MUSIC

Market Uptake Support for Intermediate Bioenergy Carriers

D5.5: Set of four Strategic Case Studies

(Public Edition)

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1 Acknowledgment & Disclaimer

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2 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 supports 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) were developed. These involve preparation of business plans for four case study regions (Nordic, Italy, Greece, and International). In each region, an advanced and a strategic case study were elaborated. The advanced case studies were discussed in the earlier Deliverable D5.2. In the current report the results of the strategic case studies are detailed. These strategic case studies are targeted to the medium-long term and are typically focused on expanding from an initial value chain implementation.

Nordic case study

In the Nordic case study, presented in Chapter 4, 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, where upgrading to marine biofuel can take place, using a dedicated process that is currently being developed by BTG, one of the MUSIC consortium members.

In the strategic case study, the pyrolysis oil quantities were set at 192,000 tonne/year, which is the equivalent of the yearly production of 8 standard-sized biomass pyrolysis plants. This is roughly 3 times the size that was studied in the advanced case study. The financial feasibility of these three plants was determined, and a choice was made to locate 4 plants in Finland and 4 in Sweden. Minimum costs for pyrolysis oil at the factory gate were determined to lie between 312 and 430 Euro/tonne, dependent on the business case of the pyrolysis oil plants. It should be noted that very recently prices have increased substantially, which is not reflected in these figures.

International transport can take place in various ways (road, rail, water) and volumes. An option involving monthly transport by sea to Rotterdam is considered technically feasible. Total costs for international transport are about 58-91 Euro/tonne, dependent on the transport frequency.

To make pyrolysis oil suitable for transport applications, upgrading of the oil is required. This is a chemical process that requires substantial amounts of hydrogen. This means both substantial costs, and it is also important for the GHG emission reductions of the entire process. To ensure that the GHG emission reduction of the entire value chain exceeds 65% (to comply with RED II requirements), hydrogen production should be combined with carbon capture and storage (CCS) and/or hydrogen should be produced from renewable sources.

In the base case, production costs for the pyrolysis-based transport fuels would amount to about 1750 Euro/tonne, which is roughly twice as much as the current (2021) price of a fossil alternative. It should be noted that since the upgrading technology is still at a lower TRL, there is a large uncertainty in the calculated cost price. If the price difference is calculated per tonne CO_2 reduced, the additional costs are a little above 300 Euro/tonne CO_2-eq.

In general, the price level in the strategic case study is higher than in the advanced case study. This is partly due to the new market reality of higher costs for biomass, logistics and materials.

Italian case study

The Italian strategic case study analyses the feasibility of collecting agricultural residues and converting these to sugars via enzymatic hydrolysis, followed by production of microbial oil. This microbial oil can be used as feedstock in the ENI refineries in Gela (Sicily) and Porto Marghera (Veneto), to produce green transport fuels. Two regions in Italy were focussed: Sicily and the Veneto region; both in Italy.

Biomass availability was year-round sufficient. The INFER-NRG model, used for assessing the biomass potential in this case study, showed a 50% biomass surplus. The average total price of dry biomass for the IBC plant use has been assessed per crop type, and values ranged in different modelling scenarios from 87 €/t to 105 €/t. Such variability is mostly related to the transport costs, which in turn is affected by the existing transport infrastructure, which is better around Veneto compared to Sicily.

Various scenarios and alternatives were considered, such as variations in the locations (decentral versus central MO production, use or sale of lignin). Depending on these choices, costs for Microbial Oil were determined to lie between 1127 €/t and 1363 €/t. It should however be noted that this Microbial Oil should still be upgraded to produce green transport fuels. Sale of the surplus lignin is considered economically advantageous for the case.

Greek case study

In the Greek strategic case study, the logistics and feasibility of a torrefied biomass value chain supplying the several district heating plants, as well as a power station and in several energy-intensive industries were studied.

As feedstock, agricultural residues (corn residues, vineyard pruning and fruit-tree pruning) were considered. District heating plants considered were operated by DETEPA, DETIP, and DEYAK. The power plant concerned was the Ptolemaida 5 coal-fired power plant. Also industrial applications at CaOHellas S.A. and Grecian Magnesite S.A. were considered. All applications considered Western Macedonia, a region in the north of Greece.

Given the Greek lignite phase-out in 2028, and the steep rise in the costs of natural gas, biomass is emerging as a viable alternative. Biomass use can provide multiple benefits (increase of rural income, enhancement of energy sustainability and mitigation of lignite phase-out consequences) in case it could be mobilized in a sustainable and cost-effective manner.

For various scenarios the total production costs for torrefied biomass is calculated at between 24 and 39 €/MWh. This is higher than the price for wood chips (16.74 €/MWh) and 20.92 €/MWh for pet-coke (a fossil alternative to lignite). Calculations have been made as to what size a torrefaction unit should have, and at what distance it should be located from the conversion location to be viable. Results were that one torrefaction unit with a capacity of 140,000 tn/a, located not further than 115 km from the conversion location is required for the total production cost to break-even with wood-chips price. In the case of pet-coke a or a torrefaction unit of 60,000 tn/a would be sufficient. It should be noted that, because of currently high carbon price) the total costs of lignite are 50.1 €/MWh. This is far higher than any alternative, including all torrefaction scenarios. Factors affecting the total IBC value chain costs are torrefaction unit capacity, biomass price, biomass location (transport cost) and demand fluctuations

Besides these favourable economics, there are a lot of enabling factors regarding biomass utilization in the Greek Case. These are for example the emphasis in the Greek National Energy and Climate Plan (NECP) on biomass and wastes and the emphasis placed in the NECP on sustainability certification schemes for biofuels, bioliquids and solid. However, the legal framework and the lack of large-scale pilot plants are major hindrances.

International case study

The International strategic case study is based on ArcelorMittal's portfolio of steel production plants. The idea is that after implementation of torrefaction equipment at the steel plant in Ghent (Belgium) the technology can be used in more steel production sites in Europe.

ArcelorMittal assessed the feasibility of implementing Torero biomass torrefaction technology in their production facilities as part of the Carbon Action Plan. ArcelorMittal 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.

The torrefaction route investigated by AM fits into their broader Smart Carbon route. An advantage of this route is that it features a number of complementary technologies which enable incremental progress and can be combined to deliver additional value. 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).

AM assessed the availability of waste wood, and assuming an average replacement rate of 60% of waste wood versus PCI (Pulverised Coal Injection – the currently used method of steel production) and a threshold of 15% of PCI being replaced by waste wood, a potential demand of 1.6 Mton of waste wood per year was estimated for ArcelorMittal. These quantities are available on the European market, but costs have increased significantly recently.

AM has committed around €300 million towards carbon-neutral technology, leveraging its 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.

Table of Contents

Abbreviations

CS	Case study
Dx.x	Deliverable
EC	European Commission
EGD	European Green Deal
EU	European Union
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
EU ETS	Emission Trading Scheme
FEC	Final Energy Consumption
FP7	European Union 7th Framework Programme for Research
GHG	Greenhouse gases
IBC	Intermediate bioenergy carrier
ktoe	kilo tonnes oil equivalent
NECP	National Energy and Climate Plan
RED	Renewable Energy Directive
TJ	Terra joule
TRL	Technology readiness level
Tx.x	Task
WP	Work Package

3 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 (Nordic, 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 strategic case study reports. These strategic case studies have been developed by the same case study teams that worked on the advanced case studies, which have been reported in MUSIC deliverables D5.2 and D5.2. The strategic case studies are meant to be expansions of the advanced case study, and as such often represent an enlargement of the case study scope and are looking at the longer term. In the Italian case study this is different, since the advanced case study was about torrefaction, while the strategic case study is about microbial oil.

The case study teams that have worked on the strategic case studies are:

- **Nordic:** 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 strategic 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 strategic case studies so that the consortium partners can use this as a basis to further develop their IBC value chains.

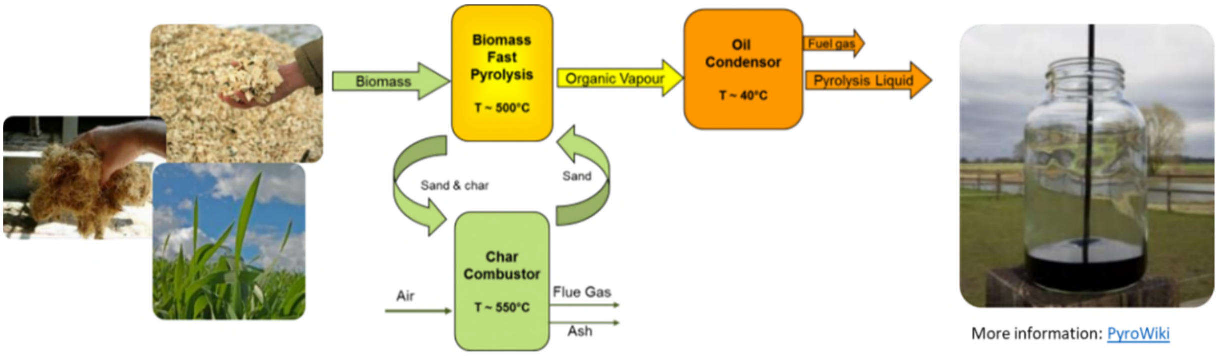
This deliverable (D5.5) is public, and can be distributed freely to all interested stakeholders and the wider public.

4 Pyrolysis production and upgrading: the Nordic case study

4.1 Pyrolysis oil technology

4.1.1 Pyrolysis process

Fast pyrolysis is a process in which organic materials are rapidly (in seconds) 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).



More information: PyroWiki

Figure 1: Fast pyrolysis process (Vos, J. et al. 2020)

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 (Vos, J. et al. 2020). 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 (Vos, J. et al. 2020).

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 ways, 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 (Buffi et al. 2020).

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.

4.1.2 Pyrolysis technology status

At this moment (2022) 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.

In the Netherlands, a 24,000 tonne/year pyrolysis plant (the Empyro plant) was built in 2015 and is operated by the company Empyro BV. This plant was sold to the local utility company **Twence** in 2018. Twence uses residues from wood pellet production and sawdust as feedstock.

Figure 2: The Twence pyrolysis plant in Hengelo, the Netherlands. The plant was commissioned in 2015 and produces 24,000 tonnes 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 Nobian Industrial Chemicals B.V.

In Sweden, the **Pyrocell** plant, located at Setra's Kastet sawmill in Gävle at the east coast, is operational since 2021. This plant uses the same technology as is used in the Empyro plant in Hengelo. The plant uses sawdust as feedstock. The pyrolysis oil produced in the plant is used 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 be the first full-scale commercial application of this type of transport fuel production.

In Finland, the first **Green Fuel Nordic** pyrolysis plant in Lieksa, in the east of the country has been build. This plant also uses the BTG Bioliquids technology. 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.

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 a plant in **Renfrew Ontario** – in 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. It was taken over by the Kerry Group. More recently (2018), another, larger scale - 38 million liters/year - plant was realised by Envergent in cooperation with Arbec Forest Products and Groupe Rémabec in Port Cartier, Quebec. This plant is not fully operational yet.

Resulting operational and planned pyrolysis oil production capacity in Europe is now in total 122,000 tonne/year, or 100 million liters per year. In energy terms its 2 PJ/year. Production capacity in Canada is about 50% of that total (see Table 1).

Table 1: Commercial-scale pyrolysis plants

Plant name	location	Volumetric capacity (Mliter/year)	Capacity in tonne (kt/y)	capacity in energy (PJ/y)
Empyro	Hengelo (NL)	20	24,000	0.38
GFN	Lieksa (FI)	20	24,000	0.38
Pyrocell	Gävle (SW)	20	24,000	0.38
Fortum	Joensuu (FI)	42	50,000	0.80

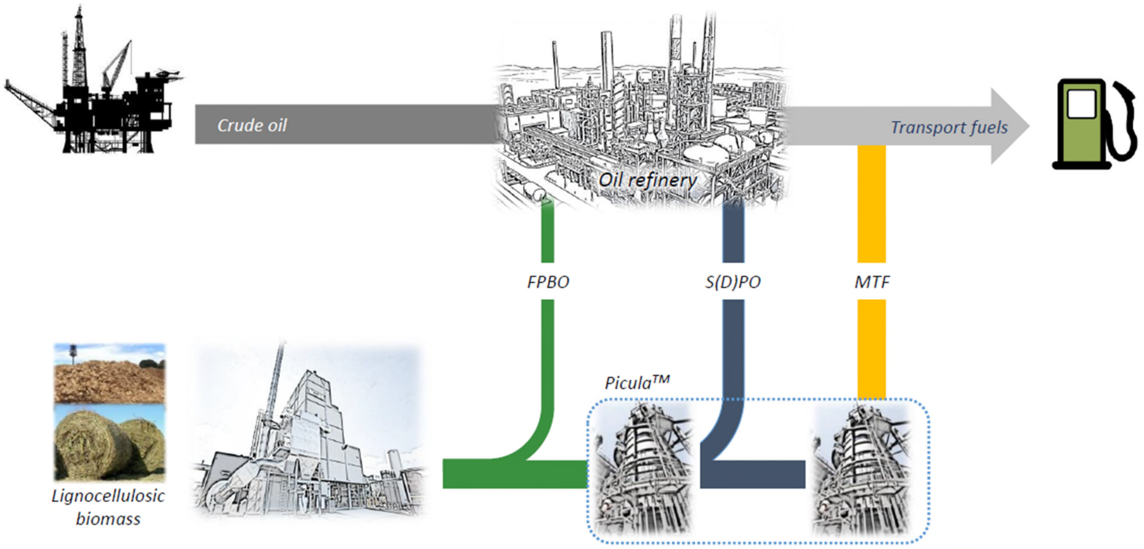
Kerry Group	Renfrew (Can)	11	13,200	0.21
Cote North	Port Cartier (Can)	38	45,600	0.73
Totals		**151**	**180,800**	**2.9**

4.1.3 Upgrading of pyrolysis oil

Untreated FBPO cannot be used as a transport fuel. It cannot be blended with regular transport fuels, and the reactivity is too high. Before "raw" FBPO can be used as a fuel "drop in" it requires upgrading, i.a. to reduce its high oxygen content.

Pyrolysis oil deoxygenation process is a two-step process. The FBPO upgrading can either take place in an existing fossil refinery or in a stand-alone installation (see Figure 3).

- In the first method, FBPO upgrading takes places in a Fluid Catalytic Cracker unit at an existing fossil refinery. After upgrading (stabilisation), a higher share of FBPO can be processed in the refinery than is the case with 'raw' pyrolysis oil.
- The second method involves complete deoxygenation of pyrolysis oil by hydrogenation in a stand-alone installation. This helps to increase the flash point. This process yields hydrotreated Pyrolysis Oil (HPO) (also called MTF (Mixed Transportation Fuels), which can be blended directly with common fuels such as diesel, for use in e.g., the maritime sector.



Source: BTG Bioliquids BV

Figure 3: Pyrolysis oil transport fuel production routes

In this case study, the production of pyrolysis oil in Sweden and Finland, followed by international transport, and subsequent upgrading marine biofuels is investigated. This strategic case study is a follow-up of the Advanced case study, which was completed in 2021.

4.2 Advanced case study results

In the so-called "Advanced Sweden/Finland case study" (Reumerman et al. 2021), 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 MUSIC 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. Currently, these prices have increased substantially.

It was determined that international transport by ship could take place in various ways and volumes. Ports were selected (see Figure 4), and an option involving monthly transport was considered technically feasible. Total costs for international transport are about 61-62 Euro/tonne of pyrolysis oil. This is substantial, but not prohibitive.

Upgrading of the pyrolysis oil requires substantial amounts of hydrogen. To ensure that the GHG emission reduction of the entire value chain is above 65% (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.

In the strategic case study, the logistics and feasibility of implementing a value chain that handles substantially larger volumes of pyrolysis oil is investigated.

Figure 4: The sailing route determined in the MUSIC advanced case study, including the three port locations

4.3 Strategic case study concept: overview of the supply chains

The strategic case study concept for the Nordic case study involves a value chain in which more pyrolysis oil is produced and upgraded. While the advanced case study investigated production quantities of 72,000 tonne of pyrolysis oil per year, the strategic case study will be about 192,000 tonnes per year of pyrolysis oil. Enough feedstock is available for these quantities in Sweden and Finland (Reumerman et al. 2021).

The strategic case study investigated the effect of this expansion on the prospective location of pyrolysis oil plants in Sweden and Finland, logistics and the use of ports in Sweden/Finland, and on the upgrading plant.

4.4 Biomass availability and plant siting

4.4.1 Biomass availability and plant siting in Sweden

Analysing the economy based on woody biomass supply, in particular forest industry by products, 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 price of by-products from forest industry are low and historically they have been purchased at the supplier's industry gate for anywhere 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 a 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 value linked to final product price.
As plant size increases, the volumes of sawdust required for full production will increase and must be supplied from more sawmills located further away from the production site. This means that marginal cost for sawdust will increase.

