant) was build in 2015 and operated by BTG Bioliquids. This plant was sold to the local utility company Twence in 2018. Twence uses residues from wood pellet production that are brought to the plant with a pellet truck that pneumatically feeds the residues to the storage vessel.

Figure 3: The Twence pyrolysis plant in Hengelo, the Netherlands. The plant was commissioned in 2015 and produces 24,000 liters of pyrolysis oil per year.

From the storage, the residues are converted to pyrolysis oil, which is subsequently combusted in a dual-fuel burner at a nearby dairy plant (owned by FrieslandCampina) to produce process steam. The pyrolysis plant has a high thermal efficiency, also because waste heat is used in the next-door salt production process of the company Nouryon Industrial Chemicals.

In Sweden, the Pyrocell plant, located at Setra's Kastet sawmill in Gävle at the east coast, is currently under development. BTG Bioliquids has a contract to supply a plant with the same capacity as the Twence plant. Start-up is planned in 2021. The plant will transform sawdust into pyrolysis oil, for further processing into renewable diesel and petrol at Preem's refinery in Lysekil. The company Pyrocell is a Joint Venture of Setra and Preem. The conversion from pyrolysis oil to transport fuels is done by co-feeding the pyrolysis oil to the Fluid Catalytic Cracker (FCC) unit in the refinery. Pilot experiments have shown that this is possible up to a percentage of about 5%. This would however be the first full-scale commercial application of this type of transport fuel production.

In Finland, the first Green Fuel Nordic pyrolysis plant is under development in Lieksa, in the east of the country. This plant is also being developed by BTG bioliquids. Here sawdust from the nearby sawmill will be used as feedstock, too. At the end of 2020 the plant was operational and has started production and supply of pyrolysis oil.

The construction is done in modules. The modules are assembled in NL, tested, disassembled again and then transported to the building site. GFN will provide oil for local/international consumers. Savon Voima in Iisalmi (Finland) is one the customers for the pyrolysis oil from GFN, and will use the PO in their district heating plant
Besides these European plants, also plants are established outside Europe. The Ensyn/ Honeywell UOP joint venture – called Envergent Technologies - has developed their own technology for pyrolysis, referred to as Rapid Thermal Processing or RTP™. Ensyn is established 1984 based on research carried out by University of Ontario, Canada.

The technology uses a circulating bed system with sand as heat carrier material. The technology has been in production for 25 years and has efficiency of 70-75%. Gas and char produced are used for running the facility and drying the woody biomass. This technology was first commissioned in 1989 for production of flavouring agents ('liquid smoke') for the food industry. In 2007, Ensyn commissioned Renfrew Ontario – in Port Cartier, Quebec (Canada) - with a capacity of 11,3 million liters of renewable fuel oil, RFO™ per year. This plant, which was upgraded in 2016, is dedicated to the fuels market.

2.2 Research and development programs of pyrolysis oil

Besides utilisation of the pyrolysis oil for energy via direct combustion, there are many other high-value applications being developed. These are discussed in the next paragraphs.

2.2.1 Pyrolysis oil fractionation

Pyrolysis oil is a complex emulsion of many different chemical substances. To be able to utilise pyrolysis oil for chemicals and materials, fractionation of pyrolysis oil can be advantageous. This process uses liquid-liquid extraction and is also called Thermo-Chemical Fractionation (TCF) [3].Pyrolysis oil can be separated by TCF into 3 main components:

1. pyrolytic lignin
2. pyrolytic sugars and an
3. water fraction

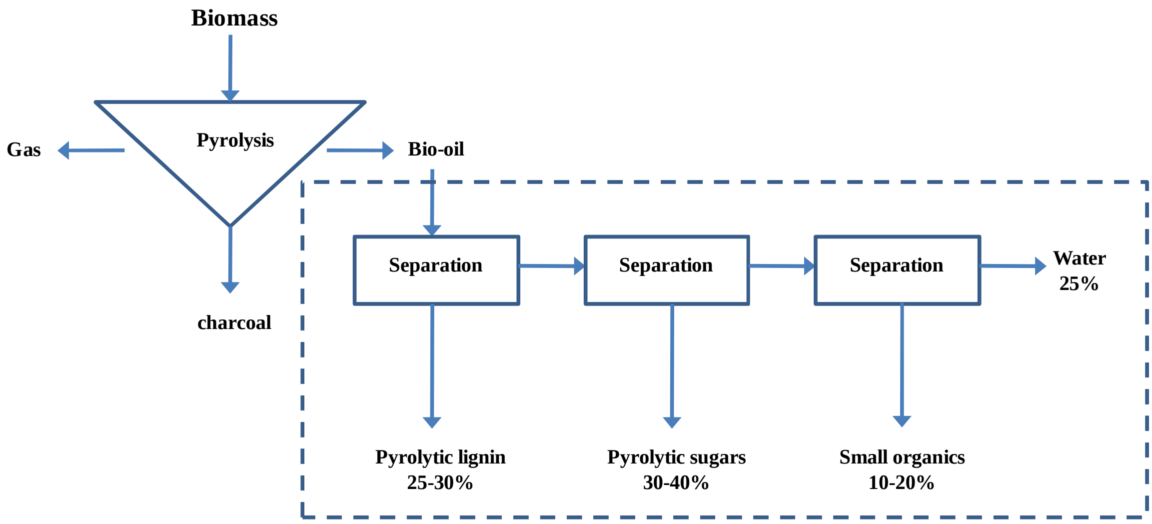

Figure 4: Pyrolysis oil fractionation

Advantages of this process are that essential functionalities are retained in the pyrolytic fractions. Fractions can be used either directly as raw material for biobased products, or as a starting point for further downstream processing. The process has no byproducts/waste because excess fractions can be mixed back in the pyrolysis liquid for fuel application. At the BTG laboratory, a 3 tonne/hour pilot plant has been commissioned in 2018.

Examples of applications of pyrolysis oil fractions that are being developed are (See also Figure 5):

- Modified wood. This involves use of the pyrolysis oil sugar fraction for wood modification. Softwood impregnated with pyrolysis oil sugars becomes thus more durable, and can even be used in outdoor applications.
- Roofing material. Roofing material is currently produced while using fossil bitumen. It has been shown that part of the bitumen can be replaced by pyrolytic ligin.
- Paints. Pyrolytic lignin can also be used as component in the production of various paints. This allows replacement of fossil components or – more expensive – biobased components.
- Phenolic resins. Part of the fossil phenol can be replaced by pyrolytic lignin, to produce insulating resins or molding resins. Especially the very high heat resistance of the material is advantageous.

Figure 5: Examples of applications of pyrolysis oil fractions. Top left: modified wood, top right: paints, bottom left: roofing material, bottom right: Phenolic resins

These applications – and others – are currently all under development. The modified wood modification is currently already being marketed as a commercial product[1]. For the other applications product development is still on-going.

2.2.2 Pyrolysis oil Upgrading

Besides fractionation, pyrolysis oil can also be upgraded to transport fuels. One of the ways this is being done is by co-feeding it into a fossil refinery, as will be done in the Preem refinery in Lysekil. However, also in stand-alone plants pyrolysis oil can be upgraded to transport fuels.

Pyrolysis oil as such is not suited for transport applications. It is not miscible with diesel/gasoline, it is acidic, contains water and the heating value is roughly half that of typical transport fuels. Main cause of these problems is the presence of oxygen in the pyrolysis oil. Removing part of this oxygen and replacing it with hydrogen (hydrodeoxygenation) converts pyrolysis oil into a transport fuel.

The technology to produce these transport fuels is not yet fully commercial. BTG has developed a two-step process in which pyrolysis oil is upgraded to (marine transport fuels). These are:

- Upgrading of the pyrolysis oil to a stabilised form – Stabilised Pyrolysis Oil or SPO - using a dedicated catalyst named PICULA^{tm}. This process takes place at pressures of about

[1] https://www.foreco.nl/en/products/faunawood

200 bar and temperatures of 100 –300 °C. About 50% of the oxygen is removed. The SPO can already be utilised for various applications, including co-refining.

- Via a more standard (commercial) catalyst, the final 50% of oxygen is removed. Process conditions are a bit less severe (100 -140 bar pressure, 250 –450 °C).

The overall hydrogen consumption is about 3.5 - 5% hydrogen per unit pyrolysis oil. This is manageable, but these quantities mean that it is advantageous to find 'green' sources of hydrogen, so that the overall CO_2 footprint of the technology is as low as possible. Pilot plant results are indicated in Figure 6.

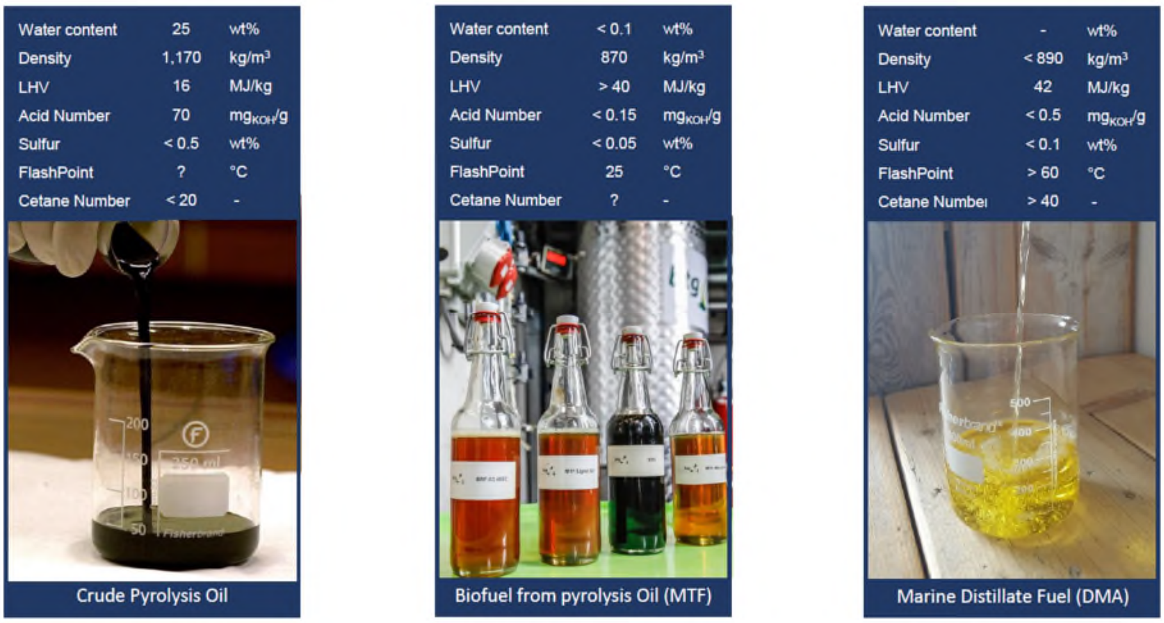

Figure 6: Change in composition of pyrolysis oil when it is converted to transport fuel

What is clear is that the water content is reduced dramatically, the density is comparable to DMA, the heating value has increased and the level of acid and sulphur has decreased significantly. The flashpoint is quite low, but a relatively simple 'flash' to distillate some of the light components increases the flashpoint to over 60°C. The biofuel from pyrolysis oil is fully miscible with common transport fuels, such as diesel [4].
The status of the technology is that it has been proven on a pilot plant scale. The next step is a Demo plant. BTG has the ambition to develop a 1000 tonne/year Demo plant by 2023, under a new company called BTG-NeXt.

2.2.3 Alternative feedstocks

The pyrolysis plants implemented so far are using wood as feedstock. Wood has the advantage of a relatively low ash content, and relative ease of handling and sizing. Also, wood residues can become available at low moisture content, and already sized, for example as sawmill residues.

However, almost all types of biomass are suitable for fast pyrolysis. Main requirements for the fast pyrolysis process are that the biomass is relatively dry (less than 10% moisture content) and a relatively small size. It is also important that the levels of minerals are comparable to those found in wood, as higher levels have a detrimental effect on the pyrolysis oil yield and quality.

One way to reduce the amount of minerals in biomass is washing with water. This way, the alkali and alkali earth metal level (Na, K, Ca, Mg, etc.) can be reduced. Washing increases the costs, but this effect is dampened by the lower feedstock costs of biomass alternatives (compared to wood). In the Dutch project PyroBEST this has been investigated[2]. One of the results was that pyrolysis of washed biomass (verge grass with an ash content of 26% was used) resulted in similar yields as with wood, and that the pyrolysis oil quality was comparable to pyrolysis oil from wood.

2.3 Markets

2.3.1 Market Drivers

2.3.1.1 EU policy drivers transport sector (Green Deal, Maritime biofuels, RED II, ETS for maritime sector, (brief, Rianne))

On the 11th of December 2019, the European Commission presented the Green Deal, with at the heart *Climate Action*. This translates in the clear ambition to become **the first climate neutral region** in the world by 2050. The Green Deal is a roadmap of key policies and measures ranging from ambitiously cutting greenhouse gas emissions, to investing in research and innovation, aimed to make the EU's economy more sustainable. Policy topics of importance are e.g. **supply of clean and affordable energy, establish a circular economy, eliminate pollution, safeguard biodiversity, and create sustainable food and transport systems.**

Climate Target Plan

As mentioned Climate Action is at the heart of the Green Deal, with cutting greenhouse gas emissions as a key focus point. The EU is already on track to meet its greenhouse gas emissions

[2] https://projecten.topsectorenergie.nl/storage/app/uploads/public/5cf/fad/17b/5cffad17b1e3e666988940.pdf

reduction target for 2020. In the **2030 Climate Target Plan**, the Commission proposed in September 2020 to raise the 2030 greenhouse gas emission reduction target, including emissions and removals, to at least 55% compared to 1990.

A European Strategy for low-emission mobility

Almost all sectors have shown progress towards the goal of emitting less climate harmful emissions, with transport being the notable exception. While overall GHG emissions declined in Europe by 22.5% from 1990 to 2018, total transport emissions increased by more than 23%. With the Green Deal and the Climate Target Plan this needs to be turned around. Cutting emissions by 55% will require raising the EU's ambitions in all areas, including renewable energies, whose share in the energy mix experts say will have to rise to 38-40% by 2030, up from a current target of 32%.

The Green Deal includes the transport sector and specifically states that this sector needs to: "Speed up the deployment of low-emission alternative energy for transport, such as advanced biofuels, electricity, hydrogen and renewable synthetic fuels and removing obstacles to the electrification of transport". In addition, Senior Expert Maria Georgiadou of DG Research and Innovation, Renewable energy R&I policy of European Commission, states about the Green Deal and the transport sector that:

"Advanced biofuels are necessary for the implementation of the new EU 2030 Climate Target Plan in the EU Green Deal".

These clear statements put pressure on the sector, however the exact legislative framework with the targets and measures for the transport sector is in the making. Especially the coming year (2021) several EU directives and targets effecting the sector will be revised or defined.

Transport and Maritime policy outlook following the Green Deal *

Following the proposed Green Deal and the 2030 Climate Target Plan, the Commission on December 9th, 2020 published the **EU strategy for Sustainable and Smart Mobility.** This recent published strategy will set out the broader policy priorities for the transport sector for the period **2021-2024**, including timelines for legislative and non-legislative proposals. The strategy is expected to propose a range of policy instruments to decarbonize the EU transport sector and cut back CO_2 emissions, and prioritizing alternative fuels across all modes of transport.
When looking at the uptake of sustainable and alternative transport fuels in general, the Commission states in the Sustainable and Smart Mobility strategy that: 'a silver bullet to decarbonizing the transport sector is lacking'. And therefore, a mix of alternative fuels is required. In the planned strategy the Commission plans to review the EU rules on alternative fuels infrastructure and consider legislative options to boost the production and supply. The introduction of alternative fuels is however much less advanced in aviation and shipping. Thus there is a need for more research, pilots, scaling-up projects and financing. To support this, the Commission

intends to propose changes to the EU rules on energy taxation and stop subsidies for fossil fuels and review tax exemptions on aviation and maritime fuels. Furthermore, the ambition for a diversified fuel mix for the future will be worked out in two FuelEU proposals, 1) FuelEU Maritime, 2) ReFuelEU Aviation.

These proposals aim to set out a pathway for low-emission fuels to be used in the maritime and aviation sectors. Specifically, the maritime sector:
The FuelEU Maritime initiative is expected to boost the production and uptake of sustainable maritime fuels and address this issue by incentivising the deployment of renewable and low-carbon fuels and feeding stationed vessels with renewable power instead of fossil energy. And the Commission will consider establishing a Renewable and Low-Carbon Fuels Value Chain Alliance in which industry and civil society will cooperate to boost the supply and deployment of the most promising fuels.

Directive Revisions 2021
As mentioned, to reach the ultimate goal of achieving climate neutrality by 2050 a series of measures will have to be taken, including the revision of a set of legislation that defines the European legal framework on energy and climate. Below a list of several directives impacting the transport sector which are foreseen to be proposed or adopted in Q2 2021:

- Renewable Energy Directive II
- Energy Efficiency Directive
- Alternative Fuel Infrastructure Directives

With regards to the maritime sector in specific the redrafting/revision in 2020/2021 is foreseen for:

- EU Emissions Trading System and the inclusion of Maritime transport: CO2 emissions from the maritime sector have not been included in the ETS system. In 2020 a majority of MEPs voted to include shipping in the scheme as of 2023, if there is no comparable system operating in the International Maritime Organisation (IMO) in 2021. Beginning of February 2020, the EU consultation was closed asking for input from all stakeholders.
- Energy Taxation Directive (ETD) - The EC will look closely at the current tax exemptions including for aviation and maritime fuels and at how best to close any loopholes.

By June 2021, the Commission will review and, where necessary, propose to revise relevant policy instruments to deliver additional greenhouse gas emissions reductions in light of the September 2020 statement to increase the target for 2030. 2021 is there for an important policy year for the transport sector, as all major directives related to transport will be revised in 2021. This also means that some targets currently in place will be revised.
The exact outcome of these revisions as well as the exact targets for several proposals is at the moment of writing (February 2021) unknown. It can however be concluded for now that it is

likely that targets in most directives need to increase to ensure increased GHG reduction. This will most likely result in increased financial frameworks to support e.g. the increased share of renewable energy in the transport fuel mix.

This part of the report will be updated at the end of the project period (M34/M35 of the project) with the correct and final information following the revisions and target setting taken place in 2021.

2.3.1.2 National legal frameworks for biofuels

Sweden

In Sweden, the parliament has decided that the vehicle fleet should be fossil independent by 2030. In connection with the decision on the climate policy framework 2017, the parliament decided that greenhouse gas emissions from domestic transport should decrease by at least 70 percent by 2030 compared to 2010. In 2018, Sweden had the largest share of renewable fuels for transport in the EU with a 23 % share. The main driver for this development has been the tax exemption for biofuels that was introduced in 2007. However, the tax exemption has been questioned several times by EU as state subsidy and permission to extend it has been granted during this period 7 times and is now valid for another year. This has not created the long term and stable energy policy landscape required for investments in domestic production of biofuels. In 2018, 85 % of the biofuels used in Sweden were imported and a reduction quota was introduced. The quota stipulates that the distributers of road transport fuels are obliged to reduce the carbon footprint from the volumes sold by 19.3 % for diesel and by 2.6 % for gasoline. The reduction quota will step by step be increased reaching 66 % for diesel, and 28 % for gasoline, in 2030. There are no present plans to introduce a national sub quota for advanced biofuels. For the biofuels distributed as high blends (HVO 100, E85, RME 100 and biogas), the tax exemption remains but there is great uncertainty if Sweden can continue to with this support after this year. The past 5 years, there has been a huge increase in the use of HVO based on a palm oil by product, PFAD (Palm Oil Fatty Acid Distillate). The possibility of double counting has made PFAD a very attractive option on the market outcompeting other biofuels. To deal with this problem, PFAD has now been reclassified from waste to by product meaning that it cannot be double counted and that it must fulfil the same sustainability criteria as other biofuels. What effect this will have on the use of PFAD in Swedish biofuel market is still yet to be seen.

With the new quota in place, interest for domestic investments in biofuel production is on the rise. Investment support (45%) from the Swedish climate leap has been granted for production of PO in Kastet Sawmill in Gävle, now under construction. The climate leap budget has been increased last year and is likely to continue the coming years. Green investments credits from Swedish state are now also available. If this support is enough to boost domestic production of biofuels is not clear and the Swedish Energy authority will analyse the drivers and barriers for domestic biofuel production and suggest further policy recommendation in autumn 2021. National implementation of the ongoing revision of RED II directive and other related EU directives will in the in the future influence Swedish market for biofuels. Other countries implementation of the RED II directive can also influence the Swedish market. The quota for advanced biofuels within RED II can also be strong market driver. Advanced biofuels produced in Sweden may be more attractive to export to countries where an advanced quota or other premiums for advanced biofuels are in place.

Finland

In addition to the EU Renewable Energy Directive (RED II) Finland has set following targets, via several National legal framework.

Table 1: Finnish National legal framework to amend the European Green Deal.

National Energy and Climate Strategy for 2030	Government of Finland, 2016	• 80-90% reduction in greenhouse gas (GHG) emissions by 2050 • The share of renewable energy to over 50 % and transport biofuels will be increased to 30% • Finland will phase out the use of coal for energy and import of oil will be halved • An obligation to blend light fuel oil used in machinery and heating with 10% of bioliquids
Finnish Laws 418/2019 and 419/2019	Effective March 2019	• Coal fired power and heating generation will be banned as of May 2029 • The obligation to distribute transport biofuels increased as of 2021, from 18% to 30% by 2029 • The obligation to distribute advanced biofuels increased from 2021 onwards reaching 10% by 2030 • The obligation to distribute heating biofuels increased as of 2021, from 3% to 10% by 2028
Government of Finland Programme	Effective June 2019	• Emissions guidance in energy production will be increased by abolishing the industrial energy tax rebate system and reducing category II electricity tax towards the minimum rate allowed by the European Union • Medium-term climate change policy plan and national climate and energy strategy will be updated so that Finland can reach the 2030 emissions reduction level required to achieve carbon neutrality

Netherlands

In the Netherlands, there is a country-specific initiative to promote the use of renewable fuels in the transport sector. This system is linked to the national renewable fuel blending obligation for fuel suppliers. In 2021, this renewable fuel blending obligation is approximately 17%, which means that 17% of the fuels supplied to the transport sector should be renewable. The obligation percentage is increasing each year. Each fuel supplier is required to meet this obligation at the end of the year.

The fuel supplier has two options to meet this target:

1. Make sure that 17% of its fuel supplied to the transport sector is renewable.
2. Purchase renewable tickets from the suppliers that have supplied more than 17% of renewable fuel to the transport sector.

These renewable tickets are key in this Dutch system. They are called HBE's which stands for Renewable Fuel Units. For each GJ of Renewable Fuel, a fuel supplier will obtain one HBE. At the end of the year, a fuel supplier needs to hand in, to the Dutch Emission Authority, as much HBE's equal to 17% of its total fuel supply. For parties that sell only biofuels to the market, the HBE's are from great value as they can sell them to parties who lack to meet the target. The revenues from HBE sales can cover the price gap between bio and fossil fuels.

When the upgraded pyrolysis oil can be used in the Dutch transport sector, it can also make use of this HBE system. This will improve the economic feasibility of the oil as well.

2.3.2 Marine fuel pricing

The fuel price is one of the most influencing factors on the financial performance of a marine logistics company. Currently, most ships are sailing on fossil diesel like Marine Gas Oil (MGO) and Very Low Sulphur Fuel Oil (VLSFO). MGO is a transparent fuel which contains 1000 ppm Sulphur and is often used within the Emission Control Areas (ECA's) near the coasts. VLSFO is more like the traditional fuel oil as it is black, not transparent and contains up to 5000 ppm Sulphur. This VLSFO is the most used fuel in the international waters outside the ECA's.

Since 2015, biofuels are also introduced into the marine sector. These are all diesel like biofuels like Biodiesel (FAME), Hydrotreated Vegetable Oil (HVO) and Biofuels Oil. FAME and HVO are from an appearance perspective more like MGO but contain less than 10 ppm Sulphur. Biofuel Oil, introduced by GoodFuels, is in its appearance more like a light VLSFO and contains up to 150 ppm Sulphur.

The International Energy Agency has recently performed research into the pricing of these biofuels and compared them with the traditional marine fuels. As can be seen in Figure 7, the prices of the biofuels are on average a couple of times more expensive than fossil fuels.

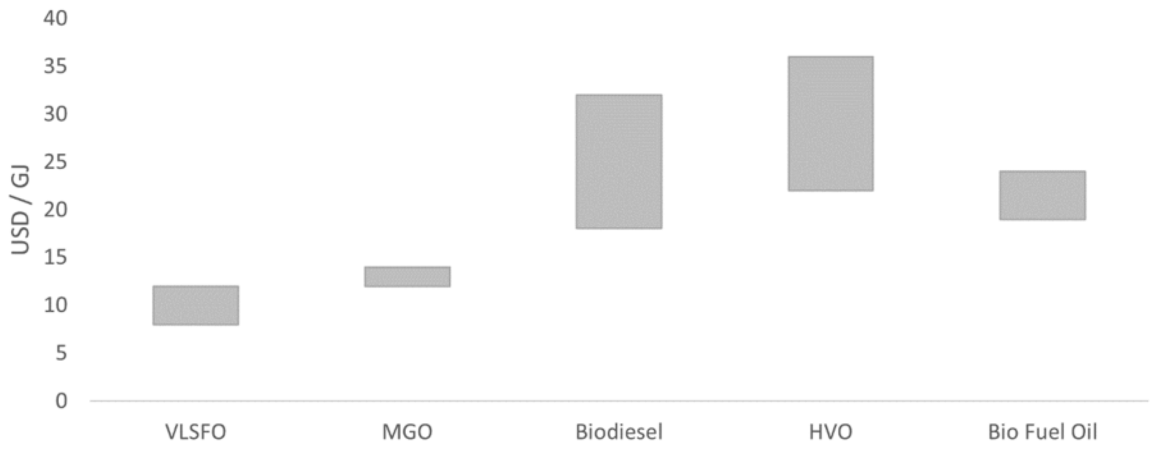

Figure 7: Indicative shipping fuel cost ranges [5]

2.4 Biomass availability and pricing

2.4.1 Biomass availability and pricing in Sweden

Forestry is a co-production system, i.e. several products are produced simultaneously, such as saw logs, pulpwood and logging residues. Therefore, the potential amounts of the different assortments are not independent. Calculating production costs for one product in a co-production system is not straightforward. Generally, there is no unambiguous way to allocate costs between the different products in an operation. Analyzing the economy based on woody biomass, in particular the energy production, is quite a complex task. The forest-based industries and the energy production sector are intricately interlinked, displaying synergies as well as competition. Sawmilling by-products are used for wood pulp (for paper as well as textile fibres) and wood-based panels manufacturing as well as for energy production, while side-streams from chemical pulping are used in the chemical industry as well as for energy production. The demand (and thus price) for sawlogs is one of the most determinant factors for the supply of primary woody biomass, including woody biomass for energy. The supply of primary woody biomass might also be affected by external factors, such as natural disturbances. Energy and material use (mainly wood-based panels but also wood pulp manufacturing, in most cases not sawmilling, as the price of saw logs is too high) also compete for primary sources (removals) of woody biomass. This means that developments in wood-based product markets are instrumental to the supply of woody biomass for energy purposes, and thus an assessment of sources and uses of woody biomass for energy needs to also consider forest-based industries.

Different assortments

In this study, four different assortments were studied; sawdust, bark, cellulose chips (c-chips), dry chips, and shavings (see Figure 8). As data has been collected from many different sources presented with different units, it is to determine the conversion rates between ton, m3sub, MWh for the different assortments (Table 2).

Figure 8: Picture of assortments, A = Bark, B = C-Chips, C = Sawdust and D = Shavings.

Table 2: Conversion rates between ton, m3sub (solid volume under bark), MWh for the assortments sawdust, bark, c-chips, dry chips, and shavings with the assumed moisture content in precent. Nd stands for no data.

Assortment	Raw ton	m^3sub	MWh	Moisture content (%)
Sawdust	1	1.2	2.3	50%
Bark	1	1.3	2.0	55%
C-Chips	1	1.1	2.2	50%
Dry Chips	1	2.0	4.3	17%
Shavings	1	Nd	4.2	Nd

As by-products come from a main process such as sawing wood at a sawmill, the potential volume available of these by-product assortments is connected to the volume the sawmill processes. From roundwood volume, around 50% becomes sawn wood products, 20% sawdust, 10% bark, 20% chips and shavings. These are average figures and quite large variation can be observed between individual sawmills. However, these variations are not considered in this report.

The price of by-products from forest industry are low and historically, they have been purchased at the suppliers industry gate at prices from zero to 15 €/ MWh. The low prices of by-products are partly explained as collection and production costs of the by-product are allocated to the main product. The lower value corresponds to a situation where you have no end consumers located within a reasonable transport distance from the supplier. The higher value corresponds to a situation where you have several end consumers close to the supplier competing for the by-products. Plants to refine feedstock such as sawdust are anticipated eventually to be located close to large amounts of low-cost feedstock and then transported to user destination in an more energy dense form. In the short term when the by-product price is low, customers may profit just from buying at a low price. When the market starts to mature and there is more competition between different end users, it is likely that the feedstock will acquire a – likely higher - value linked to final product price.

Quality of forest industry by-products

The heterogeneous nature of bark with high ash content and big particle size distribution makes it not suitable for pyrolysis oil production. Cellulose chips have an attractive quality for pulp mills and are thus assumed not to be available for alternative biorefining processes in the future. Shavings represent a small share of the total available forest industry production and as it is dry it is attractive for pellet producers. Dry chips are available in small volumes and is mostly used for combustion.

Compared to many other forest industries by-products, sawdust has unique qualities that makes it desirable for energy production, fibre board production as well as for emerging biorefining technologies. Sawdust has a well-defined and homogeneous quality, low ash content and few elements that can have a negative impact on biorefining process parameters. Particle size distribution is small with many small particles of similar size. Sawdust already exists in large quantities, thus the infrastructure for procurement is readily available.

Transportation cost

From transporting agent in northern Sweden, transport costs for all different forest industry by products has been collected. These costs are used for cost calculation in this case study, see Table 3.

Table 3: Different loadings for a normal truck and different costs for sawdust, bark, c-chips, dry chips, and shavings. The one-time costs include loading and dispatch for one tonne.

	Sawdust	Bark	C-Chips	Dry Chips	Shavings
Loading volume (raw tonnes)	41.5	41.5	41.5	22.5	22.5
Loading volume (MWh)	95.5	83.0	91.3	96.8	94.5
Transport cost (EUR/km/ton)	0.067	0.067	0.067	0.067	0.067
One-time cost EUR/ton	1.21	1.21	1.21	1.21	1.21
One-time cost EUR/MWh	0.52	0.61	0.55	0.28	0.29

In Finland, it is common practice that big sawmills also have own specialized track and trailers to deliver sawdust to client's gate. The transportation cost is then included for the lamp sum of Euro/MWh in sawdust purchase contract what client pays. Then the transportation cost optimization is in the hand of sawmill management, taking in account that sawdust can be delivered from different sawmills of the same group in the range of 200 km from Pyrolysis plant.

Sawmills in the four northern counties in Sweden

In northern Sweden, there are 28 sawmills with an annual production between 18 000 and 550 000 m3 sawn wood. To be able to include production figures from all major sawmills in northern Sweden in this case study, data has been collected and compared from 3 different sources. To collect data on the current producers, the Swedish forestry agency has published statistical yearbooks where most producers are mentioned and listed and the most recent one was used to provide an outline for what industries to include in the study. To further corroborate the list from the Swedish forest agency, the industry organization Swedish Forest Industries keeps record of members in their organisation by county. With the records the previous list could be updated to include more current information. The case study host company also provided a list of current producers and production figures to compare with.

Table 4: Sawmills in Northern Sweden. Location, owner, county, and production of sawn wood for the year 2019

Location	Owner	County	Production (m^3 sawn wood/ year)
Korpilombolo	Jutos Timber	Norrbotten	60 000
Tärendö	Krekula & Lauri	Norrbotten	52 000
Piteå, Munksund	SCA Wood	Norrbotten	420 000
Piteå, Lövholmen	Stenvalls trä	Norrbotten	140 000
Sikfors	Stenvalls trä	Norrbotten	140 000
Seskarö	Stenvalls trä	Norrbotten	0
Luleå, Örarna	Stenvalls trä	Norrbotten	65 000
Glommersträsk	Glommers Timber	Norrbotten	50 000
Älvsbyn	Älvsbyhus	Norrbotten	40 000
Brattby	Brattbysågverk	Västerbotten	50 000
Rundvik	SCA Wood	Västerbotten	315 000
Malå	Setra Trävaror AB	Västerbotten	210 000
Vännäs	NK Lundströms	Västerbotten	65 000
Sävar	Norra Skog	Västerbotten	256 000
Kåge	Norra Skog	Västerbotten	263 000
Agnäs	Norra Skog	Västerbotten	18 000
Bygdsiljum	Martinsson/Holmen	Västerbotten	430 000
Kroksjön, Skellefteå	Martinsson/Holmen	Västerbotten	117 000

Hissmofors	Norra Skog	Jämtland	120 000
Gällö	SCA Wood/Persson Invest	Jämtland	360 000
Svenstavik	Rödins Trä AB	Jämtland	78 000
Bollsta	SCA Wood	Västernorrland	550 000
Tunadal	SCA Wood	Västernorrland	550 000
Ullånger	MST Sågverk Ullånger AB	Västernorrland	35 000
Örnsköldsvik	Högland	Västernorrland	50 000
Anudsjö, Bredbyn	Högland	Västernorrland	190 000
Fränsta	Callans Trä AB	Västernorrland	85 000
Edsele	Edsele Såg AB	Västernorrland	28 000

Marginal cost curves for sawdust acquisition

From the 28 sawmills mentioned above, 4 sawmills have been chosen for this case study in the only region where supply is bigger than demand. From interview with biooil transporting agent, Skelleftea harbour has been recommended for export as suitable infrastructure already is in place there. Sawmills owned by large forest companies have not been selected as they are part of a forest industry complex, and by-products are primarily supplied internally. Smaller sawmills and sawmills far away from port of Skelleftea have not been selected. Selected sawmills have no known obstacles when it comes to expansion and environmental permitting.

All sawmills were georeferenced. Each sawmill was selected as host of the pyrolysis reactor. Using the Network Analyst module in ArcGIS10 (closest facility function) sawdust from the sawmills that were closest to the sawmill with the pyrolysis reactor was transported via the existing road network to the host sawmill. It is foreseen to collect 80 000 tonnes of saw dust per year, which is the assumed annual demand for the PO production.

The cost for sawdust acquisition and transport (Figure 9) will be between 0.76-0.81 M€, which is a rather precise number. This cost is based on the assumption that sawmills are willing to sell the sawdust picked up at the sawmill for 7.18 €/ raw ton. However, this price will in the future be negotiated by sellers and buyers based on the future market situation where also other new biorefining technologies may compete for the sawdust. It is hard to predict what the future prices will be but with higher demand, the value of sawdust will acquire a value linked to final product price. No cost for storing, handling, and feeding of the sawdust into the reactor is in-cluded. Neither is profit margins included.

All four sawmills presented here are good locations for PO production with Norra Skog Kåge as the best option. It has the lowest cost for both sawdust acquisition and for transport of PO to harbor. Possible synergies and the sawmill owner's willingness to be involved in PO production will most probably be decisive for future investments.

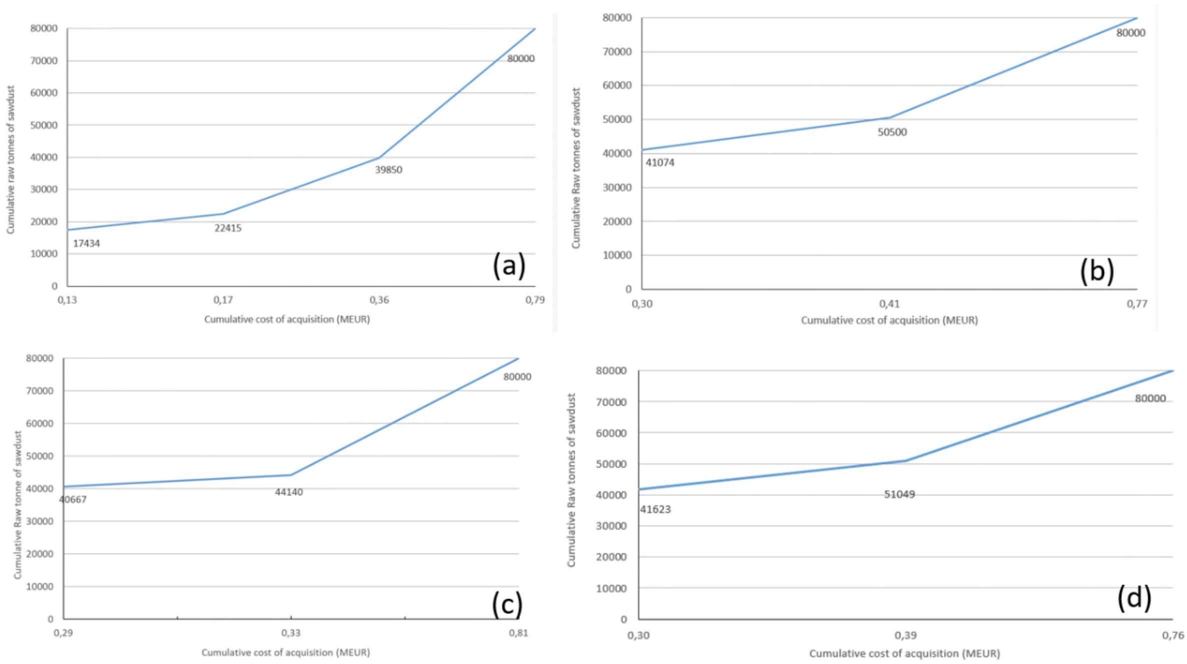

Figure 9: The cumulative cost of acquisition (MEUR) of a maximum of 80 000 raw tonnes of sawdust (a) Sikfors, (b) Bygdsylium, (c) Sävar and (d) Kåge.

Market situation

Sawn timber products and pulp and paper products have dominated the use of forest biomass over a long time but the use for energy purposes has grown rapidly over the past decades. In the near future, the use of forest biomass in biorefineries is expected to increase rapidly. As a result of the existing forest industry production, huge amounts of industry by-products are produced. As the transport cost of by- products are high, production of intermediate energy carriers preferably should be located close to the supply. Some regions have a surplus of forest industry products while regions near big CHPs sometimes have a shortage especially during cold winters. From Table 5 below shows that only the County of Västerbotten have a bigger supply than demand (+101 GWh). The County of Jämtland has the largest deficit with 450 GWh followed by the County of Norrbotten with 63.8 GWh and the County of Västernorrland with a deficit of 40.8 GWh.

Several heating plants have announced that they will stop burning peat in the coming few years. It is estimated that 500 GWh of peat must be replaced by other wood fuels in northern Sweden. Although data presented here does not consider export and import and that sawmill output is based on calculation rather than measured volumes, we can foresee that new end users of forest industry by-products are likely to cause market distortion where competition for attractive by-products like sawdust will increase. CHPs can compensate for the shortage of sawdust by burning LR (logging residues) that today are not fully utilized or other more complex fuels not suitable for upgrading. CHP technology is robust and designed to handle more complex fuels. Other end users of sawdust with no alternative raw material supply face the risk of closing down.

Table 5: County supply and demand in GWh for sawdust, bark, c-chips, dry chips, and shavings for the year 2019. C-Chips demand is not listed as everything is assumed to be sent to pulp mills directly. Specific dry chips and shavings demand does not exist

		Sawdust (GWh)	Bark (GWh)	C-Chips (GWh)	Dry Chips (GWh)	Shavings (GWh)
Västerbotten	Supply	656.7	280.7	1 632.5	130.2	49.2
	Demand	571.9	443.6	-	-	-
Norrbotten	Supply	368.3	157.5	915.7	73.1	27.6
	Demand	651.6	38.6	-	-	-
Jämtland	Supply	212.5	90.9	528.4	42.2	15.9
	Demand	626.3	185.4	-	-	-
Västernorrland	Supply	584.9	635.9	1 409.0	112.4	42.4
	Demand	1 015.9	400.6	-	-	-
SUM	*Supply*	*1 822.5*	*1 165.0*	*4 485.6*	*357.9*	*135.1*
	Demand	*2 865.6*	*1 068.2*	-	-	-

2.4.2 Biomass availability and pricing in Finland

Sawmills in Finland

The feedstock resources in the region are adequate. Total forest usage in Finland is approximately 70 million m^3/year while the usage of one pyrolysis plant is about 0.09 million m^3/year. There are about 80 industrial sawmills in Finland with a combined annual timber production of 12 million m^2 in 2018. Close to 30 % of the Finnish sawmill capacity is provided by 12 sawmills located in Lieksa (North Karelia), Iisalmi (North Savo) as well as in Kainuu regions (seeTable 6). This corresponds to a total yearly timber production of the sawmills of about 3.3 million m^3 annually and a cumulative yearly output of sawdust of 877,000 m^3.

Table 6: Sawmills in the region for GFN plants

Location	**Owner**	**Distance from** Lieksa (km)	**Distance from** Iisalmi (km)	**Sawdust output (m^3 / year)**
Keitele	Keitele Timber		92	118 125
Kuhmo	Kuhmo	109	170	105 000
Hankasalmi	Versowood		200	78 750
Lieksa	Binderholz	1	176	76 125
Kostamus	Karelian Wood Co.	200		65 625

Iisalmi	Anaika	176	0.5	60 375
Nurmes	Binderholz	55	118	60 375
Iisalmi	Iisalmen Sahat	176	15	60 375
Kajaani	Pölkky	169	81	60 375
Lieksa	Anaika	5	176	26 250
Värtsilä	Karlis-Prom	162		26 250
Hammaslahti	Kaivospuu	120		18 375

There are 10 Finnish and 1 Russian sawmill in a 200 km radius from the current GFN Lieksa pyrolysis plant. Production capacity of these sawmills is 1 239 000 MWh of sawdust per annum. Within a radius of 200 kilometers from the Iisalmi production plant, there are ten sawmills with a production capacity of 1 412 000 MWh of sawdust per annum (see Figure 10). The first choice for GFN operation will be the sawmills which are not part of the vertical integrated Pulp & Paper Companies, such as Stora Enso, UPM or Metsä Fibre.

For the Case study following assumptions are used: two companies in the region North Karelia: Kuhmo and Binderholz are main sawdust supplies to the Lieksa biorefinery. The main suppliers for the Iisalmi (North Savo) biorefinery are expected to be Keitele Timber, Anaika and Iisalmen Sahat.

As a backup GFN has an option to get from Karjalan Metsä ja Energia, to deliver 15 000 m^3 sawdust and up to 45 000 m^3 residue chips from Russia in 2021-25. The residue chips are used as a backup against possible availability and price risks of sawdust.

All the supplier companies in the region promote sustainable forestry and use FSC and PEFC certified timber.

The major considered ports (Kokkola, Kotka and Turku) are also shown in Figure 10. For the case study Kokkola is used as a destination harbor for inland bio-oil transportation.

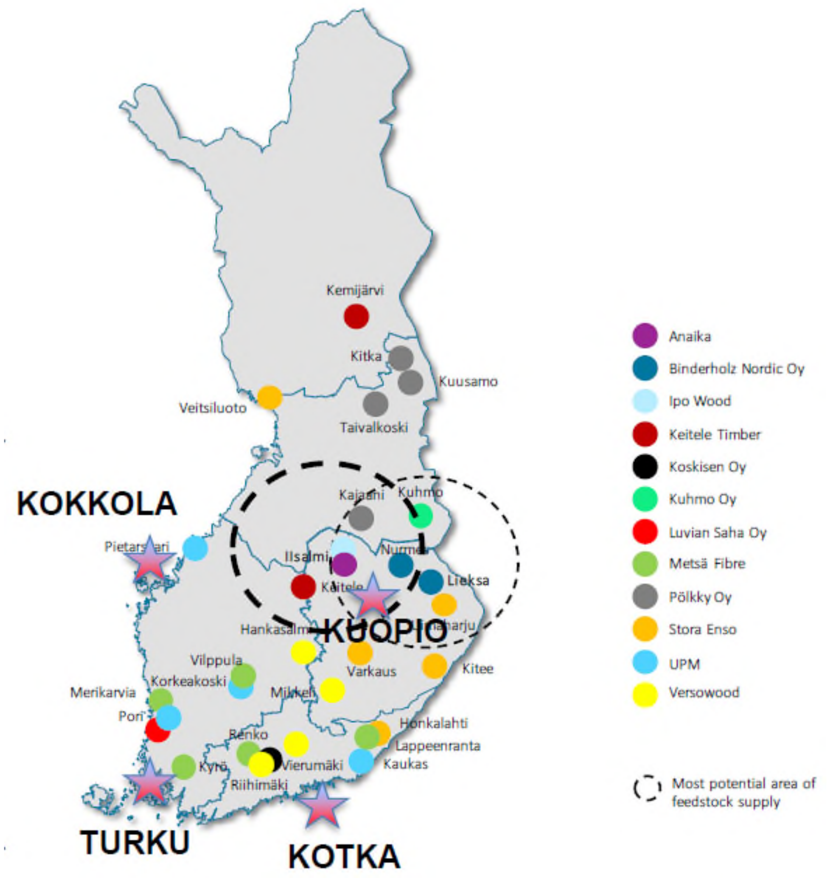

Figure 10: Major sawmills in Finland with Production > 100 000 m3 / annum /sawmill

One GFN biorefinery requires 170 000 MWh of sawdust per annum (12-14 % of available sawdust). Wood chips are also available in the area but at a higher price than sawdust. Chips have traditionally been used as a raw material for pulp production in Finland. However, there are no major pulp mills near GFN's locations except the Stora Enso's pulp mill in Uimaharju (see Figure 10), which is not considered for the present case study. In addition, residues from forest thinning can be utilised when needed.

2.5 Locations of the biorefineries in Sweden/Finland

2.5.1 Existing forest infrastructure

Sweden

For historic reasons (rivers were used for transport of round wood from inland to cost), a big majority of the pulp mills, sawmills and CHPs are located near the coast in northern Sweden providing good opportunities for synergies as well as competitions. In Figure 11 below all major biomass consuming and production industries are shown. The four sawmills chosen for this study are also marked in the figure.

The costs of harvesting, transporting, storing and handling of the biomass are prime determinants of overall biorefining costs. Thus, it is vitally important to develop local forest biomass supply systems that can efficiently supply biorefineries with sufficient raw material that meets their specific quality and seasonal demands. As a result of the existing forest industry production, huge amounts of industry by-products are produced. To maximize possible synergies, refineries can preferably be integrated just next to existing forest industries. However, most of the forest industry by-products are already used, either internally, or by pellet producers or by combined heat and power (CHP) plants. The illustration below shows the present flows of woody biomass from the forest and between different industry segments. In the near future, new processes are likely to be developed to upgrade by-products like sawdust both into high value products and to different types of biofuels. It is likely that demand for forest industry by-products, especially those with a well-defined quality, like sawdust will increase. Some regions have a surplus of forest industry products while regions near big CHPs sometimes have a shortage especially during cold winters. Market price will for this reason vary both regionally and seasonally. An average price for sawmill by-products (sawdust and bark) during the past 10 years delivered to industry gate has been estimated to approximately 20 €/MWh (effective heating value as received).

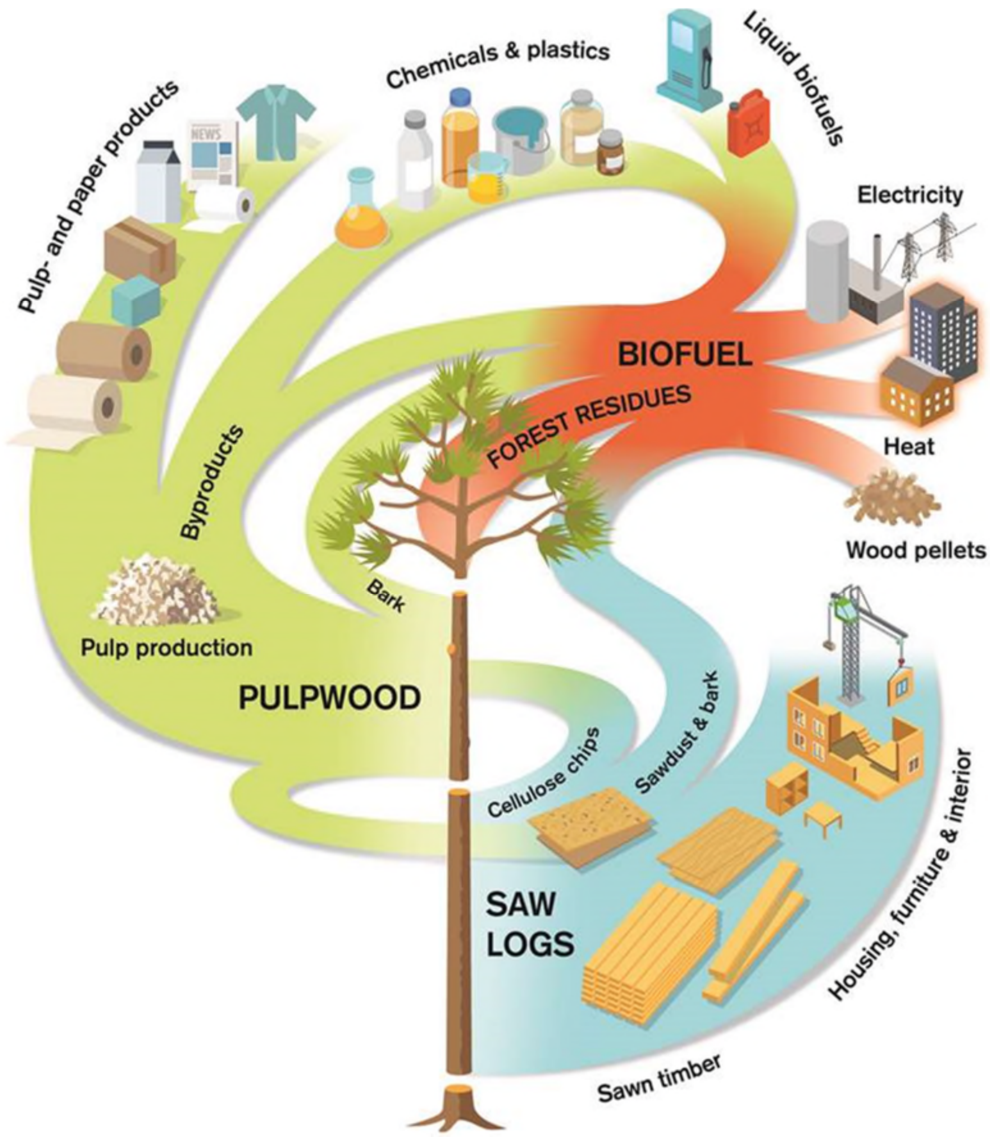

Figure 11: The value chain of the forest biomass showing the flows of woody biomass from the forest and between different industry segments.

Figure 12: Map of the existing forest industry locations in Northern Sweden.

Finland

As it can be seen from the map (Figure 13), the major wood consumers – big Pulp mills are concentrated on south and on west coast of Finland.

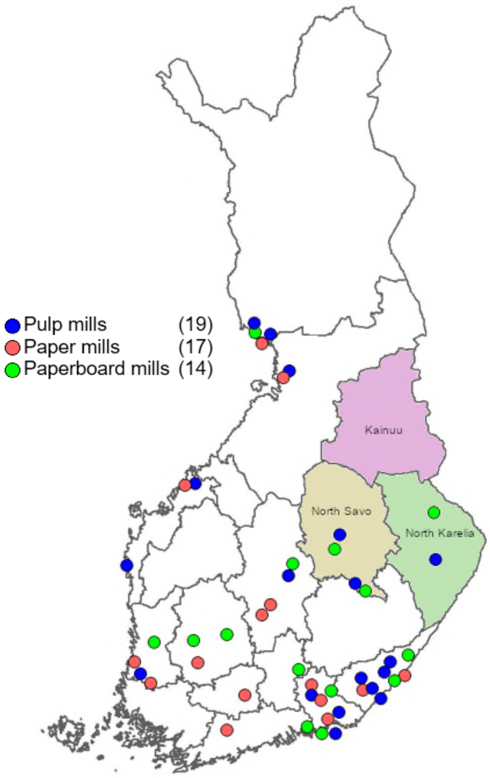

Figure 13: Map of the existing Pulp mills locations in Finland. (Source: Finnish Forest Industries Federation)

There are only two pulp mills in the area of case study interest – Mondi Powerflute (North Savo) consumes mainly birch for semi-chemical pulping and Stora Enso Enocell in Uimaharju (North Karelia), also there are no anymore close Pulp mills towards north in Kainuu province. For bio-oil plant locations, chosen for case study, there is not much competition for feedstock from Pulping industry (due to transportation distance). Thus, conservative estimation of price for sawdust can be rather stable average (Figure 14) from past 10 years with 2 Euro/MWh escalation, i.e., for modelling 15+2=17 Euro/MWh delivered to industry gate (effective heating value as received).

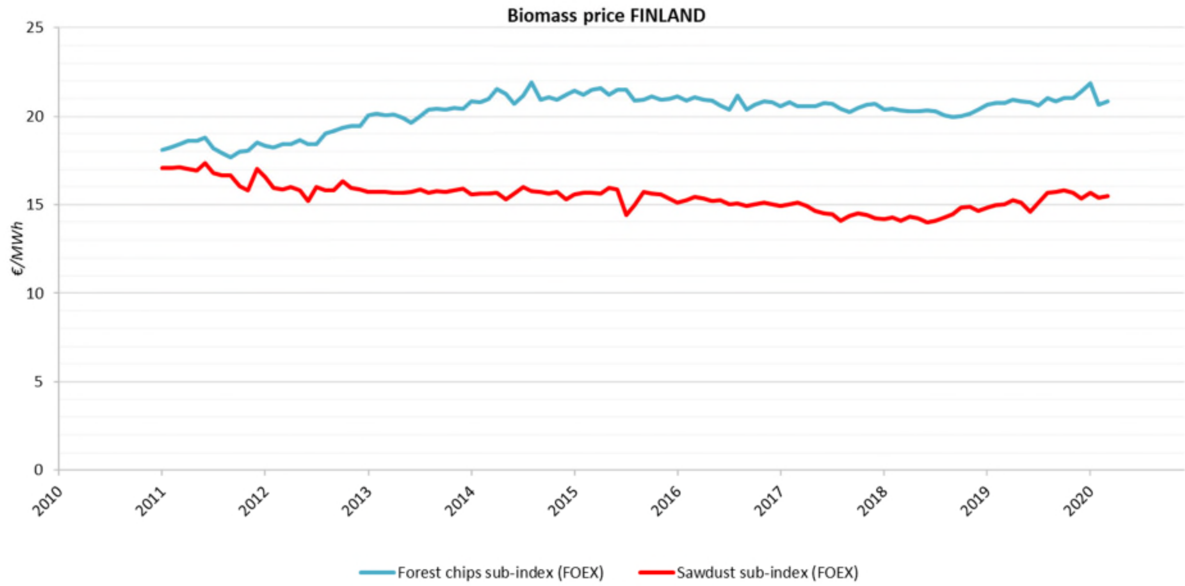

Figure 14: Biomass Price history trends in Finland 2010-2020

2.5.2 Environmental permitting and synergies with existing plants

In ***Sweden***, environmental permitting for 25 MW pyrolysis oil production plant will follow the same rules set up for large CHP plants. A general description of the impact on the landscape, natural and cultural environment should be included. A detailed environmental impact analyses of noise, air pollution, traffic safety, smell and dust and a risk must be evaluated. Best available technologies should be used. Experience from similar establishment has shown that this procedure can take approx. 1 year.

In ***Finland***, in principle, needed actions to get environmental permit are like in Sweden, however for “greenfield” plant the full procedure might be needed, i.e., first Environmental Impact Assessment (acronym in Finnish YVA) followed by actual Environmental Permitting. Environmental Impact Assessment includes among other number of discussions with authorities (AVI) and public hearing with the local community. Placement of new PO plant in the existing industrial area would help to get accepted by local community and shorten the time for assessment. Taking in account public hearing the Environmental Impact Assessment for new plant might take up to 1 year.

With completion of Environmental Impact Assessment, the sufficient data and analysis should be available to fill up Environmental Permit Application and send it to authorities (AVI). The maximum application handling time in AVI for making decision is 10 months. After that Environmental Permit can be granted.

The Environmental Permitting process can be done once for the same site with several future units to be implemented in consecutive years. This will significantly reduce the time for construction in series PO units on the same site.

Possible synergies

Locating PO production units right next to a sawmill presents many possible synergies where the cost of sawdust acquisition is the most obvious one. Use of heat produced by the pyrolysis plant can be used by the sawmill e.g., for drying of wood. Cost for material handling (storing and feeding material in the reactor) is often underestimated. Sharing of these costs and cost for personnel with costs for sawmill operations can considerably cut operating costs for PO production. Additionally, maintenance service can be shared with sawmill, which significantly reducing the overhead costs.

2.6 Inland logistics and harbour logistics

In this chapter the transport issues regarding the movement of pyrolysis oil from the production plant to the harbour, Harbour storage and loading/unloading costs are discussed.

2.6.1 Sweden

In the table below the costs for storage of pyrolysis oil at the Swedish port of Skelleftehamn are shown

Table 7: Transportations costs to the harbour, tank rental, loading and unloading costs.

Harbour	Wibax Logistics, Skelleftehamn
Cistern	New cistern
Volume	5 000 m^3
Product	Pyrolysis oil
Max storing capacity	4 750 m^3
Material surface	Acid proof stainless steel, Duplex
Insolation	Yes, 100 mm on casing, 200 mm on roof
Heating of product	Yes
Loading/Pumping in	Possible from truck or vessel.

Unloading/Pumping out	Possible to vessel.
Vessel restrictions; Max Length × Width and Depth.	180 × 35 × 9,3 m
Estimated turnover	25 000 m^3/year
Rent (€/liquid metric tonne)	Approx. 34 €/lmt first 5 years, after that 16 €/lmt
Equipment	Heating to keep product at 10-20 °C Stirring of Product.
Other costs	Harbour fees for loading of vessel Cost for heating (actual cost +15%) Cost for stirring of product

Transport costs of pyrolysis oil from production plant to harbour in Sweden are shown below.

Table 8: Distance and transportation cost for pyrolysis oil from sawmills to harbour (Skellefteåhamn).

Sawmill	Distance incl. return (km)	Transport cost (€/ton)
Stenvalls trä, Sikfors	240	13.3
Martinsson/Holmen, Bygdsiljum	140	9.6
Norra Skog, Sävar	220	12.4
Norra Skog, Kåge	60	7.0

2.6.2 Finland

Terminal operation in harbour Kokkola is handled by Wibax Tank Oy, a member of Wibax Group, and the technical data for Wibax operation in Skelleftehamn can be applied to Kokkola site too (Deepwater port, draft: 9,5 m as in Skelleftehamn). However, the cost for intermediate storage in Kokkola terminal could be lower than in Sweden within 10 €/lmt (liquid metric tonne) range. Transport cost of pyrolysis oil are shown below

Table 9: Distance and transportation cost for pyrolysis oil from Plant to harbour (Kokkola).

Pyoil Plant	Distance incl. return (km)	Transport cost (€/ton)
GFNL, Lieksa, track	803	60.0
GFNL, Lieksa, rail (min cargo 1000 lmt)		20.0
GFN, Iisalmi, track	500	30.0
GFNL, Iisalmi, rail (min cargo 1000 lmt)		10.0

Due to rather distant location of PO plants from chosen harbour terminal in case study for Finland the rail transportation might be more economical sound. It has to be taking in account that railroad infrastructure is already available next to both PO plant sites.

2.7 International logistics

In the advanced case study, three Pyrolysis plants (two in Finland and one in Sweden) will produce Pyrolysis Oil. This leads to a yearly production of 48 kt Pyrolysis Oil in Finland and 24 kt in Sweden. All the produced product, 72 kt per year, will be sent to and used in Rotterdam based Pyrolysis Oil upgrading plant.

Below all information researched and collected is presented to get an impression of the potential storage and shipment costs of the Pyrolysis Oil. These costs are all obtained from quotes at market parties in Q4 of 2020.

2.7.1 Shipping route & ports

The production facilities can only store 240 mt of product, therefore the Pyrolysis Oil needs storage in the Scandinavian ports. The oil will be transported with trucks from the production facilities to the port storage facilities. From the Scandinavia ports, the oil will be shipped in liquid bulk to the Port of Rotterdam. Once the oil arrives in Rotterdam, it will be stored in a tank and once needed, loaded into a tank truck.

Figure 15: The sailing route including the location of the three ports.

2.7.1.1 Port of Rotterdam

The Port of Rotterdam is the largest seaport in Europa and is well known for its petrochemical industry and general cargo transhipment handlings. This port is perfectly fitted for the Pyrolysis Oil upgrading plant as it has a hydrogen grit, oil storage facilities and potential off takers of the end product. Lastly, the Port of Rotterdam wants to be CO_2 neutral in 2050 which could favour their support in this case study.

2.7.1.2 Port of Kokkala

The port of Kokkola is a cargo/bulk port located on the west side of Finland. This port was chosen as it is close to the Swedish port considered in this case study. Taken ports close by allows for an optimization of the shipment costs.

2.7.1.3 Port of Skellefteå

The Port of Skellefteå is a major player among the ports of the north of Sweden. The Port has storage facilities, can be reached by all transport modes and already loads and unloads up to 2 million tons of products each year.

2.7.2 Storage

When Pyrolysis Oil is stored under the right conditions it can be stored for at least one year without any problems. In this case study, the lead time of the stored products is much lower than one year. The is due to the fact that there will be a continuous production (Scandinavian Pyrolysis plants) and consumption (Rotterdam upgrading plant) of Pyrolysis Oil.

2.7.2.1 Heating and cooling during storage

Depending on weather circumstances some heating might be required. The product needs to be stored between -5 °C and + 25 °C. In Figure 16 below, it can be seen that based on the average temperature heating is required for the Finish and Swedish storage facilities during the months: January, February, March and December. Typical costs for the heating of stored liquids are 0,16 € * m^{-3} * $°C^{-1}$. The tanks that will be used are isolated which means that the temperature of the pyrolysis oil will not fluctuate much during incidental hot days or cold nights.

All costs in the storage section are obtained from a European terminal company. As the terminal market is an international market the prices across Europe do not differ much from each other.

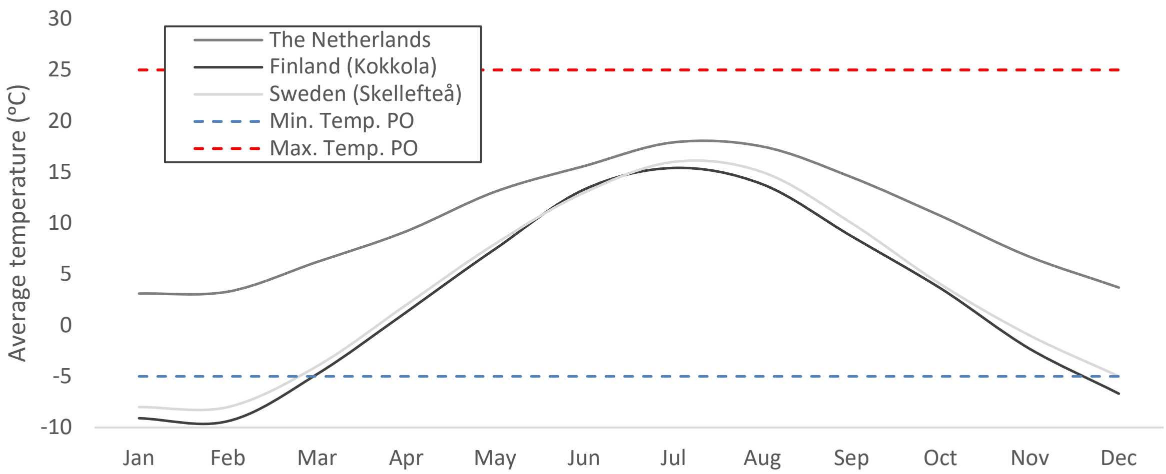

Figure 16: The average temperatures of the relevant storage locations.

2.7.2.2 Circulation during storage

According to BTG-BTL, circulation might also be needed during the storage of Pyrolysis Oil. At the Empyro Pyrolysis plant, the storage tank has a circulation pump that keeps the oil in motion to prevent possible phase separation when storing over a longer period of time. As the lead time in this case study will be approximately one month this circulation might not be needed. Standard tank terminals have the possibility to pump around the oil. The typical pumping costs are 1,25 € * m^{-3}.

2.7.2.3 The material of the storage tank

Due to the low pH of Pyrolysis Oil, a special coated tank or stainless-steel tank is needed. Those tanks are already used in the chemical industry. In this case study, it is assumed that duplex (comparable with stainless steel) will be used.

2.7.2.4 Loading and unloading of the product

For port storage facilities it is often easier to load and unload the product by barge than by truck. Therefore, one full load and unload is included in the monthly rent of the tank. When loading or unloading more than the total capacity of the tank per month an extra 1,50 € * m^{-3} will be charged.

When loading or unloading the product by truck additional costs are charged. In Scandinavia, the storage tanks will be loaded with trucks and in Rotterdam, they will be unloaded by trucks. Typical loading and unloading cost by truck are 6,00 € * m^{-3}.

2.7.2.5 Cleaning cost of a tank

When a tank is dedicated to the storage of pyrolysis oil no cleaning is required. However, when stopping the use of a tank cleaning is required. Typical cleaning costs for a tank with a storage capacity of 2.280 m^3 is 6.000 €.

2.7.3 Shipment

Shipment of a blackish product is not preferred by the active shipment companies in the Scandinavian region. A potential spill can become a disaster for the local environment. This is also the reason that the Arctic HFO ban was initiated.

2.7.3.1 ISO container shipment

Bulk shipment will be much cheaper as the volume is too large for individual ISO containers.

2.7.3.2 Bulk shipment

We've found one company willing to discuss potential costs and presented them in the figure below. It can be seen that the cost decline quite much when increasing the shipment size. Therefore, the economically most attractive route is to pick up 2kt in Skellefteå and 4kt in Kokkala and ship them together to Rotterdam.

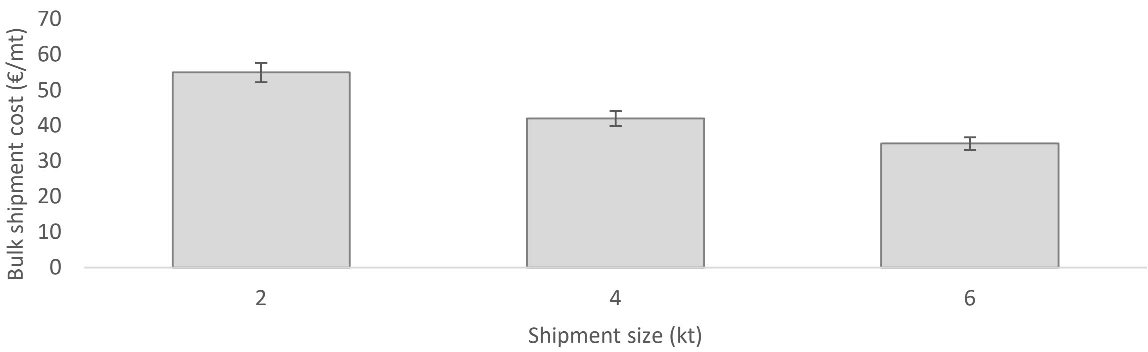

Figure 17: The bulk shipment cost per volume of the shipment. The average uncertainty of the costs is +/- 5%. Cost obtained from local chemical shipment companies.

Carriage of chemicals in bulk is covered by regulations in SOLAS Chapter VII - Carriage of dangerous goods and MARPOL Annex II - Regulations for the Control of Pollution by Noxious Liquid Substances in Bulk. Both Conventions require chemical tankers built after 1 July 1986 to comply with the International Code for the Construction and Equipment of Ships carrying Dangerous Chemicals in Bulk (IBC Code). It is at this moment uncertain whether Pyrolysis oil needs to comply with this regulation. Therefore, BTG-BTL has started a procedure at the IMO to assess this. It is expected that the first results will come in mid-2021.

2.7.3.3 Cleaning costs

The laytime of this route is only 48h. Therefore, it does not make sense to charter the vessel continuously. This means that the tanks used for the PO need to be cleaned after each shipment. The tanks will be cleaned using steam cleaning with a cleaning additive. This is a common practice in this industry. It is estimated that the cleaning costs will be around 30.000 € per time.

2.7.4 Total costs

The total monthly cost for the shipment is around 370.000 €. This means that the international shipping cost per mt of Pyrolysis Oil is 61-62 € / mt depended on the heating requirement during storage. As Pyrolysis Oil is not a commodity it cannot make use of the petroleum infrastructure. Therefore, these costs are in line with the expectations.

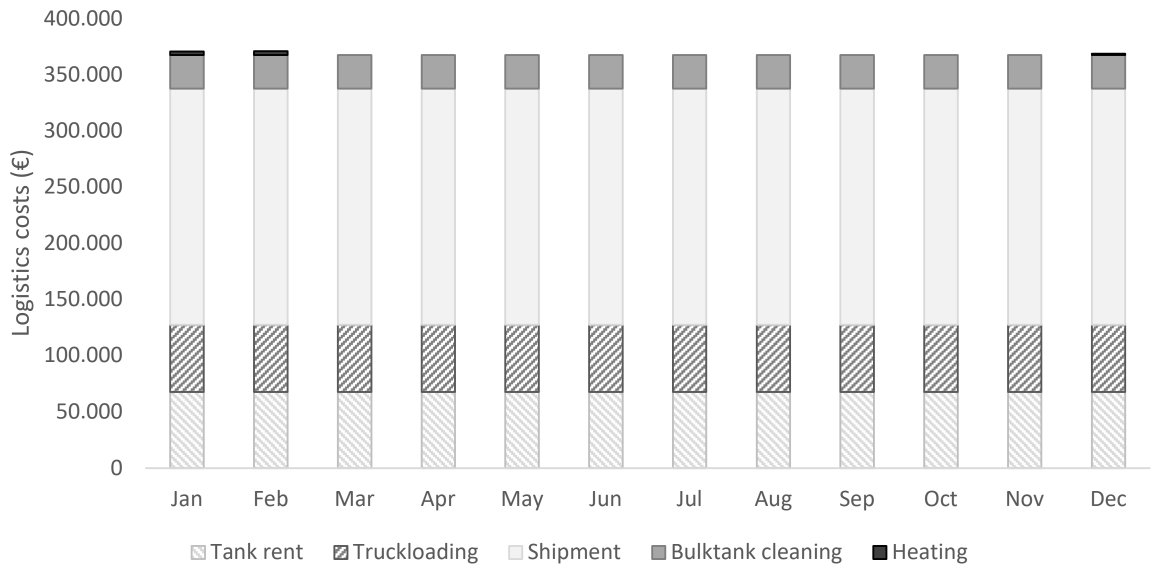

Figure 18: Breakdown of total costs of international transport of pyrolysis oil from Sweden/Finland to the Netherlands

2.8 upgrading

2.8.1 Technology description

As mentioned in paragraph 2.2.1, the technology to produce transport fuels from pyrolysis oil is not yet fully commercial. The technology, developed by BTG, currently in pilot plant stage. This means that it is necessary to rely on projections to determine the characteristics for an upgrading plant. As source for this a publication of the Dutch PBL institute is taken [6]. In 2020 they have publicised main characteristics of this technology, with as goal to determine the subsidy that this technology would need to be competitive in the Dutch market.

The upgrading plant is to be located in or near the harbour of Rotterdam. Pyrolysis oil is transported from Finland and Sweden, and stored near the upgrading plant. There the pyrolysis oil is converted to transport fuels. The process is shown in Figure 19.

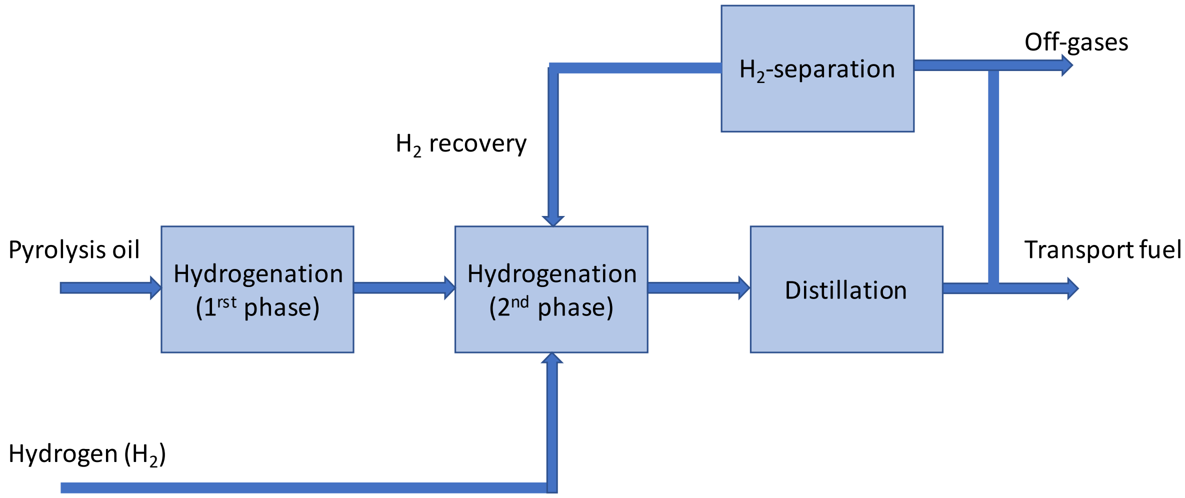

Figure 19: Schematic outline of the pyrolysis oil upgrading process.

In this figure we see the pyrolysis oil being upgraded in a two-step process. This upgrading is carried out at elevated pressure and involves (mainly) the removal of oxygen by hydrogenation, which implies a (catalytic) reaction with hydrogen. After the two-step hydrogenation, a gas which consists of light hydrocarbons, CO_2, a watery phase, and the deoxygenated pyrolysis oil is formed. In the distillation column, the transportation fuels are separated. The off-gases are being treated in a separation unit, where the remaining hydrogen gases are being separated off. The off-gases are subsequently vented. Off-gas cleaning and particulate removal is not shown, but it will obviously be required.

In the PBL report [6], integrated hydrogen production is foreseen. This Hydrogen production would take place via SMC (Steam Methane Reforming). It is however considered that for a plant of this size, on-site hydrogen production is not economical. In the current configuration, hydrogen will be purchased. Options for purchasing hydrogen are 'grey' hydrogen, which means hydrogen produced from fossil gas, 'blue' hydrogen, which is fossil hydrogen production combined with Carbon Capture, and 'green' hydrogen, which is renewable hydrogen, produced via electrolysis or from biogas.

2.8.2 Input and output characteristics

The main characteristics of the upgrading plant are given in Table 10. The input capacity of the plant is roughly twice as high as the plant capacity mentioned in the PBL report. This capacity has been increased to be in line with the scale of the value chain considered in this report.

Table 10: Main characteristics upgrading plant.

Parameter	Value	Unit
Operational hours	7,500	hours/year
Pyrolysis oil input	72,000	tonne/year
Transport fuel output	27,742	tonne/year
Average energy density	43.7	MJ/kg
Hydrogen input	3.6	kton/year

From this table it is clear that the amount of transport fuels in tonnes is lower that the pyrolysis oil input. Main reason for that is the far higher energy content of the transport fuels compared to the pyrolysis oil.

2.9 Greenhouse gas emissions

2.9.1 Environmental assessment according to RED II

According to the Renewable Energy Directive 2018/2001/EC the greenhouse gas emission savings from the use of biofuels, bioliquids and biomass fuels shall be (Article 29, paragraph 10):

a) at least 50 % for biofuels, biogas consumed in the transport sector, and bioliquids produced in installations in operation on or before 5 October 2015;
b) at least 60 % for biofuels, biogas consumed in the transport sector, and bioliquids produced in installations starting operation from 6 October 2015 until 31 December 2020;
c) at least 65 % for biofuels, biogas consumed in the transport sector, and bioliquids produced in installations starting operation from 1 January 2021;
d) at least 70 % for electricity, heating and cooling production from biomass fuels used in installations starting operation from 1 January 2021 until 31 December 2025, and 80 % for installations starting operation from 1 January 2026.

The total GHG emissions and the GHG emissions saving arising from the of IBCs are to be calculated in accordance with the methodologies and principles described in the EU RED II, and include the GHG emissions from the production and use as well as the extension necessary for including the energy conversion to electricity and/or heat and cooling produced. Special points for the calculation of GHG emissions are:

- Wastes and residues, including tree tops and branches, straw, husks, cobs and nut shells, and residues from processing, shall be considered to have zero life-cycle GHG emissions up to the process of collection.
- Emissions from the manufacture of machinery, equipment and infrastructure shall not be taken into account.
- Must include emissions from drying of raw materials, waste and leakages.

- Must include emissions from the processing itself, from waste and leakages and from the production of chemicals or products used in processing including the CO_2 emissions corresponding to the carbon contents of fossil inputs, whether or not actually combusted in the process.
- Include only non-CO_2 GHG (N_2O and CH_4) emissions for the use phase.
- In case of allocation during co-production:
    - Carnot efficiency for electricity and heat.
    - Energy content (lower heating value) in all other cases.

The GHG emission savings of the IBC value chains shall be calculated against specific fossil fuel comparators:

- 94 g CO_2 eq/MJ for transport fuels.
- 183 g CO_2 eq/MJ electricity or 212 g CO_2eq/MJ electricity for the outermost regions.
- 80 g CO_2 eq/MJ heat or 124 g CO_2 eq/MJ heat for direct physical substitution of coal.

2.9.2 Advanced case study description

The advanced case study will focus on the production of pyrolysis oil (PO) in one plant in Sweden and two in Finland, followed by sea transport to the Netherlands, where it will be upgraded to a drop-in advanced marine biofuel. The main focus is on the minimum capacity that is required to operate the upgrading plant economically. This capacity is foreseen to be equivalent to the output of three pyrolysis plants of the size implemented in Hengelo. This leads to a yearly production of 48 kt Pyrolysis Oil in Finland and 24 kt in Sweden. All the produced product, 72 kt per year, will be sent to and used in Rotterdam based Pyrolysis Oil upgrading plant. The oil will be transported with trucks from the production facilities to the port storage facilities. From the Scandinavia ports, the oil will be shipped in liquid bulk to the Port of Rotterdam (Figure 1).

Figure 20. The sailing route including the location of the three ports.

2.9.3 Environmental assessment of the potential value chain

For the **advanced case study**, a value chain concerning the production of PO and the subsequent upgrade to advanced marine biofuel will be researched. The pyrolysis plants implemented so far are using wood as feedstock. Wood has the advantage of a relatively low ash content, and relative ease of handling and sizing. Also, wood residues can become available at low moisture content, and already sized, for example as sawmill residues. Therefore, the feedstock to be considered for the pyrolysis units is sawdust. Table 11 provides the properties, the quantities and distance for the transport of the selected biomass feedstock. Note that in the Swedish case there are four different options for sawdust acquisition.

Table 11. Properties of sawdust and distance for transport

Country	**Sweden**				**Finland**	
Feedstock	Sawdust					
Moisture content (%)	55%					
Calorific value (dry basis)	17,8 MJ/kg					
Locations	Option A	Option B	Option C	Option D	Lieksa	Lisalmi

Quantity	81.054	81.054	81.054	81.054	81.054	81.054
Distance (tkm)	2.093.208	2.166.193	2.847.875	2.050.395	7.294.860	7.294.860

The GHG emission are calculated with the use of the SimaPro v9.1. software under the impact assessment method Greenhouse Gas Protocol adjusted to fit the methodology and principles of the RED II. From the data on Table 11 and considering that the sawdust will be transported via trucks we calculated the GHG emissions for the transport of biomass to the pyrolysis plants (Table 12).

Table 12. GHG emissions from the transport of sawdust.

GHG emissions (kg CO2eq)						
	Sweden				Finland	
Location	Option A	Option B	Option C	Option D	Lieksa	Lisalmi
Transport	151.000	157.000	206.000	148.000	528.000	528.000

The difference on GHG emissions per MJ of finished product between the four options is relatively negligible, so the decisive factor would only be the economics.

After the transportation stage, sawdust reaches the three pyrolysis plants for the conversion to PO. Table 13 provides the quantity of sawdust and PO of each pyrolysis plant.

Table 13. Quantity of feedstock and product of each pyrolysis plant.

Parameter	Value	Unit
Sawdust wet input	81.054	tonne sawdust wet/year
Sawdust dry input	36.474	tonne sawdust dry/year
PO output	24.000	tonne/year

Main requirements for the fast pyrolysis process are that the sawdust is relatively dry (less than 10% moisture content). For this reason, we considered a pre-treatment drying step prior to the conversion to PO. For the drying and the pyrolysis process an assumption have been made that the process heat is provided from the combustion of the char and gas generated from the pyrolysis process itself. From the relevant literature review and the databases of the SimaPro software, are required 0,18 GJ per tonne of evaporated water for the drying process and 2,8 GJ per ton of feedstock for the pyrolysis process. The source for the process heat is of biogenic nature (sawdust) therefore, according to the RED II, only non-CO_2 GHG (N_2O and CH_4) emissions are accounted.

The GHG emissions from the drying and conversion stages are provided in Table 14.

Table 14. Emissions from the processing of sawdust.

GHG emissions (kg CO2eq)	
Drying	45.935
Conversion	343.630

After the conversion the PO leaves the pyrolysis plants and transported to the ports of Skellefteå (Sweden) and Kokkala (Finland) in order to be stored and then shipped to Rotterdam. The emissions from the above mention stages are presented in Table 15.

Table 15. Emissions from the stages of transport, storage and shipment.

GHG emissions (kg CO2eq)						
	Sweden				Finland	
Locations	Option A	Option B	Option C	Option D	Lieksa	Lisalmi
Storage of PO	475				2.160	2.160
PO transport to port	143.000				720.000	434.000
PO shipment to Rotterdam	1.910.000					

The difference in emissions for the storage of PO is based on the differences in the electricity production mix of Sweden and Finland. Then, after the PO arrives at the port of Rotterdam, it is transported to the upgrade facility in order to be converted in an advanced marine biofuel by removing part of its oxygen and replacing it with hydrogen (hydrodeoxygenation). The overall hydrogen consumption is about 0.05 kg hydrogen per kg pyrolysis oil. This is manageable, but these quantities mean that it is advantageous to find 'green' sources of hydrogen, so that the overall CO_2 footprint of the process is as low as possible. Two primary methods are used to produce hydrogen: steam methane reforming (SMR) of natural gas and electrolysis of water. Steam methane reforming, with natural gas as feedstock, is the most mature production pathway and widely used process for the generation of hydrogen in large central plants. Electrolysis of water is an alternative process which can be used to produce high-quality hydrogen (≈100% hydrogen) through electrochemical conversion of water to hydrogen and oxygen. Currently, main types of industrial electrolysis systems generating hydrogen are low temperature (70–90 ^oC) including alkaline electrolyzers and proton exchange membrane (PEM) and high temperature (650–850 ^oC) electrolysis based on solid oxide electrolysis cells (SOEC). Electrolyzers can be integrated with renewable sources (RES) of electricity (solar and wind power) to provide a sustainable solution for the production of hydrogen [7].

The hydrogen production technologies that are examined are:

- PEM electrolysis (electricity from the grid)
- PEM electrolysis (electricity from RES)
- SOEC electrolysis (electricity from the grid)
- SOEC electrolysis (electricity from RES)

- Natural gas reforming (SMR) with Carbon Capture (electricity from the grid)
- Natural gas reforming (SMR) with Carbon Capture (electricity from RES)
- Natural gas reforming (SMR) without Carbon Capture (electricity from the grid)
- Natural gas reforming (SMR) without Carbon Capture (electricity from RES)

The GHG emissions of the hydrogen production technologies are presented in Table 16.

Table 16. GHG emissions of the hydrogen production technologies

	Kg CO_2 / kg H_2	g CO_2/ MJ H_2	Feedstock	Electricity from
PEM electrolysis	33,4	278,33	Electricity	Grid (Dutch)
PEM electrolysis	1,4	11,66	Electricity	RES (solar and wind)
Solid oxide electrolysis	24,9	207,50	Electricity	Grid (Dutch)
Solid oxide electrolysis	3,75	31,25	Electricity	RES (solar and wind)
Natural Gas Reforming	10,4	86,66	Natural Gas	Grid (Dutch)
Natural Gas Reforming	9,23	76,91	Natural Gas	RES (solar and wind)
Natural Gas Reforming + CO_2 capture	2,85	23,75	Natural Gas	Grid (Dutch)
Natural Gas Reforming + CO_2 capture	2,53	21,08	Natural Gas	RES (solar and wind)

The analysis revealed that the GHG emissions of the electrolysis technologies are highly dependent on the electricity source. On the other hand, natural gas reforming offers quite stable results and coupled with carbon capture can provide an efficient, economical, and environmental method with respect to commercially available production methods.

The results of the environmental assessment of the overall marine biofuel production pathway for the Nordic Advanced Case Study are presented in the Table 17, Table 18, Table 19, and Table 20. Each table presents a different option of hydrogen production.

Table 17. GHG emissions of the PEM-electrolysis upgrade pathway

PEM - Electrolysis / Electricity from the Dutch grid						
	Sweden				Finland	
	Case A	Case B	Case C	Case D	Lieksa	Lisalmi
Transport of sawdust to PO plants (g/MJ fuel)	0,374	0,389	0,510	0,366	1,307	1,307
PO production (g/MJ fuel)	0,321	0,321	0,321	0,321	0,321	0,321
- drying	0,038	0,038	0,038	0,038	0,038	0,038
- conversion	0,283	0,283	0,283	0,283	0,283	0,283
Storage (g/MJ fuel)	0,001	0,001	0,001	0,001	0,005	0,005
PO transport to port (g/MJ fuel)	0,354	0,354	0,354	0,354	1,782	1,074
Shipment to Rotterdam (g/MJ fuel)	1,575	1,575	1,575	1,575	1,575	1,575
Upgrading (g/MJ fuel)	99,181	99,181	99,181	99,181	99,181	99,181
Total CO2-eq. emission (g/MJ fuel)	101,807	101,822	101,943	101,799	104,172	103,464

Fossil fuel comparator (g/MJ fuel)	94	94	94	94	94	94
GHG emission savings (%)	**-8,31%**	**-8,32%**	**-8,45%**	**-8,30%**	**-10,82%**	**-10,07%**
PEM - Electrolysis / Electricity from renewables						
	Case A	**Case B**	**Case C**	**Case D**	**Lieksa**	**Lisalmi**
Transport of sawdust to PO plants (g/MJ fuel)	0,374	0,389	0,510	0,366	1,307	1,307
PO production (g/MJ fuel)	0,321	0,321	0,321	0,321	0,321	0,321
- drying	0,038	0,038	0,038	0,038	0,038	0,038
- conversion	0,283	0,283	0,283	0,283	0,283	0,283
Storage (g/MJ fuel)	0,001	0,001	0,001	0,001	0,005	0,005
PO transport to port (g/MJ fuel)	0,354	0,354	0,354	0,354	1,782	1,074
Shipment to Rotterdam (g/MJ fuel)	1,575	1,575	1,575	1,575	1,575	1,575
Upgrading (g/MJ fuel)	4,157	4,157	4,157	4,157	4,157	4,157
Total CO2-eq. emission (g/MJ fuel)	6,783	6,798	6,919	6,775	9,148	8,440
Fossil fuel comparator (g/MJ fuel)	94	94	94	94	94	94
GHG emission savings (%)	**92,78%**	**92,77%**	**92,64%**	**92,79%**	**90,27%**	**91,02%**

No GHG emission savings for the biofuel pathway with PEM electrolysis with electricity from the Dutch grid and extremely good performance when coupled with RES. The biofuel upgrade stage accounts 97% - 62% of the total GHG emissions, depending on the electricity source. The overall increase of the GHG emission due to the use of grid electricity as opposed to RES is 1.422%.

Table 18. GHG emissions of the solid oxide upgrade pathway

Solid Oxide - Electrolysis / Electricity from the Dutch grid						
	Sweden				**Finland**	
	Case A	**Case B**	**Case C**	**Case D**	**Lieksa**	**Lisalmi**
Transport of sawdust to PO plants (g/MJ fuel)	0,374	0,389	0,510	0,366	1,307	1,307
PO production (g/MJ fuel)	0,321	0,321	0,321	0,321	0,321	0,321
- drying	0,038	0,038	0,038	0,038	0,038	0,038
- conversion	0,283	0,283	0,283	0,283	0,283	0,283
Storage (g/MJ fuel)	0,001	0,001	0,001	0,001	0,005	0,005
PO transport to port (g/MJ fuel)	0,354	0,354	0,354	0,354	1,782	1,074
Shipment to Rotterdam (g/MJ fuel)	1,575	1,575	1,575	1,575	1,575	1,575
Upgrading (g/MJ fuel)	73,941	73,941	73,941	73,941	73,941	73,941
Total CO2-eq. emission (g/MJ fuel)	76,566	76,581	76,702	76,559	78,931	78,223
Fossil fuel comparator (g/MJ fuel)	94	94	94	94	94	94
GHG emission savings (%)	**18,55%**	**18,53%**	**18,40%**	**18,55%**	**16,03%**	**16,78%**
Solid Oxide - Electrolysis / Electricity from renewables						
	Case A	Case B	Case C	Case D	Lieksa	Lisalmi
Transport of sawdust to PO plants (g/MJ fuel)	0,374	0,389	0,510	0,366	1,307	1,307
PO production (g/MJ fuel)	0,321	0,321	0,321	0,321	0,321	0,321
- drying	0,038	0,038	0,038	0,038	0,038	0,038
- conversion	0,283	0,283	0,283	0,283	0,283	0,283

Storage (g/MJ fuel)	0,001	0,001	0,001	0,001	0,005	0,005
PO transport to port (g/MJ fuel)	0,354	0,354	0,354	0,354	1,782	1,074
Shipment to Rotterdam (g/MJ fuel)	1,575	1,575	1,575	1,575	1,575	1,575
Upgrading (g/MJ fuel)	11,136	11,136	11,136	11,136	11,136	11,136
Total CO2-eq. emission (g/MJ fuel)	13,761	13,776	13,897	13,754	16,126	15,418
Fossil fuel comparator (g/MJ fuel)	94	94	94	94	94	94
GHG emission savings (%)	**85,36%**	**85,34%**	**85,22%**	**85,37%**	**82,84%**	**83,60%**

Below the 65% GHG emission savings target of the RED II for the biofuel pathway with SOEC electrolysis (electricity from the Dutch grid) and very good performance when coupled with RES (above the target). The share of GHG emissions is 96% for the SOEC electrolysis with electricity from the grid and 78% for electricity from RES. SOEC allows a greater portion of the energy required to be provided in the form of heat rather than electricity which allows obtaining lower overall GHG emissions than PEM electrolysis. The overall increase of the GHG emission due to the use of grid electricity as opposed to RES is 455%.

Table 19. GHG emissions of the natural gas reforming (with carbon capture) pathway

Natural gas reforming with carbon capture / Electricity from the Dutch grid						
	Sweden				**Finland**	
	Case A	**Case B**	**Case C**	**Case D**	**Lieksa**	**Lisalmi**
Transport of sawdust to PO plants (g/MJ fuel)	0,374	0,389	0,510	0,366	1,307	1,307
PO production (g/MJ fuel)	0,321	0,321	0,321	0,321	0,321	0,321
- drying	0,038	0,038	0,038	0,038	0,038	0,038
- conversion	0,283	0,283	0,283	0,283	0,283	0,283
Storage (g/MJ fuel)	0,001	0,001	0,001	0,001	0,005	0,005
PO transport to port (g/MJ fuel)	0,354	0,354	0,354	0,354	1,782	1,074
Shipment to Rotterdam (g/MJ fuel)	1,575	1,575	1,575	1,575	1,575	1,575
Upgrading (g/MJ fuel)	8,463	8,463	8,463	8,463	8,463	8,463
Total CO2-eq. emission (g/MJ fuel)	11,089	11,103	11,225	11,081	13,454	12,746
Fossil fuel comparator (g/MJ fuel)	94	94	94	94	94	94
GHG emission savings (%)	**88,20%**	**88,19%**	**88,06%**	**88,21%**	**85,69%**	**86,44%**
Natural gas reforming with carbon capture / Electricity from renewables						
	Case A	**Case B**	**Case C**	**Case D**	**Lieksa**	**Lisalmi**
Transport of sawdust to PO plants (g/MJ fuel)	0,374	0,389	0,510	0,366	1,307	1,307
PO production (g/MJ fuel)	0,321	0,321	0,321	0,321	0,321	0,321
- drying	0,038	0,038	0,038	0,038	0,038	0,038
- conversion	0,283	0,283	0,283	0,283	0,283	0,283
Storage (g/MJ fuel)	0,001	0,001	0,001	0,001	0,005	0,005
PO transport to port (g/MJ fuel)	0,354	0,354	0,354	0,354	1,782	1,074
Shipment to Rotterdam (g/MJ fuel)	1,575	1,575	1,575	1,575	1,575	1,575
Upgrading (g/MJ fuel)	7,513	7,513	7,513	7,513	7,513	7,513

Total CO2-eq. emission (g/MJ fuel)	10,138	10,153	10,274	10,131	12,503	11,796
Fossil fuel comparator (g/MJ fuel)	94	94	94	94	94	94
GHG emission savings (%)	**89,21%**	**89,20%**	**89,07%**	**89,22%**	**86,70%**	**87,45%**

Although SMR with natural gas as feedstock is a slightly less efficient process, has better environmental performance than the electrolysis (electricity from grid) due to the lower GHG emissions released from processing the natural gas as opposed to generating electricity.
The SMR offers promising results of the GHG emission savings when integrated with carbon capture. The electricity source plays a smaller part (8,8% increase for grid electricity) on the overall GHG emissions than the electrolysis processes and the environmental impacts are mainly determined by the raw material (natural gas) used in the production process.

Table 20. GHG emissions of the natural gas reforming (without carbon capture) pathway

Natural gas reforming / Electricity from the Dutch grid						
	Sweden				**Finland**	
	Case A	**Case B**	**Case C**	**Case D**	**Lieksa**	**Lisalmi**
Transport of sawdust to PO plants (g/MJ fuel)	0,374	0,389	0,510	0,366	1,307	1,307
PO production (g/MJ fuel)	0,321	0,321	0,321	0,321	0,321	0,321
- drying	0,038	0,038	0,038	0,038	0,038	0,038
- conversion	0,283	0,283	0,283	0,283	0,283	0,283
Storage (g/MJ fuel)	0,001	0,001	0,001	0,001	0,005	0,005
PO transport to port (g/MJ fuel)	0,354	0,354	0,354	0,354	1,782	1,074
Shipment to Rotterdam (g/MJ fuel)	1,575	1,575	1,575	1,575	1,575	1,575
Upgrading (g/MJ fuel)	30,767	30,767	30,767	30,767	30,767	30,767
Total CO2-eq. emission (g/MJ fuel)	33,393	33,408	33,529	33,385	35,758	35,050
Fossil fuel comparator (g/MJ fuel)	94	94	94	94	94	94
GHG emission savings (%)	64,48%	64,46%	64,33%	64,48%	61,96%	62,71%
Natural gas reforming / Electricity from renewables						
	Case A	**Case B**	**Case C**	**Case D**	**Lieksa**	**Lisalmi**
Transport of sawdust to PO plants (g/MJ fuel)	0,374	0,389	0,510	0,366	1,307	1,307
PO production (g/MJ fuel)	0,321	0,321	0,321	0,321	0,321	0,321
- drying	0,038	0,038	0,038	0,038	0,038	0,038
- conversion	0,283	0,283	0,283	0,283	0,283	0,283
Storage (g/MJ fuel)	0,001	0,001	0,001	0,001	0,005	0,005
PO transport to port (g/MJ fuel)	0,354	0,354	0,354	0,354	1,782	1,074
Shipment to Rotterdam (g/MJ fuel)	1,575	1,575	1,575	1,575	1,575	1,575
Upgrading (g/MJ fuel)	27,385	27,385	27,385	27,385	27,385	27,385
Total CO2-eq. emission (g/MJ fuel)	30,011	30,026	30,147	30,003	32,376	31,668
Fossil fuel comparator (g/MJ fuel)	94	94	94	94	94	94
GHG emission savings (%)	**68,07%**	**68,06%**	**67,93%**	**68,08%**	**65,56%**	**66,31%**

As opposed to SMR with carbon capture, the electricity source plays a bigger role (11,3% increase for grid electricity) for SMR without carbon capture on the overall GHG emissions of the

biofuel pathway. This result to slightly missing the target of the RED II for 65% GHG emission savings, when the electricity originates from the grid. The integration of RES can help achieve the 65% target but with a significant impact on the economic part of the biofuel pathway.
From the evaluation of the overall value-chain that supplies advanced marine biofuel to potential end-users we conclude that the effect of the different sawmill locations (in the Swedish case) on the overall environmental performance is negligible (**0,5% - 1,5%).** The most important part – accounts from **62%** to **97%** of total GHG emissions, depending on the technology – is the production of hydrogen. The electrolytic processes (PEM and SOEC) with grid electricity have the worst GHG emission savings performance, with the electricity identified as the major contributor. Irrespective of electrolyzer technology, electrolysis is an energy-intensive method of hydrogen production, where the environmental footprint is limited to the electricity supply chain [8].

From an environmental perspective the most advantageous technology is the PEM electrolysis coupled with solar and wind electricity generation. In general, electrolytic technologies are competitive and outperform SMR only if RES electricity is used. The use of electricity from the Dutch grid is considered unfavorable, except in the case of SMR with carbon capture.
It should be noted that, although, it is outside the scope of the present assessment both electrolysis and SMR tend to have high environmental impacts per kg of water used since they require high-quality water. Also, SMR (with and without carbon capture) scores high in the fossil fuel depletion indicator (9,33 mPoints/kg hydrogen, opposed to 0,686 mPoints kg hydrogen for PEM and 3,31 mPoints kg hydrogen for SOEC).

For reasons of clarity, the main results are summarised in the next table, whereby the averaged GHG emission reduction is given for the technologies and electricity generation combinations.

Table 21: Main results of the environmental assessment

	Electricity from	**GHG emission savings (%)**
PEM electrolysis	Grid (Dutch)	-9,05%
PEM electrolysis	RES (solar and wind)	92,05%
Solid oxide electrolysis	Grid (Dutch)	17,81%
Solid oxide electrolysis	RES (solar and wind)	84,62%
Natural Gas Reforming	Grid (Dutch)	63,74%
Natural Gas Reforming	RES (solar and wind)	67,34%
Natural Gas Reforming + CO_2 capture	Grid (Dutch)	87,47%
Natural Gas Reforming + CO_2 capture	RES (solar and wind)	88,48%

If we take as a given that the plant needs to have a GHG reduction percentage of 80% or more, which will be the rule for installations starting operation from 1 January 2026, the following technologies for hydrogen production are viable:

- Electrolysis using renewable energy sources (PEM and Solid oxide technologies)
- Natural gas reforming combined with CO2 capture.

2.10 Case study feasibility results

2.10.1 Profit and loss calculation

2.10.1.1 For pyrolysis oil plant producers

Methodology

The scope of the economic study has been limited to cover the construction of three identical pyrolysis oil plants with single bio-refinery process unit (BTG Bioliquids design) in Finland (Lieksa and Iisalmi sites), as well as one plant in Sweden (either of site: Sikfors, Bygdsiljum, Sävar, Kåge).

The operation data is verified with current practise of new GFNL plant in Lieksa. Also, the second scenario was evaluated with two bio-refinery process units in the same site (i.e., Lieksa site) for verifying the economic effect from expected synergy. For the model, the stand-alone plant is considered, i.e., own infra, biomass handling, maintenance service etc. Possible sharing of resources and/or services with nearby sawmills is not counted in the model.

Profitability calculation is based on discounted cash flow method. The key indicator is net present value (NPV), which is the discounted value of the cash flow of the project. Discounting factor is the estimated Weighted Average Cost of Capital. The WACC is estimated to be 7.2%. The reasoning of WACC determination is shown on Figure 20 below.

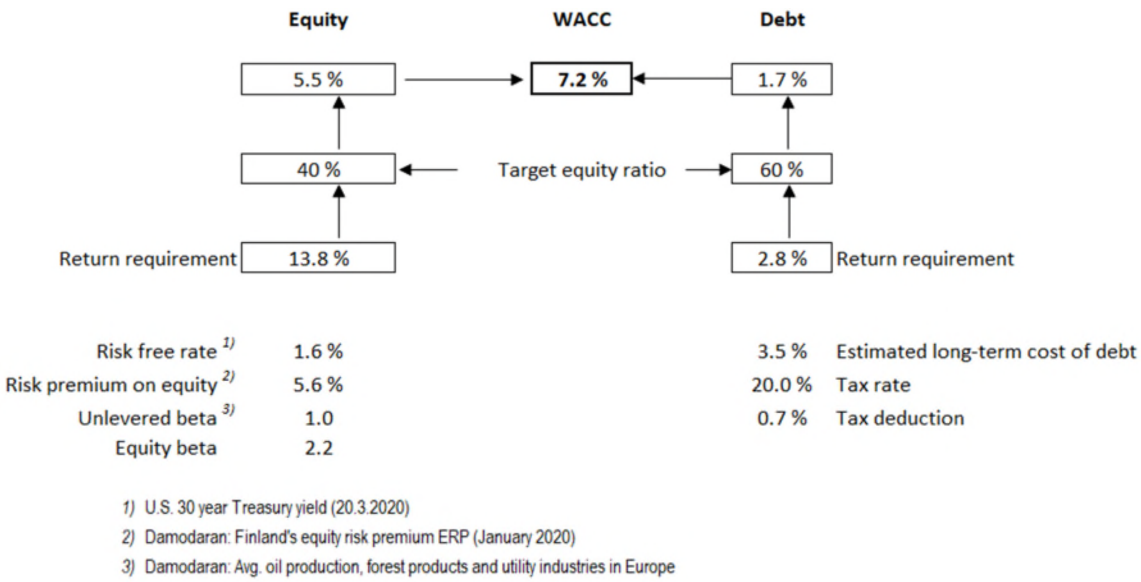

Figure 21: Project WACC estimation

The NPV value has been calculated from the Free Cash Flow. Free Cash Flow can be thought of as the after-tax cash flow that would be available to company shareholders if company had no debt. Free cash flow is before financing and not affected by the company's financial structure. The assumed financial structure and WACC affects to the result of calculation: NPV.

Calculations for the Finland plants

The profitability was calculated for two cases: Single unit plant (base scenario) and double units plant. Meanwhile, the internal rate of return (IRR) value for Free Cash Flow was used as the second indicator of profitability for suggested alternatives. Payback time was determined also from the discounted Cash Flow.

Cash flow calculation is done for three years of implementation of the construction project and following 15 operating years. With proper maintenance and upgrading investments for each unit after 15 years the economic lifespan of the plant can naturally be extended to 30 years.

Income tax rate of 20% is used to calculate taxes. Bank debt interest of 3,5% and debt maturity of 10 years are taken to calculation.

Depreciation has been considered as constant annual amounts with depreciation periods of:

- 30 years for civil construction
- 15 years for equipment

No tax depreciation has been assumed.

The investments are assumed to receive ERDF grants. The grants are paid directly to the equipment supplier and are shown as reduced book value of the investment.

Case study is built on the following project implementation schedule (Figure 22). For the double units plant the implementation is assumed as a consecutive construction of bio-oil process units, with some common infra built during the first phase of construction. The permitting process and engineering work has already been done for the first unit in Lieksa (as well as for Iisalmi site), which will significantly speed up the schedules of consecutive units. The content and suppliers of the main equipment are expected to remain the same as in Lieksa unit 1.