Figure 5 and Figure 6 illustrate the cumulative cost and the cumulative amount of sawdust that could be transported to the sawmills of Munksund (Figure 5) and Tunadal (Figure 6) in North Sweden for the production of pyrolysis oil. For each of the selected sawmill locations the distance to all other sawmills was calculated through the Network Analyst module in ArcGIS 10.7. Then the cumulative amount of sawdust was calculated. The purchase price was 74 SEK/ton according to the Swedish Energy Agency. Transport costs were calculated according to the equation delivered by wood fuel transporting agent REBIO. No consideration has been taken to ownership and willingness to sell.

To find more synergies and to keep operating costs low, two units can be at the located at the same site. From the figures below we can see a steeper increase in the marginal cost for sawdust acquisition if we locate more than two units at the same site and is therefore not recommended. Market distortion will also increase the more sawdust we require. To be cost effective we assume that all four units are run by the same business entity.

We suggest Munksund sawmill near the city of Piteå as an ideal location for two PO units. Several other sawmills are located quite close, and we also see possible synergies with pulp mill located close to sawmill. The annual cost for acquiring 160.000 raw tonnes is calculated to 17.39 million SEK.

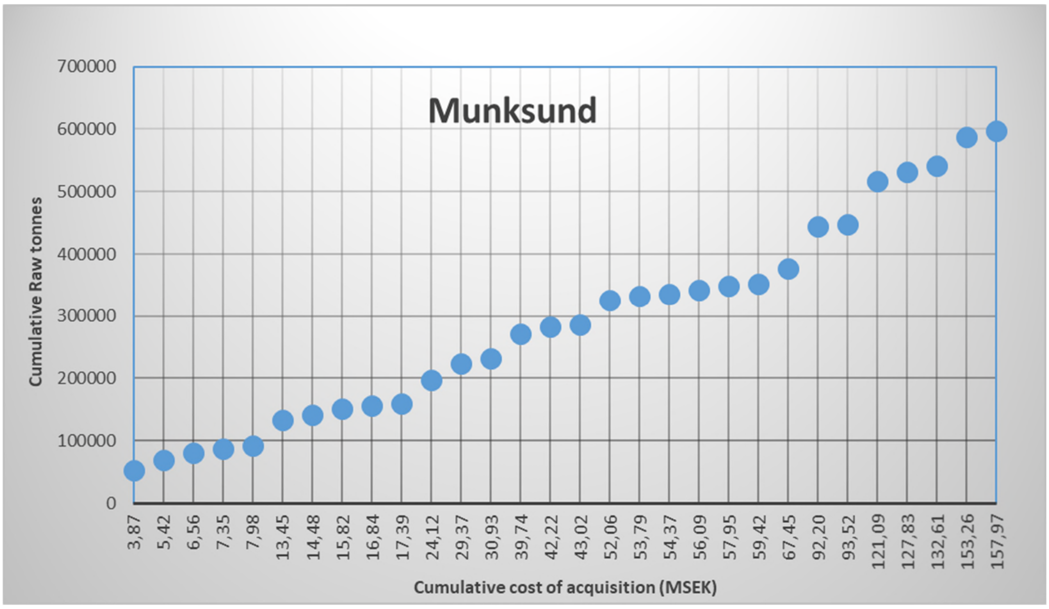


Figure 5. Cumulative cost of acquisition of sawdust for the Munksund sawmill.

We also suggest Tunadal sawmill near the city of Sundsvall as an ideal location for two PO units. Several other sawmills are located quite close. The annual cost for acquiring 160.000 raw tonnes is calculated to 18.80 million SEK.

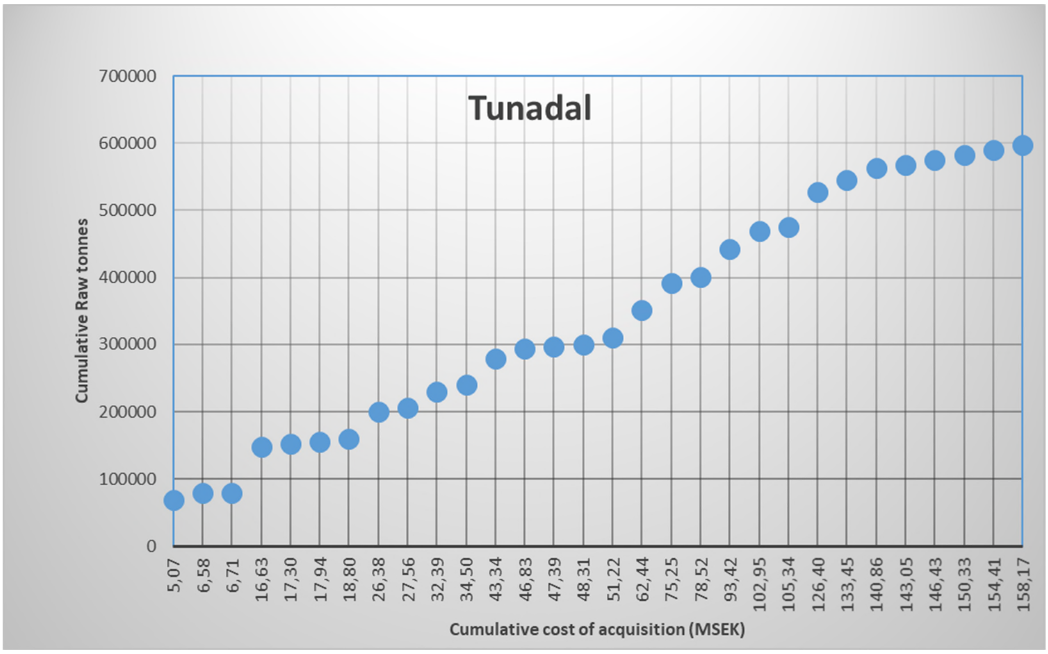


Figure 6. Cumulative cost of acquisition of sawdust for the Tunadal sawmill

4.4.2 Biomass availability and plant siting in Finland

Biomass supply

As it was derived in the Advanced Case study the feedstock resources in the Eastern Finland region should be adequate even for increased plant sizes. 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. This corresponds to a total yearly timber production of the sawmills of about 3.3 million m^3 annually (in 2020) and a cumulative yearly output of sawdust of 877,000 m^3. Which provides about 263,000 raw tonnes of potential available sawdust. This figure is conservative since in 2021 saw goods demand significantly increased and sawmills raised production and have plans to add more capacity.

This amount is mainly derived from 10 Finnish sawmills in the range of 200 km from considered PM plant sites: Iisalmi and Lieksa. Since for 4 units the raw material demand is about 316 000 tonnes, the sawdust deficiency about 53 000 tonnes should be covered with energy chips form biomass heating plants. This is supported by local heat & energy provider Nevel Oy, which operates with biomass in the region. In exchange this company is interested to purchase surplus heat from pyrolysis plants. Due to current global situation the considered in Advance Case Study option for biomass supply from Russia might not be available for certain time and thus excluded from consideration here.

Plant locations

For the Strategic Case study Plant sites Iisalmi and Lieksa are taken as earlier. Both are located in the proximity of big sawmills within 180 km from each other. In that case the available sawdust sources in region are covered homogeneously. The main suppliers for the Iisalmi (North Savo) biorefinery are expected to be Keitele Timber, Anaika and Iisalmen Sahat. And two companies in the region North Karelia: Kuhmo and Binderholz are main sawdust supplies to the Lieksa biorefinery. Also, Nevel Oy has operations in both locations.

Table 2: Finnish plant site characteristics

Iisalmi Site:	Lieksa Site:
- Industrial area SOINLAHTI on Iisalmi suburb - Available land area 15 000 m^2 - Next door (100 m) ANAIKA sawmill (NW side), and LUNAWOOD timber (SE side) - Railway track (SE side) - Iisalmi town –region centre is a source of skilful manpower.	- Industrial area Kevatniemi on Lieksa suburb - Available land area 31 000 m^2 - Side-by-side biomass terminal for Heat use and in 1200 m BINDERHOLZ sawmill (SE side) - Railway track (S side) - Lieksa town –region centre is a source of skilful manpower.

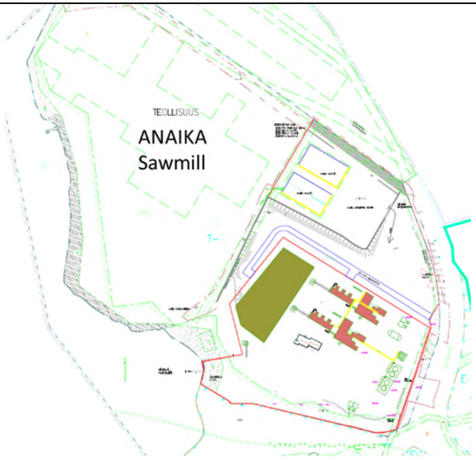


Figure 7.A) Iisalmi site with 2 CPU units

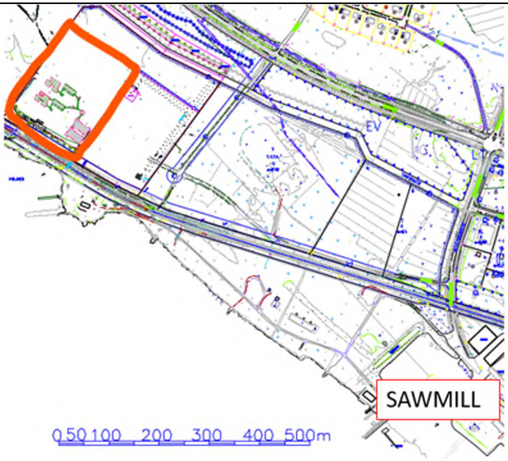


Figure 3.B) Lieksa site with 2 CPU units

4.4.3 Economic evaluation pyrolysis plants

Assumptions

The methodology for economical evaluation remains the same as for Advance Study Case. The scope of the economic study has been limited to cover the construction of two identical pyrolysis oil plants with two PO process units (BTG Bioliquids design) in Finland (Lieksa and Iisalmi sites), as well as two plants with two PO units in Sweden (Piteå and Sundsvall sites).

Compared to the Advanced Study the new scenario was evaluated for the business entity consists of two plants with two bio-refinery process units per site (Sweden and Finland respectively) . 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. However, resources optimization within business entity is accounted, compared to single PO unit plant. Additionally, the significant surplus of heat stream will be sold to neighbourhood. Having the two Plant sites with double PO units each in the same business entity provides following advantages:

- Increase the probability of guaranteed minimum annual production (equals to single PO unit, i.e., 24 000 tonnes PO) from 0,81 (single unit) to 0.964 (two units) and 0.999 (four units). This significantly improves the sustainability of business to deliver production for Customers over year.
- The spare parts and maintenance system can be better optimized, with common capital parts warehouse etc.
- The cost for administration will be also minimized, as more resources available for Client relationships
- Other advantages of larger scale capital in the business.

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. The NPV value has been calculated from the Free Cash Flow. Discounting factor is the estimated Weighted Average Cost of Capital. The WACC is estimated to be 7.2%. The reasoning of WACC is the same as for Advance Case study.

The profitability was calculated for Sweden and Finland separately. 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. The input parameters, which differ from advance case study are given in next chapters.

Time schedule

The project will be implemented during 3 years per country. Two first units on the same site will be done simultaneously and other two PO units on the second site are coming after. This way the same skilful installation and commission labour will be used.

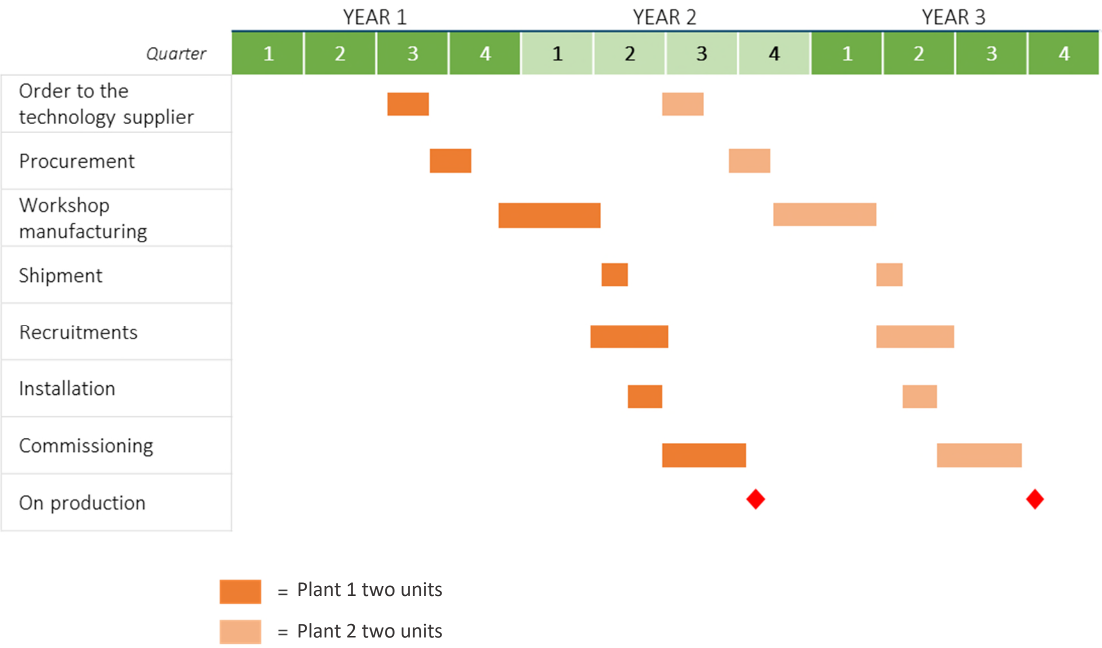


Figure 8: Construction time schedule

Market Prices and cost structure

The pyrolysis oil capacity and production assumptions are based on performance test runs by BTG’s with the Finnish and Swedish feedstock. For the Strategic Case study more conservative figure was used for single plant availability, i.e., of 81%. The production of each biorefinery unit is to be 23.430 tons of pyrolysis oil per year based on proven sawdust throughput 3,3 bio-oil tons per hour and 7.100 operating hours. The total business output (4 units in 2 locations) is then 93.720 tons of FPBO per year. The pyrolysis oil price will be set once a year. Since variable part of price is coupled with crude oil price (US Brent) the price will follow the monthly price changes of the crude oil. Contrary, the production costs are following sawdust price[1]. As it was shown in Advance Case study sawdust and energy chips prices in Sweden and Finland are much more stable over decade than crude oil price. The standard deviation is around 5% while for crude oil is more than 35% for the same period, respectively. Due to rising trend for crude oil prices, as well as energy situation on global market for Strategic Case modelling flat pyrolysis oil price of 85 €/MWh (24€/GJ or 390 €/ton PO) has been taken. This is 10% higher than estimated previously. The further effect of pyrolysis oil price was evaluated with sensitivity analysis.

From two double PO units' plants there is a significant surplus heat stream sold to the industrial or household heating grids in form of hot water. The considered locations have developed centralized heating grids both for households as well as for industrial consumers. Due to high rate of wood biomass utilization in the considered regions 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 biorefinery rises. This is accounted in the model with escalation factor 1.1. The summary of input data for study is given in Error! Reference source not found.1.

Table 3: Plant main data

Description	Units	4 units Sweden	4 units Finland
Production efficiency			
Throughput	*ton PO/hour*	13.2	13.2
Availability	*%*	81 %	81 %
Hours	*hours*	7 100	7 100
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*	93 720	93 720
	MWh	429 584	429 584
	GJ	1 546 380	1 546 380
	m^3	80 103	80 103
Heat Production			
Surplus of heat (steam)	*GJ*	131 799	131 799
Feedstock			
Heating value @55% mc	*MWh/m^3*	0.6	
	MWh/t	1.93	

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[1] *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.*

	Conversion	*ton/m^3*	0.30	
	Feedstock consumption			
		tonnes @3% mc	146 438	146 438
		MWh	612 137	612 137
		tonnes @55% mc	315 654	315 654
Yield Bio-oil				
	Mass	%	64 %	
	Energy	%	70 %	
Bio-oil price				
	Price (FCA PO Plant)	*€/ton*	390	
		€/MWh	85	
		€/GJ	24	
Heat price				
	Surplus of heat (steam)	*€/GJ*	4.2	
Sawdust price				
		€/ton @55%mc	11.4	35.6
		€/MWh	5.9	18.4
Electricity				
	Price	*€/MWh*	**42.6**	***63.3***

Figure 9 depicts the specific costs breakdown per ton of produced pyrolysis oil for Sweden and Finland.