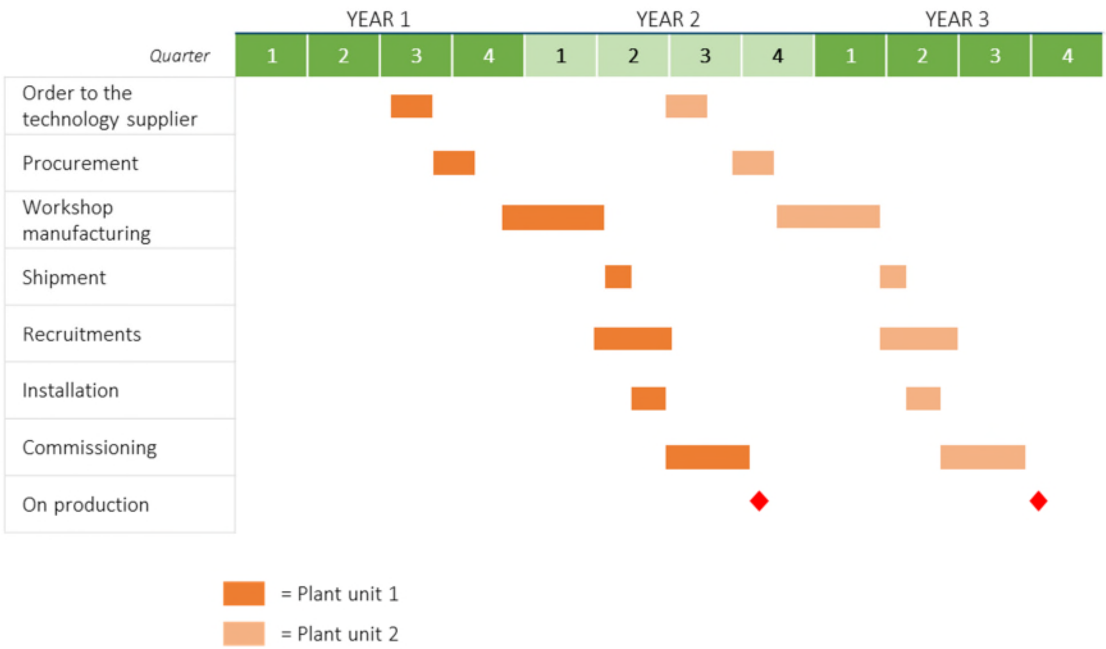

Figure 22: Construction time schedule

Market Prices and cost structure

The pyrolysis oil capacity and production assumptions are based on performance test runs by BTG's Empyro reference site with the Finnish and Swedish feedstock and the performance guarantees provided by TechnipFMC to GFNL Lieksa Plant 01.

The production of each biorefinery unit is estimated to be 24.090 tons (110 GWh) of pyrolysis oil per year based on proven sawdust throughput 3,3 bio-oil tons per hour and 7.300 operating hours per year.

The pyrolysis oil price will be set once a year and within the year the price will follow the monthly price changes of the sawdust price[3]. For modelling flat pyrolysis oil price of 77 €/MWh (21€/GJ or 353 €/ton PO) has been taken. The effect of pyrolysis oil price was evaluated with sensitivity analysis.

[3] *The monthly sawdust price (Finland) is taken from the PIX Forest Biomass Finland Index. The index is published by FOEX Indexes Ltd., which is part of the Euromoney Group and provides audited pulp, paper and wood-based biomass price indices.*

There is additional side stream, which contributes to plant income – a surplus steam sold to the industrial or household heating grids in form of hot water. The area has developed centralized heating grids both for households as well as for industrial consumers. Due to high rate of wood rejects/remains utilization in the region for heat generation, the initial purchase price of surplus steam of 15 EUR/MWh is at low possible level. However, it is foreseen that with introduction of pyrolysis oil plants in the region as an alternative and reliable source of heat, the existing heat generation from biomass would decline and price of surplus steam for bio-refinery rises.

The summary of input data for study is given in Table 22.

Table 22: Plant main data.

Description	Units	Single unit	Double units
Production efficiency			
Throughput	*ton PO/hour*	3.3	6.6
Availability	*%*	83 %	83 %
Hours	*hours*	7 300	7 300
Bio-oil			
Density	*kg/l*	1.17	
Heating value	*MJ/kg*	16.5	
Conversion	*kWh/MJ*	0.2778	
Energy content	*MWh/ton*	4.584	
Bio-oil production	*tonnes*	24 090	48 180
	MWh	110 421	220 843
	GJ	397 485	794 970
	m^3	20 590	41 179
Steam Production			
Surplus of steam produced	*GJ*	32 950	65 900
Sawdust			
Heating value @55% mc	*MWh/m^3*	0.6	
	MWh/t	1.93	
Conversion	*ton/m^3*	0.30	
Sawdust consumption			
	tonnes @3% mc	37 641	75 281
	MWh	156 864	313 728
	tonnes @55% mc	81 136	162 273
Yield			
Mass	*%*	64 %	
Energy	*%*	70 %	
Bio-oil price			
Price (FCA PO Plant)	*€/ton*	353	
	€/MWh	**77**	

	€/GJ	21	
Steam price			
Surplus of steam produced	*€/GJ*	4.2	
Sawdust price			
	€/ton @55%mc	32.9	
	€/MWh	***17.0***	
	€/ton @3%mc	70.8	
Electricity			
Price	*€/MWh*	**55**	
Volume	*MW/plant*	1.5	2.7

Figure 23 depicts the specific costs breakdown per ton of produced pyrolysis oil.

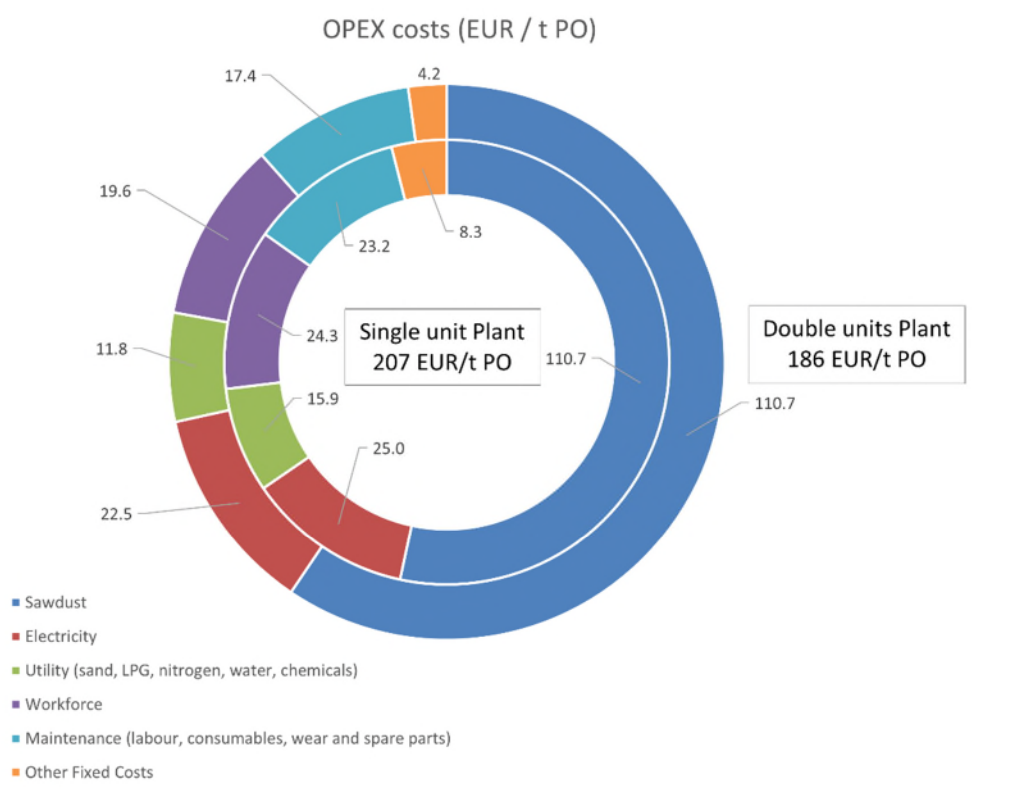

Figure 23: OPEX specific costs breakdown per ton of Pyrolysis Oil shown for Single unit and Double units plant in Finland

Sawdust purchases is the largest cost item and represent more than half of all operating costs. The given sawdust price is at bio-oil plant gate.

Electricity is another major production cost item. Each production plant in base scenario including ISBL and OSBL parts has a power demand of 1,5 MW. When the second unit is installed on the same site the synergy effect (common infra, sharing some functionality in fresh Biomass Handling) would lead to total 2.7 MW power demand. The power demand can be higher (additional 0.5 MW per unit) in case of chip milling equipment is added to the biomass handling.

Other utility items consist of a LPG storage station in leasing, liquid nitrogen storage system in leasing, sand used in the pyrolysis process and other miscellaneous materials. Water is used mainly for bio-oil cooling and as boiler feed water. There is no process effluent in normal operation. Taking LPG and nitrogen islands in leasing helps to decrease the needed CAPEX as well as provide reliable and safe supply of utilities. There are well established leasing services for LPG and liquid nitrogen in Finland and Sweden.

The production personnel for the first units in each location is assumed to be 13 persons and for the second units additional 8 persons including the CEO, CFO and technical R&D specialist.

Other Fixed costs consist of general administrative expenses, property costs, insurances etc.

For the double units plant there would be synergy of using common station of LPG, liquid nitrogen, site infra as well as maintenance, spare parts and wear houses. Therefore, the expected effects would result to lower specific costs of production.

For the sake of simplicity, the inflation was not taken in account while naturally different inflation rates for sawdust, PO prices and other costs can be observed. However, the major cost contributors - sawdust price and electricity price were taken with surplus 15% over current price level. The possible effects from these prices change are evaluated in sensitivity analysis.

Investment needed

The advantages of the fast pyrolysis bio-oil process units from BTG-Bioliquids are that they are modular, relatively quick to build and set up with minimum civil work and consequent units can easily be added according to demand.

BTG-Bioliquids is the main technology vendor. The content and suppliers of the main equipment are expected to remain the same as in Lieksa 01 (see Table 23). The investment value for the subsequent units is expected to be with discount to the first unit, as significant part of the pre-design and engineering work are not needed in the extension units.

Table 23: Project delivery battery limits

EPC Service supplier	Other Vendors
Bio refinery Central processing unit (CPU)	Biomass handling system
Biomass dryer	Site infra objects and equipment
Flue Gas cleaning package	Civil work
PO storage package	
Cooling Tower, Air-Glycol cooling, miscellaneous systems	
Engineering, Installation, Commissioning, and other work	

The financing for the first unit on site of the 27 MEUR investment consist of 7 MEUR equity injection, 7 MEUR ERDF grant and 13 MEUR debt facility from the local cooperative bank guaranteed by the Finnish government's special financing institution, Finnvera and European Investment Fund.

In Sweden, the possible grant volume for the single PO plant can be up to 12 MEUR. In Finland, the first PO unit on site can get 7 MEUR grant, while following PO units at the same site might get up to 3,5 MEUR. To keep conservative evaluation the grant volume for single unit plant was taken as of 7 MEUR, (both locations – Finland and Sweden), and the second unit for the same site adds 3,5 MEUR.

For the case with the second unit on site (double unit plant) the total investments are estimated as of 49.3 MEUR (see Table 24).

Table 24: Investments and funding sources Finland.

Description	Single unit	Double units
CAPEX		
Fast Pyrolysis Technology	*23.0 MEUR*	*43.7 MEUR*
Biomass handling system	*2.0 MEUR*	*3.4 MEUR*
Other CAPEX and engineering	*2.0 MEUR*	*2.6 MEUR*
TOTAL	*27.0 MEUR*	*49.2 MEUR*
Founding sources		
Equity	*7.0 MEUR*	*14.0 MEUR*
Debt	*13.0 MEUR*	*24.7 MEUR*
Grant	*7.0 MEUR*	*10.5 MEUR*

The targeted financial structure is to maintain over 40 % equity ratio throughout the construction period.

Profitability results

The operational cash flow of the company will turn positive on the 2nd year after start-up and increase gradually, providing internal funding. The profits of the company will increase rapidly as new units are started, which will improve the capital base significantly.

The main economic indicators are shown in Table 25. The payback time derived from discounted CF is given on Figure 24. In general, both scenarios show profitable operation, while the double units plant has faster payback as well as higher IRR and NPV.

Table 25: Profitability calculation results Finland.

Description	Unit	Single unit	Double units

NPV	*MEUR*	2.4	10.5
IRR	*%*	8.8	10.9
Sales Revenue	*MEUR / year*	8.6	17.3
Payback time from investment decision	*years*	14.5	13.2
Payback time from Operation start	*years*	10.5	9.2

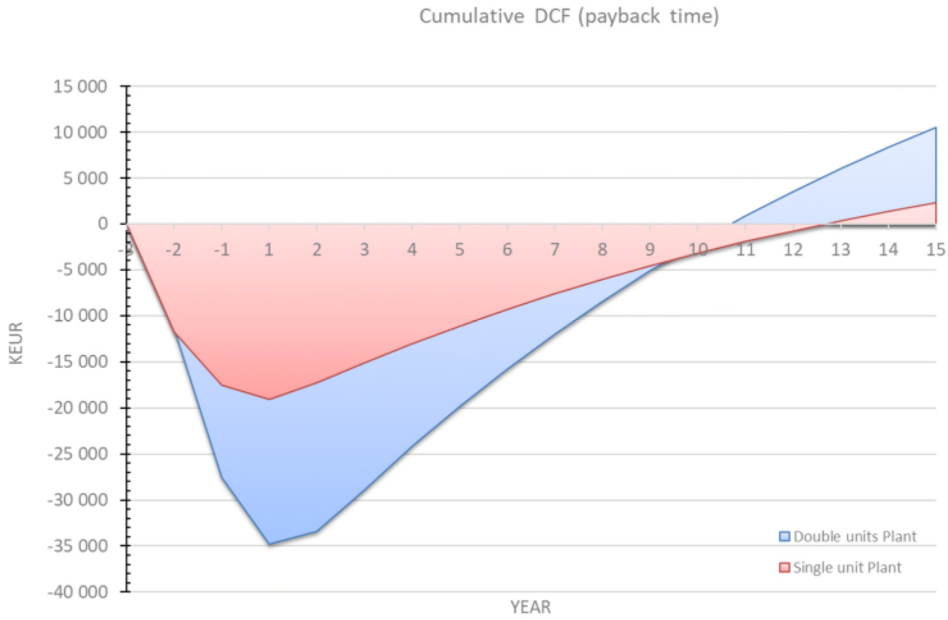

Figure 24: Payback time for alternatives Finland

The return to invested capital (as IRR indicates) exceeds the average cost of capital (WACC), which reflects the requirements of moneylenders and the equity providers. Development of IRR together with free Cash Flow is shown for both cases on Figure 25.

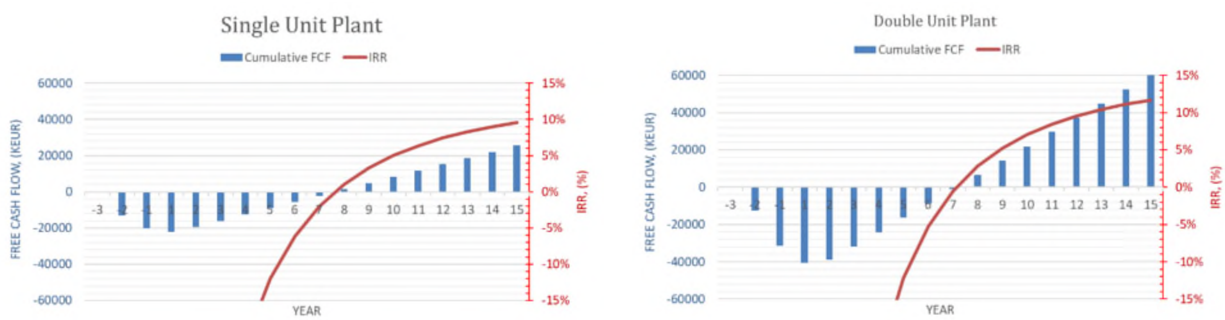

Figure 25: IRR Development

Sensitivity

Sensitivity analysis tells how much the profitability indicator changes with a change of its drivers. Sensitivity analysis does not provide information of the expected variation but provides an easy way to compare the importance of various drivers to the results.

In this study risk is considered as the variation in the project profitability. The choice here is to follow the variation internal rate of return (IRR). In general, the variation downwards is considered more serious than upside variation, which is happily welcomed. The IRR can vary due to factors affecting to the outcome, so called value drivers. Especially the downside risks can be considered as follows:

- PO price is a major driver. It is affected by market, but also by the mill. Especially the ability to produce consistently the specified good quality is appreciated in price.
- Production volume. Production volume is determined by market demand and the ability to use mill capacity efficiently. Demand on market is affected by product quality. However, for the chosen technology, the product quality is mainly affected by incoming biomass properties and stable dryness of biomass feed to CPU. Thus, after proper commissioning, the process itself does not affect much the pyrolysis oil quality, which mitigates the risk for off-specs. The increase of momentary production rate of the basic process unit (CPU) above design value is rather limited, so the annual production volume of Plant is mainly defined by efficiency of operation. The main philosophy is to multiply the number of basic CPUs for production volume increase keeping unchanged the basic process unit design.
- Investment cost. The unexpected costs can be related to improper engineering or problems in implementation. Proper engineering before the implementation is well-used money. This is like a preventive insurance against unpredicted surprises, which in case of production unit are often associated with production losses and quality defects. Proper project management, detailed engineering and purchasing are keys to successful implementation. Taking in account EPC scheme of execution and lessons learned during the first project (Lieksa 01) this risk is mitigated.
- Sawdust price. This is the major contributor to the specific cost of PO production. Securing the consistent quality, volume and cost of sawdust supply is the key for the efficient plant operation.

The result of sensitivity analysis for base scenario as change of IRR value due to critical drivers' variation is shown on Figure 26.

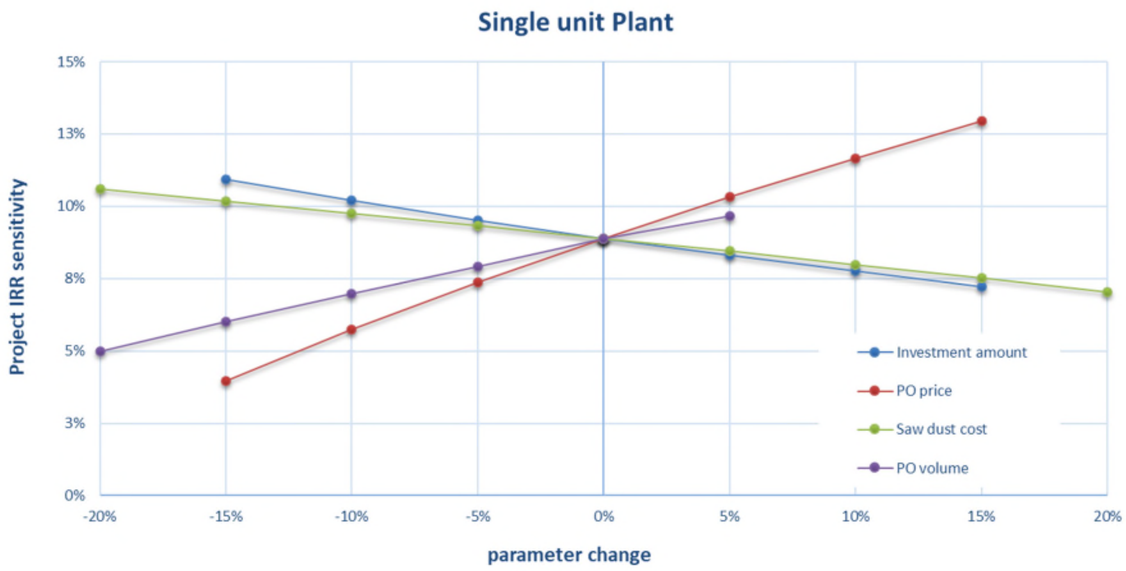

Figure 26: Sensitivity chart of main profitability indicator (Finland)

The value drivers' impact to profitability (IRR) in order of magnitude is:

- Price of product at level +/- 15%. Mainly defined by market.
- Sales volume of product + 5%, - 20%, mainly defined by Plant availability.
- Investment cost +/- 15%. Project management and implementation discipline.
- Saw dust cost +/-20%. Feedstock supply chain management.

Note that the sawdust delivery contracts are designed case by case, and the prices may vary notably. The pricing in the biomass supply agreements is linked to actual costs and the shares of the different biomass fractions (chips, saw dust) may vary over time. Therefore, a more conservative average price (than actual) of the wood biomass is used for modelling.

The sensitivity analysis results an IRR range of 0 – 15 % for the project with Single unit plant when the assumed changes of the critical variables are combined. However, the situation when all critical variables are at the worst extremum is highly unlikely.

The message of the analysis for the pyrolysis oil producer is to pay attention to factors, which help to protect pyrolysis oil price and keep up production efficiency. Such factors are the availability of production machinery and the ability of organization to run the plant efficiently as well as to secure the biomass supply chain.

Risks

A major check for the risks is to check the level of cash operating costs against minimum market prices. Mill should not operate with the sales price under this cash cost as it means money running out of the operating activities.

The effect of market price for pyrolysis oil at plant gate for both scenarios is shown on Figure 27.

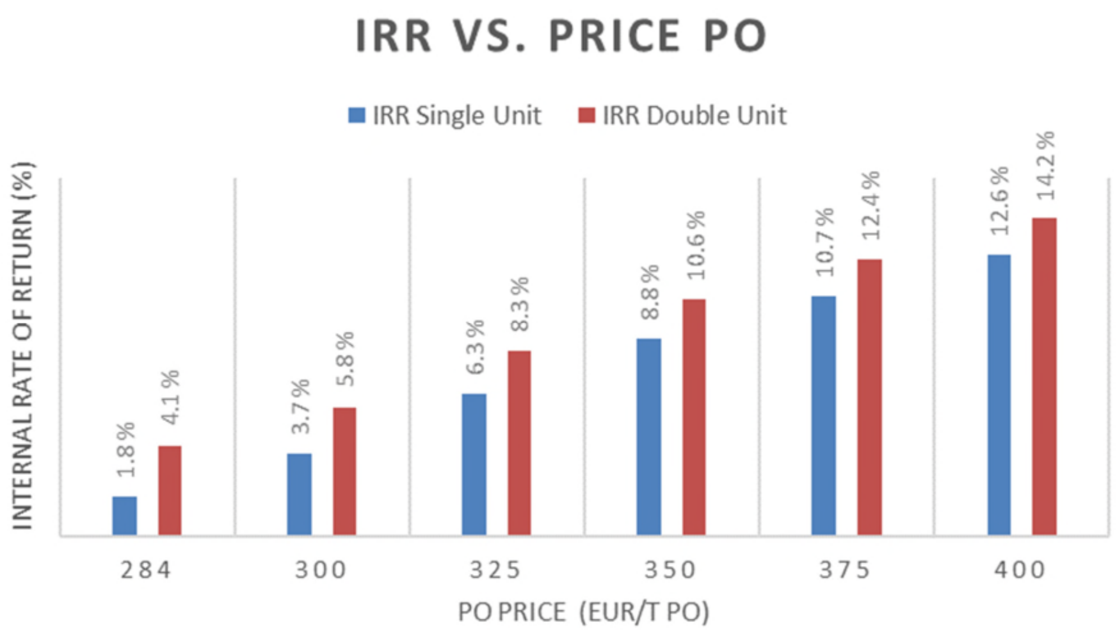

Figure 27: Effect of pyrolysis oil price on project IRR (Finland)

The project IRR with the base case assumptions is 8.8% and 10.6% for the double unit plant. The minimum price for pyrolysis oil at plant gate for single unit plant would be between 325 and 350 EUR/ton PO and 300 to 325 EUR/ton PO for double unit plant respectively.

The analysis is more favourable for a stand-alone plant consisting of two units, in comparison to one single unit. However, in case of a single unit plant that is constructed on the same premises as a sawmill, where biomass handling equipment and other services could be shared the single unit plant would show more solid economic results.

Calculations for the Sweden plant

For the feasibility calculations of the Sweden plant, the same methodology is used as for the Finland plants. Calculations are made both for a single unit and for a double unit, and the core data on plant capacity, CAPEX, feedstock requirements are the same. In this sub-paragraph the focus is on the differences between the Swedish business case and the Finnish one.

The following differences can be observed:

- The costs for electricity are – for the next few years – estimated to be a bit lower (37 Euro/MWh versus 55 Euro/MWh). This is likely caused by a surplus of renewable electricity in northern Sweden.
- The sawdust costs are estimated to be lower, namely 15 Euro/MWh as opposed to 17 Euro/MWh.
- One big difference is that the Swedish pyrolysis oil plant is implemented next to a sawmill, leading to lower maintenance costs (a reduction of 30% is foreseen) because facilities can be shared, lower CAPEX due sharing of the biomass handling, and lower personnel costs since these also can be to some extent shared with the sawmill.
- There is expected to be more financial support in Sweden for the construction of the pyrolysis plant.

All these differences lead to the following profitability calculations. When compared to the earlier table for Finland, it's clear that the Financial feasibility in Sweden is a bit better than in Finland.

Table 26: Profitability calculation results (Sweden)

Description	Unit	Single unit	Double units
NPV	*MEUR*	9.8	19.9
IRR	*%*	14.6	14.6
Sales Revenue	*MEUR / year*	8.6	17.3
Payback time from investment decision	*years*	10.7	11.1
Payback time from Operation start	*years*	6.7	7.1

This is also visible in the next graph, which shows the sensitivity of the business case with respect to the pyrolysis oil price. In the case of Sweden, the IRR for a single unit ranges from 7.7% to 18.4%, while the comparable figures for Finland are 1.8% to 12.6%.

The sensitivity of the profitability to factors such as CAPEX, feedstock costs and pyrolysis oil volume production is similar to that for the Finland plant. Since there is limited difference on the main parameters, this is according to expectations.

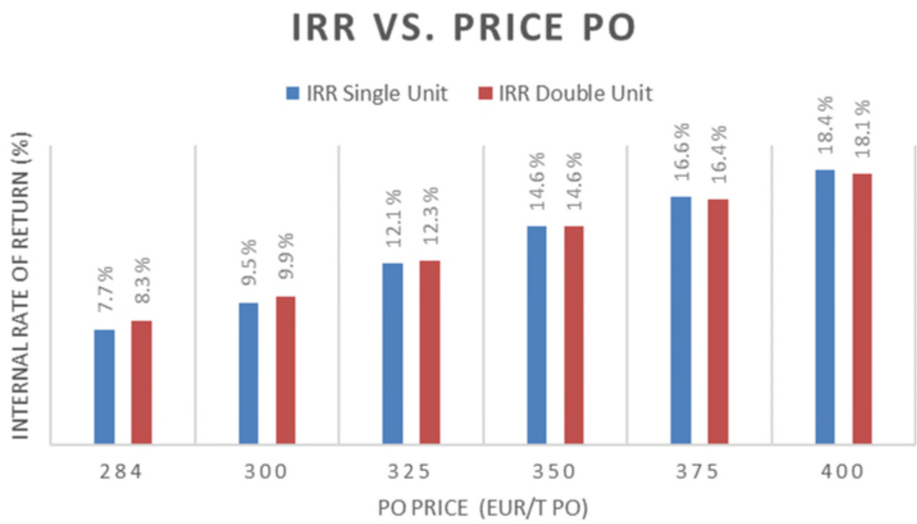

Figure 28: Effect of pyrolysis oil price on project IRR (Sweden)

2.10.1.2 For upgrading units

In this paragraph the financial feasibility of the upgrading unit is determined. The results should however be interpreted with caution, mostly because the technology is not technically mature yet. As indicated in paragraph 2.2.2, the technology is validated at pilot plant level, and further upscaling to demonstration scale is required. Because of this, the figures in this paragraph are uncertain, and a range of typically 50% for key data – for example, the total investment costs of the plant – should be taken into account.

To determine the financial feasibility of the upgrading unit, use is made of the PBL calculations [6]. With respect to the mass balance, data as presented in 2.8.2 are used. The following costs and market prices are considered:

Table 27: Costs and market prices upgrading plant.

Parameter	Value	Unit
Investment costs hydrotreatment plant	1.720	Euro/kW output
Costs pyrolysis oil - including transport	350	Euro/tonne
Costs of ‘grey’ hydrogen	1560	Euro/tonne H_2
Fixed O&M costs	3%	of investment costs
Variable O&M costs	2%	of Investment costs
Selling price marine biofuels (MGO)	10,7	Euro/GJ

The investment costs for the hydrotreatment plant are considered to include the costs for equipment; design, installation and start-up, land, auxiliaries, utilities, storage, etc.; so all non-consumable costs that need to be incurred for the upgrading to operate.

Fixed costs for O&M (Operation and Maintenance) include costs such as operating the plant, maintenance of the plant, overheads, taxes, and insurance. Variable O&M costs include costs for catalyst, electricity costs and costs for waste disposal. The selling price for the product (Marine biofuels), is taken from the values presented in 2.3.2 for MGO.

In the next table the capital costs and annual costs and income for a 72,000 tonne/year upgrading plant are shown:

Table 28: Capital costs and annual costs and income Upgrading plant.

Parameter	Value	Unit
Total investment costs	80	Meuro
Costs of pyrolysis oil	22,5	Meuro/year
Other costs	4,0	Meuro/year
Hydrogen costs	4,2	Meuro/year
Income from transport fuels	13	Meuro/year

What is clear from this table is that there needs to be some form of exploitation subsidy or mandate to increase the income from the transport fuels. The annual costs are – without any exploitation subsidy – higher than the annual income, which means that the plant is unviable.

For the calculation of the financial feasibility, the following parameters are used:

Table 29: Financial parameters Upgrading plant.

Parameter	Value	Unit
Equity share	30%	
Depreciation period	15	year
Interest on loan	2,5%	Meuro
Profit tax	21,7%	
Subsidy period	15	year
Inflation	1,5%	

These parameters are in line with the PBL starting points [6], and are considered a good basis for the feasibility calculations, since these are the result of consultations in the Dutch renewable energy sector. As shown in the table, 30% of the capital expenditure is equity, which means that 70% of the investment is financed by a loan.

Financial results

With the above data, a – relatively simple - cash flow model has been drafted. In this cashflow model, the Internal Rate of Return and the payback time is determined. For the exploitation support, four different scenarios have been included:

- Support according to the SDE++ advices as given in the PBL report [6]
- Support as would be possible when using the HBE system. This is a market-based system, where sustainable transport fuels get a premium per GJ. It is expected that this premium (the selling price of the HBE) can be double counted. When we assume a market price of 12 Euro/GJ, the total support would via the HBE system be equal to 24 Euro/GJ.
- Support according to the French TIRIB system. By way of illustration the support level of this system is included, whereby the support level is set at 50% to reflect uncertainty.
- The Support level needed to obtain an IRR equal to the SDE++ benchmark of 15% on equity.

Results are given in Table 30.

Table 30: Financial feasibility upgrading plant at various support levels.

	Equal to SDE++	Equal to HBE	TIRIB 50% (Fr)	IRR benchmark determined
Support level (Euro/GJ)	9,6	24	29,5	26,6
Total income from sales (Euro/GJ)	20,2	34,7	40,1	37,3
Income per tonne (Euro/tonne)	885	1516	1756	1630
Internal Rate of Return (IRR)	-	-	31%	15%
Payback time	-	-	3,0	4,9

Normally it would be reasonable to expect that the SDE++ support is sufficient for a viable business case, because the SDE++ is designed in such a way that most business cases are viable. In fact, an IRR (on equity) of 15% is aimed for. Reason that it does not yield a viable case in this instance is that the transport costs are higher than foreseen in the (integrated) SDE++ case. Also, the SDE++ assumes that all technologies – also the pyrolysis oil plant – are fully optimised. This is not the case for both the upgrading plant and not for the pyrolysis oil technology.

The table shows that support levels higher than the current HBE system are needed, and that for a 'good' IRR of the level that the SDE++ considers feasible (15%) higher support is needed. The TIRIB system in France yields even better results.

Sensitivity

The *costs of the pyrolysis oil* are crucial for the business case of the upgrading unit. In Figure 29 the relation between the pyrolysis oil price and the IRR of the upgrading plant is shown. The pyrolysis oil price variations take as starting point the case where the IRR is 15% (the base case for SDE support). The pyrolysis oil price is subsequently varied around the value used in this base case (see Table 27). The results of these sensitivity calculations show that when the pyrolysis oil price decreases, the IRR is increasing significantly, and vice versa.

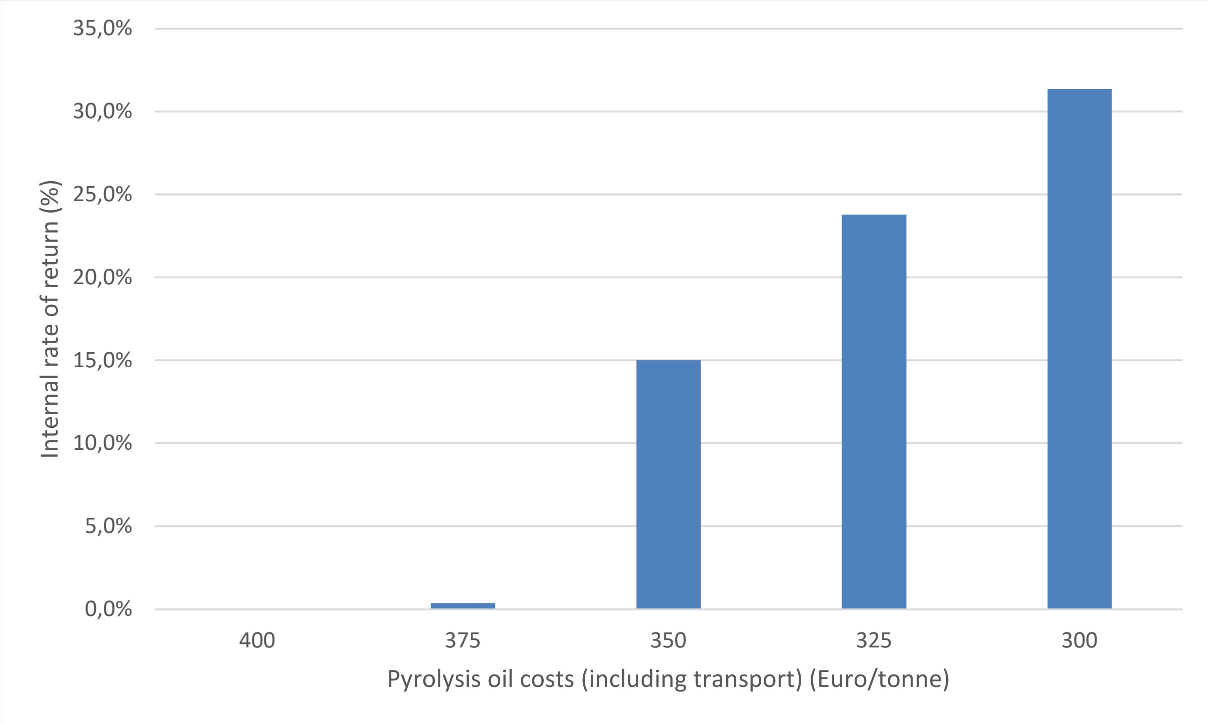

Figure 29: Influence of the pyrolysis oil price on the viability (the IRR) of the Upgrading plant

Another point on the sensitivity is the *costs of hydrogen production*. Currently, a price for 'grey' hydrogen is used as an input for the base case. The previous paragraphs have however shown that it is likely that a more renewable form of hydrogen is needed, whereby both 'blue hydrogen' – hydrogen production combined with capture and storage of CO2, and 'green hydrogen' – hydrogen produced from renewable sources are acceptable.

Cost estimations for production of either 'blue' or 'green' hydrogen vary, also because it is expected by many that the costs will come down in the future. One recent Dutch study [9] puts the long-term expected costs of 'blue' hydrogen at 1,6 Euro/kg H2, which is similar to the current price of 'grey' hydrogen, and the costs of 'green' hydrogen at 1.7 Euro/kg H2. Another study [10] puts the long term (2030) costs of blue hydrogen at 2.2 Euro/kg H2, and the costs of green hydrogen at 3 Euro/kg H2. It should be noted that both blue and green hydrogen are sufficiently low-carbon for the value chain.

Given these wide variations, the sensitivity of the IRR on equity is shown in the next figure. The hydrogen cost variations take as starting point the case where the IRR is 15% (the base case for SDE support). The hydrogen price is subsequently varied around the value used in this base case (see Table 27).

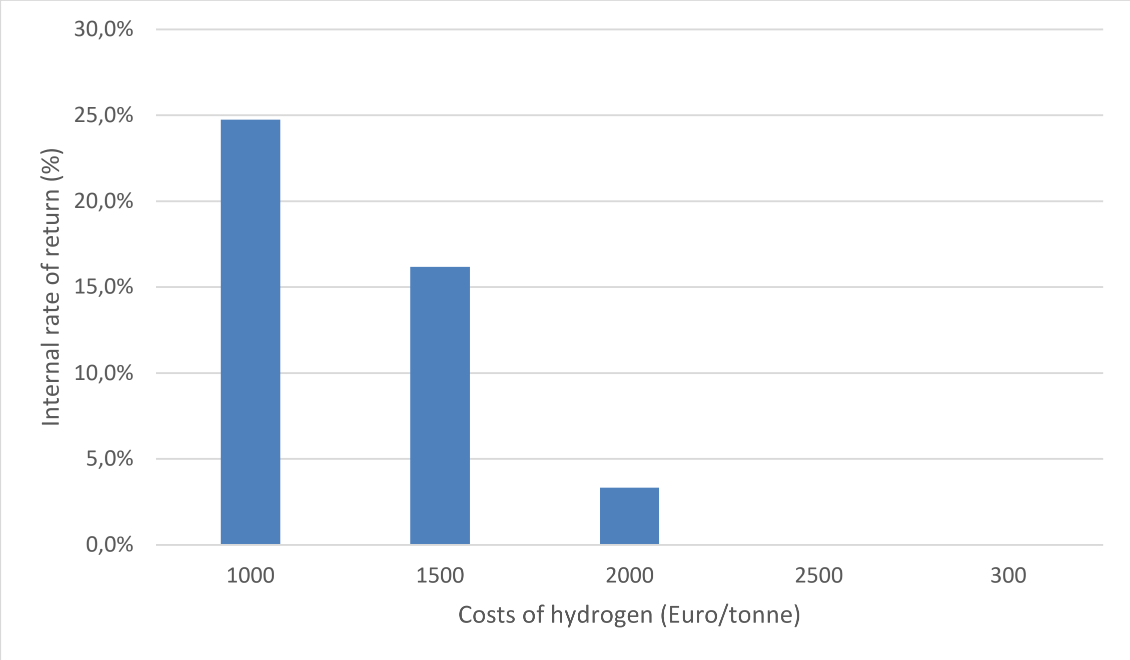

Figure 30: Influence on the costs of hydrogen on the viability (IRR) of the upgrading plant

2.11 Final Remarks

In this advanced case study, the logistics and feasibility of a long-distance value chain starting with PO production at various sites in Sweden and Finland and ending with PO upgrading to advanced marine biofuels at a site in the Netherlands has been assessed in detail.

All aspects of the value chain have been investigated, and it is clear that the value chain is technically feasible, as no 'showstoppers' have been identified so far. Costs have been identified, and the costs of producing marine biofuels in an upgrading plant in the Netherlands have been determined.

Especially regarding the upgrading plant, there are question on the financial feasibility of the value chain at this scale. When use is made of the current available stimulus for advanced biofuels, the plant is not feasible at this scale. Reasons for that are the additional costs for international transport of pyrolysis oil, but also the lower price that is paid for marine biofuels, which is roughly half that of regular transport fuels like benzine or diesel. It is expected that when a larger scale upgrading plant – in the strategic case study – is considered, the economics will improve.

The way in which the hydrogen for the upgrading plant is produced will be important for the financial feasibility of the upgrading plant. Since the GHG reduction needs to be above 80% if a plant is implemented after 2025, only hydrogen production combined with carbon capture and storage, or ‘green’ hydrogen production is possible.

3 Torrefaction of agricultural residues: the Italy case study

3.1 Introduction

The Italian Advanced case study analyses the overall feasibility of integrating a slow pyrolysis plant with a steel-making plant, where biochar would be used into a blast furnace for iron production as a replacement of pulverized injection coal (PCI) [11], while the pyrogas co-product could be used for internal energy uses of the steel-making plant. The use of alternative bio-reductants into the steel making industry is an innovative application of large interest [12], since "carbon neutrality" is one of the main pillar of the new EU Green Deal [13]. This would also allow to access additional revenue streams, i.e. from the trading of the EU Allowances, obtained through CO_2 savings, on the EU-ETS market. Moreover, the final customer could be willing to pay a small premium for a de-fossilized steel (*Green Steel*); thus, the impact of this possibility on the business case has been evaluated as well.

Ligno-cellulosic agro-residues such as olive and grapevine pruning, herbaceous agro-residues and finally dedicated energy crops, cultivated on marginal lands, such as *Arundo donax* have been evaluated as possible feedstocks for the IBC plant. The overall, high-level picture of the entire value chain is shown in Figure 31 below.

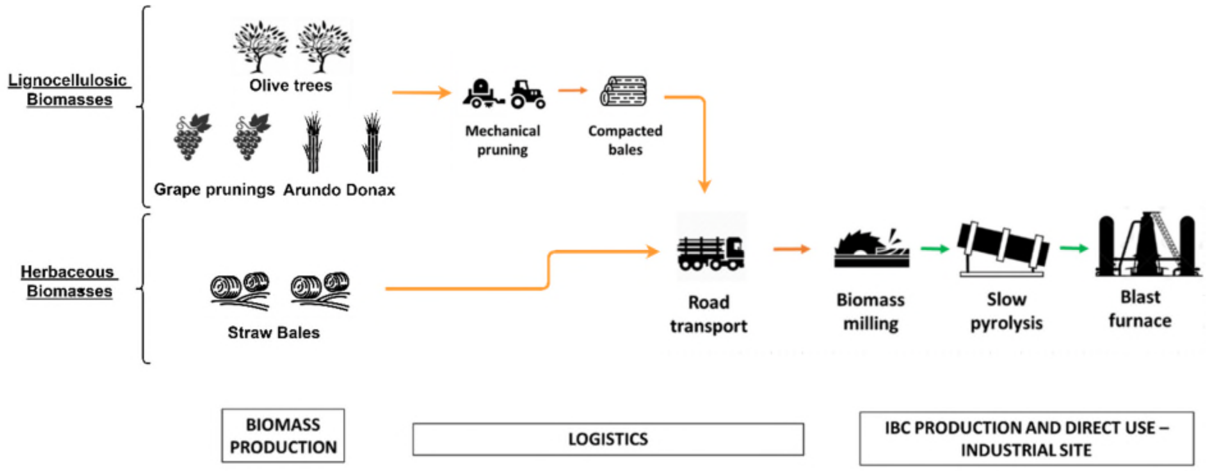

Figure 31: Advanced case study value chain layout.

In the present scenario, the IBC plant is centralized, located inside the ArcelorMittal steel making plant in Taranto, Apulia, in order to improve the overall energy balance of the value chain.

The advanced case study considers the use of 6 rotary kiln slow pyrolysis plants, each one with a nameplate capacity of around 10.5 kt/yr of biochar, for a total expected production of 63 kt/yr of biochar. The corresponding amount of dry biomass needed by the process is about 250,000 tons per year, or around 40,000 tons per year per single plant.

In order to get insights about the potential biomass availability and costs in the Italian Case Study regions, the INFER-NRG model has been developed within MUSIC WP4. INFER-NRG combines a set of crop simulation models with a logistic model under a GIS framework, with the

scope of providing optimized solutions and information support for the upstream, supply side of a techno-economic analysis for the feasibility study of an IBC production plant.
All these data are applied on a spatial grid, to be used the crop simulation models to forecast the expected agro-residues and energy crops yields over a 30-year time horizon and for several possible scenarios, based on climate forecast and crop rotations. A careful evaluation of the agricultural and harvesting periods of the various crops has been carried out, in order to grant year-round availability for the IBC plant needs.
A techno-economic model of the IBC plant has been developed, with the scope to define material and energy flows and the possible technical integration strategies with the existing processes and flows of the steel-making plant. The inherent complexity of the value chain led to a multiple-scenario approach, to better understand the impacts related to the possible parameter variation and interactions. Finally, the IBC plant economic performance has been evaluated through a standard set of financial parameters, such as Net Present Value, Internal Return Rate and expected Pay Back Time

3.1.1 Arcelor Mittal Taranto Steel-making plant (Ex-Ilva)

Italy hosts the EU's largest company of steelmaking, Ex-Ilva, which has been recently added to Arcelor Mittal Corporation. The plant is located in Taranto (Puglia, Italy), a site that is a hub for the local community and an important player in the regional economy [14] (as shown in Figure 32). One of the main pillars of the new property is the environmental sustainability of the plant, thus the use of biomass (as carbon source) in steelmaking process is particularly attractive [15]–[17]. Therefore, the scope of the present case study is to demonstrate how the use of renewable carbon source is promising for steel making industry to green the sector.

Figure 32: Geographic position of Arcelor Mittal plant in Taranto (Puglia, Italy). (Source: The New York Times)

Coal and coke are generally used into the blast furnaces, either as carbon source to remove oxygen from iron oxides to produce steel, or to provide heat to the process. This material can be added up to high quantities to replace the fossil carbon-source and has a huge potential of CO_2 emission reduction, with economic benefits in the short and medium term scenario [18]. Today blast furnaces are considered among the major contributors to greenhouse gas emissions in steel industry [15], thus greening the sector is important. In order to replace fossil coal and coke, renewable carbon in the form of char from pyrolysis and pyro-gas is considered. The potential use of charcoal into blast furnace is a topic of current interest [19] and it is particularly suggested for small size blast furnaces. The scheme proposed in the advanced Italian case study goes in parallel with the International Case Study, lead by Arcelor Mittal, which focuses on torrefied pellet production for the steel making Ghent' facility.

Figure 33: Arcelor Mittal steel making plant in Taranto (Puglia, South of Italy).

3.1.2 Recent political framework

Recent events in late 2019 regarding Taranto steel making plant have been a serious potential showstopper due to the environmental issues related to the plant. The blast furnaces in Taranto consist of old technologies, which require special authorizations to be operated due to the heavy pollution they cause, when compared to the current Italian emission limits. The Italian government promised 'legal shield' would have given Arcelor Mittal immunity from possible costly prosecution related to a planned clean-up at the plant, in order to avoid the layoff of over 8,000 workers. Up to date, Arcelor Mittal and Italian government are negotiating for a deal, which could allow a partial plant operation, in parallel with a modernization of the factory, to meet at least the minimum sustainability criteria and preserving the job positions. In addition, the upcoming European Green Deal is an opportunity to create a bioeconomy in the industry aimed to the transition to carbon-neutral future.

3.2 Slow Pyrolysis technology

Slow pyrolysis is a well- established technology, used for centuries in the production of wood charcoal. In the past, charcoal was the sole solid fuel used in steel sector, like the modern coke is used today for steelmaking process. However, the un-efficient existing production methods - such as earth kilns- caused intensive biomass consumption, with high deforestation risks. To date, thanks to the development of modern and efficient pyrolysis plants, and to the development of sustainable supply chains, the wood slow pyrolysis technology is considered one of the most promising routes towards steel sector decarbonization. Recently, the increased focus on agricultural residues and other mixed biowaste feedstock for a consistent production of biochar in terms of composition and quality, together with the need for coproduction of energy (heat, electricity) or even chemicals, pose additional challenges and opportunities in the design of slow pyrolysis reactors [20].

3.2.1 Pyrolysis process

Pyrolysis is a thermochemical anaerobic process, in which organic elements are decomposed by heating; this process always leads to three main products: a liquid phase, the "pyrolysis – oil", derived from a mixture of recovered condensable vapours, a gaseous phase, usually combustible and finally a solid carbonaceous material, the biochar. The slow pyrolysis process evolves through several reactions, which are quite undistinguishable and can simultaneously occur. Main mechanisms are [21]:

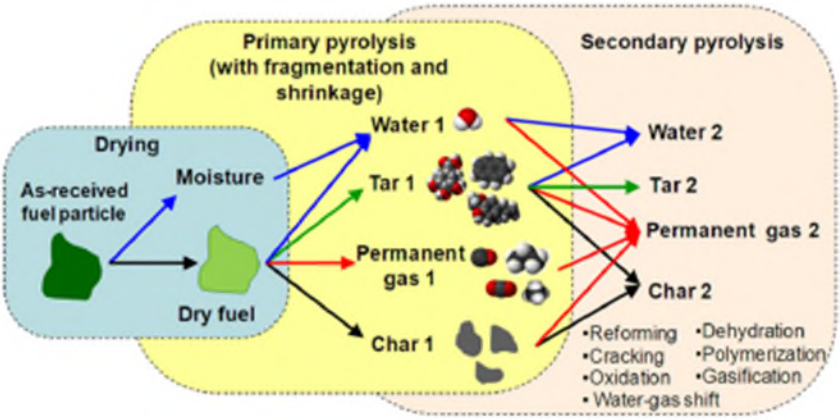

Figure 34. Pyrolysis Steps

- De – hydration: heating the feedstock to near 100 °C; moisture is removed and dry matter results. This phase should be conducted through solar heating [22] and natural ventilation systems aiming to increase energy efficiency of the involving natural and renewable sources process;
- Primary decomposition: this is how the primary reactions group of bonds breakage is named. Principal primary reactions are [23]:
  - Char formation: intra – and inter – molecular rearrangement reactions allow to transform the feedstock into a solid carbonaceous residue given by a high reticulation rank and high thermal stability, resulting in water and incondensable gas release;
  - De - polymerization: This is a slow process that persists in a relatively large temperature range, between 200 and 500 °C. During this phase, decomposition of principal biomass constituents takes place reducing polymers length and giving

rise to volatiles and condensable vapours that can be collected under bio – oil form.

- Fragmentation: this is the last phase of primary decomposition and provides the breakage of polymers' bounds around 600 °C, giving organic compounds and incondensable gases as products.
- Secondary reactions: cracking and re – polymerization mechanisms that are predominant while a 500 °C temperature in the reactor is reached. At this condition, in fact, volatiles and condensable vapours are not stable so they are forced to react with not yet decomposed solid biomass [137].

The output proportions for these three products vary depending on several process parameters. Among them, usually HVRT (Hot Vapour Residence Time) and HR (Heat Rate) are used to classify pyrolysis process as "slow" – "intermediate" – "fast / flash". Longer HVRT and lower temperature ranges lead to an increase in solid phase formation, while higher temperature levels and high HR enhance gas formation; finally, intermediate values for those parameters lead to an increase in liquid fraction.

Particle size has also a significant effect on the characteristics and yields of pyrolysis products. Smaller biomass particles offer less resistance to the escape of condensable gases which, therefore, are easily released to the surrounding environment, resulting in a higher liquid product yield. On the other hand, an increase in particle size delays the release of volatile substances and this translates into an increase in the residence time of hot vapours inside the solids, favouring the increase in char yield.

Another operating parameter that strongly affects the reaction times and the yield of coal is the initial moisture content of the biomass. A high moisture content leads to higher energy costs due to the increased water vaporization, also extending the carbonization cycle time. Therefore, the moisture content should not exceed 15-20% otherwise a drying treatment is required. However, a minimum amount of initial water is required as a heat exchange medium and in order to act as a reagent for the various biomass substances.

Moving from slow to fast pyrolysis, particle size must be reduced, temperature should increase, as well as heat rate. Solids retention time is indeed the only one of those process parameters that must decrease, in order to avoid unwanted secondary reactions. Table 31 below summarizes the main types of working modes for pyrolysis processes [24], [25].

Table 31: Biomass pyrolysis processes classification

Parameter	Torrefaction	Gasification	Fast Pyrolysis	Intermediate Pyrolysis	Slow Pyrolysis
Temperature	200 - 300 °C	800 – 900 °C	400 – 650 °C	500 – 600 °C	400 – 600 °C
Retention Time	1-2 Hours	<1 hour	0.5 - 2 s	<1 hour	1 – 5 hours
Heat Rate	1-20 °C/min	High	> 100 °C/s	>20°C/min	0.1 – 20 °C/min
Liquid Yield	1 – 5%	-	75%	50%	30 - 35%

Gas Yield	85%	95 – 99%	12%	25%	35%
Solid Yield	15%	< 1%	13%	25%	30 - 35%

3.2.2 Slow Pyrolysis

It can be seen that slow pyrolysis is characterized by lower heating rates, with temperatures of 400 – 600 °C and long vapor/ solids contact times, favouring volatile primary reactions products to react with the porous solid structure of un – pyrolyzed feedstock, which incur maximum yields in char, till 25 – 35%$_{wtDB}$ and reducing liquid fraction at 20 – 30%$_{wtDB}$. The carbon – rich solid product generated by biomass through slow pyrolysis is called "biochar", which is a functionalized highly condensed aromatic structure with inorganic mineral inclusions. It has low ash content, high heating value (LHV around 30 MJ/kg) and its density is in the range of 150 – 300 kg/m^3. Biochar could have a wide range of physicochemical properties, depending on the feedstock as well as on the applied thermochemical conversion conditions. Most of its ash constituents exhibit relatively low volatility under typical conditions applied; thus, most of the ash content in the resulting biochar is determined by the initial ash content in the biomass feedstock and the biochar yield [26]. Figure 35 reports on the influence of pyrolysis temperature on biochar fixed carbon content and yield, for lignocellulosic and herbaceous feedstocks.

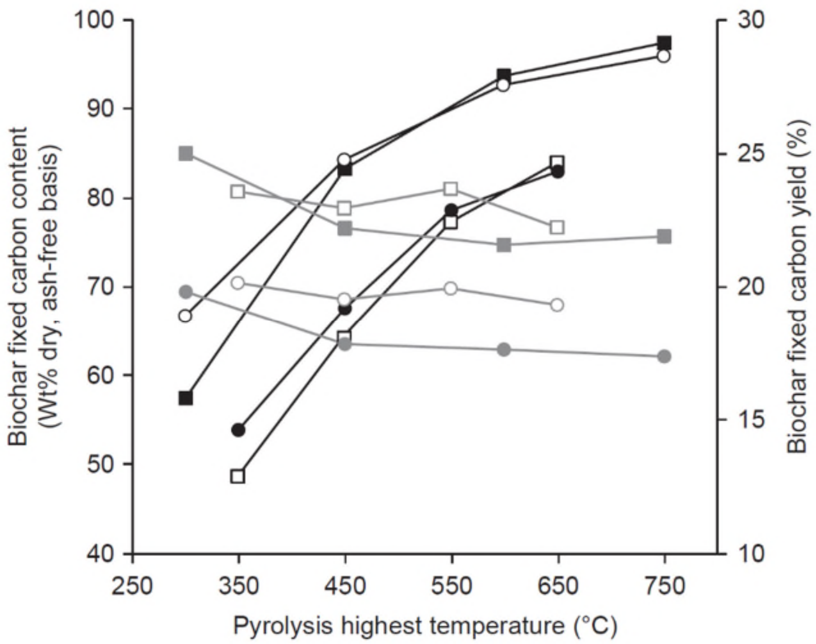

Figure 35: Influence of pyrolysis temperature on biochar fixed carbon content (Dry, Ash Free basis). Square points refers to pine wood chips and round points refers to wheat straw [20]

When compared to torrefaction (studied in the Ghent plant, International Case Study), which mostly concentrates the biomass carbon flow inside the solid product of the conversion process (i.e. torrefied material), with reduced production of process gases (5-10% db), slow pyrolysis divides the energy output (generally proportional to the carbon flow) in two main energy streams, i.e. char and pyrogas, with the latter including incondensable hydrocarbons, and water vapor (resulting from biomass moisture and process reactions). Due to the higher process temperature, slow pyrolysis has a lower char yield than torrefied process, however, slow pyrolysis char (charcoal) has some favourable properties compared to torrefied material, such as lower oxygen content, lower volatility, higher carbon content, and higher microporosity. Slow pyrolysis biochar is characterized by a highly porous structure and has a large specific surface area, which can be as large as 400 m^2g^{-1}, depending on the biomass feedstock and the pyrolysis conditions [27], [20]. Higher values of specific surface areas (i.e. > 100 m^2g^{-1}) can be attained using lignocellulosic (esp. woody based), low ash feedstocks.

During slow pyrolysis process, about 70% of the mass and 50% of the energy contained in the woody raw material is volatilised in the form of pyrogas. Pyrogas can be considered as a mixture of three fractions: non-condensable gases, condensable hydrocarbons and water vapor. The non-condensable gas mixture contains low molecular weight gases: mainly carbon dioxide, carbon monoxide, hydrogen, methane, the other fractions consists in a compound of light hydrocarbons, and complex particles and compounds such as polycyclic aromatic hydrocarbons (PAHs) [23], the water vapor fraction is the result of biomass moisture and process reaction. The lower calorific value of pyrogas on biomass dry basis is around 11 – 13 MJ/Nm^3 [28], [29]. A typical breakdown of the gaseous product resulting from dry biomass slow pyrolysis is: 20-35% condensable hydrocarbons, 4- 35% CO_2, 10 - 50% CO, 0.5 - 12% H_2, 3 - 11% CH_4, 10-30% water.

3.2.3 Rotary kiln pyrolyzer

A rotary furnace reactor is considered to be the best solution for this value chain since it has high flexibility in terms of feedstock dimensions and relatively low CAPEX compared to other solutions. It is also relatively easy to control the residence time of the biomass.

Rotary furnace, also known as rotary kiln, is a pyrolysis processing device consisting of a tilted rotating cylinder directly fired or indirectly heated, in which the material flows inside the cylinder. The proposed technology is externally heated by part of the pyrogas generated during pyrolysis, which at steady state provides the heat needed for the process, thus resulting in a simple configuration. The technology proposed has been validated for the slow pyrolysis/carbonization of fresh biomass and it is known for its efficiency in heat and mass transfer through the materials, high thermal efficiency and low operating costs. The use of the residence chamber allows to carefully control the emission level at the stack, while allowing the recovery of heat that can be used by downstream processes.
The unit can be fed with a wide range of biomass types, comprising the herbaceous and lignocellulosic agro-forest residues considered for this case study, with a maximum water content of about 20% w/w w.b.. A hopper is coupled with a feeding screw that transports the material in the rotary kiln. This system utilises a chipper to pre-treat the biomass to be converted and a screen to obtain different products in terms of granulometry for different markets and uses.

Figure 36 shows an example of rotary kiln pyrolyzer, a 100 kg/h biomass capacity demo scale unit, based on an indirectly heated reactor, operated by RE-CORD inside its experimental facility.

Figure 36: Demo-scale rotary kiln pyrolyzer available at RE-CORD experimental facilities.

3.2.3.1 Operational parameters

In order to obtain the prospected results for this case study, thus to produce 65 kt/yr of biochar, the most acceptable compromise in terms of size vs operability has been identified in the use of six identical reactors, each with an overall dry biomass capacity of 5 t/h hour with a 10% Moisture Content (MC) and operated for 7,600 h/yr. The operational parameters and kiln sizing are equal to each reactor, as well as mass and energy flows.

Basic kiln geometry dimensions (see Figure 37) have been defined after technical evaluation and iterative process, ending with a 30.7 m length, an internal diameter of 3 m and a kiln slope angle, which is the angle between the horizontal and the axis of the cylindrical reactor, of 0.5°.

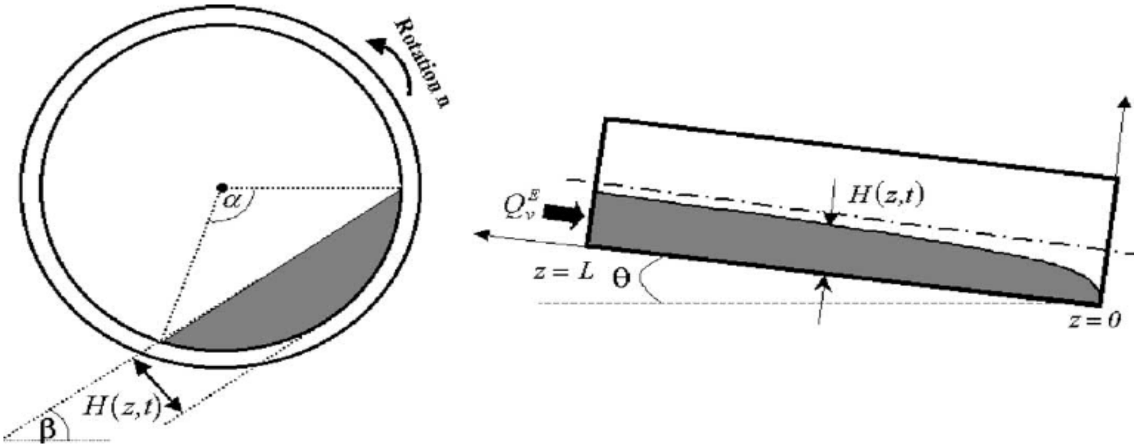

Figure 37: Basic rotary kiln dimensions

The kiln is designed to rotate with a velocity from 1 to 2 rpm. All the previous information is summarized in Table 32 below.

Table 32: Rotary kiln sizing parameters

Kiln Geometry and Sizing		
Internal Diameter	3	m
Length	30.7	m
kiln slope angle	0.5	°
Rotational Speed	2	rpm

Data on process heat transfer efficiency is included as data found in the literature [30], which reports, at 550 °C, an efficiency ranging between 30% and 65%. As a precaution, in this work, a value equal to 50% was assumed. The main process parameters, together with the mass and energy balance of a single rotary kiln reactor is provided by Table 33. Pyrogas mass flow, $m_{pyro\text{-}gas}$, takes into account all the moisture related to reaction water and input biomass moisture. The estimated LHV for such pyrogas is of around 10.6 MJ/kg.

Table 33: Slow pyrolysis process parameters and plant mass and energy balance

Slow Pyrolysis Plant Data		
Process Parameters		
Pressure	bar	1
$T_{process}$	°C	550
$T_{ambient}$	°C	25
Char Yield	%	27.19
Process Efficiency (heat transfer)	%	50
Mean Retention Time	min	98

Mass Balance – Feedstock Input & Product Output		
Operating Time	h/yr	7,600
Moisture Content	%	10
$m_{biomass\_dry}$	t/h	5.06
m_{char}	t/h	1.39
$m_{pyrogas}$	t/h	4.23
Energy Balance – Process heat and Product Output		
$P_{process\_heat}$	MW	5.88
$P_{pyrogas}$	MW	13.08
P_{Char}	MW	10.81

The process heat needed by the pyrolysis process could be fully provided by a part of the produced pyrogas; anyway, as it will be thoroughly evaluated in Chapter 3.5, the integration of the IBC plant with the steel-making plant could allow to use by-product gas streams, as well as waste heat for this purpose – at least to some extent. Reducing the pyrogas usage within the IBC plant would in turn allow to use it for more economically and environmentally valuable uses, such as for Natural Gas substitution. Anyway, a pyrogas burner will still be needed, to be dimensioned accordingly to the remaining heating needs.

Apart from the main sections of the pyrolysis plant, two other important auxiliary components are needed: a grinding unit, mainly for the straw bales, and a dryer. For the latter, the proposed plant solution provides for the use of a hot air dryer by exploiting pyrolysis flue gases or waste streams available at the steel-making plant, thus allowing for further recovery of thermal energy. Evaporation of biomass moisture, in fact, requires just low temperature thermal energy (about 95 °C is sufficient).

The power required by the dryer is expected to vary across the year, due to the different type of biomass used, and thus to the different moisture content. The topic will be discussed in more detail in chapter 3.4.1; of interest here is the fact that the overall drying power needed for the total biomass input of the IBC plant would range between 9 MW and 12 MW, with a yearly average need of 11.2 MW.

Finally, Figure 38 highlights the mass and energy flows of the IBC plant. The integration of the IBC plant with the steel-making plant will be evaluated in the following chapter.

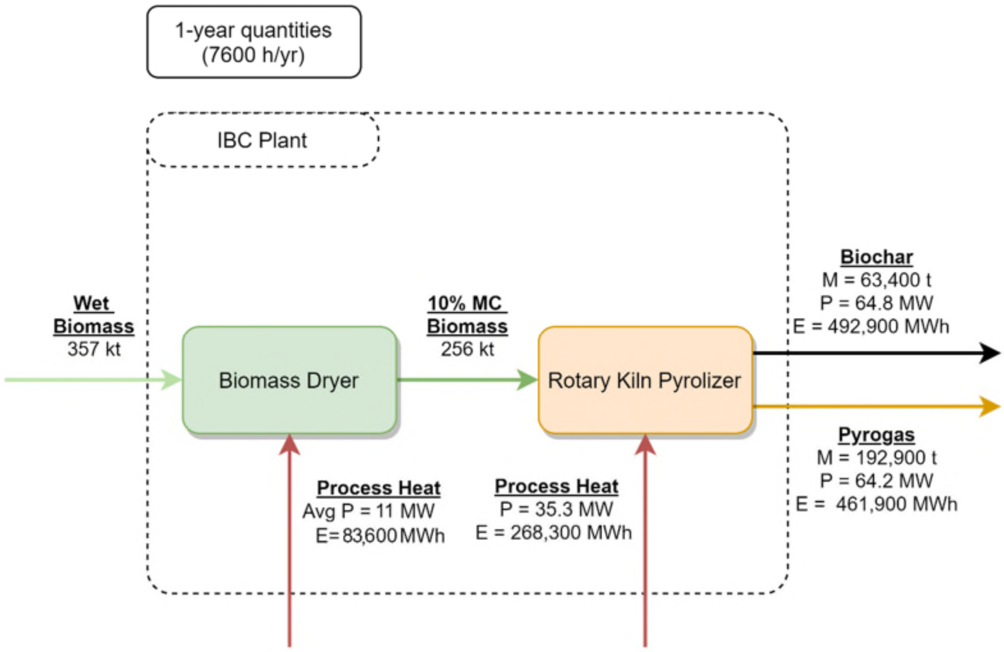

Figure 38: IBC plant mass and energy balance

3.2.3.2 IBC plant projected CAPEX and OPEX

The expected IBC plant CAPEX has been calculated in a two-step process: at first, an extensive literature and market research on the costs for similar installation has been conducted. A CAPEX of 0.85 M€ for a rotary kiln capable of 1 t/h of dry biomass input was found, with an additional 40 % for installation and civil costs [31].

Then, stakeholders and building contractors have been interviewed in order to scale the acquired cost data to the size of our model, comprising six IBC plants, each with nominal capacity of 5 t/h of dry biomass input. Moreover, during the interviews, possible cost reductions related to upscaling and sharing of auxiliaries and common units have been discussed.

Finally, a 7.5 M€ CAPEX was defined for each of the 6 rotary kilns, with an input capacity of 5 t/h of dry biomass, to which it should be added a 20 % increase for installation and auxiliary units costs.

Dryer CAPEX was assessed from literature, accounting for around 8.4 M€, or around 200 k€ for each t/h of wet biomass processed [32], [33], [34].

Table 34 shows CAPEX and OPEX values, the latter being further divided among cost sub-sections. It can be noted that CAPEX cost includes the hardware costs, comprising loading and unloading sections and the grinder unit. It also includes installation costs, cost of auxiliary equipment and civil work costs. It accounts also for hardware and installation costs of the dryer unit and the pyrogas condensation unit, the latter used to clean the pyrogas and separate it from condensable, with the scope of using it into the existing gas network of the steel-making plant.

Finally, also the cost of the needed connections to the steel making plant have been considered; such connections are required for:

- Having access to the various gaseous streams carried by the internal gas network, such as Coke Oven Gas (COG) and Blast Furnace Gas (BFG), in order to use them to provide at least part of the energy needed by the pyrolysis process.
- Biochar to be conveyed to the coal grinding unit, where Pulverized Coal (PC) is produced.
- Pyrolysis gas to be conveyed into the internal gas network.

OPEX costs includes.

- Personnel costs: calculated by considering a 24h supervision of at least one technician for each 5 t/h unit.
- Electricity costs: related to motors and fans used by the various units.
- Maintenance costs: evaluated as the 5% of IBC plant and pyrogas condensation unit CAPEX and the 2.5% of the dryer CAPEX.
- Biomass feedstock costs: they are provided as a range, taking into account the consideration on possible price scenarios explained in chapter 3.4.3 and 3.5.

Table 34: IBC plant CAPEX and OPEX breakdown

Slow Pyrolysis Plant CAPEX and OPEX		
	Cost	Notes
CAPEX	72.95 M€	Including: - Hardware - Installation, auxiliaries, civil works - Dryer (hardware and installation) - Pyrogas condensation unit (when considered) - Connections to steel making plant
OPEX	24.67 – 27.44 M€	
Personnel costs	0.68 M€	
Electricity costs	1.66 M€	Considering 0.08€/kWh electricity price
Maintenance costs	3.21 M€	
Biomass costs	19.12 - 21.89 M€	Depending on price scenario

3.2.4 Integration with Steel making plant

There are various means by which biomass-based products can replace fossil carbon in metal production and processing. For example, in an integrated steel plant, solid biomass products can be used for [11]:

- coke-making for production of bio-coke;
- sintering process for production of bio-sinter;

- pelletizing/briquetting for production of bio-composites and/or bio-briquettes;
- partial replacement of fuel injected into the blast furnace through Pulverized Coal Injection (PCI);
- bio-recarburization of steel in the ladle furnace

Anyway, the partial replacement of Pulverized Coal (PC) with biochar in the Pulverized Coal Injection (PCI) in the Blast Furnace represents the technically more straightforward option [15], thus this pathway has been selected in this Case Study. From a revenue perspective this is not the optimal solution, given the higher cost of coke, when compared to coal. On the other hand, it is proven that biochar could be successfully blended with PC, while the replacement of coke with biochar still faces difficulties because of the quality requirements, including high coke strength after reaction (CSR,> 60%) and low coke reactivity index (CRI, 20–30%), which are required to ensure sufficient permeability in the upper part of the BF shaft and low-pressure loss in the furnace [35], [36].

Another valuable energy stream from the IBC plant is represented by the pyrogas, as it is extendedly reported in chapter 3.2 and 3.5; it can be used to replace fossil energy coming from either Natural Gas or COG and BFG, but it necessarily has be maintained at high temperature in order to avoid condensing of its tar and moisture content. Otherwise, pyrogas has to be cleaned and its condensable fraction and tar content have to be separated, thus obtaining a pyrolysis oil stream with high calorific value (around 22-25 MJ/kg) that has itself a valuable energy content and could be used as fuel in the steel-making plant.

3.2.4.1 Requirements for substitution of coke and coal and overall volumes in Taranto steel-making plant

The ArcelorMittal steel plant in Taranto is a fully integrated facility with 5 blast furnaces of which 3 are operational. Total hot metal production is approximately 4.5 Mton/year (2018 number), but the potential capacity is 6 Mton/year hot metal.
The equivalent coke rate is 595 kg/ton hot metal (thm) of which:

- 335 kg/thm coke
- 30 kg/thm nut coke
- 170 kg/thm PCI (with Replacement Rate of 0.78)

As explained in the previous section, in a first step the biochar could partially replace the PC. Since biochar would have a higher carbon content when compared to torrefied biomass (61 % carbon) a replacement rate similar to PCI could be expected (given an approximate carbon content of 78%). The LHV of the biochar is assessed around 28 MJ/kg, thus similar to the one of PC, i.e. 31 MJ/kg.

<u>Requirement for PCI:</u>

Differently from torrefaction, charcoal produced from biomass slow pyrolysis is a coal-like material with high C content and low volatility, able to fully replace fossil coal as PCI in Blast Furnaces. Table 35 below includes the quality of three different coal qualities used in as PCI, which can be considered as a quality target for the obtained charcoal.

Table 35: Element composition of several coal samples

Feature	Anthracite	Australian Coal Sample	North American Coal Sample	Measure Unit
C	77.38	79.22	75.62	$\%wt_{db}$
H	3.61	3.53	3.57	$\%wt_{db}$
O	1.35	3.56	1.60	$\%wt_{db}$
N	0.86	1.66	0.86	$\%wt_{db}$
S	0.90	0.43	0.82	$\%wt_{db}$
Ash content	15.02	9.10	5.08	$\%wt_{db}$
Fixed Carbon	70.93	64.87	67.00	$\%wt_{db}$
Volatile matter	13.21	18.03	19.92	$\%wt_{db}$
Moisture	0.84	8.00	8.00	$\%wt_{db}$

Given the low sulphur content of biomass compared to fossil coals, charcoal obtained from slow pyrolysis is expected to have Sulphur content of less than 0.3% db.
Assuming that the charcoal would be of required Replacement Rate and LHV, all the PCI could be theoretically replaced, thus resulting in a potential of:

- 0.170 t_{coal}/t_{hm} x 4.5 Mt_{hm} = 765,000 ton/year biochar (under current operations)
- 0.170 t_{coal}/t_{hm} x 6 Mt_{hm} = 1,020,000 ton/year biochar (blast furnaces operated at full capacity).

Considering that the IBC plant is expected to produce 62,500 t/yr of biochar, this means that it could cover between 6.1 % and 8.2% of the overall PCI needs. In other words, for each ton of hot metal produced, it is expected to be used 10.4 kg to 13.8 kg of biochar, to replace a part of the total 170 kg of Pulverized Coal.

Requirement for COKE replacement

The replacement of coke offers an even larger potential, since currently still coke is used as reductant compared to PCI. There is however a limitation in the physical properties of the coke. Measurement of physical properties aid in determining coke behaviour both inside and outside the blast furnace. In terms of coke strength, the coke stability and Coke Strength After Reaction with CO_2 (CSR) are the most important parameters. The stability measures the ability of coke to withstand breakage at room temperature and reflects coke behaviour outside the blast furnace and in the upper part of the blast furnace. CSR measures the potential of the coke to break into smaller size under a high temperature CO/CO_2 environment that exists throughout the lower two-thirds of the blast furnace. A large mean size with narrow size variations helps maintain a stable void fraction in the blast furnace permitting the upward flow of gases and downward of molten iron and slag thus improving blast furnace productivity. Quality requirements for a coke to be used in a European blast furnace are following reported in Table 36, data provided by [37].

Table 36: Coke properties for Blast Furnace steelmaking application

Property parameter	Required	Applied
CSR	>65%	60.0 – 68.4
CRI	<23%	20.0 – 31.9
Mean size	50 – 55 mm	47 – 75 mm
Ash	<9%	8.67 – 11.35
S	<0.7%	0.51 – 0.93
P	<0.025	0.02 – 0.06
Alkali	<0.2	0.16 – 0.38
Moisture	<5.0	1.5 – 5.5

Results for analysis on a sample used in a Polish plant is reported in Table 37 below [38].

Table 37: Coke properties for a sample used in a Polish steel-making plant

Property	Value	Measure Unit
Carbon Content	88.83	%wt
Ash Content	10.20	%wt
Volatiles	0.57	%wt
S	0.49	%wt

Charcoal usually exhibits the required chemical properties of both coal and coke; but it difficultly achieves the required coke physical properties, so only small fractions of the coke can be replaced by charcoal. Assuming 5 % of the coke could be replaced theoretically, would result in a potential of

- 0.05 x 0.335 t_{coke}/t_{hm} x 4.5 Mt_{hm} = 75,375 ton/year charcoal (under current operations), or
- 0.05 x 0.335 t_{coke}/t_{hm} x 6 Mt_{hm} = 100,500 ton/year charcoal (blast furnaces operated at full capacity).

Following the same approach used in the above paragraph for the evaluation of PCI substitution rates, it can be seen that in the case of coke, the IBC plant biochar output accounts for around 62.2 % to 82.9 % of the theoretical substitution threshold.

According to what stated in above paragraph, as well as in a wide range of publications, charcoal use in steelmaking processes like Blast furnace, or coking doesn't present relevant technical barriers.
However, in order to increase the energy efficiency of the proposed solution, and thus to valorise slow pyrolysis pyrogas as renewable energy source, RE-CORD and ArcelorMittal, partners into the CS development, started a discussion on the potential use of the hot pyrogas leaving the pyrolyzer as a renewable energy source for the facilities operating in Taranto steelmaking site. However, the feasibility of using pyrogas in steelmaking processes like Blast furnace, or coking, encountered some technical issues: pyrogas contains some potential detrimental organic compounds, and a high amount of water vapor, that potentially have an impact on steel making process efficiency. Additionally, before the injection in Blast furnace, pyrogas should be compressed at 6 to 7 bar minimum, since it should be injected in the lower part of the Blast Furnace, where temperatures are higher. The pressure would bring to the condensation of the pyrogas organic hydrocarbons, and of water vapor, making the injection impossible.
Anyway, the hot pyrolysis gases contain a significant amount of energy and could be used in the steel-making plant as a replacement for fossil energy.

3.2.4.2 Possible technical scenarios for the integration of the IBC plant in the steel-making plant

In the light of all the previous considerations, the biochar has been conservatively considered as a green substitute of fossil coal for PC consumptions. A partial replacement is foreseen due to the high amount of pulverized coal required by the Blast Furnace. Thus, it could be mixed with raw coal before entering the grinding units.
The use of pyrogas for the replacement of fossil streams in the steel-making plant could increase the environmental and economic sustainability of the proposed solution, but it poses higher technical and logistic issues. After confrontation with Arcelor Mittal, the use of pyrogas in the Blast Furnace has been discarded, while it remained confirmed the possibility to use it for energy purposes (see Figure 39 below).

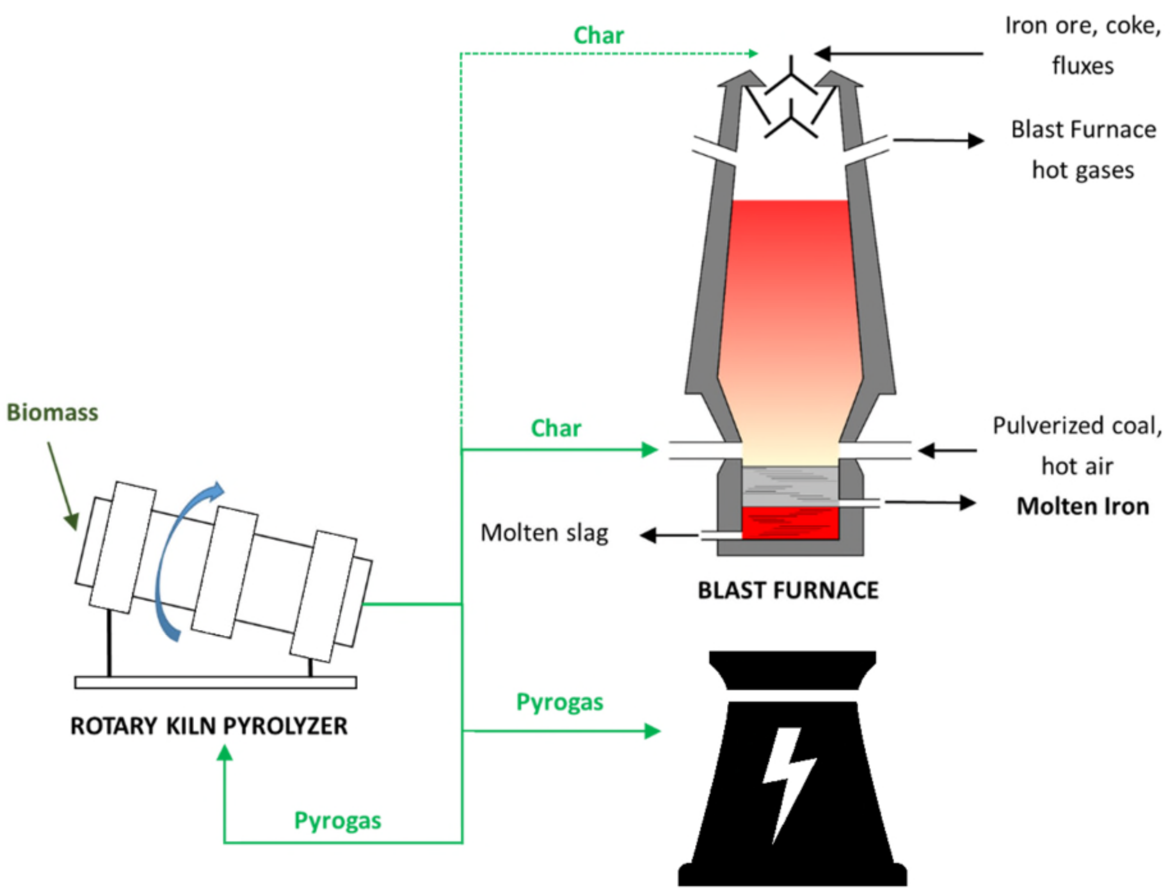

Figure 39: Possible integration routes for IBC plant output products within steel-making plant

The main consumer of Natural Gas, as shown in Figure 40, is the Power Plant (PP), with more than 11,00,000 GJ/yr; the total yearly consumption for the whole steel-making plant is around 21,000,000 GJ. As a comparison, the total pyrogas produced by the IBC plant accounts for 2,150,000 GJ/yr (not taking into account that part of it would be used to provide energy to the pyrolysis process).

		COG GJ	BFG GJ	BOFG GJ	NG GJ	Electricity Generation MWh	Electricity Consumption MWh	Steam TJ	Steam ton
in	Production	11.170.143	27.311.016	3.400.411			3.093.117	2.290	729.197
	Purchase				21.379.367		359.091		
consumption	CB	416.231	5.165.820		3.600		47.081	1.069	340.398
	SP	481.407			264		277.242		
	ASU				35.591		699.565	229	72.920
	BF		8.045.175		2.776.354	57.701	217.392	74	23.564
	BOF				636.462		311.317	612	194.877
	CC+SY				299.901		89.993	0	0
	HSM+PM	5.680.826			4.071.961		529.049	0	0
	CRM+PIC+HDG (Taranto)				956.432		125.556	293	93.299
	Pipe				14.496		20.902		
	PP	4.585.943	14.066.287	3.042.332	11.079.963	3.035.264	201.243		
	Service & Utilities (=water and energy dispatch: ENE+DTA)		9.512		1.504.343	152	837.464		
	Others						0	974	310.148
out	Sales						50.262		
	Flare	5.736	24.221	358.079			45.142		
	Total	11.170.143	27.311.015	3.400.411	21.379.367	3.093.117	3.452.208	3.251	1.035.205
	Up to HR (w/o ASU, w/ flares)	6.584.200	13.235.216	358.079	7.788.542	57.701	1.517.216	1.755	558.839
	Balance	0	1	0	0	0	0		

Figure 40: Production and Consumption of fuel gases, electricity and steam in the main section of the steel-making plant (courtesy Arcelor Mittal)

Some of the main issues of pyrogas use as a fuel, are the high water content, and the high condensation temperature of the organic condensable hydrocarbons. The organic condensable fraction, in particular TARs, condensate at temperatures below 300°C, creating fouling and clogging in pipelines and injection systems. Water content can create problems during gas injection. These two main barriers can be avoided if pyrogas can be directly reused next to the pyrolysis plant, avoiding condensation. Otherwise, in order to use the pyrogas i.e. in the Power Plant, it is necessary to separate the tars and the condensable hydrocarbons from the pyrogas. To do so, it could be possible to use the coke oven by-product plant that is located near to the Coke Oven.

The Coke Oven is an airless kiln for the industrial production of coke from coal; there, the coal is baked temperatures usually around 1,000°C –1,100 °C. This process vaporises or decomposes organic substances in the coal, driving off volatile products, including water, in the form of coal-gas and coal-tar. The non-volatile residue of the decomposition is mostly carbon, in the form of a hard somewhat glassy solid that cements together the original coal particles and minerals. The coke oven by-product plant has the function of recovering chemical by-products from the liquid condensate stream that forms after the raw coke oven gas is cooled, and of conditioning the remaining gas stream into a fuel gas.

After cleaning the pyrogas, the incondensable gas fraction could be injected in the steel making plant gas pipeline to feed the power plant, while the condensed pyrolysis oil, with high calorific value, could be reused as liquid biofuel for bioenergy generation to be used on site - for example in the HRSG of the existing thermo-electric combined cycle plant - or further upgraded for external industrial uses.

Figure 41 develop the framework previously defined in Figure 38, adding the possible integrating measures with the steel-making plant.

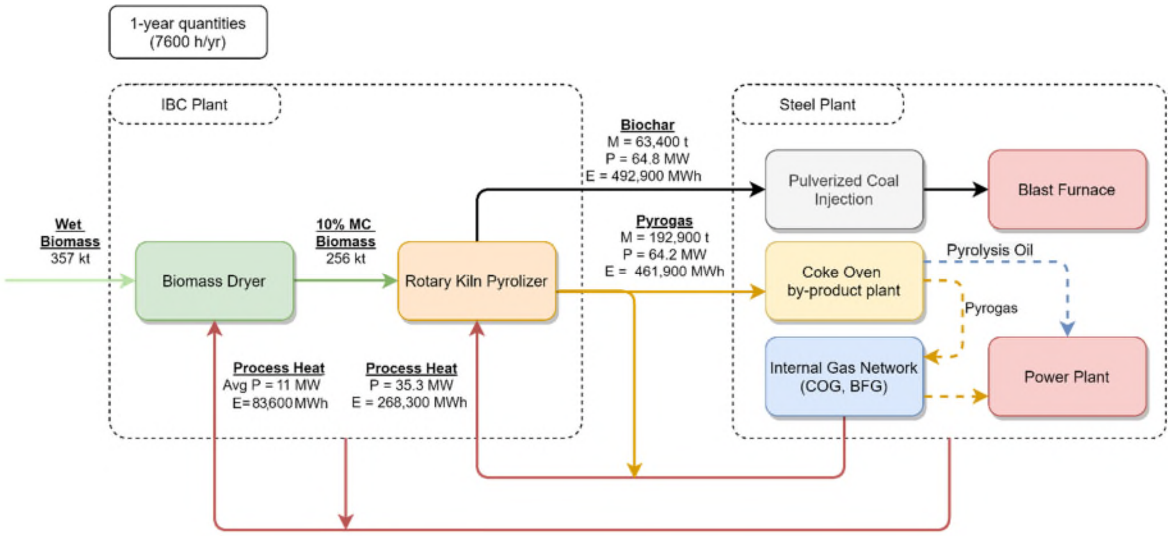

Figure 41: IBC plant mass and energy flows, integrated with steel-making plant

Thus, a possible location for the IBC plant has been found near to the Coke Oven, bringing several benefits for the IBC plant:

- It makes possible to use the coke oven by-product plant to remove the tar from the pyrogas; this, in turn, would avoid the installation of an additional (and costly) pyrogas cleaning unit, still allowing a much easier transport of the pyrogas within the steel-making plant.
- In perspective, it would make possible to access the waste heat from the heat exchangers of the COG cooling units (see Figure 42, [39]) and use it, i.e., to pre-heat the process air for the combustion of the pyrogas needed to power the pyrolysis process.
- In perspective, it would allow to easily feed at least part of the biochar into the coke stream that would be located nearby.

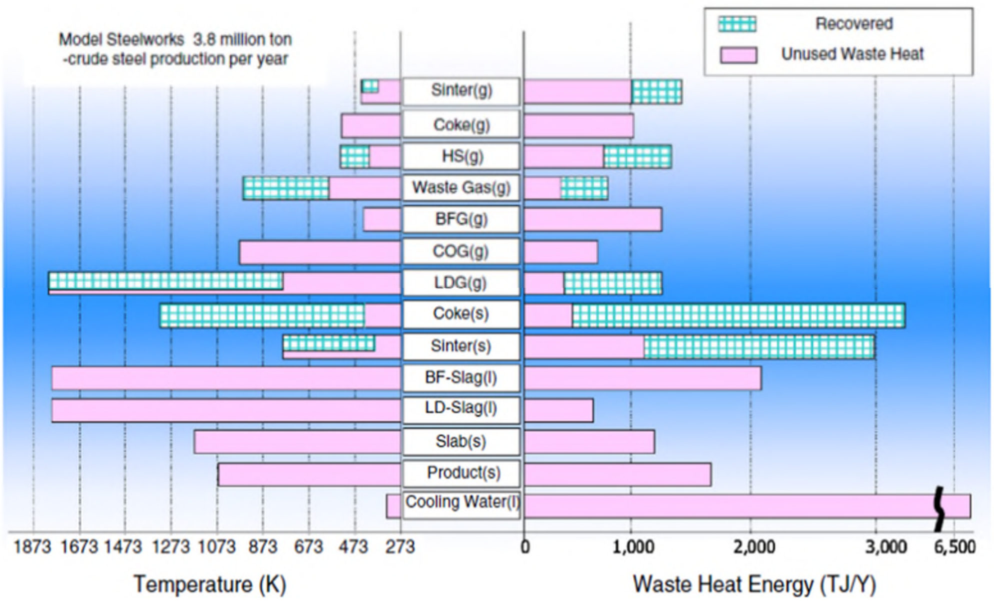

Figure 42: Waste heat energy and temperature for the various sources in a steel-making plant

In fact, once the pyrogas is clean and the tar removed, it would be possible to inject it into the plant gas network, while the condensate fraction could still be used for energy purposes.

3.3 Markets and drivers

The main revenue sources for the IBC plant could be categorized in terms of:

- avoided cost due to substitution of raw material inputs, such as the case of Coal and Natural Gas;
- earnings from incentive schemes, which in this case is EU-ETS;
- increased sale price of final material thanks to an additional premium paid by the customer, such as with a Green Steel scheme.

3.3.1 Coal and Natural Gas

According to the WCA (World Coal Association), 70% of steel industry is dependent on coal. The metallurgical (met) coal market volume accounts for about one-third the of the thermal coal market one, and it is characterized by a stronger role of international trade. Australia (52% share in 2019) is positioned as the dominant global supplier while Europe, due to its its large iron and steel production capacities and shortage of domestic supply, remained one of the largest importers, accounting for 18% of all imports.

Pig iron and steel production in Europe experienced a significant decline related to pandemic measures and subsequent economic turmoil. As a result, a decrease in met coal imports by 6 Mt (-11%) in 2020 was estimated, while an almost complete recovery is expected in 2021 [40].

Figure 43 shows coal price trends of recent years, ranging between 40 USD/t and 120 USD/t.

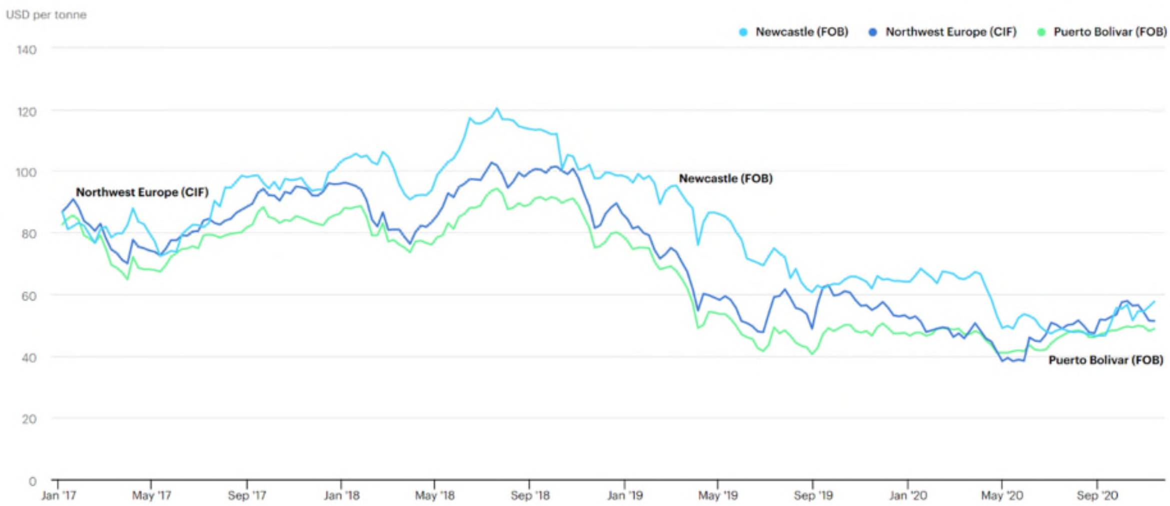

Figure 43: Historical price trends for coal in Europe and Asia [41]

3.3.2 The European Union Emissions Trading System (EU-ETS)

The European Union Emissions Trading System (EU ETS) covers ~45% of the EU's emissions, from the power sector, manufacturing industry, and aviation (limited to flights within the European Economic Area).

Actually, Phase 4 is operative, started in 2021 and lasting up to 2030. No change in scope was agreed in comparison to the previous Phase 3; the single EU-wide cap for stationary sources of 1,816 MtCO2e in 2020 has a reduction factor of 2.2% annually applied, without a *sunset* clause, so it will continue to decline beyond 2030 [42].

Manufacturing industry received 30 % of its allowances for free in 2020 and will continue to receive a share of their emission allowances for free beyond 2020. Free allocation follows product-based benchmarks, set at the average of the 10% most efficient installations for each sector. The amount of free allocation is calculated based on a formula where the production quantity (in tonnes of product) of a certain installation is multiplied with the benchmark value for that particular product (measured in emissions per tonne of product). In principle, installations in sectors exposed to a significant risk of carbon leakage, are eligible to receive 100 % free allocation. Anyway, since benchmarks are based on the performance of the most efficient installations in each sector, only them would receive enough free allowances to cover all their needs. All the others would have to purchase the remaining part on the market [43].

During phase four, benchmark values will be updated twice to reflect technological progress in different sectors. The first set of benchmark values will apply to the period 2021-2025; the second set of values will cover the period from 2026 to 2030.

A lower annual reduction rate of 0.2% will be applied to steel sector benchmarks since it faces high abatement costs and carbon leakage risks.

Carbon leakage refers to the situation that may occur if, for reasons of costs related to climate policies, businesses were to transfer production to other countries with laxer emission constraints [44]. For phase 4 (2021-2030), a new list of sectors at risk for carbon leakage was adopted [45].

Figure 44 shows the historical trend of EU allowance prices for the last seven years. The rising trend is clear, as well as the pandemic-related dip is.

Figure 44: Historical trend of EU Allowance price [41]

3.3.3 Green Steel Premium

Within this Case Study, the *Green Steel* term addresses a 100 % "defossilized" steel, or, in other terms, a steel in which the coal has been replaced with other carbon-neutral sources, or which carbon content has been otherwise offset through other measures.

Several steel companies, among which ArcelorMittal Europe [46], are currently offering – or plan to offer – green flat steel products; ArcelorMittal is using a system of certificates which are linked to the tonnes of CO_2 savings achieved through the company's investment in decarbonization technologies in Europe, and certified by independent auditor companies [47].

An hypothetical premium ranging across 40 €/t_{steel} and 60 €/t_{steel} has been introduced in the Advanced Case Study techno-economic analysis; this in turn have been translated into € per tons of replaced carbon, considering a usage of 0.6 tons of coal per ton of hot metal produced.

3.3.4 Other possible uses of bio-char

The deployment of the projected IBC plant and the development of the inherent value chain (especially for the upstream) could act as an enabler for a biochar market expansion in the region. Among the various beneficial aspects that such expansion could bring, the environmental one could play an important role in the case study regions. In fact, biochar is particularly important for sustainable agriculture, as it improves the water-holding capacity and the organic matter content in soil [48]. This feature is particularly interesting in marginal lands and regions where rain is scarce, and irrigation is difficult for a number of environmental or economic reasons [49]. Studies demonstrate that microbial mineralization of biochar to CO_2 does occur eventually, converting biochar back to atmospheric CO_2; however, this process occurs very slowly and may take thousands of years. Therefore, biochar contributes to long-term atmospheric C

sequestration in soils, offering a rather low-complexity solution if compared to most of the available carbon sequestering state-of-the-art technologies [50].
Indeed, biochar can be used as soil amendment, compost additive and fertilizer support in all European countries. Voluntary biochar quality standards have been formed in Europe with the European Biochar Certificate, in the UK with the Biochar Quality Mandate and in the USA with the IBI Standard which is intended to be used internationally.

in a wider perspective, in some countries, charcoal is still the main domestic fuel and it is used also for cooking (also in industrialized countries where vegetable carbon is mainly used for barbeque). Due to its high stability and porosity, biochar can be also used as filter in water treatment plants; furthermore, to increase its purifying property, it can be subjected to an activation process to produce activated carbon (used in gases and vapours treatments, such as air purification, odour control, etc.). Biochar is also used for many other innovative applications: it can be used in the pigment industry, in technical sport textiles, in green building (as a moisture regulator, thermal and acoustic insulator, antibacterial and fungicide) and cosmetics (for the production of soaps, scrubs and toothpastes) [51].
The use of biochar as animal feed additive is regulated by the UE 68/2013 regulation [52] and it is reported to bring a wide variety of advantages.
Biochar can also be used by humans and its utilization as food additive is regulated by the UE 231/2012 regulation [45]. Carbonized biomass can be used also in pharmaceuticals, thanks to its high adsorption potential and indeed activated carbon is listed on the World Health Organization's (WHO) Model List of Essential Medicines as an antidote for nonspecific poisonings [53].

3.4 Biomass supply chain

Puglia Region is the largest olive oil production area in Italy. Today, Italian olive production covers approximately 1,700,000 ha, and 80 % of this area is located in southern Italy. Puglia is the region with the highest share, with about 370,000 ha of olive trees, thus pruning can be seen as a huge biomass source of the area.
The Italian Advanced Case Study relies on ligno-cellulosic agro-residues such as olive and grapevine pruning, herbaceous agro-residues and finally dedicated energy crops, cultivated on marginal lands, such as *Arundo donax* [54].
The INFER-NRG model has been developed within MUSIC WP4 to get insights about the potential biomass availability and costs in the Italian Case Study regions. INFER-NRG combines a set of crop simulation models with a logistic model under a GIS framework, with the scope of providing optimized, strategic solutions and information support for the upstream, supply side of a techno-economic analysis for the feasibility study of an IBC production plant, also taking into account climate change.
Core of the model is the geographical database, which contains all the input information needed by both crop models and logistic model to correctly operate, such as the ones regarding

Climate, Soil, Administrative layers, Land Use, Crop productivity and phenology, Cultivation techniques (rotations, fertilizations etc) and Road networks.
All these data are then applied on a spatial grid, to be used in several crop simulation models to forecast the expected agro-residues and energy crops yields over a 30-years time horizon and across several possible scenarios, based on climate forecast and crop rotations.
The limiting spatial resolution was represented by the crop information (yield and phenology), which is provided by the ISTAT at provincial (NUTS3) level.
Consequently, the best spatial resolution could be achieved by running the simulations for the cells (hereinafter referred to as *simcells*, see Figure 45 below) representing (i) each soil type available in (ii) each climate cell (12km x 12km) within (iii) each province.
The number of the simcells (2425) can be derived by the following formula:

$$(A * B * C), \qquad where \begin{cases} A = \text{ n. of the considered provinces} \\ B = \text{ n. of the climate cells for each considered province} \\ C = \text{ n. of soils for each climate cell} \end{cases}$$

Each of the 67,430 *single cells* was associated with the relevant simcell on the basis of the *meteo cell* and soil.

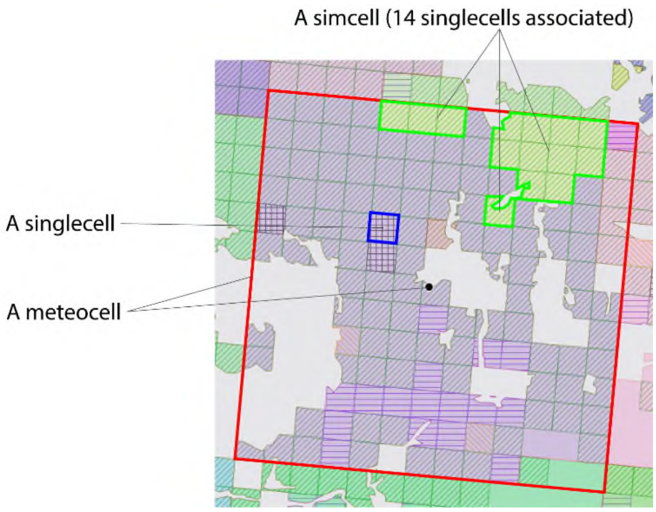

Figure 45: *Meteo cells*, *simcells* and *single cells*. Please notice that the purple *simcell* includes *single cells* with marginal land, arable land, olive groves and vineyards.

The model was implemented in the framework of WP4, with additional information collected from farmers surveys/interviews in the territory of interest and during national workshops/events.

3.4.1 Biomass feedstocks availability and cost

As previously mentioned, the Italian Advanced Case Study relies on the use of ligno-cellulosic agro-residues such as olive and grapevine pruning, herbaceous agro-residues and finally dedicated energy crops, cultivated on marginal lands, such as *Arundo donax*. A careful evaluation of their agricultural and harvesting periods has been carried out, in order to grant year-round availability for the IBC plant needs. Currently, most of the olive tree residues are burned in the field, as it happens with vineyards residues as well. Sometimes farmers manage to sell bigger-sized olive trees residues on the local market. Herbaceous agro-residues are used in livestock farms. In order to consider possible competing biomass uses and markets, INFER-NRG model analysed an area capable to provide 150 % in weight of the biomass needed by the IBC plant. Table 38 reports the calendar availability for the various feedstocks, together with their average Moisture Content after harvesting and LHV [55].

Table 38: Biomass feedstocks calendar availability and properties

Month	Crop residues	Moisture Content	LHV (MJ/kg_{dm})
January - February	Grapevine pruning	40%	16-19
March	Olive pruning	10%	17-19
April - May	Olive pruning & Straw	See Olive and Straw data	
June - September	Straw	20%	17.5-19.5
October - December	Arundo	20%	16-17.5

The INFER-NRG model produced as an output a series of GIS-based maps reporting the monthly availability of each biomass type in the Case Study area (see Figure 46). Such availability is included in a set of scenarios (see Deliverable 4.2 for thorough explanation):

- Climate/Society: RCP4.5, RCP8.5;
- Crop Rotation: Business As Usual (BAU, the typical crop rotation of the territory), Energetic (a rotation more focused on biomass production for energy), Livestock (a rotation more focused on producing food for livestock);
- Single crops: olive trees, grapevines (not included in the crop rotation, being on other cells);
- Energy crop on marginal land (*Arundo donax*): a scenario in which the marginal land (Corine Land Cover classes 321, 322, 324) is cultivated with *Arundo donax*.

Thus, on a high level, a total of 6+1 scenarios is evaluated; at single cell level the variability is reduced, since not all the scenarios affect all types of cells (e.g. single crops are perennial, therefore not included in rotation and affected only by Climate/Society scenarios).

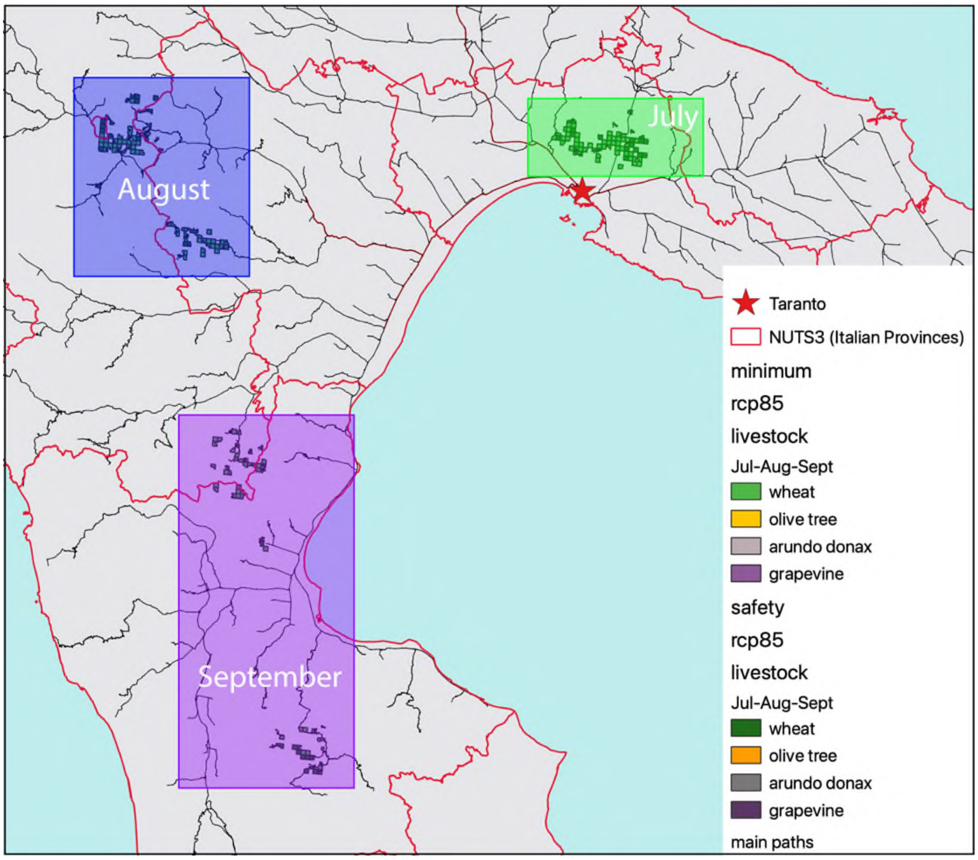

Figure 46: Single cells providing biomass during July, August and September, RCP85, advanced case study

Not all the biomass produced in the evaluated areas is required to cover the raw materials need of the IBC plant, which are set at 21.5 kt/month. Therefore, each *single cells* production dataset (climate scenario, rotation + single crops, month) was ordered by time and distance from the IBC plant, then the cells were progressively added to the selected sub-set until the cumulative amount of dry biomass provided reached the imposed threshold (e.g., for the Adv. Case Study, 25 kt/month). An additional threshold of 34 kt/month has been successfully evaluated, as a safety measure to ensure a wider basin of availability in case of unfavourable events, such as reduced biomass availability. Figure 47 shows an example involving *Arundo donax*, with the light grey cells being sufficient to reach the 25 kt/month threshold (*minimum sufficient supply*), and the additional dark grey cells being required to address the 34 kt/month threshold (*safety supply*).