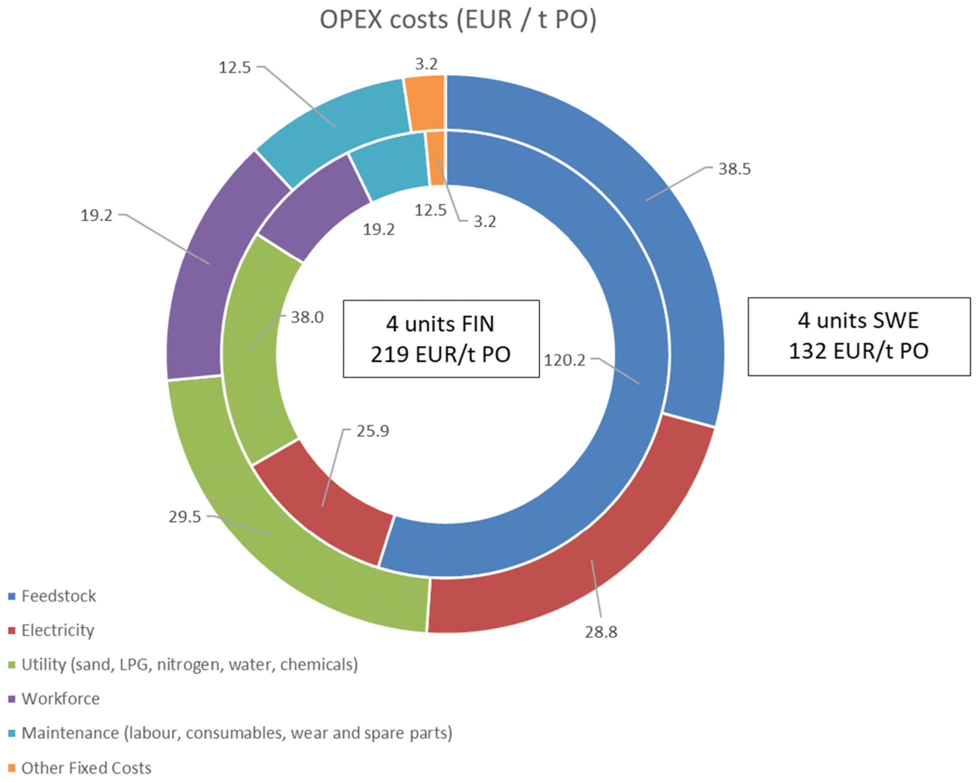


Figure 9: OPEX specific costs breakdown per ton of Pyrolysis Oil shown for Business entity with 2x2 plants in Sweden and Finland

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. Compared to Advance Case study the feedstock price for chosen locations in Sweden is lower now, since earlier it was taken general level of sawdust prices in Sweden. It is now 6 Euro/MWh versus 17 Euro/MWh in Advance Case study. In contrast, the sawdust availability in Finland for 4 units is under pressure taking in account current geopolitical situation. Thus, up to 20% energy chips is assumed in feedstock volume. This increases the feedstock costs to 18.4 Euro/MWh in Finland model.

Electricity is another major production cost item. Current situation with rising energy demand in Europe was reflected in higher Electricity costs for the model (factor 1.15). Also, Sweden has better situation. The power demand for Finland is higher (additional 0.5 MW per unit) due to added chip milling equipment to the biomass handling. LPG cost in the model was increased by 1.15, which effects general utilities costs. Utilities consisted 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.

The production personnel for two sites is assumed to be 40 persons with the same management of the business entity, i.e., the CEO, CFO and technical R&D specialist. Other Fixed costs consist of general administrative expenses, property costs, insurances etc.
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. The possible effects of major costs contributors – feedstock and electricity prices 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 **Error! Reference source not found.**). 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 4: 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 support with grants is considered also in Strategic Case for both locations per country since it is different communes and budgets. However, it is taken that such support will be per location, not per unit as in Advance Case. Then in Sweden, the possible total grant volume for 4 units can be up to 20.8 MEUR, while in Finland it is considered of 15,8 MEUR.
The total investment for Sweden and Finland are estimated as of 96.7 MEUR and 100.3 MEUR, respectively (see Table 5). The difference comes from the additional equipment for chips milling in Finland plants. It should be noted that current CAPEX are higher, due to the recently changed market conditions.

Table 5: Investments and funding sources

Description	**4 units Sweden**	**4 units Finland**
CAPEX		
Fast Pyrolysis Technology	*87.4 MEUR*	*87.4 MEUR*
Biomass handling system	*4.1 MEUR*	*7.6 MEUR*
Other CAPEX and engineering	*5.2 MEUR*	*5.2 MEUR*
TOTAL	*96.7 MEUR*	*100.3 MEUR*
Founding sources		
Equity	*29.0 MEUR*	*30.0 MEUR*
Debt	*46.9 MEUR*	*54.5 MEUR*
Grant	*20.8 MEUR*	*15.8 MEUR*

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 4. The payback time derived from discounted CF is given on Figure 6. In general, both countries show profitable operation, while the Swedish case has faster payback as well as higher IRR and NPV.
The following differences between the Swedish business case and the Finnish one are:

- The costs for electricity is estimated to be lower even after current rising (42.6 Euro/MWh versus 63.3 Euro/MWh). This is likely caused by a surplus of renewable electricity in northern Sweden.
- The feedstock costs is estimated to be lower, namely 6 Euro/MWh as opposed to 18.4 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 given input for Finland, it’s clear that the financial feasibility in Sweden is better than in Finland.

Table 4: Profitability calculation results.

Description	**Unit**	4 units Sweden	4 units Finland
NPV	*MEUR*	82.1	57.7
IRR	*%*	19.7	15.0
Sales Revenue	*MEUR / year*	37.1	37.1
Payback time from investment decision	*years*	9.3	11.8
Payback time from Operation start	*years*	5.3	7.8

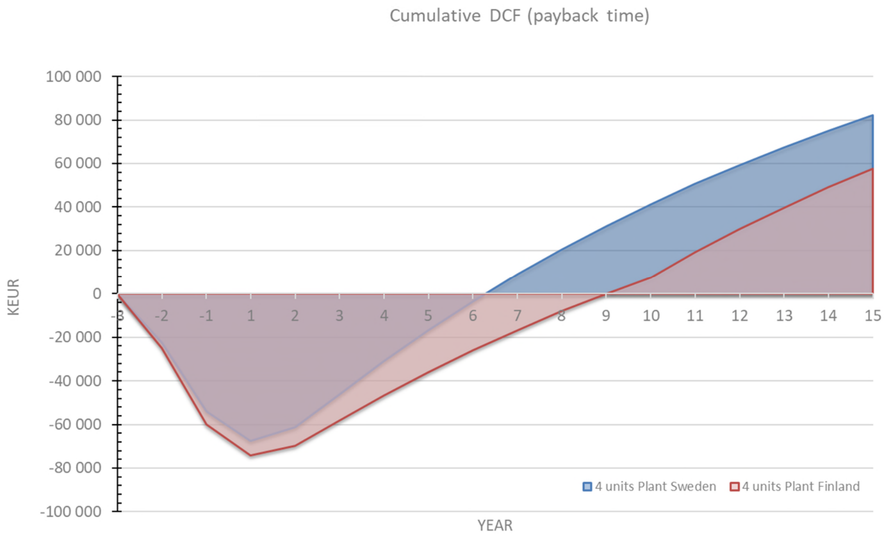


Figure 10: Payback time for alternatives Nordic

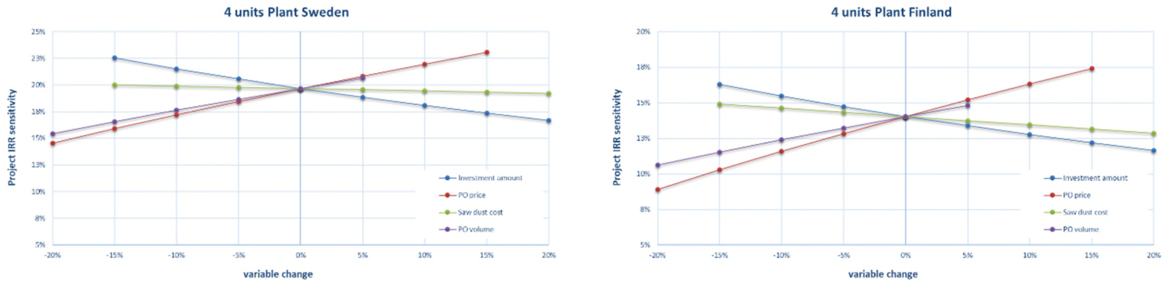
Sensitivity

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.
- Feedstock 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 11.



A) B)

Figure 11: Sensitivity chart of main profitability indicator. A) Sweden, B) 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.

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 12.

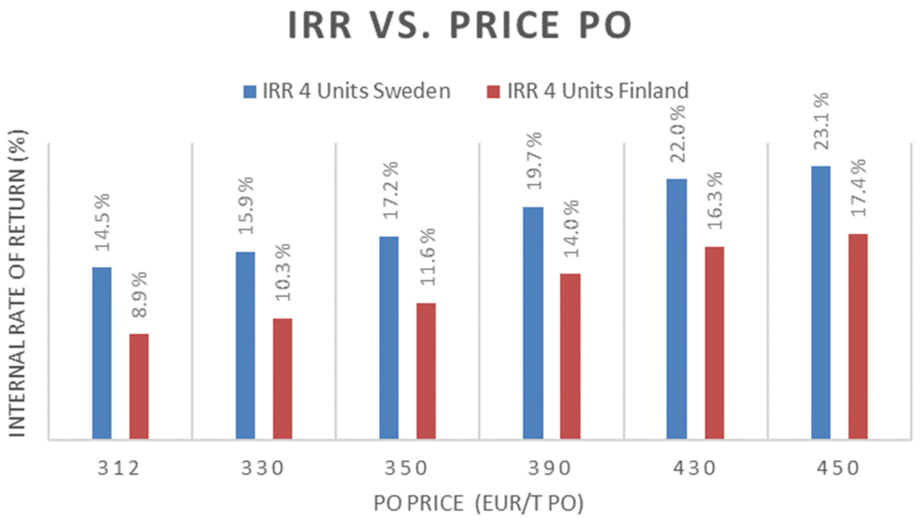


Figure 12: Effect of pyrolysis oil price on project IRR Nordic

Taking in account optimized feedstock pricing for Swedish Strategic case the project IRR improves significantly, while for Finland this remains at about the same level as in Advance Case study. The minimum price for pyrolysis oil at the plant gate for Sweden can be 300 EUR/ton PO, while for Finland it is 390 EUR/ton PO.

4.4.4 Alternative raw material supply

The costs of harvesting collecting, transporting, storing, and handling of the biomass are prime determinants of overall biorefining costs. Thus, it is vitally important to secure over a long time (>10 years) a regional woody biomass supply systems that can efficiently supply biorefineries with a continuous and sufficient raw material supply that meets their specific quality demands.

This could mean redirecting pulpwood, energy wood or industrial by-product flows into new processes. Redirecting the current energy wood and industrial by-product flows would create a respective deficiency in the raw material supply for energy production, which should be compensated in one way or another. In principle, moving renewable raw material from energy production to biorefining and replacing it by fossil materials, such as coal, does not sound very appealing. To satisfy the raw material demand of biorefining would be to enhance the utilization of existing biomass resources. This supply would only be limited by the economic and ecological sustainability of forest management and, naturally, the quantity of the biomass reserves.

Forest industry by products

Low hanging fruits are forest industry by products like sawdust as they are available in large amounts in one place. To maximize possible synergies, refineries can preferably be integrated just next to existing forest industries. 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. However, most of the forest industry by products are already used, either internally, or by pellet producers or CHP plants. In the near future, several investments to upgrade by products like sawdust is expected, both into high value products and to different types of biofuels. It is likely that competition for forest industry by products, especially those with a well-defined quality, like sawdust will increase. As a result of EU climate polices, several countries are introducing biofuel blending mandates, not only for road transports but also for aviation and sea transports. As it is likely that available amounts of sawdust will not be able to meet the growing demand, other more complex woody biomass assortments should be considered.
Cellulose chips have an attractive quality for pulp mills and is assumed not to be available for alternative biorefining processes in the future. Bark is available in large volumes but the heterogeneous nature of bark with high ash content and big particle size distribution makes it not suitable for pyrolysis oil production. 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.

By products from forest operations

The tree stem, excluding bark, is a relatively homogeneous material and its chemical and physical properties are well known, while bark. needles and branches have a much more heterogeneous chemical composition. Thus, for many refining processes stem wood is arguably the most straightforward production material. Most of the stem wood harvest is today used by sawmills and pulp mills. There are rising fears that harvested volumes will decrease as a result of EU polices. This would have an immediate effect of the available volumes of by-products. As a result of forest management schemes, large amount of forestry by products are available. Most of this potential is today not used because the costs of harvesting, transport, storing and handling is too high. What is used, is mainly used for combustion. Higher prices are needed to increase the supply of forest raw materials like logging residues, stumps and young trees.

Logging residues
As a result of logging operations, large volumes of logging residues (treetops and branches) are available. Logging residues have much higher contents of extractives and various other compounds than stem wood, which is a significant determinant of the suitability of feedstock materials for biorefining processes.

Young trees
Young forests contain a large potential of usable biomass. Generally, roundwood yields are small or negligible in thinning stands and harvesting costs tend to be high. Besides pure roundwood thinning's, the tree biomass of young stands is currently utilized as energy wood, which is either harvested as delimbed stem wood or as whole trees. In stands of sufficient stem volume, roundwood and energy wood harvestings can also be integrated. The potential of small diameter thinning wood is larger than that of logging residues from final fillings. Most of this potential remain unutilized. However, to make larger volumes available, forest management practices need to be changed. Young trees including bark together with round wood with qualities not suitable for pulp mills or sawmills could be a suitable feedstock for biorefining.

Stump wood
Stump wood is quite similar to stem wood, with the exception of a somewhat higher concentration of extractives. However, there is a possible negative aspect in using stump and root biomass as a feedstock.
Harvested stumps always contain soil residue, such as sand or rocks (in practice 4-8% ash), and these impurities could cause problems in refining processes. Although environmental problems have been found to be small, stump harvested is not in line with certification practices (FSC). For these reasons, stump wood is not likely to be considered.

4.5 Logistic overview and alternatives

4.5.1 General consideration for handling and storage

To plan the logistics of the pyrolysis oil – marine transport fuels value chain, it is necessary to consider the legislative requirements and regulations needed to safely transport this liquid. Pyrolysis oil has been given the classification of "Flammable liquid"; thus, it is likely to be classified under "hazardous substance" by international authorities.

The transport regulation of goods attributed as hazardous is done by the Economic and Social Council (ECOSOC) Committee of Experts on the Transport of Dangerous Goods. Depending on where the logistic takes place, different organization will provide guidance, e.g., International Maritime Organization (IMO) and Intergovernmental Organization for International Carriage by Rail (OTIF), water and rail, respectively.

Pyrolysis oil can be transported from small (mL) to large volumes (kton), in a single or multiple packaging. In general, the degree of filling is 90% (may vary with container size) and temperature is 15^{O}C. Due to its physicochemical properties (e.g., flash point), and the presence of toxic chemicals (e.g., phenol) Pyrolysis oil classifies as Class 3 and 6.1, respectively, and must be associated to the following hazard symbols.

Class 3 Flammable Liquid
Label 3

Class 6 Toxic substances
Label 6.1

Store this way up
Model 11

Figure 13: Labels for pyrolysis liquid holders

For samples over 400 kg, the containers must adhere to the ADR regulations and display the UN code on the bottom. The preferred packaging for land transport are containers and tanks (acid resistant), and the vehicle should display the labels depicted in Figure 13, especially for size over 3 m^3 or 670 x 670 mm. Pyrolysis oil cannot be shipped together with other dangerous goods, especially articles Class 1, 5.2 and 7 (Peacocke and Bridgwate 2008).

4.5.2 Scenario's description

This study elaborates on the logistics of pyrolysis oil produced in Sweden and Finland to the Port of Rotterdam. The total production capacity is 192 thousand metric tons per year basis, equally distributed among 8 plants, 4 in each country.

For both countries, the plants' locations were chosen based local feedstock availability and efficient outflow of the produced pyrolysis oil. In Sweden, two plants are considered in the region around the Port of Skellefteå and 2 around the Port of Skutskär. In Finland, the four plants would be located in the region of the Port of Kokkola.

The volume of material to be transported was calculated assuming the following conditions:

- 11 months of activity per year and 1 month of maintenance;

- Constant productivity along the active months (24 kt/ 11 months)
- The storage capacity at the plant is 3 days. On day 4, the production is transported to the respective port where it is stored in onshore tanks until shipment.

For the base case explained above, two different transport strategies are considered:

a) Port-to-port

The product is collected from each port in Sweden and Finland by a single ship and unloaded at the Port of Rotterdam. In this context two scenarios were developed. In the **first scenario**, 100 % of the pyrolysis oil is upgraded in the Netherlands. In the **second scenario,** 75 % of the pyrolysis oil is further transported to Germany through the Rhine River. In Germany, the material is unloaded in the area between Düsseldorf and Bonn.

b) Sweden Hub

In this strategy, both Swedish and Finish production are transported to a collection hub located in the south of Sweden, from where the product is collected and transported to Rotterdam. From Rotterdam, the transport of 75 % of the pyrolysis oil to Germany is also considered as an alternative, as previously described.

4.5.3 Method

Model

To account for all costs related to logistics, the following model can be applied (De Jong, Ben-Akiva, and Baak 2010):

$$\boldsymbol{G} = \boldsymbol{O} + \boldsymbol{T} + \boldsymbol{Y} + \boldsymbol{I} + \boldsymbol{K}$$

where G stands for total annual logistics costs, O for order costs, T for transport cost (including consolidations and distributions), Y for capital costs of goods during transit, I for inventory costs (storage costs), and K for capital cost of inventory.

In the context of the MUSIC project, however, not all the above-mentioned variables are relevant, where the most impacting costs are those related to transport (T) and inventory (I).

Transport costs consist of:

- Distance-based costs (d)
- Time-based (t)

- Vehicle/vessel type (C)
- Vehicle/vessel pair – related to transfer (v_t)

Vehicle/vessel pair is important when optimizing already existing routes and, consequently, is not considered in this work. The Inventory cost (I) consists of the cost related to storage (S) at the harbour area and it is assumed to be equivalent among all the ports considered in this work. The costs related to heating and agitation are also accounted within the Inventory costs. Taken together, the cost-based logistic model can be expressed as

$$\frac{€}{ton} = \frac{\sum_{n=i}(T_n + S_n)}{Q}$$

where, T_n stands for the transport cost in voyage n, Q for total volume to be transported and S_n for storage costs for the voyage n. The transport of pyrolysis oil from the Nordic countries to the Port of Rotterdam stands for voyage n; then, from Rotterdam to Germany n+1.

Inputs

Sea transport

The fright rates for sea voyage used for the calculations, based on enquires for fuel oil transportation from logistic companies operating in the Baltic and North Sea, are summarized in Table 6. The values provided already consider the costs related to loading and unloading at the harbour.

Table 6: Freight rates for sea-going transport of pyrolysis oil Baltic/Nordic Sea.

Capacity [kt]	Route	EUR/kton	
5	Skellefteå or Kokkola– Rotterdam	€	39.000
15	Skellefteå or Kokkola– Rotterdam	€	20.640
15	Skutskär - Rotterdam	€	20.067
20	Skellefteå or Kokkola– Rotterdam	€	18.060
20	Skutskär - Rotterdam	€	17.630
20	Gothenburg - Rotterdam	€	8.772

In the table the transport of small quantities (< 15 kt) is also included. However, this is capped by the limited number of suitable vessels for so-called ‘dirty’ transport. Therefore, 15 kt and 20 kt are the reasonable sizes to consider in this study. The classification between clean and dirty material can be done following ASTM D 1500 method, previous called NPA. The method classifies the product against a colour scale, ranging from 1 (water) to 8 (extra dark). Clean products are usually under 2.5 NPA.

Additional stops in intermediate port adds € 40 thousand on the top of total costs, per stop. For example, the costs of 15 kt shipment from Skellefteå to Rotterdam stopping in Kokkola and Skutskär will be calculated as (15 x € 20.640) + € 80.000.

Inland transport

The values for inland transportation, between the production sites and the harbours, were taken from the previous technical report (D5.2: Set of four Advanced Case Studies), i.e., € 12.1 per ton (Sweden) and € 20 per ton (Finland).

For the Sweden Hub strategy, the operation cost was based on enquire for train transport between Piteå and Gothenburg (via First Row Shipping & Logistics AB). Operation costs refers to transport, loading, unloading, and cleaning. In addition, it is necessary to account for the wagon tank's rental costs. The rental cost is calculated per wagon-day, in another words, how many wagons are rented for how many days (dedicated). Based on the assumptions considered, a total of 30 wagons are necessary to accommodate the total volume every 3 days (~1,750 tons) from Swedish and Finish production to the hub. The type of wagon also influences the cost of rental. Insulated, heated and stainless-steel wagon tanks are considered, following the recommendations given in the previous technical report (D5.2: Set of four Advanced Case Studies). Taking together, the rental cost used is of € 70 per wagon per day, approximately €4 per ton, for a minimum of 3 years (based on service providers quotations). Longer contracts do not lead to cheaper prices due to the high number of stainless steel wagons requested. The figures related to rail transport are summarized in Table 7.

It is important to highlight that there is no rail connection between Finland and Sweden and, therefore, the Finish production relies on multi-modal logistics to reach the north of Sweden, starting with trains towards the north of Finland, trucks between Finland and Sweden, and finally trains to the hub. The costs of transfer between modes are not explored in this work and are assumed to be within the provided operation costs.

Table 7: Rail Transport Figures

Wagon Tank	
Nominal/ Useful Capacity	77 m^3 / 58t*
Rental Cost	€ 70 per wagon/day (€4 per ton)
Finland to Piteå	€ 50/ ton
Operation Cost Piteå to Hub	€ 40.50/ ton

The transport from Rotterdam to Germany will be done through the Rhine River using barge ships, which is the most cost-effective strategy. The fright rate for a 2 kt – 3 kt barge traveling between Port of Rotterdam and Cologne is € 8.75 per ton, based on spot prices. However, the volatility on spot market can increase prices up to sevenfold when water levels of Rhine are low, which decreases the transport volume offered. Therefore, it is recommended to conduct long-term negotiations, fixing a flat price on a yearly basis. For the present work a price of € 9.75 (EUR 8.75 + 1.00) per ton is assumed considering a long-term (> 1 year) negotiation. Examples of ship tankers, barges and tank wagons are given in Figure 14 - Figure 16.

Figure 14: Tanker Ship example for sea-going transport

Figure 15: Barge example for inland transport

Figure 16: Stainless steel wagon tank

Storage

As detailed in the previous report (D5.2: Set of four Advanced Case Studies), pyrolysis oil must be stored in stainless steel tanks, in a temperature between -5 °C and 25 °C and, preferably, under agitation to avoid sedimentation. The storage cost is assumed to be equivalent among the studied ports and was obtained from a European terminal company as € 10/ m^3 per month, of which € 1.5 and € 2.5 / m^3 account for agitation and heating, respectively.

4.5.4 Results

Based on the assumptions provided, the mass flow of pyrolysis oil from each plant to the harbour is 220 t every 3 days, as presented in Table 8.

Table 8: Mass of Pyrolysis oil, in tons, stored at each harbour as function of shipment interval. The values in the Rotterdam column also indicate the total shipment size

Shipment Interval (Days)	Skellefteå and Skutskär (each) (t)	Kokkola (t)	Rotterdam (t)
3	440	880	1,760
6	880	1,760	3,520
9	1,320	2,640	5,280
12	1,760	3,520	7,040
15	2,200	4,400	8,800
18	2,640	5,280	10,560
21	3,080	6,160	12,320
24	3,520	7,040	14,080
27	3,960	7,920	15,840
30	4,400	8,800	17,600

An average density of 1200 kg/m^3 was taken to calculate the volumes of the tanks needed at the harbour, assuming a working capacity of 90%.

4.5.4.1 Port-to-Port

For the Port-to-Port strategy the lead time for the loaded voyage is estimated to be around 11 days, 8 days sailing and 3 days of laytime. The voyage will follow the port sequence Skellefteå, Kokkola, Skutskär and Rotterdam. Only the sailing time is considered for the round voyage (empty vessel), thereby, the total lead time is 19 days. The voyage between Rotterdam and Cologne trough the river Rhine is estimated to be 3 days; 2 days sailing and 1 of laytime.

Although shipments of 5 kt from the Baltic Sea to the Port of Rotterdam are currently hardly available for dirty products, this picture might change if potential streams, such as those proposed by MUSIC project, come at commercial scale. Thereby, three shipment intervals were considered, namely, 9, 24 and 30 days, as shown in **Error! Reference source not found.**.

Some of the costs reported for the Strategic case study diverge from those previously reported in the Advanced case study (D5.2: Set of four Advanced Case Studies). The difference is due to the additional costs assumed in the Strategic case, namely inland transport in the Nordic countries (~15 €/ton), additional port calls (~5 €/ton) and changes in freight costs.

Table 9: Logistics costs, Port-to-Port strategy

Shipment interval	Pyrolysis oil arriving in Rotterdam (kt)	Logistics cost including Storage at the Port of Rotterdam (€/ton)	Logistics Cost at Cologne – Germany (€/ton)
9	5.3	81	91
24	14.1	61	71
30	17.6	58	67

4.5.4.1 Sweden Hub

For the Sweden Hub strategy, it is assumed that both Swedish and Finish production will be transported to Piteå (SE), where a storage capacity of 3 days production is assumed. From there, the production is transported to Gothenburg trough rail system. At the Port of Gothenburg, the total production is stored until sea transport to the Port of Rotterdam. Similarly, to the Port-to Port strategy, three shipment sizes are considered as shown in

Table 10: Logistics cost and quantities, Sweden hub case study strategy

Shipment interval	Pyrolysis oil arriving in Rotterdam (kt)	Logistics cost including Storage at the	Logistics Cost at Cologne –

		Port of Rotterdam (€/ton)	Germany (€/ton)
9	5.3	95	105
24	14.1	93	103
30	17.6	88	98

The cost breakdown between logistics and storage is shown in Figure 17. To understand how the total cost is influenced by certain parameters, a sensibility analysis is depicted in Figure 18 considering a variation range of ± 20% in the costs for 14.1 kt scenario (see **Error! Reference source not found.** and Table 10). From the results it is possible to observe a higher influence of the storage cost in the Port-to-Port strategy.

For the Sweden hub strategy, the cost driver is the Inland transport in the Nordic countries. Finally, both strategies are slightly affected by the sea transport. It is important to mention, however, that the costs related to the transport trough Rhine (Inland EU) might vary around 70 % between winter and summer seasons, which can be mitigated by long term contracts, as already mentioned.

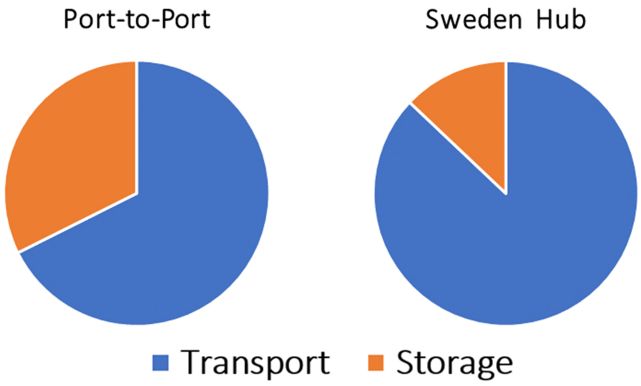
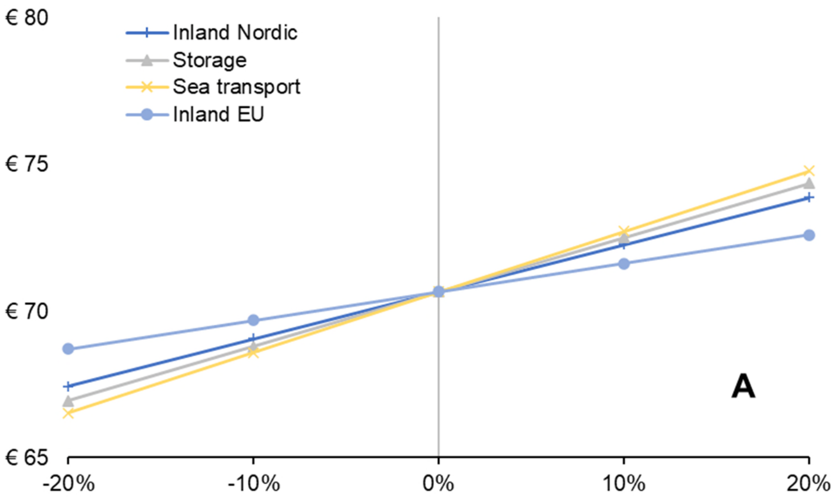


Figure 17: Cost breakdown into transport and storage



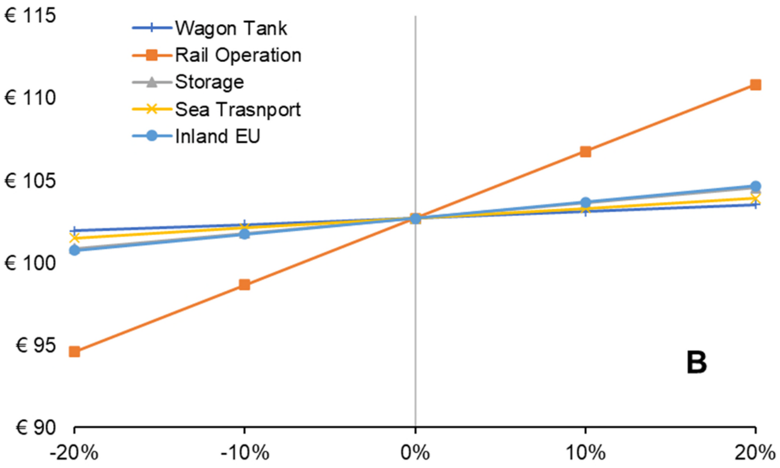


Figure 18: Sensibility analysis of total logistics' cost per ton assuming ± 20% variation ion the cost of key parameters. A: Port-to-port. B: Sweden Hub

4.6 Upgrading

The technology to produce transport fuels from pyrolysis oil is not yet fully commercial. The technology, developed by BTG, is currently in pilot plant stage. This means that it is necessary to rely on projections to determine the characteristics for an upgrading plant. In the Advanced case study (Reumerman et al. 2021), estimations from public literature were used, namely a publication of the Dutch PBL institute (PBL 2021). In this case study (the strategic case study) own projections will be presented.

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. An impression of the key operations in the upgrading process is given in Figure 19.

As mentioned in the Advanced case study report, the pyrolysis oil is being upgraded in a two-step process. This upgrading is carried out at elevated pressure and temperature and involves (mainly) the removal of oxygen by hydrogenation and dehydration, in two steps. In the first step a proprietary catalyst – called Picula - is used, while in the second step more conventional hydrotreating catalysts is sufficient.

Even though the upgrading plant considered in this strategic case study is about three times as large as the plant considered in the advanced case study, on-site hydrogen production is still not considered economical. There are three options for the hydrogen:

- ‘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 using renewable electricity, or from bio-resources

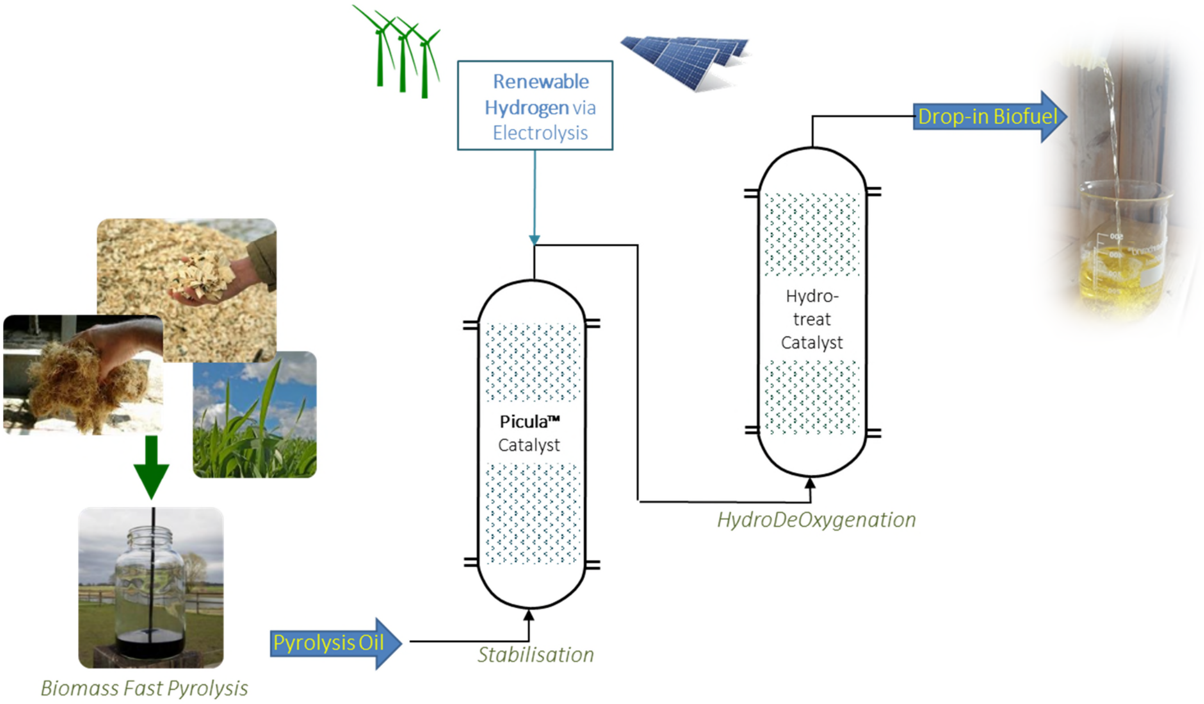


Figure 19: Schematic outline of the pyrolysis oil upgrading process.

It is expected that either blue or green hydrogen is needed to satisfy the RED II emission reduction requirements, or measures such as CCS (carbon capture and storage) at the pyrolysis plants.

4.6.1 Input and output characteristics

The main characteristics of the upgrading plant are given in Table 11.

Table 11: Main characteristics upgrading plant.

Parameter	Value	Unit
Operational hours	8,000	hours/year
Pyrolysis oil input	240,000	tonne/year
Transport fuel output	90,000	tonne/year
Average energy density HPO	43.7	MJ/kg
Hydrogen input	12,200	tonne/year

These figures are quite similar to those listed in the Advanced case study report. It is considered that for these types of plant 8.000 hours of operating time is feasible. Transport fuels production is 37.5% (mass based) of pyrolysis oil input (advanced case study; 38.5%), and the hydrogen input is basically the same (5% (mass based) of Pyrolysis oil input). Pyrolysis oil input is higher than the 192.000 tonne/year mentioned earlier in this report. It is considered that additional pyrolysis oil can be sourced to get to the mentioned 240.000 tonne/year.