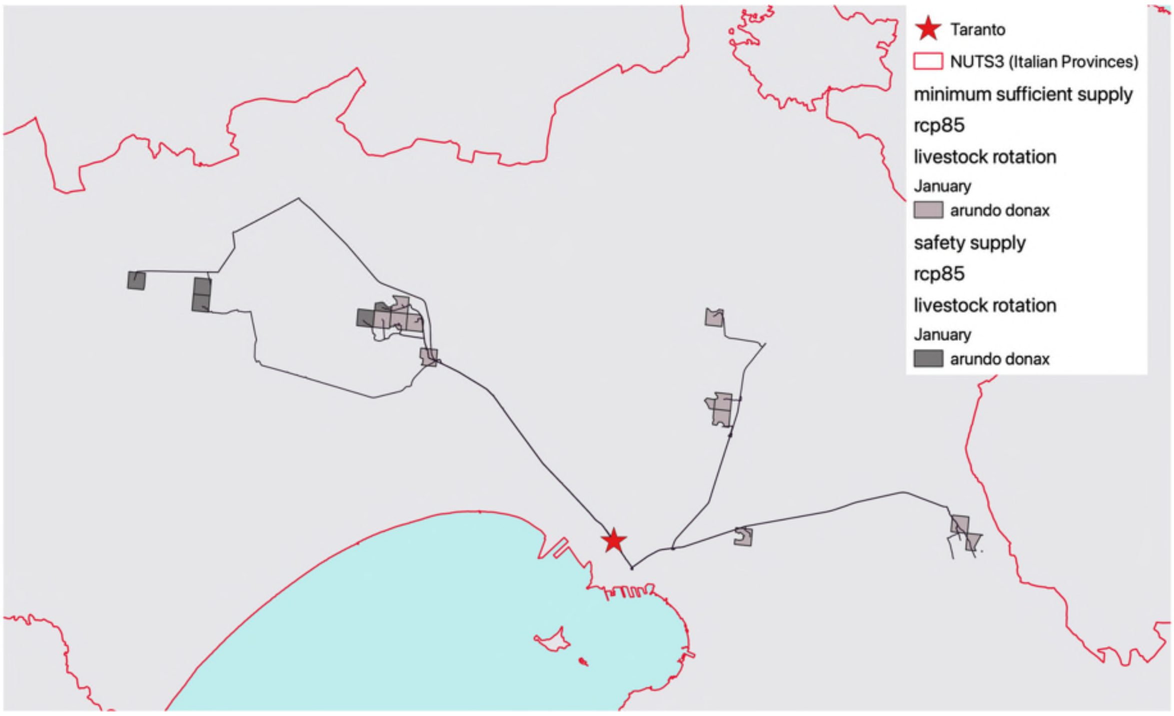

Figure 47: Minimum and safety supply areas for January, RCP85, advanced case study.

Depending on the type of biomass available (see Table 38), the quantity of wet biomass needed to reach the monthly target varies. Below you can find Table 39 with the wet (and dry) yearly quantities for each biomass type, for each climate and rotation scenario, plus an average value across the scenarios. It is worth noticing that only Olive and Straw quantities slightly variate across scenarios. This is due to the fact that they are collected together in the same months, so they both concur to the 22.5 kt/month of dry biomass target; in the other months there is only one type of biomass available, so the quantity is simply the one needed to fulfil the target (an overall area expected to produce 50% more biomass than needed was always considered).

Table 39: Biomass used on a yearly basis for the advanced C.S.

Scenario		Wet (dry) biomass, average quantity used as input			
Climate	Rotation	Grape	Olive	Straw	Arundo
RCP45	Ordinary	66,667 (42,667)	53,016 (46,268)	117,198 (99,432)	120,000 (64,020)
	Zootech-nical		50,548 (47,827)	119,813 (101,853)	
RCP85	Ordinary	66,667 (42,667)	50,991 (47,882)	119,430 (101,525)	120.000 (64,020)
	Zootech-nical		50,442 (44,369)	120,016 (95,631)	
Average		66.667 (42,667)	51,249 (47,927)	119,114 (101,402)	120,000 (64,020)

Biomass costs

The costs of the different biomass crops have been deduced with different methodologies; where there was a quotation on the biomass market, it was decided to consider the purchase price. This is the case of hay bales which are generally purchased for zootechnical purposes; in the case of the vine instead, as there is no commercial quotation, it has been decided to construct the cost bottom-up from the expenses incurred by the seller.

Finally, as far as the olive tree pruning is concerned, we considered the price of wood chips on the market, assuming the sure presence of a chipper on the farm; in relation to this hypothesis, from market surveys we have found that the purchase of a chipper is a sustainable cost for the farmer, as a consequence of the creation of a source of income that does not exist today and is considered as a cost for the management of crops.

In order to validate the costs of wood chips, in addition to market prices, a bibliographic search was conducted on publications concerning the economic aspect of the use of crop residues from tree plants [56].

Regarding the cost of the *Arundo donax,* we have considered the agronomic costs for its cultivation; being it a perennial crop, in addition to the costs of the first plant, it needs only annual fertilization interventions. Table 40 summarizes the information.

Table 40 Biomass costs for the considered feedstock types

	Grapevine	Olive trees	Arundo donax	Wheat bales
Fresh biomass price (market quotation)	50 €/t	50 €/t	34[4] €/t	62 €/t

3.4.1.1 Focus: Xylella Fastidiosa disease

Xylella fastidiosa is a bacterial plant pathogen transmitted by vector insects and associated with serious diseases affecting a wide variety of plants; since 2010, this bacterium has spread mainly in Puglia, affecting olive cultivation and causing a disease known as Complex of rapid drying of the olive tree. The number of plants present in the infected area is about 21 million (Source: Coldiretti), and after an initial phase of resistance by the local community to the eradication measures issued by the European Commission, about 12,000 olive trees have been explanted to date.

[4] Based on the estimated cost of production (Candolo, 2006)

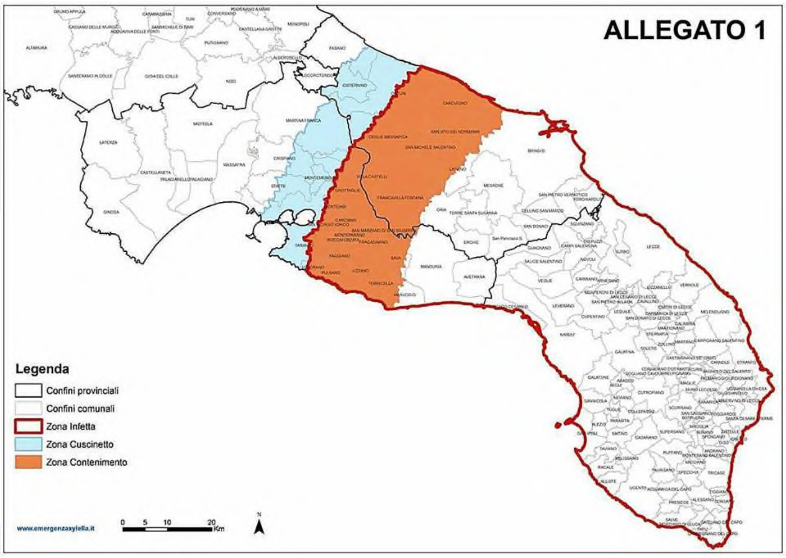

Figure 48: Puglia area infected by Xylella (inside the RED line), including Taranto district area where the Arcelor Mittal plant is located [57]

It is estimated that in the next few years, without containment measures, the number of plants subject to eradication could reach the quota of 300,000 olive trees.

Since the incidence of this disease affects both the agricultural sector, with a lower production of olive oil, and the landscape (thus tourism), recently the containment practices have been put into operation and thus have begun to have an effect on the previously uncontrolled spread of the pathogen.

Table 41: Report on Xylella-positive plants [58]

Sampling campaign	Number of samples infected area	plants positive to Xylella	% plants positive to Xylella	Total number of samples	total number of plants positive to Xylella	% plants positive to Xylella
Nov. 2013-Nov. 2014	--	--	--	13250	242	1,82
Oct 2014-Jun 2015	25516	612	2.39	26755	612	2,28
2017-2018	--	--	--	169124	3058	1,81
2018-2019	52669	993	1.88	61558	993	1, 61

Furthermore, since Xylella is an ubiquitous and easily transportable pathogen through vectors, it would it would be safer to restrict transport with plant material from infected areas. Instead, the eradicated whole plants should be transported to the final destination (in our case the IBC plant) and chipped there, with a significant increase in transport costs due to the less-than-optimal use of truck volumes.

On a technical level, Xylella-infected biomass could have been considered in the model, in order to fulfil the IBC plant needs, even if only on a “single-time” basis for each affected area.

Anyway, it has been decided not to take this biomass source into account, and thus to rely on it for the techno-economic analysis, since the uncertainty on the effectiveness of the containment measures, does not allow to foresee a certain quantity of eradicated plants that can be used as a source of biomass in the medium-long term.

This choice inherently made the techno-economic analysis "safer", since at least part of this Xylella-infected biomass could anyway be considered as available, at least in the short-to-medium term, for the IBC plant consumption, if needed. Thus, this can be seen as a potential additional source, allowing for a certain degree of error in terms of total calculation of available biomass residues.

3.4.2 Logistics choices and costs

The selected processes for biomass collection and pre-treatment, at farm level, are:

- harvesting of the residues distributed in the plot;
- chipping of the ligno-cellulosic residues and energy crops
- the use of bales for the herbaceous residues.

The processing times for the chipping of the vineyard residues are lower than the chipping of the olive residues, due to the reduced thickness of the shoots which facilitates the processing, while the harvesting of the vine shoots requires more time due to the espalier arrangement of the vine cultivation.

The mowing of the *Arundo donax* is a simpler process and involves lower costs for the company as shown by the final value of the *Arundo donax* wood chips compared to that relating to the vine and olive tree crops.

For the transport of biomass from farms to delivery, a not too bulky means of transport, which can easily travel along country roads, but not too small (e.g. tractor), in order not to increase transport costs should be chosen. Furthermore, choosing the most popular medium-range trucks on the market, would give the opportunity to compare the estimates of a greater number of contractors, in order to be able to choose the cheapest. Thus, the most suitable means for transporting pruning residues and round bales is a truck with a transport capacity from 5 to 10 tons.

Within logistics costs, loading costs are limited and therefore are generally included by the transport companies in the offered prices. Contractor's waiting times for biomass loading/unloading were not considered, because on average they are estimated to be less than one hour per travel and specific interviews with contractors, regarding such topic and the possibility of any related cost validated this hypothesis.

Finally, information on transport costs were gathered from regional price lists of trade associations, as well as interviews with local contractors. The transport price lists are expressed in Euro per hour and based on the type of means used; as a result of the research activity, a cost of 50 €/hr for the loading, unloading and transport phases, using the 8 tons truck previously mentioned has been defined.

Figure 49 below summarizes all the above-mentioned considerations, organizing them in successive logical steps.

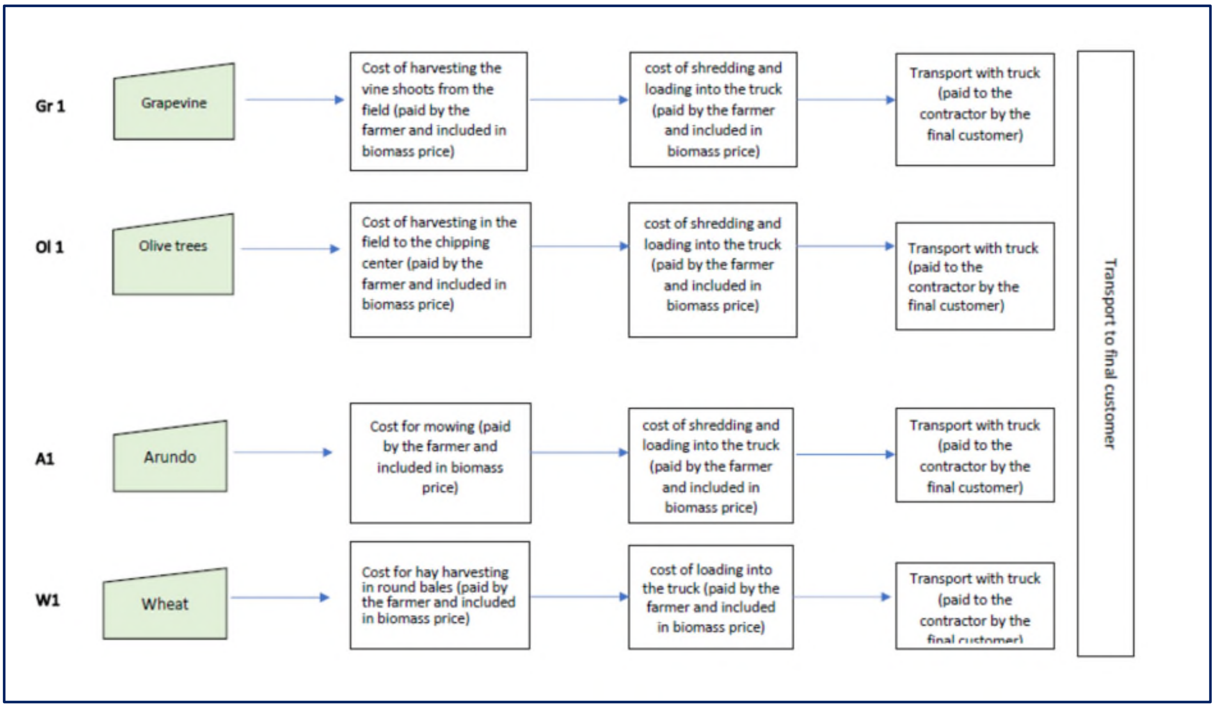

Figure 49 – Pre-processing and logistics cost components based on crop types

Given the fact that logistics costs are given by the third-party operators on a €/h basis, all the single cell-IBC plant distances have been converted in times of travel. Figure 50 reports the used iso-duration map; In black the most used path, while the colour scale represents the different travel times.

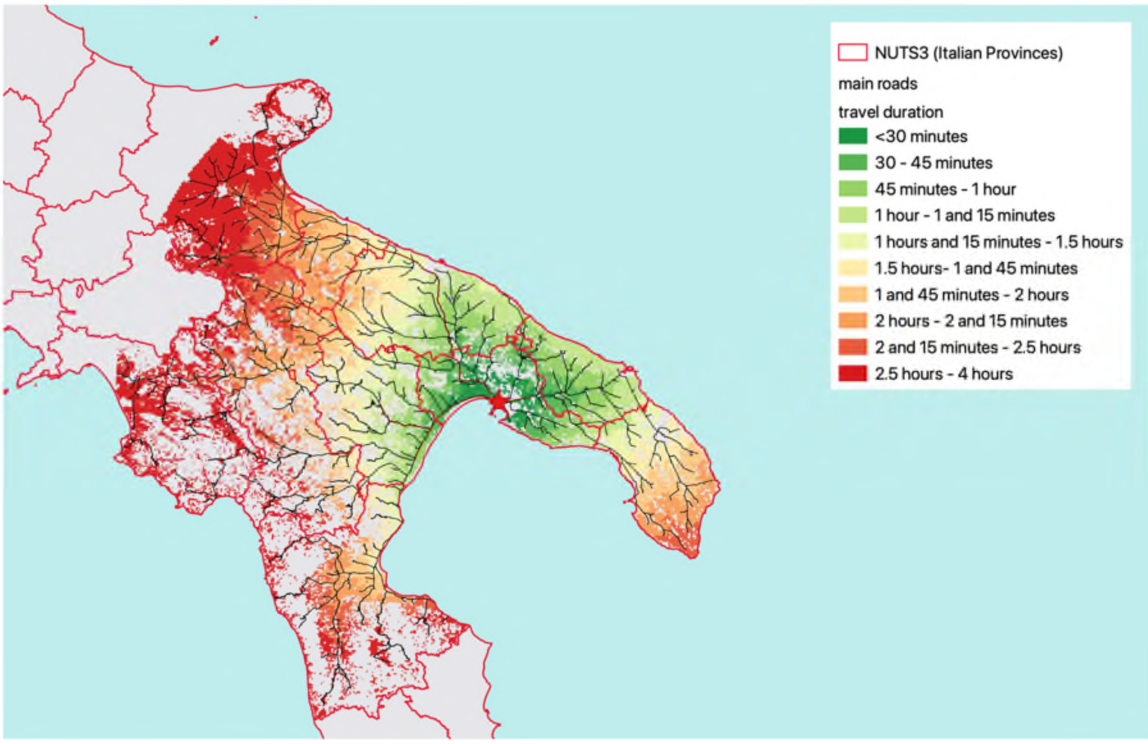

Figure 50 - Trip duration from each singlecell to the IBC plant.

3.4.3 Total biomass cost

Given the information gathered in the previous phases and the overall choices defined for the CS, the crops/logistics model gives as output the overall biomass and logistics costs.
These outputs are made available by the model at *single cell* level; they are then aggregated to be used as inputs for the CS techno-economic model. The availability of this great amount of data and scenarios as inputs could anyway be further exploited for sensitivity analyses addressing specific topics, such as the impact of the use of crops cultivated on marginal lands on the economics of the IBC plant.
As already described, the outputs from the crops/logistics model could slightly change across the various considered climate/crop/etc. scenarios. Anyway, in the Italian Advanced Case Study framework, this difference has been found to be negligible. In the techno-economic model, this variability it has instead been evaluated the possibility to obtain discounted purchase agreement thanks to their long timeframe. Figure 51 below reports the division in biomass total costs between feedstock and logistics. It is worth noticing that the lowest cost is obtained by olive pruning. As already pointed out in the previous chapter, this result is obtained due to the much lower biomass cost, when compared to the other biomasses[5], and to the overall lowers logistics cost as well (even if the difference is not pronounced). The *Arundo donax* is slightly penalized by the highest logistics cost, related to its distance from the IBC plant.

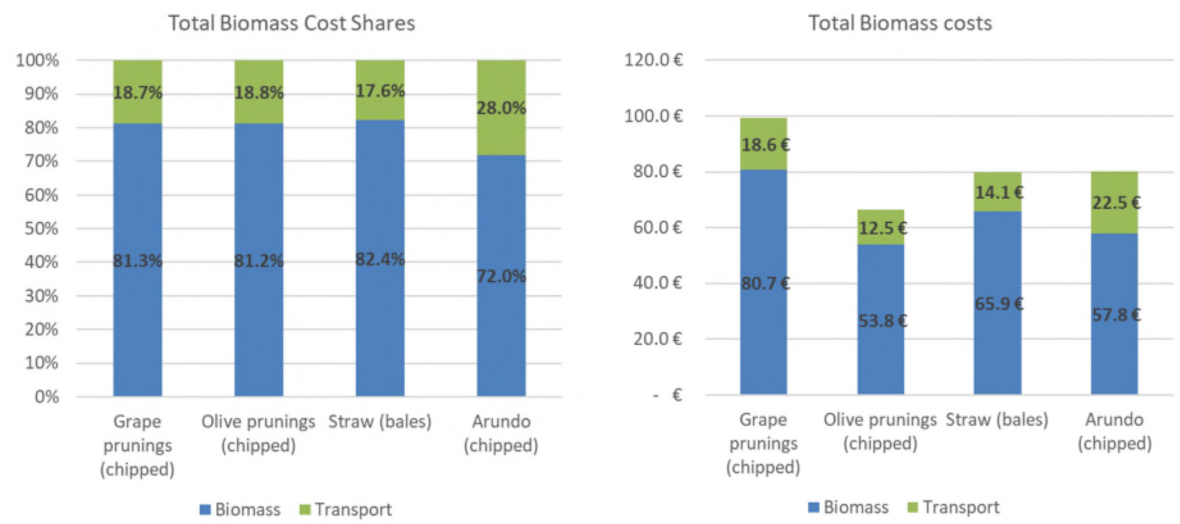

Figure 51: Total biomass cost (feedstock + logistics). Shares of the total (left); overall costs (right)

[5] As better explained in D4.2 on the biomass availability and logistics model, the biomass (feedstock) share of the cost does not only consider (when present) biomass costs, but also incorporates the harvesting and processing costs, occurring within the farm. The sum of these two costs favours olive trees when compared with vineyard residues, mostly because the harvesting of the vine shoots requires much more time, due to the espalier arrangement of the vine cultivation.

3.5 Scenario building and optimization

Chapter 3.2.4 provided an overview of the possible technical solutions for the integration of the IBC plant with a steel-making plant, especially regarding the Italian Advanced Case Study situation. It has been assessed the possibility of using the total biochar production as a partial replacement for PC consumptions; regarding pyrogas, a variable part of it was devoted to fulfilling the internal energy uses of the steel making plant, after being cleaned and having tar and moisture content removed. Moreover, it has been identified the possibility to use the existing coke plant by-product plant for pyrogas cleaning; this could have an impact on the IBC plant CAPEX, since it would remove the necessity for an additional pyrogas cleaning section. After cleaning the pyrogas, the incondensable gas fraction could be injected in the steel making plant gas pipeline to feed the power plant, while the condensed pyrolysis oil, with high calorific value, could be reused as liquid biofuel for bioenergy generation to be used on site - for example in the HRSG of the existing thermo-electric combined cycle plant - or further up-graded for external industrial uses.

In order to capture the effects on the IBC plant economics of all these parameters, together with the ones described in Chapter 3.2 and 3.4, a series of sensitivity analyses have been conducted:

- Plant CAPEX: the effect of a ± 10 % variation over the baseline value have been evaluated, in order to assess the impact of, i.e., remove the necessity for an additional pyrogas cleaning section on one side, and on the other of some additional, unexpected expenses.
- Pyrogas used for steel making plant energy uses: three scenarios have been evaluated, one where only around 15 % of total pyrogas is used to power the pyrolysis process, a second where the amount of pyrogas is raised to around 30 % and a final one where all the energy needs of the pyrolysis process are covered by the internally produced pyrogas (around 45% of the total). This last scenario avoids the necessity to divert some fraction of gas streams produced in the steel-making plant toward the rotary kiln, thus “decoupling” to some extent the IBC plant from the steel-making plant. For sake of simplicity, the pyrogas used to cover steel making plant energy needs has been considered as directly substituting an equal amount of Natural Gas, on energy basis.
- Total biomass costs: three scenarios have been evaluated, one with higher constant prices, obtained directly from current market prices; one with 10% lower constant prices, made under the assumption that long-term purchase agreement with farmers and transporters could help in lowering the overall prices of feedstock. Finally, a third one starting with the higher prices and linearly decreasing along the considered time period to the lower prices. This final scenario is the “*slower market*” version of the second one.
- Coal cost and NG cost: for both parameters, the results of a ± 10 % variation over the baseline value have been evaluated, to gain perspective on the effect of the existing market price variability.

- **EU Allowances (EUA):** three possible forecast scenario have been considered: one with lower prices, developed under the assumption that all key EU ETS parameters including Market Stability Reserve (MSR) and Linear Reduction Factor remain as currently set in legislation; a second taking into account a legislation influenced by the Green Deal, translating into a steeper emissions reduction curve and a third – EUA cancellation – focusing on the effect of coal phase out in power generation around 2025 on the market (see Figure 52). Given the long timeframe of the analysis, after year 2030 the EUA price trends have been "*frozen*" and capped in terms of maximum value, to avoid unwanted distortions to the entire techno-economic evaluation. Anyway, it should be stressed the high uncertainty related to these scenarios and to the overall price trends of the EUA, and the high impact that this has on the overall viability of the presented business case.

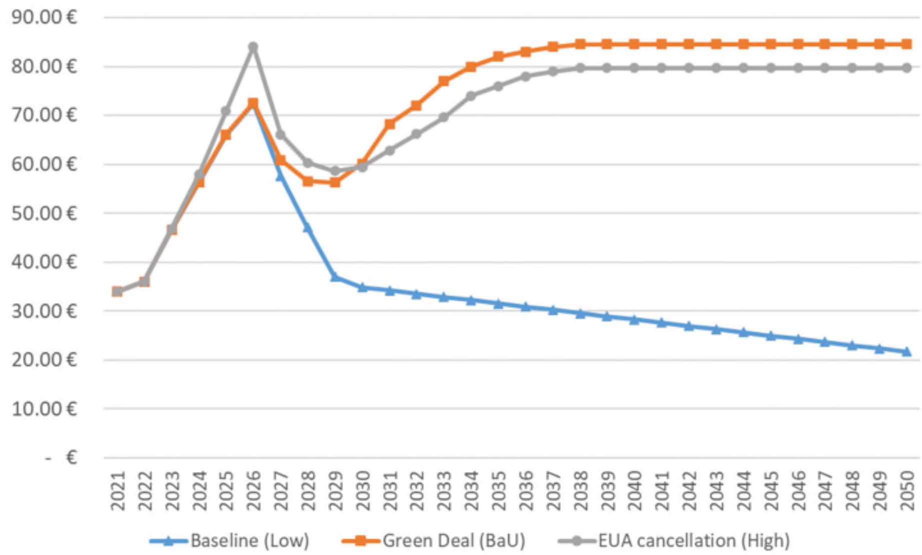

Figure 52: EU Allowances forecasted trends for the three different scenarios (source: Arcelor Mittal)

- **Green Steel premium:** the results of a ± 10 % variation over the baseline value have been evaluated, to gain perspective on the effect of a possible range of prices that customers could be willing to pay.

The values of all the parameters used for the techno-economic evaluation of the IBC plant are shown in Table 42 below.

Table 42: Summary of the values of the parameters involved in the techno-economic analysis

			Low	Baseline	High
Prices	Biomass price (dry)	€/t	82.5	82.5	93.4
	Coal price	€/t	99	110	121
	Natural Gas price	€/Nm3	0.18	0.2	0.22
	Electricity price	€/kWh		0.08	
Incentives / Premiums	Green carbon premium	€/t_C	75	83.3	91.6
	EUA price	€/t_{CO2}	variable	variable	variable

CAPEX / OPEX	CAPEX	€	65,642,069	72,935,633	80,229,196
	OPEX	€/yr	3,894,099		

Three meta-scenarios, obtained through a combination of the previous parameters, have then been defined, in order to evaluate favourable and unfavourable overall situations. The main parameters of such scenarios are shown in Table 43 below.

Table 43: Meta-scenarios parameters definition

Meta-Scenario	CAPEX	Pyro-gas	Biomass cost	Coal cost	NG cost	EUA price	Green Steel premium
Best Case	Baseline	15 %	Low	Actual	Actual	GD	Avg.
Baseline	Baseline	30 %	Low	Actual	Actual	Actual	Avg.
Worst Case	Baseline	45 %	High	Actual	Actual	Baseline	- 10 %

In the *Baseline* meta-scenario, biomass costs are considered in the lower range, while the EU allowances price is considered to be constant across the timeframe, on the same actual price levels.

The *Best Case* meta-scenario is built under the assumption of having wider access to COG and waste heat streams to provide energy to the pyrolysis process, thus making available more pyrogas for NG substitution. The EU Allowances prices are projected under the assumptions of the more favourable "Green Deal" scenario.

The *Worst Case* meta-scenario refers to a situation where the IBC plant needs to be energetically self-sufficient, where EU Allowances prices are projected under unfavourable trends and where the green steel premium is set to a lower level, due to reduced acceptance by the customers.

It could be noted that CAPEX, coal cost and NG cost parameters have been left unchanged across the three scenarios. This is related to the high inherent uncertainty that characterize these three parameters; thus, it has been decided not to use them to influence the resulting meta-scenarios, considering as sufficient their evaluation within the single sensitivity analyses.

Table 44 reports the standard values of the main technical and financial parameters that have been used to calculate the performance indicators of the IBC plant investment, such as Net Present Value (NPV), Internal Return Rate (IRR) and Pay Back Time (PBT), in the various scenario [59], [60].

Table 44: Financial parameters used for the techno-economic analysis

Depreciation	yr	10
Lifespan	yr	30
Discount Rate	%	7.0
Tax Rate	%	50

Net Present Value has been calculated as:

$$NPV = \sum_{t=1}^{n} \frac{NCF_t}{(1+DR)^t} - CAPEX$$

Where NCF_t is the Net Cash Flow at year t and DR is the Discount Rate.
Internal Return Rate IRR is calculated as follow:

$$NPV = \sum_{t=1}^{n} \frac{NCF_t}{(1+\overline{DR})^t} - CAPEX = 0 \ \rightarrow \overline{DR} = IRR$$

A research for literature sources and case studies has been made to define appropriate Discount Rate (DR) and Tax Rate (TR) for the project. Its findings highlighted a wide spread of possible values that could be attributed to such parameters. Considering TR, as an example, the World Bank Group defined a Total Tax and Contribution Rate (TTCR) in the report "Paying taxes 2020" [61], to measure how much tax businesses pay. TTCR is defined as the sum of all the taxes and mandatory social contributions paid, expressed as a percentage of the company's commercial profit. On average, it reported a 2018 TTCR of 59.1 % related to Italian companies, while the EU average remained a little below of 40 %.Considering only the specific Italian taxes on corporate income, such as IRAP and IRES led to lower Tax Rate, of around 28% [62]. In order to take into account the high variability of such parameters, as emerged from the research results, another sensitivity analysis has been performed on the *Best case* and *Worst case* meta-scenario, to evaluate the impact on NPV and IRR of various DR and TR values.

3.5.1 Case study feasibility results

Overall, the case study reported quite favourable results. *Baseline* meta-scenario indicators are shown in Table 45; only two of the analysed cases have proven as not economically viable, the *Low EU Allowance price* scenario and the *Worst case* meta-scenario. In the other 22 sensitivity analyses, scenario and meta-scenario evaluated the NPV ranged between -39.8 % and + 57.7 %, the IRR ranged between – 14.4 % and + 20.7 %, with respect to the baseline value. The PBT ranged between 12 and 19 years. These topics are discussed in greater detail in the following two sections.

Table 45: Performance indicators of the *Baseline* meta-Scenario

Baseline meta-Scenario		
NPV	PBT	IRR
39,188,690 €	15	11.1%

The PBT is longer than it could expected, especially when looking at IRR value. This is an effect of NCF variability: in the first years of the project NCF is expected to be lower than the lifespan average, as Figure 53 shows, and this postpone PBT. NCF variability is mostly an effect of EU Allowances price forecasts, since they are highly variable, as reported in Figure 52, and heavily impacting on overall plant revenues, as Figure 59 shows.

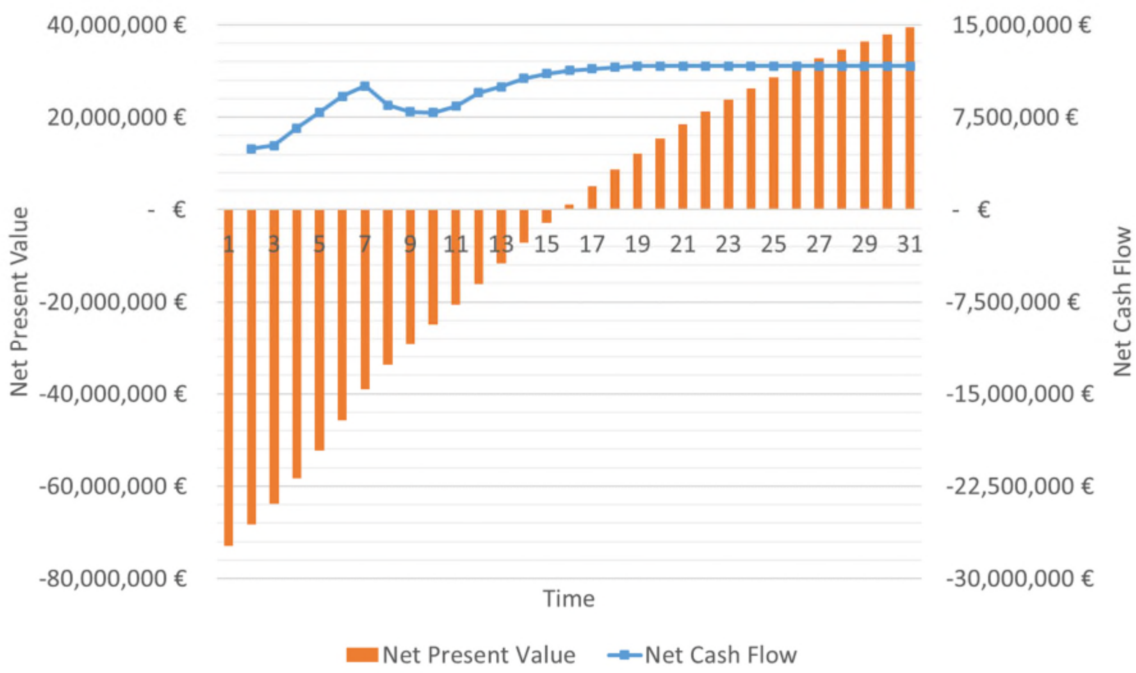

Figure 53: Net Cash Flow (NCF) trends and Net Present Value (NPV) variation across project lifetime

3.5.1.1 Sensitivity Analyses results

A first set of sensitivity analyses, as already mentioned in the previous section, has been conducted with a standardized methodology, regarding the range of variation of the main parameters, set within a ± 10 % range from the *Baseline* value (see Table 42).

Then, a second set comprising Biomass cost forecast scenarios and pyrogas use scenarios are separately reported, due to the different methodology applied for the selection of the main parameters value (scenarios vs variation range).

The results for the EU Allowance sensitivity analysis are not reported, since the Low-Baseline scenario proved to be not viable and the BaU-Green Deal and the High-EUA cancellation reported negligible differences. Anyway, as it will be better explained in the following section, EUA prices have one of the stronger impacts on the business case among all the parameters.

In order to allow for a simpler comparison between the various sensitivity analyses, the resulting NPV and IRR values have been normalized against the *Baseline* meta-scenario values, which were previously reported in Table 45. Thus, all the following pictures will present the results in term of positive or negative variations from the *Baseline* values. It should be noted that in all the sensitivity analyses Discount Rate is set at 7 % and Tax Rate at 50 %, as in the *Baseline* meta-scenario. Table 63 in the Annex reports the absolute values obtained for NPV, IRR and PBT in each sensitivity analysis, sensitivity scenario and meta-scenario, including the not viable ones due to negative NPV at the end of the plant lifetime.

CAPEX, Coal, Natural Gas, Green Carbon premium sensitivity analyses

Among the various parameters, Coal price and Natural Gas price variations have the stronger impact on NPV, as Figure 54 shows, with a more than proportional effect, while CAPEX variations have a slightly lower, less than proportional impact. The inverted trend of CAPEX with respect to the parameter variation is also evident: in fact, here a positive variation has a negative impact on the business case (for obvious reasons). The reason for having NPV positive effects generated by an increase of the price of coal or NG could anyway be less obvious; indeed, from the IBC plant perspective, coal and NG are considered in terms of their replacement, thus as avoided costs. Finally, Green Steel premium variations have the lower impact; this is due to the fact that unitary cost of the premium is lower and tied to the renewable carbon flow and not to the energy flow. Anyway, the effect of the Green Steel premium on the business case should not be underestimated; in fact, it accounts for around 11 % of revenues on average in the *Baseline* meta-scenario, as reported in Figure 59 in the following section.

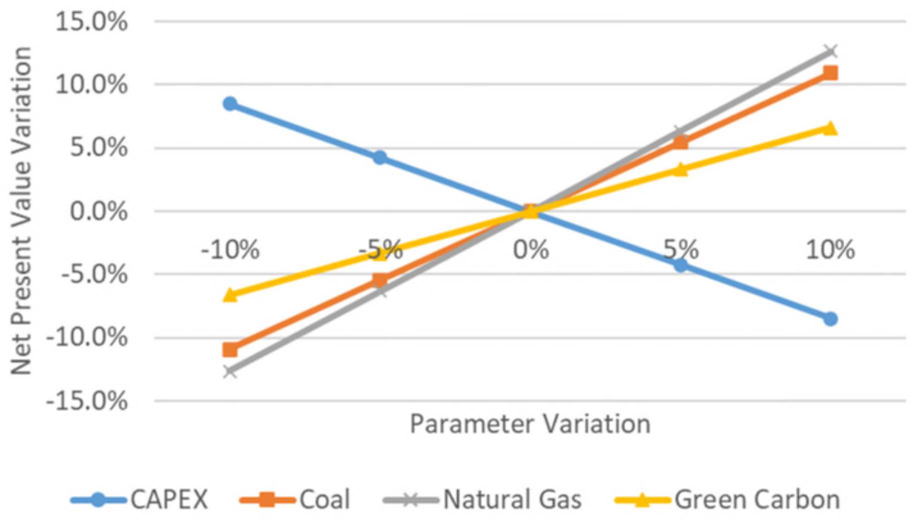

Figure 54: NPV variation (compared to Baseline) for the CAPEX, Coal, NG and Green Carbon sensitivity analyses.

Figure 55 below shows the trends for the IRR variation in a similar fashion. It should be noted that in this case the stronger impact is related to the CAPEX variations; overall, all the trends are less linear and asymmetric with respect to the Baseline point.

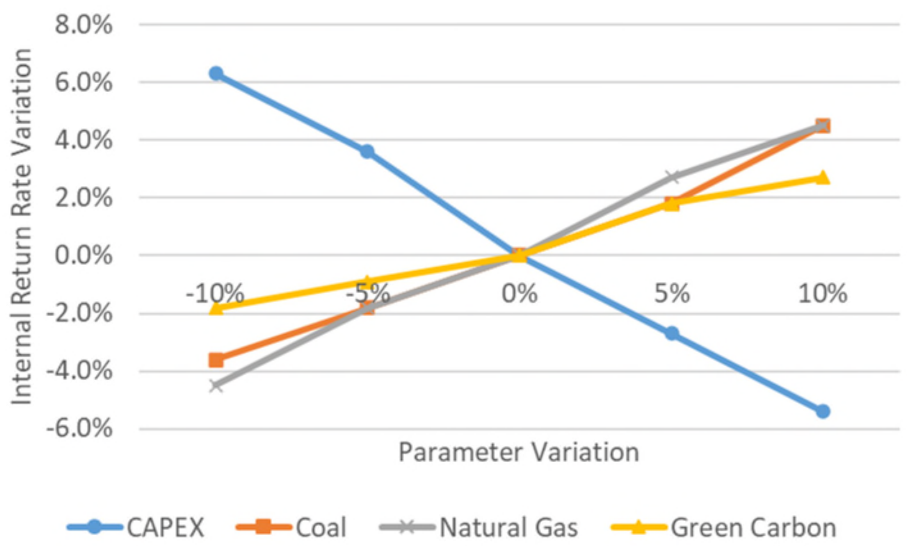

Figure 55: IRR variation (compared to Baseline) for the CAPEX, Coal, NG and Green Carbon sensitivity analyses

Total Dry Biomass Cost sensitivity analysis

Figure 56 highlight the importance of securing low biomass costs for a successful business case. As shown in Table 34, biomass purchase is the highest OPEX cost by far and its impact is more than substantial (in fact, the *Worst case* meta-scenario is the *Total Dry Biomass Cost-High* scenario).

Another clear information that stems out of Figure 56 is that low price, long term agreements should be secured from the start of the project, or at least in the first period of operation; in fact, a slow transition as the one depicted in the *High-to-Low* scenario doesn't seem to be highly beneficial, ending with results which are quite similar to the ones of the *High* scenario.

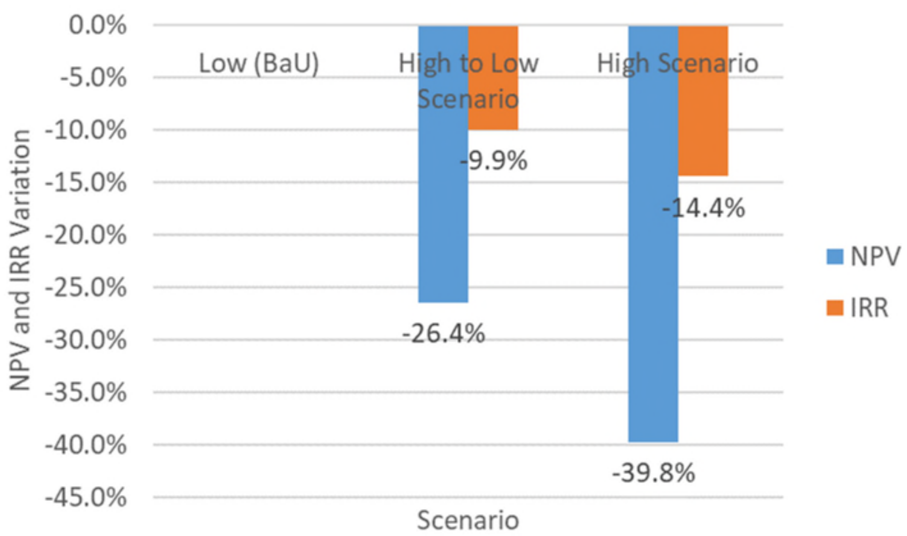

Figure 56: NPV and IRR variation (compared to Baseline) for the various scenario regarding dry biomass total costs

Pyrogas use for NG substitution sensitivity analysis:
Three scenarios have been evaluated: one where only around 15 % of total pyrogas is used to power the pyrolysis process, a second where the amount of pyrogas is raised to around 30 % and a final one where all the energy needs of the pyrolysis process are covered by the internally produced pyrogas (around 45% of the total).
This last scenario avoids the necessity to divert some fraction of gas streams produced in the steel-making plant toward the rotary kiln, thus "decoupling" to some extent the IBC plant from the steel-making plant.
Figure 57 shows that the impact of this parameters is the more substantial among all the evaluated ones: in fact, the resulting economic parameters of the *15% internal use* scenario are quite similar to the *Best case* meta-scenario ones, which is obtained with the further support of other favourable situations (see Table 43). The *Self-sufficient* scenario instead shows a quite detrimental result, near to the one of the *Worst case* meta-scenario. These results suggest that only a careful implementation of a synergistical integration of the IBC plant with the steel-making plant, in terms of mutual exchanges of energy flows, could allow to exploit all the existing potentials of this case study.

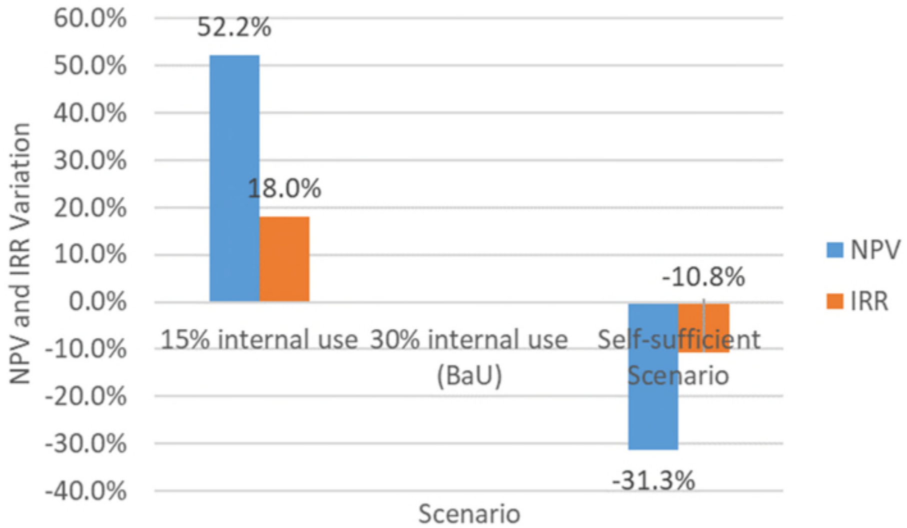

Figure 57: NPV and IRR variation (compared to Baseline) for the various scenario regarding pyrogas use

Finally, Figure 58 reports the different PBT obtained in the various scenarios for the sensitivity analyses. The parameters CAPEX, Coal, NG and Green Steel are shown separately from the Biomass Cost and Pyrogas use ones, due to the different definition of the variation ranges. This has also an impact on PBT variations, which are much more pronounced in the second set.

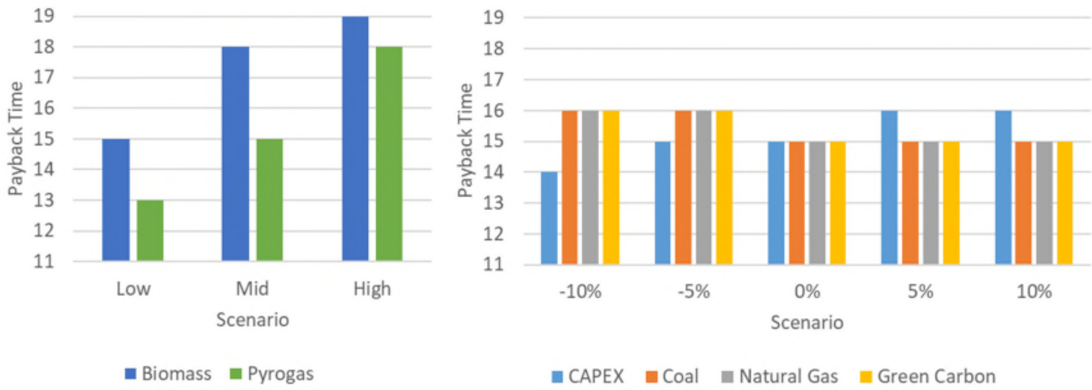

Figure 58:PayBack Time for the various sensitivity analyses, across the considered variation scenarios

3.5.1.2 Meta-scenario analysis results

The scope for the introduction of the meta-scenarios is to combine together plausible values of the various evaluated parameters, in order to move from sensitivity analysis to overall scenario evaluations. Table 46 reports a summary of the results; it is worth reminding that these results are obtained under the financial and operating parameters described in Table 43. While the *Baseline* meta-scenario has already been evaluated before, it can be noted that even the *Worst case* presents decent performance indicators, with the exception of a quite high PBT. Indeed, the *Best case* is accounted for good overall performance indicators and really good improvements with regards to the *Baseline.*

Table 46: Summary of meta-scenario performance indicators

Meta-scenario	NPV	Δ NPV	PBT	IRR	Δ IRR
Baseline	39,188,690 €	N.A.	15	11.1%	N.A.
Worst case	23,608,738 €	-39.8%	19	9.5%	-14.4%
Best case	61,804,793 €	57.7%	12	13.4%	20.7%

Figure 59 reports on the average impact of each revenue stream on the overall business case, as evaluated within the *Baseline* meta-scenario. It seems worth noticing the weight of EU Allowance prices and the Green Steel premium together account for more than 60 % of the total (green area in Figure 59), while material fossil carbon substitution is worth slightly less than 40 %.

Looking at the picture under a different perspective, Coal substitution with biochar triggers 64 % of the total revenues (more than 2/3 of it from incentives and premiums), with NG substitution complementing with 36 % (similarly shared, but in a less pronounced way).

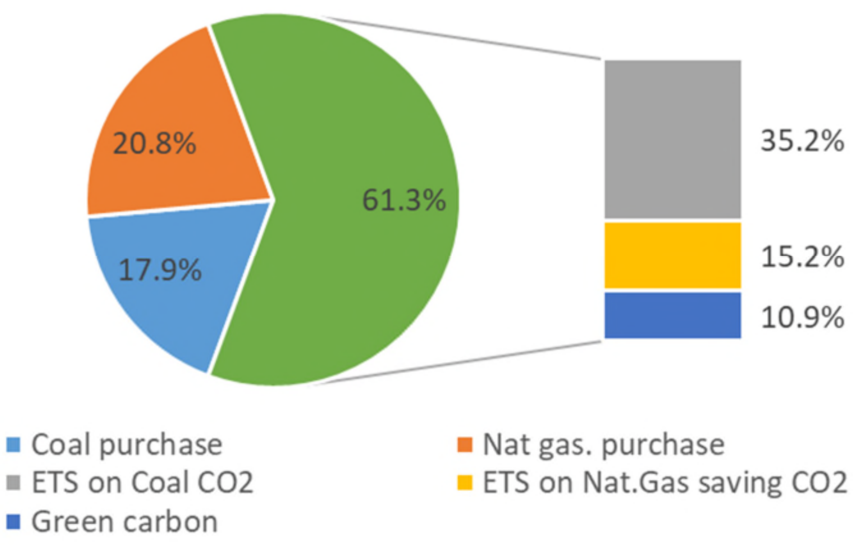

Figure 59: Breakdown of average expected revenues in the Baseline meta-scenario

Finally, the uncertainty in defining appropriate Discount Rate and Tax Rate for the project led to a last sensitivity analysis, performed on the *Best case* and *Worst case* meta-scenario to evaluate the impact of changing DR and TR on NPV and IRR.
For each meta-scenario three Tax Rate level has been evaluated, namely 30 %, 50 % and 70 %; the Discount Rate ranged up to 20 %. Anyway, as Figure 60 shows, the best IRR obtainable is 15 % for *Best case – TR=30 %*.

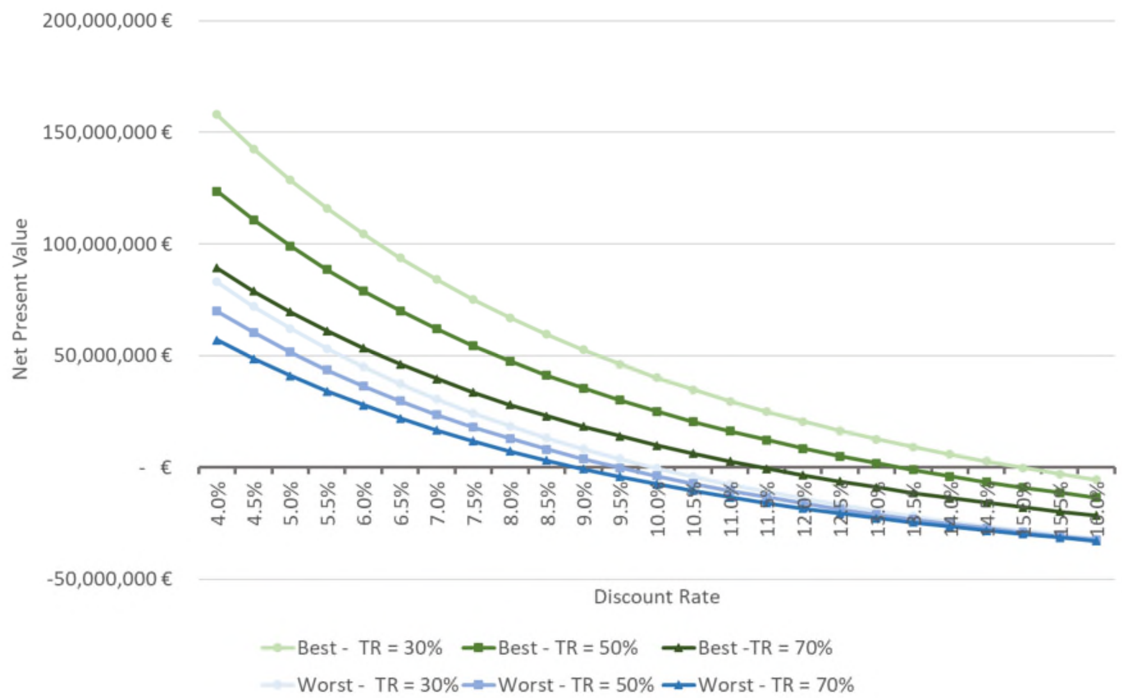

Figure 60: NPV trends as a function of DR (Discount Rate) and TR (Tax Rate) for the *Best case* and *Worst case* meta-scenarios (IRR can be evaluated as the intersection with the horizontal axis)

As expected, lower Tax Rates are more beneficial with higher NPV, such as in the *Best case.* IRR ranges across 13 % and 15 % for the *Best case* and between 9 % and 10 % for the *Worst case.*

In order to clarify the impact magnitude that the choice of i.e. Discount Rate has on project NPV, Table 47 reports the NPV variation within the *Baseline* meta-scenario as a function of the choice of Discount Rate and Tax Rate (when compared with DR = 7.0% and TR = 50 %). It can be appreciated that, all other parameters unchanged, applying a DR of 5.0 % instead of 7.0 % alone in the *Baseline,* leads to a 60 % increase in NPV.