4.7 Greenhouse gas emission

The Advanced Case study focuses on the production of 72,000 tonnes of pyrolysis oil (PO) from sawdust per year in 2 plants in Finland and 1 in Sweden. Subsequently the PO is shipped to the Netherlands, where it is upgraded to a drop-in advanced marine biofuel. The strategic case study builds upon this concept and examines the logistics and feasibility of implementing a value chain that handles substantially larger volumes of pyrolysis oil, particularly, 192,000 tonnes of PO per year are equally produced in 8 plants, 4 in Sweden (2 around the Port of Skellefteå and 2 around the Port of Skutskär) and 4 in Finland (2 in Lieksa and 2 in Iisalmi).

This study considers more elaborate logistics for the PO produced in Sweden and Finland – two different transport strategies to the Port of Rotterdam:

1. Port-to-Port. PO is transported each port in Sweden and Finland and then collected by a single ship, following the port sequence Skellefteå, Kokkola, Skutskär and Rotterdam.
2. Sweden Hub. Swedish and Finish production of PO are transported to a collection hub in Piteå, from there, the PO is transported to Gothenburg through rail system. At the Port of Gothenburg, the total production is stored until sea transport to the Port of Rotterdam. Notably, as there is no rail connection between Finland and Sweden, the Finish production transport incorporates, trains towards the north of Finland, trucks between Finland and Sweden, and finally trains to the hub.

Additionally, for both strategies, two scenarios were developed. In the first scenario, 100 % of the PO is upgraded in the Netherlands. In the second scenario, 75 % of the pyrolysis oil is further transported to Germany through the Rhine River. In Germany, the PO is unloaded in the area between Düsseldorf and Bonn.

According to the RED II: *"The greenhouse gas (GHG) emission savings from the use of biofuels shall be at least 65% for biofuels, biogas consumed in the transport sector, and bioliquids produced in installations starting operation from 1 January 2021"* (Article 29, paragraph 10). Upgrading of the PO requires substantial amounts of hydrogen, which, as seen in the advanced case study, represents 61 to 97% of the total GHG emissions, depending on the production technology. Therefore, hydrogen should be produced via electrolysis from renewable resources (wind and solar electricity) or the hydrogen production should be coupled with carbon capture and storage technologies (CCS) to ensure that the GHG emission reduction of the entire value chain is above 65%.

Consequently, the most promising hydrogen production schemes are: (a) Proton Exchange Membrane (PEM) water electrolysis; (b) Natural Gas (NG) reforming combined with CCS (chemical absorption of CO_2 with monoethanolamine); and (c) NG reforming. For each scheme, renewable electricity from wind and solar farms is considered as the optimal choice.

The GHG emissions and the emission savings, of the entire drop-in advanced marine biofuel value chain, have been assessed using the methodology given in Annex VI of the RED II.

The results of the environmental assessment of the overall marine biofuel production pathway for the Nordic Strategic Case Study are presented in Table 12, Table 13, Table 14, Table 15, Table 16 and Table 17. Each table presents a different option of hydrogen production and transport strategy

Table 12. GHG emissions of the PEM electrolysis upgrade pathway for the Port-to-Port strategy

Scenario 1						
	Sweden				Finland	
	Bygdsylium	Sävar	Kåge	Tunadal	Lieksa	Iisalmi
Transport of sawdust to PO plants (g/MJ fuel)	0.387	0.508	0.366	0.014	0.926	0.514
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)	0.300	0.471	0.129	0.998	1.778	1.071
Shipment to Rotterdam (g/MJ fuel)	1.573	1.573	1.573	1.155	1.492	1.492
Upgrading (g/MJ fuel)	4.157	4.157	4.157	4.157	4.157	4.157
Total CO2-eq. emission (g/MJ fuel)	6.739	7.033	6.547	6.647	8.680	7.561

Fossil fuel comparator (g/MJ fuel)	94	94	94	94	94	94
GHG emission savings (%)	92.83%	92.52%	93.03%	92.93%	90.77%	91.96%
	Scenario 2					
	Sweden				Finland	
Transport of sawdust to PO plants (g/MJ fuel)	0.387	0.508	0.366	0.014	0.926	0.514
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)	0.300	0.471	0.129	0.998	1.778	1.071
Shipment to Rotterdam (g/MJ fuel)	1.573	1.573	1.573	1.155	1.492	1.492
Shipment through Rhine (g/MJ fuel)	0.725	0.725	0.725	0.725	0.725	0.725
Upgrading (g/MJ fuel)	4.157	4.157	4.157	4.157	4.157	4.157
Total CO2-eq. emission (g/MJ fuel)	7.464	7.757	7.272	7.372	9.405	8.286
Fossil fuel comparator (g/MJ fuel)	94	94	94	94	94	94
GHG emission savings (%)	92.06%	91.75%	92.26%	92.16%	90.00%	91.19%

The GHG emission savings for the PEM electrolysis crosses the bar of the 65% set by RED II. The additional transport step in Scenario 2 has a minimal effect on total GHG emissions as they are dominated by the upgrading step and particular the production of hydrogen.

Table 13. GHG emissions of the NG reforming with CCS upgrade pathway for the Port-to-Port strategy

	Scenario 1					
	Sweden				Finland	
	Bygdsylium	Sävar	Kåge	Tunadal	Lieksa	Iisalmi
Transport of sawdust to PO plants (g/MJ fuel)	0.387	0.508	0.366	0.014	0.926	0.514
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)	0.300	0.471	0.129	0.998	1.778	1.071
Shipment to Rotterdam (g/MJ fuel)	1.573	1.573	1.573	1.155	1.492	1.492
Upgrading (g/MJ fuel)	7.513	7.513	7.513	7.513	7.513	7.513
Total CO2-eq. emission (g/MJ fuel)	10.095	10.388	9.903	10.003	12.036	10.917
Fossil fuel comparator (g/MJ fuel)	94	94	94	94	94	94
GHG emission savings (%)	89.26%	88.95%	89.46%	89.36%	87.20%	88.39%
	Scenario 2					
	Sweden				Finland	
Transport of sawdust to PO plants (g/MJ fuel)	0.387	0.508	0.366	0.014	0.926	0.514
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)	0.300	0.471	0.129	0.998	1.778	1.071
Shipment to Rotterdam (g/MJ fuel)	1.573	1.573	1.573	1.155	1.492	1.492
Shipment through Rhine (g/MJ fuel)	0.725	0.725	0.725	0.725	0.725	0.725
Upgrading (g/MJ fuel)	7.513	7.513	7.513	7.513	7.513	7.513
Total CO2-eq. emission (g/MJ fuel)	10.820	11.113	10.628	10.727	12.760	11.642
Fossil fuel comparator (g/MJ fuel)	94	94	94	94	94	94
GHG emission savings (%)	88.49%	88.18%	88.69%	88.59%	86.43%	87.62%

As with PEM electrolysis, NG reforming with CCS, presents GHG emission savings well above the 65% limit. Again, the transport strategy, from an environmental perspective doesn't play a decisive role.

Table 14. GHG emissions of the NG reforming upgrade pathway for the Port-to-Port strategy

	Scenario 1					
	Sweden				Finland	
	Bygdsylium	Sävar	Kåge	Tunadal	Lieksa	Iisalmi
Transport of sawdust to PO plants (g/MJ fuel)	0.387	0.508	0.366	0.014	0.926	0.514
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)	0.300	0.471	0.129	0.998	1.778	1.071
Shipment to Rotterdam (g/MJ fuel)	1.573	1.573	1.573	1.155	1.492	1.492
Upgrading (g/MJ fuel)	27.385	27.385	27.385	27.385	27.385	27.385
Total CO2-eq. emission (g/MJ fuel)	29.968	30.261	29.776	29.875	31.908	30.790
Fossil fuel comparator (g/MJ fuel)	94	94	94	94	94	94
GHG emission savings (%)	68.12%	67.81%	68.32%	68.22%	66.06%	67.25%
	Scenario 2					
	Sweden				Finland	
Transport of sawdust to PO plants (g/MJ fuel)	0.387	0.508	0.366	0.014	0.926	0.514
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)	0.300	0.471	0.129	0.998	1.778	1.071
Shipment to Rotterdam (g/MJ fuel)	1.573	1.573	1.573	1.155	1.492	1.492
Shipment through Rhine (g/MJ fuel)	0.725	0.725	0.725	0.725	0.725	0.725
Upgrading (g/MJ fuel)	27.385	27.385	27.385	27.385	27.385	27.385
Total CO2-eq. emission (g/MJ fuel)	30.692	30.985	30.500	30.600	32.633	31.514
Fossil fuel comparator (g/MJ fuel)	94	94	94	94	94	94
GHG emission savings (%)	67.35%	67.04%	67.55%	67.45%	65.28%	66.47%

In the NG reforming upgrade pathway, GHG emissions savings are just above the 65% in some cases, the transport stages of sawdust and PO account approximately 8% of the total GHG emissions, therefore, in borderline situations like this, the overall logistics could have a huge impact.

Table 15. GHG emissions of the PEM electrolysis upgrade pathway for the Sweden Hub strategy

Scenario 1						
	Sweden				Finland	
	Bygdsylium	Sävar	Kåge	Tunadal	Lieksa	Iisalmi
Transport of sawdust to PO plants (g/MJ fuel)	0.387	0.508	0.366	0.014	0.926	0.514
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
Transport of PO to Piteå (g/MJ fuel)	0.600	0.840	0.300	3.012	2.423	1.652
Transport of PO to Gothenburg (g/MJ fuel)	3.284	3.284	3.284	3.284	3.284	3.284
Storage (g/MJ fuel)	0.001	0.001	0.001	0.001	0.005	0.005
Shipment to Rotterdam (g/MJ fuel)	0.417	0.417	0.417	0.417	0.417	0.417
Upgrading (g/MJ fuel)	4.157	4.157	4.157	4.157	4.157	4.157
Total CO2-eq. emission (g/MJ fuel)	9.168	9.530	8.847	11.208	11.534	10.351
Fossil fuel comparator (g/MJ fuel)	94	94	94	94	94	94
GHG emission savings (%)	90.25%	89.86%	90.59%	88.08%	87.73%	88.99%
Scenario 2						
	Sweden				Finland	
	Bygdsylium	Sävar	Kåge	Tunadal	Lieksa	Iisalmi
Transport of sawdust to PO plants (g/MJ fuel)	0.387	0.508	0.366	0.014	0.926	0.514
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
Transport of PO to Piteå (g/MJ fuel)	0.600	0.840	0.300	3.012	2.423	1.652
Transport of PO to Gothenburg (g/MJ fuel)	3.284	3.284	3.284	3.284	3.284	3.284
Storage (g/MJ fuel)	0.001	0.001	0.001	0.001	0.005	0.005
Shipment to Rotterdam (g/MJ fuel)	0.417	0.417	0.417	0.417	0.417	0.417
Shipment through Rhine (g/MJ fuel)	0.725	0.725	0.725	0.725	0.725	0.725
Upgrading (g/MJ fuel)	4.157	4.157	4.157	4.157	4.157	4.157
Total CO2-eq. emission (g/MJ fuel)	9.893	10.254	9.572	11.932	12.259	11.076
Fossil fuel comparator (g/MJ fuel)	94	94	94	94	94	94
GHG emission savings (%)	89.48%	89.09%	89.82%	87.31%	86.96%	88.22%

For the Sweden Hub strategy, PEM electrolysis pathway presents equally high emission savings as with the Port-to-Port strategy, however, the transport to the Port of Gothenburg accounts for 27 to 33% of total GHG emissions.

Table 16. GHG emissions of the NG reforming with CCS upgrade pathway for the Sweden Hub strategy

Scenario 1						
	Sweden				Finland	
	Bygdsylium	Sävar	Kåge	Tunadal	Lieksa	Iisalmi
Transport of sawdust to PO plants (g/MJ fuel)	0.387	0.508	0.366	0.014	0.926	0.514
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
Transport of PO to Piteå (g/MJ fuel)	0.600	0.840	0.300	3.012	2.423	1.652
Transport of PO to Gothenburg (g/MJ fuel)	3.284	3.284	3.284	3.284	3.284	3.284
Storage (g/MJ fuel)	0.001	0.001	0.001	0.001	0.005	0.005
Shipment to Rotterdam (g/MJ fuel)	0.417	0.417	0.417	0.417	0.417	0.417
Upgrading (g/MJ fuel)	7.513	7.513	7.513	7.513	7.513	7.513
Total CO2-eq. emission (g/MJ fuel)	12.523	12.885	12.203	14.563	14.890	13.707
Fossil fuel comparator (g/MJ fuel)	94	94	94	94	94	94
GHG emission savings (%)	86.68%	86.29%	87.02%	84.51%	84.16%	85.42%
Scenario 2						
	Sweden				Finland	
	Bygdsylium	Sävar	Kåge	Tunadal	Lieksa	Iisalmi
Transport of sawdust to PO plants (g/MJ fuel)	0.387	0.508	0.366	0.014	0.926	0.514
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
Transport of PO to Piteå (g/MJ fuel)	0.600	0.840	0.300	3.012	2.423	1.652
Transport of PO to Gothenburg (g/MJ fuel)	3.284	3.284	3.284	3.284	3.284	3.284
Storage (g/MJ fuel)	0.001	0.001	0.001	0.001	0.005	0.005
Shipment to Rotterdam (g/MJ fuel)	0.417	0.417	0.417	0.417	0.417	0.417
Shipment through Rhine (g/MJ fuel)	0.725	0.725	0.725	0.725	0.725	0.725
Upgrading (g/MJ fuel)	7.513	7.513	7.513	7.513	7.513	7.513
Total CO2-eq. emission (g/MJ fuel)	13.248	13.610	12.927	15.288	15.614	14.431
Fossil fuel comparator (g/MJ fuel)	94	94	94	94	94	94
GHG emission savings (%)	85.91%	85.52%	86.25%	83.74%	83.39%	84.65%

NG reforming coupled with CCS, is proving to be a very good alternative to PEM electrolysis in the Sweden Hub as well.

Table 17. GHG emissions of the NG reforming upgrade pathway for the Sweden Hub strategy

Scenario 1						
	Sweden				Finland	
	Bygdsylium	Sävar	Kåge	Tunadal	Lieksa	Iisalmi
Transport of sawdust to PO plants (g/MJ fuel)	0.387	0.508	0.366	0.014	0.926	0.514
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
Transport of PO to Piteå (g/MJ fuel)	0.600	0.840	0.300	3.012	2.423	1.652
Transport of PO to Gothenburg (g/MJ fuel)	3.284	3.284	3.284	3.284	3.284	3.284
Storage (g/MJ fuel)	0.001	0.001	0.001	0.001	0.005	0.005
Shipment to Rotterdam (g/MJ fuel)	0.417	0.417	0.417	0.417	0.417	0.417
Upgrading (g/MJ fuel)	27.385	27.385	27.385	27.385	27.385	27.385
Total CO2-eq. emission (g/MJ fuel)	32.396	32.758	32.075	34.436	34.762	33.579
Fossil fuel comparator (g/MJ fuel)	94	94	94	94	94	94
GHG emission savings (%)	65.54%	65.15%	65.88%	63.37%	63.02%	64.28%
Scenario 2						
	Sweden				Finland	
	Bygdsylium	Sävar	Kåge	Tunadal	Lieksa	Iisalmi
Transport of sawdust to PO plants (g/MJ fuel)	0.387	0.508	0.366	0.014	0.926	0.514
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
Transport of PO to Piteå (g/MJ fuel)	0.600	0.840	0.300	3.012	2.423	1.652
Transport of PO to Gothenburg (g/MJ fuel)	3.284	3.284	3.284	3.284	3.284	3.284
Storage (g/MJ fuel)	0.001	0.001	0.001	0.001	0.005	0.005
Shipment to Rotterdam (g/MJ fuel)	0.417	0.417	0.417	0.417	0.417	0.417
Shipment through Rhine (g/MJ fuel)	0.725	0.725	0.725	0.725	0.725	0.725
Upgrading (g/MJ fuel)	27.385	27.385	27.385	27.385	27.385	27.385
Total CO2-eq. emission (g/MJ fuel)	33.121	33.482	32.800	35.160	35.487	34.304
Fossil fuel comparator (g/MJ fuel)	94	94	94	94	94	94
GHG emission savings (%)	64.77%	64.38%	65.11%	62.60%	62.25%	63.51%

NG reforming upgrade strategy presents slightly higher emission savings than the 65% limit for the Swedish cases in Scenario 1, while for the Finish cases in both scenarios, the savings are lower than that. In comparison with the Port-to-Port strategy, while the hydrogen production still accounts for the highest part of the total GHG emissions, the additional transport steps, ultimately affect the compliance with RED II.

Overall, the production of hydrogen determines the environmental performance of the drop-in advanced marine biofuel chain, depending though on the technology. PEM electrolysis and NG reforming coupled with CCS technologies, regardless of the transport strategy, are the most advantageous technologies. NG reforming marginally achieves or slightly misses the target of the RED II for 65% GHG emission savings. Logistics highly affects this particular pathway – long inland transportation of PO, either by train or truck, have significantly higher GHG emissions than the sea transport. The effect of the sawmill location is negligible (bellow 1.5%), in oppose to the collection point of PO (8.5 to 27%). The additional transport step through Rhine River affects the low GHG emission technologies – 10% of the total emissions of PEM electrolysis pathway, while for NG reforming accounts for 2%.

4.8 Certification

4.8.1 Background

The environmental assessment of the value chains developed in the advanced and strategic case studies includes a sustainability certification assessment. The production of biofuels and heat and power from biomass in the European Union takes place in a regulated market. The regulatory framework has been evaluated in WP2. The value chain of the MUSIC case studies are particularly regulated by the Renewable Energy Directive (RED II) or rather the national implementations in the member states.

Biomass and bioenergy under the scope of the RED II can be subject to sustainability and greenhouse gas emissions saving criteria. Conformity with the criteria is ensured by means of sustainability certification. This means, that operators in respective supply chains are to be certified towards voluntary or national certification schemes recognized by the EU Commission. There is no formal obligation to comply with the RED II. However, conformity is a condition for any financial incentive and the ability to count energy towards targets on EU and national level (Buffi et al. 2020). The goal of this assessment was to identify the specific requirements and highlight potential “showstoppers” which can hamper the further (commercial) development of the value chain. This background applies to all of the case studies and is therefore not repeated in the following chapters dealing with the Italian, Greek and international case studies.

4.8.2 Description of the value chain and identification of interfaces

In the considered value chain residue feedstock from forest industry is collected in defined regions in Sweden and Finland. Specifically, saw dust is foreseen as feedstock. The feedstock is converted into fast pyrolysis oil and further processed into advanced marine biofuel after transport in vessels from the Nordic countries to the Netherlands (Figure 20). Advanced biofuels are defined as being produced from feedstock listed in the RED II directive, Annex IX and with advanced technologies. They can be considered twice their energy content for the counting towards the minimum target of renewable energy in the transport sector.

There are different EU member states included in the supply chain. Pyrolysis oil as intermediate bioenergy carrier (IBC) is produced in Sweden and Finland. Further processing to a marine biofuel takes place in the Netherlands. Moreover, the final product will be put on the market in the Netherlands as the fuelling will be done in the harbour of Rotterdam.

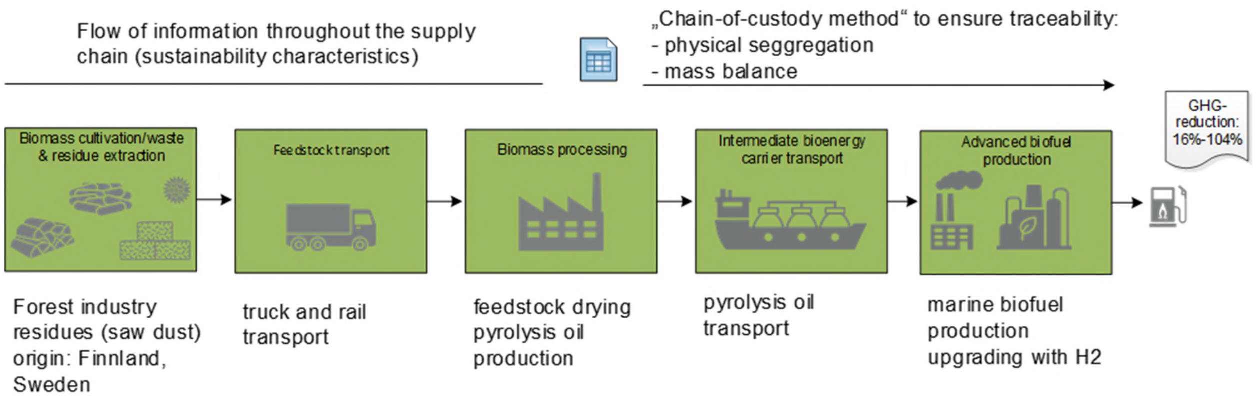


Figure 20: Interfaces along the value chain for the production of marine biofuel from pyrolysis oil

4.8.3 Relevance for the value chain

As only waste and residue feedstock is used in the value chain, most of the RED II criteria do not apply (Table 18). GHG emission reduction has been assessed using the methodology given in Annex VI of the RED II. Thereby, different cases were calculated to allow for the consideration of different technologies. The results indicate that the GHG emission savings criteria can be fulfilled. However, the GHG emission reduction is highly dependent on the technology (and the carbon intensity of the electricity) for the production of hydrogen which is used to upgrade pyrolysis oil to marine biofuel.

Table 18: Overview of RED II criteria and applicability to the Nordic case study value chain

RED II reference	Criteria summarised	Applicability	Relevance for the case study
29(2)	Monitoring and management of impacts on soil carbon and soil quality	Wastes and residues from agricultural land	no
29(3)	Protection of land with high biodiversity value	Agricultural biomass for energy	no
29(4)	Protection of land with high carbon stock	Agricultural biomass for energy	no
29(5)	Protection of peatland	Agricultural biomass for energy	no
29(6)	Sustainable forest management	Forest biomass for energy	no
29(7)	LULUCF criteria	Forest biomass for energy	no
29(10)	GHG emission savings criteria depending on the staring date of the operation: at least 50% (< 2015-10-05) at least 60% (2015-10-06-2020-12-31) at least 65% (> 2021-01-01)	Wastes and residues agricultural biomass forest biomass	yes

29(11)	Energy efficiency criteria for electricity production from biomass fuels	Electricity generation	no
30(1)	Mass balance system	Once sustainability and GHG emission savings criteria are to be verified	yes

4.8.4 National implementation

Although the relevant policy framework is valid for the entire EU, the RED II has to be implemented in national law within the member states. The rules and requirements can be implemented identically to facilitate trade and international supply chains. However, to a certain degree sustainability criteria can be implemented in a stricter way and even additional criteria can be implemented on member state level. Considering international value chains, the regulation in the country in which biofuel is put on the market and counting towards the national target takes place will be critical.

The Netherlands

The Dutch government has developed a 'sustainability framework' for biomass. The scope is biomass for energy applications, but also for materials and chemicals. In this sustainability framework, all RED II sustainability criteria will be included. The transposition of the RED II was legally carried out by changing the environmental law. This was done in June 2021[2] . The way in which the RED sustainability criteria were transposed, closely followed the EU RED II. In the Dutch SDE++ subsidy scheme these rules have been detailed. The minimum size of the solid biomass plants for which RED II sustainability criteria apply is 20 MW, and no additional socio-economic sustainability criteria are formulated. All EU approved certification schemes can be utilized.[3]

Sweden

The RED II was implemented into Swedish law in 2021 (Cancian 2021).

Finland

RED II was implemented before 20th of June 2021. The relevant national legislation is the Sustainability Act (393/2013). No lower thermal input level for installations or any additional sustainability criteria were formulated (1:1 implementation) (Kaitazis 2021). In contrast to most EU member states Finland introduced a national scheme. Operators may use the national scheme or one of voluntary schemes to proof compliance with the sustainability criteria.

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[2] https://www.emissieautoriteit.nl/actueel/nieuws/2021/07/01/implementatie-red2-aangenomen-in-tweede--en-eerste-kamer

[3] https://www.rvo.nl/sites/default/files/2021/12/Verificatieprotocol_duurzaamheid_REDII_2022.pdf

Germany

The RED II implementation in Germany is completed. The sustainability criteria are implemented by two decrees, the BioSt-NachV and BioKraft-NachV. Both entered into force in December 2021. No additional criteria or thresholds have been implemented.

4.8.5 Demonstration of RED II compliance

To demonstrate compliance, economic operators have to become certified towards a scheme recognized by the EU Commission. Voluntary and national schemes, passing successfully the recognition process are listed online[4].

The schemes differ according to their scope, regarding:

- Applicable countries
- Value chain coverage (some schemes cover the entire value chain, others only parts, e.g., biomass cultivation)
- Limitation to certain biomass types
- Limitation of certain final uses (biofuels, electricity, heating, cooling)

The actual certification process usually follows these steps:

- An operator chooses a suitable scheme and applies for certification at a certification body (which is approved for the scheme).
- The operator will prepare for an audit, which includes for the most part the setting up of a management system, a mass balance, the GHG emission calculation, etc. The Requirements are specified in the system documents of the certification scheme
- An auditor will be commissioned by the certification body to conduct an audit on site for verification of the scheme´s requirements.
- The audit report will be reviewed and evaluated by the certification body. As a result, a certificate will be issued eventually. Successful certification enables the operator to trade material as “sustainable”.
- On a yearly basis, surveillance audits (or re-certification audits) will secure the conformity.

This general description of verification of the criteria arising from the RED II in practice is valid for all of the MUSIC case studies and for that reason not included in the following chapters.

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[4] https://energy.ec.europa.eu/topics/renewable-energy/biofuels/voluntary-schemes_en

4.8.6 Conclusions

The conformity of the examined value chain with the requirements of the RED II is achievable. Due to the focus on waste and residue feedstock, most criteria arising from Article 29 of the RED II do not apply. The required GHG emission savings are achievable.

However, there is limited certainty about the eligibility of the feedstock for the production of advanced biofuels. Annex IX Part A lists eligible feedstocks for advanced biofuels. In the current version of this Annex the feedstock considered in the case study is covered. According to Article 28(6) there is a biannual review process of the list of feedstocks in Annex IX. This review takes an assessment of potential feedstocks into account[5]. With delegated acts the EU Commission can update Annex IX. However, these updates can add feedstocks but not remove feedstocks from the list. Within the validity period of the RED II, the eligibility of the foreseen feedstock can be taken for granted. However, national RED II implementation can also differ in terms of eligible feedstocks. In the considered value chain, future developments of the legislation within the Netherlands should be followed continuously. Current regulation only indicates the phase-out of soy-based biofuels besides palm oil-based biofuels.

4.9 Financial parameters

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. The technology has not been demonstrated on full, commercial scale. Furthermore, a detailed process design is not available yet. This means significant uncertainties in the order of 50%, especially with respect to the estimations of the capital expenditure.

To determine the financial feasibility of the upgrading unit, own cost projections are used. The cost figures used are given in Table 19.

Table 19: Costs and market prices upgrading plant

Parameter	Value	Unit
Investment costs hydrotreatment plant	2.039	Euro/kW output
Costs pyrolysis oil	325	Euro/tonne
Pyrolysis oil transport	61	Euro/tonne
Costs of ‘grey’ hydrogen	1.560	Euro/tonne H_2
Fixed O&M costs	3%	of investment costs

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[5] https://www.e4tech.com/resources/239-assessment-of-the-potential-for-new-feedstocks-for-the-production-of-advanced-biofuels-renewable-energy-directive-annex-ix.php

Variable O&M costs	4%	of Investment costs

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. Transport costs are derived from the port-to-port scenario discussed in paragraph 4.5.

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. These costs are all quite similar compared to the cost's projections given in the Advanced case study report, with the exception of the variable O&M costs (2% in Advanced Case study report). Costs for utilities, chemicals, energy, and catalysts are expected to be higher than originally thought.

In Table 20 the capital costs and annual costs and income for a 240,000 tonne/year upgrading plant are shown

Table 20: Estimated capital and operational costs Upgrading plant

Parameter	Value	Unit
Total investment costs	268	Meuro
Costs of pyrolysis oil	78	Meuro/year
Costs of pyrolysis oil transport	14,64	Meuro/year
Other costs	16,9	Meuro/year
Hydrogen costs	19,0	Meuro/year

For the calculation of the financial feasibility, the parameters of Table 21 are used

Table 21: Financial parameters Upgrading plant.

Parameter	Value	Unit
Equity share	30%	
Depreciation period	15	Year
Interest on loan	2.5%	Meuro
Profit tax	21.7%	
Inflation	1.5%	

These financial parameters are the same as used in the PBL starting points (PBL 2021) and were also used in the Advanced case study report.

Financial results

The required sales price that is needed to achieve a 15% return on equity is given in Table 22.

Table 22: Sales price transport fuels with a fixed return on equity

Parameter	Value	Unit
Return on Equity target	15%	
Transport fuels sales price	1748	Euro/tonne
Current price fossil alternative	831[6]	Euro/tonne

This price is considered to representative of the actual sales price, plus any subsidies or additional premiums that may be received. This total sales price is higher than the one determined in the Advanced case study (1650 Euro/tonne). Reasons for this are higher estimated costs for both pyrolysis oil and transport of the oil. These costs have increased substantially over the last year. However, also the costs of fossil alternatives (MGO, or Marine Gas Oil) have increased substantially. The benchmark 15% return on equity translates into a payback time of 6 years, and is selected to be in line with the benchmark used in the determination of Dutch SDE++ subsidies (PBL 2021).

Sensitivity

In Figure 21 the effects of changes in the hydrogen cost price, the pyrolysis oil cost price and the capital costs of the upgrading plant are shown. Shown in the graph is the effect of these cost price changes on the resulting transport fuel sales prices that is needed to obtain a return on equity of 15%.

The graph shows, predictably, that the pyrolysis oil cost prices has a large effect. This is to be expected, since a large part of the OPEX (see Table 20) are pyrolysis oil cost. The influence of capital cost variations is enhanced because these also have an effect on operation and maintenance.

The costs of hydrogen do not seem to have a very high impact on the sales price, though it should be mentioned that currently a price equal to ‘grey’ hydrogen is taken, whereby it is assumed that costs for ‘blue’ or ‘green’ hydrogen could come down to this level. According to some (not all) literature sources (see e.g. (Mulder, Perey, and Jose 2019) and (CE Delft 2018)) this is realistic.

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[6] https://shipandbunker.com/prices/emea/nwe/nl-rtm-rotterdam#MGO

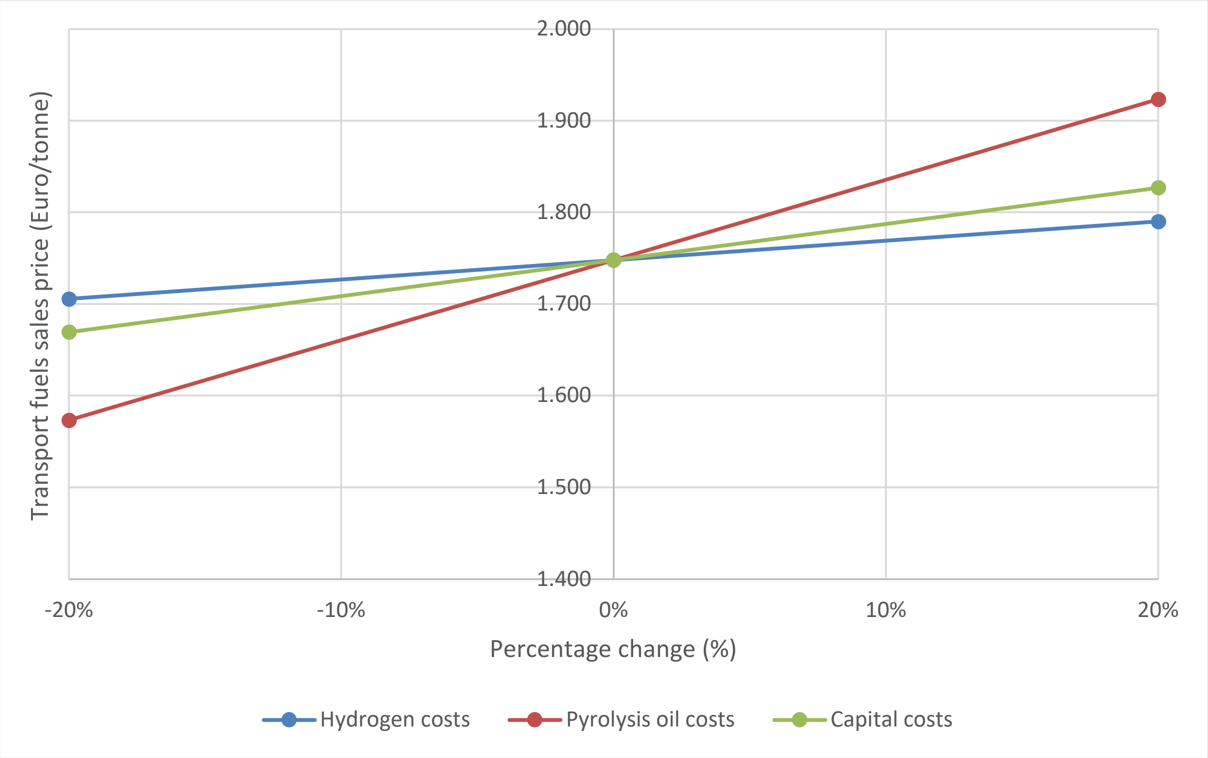

Figure 21: Sensitivity of the transport fuel sales price to changes in selected parameters

Costs per tonne of CO_2-eq. saved

The costs per tonne of CO_2-eq. saved depends on the amount of CO_2-eq. saved per MJ of fuel, and the costs of producing the fuel. These two factors are linked, since the use of low-emission inputs - like sustainable hydrogen – means that costs of fuel production go up.