Table 47: NPV variation (within the *Baseline* meta-scenario) as a function of Tax Rate and Discount Rate variations

TR	Discount Rate				
	5.0%	6.0%	7.0%	8.0%	9.0%
30%	108%	69%	36%	8%	-15%
50%	60%	27%	0%	-23%	-43%
70%	13%	-14%	-36%	-55%	-70%

3.6 Greenhouse gas emission

3.6.1 Environmental assessment according to RED II

According to the Renewable Energy Directive 2018/2001/EC the greenhouse gas emission savings from the use of biofuels, bioliquids and biomass fuels shall be (Article 29, paragraph 10):

e) at least 50 % for biofuels, biogas consumed in the transport sector, and bioliquids produced in installations in operation on or before 5 October 2015;
f) at least 60 % for biofuels, biogas consumed in the transport sector, and bioliquids produced in installations starting operation from 6 October 2015 until 31 December 2020;
g) at least 65 % for biofuels, biogas consumed in the transport sector, and bioliquids produced in installations starting operation from 1 January 2021;
h) at least 70 % for electricity, heating and cooling production from biomass fuels used in installations starting operation from 1 January 2021 until 31 December 2025, and 80 % for installations starting operation from 1 January 2026.

The total GHG emissions and the GHG emissions saving arising from the of IBCs are to be calculated in accordance with the methodologies and principles described in the EU RED II, and include the GHG emissions from the production and use as well as the extension necessary for including the energy conversion to electricity and/or heat and cooling produced. Special points for the calculation of GHG emissions are:

- Wastes and residues, including tree tops and branches, straw, husks, cobs and nut shells, and residues from processing, shall be considered to have zero life-cycle GHG emissions up to the process of collection.
- Emissions from the manufacture of machinery, equipment and infrastructure shall not be taken into account.
- Must include emissions from drying of raw materials, waste and leakages.
- Must include emissions from the processing itself, from waste and leakages and from the production of chemicals or products used in processing including the CO_2 emissions corresponding to the carbon contents of fossil inputs, whether or not actually combusted in the process.
- Include only non-CO_2 GHG (N_2O and CH_4) emissions for the use phase.
- In case of allocation during co-production:
    - Carnot efficiency for electricity and heat.
    - Energy content (lower heating value) in all other cases.

The GHG emission savings of the IBC value chains shall be calculated against specific fossil fuel comparators:

- 94 g CO_2 eq/MJ for transport fuels.
- 183 g CO_2 eq/MJ electricity or 212 g CO_2eq/MJ electricity for the outermost regions.
- 80 g CO_2 eq/MJ heat or 124 g CO_2 eq/MJ heat for direct physical substitution of coal.

3.6.2 Advanced case study assumptions

The advanced case study focuses on the use of the slow pyrolysis products (i.e. pyrogas and char) into an existing steel making plant, in particular using biochar into a blast furnace for iron production, as a partial substitute of pulverized coal. Pyrogas, instead, is used as a partial replacement of Natural Gas already used in the steel making plant, mostly for process heat needs (see Figure 39). In the present scenario the IBC plants consists in a rotary kiln pyrolizer, indirectly heated by part of the pyrogas produced from pyrolysis, and are located inside the ArcelorMittal' steel making plant in Taranto, due to the necessity to centralize all conversion plants in the same site to improve the overall energy balance of the value chain.

For the **advanced case study**, a value chain concerning the production of charcoal/pyrogas from regional biomass for use in the Arcelor Mittal steel mill in Taranto (Puglia, South of Italy) has been researched. Feedstocks to be considered include olive pruning, grapevine pruning, straw and *Arundo donax*. Table 38 provides the properties and the seasonal availability of the selected biomass feedstocks for pyrolysis unit.

As already explained in Ch. 3.4, the needed biomass quantities are projected at local level, through GIS processing. Table 39 summarizes the wet and dry yearly quantities for each biomass type, for each climate and rotation scenario, plus an average value across the scenarios.

It can be seen that only Olive and Straw shares slightly variate across scenarios. This is due to the fact that they are collected together in the same months, so they both concur to the 21 kt/month of dry biomass target; in the other months there is only one type of biomass available, so the quantity is the one needed to fulfil the target. From an environmental perspective, these variations in biomass quantities are considered negligible, so for the calculation of the GHG emissions the average value across the scenarios was employed. Grapevine prunings, olive tree prunings and straw are categorized as residues according to the RED II, so they do not carry any life-cycle GHG emissions up to the process of collection, on the contrary, *Arundo donax*, as an energy crop bears the emissions from the cultivation process.

Prior to transportation to the IBC plant, the different biomass feedstocks are pre-treated inside the farm, possibly at the farm's gate where the pre-treated biomass is collected:

- Ligno-cellulosic biomass → chipping
- Herbaceous biomass → bales (squared)

The total distance for the transport of biomass to the IBC plant is the sum of all the voyages needed, on a cell basis. Under the hypothesis of using only a truck similar to the one in Figure 61 (dimensions 8x2.44x2.6m, capacity 8t of chipped wood / 8t of squared bales), as a rough estimation, around 1.6 Mkm are needed every year to bring the total amount of wet biomass to the IBC plant. This translates into 12.800 ktkm in a yearly basis.

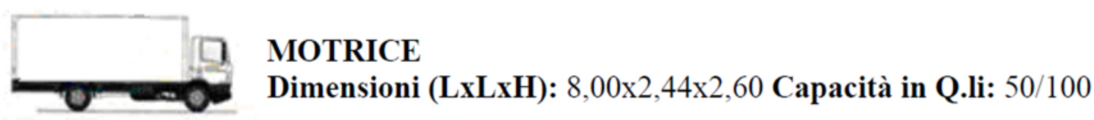

Figure 61. Characteristics of the truck used for biomass transportation.

All the main input and output energy and mass flows of the IBC plant in the main scenario are summarized in Figure 41. It considers a centralized IBC plant integrated within the steel making plant in Taranto; the steel-making plant provides part of the energy needed for the process heat, using the thermal and chemical energy of the Coke Oven Gas (COG). The biomass feedstock to char and pyrogas ratio could be slightly variable for the various feedstocks; an average 27% dry biomass-to-biochar ratio and an average 73% dry biomass-to-pyrogas (comprising gas, organics and reaction water) ratio has been considered for the calculation.

In the main scenario, considering a centralized and integrated IBC plant, the process heat required by the pyrolysis process is expected to be partially covered by the COG from the coking process. Around 30 % of the pyrogas is used in the IBC plant to cover part of the pyrolysis energy needs, while the rest is used to cover energy needs in the steel-making plant. In this study it is considered as replacing part of the Natural Gas used in the steel-making plant, mostly for process heat needs.

The whole amount of biochar produced is used in the blast furnace, as a partial replacement of pulverized coal. Thus, it is sent to coal grinding together with fossil coal and then injected in the blast furnace through the Pulverized Coal Injectors. The properties of char and pyrogas (LHV) are:

- Char: 28 MJ/kg (from RE-CORD experimental works and analyses)
- Pyrogas: around 10.6 MJ/kg (considering also the moisture content from the input biomass)

The biomass dryer, as illustrated, lies inside the boundaries of the IBC plant and is considered as a part of the integrated process; however, it does not obtain the necessary heat from the COG but rather from waste heat recovery. Another option sees the use of part of the pyrogas to provide the heat needed for the drying process.

3.6.3 Advanced Case Study results

The GHG emission are calculated with the use of the SimaPro v9.1. software under the impact assessment method Greenhouse Gas Protocol adjusted to fit the methodology and principles of the RED II. The results of the environmental assessment of the Italian Advanced Case Study are summarized in Table 48 below.

Table 48: Results of the GHG emission calculations

GHG emissions (kg CO2eq)				
Feedstock	Grape	Olive	Straw	Arundo
Stage				
On-field operations	1.110.000	780.000	1.860.000	3.840.000
Transport	915.000			
Drying	1.730.000			
Pyrolysis (Coke oven)	18.600.000			
Pyrolysis (Pyrogas)	33.256			
Total	28.868.256			
Allocation (energy based)	Biochar		Pyrogas	
	51,62%		48,38%	
Biochar use	371.815			
Biochar grinding	258.000			
Pyrogas use	112.307			
GHG (g/MJ fuel)				
Biochar	8,754			
Pyrogas	8,466			
GHG emission savings				
Biochar (replacing coal)	90,35%			
Pyrogas (replacing NG)	88,24%			

From the evaluation of the overall value-chain that supplies ArcelorMittal' steel making plant in Taranto with char and pyrogas, we calculated that they are emitted **8,754 gr CO_2 eq per MJ of char** and **8,466 gr CO_2 eq per MJ of pyrogas** resulting in a **90,35 % GHG emission savings** in the case of direct physical substitution of coal and **88,24 % GHG emission savings** for the replacement of Natural Gas for process heat needs. The environmental performance of the IBC value chain can be described (and in comparison, with the typical values of GHG emission savings given in RED II) as particularly good. Two points that need to be addresses in order to reach higher GHG emission savings are:

- The use of trucks with 8 tons capacity for the transport of biomass. Although the size of the trucks is largely determined by the condition of the road network, a larger capacity truck will offer a transport with lower emissions per ton of biomass. Furthermore, it could also be considered the employment of intermediate storage points and several different means of transport adapted to the needs and particularities of the transport network.
- Coke Oven Gas use for the pyrolysis process accounts for about 72% of total GHG emissions. The utilization of pyrogas in the pyrolysis process will greatly improve the environmental footprint of the IBC plant.

The quantified value-chain of the Italian Advanced Case Study is presented in Figure 62.

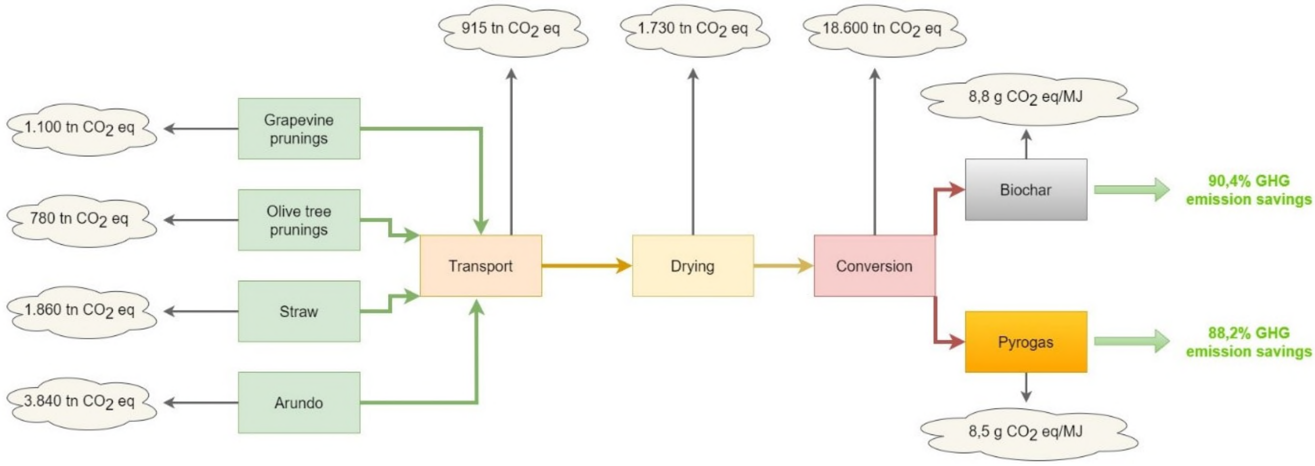

Figure 62: GHG emissions and savings of the IBC value chain

3.7 Final remarks

INFER-NRG model assessed that the considered Southern Italy areas could be able to provide enough biomass to fulfil the needs of the modelled IBC plant, year-round. In fact, a 50 % higher monthly request has been successfully evaluated, as a safety measure to ensure a wider basin of availability in case of unfavourable events that could lead to reduced biomass availability.

The average total price of dry biomass for the IBC plant use has been assessed for each crop type, with an average value ranging from 82.5€/t to 93.4 €/t.

The IBC plant operations and the possible integrations with the steel-making plant have been carefully evaluated and translated into the developed techno-economic model. The biochar has been conservatively considered as a partial replacement for PC consumptions, thus, it would be mixed with raw coal before entering the grinding units.
The use of pyrogas for the replacement of fossil streams in the steel-making plant posed higher technical and logistic issues. After confrontation with Arcelor Mittal, it remained confirmed the possibility to use it for energy uses in the steel making plant, both the incondensable gas fraction, that could be injected in the steel making plant gas pipeline to feed the power plant, and the condensed pyrolysis oil. To do so, it could be possible to use the coke oven by-product plant located near to the Coke Oven; otherwise, an additional pyrogas cleaning unit should be considered within the IBC plant.

Overall, the case study reported quite favourable results. *Baseline* meta-scenario reports an NPV of 39,188,690 €, a 15 years PBT and an IRR of 11.1%. Only two of the analysed cases have proven not to be economically viable. In the other 22 sensitivity analyses and meta-scenario evaluated the NPV ranged between -39.8 % and + 57.7 % in comparison to the *Baseline* meta-scenario value, while the IRR ranged between – 14.4 % and + 20.7 % with respect to the *Baseline* meta-scenario value. PBT ranged between 12 and 19 years.

Looking to the impact of the various parameters involved into the techno-economic evaluation, the importance of securing low biomass costs right at the beginning of the project, for a successful business case, stands out clearly. In fact, a slow transition toward better purchase agreement does not seem to be highly beneficial, ending with poor financial results.

Another high-impact parameter is the amount of pyrogas used to power the pyrolysis process: in fact, the economic parameters of the scenario that use most of the pyrogas for NG substitution are quite similar to the *Best case* meta-scenario ones, which is obtained with the further support of several other favourable situations. The *Self-sufficient* scenario instead shows a quite detrimental result, near to the one of the *Worst case* meta-scenario. These results suggest that only a careful implementation of a synergistical integration of the IBC plant with the steel-making plant, in terms of mutual exchanges of energy flows, could allow to exploit all the existing potentials of this case study.

It seems worth noticing the weight of EU Allowance prices and Green Steel premium, that together account for more than 60 % of the total, while material fossil carbon substitution is worth slightly less than 40 %. Finally, the effect of the Green Steel premium on the business case shouldn't be underestimated; in fact, it accounts for around 15 % of revenues on average in the *Baseline* meta-scenario.

4 Torrefaction to replace lignite coal: the Greek case study

4.1 Introduction

Western Macedonia (NW Greece), also known as the energy pillar of Greece, is presently in the middle of a major transition from lignite to green renewable energy sources as, in September 2019, Greece announced that the country will gradually phase out the use of lignite in power plants. This decision includes the ceasing of operations of the existing Public Power Corporation (PPC) lignite units by 2023, except Ptolemaida's unit VI, which will be closed by 2028.

This prospect, apart from being a serious blow to this region's GDP and employment (the economic activity in Western Macedonia is heavily dependent on PPC's activities), is also a key blow to the municipal district heating companies in the areas of Amyntaio, Ptolemaida and Kozani. DETEPA (district heating company of Amyntaio), in order to face the closure of the local Combined Heat and Power (CHP) plant, implemented a 30 MW_{th} biomass-fired district heating plant to completely cover the demands of the 3,000-5,000 residents of the area. On the other hand, DETIP (district heating company of Ptolemaida) and DEYAK (district heating company of Kozani) are in dire straits. DETIP currently utilizes up to 100 MW_{th} of heat, produced in PPC's Kardia Power plant and DEYAK utilizes up to 137 MW_{th} of heat, produced in Agios Dimitrios Power Plant. As a result, there is an immediate and urgent need for alternative fuels for these units. A solution that can provide multiple benefits to the local economy (increase of rural income, enhancement of energy sustainability and mitigation of lignite phase-out consequences) is the mobilization and use of locally available biomass. In general, Western Macedonia presents a significant amount of biomass potential (**Figure 1**), especially in the regions of Kozani and Florina, due to the large agricultural activity. More specifically, biomass residues are widely available, though only a small fraction is collected and utilized -mostly as fodder-, while the remaining amounts are cut and left on the field or usually burned. This is due to the lack of organized biomass supply chains that can overcome its high spatial distribution and seasonality. In addition, a major obstacle is the high cost for handling, transporting and storing biomass and relevant residues.

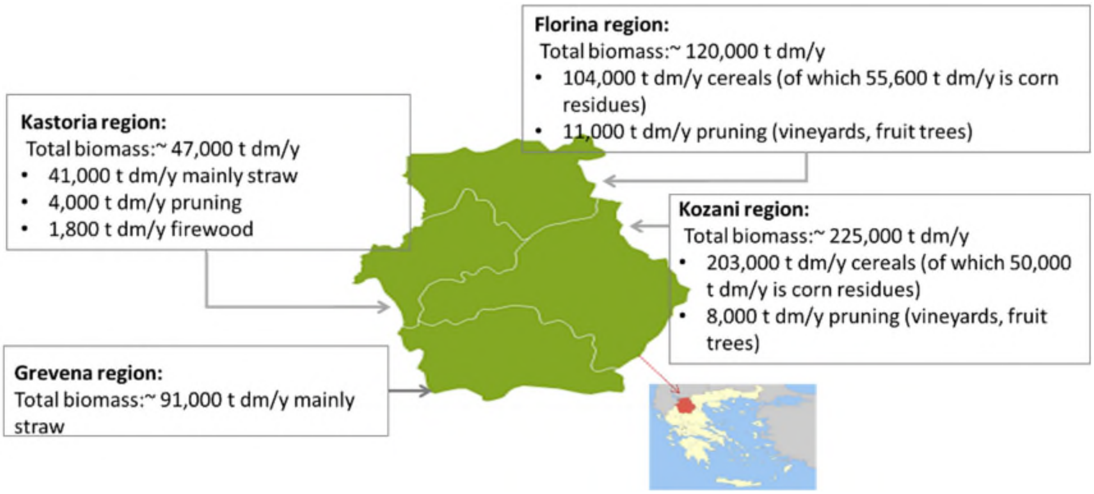

Figure 63. Biomass potential in Western Macedonia.

DETEPA's position on bioenergy is important for the development and establishment of a biomass value chain in Western Macedonia. Although DETEPA (30 MW_{th}), is the smallest of the three district heating companies in the region of Western Macedonia (DEYAK – 137 MW_{th}, DETIP – 100 MW_{th}), however, implemented the first district heating plant that uses local biomass on a large scale in the region. In brief DETEPA's background:

- Established in 1997, according to the Municipal law (410/95), as a public body, owned 100% by the municipality of Amyntaio, in order to administrate the District Heating (DH) system.
- Constitutes a Municipal Company, intended to construct and Operate all the necessary DH infrastructure, develop and utilize RES projects.
- Operates an extensive network connecting approximately 2.000 public and residential buildings.
- Originally constructed during 2000-2004, the district heating network is being expanded to cover a larger share of the wider area of Amyntaio heating requirements.
- The Amyntaio district heating project is the third project of its kind in Greece following similar projects in Kozani and Ptolemaida.
- The system has been installed in the wider region of Amyntaio by municipal services, due to co-financing.
- The core of the investment program for the DH system of Amyntaio is the installation of a new biomass combustion plant to serve Amyntaio's existing district heating system as well as its future extensions. The thermal energy production unit is biomass-based. It has a total capacity of 30 MW (2×15MW) and will cover the thermal needs of the existing district heating network in the villages of Amyntaion, Filotas, and Levaia as well as future thermal needs.
- From 2005 until 2020, received its heat capacity from Amyntaion power plant.

Thermal energy consumption from district heating stood at 42.732 MWh in 2015 and 44.220 MWh in 2016. Anticipating a population increase in the near future, the plant has a nominal capacity of 60.000 MWh/yr, requiring approximately 18.000 tn of raw biomass to completely cover the thermal demand (Annex – Table 4), a relatively large amount to mobilize, especially in an underdeveloped biomass supply market. For this reason, the combustion unit of the district heating plant was designed for mixtures of lignite and biomass with typical moisture rates of 25% and 45%, respectively. The boiler technology is based on grate firing – able to operate with high-ash and/or low-ash fuels. DETEPA mainly utilizes a fuel mix of wood-chips and lignite in a 50%-50% ratio (energy based). Besides wood-chips, DETEPA uses char from a local gasification unit, as well as, other types of biomass like waste wood, wood pellets, fruit tree and vineyard prunings (information about the properties of these materials is given in the Annex – Table 5). Woody biomass is easier and cheaper to be handled and fed into the combustion unit. Corn residues and straw, due to their physical properties, require additional treatment in order to be transported and stored in lower costs and to prevent any problems in the feeding system of the district heating plant.

To this purpose, the conversion of agricultural residues to Intermediate Bioenergy Carriers (IBC) is considered. IBCs are produced from biomass (forest biomass, agricultural biomass, energy crops, and waste). Biomass is processed via different conversion routes, namely, thermo-chemical conversion, physical-chemical conversion and bio-chemical conversion to energetically denser, storable and transportable intermediate products, analogous to coal, oil and gaseous fossil energy carriers, for easier transport, storage and use than biomass residues. IBCs can contribute to energy security, reduce greenhouse gas emissions and provide a sustainable alternative to lignite in Western Macedonia.

4.2 Torrefaction technology

Torrefaction refers to the thermal treatment of biomass, where raw biomass is heated in an inert atmosphere at temperatures between 200-320 ^{o}C (temperature depends on feedstock and degree of torrefaction) to generate an upgraded solid fuel (Figure 2).

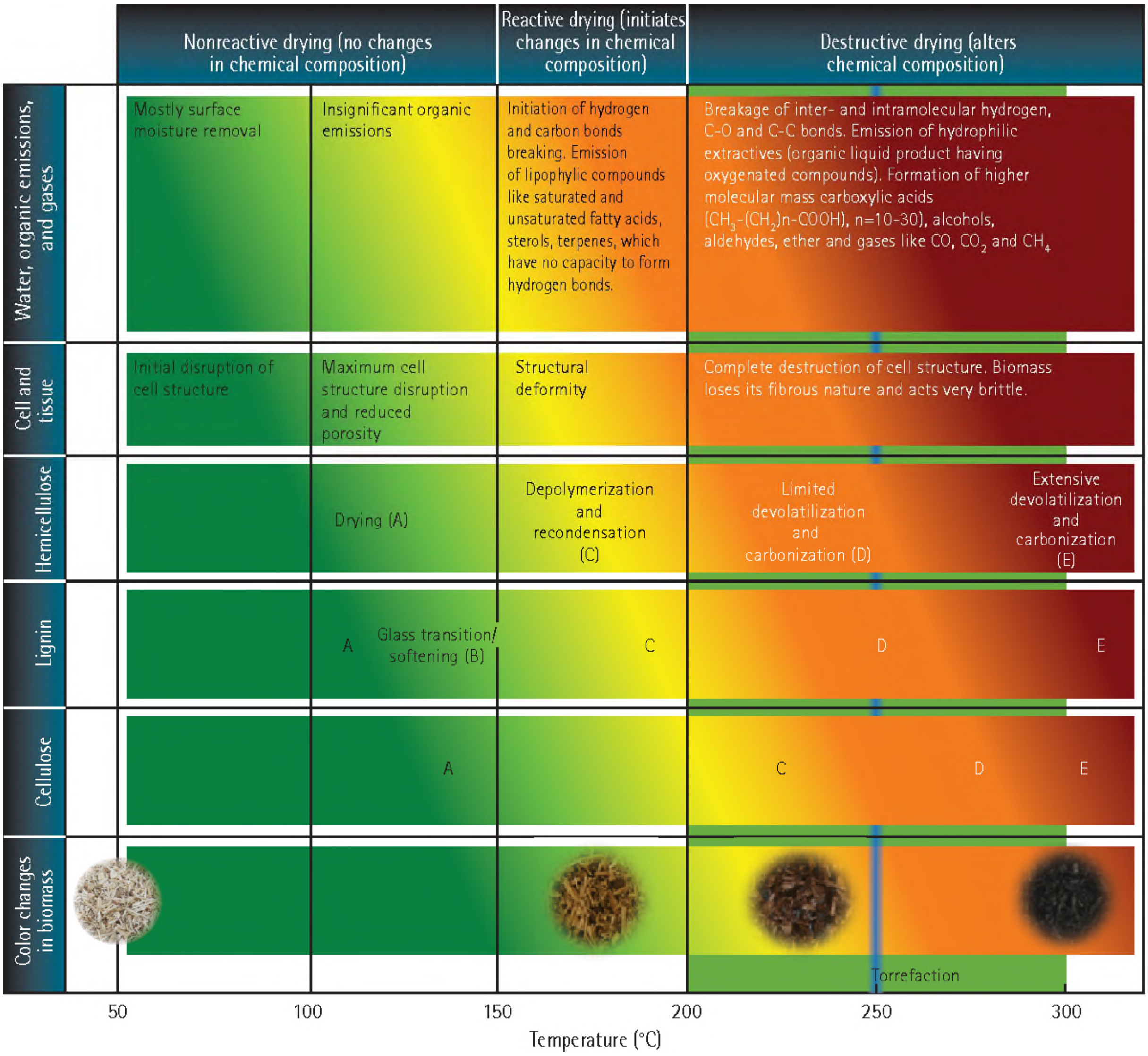

Figure 64. Physiochemical changes in biomass during torrefaction (image from Bergman et al. 2005).

During torrefaction, three products are generated (Annex – Table 6):

1. Brown to black uniform solid biomass, used for bioenergy applications.
2. Condensable volatile organic compounds comprising water, acetic acid, aldehydes, alcohols, and ketones.
3. Non-condensable gases like CO_2, CO, and small amounts of methane.

The gaseous product of the torrefaction process, also referred to as torr-gas, is combusted to generate heat for the drying and torrefaction phases of the overall process (Figure 3).

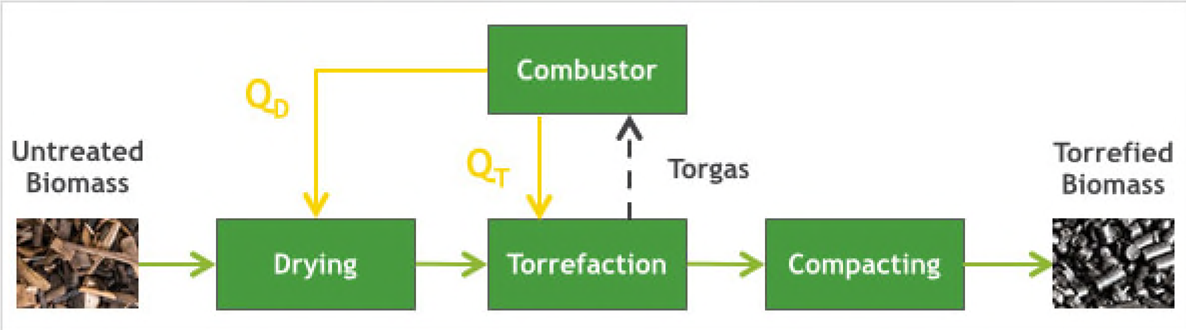

Figure 65. Simplified schematic of the torrefaction process (image from Torr-Coal).

4.2.1 Torrefaction process

The torrefaction process can be divided into distinct phases: Heating, drying, torrefaction, and cooling. The drying process is subdivided into two phases, making torrefaction a process that consists of five different phases, as explained below:

1. Heating. Biomass is heated until the drying temperature is obtained and the biomass' humidity starts to evaporate.
2. Pre-drying. Occurs at 100 °C, when the present in biomass free water evaporates under constant temperature.
3. Post-drying. The temperature is increased up to 250 °C. The residual water, present on biomass chemical bonds, is completely evaporated. This phase is responsible for mass loss due to the evaporation of several biomass components.
4. Torrefaction. Main phase of the process. It occurs at 250 °C and is responsible for the main mass loss. The torrefaction temperature (TT) is defined as the maximum used stable temperature.
5. Cooling. To avoid auto ignition, the final product is cooled below 50 °C before it contacts atmospheric air.

There is a wide range of parameters that affect the torrefaction process and the product characteristics. These parameters include temperature, residence time, heating rate, atmospheric composition, control of process instability and reactor type.
Although there are not many studies dealing with the optimization of the above parameters, an ideal process would ensure the maximization of the quality of the torrefied biomass production.

4.2.2 Torrefaction technology status

Different reactor configurations, which were originally developed for other applications, have been modified for biomass torrefaction. Some torrefaction technologies are capable of processing feedstock with only small particles such as sawdust, whereas others can process large particles. Only a few reactor types can handle a wider range of particle sizes (Annex – Table 7).

This means that the selection of the applied technology should be based on the characteristics of the feedstock, or alternatively, the feedstock needs to be pre-processed, prior entering the torrefaction reactor. The need for size reduction equipment, such as scalpers for handling over-sized material or sieves for recovery of small particles, will increase both capital and operating costs of a torrefaction plant. This should be counterbalanced by the lower cost of feedstock that requires such pre-processing.

Potential environmental, health and safety concerns associated with torrefaction process include the:

- dust produced by torrefaction presents a similar fire hazard risk with charcoal (which has been known to spontaneously combust). The volatiles potentially present in torrefied biomass also present a fire hazard. Suitable care is therefore required to minimise dust accumulation. The combustion risk may require active management through addition of fire retardants or handling within an inert atmosphere.
- depending on the feedstock and the process conditions, the torrefied biomass may also contain crystalline silica or other materials which require limited exposure.
- condensable and non-condensable gas compounds may require safe handling and/or special treatment or disposal methods.
- leaching characteristics of torrefied biomass compounds is not yet fully understood and may be of concern depending on the feedstock and process conditions.
-

4.2.3 Torrefied biomass properties

During torrefaction, biomass is upgraded to a solid fuel of better characteristics for handling and energy exploitation. The torrefied products show relatively similar characteristics as coal. Torrefaction combined with densification provides an energy dense fuel of 19 to 24 GJ/tn (Annex – Table 8).

4.3 Implementation of a torrefaction unit to serve district heating plants

In general, the success of DETEPAs endeavour with biomass utilization will greatly affect the other two district heating companies, DEYAK and DETIP, perhaps even the PPC which is in transition phase and is exploring its options for the operation of the new unit, Ptolemaida V. Accordingly, the existence of biomass end-users, will stimulate the interest of local farmers and agricultural cooperatives, to channel this hitherto almost untapped part of agricultural production. Thus, leading to the creation of synergies between the relevant stakeholders, generation of additional agricultural capital and consequently the creation of a stable and sustainable biomass market. As a next step, this biomass value chain could be upgraded and developed to include corn residues, through the conversion to IBCs (torrefaction). This will improve the physical and chemical properties, provide added value to biomass and also foster a secondary market of standardized solid energy products for channeling, in the domestic and international market (Figure 4).

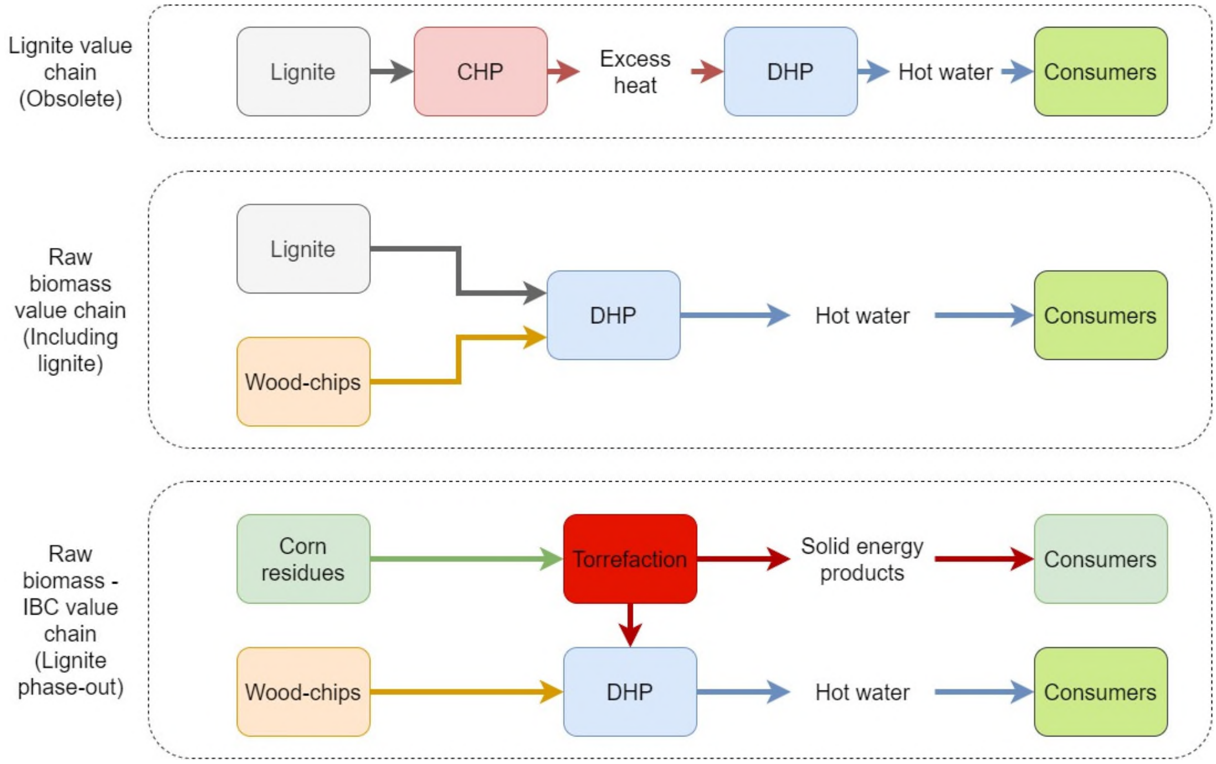

Figure 66. Obsolete lignite value chain and potential raw biomass - IBC value chains.

In this context, the advanced case study deals with the conversion of agricultural residues, such as corn cultivation residues, to IBCs through torrefaction (thermo-chemical conversion) and their subsequent utilization -as alternative to lignite- in the district heating plant of DETEPA. Torrefaction could be greatly beneficial for DETEPA, as a biomass treatment method, by increasing the energy and bulk density of corn residues, improving the physical properties for better handling and solving the feeding system problem, minimizing storage capacity requirements and creating an energy product with added value. Therefrom, DETEPA has the opportunity to expand its activities and also become a seller of standardized solid energy products.

The feasibility analysis of the novel (upgraded) value chain for the district heating plant of DETEPA as well as the local conversion to IBCs are analysed in the following paragraphs. Firstly, presented the different biomass types that torrefaction could be beneficial for. Then, based on spatial availability of corn residues, a potential location for the torrefaction unit is provided, followed by the analysis of the biomass supply chains and particularly the collection procedures. In Western Macedonia, there is not a developed supply chain for agricultural residues. Besides the lack of end-users, the uncertainty regarding the economic part of the collection procedures, is the most important reason. This analysis tries to shed some light on the cost per stage of the biomass value chain and identify any problems and obstacles about the physical supply chain. Finally, after defining the operational parameters of the torrefaction unit, a simplified mass-energy balance model and a supply chain optimization model were employed to determine the capital expenditure (CAPEX) and the operational expenditures (OPEX) of the torrefaction unit. 6 months and 12 months are considered as the two different options for the operating time of the torrefaction unit. The comparison between the prices of the current fuel-mix and the operating time options indicates the feasibility of torrefaction in the case of DETEPA.

A visualized summary of the results is provided in **Figure 5.**

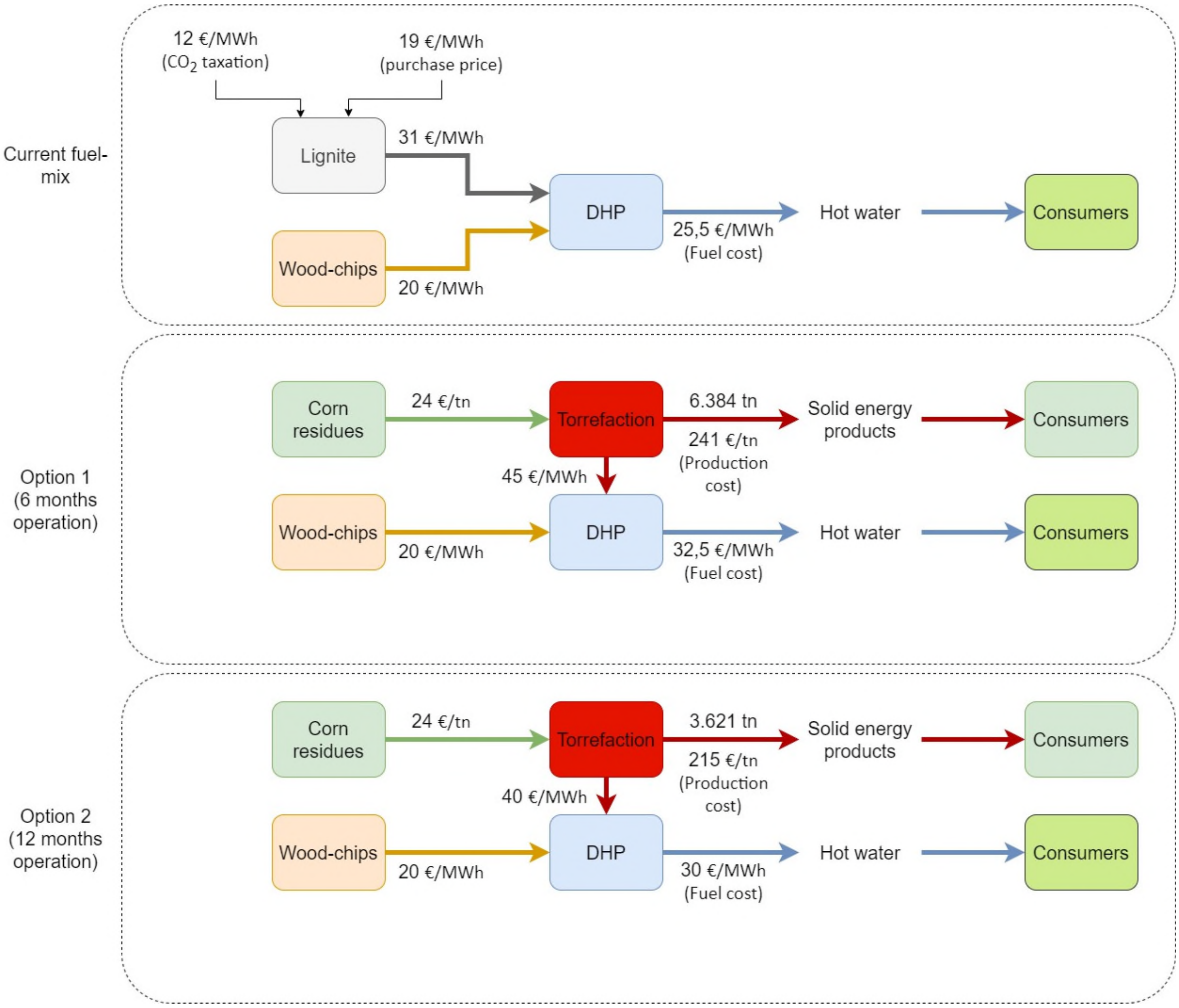

Figure 67. Fuel-mix cost of each value chain.

4.3.1 Types of biomass feedstock

Based on the technical specifications of DETEPAs district heating plant and the current infrastructure conditions, woody biomass can be handled and utilized without issues. Problems arise with the non-woody materials such as corn residues. Where the physical and chemical characteristics of this biomass type creates a series of problems, especially in the feeding system. At this end, torrefaction in the case of DETEPA should primarily contribute to improve the properties of corn residues.

4.3.2 Biomass availability – Location of the torrefaction unit

Western Macedonia presents a significant amount of biomass potential, as shown in Figure 1, particularly Kozani and Florina region, where DETEPA's district heating plant is located.
Based on a simplified spatial analysis there are potentially available 51 tn dm of biomass per km^2 annually in the region of Western Macedonia, where 35% (18 tn dm/km^2) are corn residues. According to the thermal need of the district heating plant (Annex – Table 9), the required biomass for the torrefaction unit can be found in an area (Annex – Figure 9) of 13 km radius around DETEPA (potential location of the torrefaction unit). As a worst-case scenario, is considered, that all the required biomass is located on the circumference of the circular area. A factor of 1,8 is used to correct the difference between the straight line and the actual transport network. Consequently, the transport distance for biomass to reach the torrefaction unit is considered 23,5 km. Ultimately, it is possible to mobilise biomass from a relatively close distance with correspondingly low transport costs, without import of additional biomass from neighbouring regions.

4.3.3 Biomass supply chain – Collection & Transport

The most important factors that will determine DETEPA's decision in torrefaction are the CAPEX and OPEX and their effect on the final price of fuel per MWh. A significant part of operational cost is the biomass acquisition.

CERTH participated in the collection procedures of corn residues in Western Macedonia. The collection parameters (biomass quantity, collection time, diesel fuel consumption, equipment needed, workforce, techniques, hindrances, problems and solutions) were recorded and captured with audiovisual means from the research team of CERTH and CluBe (information about the equipment used is given in the Annex – Table 10).

Residual corn biomass was collected in a field of 6,2 hectares (Figure 6). After the collection procedures, residual corn biomass in the form of rectangular bales were loaded on a truck with a mounted platform and led for intermediate storage at a distance of 24 km, while after 6 days were transferred for storage and utilization at DETEPA, at a distance of 81,3 km from the intermediate storage point. The intermediate storage phase is considered irrelevant at this stage and wasn't considered as a part of the biomass supply chain.

Figure 68. Collection point (image from Google Maps).

The data analysis of the overall supply chain revealed (Annex – Table 11) that the biomass procurement cost is approximately 24 €/tn and the transportation cost is 0,05 €/tkm (tkm is a unit of measure of freight transport which represents the transport of 1 tn of goods over a distance of 1 km).

From the analysis of the collection procedures, the following conclusions were drawn, regarding the development of biomass supply chain in Western Macedonia:

- Biomass collection should be done locally. The travel of agricultural machinery through provincial roads increases their consumption with the consequence that this cost is passed on to the final product, at the same time the increased agricultural activity causes traffic congestion, so it is preferable that the biomass transport should take place during the afternoon/evening and specifically after the end of the other agricultural activities in the area.
- Using an agricultural tractor for multiple tasks reduces the total investment cost but in case of malfunction, delays or interrupts all the following processes. Mulching is the first step in collection procedures. Problems and delays affect all the following processes.
- Choosing the right machinery for every stage and not just from the available ones reduces the cost of the supply chain in the long run. It is necessary to link the cost of ownership with the operational cost to determine the actual cost of the supply chain. The use of agricultural tractors with high horsepower (over 100 hp) increases the collection cost (high consumption).
- Choices and decisions at previous stages (such as harvest time) affect the performance of subsequent ones. Also, management options, for example square bales instead of

round ones for easier and cheaper transport, can increase costs disproportionately at all other stages. Synergy between the stages of grain collection and residual biomass collection is essential. It would be useful for these two to be treated as one activity (regardless the time lapse) that produces multiple products. Baling of residues immediately after threshing is not recommended (high moisture content).

- Rectangular bales require careful handling by experienced staff. Handling of bales presents the greatest biomass losses. Careless handling, leads to the unbundling of the bale, re-bundling is possible but, in the process, materials are transferred from the ground to the biomass and consequently to the final energy product. It also increases management costs and time. DETEPA’s staff lacks experience in handling rectangular bales, resulting in losses and delays.
- Storage spaces should be tailored to the needs of biomass procurement planning. DETEPA's storage space is not designed to support the storage and management of large quantities of bales. This can be a problem during biomass procurement planning.
- The boiler of the district heating plant can operate with corn residues, the feeding system cannot handle bales nor shreds of corn residues without prior treatment, like torrefaction.

In summary, torrefaction could solve the handling and storage issues associated with residual biomass, improve the chemical properties and help the development of a secondary market of standardized solid energy products. Biomass treatment is the last (or second to last, if we consider utilization) link of the overall IBC value chain, so particular attention should be paid to the prior stages, specifically to the collection phase. The lack of an organized supply chain jeopardizes the continuous and steady flow of biomass, so synergy between biomass producers, transporters and end-users (whether they are energy or IBC producers) is essential to the successful biomass mobilization in the Western Macedonia.

4.3.4 Torrefaction unit – Operational parameters

The most important factors of the overall torrefaction unit are the mass yield and the energy efficiency. These two factors (considered as key torrefaction performance indicators) reveal the mass lost during torrefaction and the energy retained in the solid product. To determine the feedstock to product ratio and the thermal efficiency, a simplified mass-energy balance model was employed, the design and results of which are presented in the Annex – Figure 10. The model is based on the principles of preservation of mass and energy, and is composed of a simplified theoretical model (based on data from Torr-coal), adjusted by using information of the mass and energy flows from literature and the feedstock characteristics. The energy and mass balance and a series of process parameters (e.g., heating value of torrefied product, moisture content of biomass) need to be predefined while, others are calculated (e.g., heating value of torr-gas).

An important outcome of the model is to achieve autothermal operation by effective utilisation of torr-gas heat for the torrefaction and drying processes, without the use of an external heat source. Biomass feedstock and air to the combustor are the input streams, while torrefied biomass and flue gas are the only output streams. The ash that remains after combustion is considered negligible (on both mass and energy basis) and is therefore not included in the mass and energy balance.

The key modelling parameters are:

- Autothermal operation – Torrefaction and drying thermal needs covered from torr-gas.
- Total mass loss (from raw biomass to torrefied biomass): 52% (including drying).
- Raw biomass: 12 GJ/tn (a.r.) LHV
- Torrefaction efficiency: 80%.
- Torrefaction process: 1 primary product (torrefied material) and 1 co-product (torr-gas). Torr-gas is combusted to supply with heat the overall process.
- Torrefied material: 19,22 GJ/tn (a.r.) LHV – 5% moisture content.
- Torr-gas: 6,5 GJ/tn (a.r.) LHV - Calculated from mass and energy balances.

Several process parameters such as the efficiencies of the process steps, air to fuel ratio of the combustor, heat demand of the dryer and characteristics of the torr-gas could be varied in the model.

The operational parameters of the torrefaction unit and the quantities of torrefied material is based on DETEPAs monthly demand (Annex – Table 12).

4.3.4.1 Supply chain optimization – Biomass procurement planning & Optimal torrefaction reactor size

The Greek Advance Case study deals with the conversion of agricultural residues, such as corn residues, to Intermediate Bioenergy Carriers (IBC) through torrefaction and their subsequent utilization -as alternative to lignite- in the district heating plant of DETEPA.

To do so, the economic feasibility of two stand-alone torrefaction concepts were studied in terms of: seasonal biomass availability, seasonal biomass procurance cost, storage cost, logistics cost, capital investment, operational cost, energy demand and optimal minimum capacity of torrefaction unit. The scenarios that were analysed and compared concern application in the district heating plant of DETEPA in the region of Western Macedonia.

In order to evaluate the effect of the above-mentioned parameters on the cost per MWh, in the case of replacing lignite with torrefied biomass as fuel, an optimization tool has been developed and employed. Specifically, a biomass supply optimization tool (Annex – Figure 11), based on non-linear programming, is used to determine the optimal use of biomass for each option and minimize the cost of the different case scenarios through optimal time planning for biomass procurement and maximum torrefaction unit capacity.

Currently, DETEPA utilizes lignite and wood-chips, priced at **35 €** and **89 €** per tonne respectively, with a final cost of **25,5 €** per MWh of fuel-mix, including the carbon tax for the CO_2 emissions from the use of lignite. As already mentioned, in this case study the replacement of the lignite part of the fuel-mix with torrefied biomass from corn residues (Annex – Table 9) was considered.

Corn residues are available for approximately two – three months annually (Annex – Table 13), so for the biomass supply chains we considered that the procurement price remains stable during these months. For the torrefaction unit two operational options were examined:

- Option 1. Operation for six months (or 4.000 hrs.).
- Option 2. Operation for twelve months (or 8.000 hrs.).

These options differ mainly in the size of the torrefaction reactor required (CAPEX) and secondarily in the storage needs of raw and torrefied biomass (OPEX). Both options cover the monthly fluctuations in the thermal energy demand.

4.3.5 Torrefaction investment cost (CAPEX)

For a torrefaction unit, CAPEX consists of the construction of the facility, including the torrefaction reactor. This includes direct costs, such as bare equipment and installation while, indirect costs include the engineering design of the plant, supervision, fees and contingencies. Since torrefaction is a developing technology, the estimation of the equipment investment costs has some uncertainties due to the limited available information. In this case study, the equipment cost data for biomass torrefaction was taken from literature. Overall, a scaling factor of 0,7 is used for the torrefaction unit (Annex – Table 14).

For the 4.000 hrs/yr. operation option the Total Capital Investment (TCI) is **9.467.024 €**, while for the 8.000 hrs./yr. option is **7.981.373 €**. The annualized capital cost is **1.111.993 €** and **937.489 €** respectively (Table 1). The decisive factor for the TCI is the large fluctuations of the energy demand during specific periods, as they determine the size of the torrefaction reactor (constitutes approximately 70% of the CAPEX).

Table 49. Torrefaction unit CAPEX.

Parameter	Option 1	Option 2
Annual operational hours	4.000	8.000
Nominal capacity (tn/yr)	12.768*	10.005
Operational capacity (tn/month)	1.064	834

Operational capacity (tn/hr)	1,60	0,80
Total capital investment (TCI)	**9.467.024 €**	**7.981.373 €**
Annualized capital costs €/yr	1.111.993 €	937.489 €

4.3.6 Torrefaction operational cost (OPEX)

OPEX include the energy costs, labour, transport, storage and biomass feedstock cost. The annual OPEX for the 4.000 hrs/yr. operation option is 424.046 € and for the 8.000 hrs./yr. option is 433.329 € (Table 2).

In both options the cost of procurance and transport are the same, what changes is the cost for storage. As torrefied biomass has a higher bulk density it can be stored at a lower cost than raw biomass. In the first option, due to the larger capacity of the torrefaction reactor, the raw biomass is converted to torrefied almost when it reaches the unit, without the need for storage for a long time, the opposite happens in the second scenario.

In any case, the difference in the OPEX of the options is negligible and the most important part of the annual expenses concerns the capital investment.

Table 50. Torrefaction unit OPEX.

Parameter	Option 1	Option 2
Torrefied biomass demand (tn)	6.384	6.384
Raw biomass demand for torrefaction (tn)	13.342	13.342
Nominal capacity (tn/yr)	**12.768**	**10.005**
Annualized capital cost (€/yr)	**1.111.993 €**	**937.489 €**
Annual operational cost (€)	**424.046 €**	**433.329 €**
Raw biomass procurance	351.424 €	351.424 €
Raw biomass transport	53.501 €	53.501 €
Raw biomass storage	14.786 €	25.653 €
Torrefied biomass storage	4.336 €	2.751 €
Annual torrefied biomass energy content (MWh)	34.091	34.091
Total cost (€/yr)	**1.536.039 €**	**1.370.818 €**
Per tonne produced	240,61 €	214,72 €
Per MWh produced	**45,06 €**	**40,21 €**

4.3.7 Comparison of fuel-mixture prices

For DETEPA the current fuel-mix (50% wood-chips, 50% lignite has a final cost of **25,5 €** per MWh of fuel, including the carbon tax for the CO_2 emissions from the use of lignite. For **Option 1** the cost is **32,5 €** per MWh, while for **Option 2**, 30 € per MWh (**Table 3**).

From the above data we can make the assumption that lignite (even with the carbon tax) and wood-chips fuel mix is the most attractive option from an economic point of view. However, it is only feasible as long as lignite is available and in prices below **46 €** per tonne. Additionally, torrefaction process doubles the cost in comparison with the utilization of raw biomass (**15 €** per MWh), in the context of energy equivalency.

Nevertheless, although torrefaction does not seem to be financially advantageous for DETEPA, it could solve the handling issues of non-woody biomass and create a secondary market of standardized solid biomass fuels, that will generate enough revenue for DETEPA to offset investment costs.

Table 51. Comparison of fuel-mix price (*including CO_2 tax 33 €/tn CO_2 ETS).

Fuel mix	**50% lignite - 50 % wood chips (current mix)**		**50 % wood chips - 50 % torrefied material (Option 1)**		**50 % wood chips - 50 % torrefied material (Option 2)**	
Fuel	Lignite	Wood chips	Torrefied material	Wood chips	Torrefied material	Wood chips
Fuel demand (MWh)	34.091	34.091	34.091	34.091	34091	34.091
Fuel demand (tn)	18.510	7.600	6.384	7.600	6.384	7.600
Fuel cost	647.729 €	676.365 €	1.536.039 €	676.365 €	1.370.818 €	676.365 €
CO_2eq (tn)	**12.587**					
Carbon tax (€)	**415.364* €**					
Fuel price per MWh	31,18 €	19,84 €	**45,06 €**	19,84	**40,21 €**	19,84
Fuel mix price per MWh	**25,51 €**		**32,45 €**		**30,03 €**	
Annual fuel mix cost	**1.739.459 €**		**2.212.404 €**		**2.047.183 €**	

4.4 Environmental assessment according to RED II

Following the EU and national legislations and directives, Greece has recently developed the new National Energy and Climate Plan 2021-2030 to enhance the use of Renewable Energy Sources (RES) and to promote energy savings by 2030.

The main targets of this action plan, are:

1. Reduction in the mining of lignite and its use for power generation purposes. There will be a direct and indirect impact on growth and employment in the local communities of the lignite-producing areas. Therefore, specific transition policies will have to be developed.
2. About 65% of the gross final electricity consumption, compared to previous 55%, must derive from RES. In practice this means that – for bioenergy - from approximately 6 GW today, have to reach 14,5 GW.
3. E-mobility maintains the target of 10% of all passenger cars in Greece in the year 2030 to be electrically driven.
4. Promotion of bioenergy, implementation of biomass projects of in total 320 MW capacity, to produce final energy from biomass equal to 0,27-0,41 Million Tonnes of Oil Equivalent (Mtoe), to strengthen the available district heating installations, especially those using renewable energy sources and to take advantage of the biomass produced from agricultural and agro-food industries.

The success of the national action plan and in particular the achievement of the targets in points 1 & 4 will have a very significant impact on Western Macedonia, a region where its GDP is directly linked to PPC and its lignite-related activities. The economic viability of the technologies that will be applied in the region, goes through the fulfilment of very specific environmental criteria, particularly, according to the Renewable Energy Directive 2018/2001/EC the greenhouse gas emission savings from the use of biofuels, bioliquids and biomass fuels shall be (Article 29, paragraph 10):

i) at least 50 % for biofuels, biogas consumed in the transport sector, and bioliquids produced in installations in operation on or before 5 October 2015;

j) at least 60 % for biofuels, biogas consumed in the transport sector, and bioliquids produced in installations starting operation from 6 October 2015 until 31 December 2020;

k) at least 65 % for biofuels, biogas consumed in the transport sector, and bioliquids produced in installations starting operation from 1 January 2021;

l) at least 70 % for electricity, heating and cooling production from biomass fuels used in installations starting operation from 1 January 2021 until 31 December 2025, and 80 % for installations starting operation from 1 January 2026.

For this reason, the environmental assessment of the production pathways and the use of IBCs (in our case the production of torrefied biomass for use in DETEPA) is particularly important.

The total GHG emissions and the GHG emissions saving arising from the of IBCs are to be calculated in accordance with the methodologies and principles described in the EU RED II, and include the GHG emissions from the production and use as well as the extension necessary for including the energy conversion to electricity and/or heat and cooling produced. Special points for the calculation of GHG emissions are:

- Wastes and residues, including tree tops and branches, straw, husks, cobs and nut shells, and residues from processing, shall be considered to have zero life-cycle GHG emissions up to the process of collection.
- Emissions from the manufacture of machinery, equipment and infrastructure shall not be taken into account.
- Must include emissions from drying of raw materials, waste and leakages.
- Must include emissions from the processing itself, from waste and leakages and from the production of chemicals or products used in processing including the CO_2 emissions corresponding to the carbon contents of fossil inputs, whether or not actually combusted in the process.
- Include only non-CO_2 GHG (N_2O and CH_4) emissions for the use phase.
- In case of allocation during co-production:
    - Carnot efficiency for electricity and heat.
    - Energy content (lower heating value) in all other cases.

The GHG emission savings of the IBC value chains shall be calculated against specific fossil fuel comparators:

- 94 g CO_2 eq/MJ for transport fuels.
- 183 g CO_2 eq/MJ electricity or 212 g CO_2eq/MJ electricity for the outermost regions.
- 80 g CO_2 eq/MJ heat or 124 g CO_2 eq/MJ heat for direct physical substitution of coal.

The evaluation of the overall torrefied biomass value-chain that supplies the district heating plant of DETEPA for thermal energy production, revealed that they are emitted **8,9 gr CO_2 eq per MJ of heat** resulting in a **92,7% GHG emission savings** in the case of direct physical substitution of coal or **88,9% GHG emission savings** for all other fossil fuels (**Figures 7,8**).

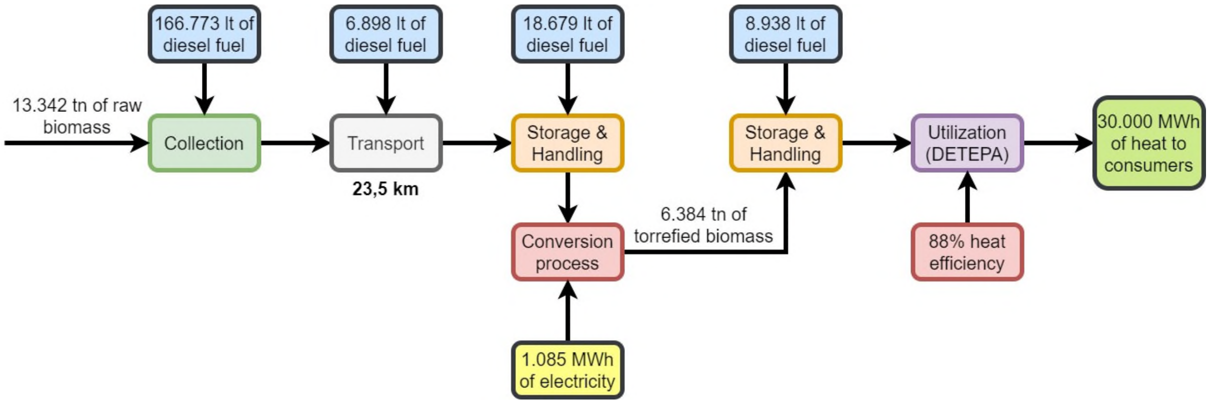

Figure 69. Quantified value chain of Greek case study.

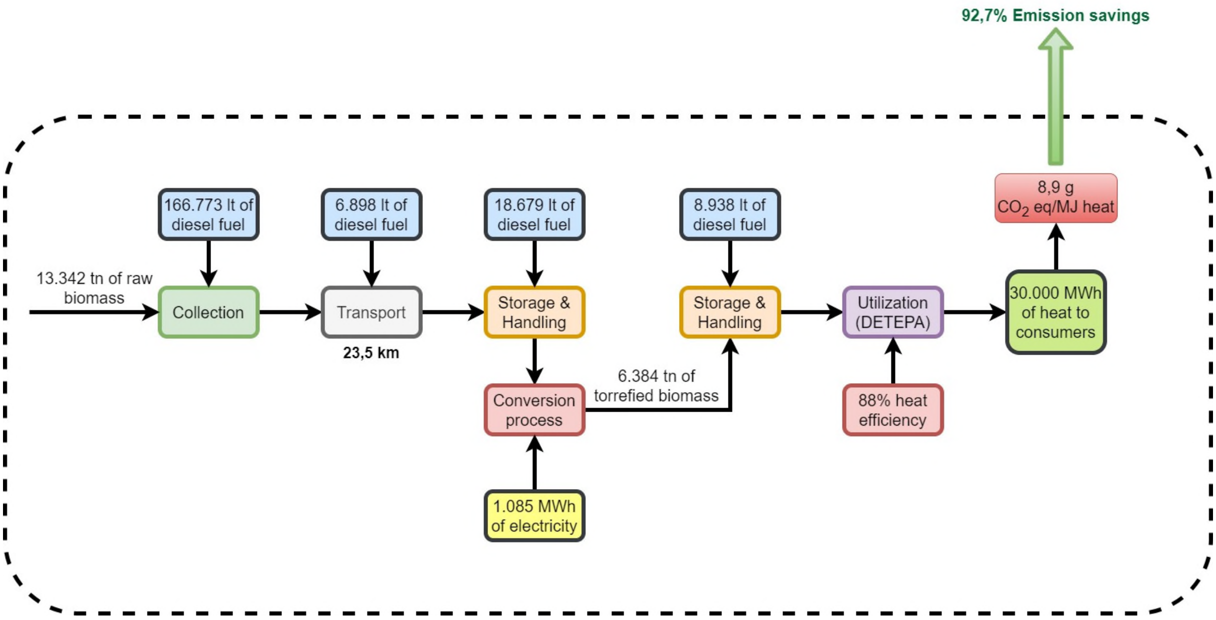

Figure 70. g CO_2 eq/MJ heat and GHG emission savings of the Greek value chain.

These results, in comparison with the typical values of GHG emission savings given in RED II, Annexes V & VI, suggest that the potential torrefied biomass value-chain in the region of Western Macedonia has a very good environmental performance. In the case of DETEPA it may not be particularly important, as it has a high energy efficiency (88%) and the carbon taxes are lower than the investment cost, however, this may motivate other industries, with a greater carbon footprint than DETEPA (like PPC or even cement, quick lime or magnesite industries), operating in the area, to invest in a technology such as torrefaction. This possibility will be explored in the Strategic Case Studies.

4.5 Final remarks and conclusions

The following final remarks and conclusions can be made:

- DETEPA can handle woody-biomass without issues.

- Agricultural residues like corn stalks can be combusted in the district heating plant boiler without prior treatment.
- Torrefaction could solve the handling problems of non-woody biomass.
- Enough biomass is widely available around the torrefaction unit. There is no need for long-distance transport.
- The torrefaction investment cost is mainly related to the torrefaction reactor size (70% of the CAPEX).
- Biomass procurement cost is inextricably linked to the existence of an established biomass market.
- Torrefaction doubles the operational cost in comparison with the utilization of the energy-equivalent raw biomass.
- Lignite (even with the carbon tax) and wood-chips fuel mix is the most attractive option from an economic point of view. However, it is only feasible as long as lignite is available and in prices below 46 €/tn.
- DETEPA can make a financial profit from torrefaction investment in case it expands its activities. DETEPA can act both as an energy producer and as a seller of standardized solid biomass fuels.
- Although there are substantial environmental benefits from the lignite phase-out, the energy sector will suffer from significant increases in production costs.
- Most of the knowledge about torrefaction is ''imported''. The analysis of key aspects of biomass torrefaction value chain in a regional level provides the relevant stakeholders a very good and personal taste of the technology.
- Lignite phase-out is a huge challenge for Western Macedonia. Region's GDP is deeply intertwined with PPCs activities. An industry that will exploit the experienced workforce and succeed to utilize the existing infrastructures with limited modifications will create a positive impact and benefit to a great extend the employment development.
- The experience gained from investigating the agricultural practices leads to a better understanding of the biomass supply chain which ultimately drove us to discover the applicability (technologically and economically) of a torrefied biomass value chain supplying the DETEPA plant. Consequently, this endeavour constitutes the road map for large-scale implementation at multiple regional (district) heating plants and relevant (cement, quick lime or magnesite) industries in the region.
- DETEPAs potential success will intrigue the farmers and ''plant the seed'' for optimal residual biomass utilization and ultimately ''grow'' into desire for exploring possible collaborations that will expand their capacity and make better use of their individual capabilities.

5 Torrefaction for steel production: The International case study

5.1 Introduction

5.1.1 Arcelor Mittal's commitment to carbon-neutral steelmaking

ArcelorMittal (AM) Europe has committed to reduce CO_2 emissions by 30% by 2030, with a further ambition to be carbon neutral by 2050, in line with the EU's Green Deal and the Paris Agreement. As Europe's largest steelmaker, with blast furnace, electric arc furnace and direct reduced iron operations across seven countries, AM has a significant role to play in contributing to the EU's green ambitions. To transform its operations to become carbon neutral, AM needs to move primary (iron ore-based) steel production away from a reliance on fossil fuel energy, towards the use of "clean energy" – in the form of clean electricity, circular carbon, and carbon capture and storage (CCS).

As part of its Carbon Action Plan AM Europe has committed around €300 million towards carbon-neutral technology, leveraging their R&D facilities around the world, and the support of public funding. The progress AM is making gives AM confidence some technologies could reach commercial maturity before 2025, but scaling this up will require continued public funding, given the billions of euros needed to achieve large-scale carbon-neutral steelmaking.

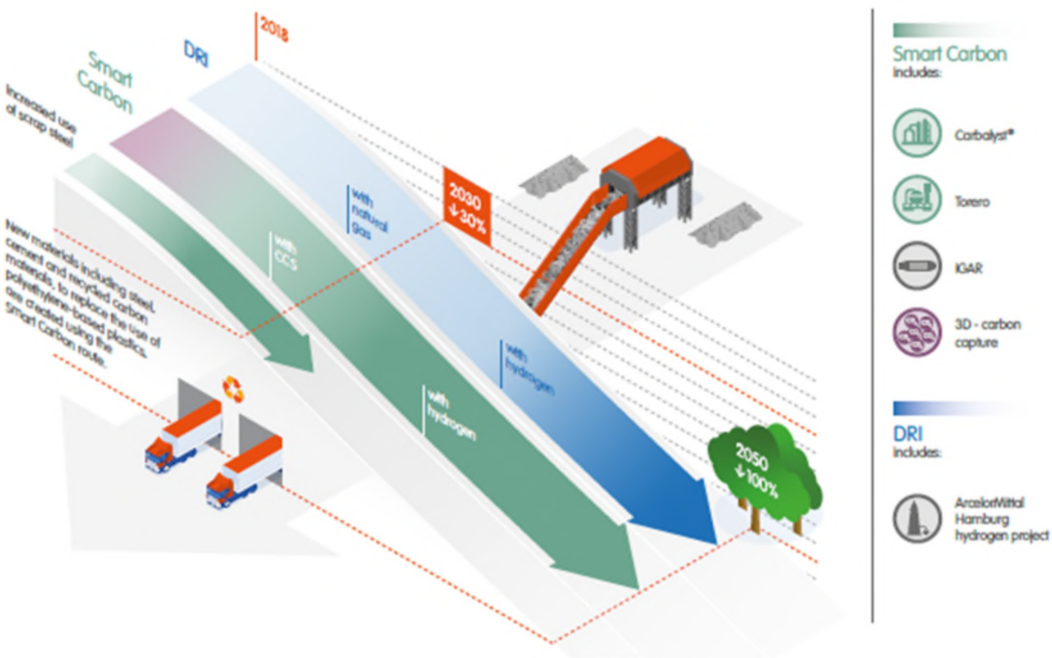

Figure 71: ArcelorMittal Europe Carbon Action Plan.

One of the most attractive elements of the Smart Carbon route is that it features a number of complementary technologies which enable incremental progress and can be combined to deliver additional value. As shown in (see Figure 71) these include Torero (turning waste wood into bio-coal to replace coal as a reductant in ironmaking); IGAR (making synthetic gas from waste CO_2 as a replacement for fossil fuels); and Carbalyst® (converting off-gases into bio-ethanol).

5.1.2 The Torero project: reducing iron ore with waste carbon

With its high-tech gasification technology, the modern steel industry is the ideal sector to advance the circular economy by reusing bio-waste, plastic waste, and agricultural and forestry residues. Torero, the acronym for *TORrefying wood with Ethanol as a Renewable Output*, is a €40 million demonstration plant at the AM steel mill in Ghent, Belgium, set to convert 120,000 tonnes of waste wood into biocoal for use in iron ore reduction in place of coal. Torero[6] covers the torrefaction of biomass as well as the broader objective of demonstrating a cost-, resource-, and energy-efficient technology concept for producing bioethanol from a wood waste feedstock, fully integrated in a large-scale functional steel mill. The international case study sets to builds further on the Torero project, which is currently under construction (see Figure 72).

Figure 72: Construction site of the Torero pilot at AM Ghent

[6] The TORERO project (www.torero.eu) is funded under H2020-EU.3.3.3: Alternative fuels and mobile energy sources. Project ID: 745810. See also https://ec.europa.eu/inea/en/horizon-2020/projects/h2020-energy/biofuels/torero or http://cordis.europa.eu/project/rcn/209957_en.html. TORERO not only covers the torrefaction of biomass but has the broader objective of demonstrating a cost-, resource-, and energy-efficient technology concept for producing bioethanol from a wood waste feedstock, fully integrated in a large-scale functional steel mill.

The construction of the Torero demonstration plant is experiencing large delays due to external factors (e.g. COVID-19 crisis). Construction works started in January 2021, and start-up of the demonstration plant is now foreseen in June 2022, when the MUSIC project would be largely completed. As a consequence, no industrial results will be available as input for the MUSIC case studies. It was therefore decided to use engineering and simulation data of the Torero project instead, and to update the case study later when experimental results are available.

5.1.3 The MUSIC project: expanding the use of torrefied biomass

Based on its long track record as biomass user and on early Torero research findings, AM anticipates good opportunities and a substantial potential to expand the use of torrefied biomass to replace a significant portion of fossil fuel used in its blast furnace. Beyond waste wood a number of hybrid feedstocks that are partially biogenic may be used, including SRF (Solid Recovered Fuel), RDF (Refuse Derived Fuel), etc. The advanced case study will assess a value chain broadening the range of biomass feedstocks to be torrefied at AM's Ghent facility. The strategic case study will investigate the logistics and feasibility of torrefied material made from a range of different feedstocks for use at other AM steel mills in e.g. Asturias (Spain), Bremen, Eisenhuttenstadt (Germany), Dunkerque, Fos-sur-Mer (France), and Dabrowa (Poland).

Overall goals of the International case study

- Assess a range of (hybrid) biomass feedstocks to be torrefied at AM’s Ghent facility.
- Investigate the logistics and feasibility for a range of different feedstocks for roll-out the torrefaction concept in AM steel mills in Belgium, North/South France, North Spain, North Germany, and Poland. The AM plant in Italy is covered in the Italian advanced case study.
- Conduct a value chain assessment of utilising the new feedstocks at the AM Ghent facility (advanced case study)
- Develop an expansion strategy (strategic case study)

Activities

Activities are linked to the overall goals, and are as follows:

1. Feedstock assessment
2. Use of waste wood and alternative feedstock exploration

3. Policy impact and stakeholder management related to the feedstock
4. Conduct a value chain assessment of utilizing the new feedstocks at the AM Ghent facility (advanced case study)
5. Expansion strategy

MUSIC partners involved in the case study are: ArcelorMittal, Renewi and Torr-Coal.

5.2 Advanced case study

5.2.1 Background on the Torero demonstration plant

Torero: objectives

The objectives of the TORERO demonstration plant at the ArcelorMittal Ghent plant are:

- Demonstrating biomass torrefaction based on technology developed by Torr-Coal
- Using Type B wood waste to replace fossil fuels for the ArcelorMittal (AM) bioethanol production plant (under construction)
- Reducing environmental problems lined to logistics, involving by waste management company Renewi
- Detailed calculation of life cycle assessment (LCA) (environmental impact), social life cycle assessment (sLCA) and techno-economic evaluation (economic cost targets and technical performance) to determine the overall impact of the bioethanol production concept. This work will be executed by Joanneum Research, Chalmers University of Technology and University of Graz.
- Ensuring that the technology concept and project results will be fully exploited and replicated throughout Europe by stakeholders in the energy and transport sectors.

Torero: literature research exploring biomass use in steel making

There are several options to substitute fossil carbon with biogenic carbon in an integrated steel mill route. Studies from the literature have identified that substitution of coal by biomass in the pulverized coal injection (PCI) unit is the most promising option. Biomass integration within the integrated blast furnace route shows great potential for partial substitution of coke as fuel and reductant. The core of the process in the blast furnace is to convert iron oxides into hot metal by means of carbon and hydrogen-based reducing agents. The main fossil-based reducing agents used in steelmaking are coke, heavy oil, pulverized coal, natural gas and hot reducing gases. Coke is the primary fuel and reducing agent in the blast furnace process; the amounts used are in the range of 350 - 400 kg/t of hot metal in modern blast furnaces. The main functions of coke in the blast furnace are: i) acting as reducing agent, ii) supplying energy to the process, and iii) functioning as a support medium to the burden material. Pulverized coal is the most widely used auxiliary fuel in blast furnace, and hence it can significantly reduce the injection of coke, increasing the blast furnace route efficiency. Note that the ash amount reduces the heating value of coal. According to the literature, the total injection of pulverized coal can reach over 200 kg/t hot metal. Natural gas can also be used as reducing agent, especially in countries where natural gas is inexpensive (up to 155 kg/t of hot metal in USA). In addition, hot reducing gases can be employed in the blast furnace. These gases can come from coal gasification and introduced in blast furnace. For optimal blast furnace performance, the key is to have reducing agents with enough energy content and that provide a suitable reducing atmosphere in the furnace conditions, without compromising blast furnace efficiency, nor increasing coke feed rate. The low energy density of (raw) biomass is explained by its high oxygen content, which in turns increases the need for O_2 enrichment of the blast, so that the race-away adiabatic flame temperature (RAFT) in the blast furnace is kept constant. Before it can be injected into the modern blast furnaces (woody) biomass must be upgraded in order to reach chemical and physical properties similar to coal. Torrefaction and pyrolysis give a solid carbon-rich and crushable product, with different qualities of upgraded biomass.

The four main practical limitations for biomass injection in blast furnaces are:

- Lower calorific value of biomass products compared to coal require efficient pre-treatment and pyrolysis.
- Difficulties of biomass injection at a high rate due to the porous nature which requires optimization for the injection process.
- Wider particle size distribution of biomass after grinding which requires efficient sieving to get the proper particle size for injection.
- Higher alkalis in some biomass products which should be controlled and minimized to avoid its negative impact on the refractory materials.

According to literature, injection of charcoal in blast furnace can reach 200 kg/ton hot metal. However, this is considered for charcoals with high carbon content and low ash content. Charcoal from woody biomass has relatively low ash content, and high quality of ash (high Ca and high basicity) that can lead to the reduction of limestone addition in the blast furnace and reduced slag from blast furnace compared to pulverized coal. Torrefaction is a less severe thermal process than full carbonisation. It takes place in an inert atmosphere at temperatures of 250–320 ^{o}C for the purpose of upgrading solid biomass fuel to “biocoal”. The fixed carbon content of torrefied biomass is substantially lower than that of charcoal. In the Torero project, a key aspect limiting the substitution ratio of PCI by biocoal from torrefaction of B-wood is the need to obtain high carbon content in the biocoal for injection in blast furnace.

Torero: implementation progress

The conceptual design of the Torero plant has been completed and the location determined. After evaluating a number of alternatives the idea of integration with the sinter plant was retained. Initial biocoal production capacity with the demonstration reactor will be within a range of 30,000 to 50,000 ton/year. The AM engineering team estimates that the most likely initial production capacity of a single reactor will be about 37,000 ton/year.

Figure 73: Pictures Torero plant

The basic engineering of the plant has also been completed. In Figure 74 below a 3D-view of the pre-handling, torrefaction and grinding installations is presented.

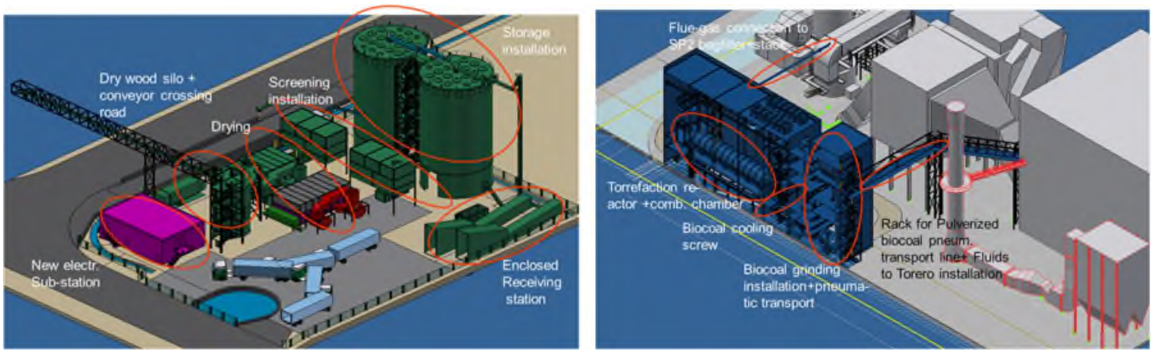

Figure 74: Schematic representation Torero plant

Wet Type-B waste wood (hereafter ”B-wood”) will be received in an enclosed receiving station where over- and undersized wood will be removed. The wood is transported via a bucket elevator and chain conveyor to a wet silo (2000 m³). At the bottom of the silo the wood is brought via an internal screw to the ferro and non-ferro metals screening installation. Next the screened wood is brought to the continuous belt dryer for drying. The dried wood is stored in a small dry wood silo where it can be extracted at the bottom. From the dry silo wood is transported via bucket elevator to a rack with chain conveyor to cross the road and to bring the wood to the torrefaction reactor. In this reactor the wood is torrefied to biocoal, whereas torrgas is produced as a co-product. The torrgas is burned at 1000°C and the generated heat recuperated for heating the reactor and making steam to dry the wet B-wood. The 200°C flue gas is brought to a bag filter and to a flue gas stack. The biocoal is cooled down with a cooling screw to about

90°C and pulverized in the grinding installation. The pulverized biocoal is stored in a pulverized biocoal silo and send via pneumatic transport to the blast furnace.

5.2.2 Feedstock assessment: wood waste

Wood waste is one of the largest biomass waste streams released by companies and households. Depending on the origin and method of use, wood waste properties vary considerably. Therefore, wood waste is usually classified into several streams. Some classification systems that are currently in use:

- In Vlarem, the Flemish environmental regulation, wood waste is classified into (i) untreated (ii) non-contaminated untreated (iii) contaminated treated wood waste.
- Wood waste can also be classified, depending on the point of release in the supply chain, into primary (pre-consumer) wood waste and post-consumer wood waste
- In the wood waste market, a division is commonly made into type-A, type-B and type-C wood waste, depending on the types of treatment that wood has undergone.

Primary and post-consumer wood waste

Primary wood waste originates within the wood processing sector (sawmills, carpentry, joinery, furniture factory etc.). The pure untreated wood waste has a high value. In primary production – mainly in the wood processing industry – it is used for energy valorisation in their own heating plants. Untreated wood shavings serve as a raw material in the chipboard industry, for the production of pellets or are sold as litter. Waste from panels or coated wood is used as fuel for incinerations, the fine fraction can be used to solidify liquid waste. This wood is deposited by collectors and processed together with post-consumer waste.
Post-consumer wood waste, is created after households and companies dispose of wooden products and materials at their 'end-of-life'. It usually consists of a heterogeneous mass of different wood qualities. The two most important markets are chipboard industry and energetic valorisation. This waste stream is pre-treated at specialized companies to remove impurities before further use. Chipboard contains about 85% recycled post-consumer wood waste, energetic valorisation usually takes place in industrial incineration plants.

Type A, B, and C- wood: characteristics and uses

The waste wood qualities commonly distinguished in the market are type-A, type-B and type-C. Here, waste wood is classified based on the types of treatment that wood has undergone before it is discarded (see Table 52). Beyond these three main categories a further subdivision can be applied. For example, the market also makes a distinction between solid B-wood and glued/residual B-wood. To reach the desired quality and to meet the specifications set by wood recyclers, a waste wood collector and/or processor takes care of mixing and reprocessing (breaking, sieving and dusting) different streams of waste wood.

Table 52: Types of waste wood

Commercial	Type A-Waste wood	Type B-Waste wood	Type C-Waste wood
VLAREM legislation	Untreated wood	Non-contaminated untreated wood	Contaminated treated wood
Hazard status	Not dangerous	Not dangerous	dangerous

A-wood - Untreated wood (not painted, not impregnated, not glued, etc.) This wood can be released at source as a mono stream (the wood is kept separate). A-wood as a mono stream can also originate from sorting a mixture of A and B wood or other mixed waste streams. A-wood has the properties that it is pure (no pollutants and impurities) and dry (in contrast to fresh wood from forests). For these reasons it is in demand for the production of chipboard products, but also for making fuel pellets or broken wood. To burn these clean fuels, a combustion boiler does not have to have additional cleaning techniques for removing contaminants that are present in the woody fuel.

B-wood - All waste wood that is not A-wood or C-wood. This wood can also be described as not dangerous treated wood. A distinction is often made between solid B-wood and glued B-wood. Solid B-wood is unglued wood with negligible amounts of paint compared to the wood itself. This wood is therefore very useful as a fuel and is also suitable for recycling. After fragmentation, the quality of this wood is almost equivalent to the quality of A-wood. The above does not apply to glued B-wood, such as hardboard, soft board or medium-density fibreboard (MDF). The glue is an undesirable contamination of the wood. Glued B-wood can only be recycled into new products to a very limited extent. That is why B-wood chips are often burned as fuel in Biomass Energy Plants.

C-wood - Wood that has been preserved by adding substances to it that could endanger the environment and human health Examples of this type of waste wood are e.g. polarized wood (contains heavy metals) and creosote wood (contains tar).

Type A, B, and C-wood: markets

Markets of Type A, B, C-Wood

The waste wood market is an international market. For the AM plan in Ghent, waste wood markets of direct relevance are first and foremost Belgium and the Netherlands (because of their proximity), but also the whole of North-West Europe. As shown in Table 53 there is substantial international trade (import and export) of waste wood, in particular of B-wood.

The waste wood market is volatile. The most important factors that can lead to (large local) fluctuations in availability and price are:

- Expansion of processing capacity (possibly with subsidy for biomass energy)
- Fluctuations in processing capacity due to malfunctions / maintenance
- Changing economic climate
- Seasonal and weather influences
- Innovative buyers
- Changing waste policy in the Netherlands / Belgium or abroad

Provided the changes are not too abrupt, the waste wood market can deal with them. If necessary, the negative returns from collectors are passed on to disposers.

Table 53: Waste wood imports and export volumes in NW-Europe

Country	Mass (1000t)				
	Type A and B	Type A	Type B recyclable for materials	Type B for energy	Type C
Nederlands	1.367	246	369	752	103
Belgium	919	165	248	506	69
Luxembourg	48	9	13	26	4
Germany	6.448	1.161	1.741	3.546	484
Denmark	448	81	121	247	34
Sweden	797	143	215	438	60
Norway	423	76	114	233	32
Finland	441	79	119	243	33
UK	5.182	933	1.399	2.850	389
France	5.025	905	1.357	2.764	377

Because of its wide availability, lower price (than A-wood) and non-dangerous nature B-wood would seem to be an interesting feedstock for torrefaction and subsequent use in blast furnaces. Therefore this biomass waste stream was investigated in more detail.

Wooden materials ending up in B-wood

Discarded wooden materials that end up in B-wood include: (a) particle boards, (b) veneer (c) plywood and (d) fibre boards.

Particle boards

Particle boards are made by gluing wood particles together. These particles are flakes or flake-like forms such as wafers and strands, planer shavings, slivers (or splinters), and fines produced form wood by cutting, breaking or friction. Sources of particles include residues from sawmills and other wood using industries, small-diameter roundwood, defective logs and harvesting residues.

Veneer
This type of wood is primarily used for plywood and furniture, but is also used in toys, various containers, matches, battery separations and other products.

Plywood and laminated wood are both made of layers (laminate) of wood glued together. The basic difference is that in plywood the grain of alternate layers is crossed, in general at right angles, whereas in laminated wood it's done in parallel. The development of these products was possible due to the production of improved adhesives.

Fibre board is made out of wood fibres. A resin adhesive is not always used in fibreboard manufacture; in some cases the boards are held together by physical forces, the flow of the natural lignin present among the fibres. As in the case of particle board, residues and wood of low quality can be used. Production of fibreboard involves reduction of the wood to particles, pulping, sheet formation, pressing, and finishing treatment. There are two types of fibreboard, i) insulation and ii) compressed (represented mainly by hardboard). The distinction is based on the density and the method of the production.

- Insulation board is used in construction as insulation and cushioning.
- Compressed hardboard has a wide variety of uses, including furniture, house siding, wall panelling, and concrete forms. A relatively new compressed product is medium-density fibreboard (MDF). MDF is manufactured in a range of thicknesses (6–40 mm), usually by the dry process, and it is less dense than hardboard. It can be processed and machined as solid wood and has many uses e.g. furniture, panelling or siding.

The above mentioned wooden materials find application in all kind of wooden end-products that after their use end up in type-B waste wood. Typical examples of products ending up as B- wood are window frames, doors, kitchen cabinets, furniture, office desks, painted wood, floor and wall panels, demolition wood, residues of lumber.

Current processing of Type B waste wood

To arrive at B-wood, post-consumer wood waste from households and companies is processed in a sequence of treatment steps, ((depends on requirements of end-user) typically including:

- Collection of at waste management sites by container or walking floor transport
- In case of mixed streams: pre-sorting by cranes to recover as much as possible A-wood
- Further removal of impurities such as plastics, paper, stones, glass, etc.…
- Pre-shredding and iron removal
- Shredding to wood chips (on specification of end-user)
- Fine iron removal, in some cases a non-ferro removal (on specification of end-user)
- Sieving into several fractions
- Transport to end-user, by vessel or road transport

Shredding can take place in a stationary or a mobile unit, depending on the storage capacity, mobilization costs and outlet possibilities. In a stationary unit shredding is usually combined with further processing (sorting, removing and sieving). However, shredding often takes place in mobile units. Shredding of e.g. particle boards generates large amounts of wood dust. When and where dust nuisance is an issue dust control measures are needed such as using other shredder technics, slower turning, spraying the wood before and during the shredder process, special layout of the site taking account with the wind direction etc.

5.2.3 se of waste wood and alternative feedstock exploration.

Torrefacton: technologies

Thermal treatment in a low oxygen environment can be performed at different temperatures. At temperatures between 270 °C and 330 °C this process is known as torrefaction. Increase of torrefaction process temperature means for the solid torrefied biomass containing material: an increasing hydrophobic behaviour; a more favourable grinding behaviour; a further increase of the energy density, decrease of the volatile content; an increase of the total carbon content. However, one must realize that there is an increas-

ing loss of solid mass (increasing amount of process-gas) at a higher process torrefaction temperature and by that the energy efficiency decreases.

Over the years, many torrefaction reactor concepts have been considered, often derived from reactor technology concepts proven for other applications (drying, pyrolysis, combustion). Examples include: multiple hearth furnace, rotary drum reactor, moving bed reactor, crew conveyor reactor, torbed reactor, oscillating belt reactor, turbo dryer, and microware reactor[7]

Torrefaction: screening different types of feedstock

To get optimal torrefaction results, biomass feedstock will need to meet a number of key requirements, with regard to: bulk density, particle size and morphology, moisture content, ash content, etc. The intended use of the torrefied product may impose further requirements on the feedstock.

Pre-drying to a moisture content of about 5 %, before entering the torrefaction reactor, is essential. During pre-drying trapped sand (part of the ash) will come off in the form of small particles and can be removed by sieving.

Particles that are too small (<4 mm.) can lead to dust issues. Also, small particles of woody biomass can have a high ash content (up to 30 %). Therefore, small particles should be remove, preferably after pre-drying. Particles that are too large (> 50 mm.) can block and damage the transport systems mechanically and will lead to a disruption of the torrefaction process.

The morphology of fresh woody biomass will be mostly chips with a bulk density (dry) of about 0.20 ton/m³. Used wood (treated and untreated; a mixture of particleboard, multiplexing plates, OSB-plate, painted wood, demolition wood, furniture wood, MDFs, hard and soft board plates, paper and cardboard.) mostly have been shredded and shows a somewhat lower bulk density (about 0.18 ton/m³).

Herbaceous biomass shows different kind of morphology like shells, leaves, straw, cut stems, etc. Mostly the bulk density of this kind of biomass is rather low (about 0.10 ton/m³ or even lower; except for shells) and by that it is difficult to get sufficient mass amount per unit time in the torrefaction reactor (less product output per unit time). Also there is a large chance on bridging and clogging.

[7] For a basic overview of these technologies see e.g. “Biomass Torrefaction - Recent experiences and best-in-class examples”, part of MUSIC Deliverable 2.1, or the recent presentation of Jaap Kiel (TNO Energy Transition), “Torrefied biomass: current focuses of research” at the IBTC/ETIPBioenergy/MUSIC webinar 'Torrefaction: Opportune time for Development', 7 April 2021

Solid Recovered Fuel (SRF) is a rest stream of sized, dried and separated household waste and mainly consists of wood, plastics, paper, leather, cotton/linen and fruit/vegetable. SRF is available in three different embodiments: fluff, soft pellets and hard pellets. SRF fluff shows rather some disadvantages for use in torrefaction. The bulk density is rather low (about 0. 12 ton/m³) and not easy to get it in the torrefaction reactor because of bridging and clogging. SRF soft pellets are more suitable for the torrefaction process. The bulk density is about 0.3 ton/m³ and the chance on bridging and clogging is small. SRF hard pellets show a bulk density of about 0.5 ton/m³.

The elemental composition of the biomass containing feedstock (= the respective shares of lignin, cellulose and hemicellulose) determines to a large extent the quality of the torrefied product. Table 54 illustrates the typical elemental composition of different types of biomass:

Table 54: Woody biomass composition.

Polymer (wt%)	Deciduous	Coniferous	Herbaceous
Lignin	18-25	25-35	15-25
Cellulose	40-44	40-44	30-50
Hemicellulose	15-35	20-32	20-40

Torrefaction tests with different types of feedstock

Torr-Coal operates an indirectly-heated rotary drum reactor at its research centre located in Dilsen-Stokkem, Belgium. In this type of torrefaction reactor a wide range of biomass feedstocks can be used. The Torr-Coal facility was used to test different kinds of biomass at various operational conditions (see Table 55. Woody biomass tested at pilot scale included; mixed woodchips; acacia wood; eucalyptus wood; used untreated pine / spruce wood; treated used mixed wood; blends of Solid Recovered Fuel (SRF) and mixed woodchips. In addition, different types of herbaceous biomass were tested on laboratory scale.

Table 55: Overview of feedstocks, which have been used and tested by Torr-Coal

Input > 98 % renewable			**Torr-Coal process**	
classification according ISO 17225-1: 2014			process max. torrefaction temp.	
1 Woody biomass 1.1 Forest, plantation and other virgin wood	fresh mixed woodchips West Europe		mild torrefaction	290 °C
			severe torrefaction	320 °C
				340 °C
			pyrolysis	400 °C
				450 °C
	eucalyptus woodchips Portugal		290 °C	
	shredded acacia wood South Africa		285 °C	
1 Woody biomass 1.3 used wood	shredded used untreated pine / spruce wood	A-wood	290 °C	
	shredded used treated mixed wood	B-wood	pilot scale different tests	
2 Herbaceous biomass	Bagasse; Banagrass; Miscanthus; Empty Fruit Bunches (EFB); HiCross; Palmoil Kernel Scales (PKS)		lab. scale different tests	

Input partly (> 50 %) renewable	**Torr-Coal process**
	process max. torrefaction temp.
blends of Solid Recovered Fuel (SRF: classification according NEN-EN 15359: 2011) and woody biomass (classification according ISO 17225-1: 2014)	340 °C - 360 °C pilot scale different tests

Table 56 shows the parameters that Torr-Coal assessed for the various types of biomass feedstock, i.e. proximate, ultimate, calorific value, elements and trace elements. Table 57 details the ten different woody biomass feedstock – operating conditions combinations tested. The first 8 tests involved forest, plantation and other virgin wood; test no. 9 involved A-type waste wood and test no. 10 involved B-type waste wood. Test results for tests 1-9 are summarised in Table 58.

Table 56: Parameters determining biomass composition.

Proximate

Moisture	% (a.r.)
Ash	% (d.b.)
Volatiles	% (daf)
Fixed Carbon	% (daf)

Ultimate

Hydrogen	% (daf)
Carbon	% (daf)
Nitrogen	% (daf)
Oxygen	% (daf)

Clorine	% (d.b.)
Sulfur	% (d.b.)

Calorific value

GCV (daf)	MJ/kg
NCV (a.r.)	MJ/kg

elements (determines to a great extend ash compostion)

Ca	g/kg (d.b.)
Na	g/kg (d.b.)
K	g/kg (d.b.)
Mg	g/kg (d.b.)
Fe	g/kg (d.b.)
Si	g/kg (d.b.)
Al	g/kg (d.b.)
Fe	g/kg (d.b.)
P	g/kg (d.b.)

trace elements (can be toxic)

Cd	mg/kg (d.b.)
Pb	mg/kg (d.b.)
Hg	mg/kg (d.b.)
Cr	mg/kg (d.b.)
Cu	mg/kg (d.b.)
Ni	mg/kg (d.b.)
Zn	mg/kg (d.b.)
Sb	mg/kg (d.b.)
Mn	mg/kg (d.b.)

Table 57: Feedstock inputs and outputs

Input > 98 % renewable			**Torr-Coal process**		Output
classification according ISO 17225-1: 2014			process max. torrefaction temp.		analysis results
1 Woody biomass 1.1 Forest, plantation and other virgin wood	fresh mixed woodchips West Europe		mild torrefaction	290 °C	1
					2
			severe torrefaction	320 °C	3
				340 °C	4
			pyrolysis	400 °C	5
				450 °C	6
	eucalyptus woodchips Portugal		290 °C		7
	shredded acacia wood South Africa		285 °C		8
1 Woody biomass 1.3 used wood	shredded used untreated pine / spruce wood	A-wood	290 °C		9
	shredded used treated mixed wood	B-wood	pilot scale different tests		10
2 Herbaceous biomass	Bagasse; Banagrass; Miscanthus; Empty Fruit Bunches (EFB); HiCross; Palmoil Kernel Scales (PKS)		lab. scale different tests		not available

Input partly (> 50 %) renewable	**Torr-Coal process**	Output
	process max. torrefaction temp.	analysis results
blends of Solid Recovered Fuel (SRF: classification according NEN-EN 15359: 2011) and woody biomass (classification according ISO 17225-1: 2014)	340 °C - 360 °C pilot scale different tests	11

Table 58: Analysis results initial feedstock testing

		1	2	3	4	5	6	7	8	9
Moisture	% (a.r.)	4,4	0,9	2,2	0,9	1,1	1,3	0,6	0,8	4,2
Ash	% (d.b.)	2,9	2,7	2,5	3,0	4,9	6,6	1,7	6,7	1,4
Volatiles	% (daf)	69,9	71,3	48,3	28,4	24,8	27,2	62,5	59,6	70,0
GCV (daf)	MJ/kg	23,8	23,6	28,4	31,5	35,2	34,0	25,4	26,1	23,7
NCV (a.r.)	MJ/kg	20,9	21,6	26,0	29,4	33,8	32,6	23,7	23,0	21,1
Hydrogen	% (daf)	5,9	5,7	5,2	4,1	3,7	3,4	5,5	5,4	6,0
Carbon	% (daf)	60,8	59,2	71,8	81,0	84,8	86,3	62,8	65,1	60,7
Nitrogen	% (daf)	0,68	0,47	0,30	0,56	0,60	0,71	0,27	1,03	0,62
Sulfur	% (daf)	0,04	0,05	0,07	0,02	0,03	0,02	0,01	0,04	0,02
Oxygen	% (daf)	32,6	34,6	22,6	14,3	10,9	9,6	31,5	28,4	32,6

Based on the above results, it was decided to implement more elaborate tests with (blends of) the following two types of feedstock:

- shredded used mixed treated wood (a type of B-wood)
- different blends of Solid Recovered Fuel (SRF) and fresh mixed woodchips

Both types of feedstock were selected for their large availability and attractive pricing in NW Europe, rendering them highly promising candidates for torrefaction.

Table 59 presents analysis results for pilot scale torrefaction trials with 100% shredded used mixed treated wood (B-wood). It shows how an increase of torrefaction temperature leads to an increase of mass loss, increase of calorific value, increase of carbon content and decrease of volatile content.

Table 59: Analysis results shredded used mixed treated wood (B-wood)

feedstock B-wood									
GCV (daf) MJ/kg	NCV (daf) MJ/kg (cV)	Volatiles (daf)	C (daf) content	O (daf) content	H (daf) content	N (daf) content	S (daf) content	Cl-content on dry base	ash content on dry base
20,46	19,22	81,5%	52,3%	39,7%	6,02%	1,86%	0,06%	0,086%	3,30%

torrefaction product										
mass loss on dry base	GCV (daf) MJ/kg	NCV (daf) MJ/kg (cV)	Volatiles (daf)	C (daf) content	O (daf) content	H (daf) content	N (daf) content	S (daf) content	Cl-content on dry base	ash content on dry base
33,0%	24,74	23,72	60,7%	63,9%	28,5%	5,01%	2,49%	0,13%	0,038%	6,55%
45,0%	26,64	25,73	52,0%	69,8%	22,9%	4,47%	2,69%	0,19%	0,047%	7,80%
52,9%	28,56	27,81	42,6%	73,8%	19,5%	3,77%	2,74%	0,21%	0,051%	10,78%
55,7%	29,02	28,28	39,8%	77,5%	15,5%	3,66%	3,14%	0,20%	0,043%	12,02%

Likewise, Table 60 presents analysis results for pilot scale torrefaction trials with blends of Solid Recovered Fuel (SRF) and fresh woodchips. The first test (at T = 340 °C) was done with 30 wt% SRF and 70 wt% woodchips; the second test (at T = 360 °C) with 50 wt% SRF and 50 wt% wood-chips.

Table 60: Analysis results blended SRF and fresh mixed woodchips

		30 % / 70 % 340 °C	50 % / 50 % 360 °C
Moisture	% (a.r.)	0,1	0,1
Ash	% (d.b.)	4,7	13,1
Volatiles	% (daf)	38,0	60,9
GCV (daf)	MJ/kg	31,6	34,4
NCV (a.r.)	MJ/kg	29,1	28,5
Hydrogen	% (daf)	5,1	7,6
Carbon	% (daf)	79,7	78,3
Nitrogen	% (daf)	0,74	0,88
Sulfur	% (daf)	0,18	0,31
Oxygen	% (daf)	14,3	12,8

(*) Due to inhomogeneity and composition variation over time of SRF feedstock, wide spread on analysis results can be expected.
The results reported are based on limiting number of sample analysis and therefore values presented should be considered indicative

Environmental considerations

In terms of availability, price and torrefaction product yield shredded used treated wood (B-wood) and SRF, or blends thereof, are the most promising feedstock. However, the content of ash, chlorine and sulphur and the presence of toxic heavy metals requires proper attention (see Table 61).

Table 61: Max concentrations in fresh mixed woodchips B-wood and SRF

Parameter	Shredded used treated wood (B-wood)	Solid Recovered Fuel (SRF)
Ash content	Up to 5 wt%	Up to 10 wt%
Chlorine content	Up to 0.2 wt%	Up to 1.0 wt%
Sulphur content	Up to 0.2 wt%	Up to 0.3 wt%
Total toxic heavy metals	1000 mg/kg (dry base)	1000 mg/kg (dry base)

The maximum expected values for individual heavy metal elements are show in Table 62.

Due to the higher chlorine and sulphur content in the feedstock the torrefaction process needs to be equipped with a flue gas cleaning system to limit the emission of HCl and SO_2. After torrefaction, part of this chlorine and sulphur will be present in the solid torrefied material and part in the torrefaction process gas (torrgas). This torrefaction process gas is burned and the resulting flue gas contains a certain amount of HCl and SO_2, which (after useful heat exchange) will be emitted to open air.

The rather high ash content of the feedstock is not really a problem for the torrefaction process. However, after torrefaction the ash content of the resulting product will be double. Depending on the application of the torrefied product this ash content can lead to customer problems, like an unacceptable ash melting and ash drain behaviour. Ash melting behaviour (temperature) is strongly determined by the ash composition (Si, Ca, Na, K, Mg ratio) and will give rise to fouling and blocked ash drain.

Table 62: Max expected values for individual heavy metal elements B-wood and SRF

max. expected heavy metal content of SRF and B-wood

Cd	mg/kg (d.b.)	4
Pb	mg/kg (d.b.)	400
Hg	mg/kg (d.b.)	0,4
Cr	mg/kg (d.b.)	150
Cu	mg/kg (d.b.)	150
Ni	mg/kg (d.b.)	50
Zn	mg/kg (d.b.)	500
Sb	mg/kg (d.b.)	150
Mn	mg/kg (d.b.)	200

(*) Due to inhomogeneity and composition variation over time of SRF and B-wood feedstock, wide spread on analysis results can be expected. The results reported are based on limiting number of sample analysis and therefore values presented should be considered indicative.

The quantities of heavy metals found in the SRF / B-wood feedstock, although not alarming, are a point of attention. Due to inhomogeneity and composition variation in time it cannot be excluded that sporadically elevated values are found. Depending on the application of the torrefied product this can be problematic for the customer (soil, water and air pollution).

5.2.4 Policy impact and stakeholder management related to the feedstock

Background: Policy aspects

The policy on the use of waste is evolving rapidly the last years, triggered by the 'circular economy' concepts which are included more and more in national sustainability strategies. We investigate in detail the policy on waste wood (biomass) in Flanders.

Result Flanders

Within "Flanders Circular", various actors work together to realize the transition to a circular economy. "Biomass and food" is one of the five priority themes within the Transition Circular Economy. One of the goals is a reduced footprint of our food production and a high-quality use of biomass through a circular approach to the food chain and less food loss. With the support of projects via the calls Circular Economy, Flanders Circular wants to encourage the closing of the chain.

The environmental analysis also establishes a link with the bio-economy strategy, the climate and energy policy, the forest and nature policy and the agricultural policy in Flanders.

In the coming policy period, the Flemish coalition agreement 2019-2024 will also devote the necessary attention to various aspects of the biological cycle:

- Reduce "food waste" with 50% by 2030;
- Optimization of the distribution of food surpluses;
- By 2030, 50% of the recyclable fraction of household and industrial waste will be additionally recycled. There is a strong focus on the selective collection of organic-biological waste, coupled with the stimulation of pre-fermentation in biodegradable composting;
- Well-considered use of biodegradable plastics;
- Refocusing agricultural policy in support of a strong food policy, in which the food chain is viewed in an integral and circular manner;
- Strengthen the circular approach to animal manure and other organic residual flows;
- Encouraging the use of biogas and sustainable biomass; greening of heat.

The materials hierarchy and the cascade principle are central to waste and materials policy. The main goal of the materials hierarchy and the cascade is to apply (residual) flows as high-quality as possible:

- The materials hierarchy contained in the Materials Decree implies this order of priority: prevention-reuse-recycling-other forms of recovery (e.g. energy applications)-disposal.
- For the food cycle from producer to consumer, the cascade principle uses this order of priorities: food-animal feed-material-energy. However, the application is not only chosen in function of one particular link. The entire chain is charged. For example, it is important to also look at the following links in the chain and to investigate which applications are possible with the products that remain after the chosen application. The cascade principle results in a chain approach that takes into account the added value of a series of successive applications. The chain is assessed in function of the objectives and preconditions, including the economic feasibility.

The cascade in concrete terms:

Although the cascade creates a framework for the sustainable use of biomass, it cannot be applied in every situation. The concrete economic feasibility (type of residual flow, location, time, etc.) and specific legislation also determine whether or not the cascade can be followed. This can be motivated on the basis of life cycle thinking or comparable integrated analyses. We must strive for maximum efficiency in every step of the cascade. Communication, information and harmonization between the different links in the chain are important at all times. This is crucial to streamline the chain approach and align the interests of the various sectors involved.

Impact of Torero on the policy

Torero I falls under material (in particular chemical) recycling of wood for the sake of recovering carbon and hydrogen. These components, present in the wood, are converted back into usable materials. Torero - Steelanol has its place in the waste wood recycling landscape. Different techniques and applications focus on the recycling of the wood fibre, other techniques aim at the recycling of the chemical components, yet other techniques are only interested in the energy content of wood. Torero is operational on an industrial scale and can reduce CO_2 emissions by 400,000 tons per year at full capacity at one location and keep carbon in the chain. With this, Torero scores better in terms of circularity than the loss of carbon through combustion (Energy) and through biodegradation (Soil).

Torero is an added value for the recycling of waste wood. Torero can process all types of wood products (solid wood, laminate, chipboard, MDF, ...) as long as carbon is naturally present. It concerns a large and stable capacity that can be processed with this technology. Due to the integration and combination of new with existing techniques, with the blast furnace as the central installation, the space taken up is limited.

Torero - Steelanol initially realizes a platform for non-food based ethanol. Ethanol already has various applications, for which the European Commission has formulated ambitious targets by 2030, being 7% admixture with fuel in the transport sector. In the next phase, the platform can be adapted to other basic chemicals in order to provide the chemical sector with a large amount of renewable raw materials from one existing location. As a result, the carbon from wood is used in products with a higher technical value (high-quality valorisation). The use of waste wood in Torero I is important to strengthen Flanders' strategic position in the geopolitical field. The reduction in the use of fossil reducers means that Flanders is less dependent on international actors for the production of steel.

Therefore the Torero process should impact the current policy as follows:

- Include the route for chemical recycling of wood in the plan. In addition to the recycling of wood because of the properties of the fibre (mechanical recycling), there is the recycling of wood because of the carbon and / or hydrogen content. By analogy with plastics, there is therefore also a material (chemical) recycling route for wood.