To determine the impact of that effect, the costs per tonne of CO_2-eq saved will be calculated for three cases of hydrogen production, namely 1) fully ‘green’, 2) a mix between ‘green’ and ‘grey’ and 3) fully ‘grey’. Input data is listed in Table 23:

Table 23: Input data for determining costs per tonne of CO_2-eq saved

Parameter	Value	Unit
H_2 emissions - PEM electrolysis	1,4	kg CO2-eq/kg H2
H_2 emissions NG reforming (RES electricity)	9,2	kg CO2-eq/kg H2
H_2 emissions NG+CO_2 capture (RES electricity)	2,53	kg CO2-eq/kg H2
CO_2 emissions PO oil production and transport	3,27	tonne CO2/tonne fuel
Fossil fuel comparator for transport fuels	94	g CO2-eq/MJ fuel
Price of regular marine fuel	831	Euro/tonne fuel
H_2 costs - PEM electrolysis	3.300	Euro/tonne H2
H_2 costs NG reforming (RES electricity)	1.560	Euro/tonne H2
H_2 costs NG+CO_2 capture (RES electricity)	2.200	Euro/tonne H2

The specific CO2-eq. emissions for the three hydrogen production technologies is derived from the Advanced case study report. PEM electrolysis can be considered ‘fully green’. Reforming of natural gas (NG reforming) is considered ‘grey’, while a third option (NG reforming plus CO_2 capture) is included as well. The basis CO_2 emissions associated with pyrolysis oil production and transport have been recalculated in this Strategic case study report (see paragraph 4.7). Costs for the various hydrogen production methods are derived from (CE Delft 2018) which projected these costs to be valid in 2030. Other sources show smaller costs for renewable alternatives, but in order to be conservative, the listed figures are used.

With these input data, the three hydrogen production mixes can be defined. In Table 24 these are listed, together with the CO_2-eq emissions that are saved, in absolute numbers and in percentage.

Table 24: Emissions savings for three hydrogen production mixes

Parameter	Fully 'green'	Mix of 'green' and 'grey'	Fully 'grey'
Percentage production H2			
- PEM Electrolysis	100%	50%	0%
- NG reforming (RES electricity)	0%	40%	100%
- NG+CO_2 capture (RES electricity)	0%	10%	0%
CO_2 emissions transport fuel (tonne CO_2-eq./MJ fuel)	7,8	18,2	32,9
Emission savings compared to comparator (tonne CO_2-eq. /MJ fuel	86,2	75,8	61,1
Emission savings percentage	92%	81%	65%
Emission savings (tonne CO_2-eq/tonne of fuel)	3,77	3,31	2,67

This table shows that when hydrogen is exclusively produced by renewable resources (PEM electrolysis with green electricity), the emission savings are quite high with 91%. When fully grey hydrogen is used, the emission savings are just at the minimum limit prescribed in the RED II. Based on the emission savings per MJ fuel (third line from the bottom), the emission savings per tonne of fuel can be computed (last line of the table).

With the emission savings listed in Table 24, and the costs of the various hydrogen production methods from Table 23, the costs per tonne of CO_2 can now be computed.

Table 25: Costs per tonne of CO2 saved for various hydrogen production mixes

Parameter	Fully 'green'	Mix of 'green' and 'grey'	Fully 'grey'
Averaged costs of hydrogen (Euro/tonne H_2)	3.300	2.494	1.560
Total costs hydrogen (MEuro/year)	40,1	30,3	19,0
Resulting costs of transport fuels (Euro/tonne fuel)	1.983	1.875	1.748
Price difference with regular fuel (Euro/tonne fuel)	1.152	1.044	917
Costs per tonne of CO_2-eq saved (Euro/tonne CO_2-eq)	306	315	344

In this table we see the averaged costs of hydrogen, which are equal to the costs of PEM electrolysis H_2 in mix 1, and equal to the grey H_2 costs in case of mix 3. The resulting transport costs are determined again using the benchmark of 15% return on equity, using all the same assumptions as earlier in this paragraph. It should be noted that in all cases the costs per tonne of CO2-eq saved are higher than the value determined in the Dutch SDE++ system (PBL 2021).

This table shows that even when costs for green hydrogen are relatively high, the costs per tonne of CO_2-eq saved can be lower than when grey hydrogen is used. This is in spite of the higher total costs of transport fuels.

4.10 Final remarks

In this strategic 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. Also, alternative logistic solutions, such as ‘hub’ in the South of Sweden, have been assessed.

Compared to the advanced case study results, costs have increased, which is visible in the costs for biomass as well as the costs for logistics and transport. The costs of the fossil alternatives have however also increased in price. However, despite that, there still will need to be additional stimulus given to make this value chain feasible, either in the form of subsidies, taxes on fossil fuels or mandates.

Other aspects that are noteworthy are the availability of sawdust in Sweden and Finland. In both countries it is clear that the required biomass quantities are available but implementing a significant number of pyrolysis oil production plants – eight in the case of this strategic case study – distorts the market, and it could have an upward effect on the price of biomass.

With respect to upgrading, it is noteworthy that if the costs per tonne of avoided CO2-eq is taken as a yardstick, it is advantageous to minimise CO2-eq emissions. This is most easily done by sourcing 'green' hydrogen, even though it is more expensive than hydrogen produced from natural (fossil) gas.

5 Microbial Oil production from agricultural residues: the Italy case study

5.1 Introduction

The Italian Strategic case study evaluates the feasibility across the whole value chain of the production of Microbial Oil from ligno-cellulosic agricultural residues and dedicated crops cultivated on marginal lands, to be used in a bio-refinery for the production of biofuels such as HVO diesel.

Microbial Oil (MO) (produced by oleaginous yeasts from lignocellulosic biomass) is presently at early stages of development as potential feedstock for an EU bio-based economy, with a Technology Readiness Level (TRL) currently ranging between 4 and 5. However, MO has a very large potential as a substitute for vegetable oils and food-related lipid feedstocks, i.e., for commercial Hydrotreated Vegetable Oil (HVO) biorefineries. This is especially true since the Renewable Energy Directive II set a cap for such food- and feed-based biofuels, and also defined targets to reduce the use of high Indirect Land Use Change (ILUC)-risk feedstocks - such as palm oil - starting in 2023 and with a complete phase out by 2030. MO could also be of specific interest for the fossil refineries sector when used as co-feeding feedstock, supporting their transition towards a low-carbon economy.

Ligno-cellulosic agro-residues such as olive and grapevine pruning and maize stocks, herbaceous agro-residues such as barley, triticale, sorghum, 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 22 below.

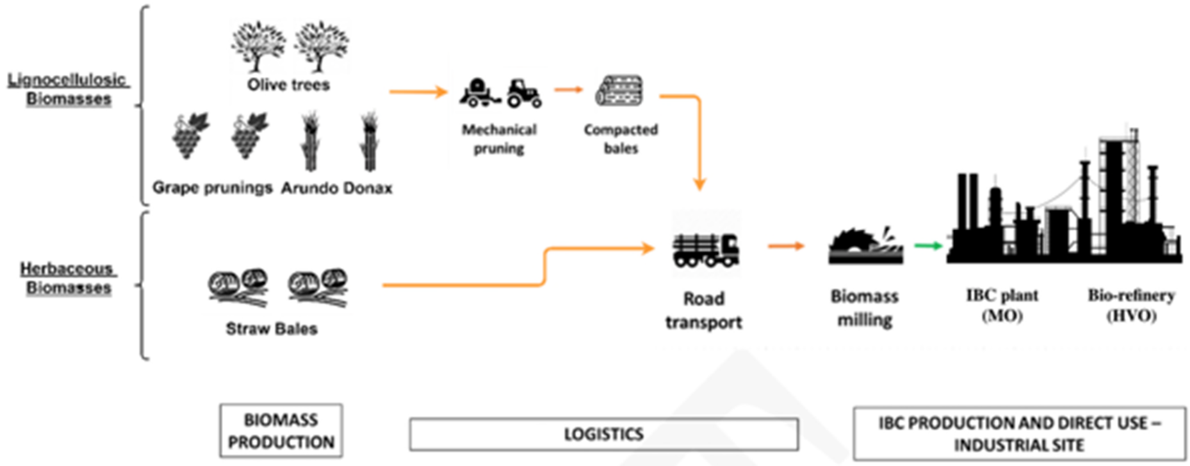

Figure 22: Strategic case study value chain layout.

The MO target production for the overall Strategic case study is set at 100 kt/a, corresponding to around 715 kt/a of dry biomass. The Strategic CS involves the areas around ENI bio-refineries of Porto Marghera, in the north of Italy and Gela, in the southern Italian island of Sicily, thus it is considering two subcases: one for the IBC plant in Porto Maghera (Veneto region, northern Italy), and one for the IBC plant in Gela (Sicily, southern Italy). For each geographical subcase, two different scenarios have been considered:

- A **centralized scenario,** where an IBC plant with a nameplate capacity of 50 kt/a of MO output is deployed in the premises of the bio-refinery, to take advantage of the facilities already existing on site
- A **decentralized scenario,** where two IBC plants, each with a nameplate capacity of 25 kt/a of MO output are deployed near to the biomass production areas, to take advantage of the densification obtained converting the starting biomass feedstock into the MO output (almost seven-fold) and optimize logistics costs.

For each IBC plant location scenario, other two scenario were considered, taking into account the use of the most abundant process co-product, lignin. In one scenario (Baseline), lignin is considered to be burnt completely for internal plant energy uses, while in the other (Lignin) at least part of it is sold on the market to generate a new revenue stream.

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 methodology has been developed to define the optimal location of the decentralized IBC plants, taking into account a set of location constraints, logistics costs and the year-round availability of residual biomass, as reported by the output data from INFER-NRG model.

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.

5.1.1 ENI Italian bio-refineries R&D Center

Currently ENI has a total processing capacity of 1.1 Mt/a of raw biomaterials such as vegetable oils, animal fats, used cooking oils or algae extracts; a doubling of its total capacity is projected for 2024, and 5–6 Mt of HVO production capacity are expected to be reached by 2050. Furthermore, ENI committed to make its biorefineries palm oil free by 2023 (ENI 2022).

In 2020 ENI Venice biorefinery was accounted for a 350,000 t/a capacity, and Gela for 650,000 t/a. ENI stated a CAPEX of around $300-400/t/a of HVO for its biorefineries, equating to 105-140 M USD for Venice and 195-260 M USD for Gela (Argus 2020).

Gela ENI bio-refinery

Gela bio-refinery was launched in August 2019 and its construction began in early 2020; it is able to treat used vegetable and frying oil, regenerated used cooking oil, animal fats, algae and waste/advanced by-products, up to 100% of its processing capacity, to produce biofuels. In March 2021 a new Biomass Treatment Unit started production, with the aim of using raw material waste for biofuel production, to create a zero-kilometre circular economy model for the production of biodiesel, bio-naphtha, bio-LPG and bio-jet. In the effort to completely replace palm oil, castor oil will also be used to feed the Gela biorefinery, thanks to an experimental project to grow castor plants on semi-desert land in Tunisia.

Figure 23: Geographical location of Gela ENI bio-refinery

In addition to the new biorefinery, the Gela site is also home to the Waste-to-Fuel pilot plant since December 2018. Transforming up to 150,000 t/a of OFMSW (Organic Fraction of Municipal Solid Waste) into water and bio-oil, the plant and can also extract biomethane.

Porto Marghera ENI bio-refinery

The bio-refinery of Venice is the first conventional refinery in the world to be converted into a bio-refinery in 2014. Since then, about 360,000 t/a of raw materials of biological origin have been treated and converted; by 2024, thanks to planned upgrades, the plant will increase its processing capacity to 560,000 t/a, with a larger input deriving from waste oils, animal fats and other advanced by-products. At that point, the Venice biorefinery will produce 420,000 t/a of HVO biofuel using ENI proprietary process Ecofining ™.

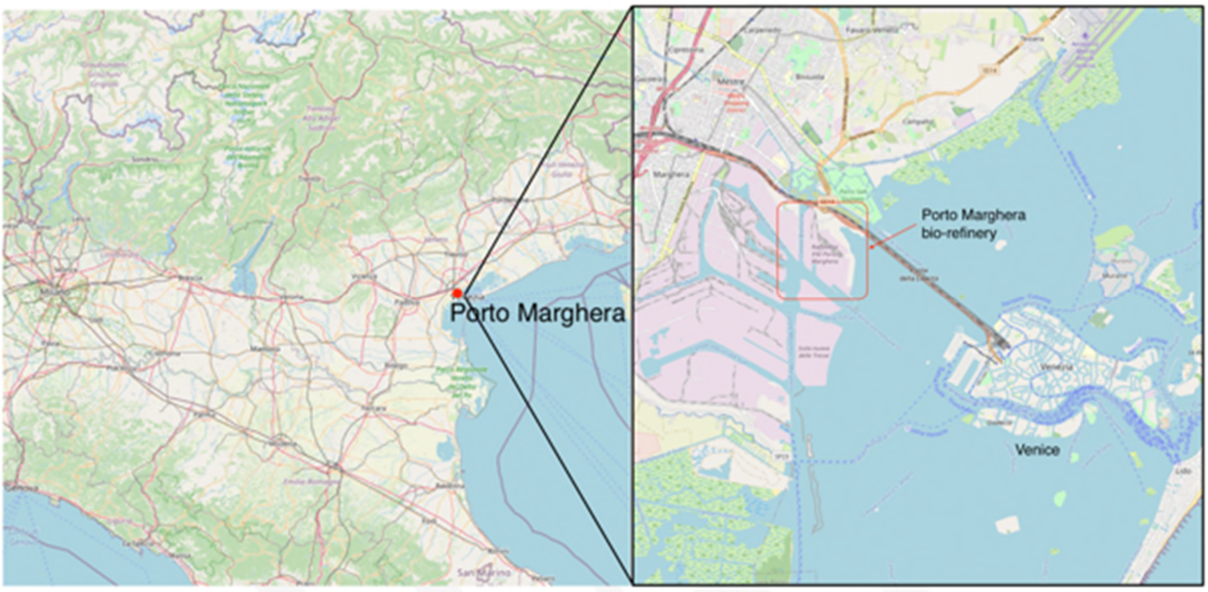

Figure 24: Geographical location of Porto Marghera ENI bio-refinery

ENI Renewable Energy and Environmental R&D Center

The research centre based in Novara is carrying on the scientific work of the Donegani Institute, one of the first industrial chemical research centres in Europe. Research is carried out in several fields, such as solar photovoltaics, electricity storage and biofuels. The Biomass-To-Fuel (B2F) technology that uses the oleaginous micro-organisms from farm and forest cuttings to make biofuel is born in Novara and is developed by ENI-Versalis at Crescentino plant[7]. This technology is used as a conceptual base for the IBC plant model developed for this case study. Figure 25 provides a high-level description of the underlying process.

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[7] https://www.eni.com/en-IT/operations/renewable-energy-res.html

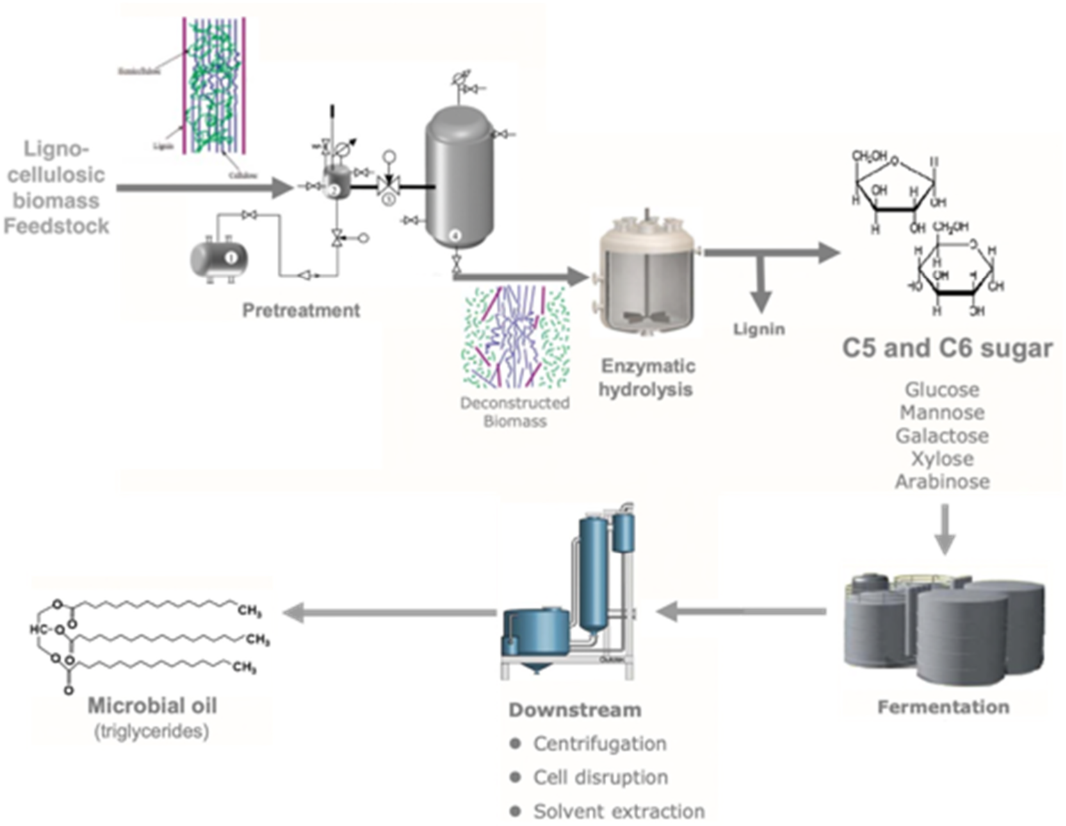

Figure 25: High-level description of the MO production process as defined by ENI B2F technology (author's elaboration on (Perego and Bianchi 2017))

Figure 26 provides a picture of the lab-scale MO plant at the ENI R&D facilities, and shows it successive steps of evolution, together with the final target size.