- Chemical recycling of wood is a second track within material recycling. The chemical recycling of wood is a thermal process, just as with plastics. The matrix is broken down into smaller platform molecules, which enable the production of a large group of materials (chemicals, fibres, other products,...). Ethanol is the ideal chemical platform at Torero to build on for the production of other chemicals. However, the thermal decomposition process is different from combustion. During combustion, the matrix is broken down and the components are completely oxidized to CO_2 and H_2O. In that case, no new products can be made with it. In Torero - Steelanol, the matrix is partially oxidized to CO, from which ethanol can be synthesized.

- View the potential of Torero from the steel sector's point of view. In other words give attention in the action program to the development of the use of wood in existing sectors such as sustainable metallurgy in Flanders. The use of biomass is an important phase in the development of the CO_2-free production of steel. It is part of a transition that can already start on an industrial scale and will be applied for decades to come. It is expected that in the future other techniques, including the use of hydrogen or direct electricity, will be mature enough to be applied on an industrial scale.

- Take into account in the action program the advantage of scale, flexibility of the technology (adaptability - deployability of other non-recyclable carbon sources - carbon recycling technologies), security of capacity, availability of the infrastructure and production. Pay attention to the potential impact on CO_2 emission reduction in the action program.

- In the integrated concept of production of steel and production of chemicals, the blast furnace acts as the central unit for gasification of reductants and for reducing melting of ferrous materials. The volumes are large and the production stable. In this way, the installation ensures a guaranteed sale of locally collected waste wood on an industrial scale centrally in Flanders. The ability to be significant

- In the integrated concept of production of steel and production of chemicals, the blast furnace acts as the central unit for gasification of reductants and for reducing melting of ferrous materials. The volumes are large and the production stable. In this way, the installation ensures a guaranteed sale of locally collected waste wood on an industrial scale centrally in Flanders. The ability to significantly intervene on the emissions of such a large source at one location is unique, highly efficient and has a major impact locally and regionally. This means an annual CO_2 emission reduction of 400,000 tons. The rollout to other locations would mean a multiple of this reduction.

- Involving the social and economic importance of sustainable steel production for the region. As indicated above, pay attention in the action program to the importance of making existing sectors more sustainable by using waste wood. Being able to roll out the use of waste wood for this production site means the realization in Flanders of a model for the steel industry that can be rolled out internationally. This guarantees the preservation of the steel industry in the region and the maintenance of employment. The presence of local steel production is of great benefit to several other local sectors.

- Pay attention to the investment potential in Flanders in the action program. All in all, it concerns an investment of 200 million euros in Flanders. This investment also opens the possibility for new investments in the use of alternative raw materials in the steel industry and in the conversion of CO and CO_2 into platform molecules. The conversion of CO and CO_2 is not limited to the steel industry and can therefore also lead to other investments in the Flemish industrial landscape.

- Pay attention in the action program to the potential for further development of a technology. In other words, a technology that offers no additional development possibilities towards even more benefits and can only take the current situation into account is less valuable. This can be an investment that inhibits further development of a market. In addition to wood, the Torero technology can be expanded with other raw materials, including other biomass flows and plastics. The Steelanol technology can be extended in a similar way to convert CO_2-rich streams into platform molecules. This is interesting in the context of carbon capture and utilization.

- When developing the Biomass Action Plan, it must be ensured that the strategy is in line with other policies, including European policy with, among others, the Renewable Energy Directive, the Flemish Energy and Climate Plan.

5.2.5 Value chain assessment alternative feedstocks use at AM Ghent facility

A detailed techno-economic analysis was performed, which included a value chain assessment of using biocoal made from (a) B-wood and (b) SRF/RDF as substitute reductant at the AM steel mill in Ghent.

Based on a gate fee for Type-B waste wood of 10-30 euro/ton, and total costs of processing (including crushing, cleaning, screening, preheating, grinding and torrefaction) of 110 euro/ton, biocoal can be produced from B-wood at a price of 80-100 euro/ton.

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Based on a gate fee for municipal, commercial and industrial solid waste of 10-25 euro/ton; the costs for feedstock treatment, selling/disposing unused sub-streams, and final compacting of the main product, different qualities of SRF/RDF (fluff, briquettes, pellets, and bales) can be produced for a prices between minus 5 and plus 20 euro/ton.

When calculating the break-even price for torrefied feedstock versus PCI (both at the BF gate), common biomass pellets are much too expensive but all investigate alternative feedstocks (torrefied waste wood, SRF/RDF pellets and SRF/RDF fluff) would appear to offer attractive economics, thus warranting further exploration of the torrefaction technology. However, there are a lot of uncertain factors that influence the value at use of alternative reductants (such as the pricing of CO2 emissions), therefore a final conclusion with regard to the financial viability of replacing PCI with the considered alternatives cannot be drawn yet.

Environmental performance: allocation of greenhouse gas reductions

To determine the environmental performance of the use of biomass in the blast furnace a thorough study was made by Chalmers University, one the partners in the TORERO project, responsible for the techno-economic analysis. The results have been published in a scientific paper "*Carbon Allocation in Multi-Product Steel Mills That Co-process Biogenic and Fossil Feedstocks and Adopt Carbon Capture Utilization and Storage Technologies , Maximilian Biermann*, Rubén M. Montañés, Fredrik Normann and Filip Johnsson, Frontiers in Chemical Engineering, 9 December 2020.*

The paper discusses the effects of carbon allocation on the emissions intensities of low-carbon products generated in facilities that co-process biogenic and fossil feedstocks, using the integrated steel mill (blast furnace route) as an example. The potential for CO_2 mitigation is investigated for biocoal injection into the blast furnace (Bio-PCI), carbon capture and storage (CCS), and microbial fermentation of steel mill off-gases to produce ethanol. The emissions intensities of cogenerated low-carbon products are discussed for the allocation of biogenic inputs and avoided CO_2 emissions between the cogenerated steel, ethanol, and electricity.

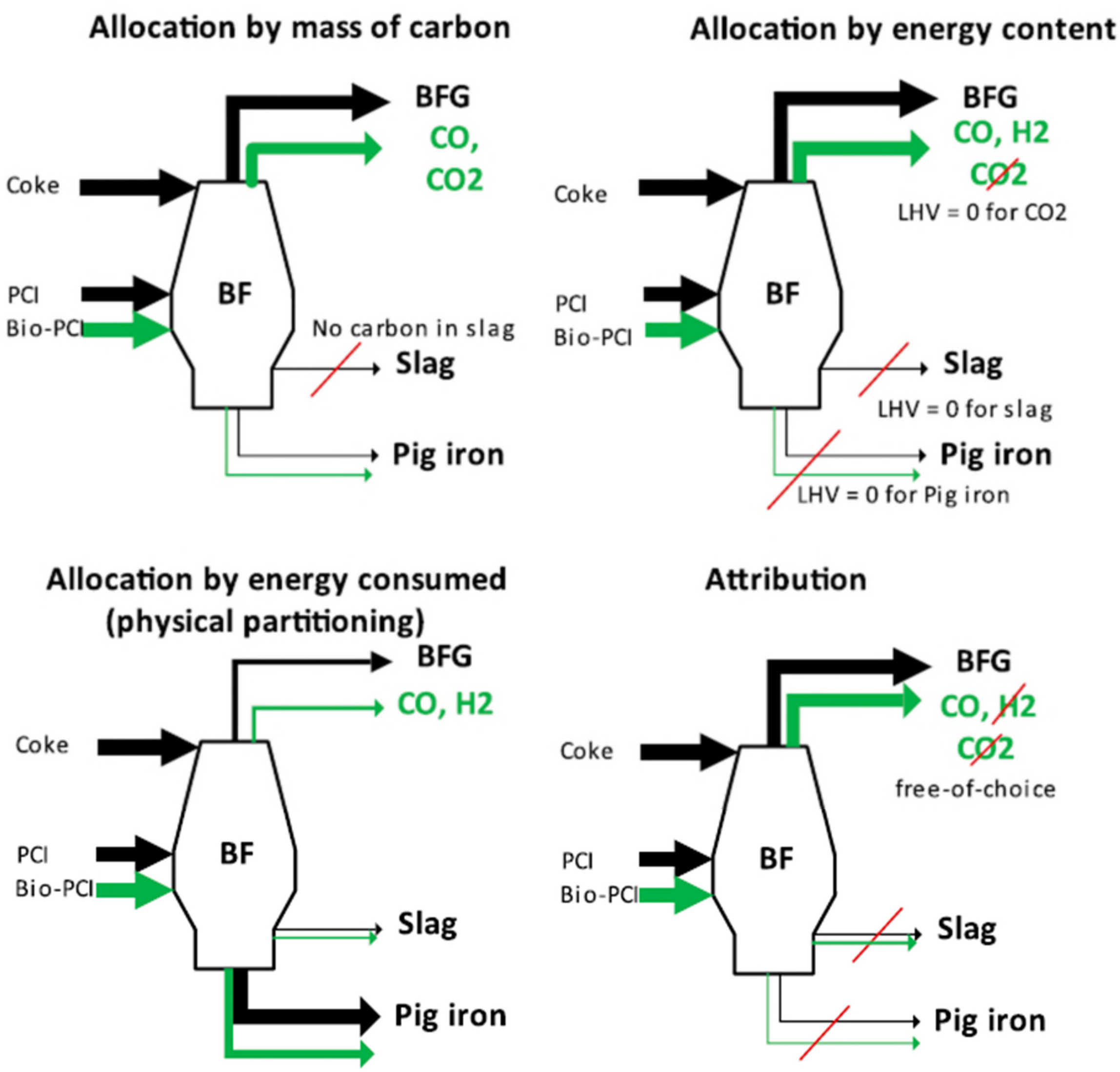

Figure 75: Biomass allocation schemes

Carbon can be allocated in four ways: by mass (top-left panel), by energy content (top-right panel), and by physical partitioning (bottom-left panel) versus free-choice carbon attribution (bottom-right panel). The attribution example is arbitrary and may resemble the choice to favour energy-related products from BFG in terms of its associated production emissions. The black arrows indicate fossil carbon flows, and the green arrows indicate biogenic carbon flows.

Concerning the technical potential for emissions reductions in a reference integrated steel mill in Europe (4 Mt HRC and 8,377 ktCO_2 per year), they conclude the following.

- Replacement of 10% of fossil PCI with biocoal, which is possible without affecting the blast furnace operation, would lead to emission reductions of 2.5–3.5% for any product (e.g., electricity or ethanol) made from the CO and H_2 in the BFG.
- Theoretical replacement of 100% of the fossil PCI with biochar and a 99% capture rate from the BFG would lead to ~21–24% emissions reduction

Thus, the set of valid allocation schemes determines the extent of flexibility that manufacturers have in producing low-carbon products, which is relevant for industries whose product target sectors that value emissions differently. The authors of the carbon allocation paper recommend that policymakers consider the emerging relevance of co-processing in non-refining facilities. Provided there is no double-accounting of emissions, policies should allow a reasonable degree of freedom in the allocation of emissions savings to low-carbon products, so as to promote the sale of these savings, thereby making investments in mitigation technologies more attractive to stakeholders.

Sustainability and certification

Two legislative frameworks are in place that concern the sustainability of biomass use in steelmaking.

- ETS framework (EU ETS Directive 2003 87 /EC and Monitoring and Report Regulation 2018 2066. In both documents the regulations is that the emission factor for biomass shall be zero.

- Energy framework. The Renewable Energy Directive REDII 2018/2001 sets out only targets for renewable energy consumption, non-energy use of biomass doesn't count towards the target and are then exempt from the sustainability criteria stablished in this directive. ArcelorMittal considers the use of waste wood in projects as reductant to replace fossil carbon in the blast furnaces and reduce carbon emissions in the production process therefore emission factor for biomass shall also be considered zero.

  However there is an upcoming revision of legislation. In the 2030 Climate Target Plan, COM communicated that the use of biomass will be revisited and reviewed in a coherent way with other fuel initiatives like the sustainability criteria in the Renewables Energy Directive RED II that could impact directly the monitoring and reporting rules in ETS for users of biomass
  Rules for carbon accountancy for ArcelorMittal projects can change if new sustainability criteria are included in the new legislation that affects the ETS framework for different uses of biomass (e.g. where ArcelorMittal projects fall and/or a change in carbon accountancy rules for wood wastes. If a change in legislation occurs and affects the Biomass projects, ArcelorMittal needs to develop a plan and demonstrate that waste wood considered for the projects are in the end of the waste hierarchy, in accordance with the circular economy and cannot be considered under the same rules as grown forest and raw wood used for energy production.

5.2.6 Roll-out plan and expansion at other AM steel plants

The objective of the roll-out plan is to determine the best manner on how to replicate a possible torrefaction process and torrefied wood as biomass use at similar AM steel plants.

- The first action will be a market analysis, in terms of the size of the potential market, time to market, and competition of other technologies.
- With Renewi initial estimates were made for the costs of waste wood input strategies
- Next the outcome of the conceptual design was used to determine the energy mass balance, and associated costs for processing the waste wood.
- By combining these different elements (market analysis, energy-mass balance, feedstock and processing costs) an initial business case was developed.

Market analysis

Steel production in the EU28 takes place at 500 production sites in 23 countries. Over 177 million tons of steel are produced each year, of which 115 million tons via the BF-route, accounting for 11% of the global steel production, making the EU the second largest producer of steel in the world after China.

- The technology demonstrated in the Torero project, replacing part of the fossil fuel by torrefied wood powder, can be easily transferred to other steel plants. In theory, all existing steel plants in the EU equipped with a blast furnace can apply it to lower their greenhouse gas emission.
- In the Torero demonstration plant, a yearly capacity of 100,000 ton type B wood is targeted, which is the equivalent of 50,000 tons of torrefied material. At full commercial scale, this capacity will be higher and the level of capital investment (CAPEX) needed will decrease as the number of plants grows in the EU. The feedstock is abundantly available. According to '*Understanding waste streams*' briefing to the European parliament of July 2015: 52.9 million ton of wood waste was treated in EU28 in 2012. Moreover, "Treatment of According to the quality grade, wood waste is recycled (e.g. as panels or pellets); incinerated, with energy recovery; or treated at special facilities. In 2012, 51% of EU wood waste was incinerated, while 46% was recycled, according to Eurostat."
- If this technology is adapted throughout the entire European steel industry, this would result in a reliable production system of bio-ethanol, delivering millions of bioethanol each year, to be used as bio-fuel. At this moment the demand for bioethanol is bigger than the supply, sustaining the expected price increase the coming years. This technology could also have a stabilizing effect on the market price of bioethanol, through its large supply.

Figure 76: Integrated Steel Plants (BF-operated) in EU

First thoughts on ArcelorMittal roll-out strategy in EU

ArcelorMittal has assessed the potential contribution of implementing Torero-type torrefaction technology at its European production facilities, **taking into account local feedstock conditions.**

The total BF production Europe is estimated at 31.5 Mton. Based on the average coal consumption of a blast furnaces the total volumes of (powder) coal use can be calculated at:

- 16.4 Mton of coal (522 kg/t hot metal), resulting in 11 Mton of coke (350 kg/t hot metal)
- 4.7 Mton (150 kg/ ton hot metal) of PCI (powder coal for injection)

Assuming an average replacement rate of 60% of waste wood versus PCI and a threshold of 15% of PCI being replaced by waste wood, we estimate a potential demand of 4.7 x 0.2 / 60% = 1.6 Mton of waste wood for ArcelorMittal.

Extrapolating to the overall EU steel production (via BF-route) of 115 Mton the total waste wood demand would be 5.8 Mton.

The total volume of waste wood treated in Europe is estimated at 50 Mton. Therefore, we conclude that there should be sufficient volume of waste wood available to supply the steel sector in Europe with waste wood as alternative renewable feedstock for PCI (15%).

Figure 77: ArcelorMittal production plants in Europe

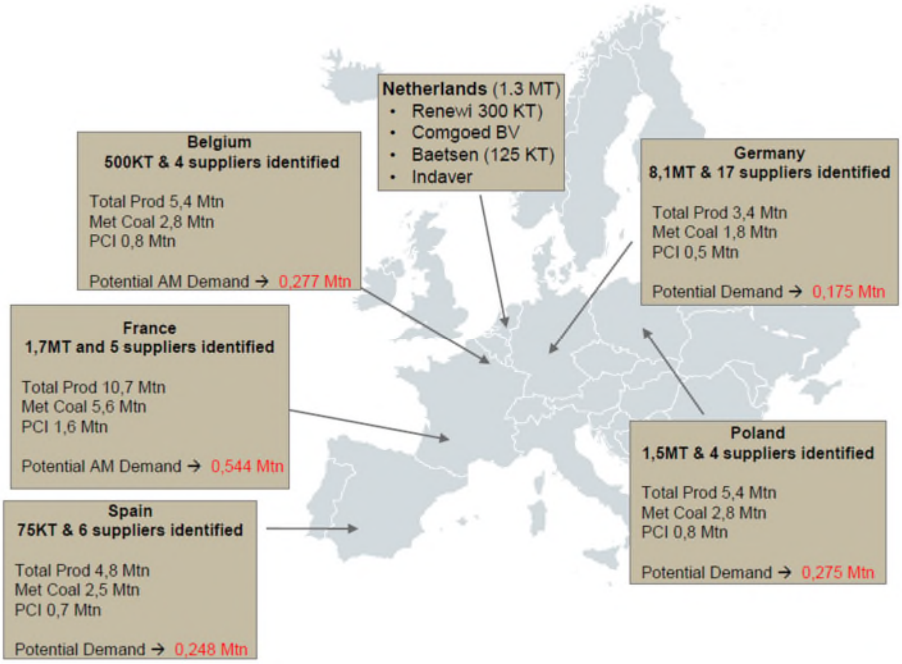

Figure 78: Potential waste wood demand AM [63]

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Annexes

Italian Case Study - Seasonal Biomass Productivity Maps

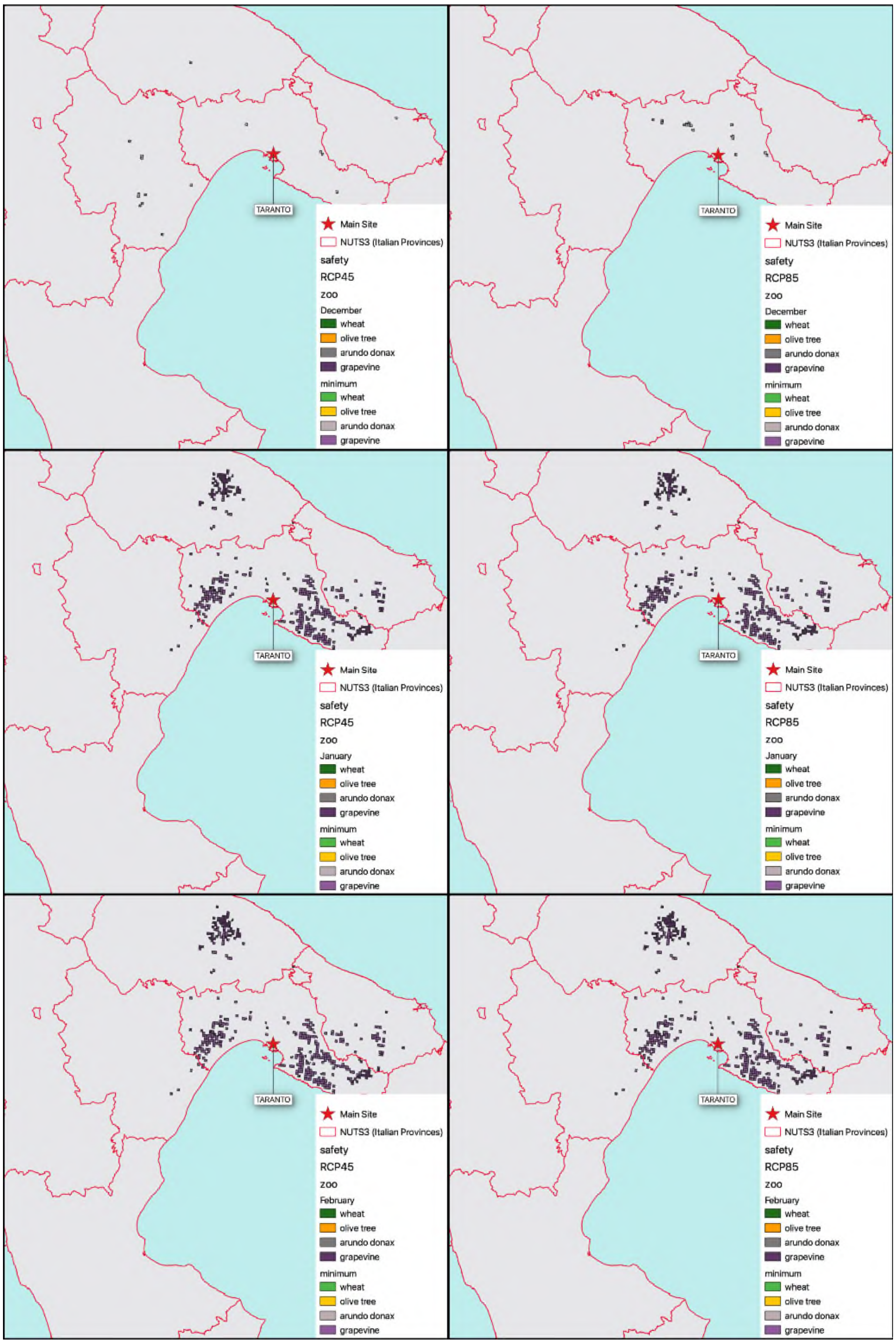

Figure 79: Winter biomass productivity map (December – February)

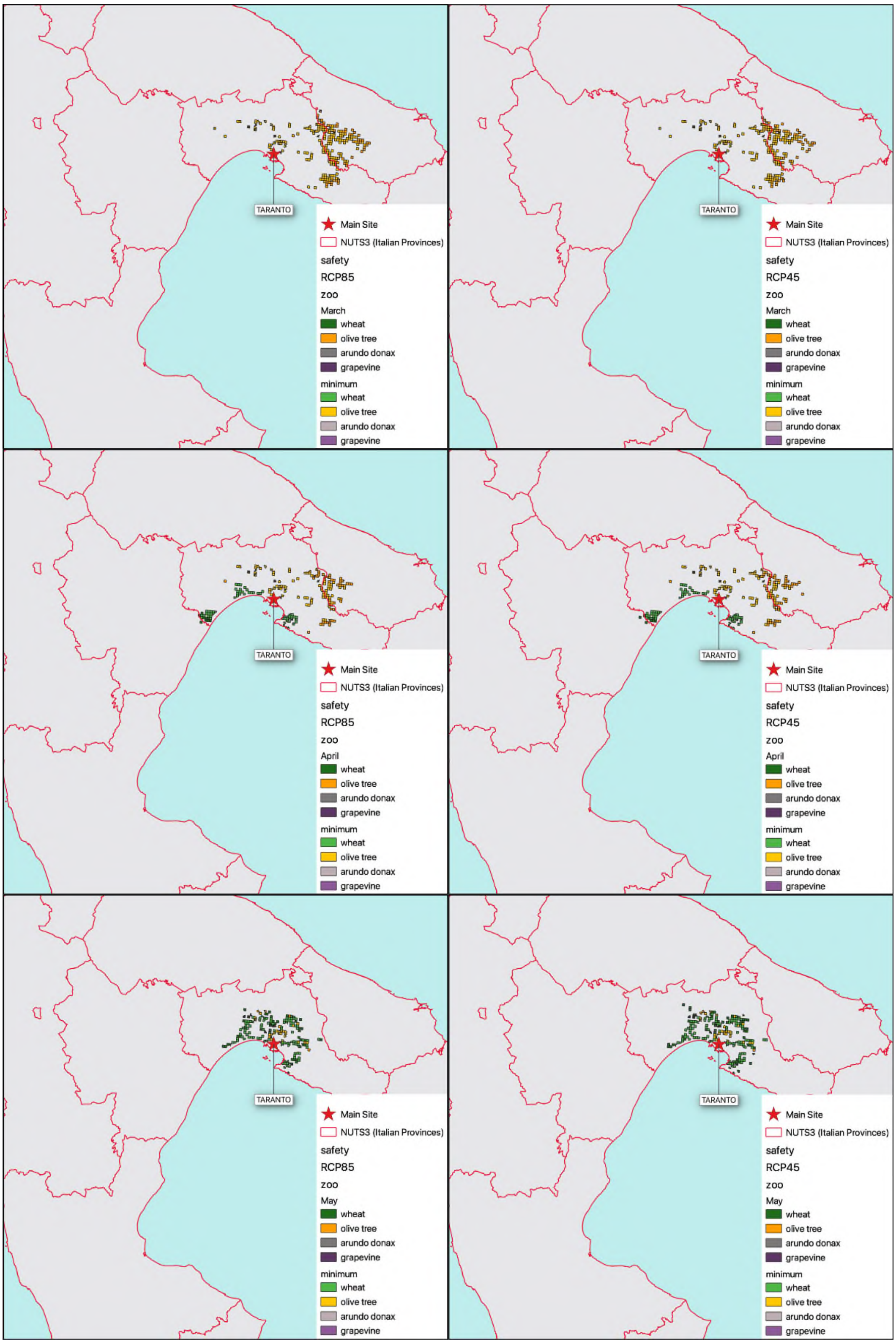

Figure 80: Spring biomass productivity map (March – May)

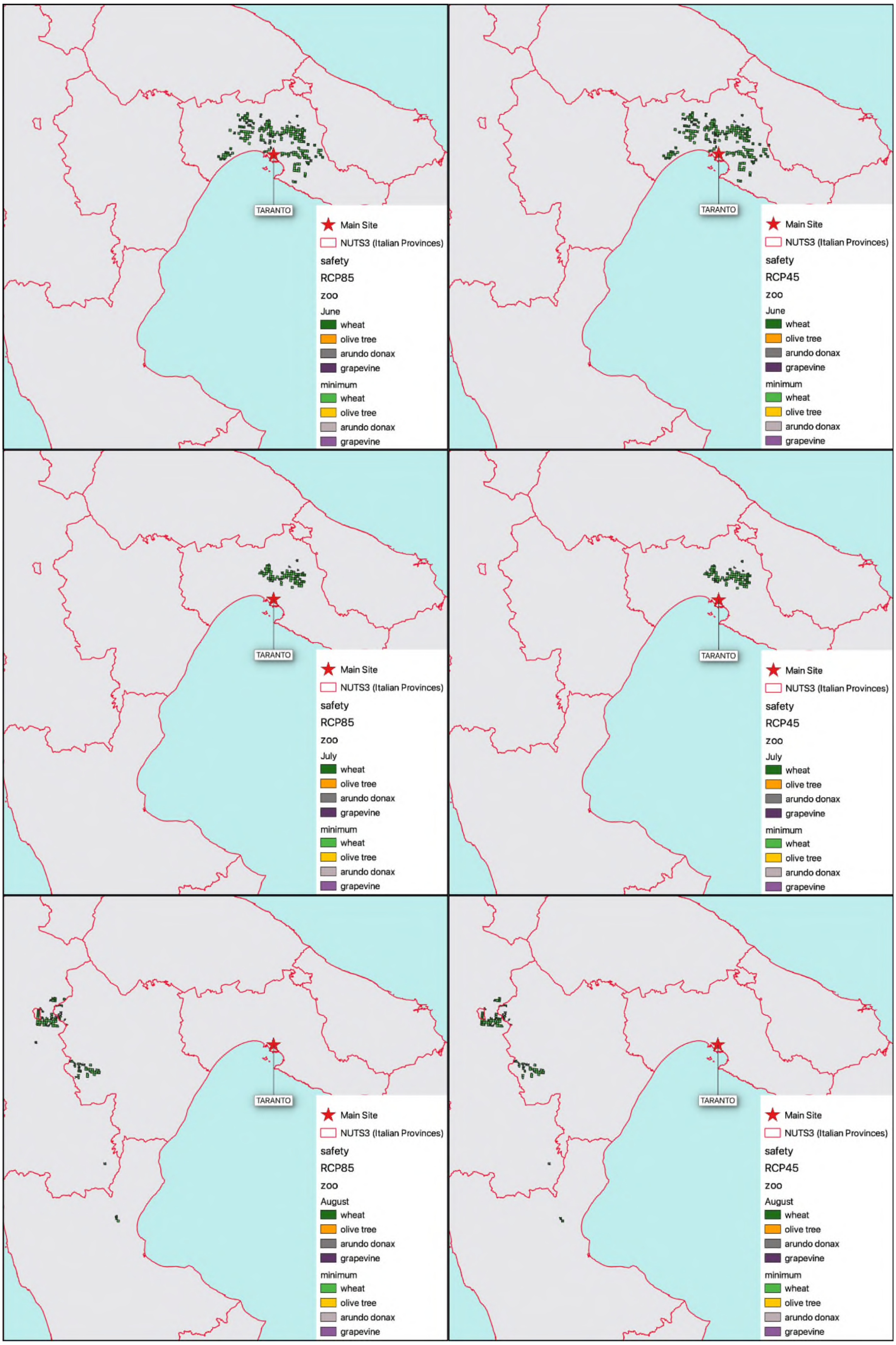

Figure 81: Summer biomass productivity map (June – August)

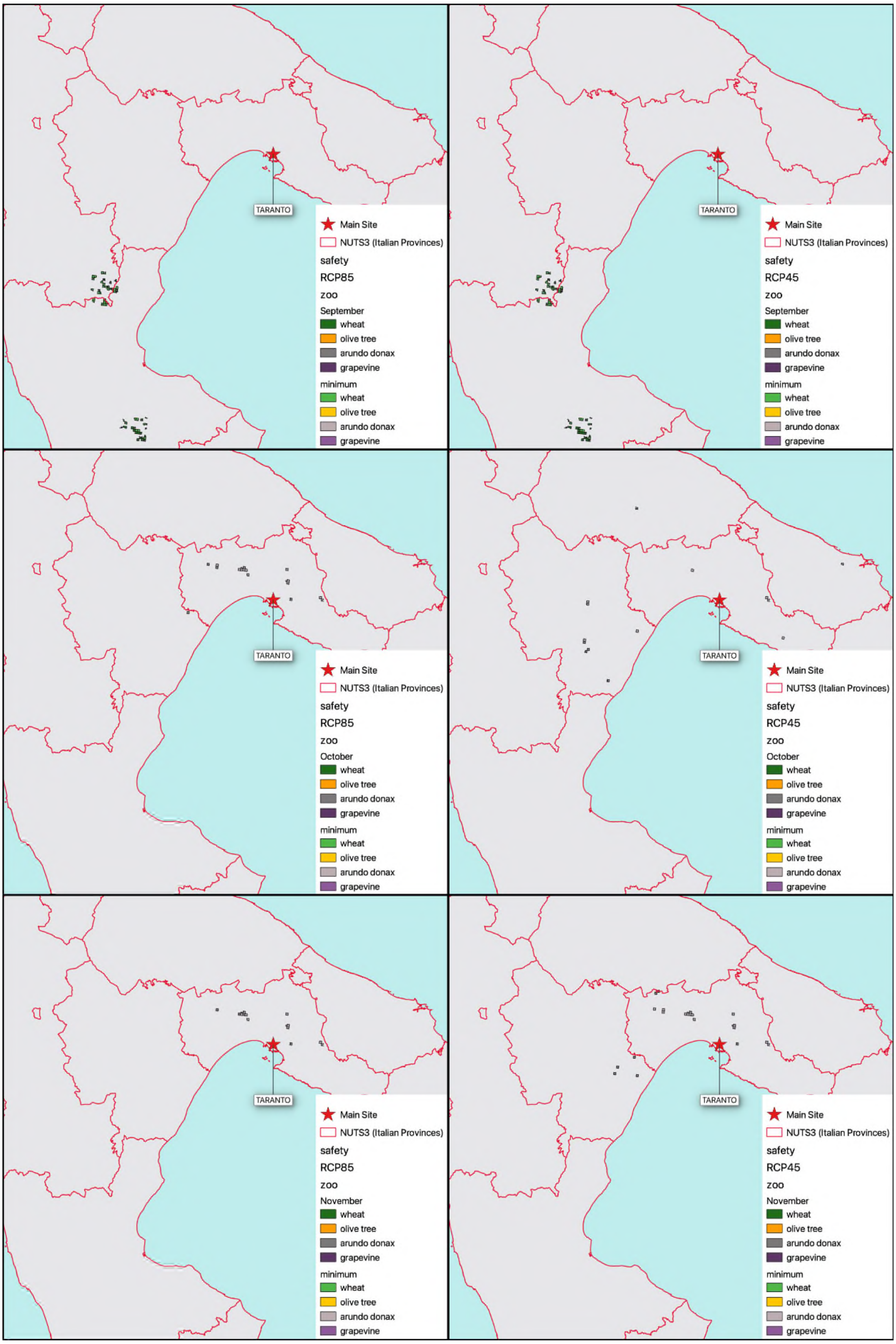

Figure 82: Autumn biomass productivity map (September – November)

Italian Case Study - Summary of techno-economic indicators obtained for the analysed scenarios.

Table 63: Summary of techno-economic indicators obtained for the analysed scenarios

Scenario		NPV	Δ NPV	PBT	IRR	Δ IRR	Notes
Meta scenarios	*Baseline*	39,188,690 €	N.A.	15	11.1%	N.A.	
	Worst Case	- 41,402,483 €	-205.6%	N.A.	N.A.	N.A.	Not Viable
	Best Case	61,804,793 €	57.7%	12	13.4%	20.7%	
CAPEX	-10%	42,521,165 €	8.5%	14	11.8%	6.3%	
	-5%	40,854,928 €	4.3%	15	11.5%	3.6%	
	5%	37,522,452 €	-4.3%	16	10.8%	-2.7%	
	10%	35,856,215 €	-8.5%	16	10.5%	-5.4%	
Coal	-10%	34,913,322 €	-10.9%	16	10.7%	-3.6%	
	-5%	37,051,006 €	-5.5%	16	10.9%	-1.8%	
	5%	41,326,374 €	5.5%	15	11.3%	1.8%	
	10%	43,464,058 €	10.9%	15	11.6%	4.5%	
Natural Gas	-10%	34,239,067 €	-12.6%	16	10.6%	-4.5%	
	-5%	36,713,878 €	-6.3%	16	10.9%	-1.8%	
	5%	41,663,502 €	6.3%	15	11.4%	2.7%	
	10%	44,138,313 €	12.6%	15	11.6%	4.5%	
Green Carbon	-10%	36,597,662 €	-6.6%	16	10.9%	-1.8%	
	-5%	37,893,176 €	-3.3%	16	11.0%	-0.9%	
	5%	40,484,204 €	3.3%	15	11.3%	1.8%	
	10%	41,779,718 €	6.6%	15	11.4%	2.7%	
Biomass	High - Low	28,846,118 €	-26.4%	18	10.0%	-9.9%	

	High	23,608,738 €	-39.8%	19	9.5%	-14.4%	Alt. Worst case (used)
Pyrogas	15% internal use	59,628,538 €	52.2%	13	13.1%	18.0%	
	45% internal use	26,924,781 €	-31.3%	18	9.9%	-10.8%	
EUA	HIGH	37,992,244 €	-3.1%	15	11.2%	0.9%	
	LOW	- 1,487,482 €	-103.8%	N.A.	N.A.	N.A.	Not Viable

Tables Greek Case Study

Table 64. Monthly thermal energy consumption.

Month	2014/2015	2015/2016	Forecast	Raw biomass demand
October	2.486	1.772	2.938	852
November	5.066	4.872	6.858	1.988
December	7.317	9.452	11.571	3.354
January	8.757	11.002	13.634	3.952
February	7.325	6.987	9.876	2.863
March	7.250	7.205	9.974	2.891
April	3.985	2.390	4.399	1.275
May	545	541	749	217
Total	**42.732 MWh**	**44.220 MWh**	**60.000 MWh**	**17.393 tn**

Table 65. Properties of alternative fuels

Parameter	Base	Wood residues	Sunflower pellets	Wood hog	Char
Moisture content	a.r.	43,5%	8,20%	34,50%	11,30%
Ash	dry	2,5%	3,60%	3,90%	9,10%
Volatiles	dry	79,2%	76,60%	77,60%	11,00%
Ash	a.r.	1,4%	3,40%	2,50%	8,10%
Volatiles	a.r.	44,8%	70,40%	50,90%	9,80%
C	dry	49,8%	50,12%	49,27%	87,10%
H	dry	5,97%	6,10%	6,35%	0,21%
N	dry	-	1,10%	0,45%	0,33%
S	dry	<0,03%	0,14%	<0,03%	<0,03%
Cl	dry	-	0,07%	-	-
HHV (MJ/kg)	dry	19,53	19,85	19,38	30,44
LHV (MJ/kg)	dry	18,23	18,52	18,00	30,39
HHV (MJ/kg)	a.r.	11,04	18,23	12,70	27,01
LHV (MJ/kg)	a.r.	9,24	16,81	10,95	26,69

Table 66. Effect of torrefaction temperature on chemical degradation.

Classification	Light	Mild	Severe
Temperature (°C)	200-235	235-275	275-320
Consumption			
Hemicellulose	Mild	Mild to severe	Severe
Cellulose	Slight	Slight to mild	Mild to severe
Lignin	Slight	Slight	Slight
Liquid color	Brown	Brown dark	Black

Product	
Gas	H_2, CO, CO_2, CH_4, toluene, benzene and C_xH_y
Liquid	H_2O, acetic acids, alcohols, aldehydes and ketones
Solid	Char and ash

Table 67. Torrefaction technology status.

Torrefaction technologies		Proven techn.	Heating integration	Heat transfer	heating rate	Temp. control	Particle size tol.	Mixing	Res. time control
Rotary drum reactor	Direct heating	+	+	+	+	0	+	+	+
	Indirect heating	+	+	0	0	+	+	+	+
Fluidized bed reactor	Direct heating	+	0	+	+	0	0	+	0
Moving bed reactor	Direct heating	0	+	0	0	0	+	0	+
Vibrating belt reactor	Direct heating	+	+	+	+	0	+	+	+
Screw conveyor reactor	Direct heating	+	+	+	+	0	+	+	+
	Indirect heating	+	+	0	0	+	+	+	+
Multiple hearth furnace	Direct heating	+	+	+	+	0	+	+	+

Table 68. Indicative properties of different biomass and coal-based fuels.

	Wood	Wood pellets	Torrefied wood pellets	Charcoal	Coal
Moisture content (% wt)	30-45	7-10	3-8	1-5	10-15
Net Calorific value a.r. (MJ/kg)	9-12	15-16	19-24	30-32	23-28
Volatiles (% db)	70-75	70-75	55-65	10-12	15-30
Fixed carbon (% bd)	20-25	20-25	28-35	85-87	50-55
Bulk density (kg/l)	0,2-0,25	0,55-0,75	0,65-0,75	0,2	0,8-0,85
Energy density (GJ/m^3)	2-3	7,5-10,4	15-18,7	6-6,4	18,4-23,8
Dust	Average	Limited	Limited	high	Limited
Hygroscopic properties	Hydrofilic	Hydrophilic	Hydrophobic	Hydrophobic	Hydrophobic
Grindability	Worse	Worse	Better	Better	Better

Biological degradation	Yes	Yes	No	No	No
Handling requirements	Special	Easy	Classic	Classic	Classic
Product consistensy	Limited	High	High	High	High
Transport cost	High	Average	Low	Average	Low

Table 69. Thermal energy consumption, raw biomass and torrefied biomass demand for the 50% of the fuel demand.

Month	Thermal energy consumption (MWh)	Energy demand from fuel (MWh)	Raw biomass demand (50%) (tn)	Torrefied biomass demand (50%) (tn)
October	2.938	3.339	426	313
November	6.858	7.793	994	730
December	11.571	13.149	1.677	1.231
January	13.634	15.494	1.976	1.451
February	9.876	11.222	1.432	1.051
March	9.974	11.335	1.446	1.062
April	4.399	4.999	638	468
May	749	852	109	80
Total	**60.000**	**68.182**	**8.697**	**6.384**

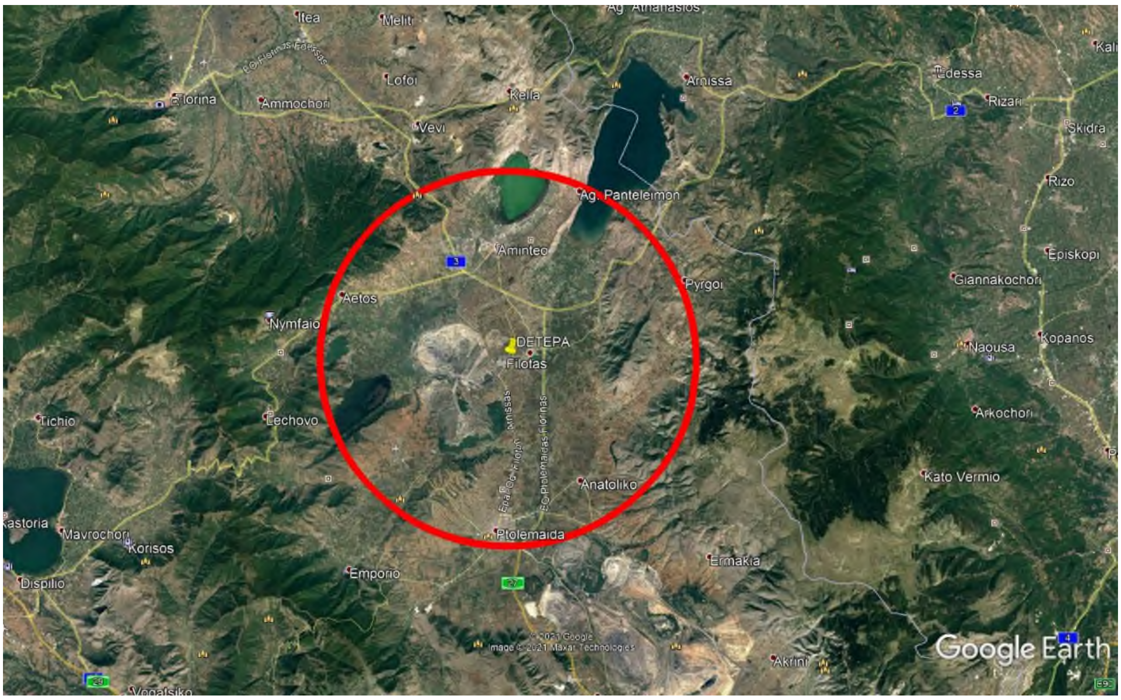

Figure 83. Area of potentially available biomass to cover DETEPAs fuel needs.

Table 70. Machinery and acquisition cost per stage.

Stage	Machinery	Type	Cost
Mulching	Renault Ergos 95	Agricultural tractor	**20.000 € (used with front-end loader)**
	John Deere 6920S	Agricultural tractor	**50.000 € (used)**

	Desvoys SH320	Mulcher	**2.500 € (used)**
Windrowing	John Deere 2850	Agricultural tractor	**17.000 € (used)**
	Stoll Drive 782 Hydro	Windrower	**4.500 € (used)**
Baling	John Deere 6920S	Agricultural tractor	**50.000 € (used)**
	Case IH 540	Baler	**20.000 € (used)**
Loading	John Deere 6920S	Agricultural tractor	**50.000 € (used)**
	Faucheux f255	Front-end loader	**Bough along with Renault Ergos 95**
Transport	Scania R500 Hydro	Truck	**10.000 - 18.000 € (used)**
	Kögel	Platform	**4.000 – 7.000 € (used)**

Table 71. Biomass supply chain cost.

Stage	Machinery/Equipment	Total cost	Total cost
Mulching	John Deere 6920S	82,57 €	5,73 €/tn
	Desvoys SH320		
Windrowing	John Deere 2850	47,79 €	3,32 €/tn
	Stoll Drive 782 Hydro		
Baling	John Deere 6920S	121,49 €	7,44 €/tn
	Case IH 540		
Loading	John Deere 6920S	101,87 €	6,07 €/tn
	Faucheux f255		
Unloading	Komatsu	25,68 €	1,78 €/tn
Transport	Scania R500 hydro	57,7 €	0,05 €/tkm
	Total	**437,1 €**	

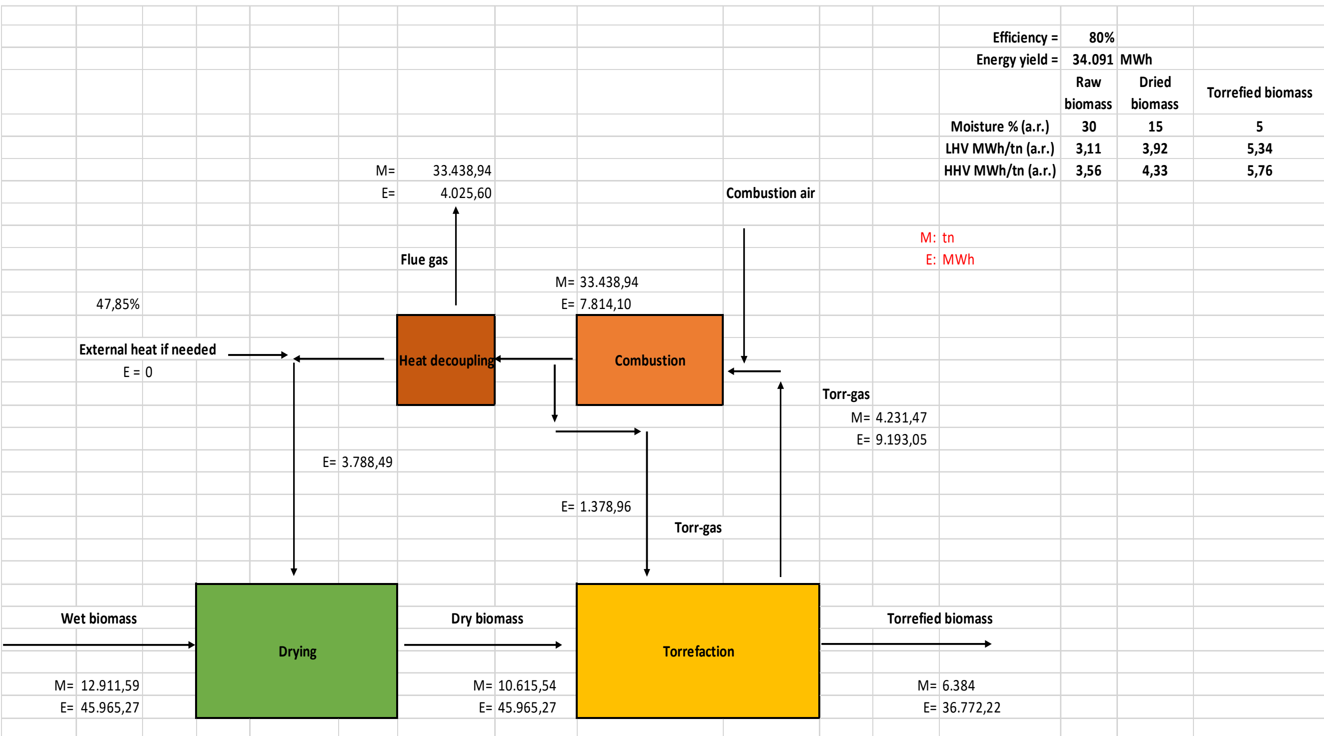

Figure 84. Simplified mass-energy balance model.

Table 72. Torrefaction unit operational parameters.

Parameter	Value	Unit
Energy efficiency	80	%
Feedstock to product ratio	2,022	
Electricity	170	kWh/tn product
Scale (operational)	6.384	tn/yr
Operation	8.000	hr/yr
Feedstock moisture content	30	%
Product moisture content	5	%
Fossil fuel input	0	
Feedstock energy content	3,11	MWh/t
Product energy content	5,34	MWh/tn
Co-product energy content	1,8	MWh/tn

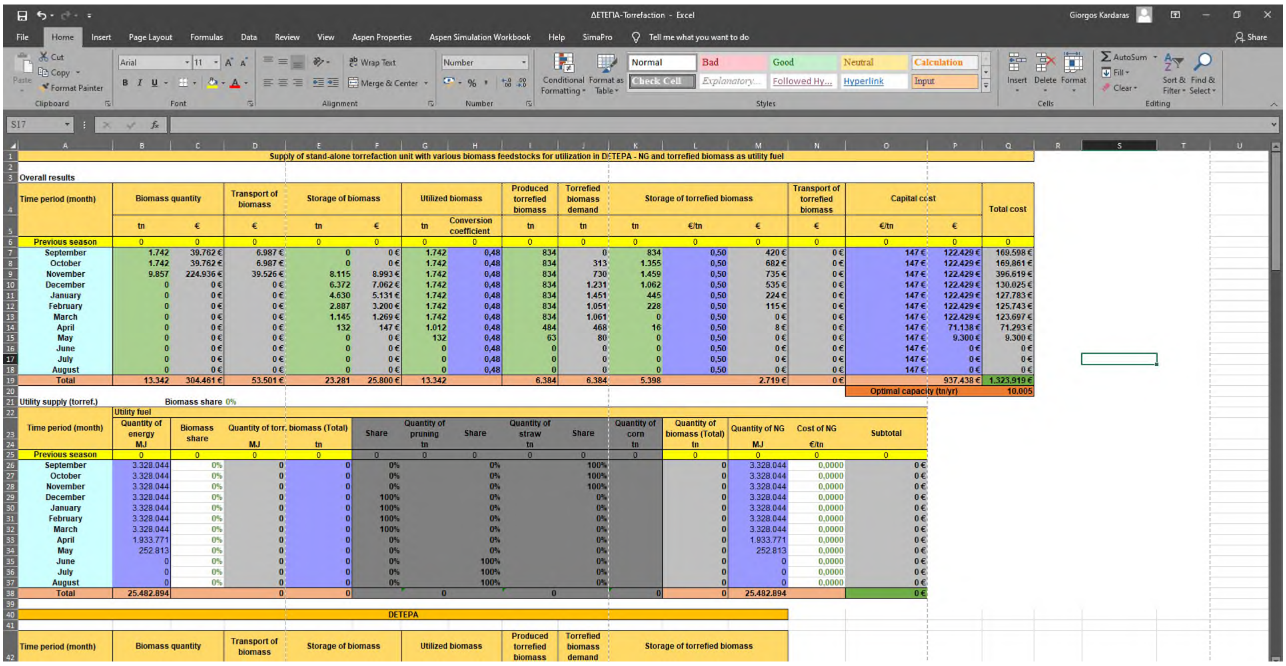

Figure 85. Screenshot of the biomass supply optimization tool.

Table 73. Biomass seasonal availability in Western Macedonia.

Months	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**June**	**July**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**
Wheat straw												
Corn stalks												
Tree pruning												

Table 74. Investment cost of a base case torrefaction unit.

	Stand-alone

	Base case
Capacity (tn/year)	**79.200**
Capacity (tn/month)	**6.600**
Capacity (tn/hr)	**10**
Torrefaction	
Front end loader	260.304 €
Wood chips hopper	214.232 €
Conveyor	353.599 €
Blowers	180.359 €
Dryer	1.981.075 €
Torrefaction unit	14.627.703 €
Hammer mill	307.527 €
Pellet mill	1.619.413 €
Pellet cooler	460.715 €
Pellets screening	125.545 €
Pellet storage	89.839 €
Boiler	562.986 €
Heat energy recovery	
Heat exchangers	538.500 €
Site and building	
Paving, receiving station and load area	58.503 €
Building and office space	994.554 €
Total capital investment on equipment, land and buildings (CIE)	**22.374.854 €**
Other capital expenses	
Startup expenses	2.237.485 €
Engineering and supervision cost	2.684.982 €
Contingency	2.237.485 €
Fixed capital investment (FCI)	**29.534.807 €**
Working capital	4.430.221 €
Total capital investment (TCI)	**33.965.028 €**
Annualized capital costs €/yr	**3.989.519 €**
Capital cost €/tn	**50 €**
Production costs €/yr	
Annual cost €/yr	
Total cost €/tn	**50 €**

Table 75. Data from the corn residues collection procedures.

Stage	Machinery	Opera-tion	Diesel consumption (lt)	Biomass quantity (tn)	Field area (ha)
Mulching	John Deere 6920S	66 min	44	14,4	6,2

Windrowing	John Deere 2850	89 min	22	14,4	6,2
Baling	John Deere 6920S	77 min	45	14,4	6,2
Loading		62 min	69	14,4	6,2
Transport	Scania R500 hydro	81,3 km	30	14,4	6,2
Unloading	Komatsu	76 min	11,54	14,4	6,2
Total			**221,54**		

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