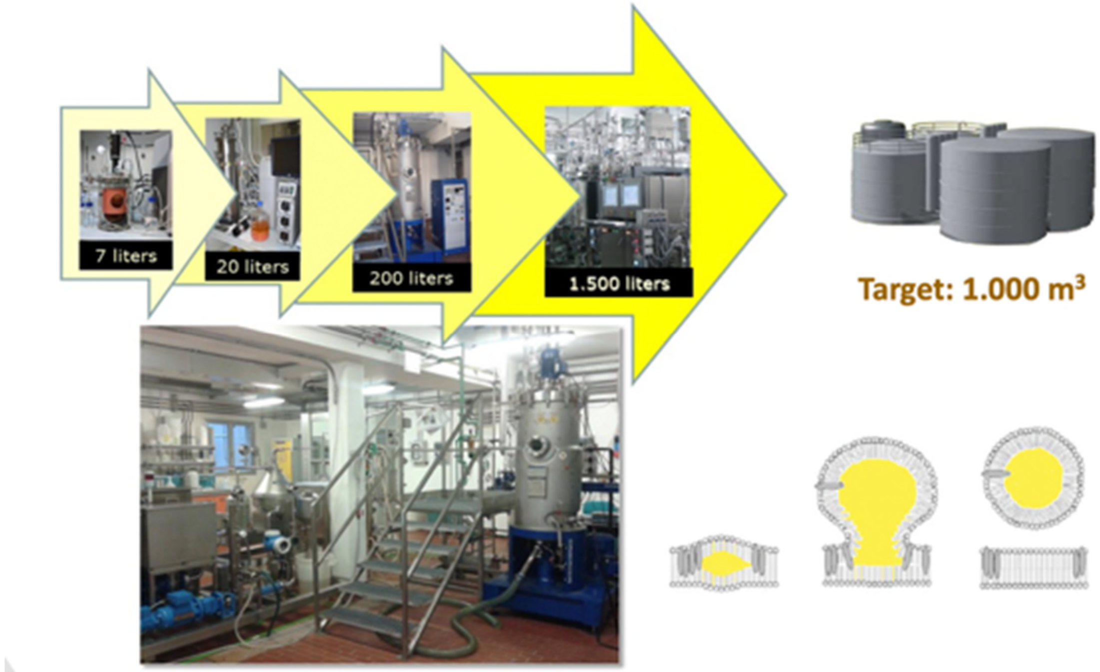

Figure 26: ENI MO lab-scale plant, scale-up steps and lipids accumulation model in oleaginous microorganisms (author's elaboration from (Delbianco 2017))

5.2 Microbial oil production technology

The first part of this chapter reports an overall description of what is MO, which kind of microorganisms are involved, the basics of the production process and the main feedstocks used. In the second part the MO production plant model is described in detail, together with its main operational parameters and yield, and its economics.

Microbial Oil (MO) (produced by oleaginous yeasts from lignocellulosic biomass) is presently at early stages of development as potential feedstock for an EU bio-based economy, with a Technology Readiness Level (TRL) currently ranging between 4 and 5. However, MO has a very large potential as a substitute for vegetable oils and food-related lipid feedstocks, i.e., for commercial Hydrotreated Vegetable Oil (HVO) biorefineries. Moreover, MO benefits from the possibility to use several already developed technologies in the upstream phases of preprocessing and enzymatic hydrolysis, inherited from the bioethanol production processes, as well as from other well-developed industrial processes.

The use of oleaginous yeasts for biofuels, nutraceutical or biochemical production could prove more advantageous than the use of microalgae or vegetable oils. Yeasts cultivation is not affected by environmental conditions, seasonal production or geographic location; other yeasts advantages are related to their low duplication times and metabolic versatility. Moreover, they possibly present no competition with food or feed productions, given the fact that they can grow and accumulate MO on several renewable feedstock including **agricultural residues**, **industrial waste streams** and **non-food crops** (Koutinas et al. 2014).

5.2.1 Microbial Lipids

Lipids are attractive feedstocks for production of renewable fuels due to their high carbon-to-heteroatom ratios. They can be acquired from a variety of renewable resources such as oil plants, side streams, and from a variety of microorganisms. In this latter case, **archaea, bacteria, yeast, fungi,** and **microalgae** can be sourced for a significant amount of lipids, produced for essential structural and functional roles mainly in the form of **triacylglycerides** (TAGs) and **fatty acids** (FAs) (Galán et al. 2020).

These **microbial lipids** or **microbial oils** are also found under the name **single cell oils** (SCOs). **SCO** initially designated the triacylglycerol (TAG) fraction of the total cell lipids (Ratledge and Lippmeier 2017); however, it is now used to include all types of fatty acid (FA) containing lipids, **produced by oleaginous microorganisms able to accumulate more than 20% of their cell dry weight as lipids** (Bruder et al. 2018).

One of the main advantages of SCOs production processes is that they are **independent from seasonality and climate**; moreover, they can be **obtained from a wide range of carbon sources**, including renewable ones and organic wastes. SCOs could as well be considered as Intermediate Bioenergy Carriers (IBC), suitable for vegetable oils substitution for **biofuels production** (Ryan Davis et al. 2013; Ahmad et al. 2019; Walls and Rios-Solis 2020; Bergman and Siewers 2016; W.-C. Wang et al. 2016; Ko et al. 2020).

Oleaginous microorganisms can be found among various species of microalgae, fungi (filamentous and yeasts) and bacteria (Galán et al. 2020), (Valdés, Mendonça, and Aggelis 2020; Subramaniam et al. 2010)

- **Filamentous fungi and yeasts:** Yeast oil contents from literature range from 58% to 72% of cell dry weight, with a *Rhodotorula glutinis* strain accumulating the highest level; molds oil contents are reported as ranging from 57% to 86%, with a strain of *Mortierella isabellina* presenting the highest level in the range.
- **Bacteria:** oil accumulations are reported as ranging from 24% to 78% of dry weight, with the highest levels reported for *Arthrobacter* sp. at >40%, and up to 78% from glucose feedstock (Kosa and Ragauskas 2011)
- **Microalgae:** the highest reported oil contents range from 20% to 77% of dry weight, with *Schizochytrium* ranging from 20% to 77%.

The **FA profile of microbial oil** is usually quite similar to that of the oils produced by oleaginous plants (i.e. soybean, rapeseed, sunflower and palm oils); anyhow, it slightly variates according to the genus and species (Valdés, Mendonça, and Aggelis 2020):

- **Oleaginous yeasts and filamentous fungi** SCOs mainly consist of myristic (C14:0), palmitic (C16:0), palmitoleic (C16:1), stearic (C18:0), oleic (C18:1), linoleic (C18:2) and αand γ-linolenic (C18:3) acids, with palmitoleic, oleic and linoleic usually being the most abundant.

- The **oleaginous bacteria** are characterized by the presence of more saturated FAs, such as lauric acid (C12:0), C14:0, C16:0 and C18:0.
- **Microalgae species** are able to synthesize long-chain FAs with a higher number of double bonds, such as docosahexaenoic acid (DHA) (C22:6), eicosapentaenoic acid (EPA) (C20:5) and arachidonic acid (C20:4). These polyunsaturated fatty acids are mostly used to produce cosmetics, nutraceuticals and animal feed.

5.2.2 Accumulation and maximum yields in oleaginous microorganisms

In order to accumulate high levels of lipid in a microorganism, **its metabolic pathways must be manipulated**, to stop cells from multiplying beyond a certain limit. A culture medium with a limited amount of **available nitrogen** is a commonly used method to obtain lipids accumulation; when nitrogen is depleted, the cells become unable to synthesize further amounts of proteins and nucleic acids, since they require it for their synthesis. Aside from nitrogen, **carbon supply** should always be available in the culture medium, and it is usually provided in the form of **glucose**. Many other carbohydrate feedstocks can be used aside from glucose, with the only obvious limitation of the cost (Ahmad et al. 2019; Ryan Davis et al. 2013)

Under this framework, it is possible to divide the culture of an oleaginous microorganism into two distinct phases. The **first phase**, when all the nutrients needed are available, sees a **balanced growth of the cells**. This phase finishes when the growth-limiting nutrient becomes exhausted (i.e., Nitrogen). In this situation, cells are no longer able to multiply but are still metabolically active. Thus, in this **second phase** of the process, related to lipid accumulation, the cells continue to take up the carbon source in the medium and channel it into lipid biosynthesis, since they no longer need to produce a high amount of metabolically available energy (Galán et al. 2020; Ratledge and Lippmeier 2017). Figure 27 below visually summarizes the ideal trends of nutrients availability in the culture medium, together with the biomass and lipids accumulation trends, across the process timeframe.

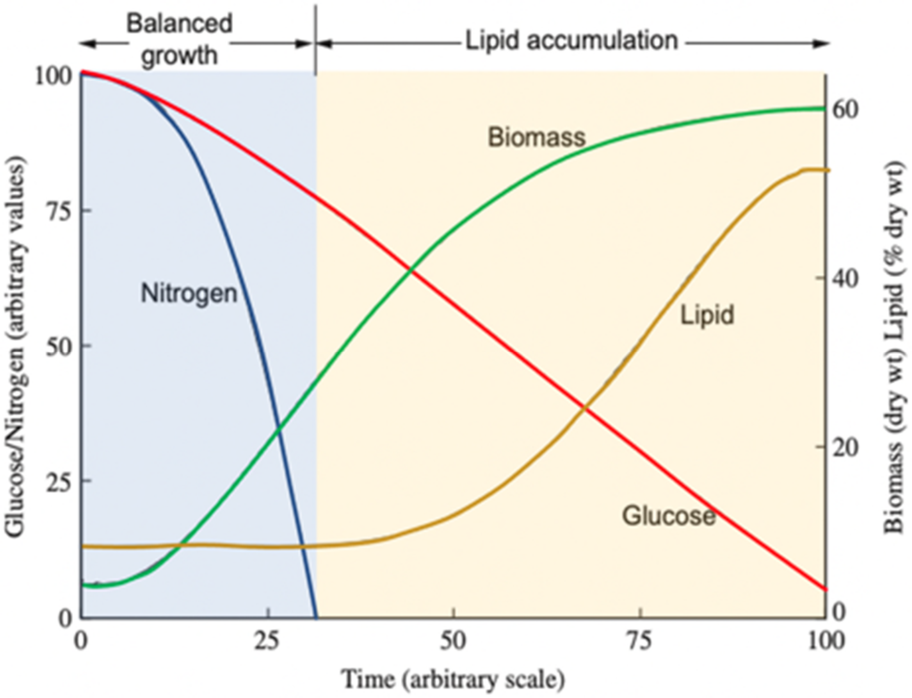

Figure 27: Lipid accumulation trends for oleaginous microorganism (author's elaboration on (Ratledge and Lippmeier 2017))

Several potential metabolic pathways and products exist for biological conversion of sugars to long-chain hydrocarbons, such as isoprenoids, fatty acids, triglycerides, and paraffins (Humbird et al. 2002). Each pathway exhibits **varying theoretical yields**, dictated by underlying metabolic mass and energy yields; i.e. regarding oleaginous microorganisms literature reports a theoretical maximum yield of **25g to 35g TAG from 100g glucose**, depending on the involved metabolic pathway (Ratledge 2014; Rude and Schirmer 2009).

Table 26 open this evaluation to various product pathways; in this framework, ethanol still proves to be a superior product for bioconversion of sugars in the context of fuel molecules, both in terms of theoretical mass and energy yield (e.g., heating value) of product relative to sugar. The energy yield for hydrocarbon products is close, but still remains 5% to 24% lower. All these example products are diesel-range molecules; however, products in the gasoline or jet-range generally compare similarly in terms of the energy yields (Humbird et al. 2002).

Table 26: Theoretical Metabolic Yields for Various Product Pathway

	Mass yield	Carbon yield	Energy yield (HHV basis)
Ethanol	51%	67%	98%
Pentadecane	29%	62%	88%
Farnesene (DXP pathway)	29%	64%	85%

Farnesene (MVA pathway)	25%	56%	74%
Fatty Acid (Palmitic acid)	36%	67%	89%
FAEE (Ethyl palmitate)	35%	67%	90%
Fatty Alcohol (Hexadecanol)	34%	67%	93%

5.2.3 Microbial Oil suitable feedstocks and production processes

As heterotrophic organisms, yeasts metabolize C from simple sugars or C-containing compounds such as glycerol. Thus, **fermentation feedstocks** can be monosaccharides such as **glucose**, or **C5 and C6 saccharide-containing hydrolysate** derived from the breakdown of lignocellulosic biomass (Parsons et al. 2019). Yeasts can utilize many different carbon sources (e.g., glucose, xylose, starch, cellulose hydrolysates, glycerol, as well as industrial and municipal organic wastes).

The theoretical sugar-to-oil yield of around 25-35% (depending on the considered metabolic pathway), leads to the consideration that 3 to 4 tons of sugar are needed to produce 1 ton of MO (Ratledge and Lippmeier 2017); this clearly highlights the importance of using low-cost feedstocks, i.e. lignocellulosic materials (also as agro-residues) and organic wastes, in order for MO to be competitive with the selling price of a plant commodity oil.

Lignocellulose is a complex biopolymer composed of the polysaccharides **cellulose** and **hemicellulose**, the amorphous polymer **lignin** and of a remaining smaller fraction which includes **pectin, proteins, extractives and ash**. Approximately two thirds of lignocellulosic biomass total dry weight is composed by the structural carbohydrates, which can be used as carbon source for MO production, after hydrolysis to fermentable sugars. Agricultural residues contains around 30% of cellulose, while woods such as poplar pinewood and spruce reach 40% and more (Santek, Beluhan, and Santek 2018).

The NREL report (Humbird et al. 2002) evaluates the composition in terms of carbohydrate components (cellulose and hemicellulose), lignin, acetate and ash of a **blended feedstock** consisting of **agro-residues** such as multi-pass corn stover, single-pass corn stover, and switchgrass (see Table 2 below), with an assumed moisture content of 20% (SF et al. 2007). Arundo Donax and grapevine are evaluated by (Ramos et al. 2018).

Table 27: Typical agro-residues, ligno-cellulosic feedstock composition (R Davis et al. 2013)

Component	Composition (dry wt)

Glucan	35,1%
Xylan	19,5%
Arabinan	2,4%
Galactan	1,4%
Mannan	0,6%
Total structural carbohydrate	*59,0%*
Sucrose	0,8%
Total structural carbohydrate + sucrose	*59,8%*
Lignin	15,8% - 22.4%
Extractives	9.3% - 14,7%
Ash	3.7% - 4,9%
Protein	3,1%
Acetate	1,8%

The bioconversion of lignocellulose to microbial lipids includes following steps (Valdés, Mendonça, and Aggelis 2020; R Davis et al. 2013; Santek, Beluhan, and Santek 2018; Jin et al. 2015):

1. **Pre-treatment of lignocellulosic biomass:** This step allows to reduce biomass particles size, thus decreasing the degree of polymerization and increasing surface area and porosity of biomass; as a result, the exposure to reagents is improved. Further processes such as chemical, physicochemical and biological could then be applied.
2. **Hydrolysis of structural carbohydrates to fermentable sugars:** During enzymatic hydrolysis of lignocellulose, cellulases and hemicellulases enzymes are used to convert, respectively, cellulose and hemicelluloses into glucose and a mixture of pentoses and hexoses.
3. **Microbial production of lipids:** The glucose and other sugars hydrolyzed in the previous step are then conditioned to remove insoluble solids such as lignin, then are partially concentrated, and converted into hydrocarbon molecules with bioconversion processes.
4. **Isolation and purification of the product:** Lipid recovery from fermentation broth involves microbial cells harvesting from the broth, either by drying cell biomass or by forcing cell disruption, and successive lipid extraction. Centrifugation, filtration, and coagulation or flocculation are among the most commonly used cell-harvesting methods.

All of these process steps can be found in the IBC plant model developed and used for this Strategic Case Study; they are thoroughly analysed and described in the following section.

5.3 MO production plant model description

Several steps of the MO production process are similar to lignocellulosic bioethanol production, as shown in Figure 28 below. More precisely, both the biomass smart cooking section (where the biomass pre-treatment is made) and the hydrolysis section (where cellulose is converted to sugars) are almost identical in the two processes. The main differences can be found in the sugar fermentation section. There, the MO production process requires the use of different yeast strains, as well as a prior lignin separation from the feedstock stream, as a solid residue. Moreover, an additional intermediate step before fermentation is required, to increase the sugar concentration of the remaining sugars-water solution. The downstream final sections differ as well between the two processes, having respectively a distillation section for ethanol and an oil extraction section for MO.

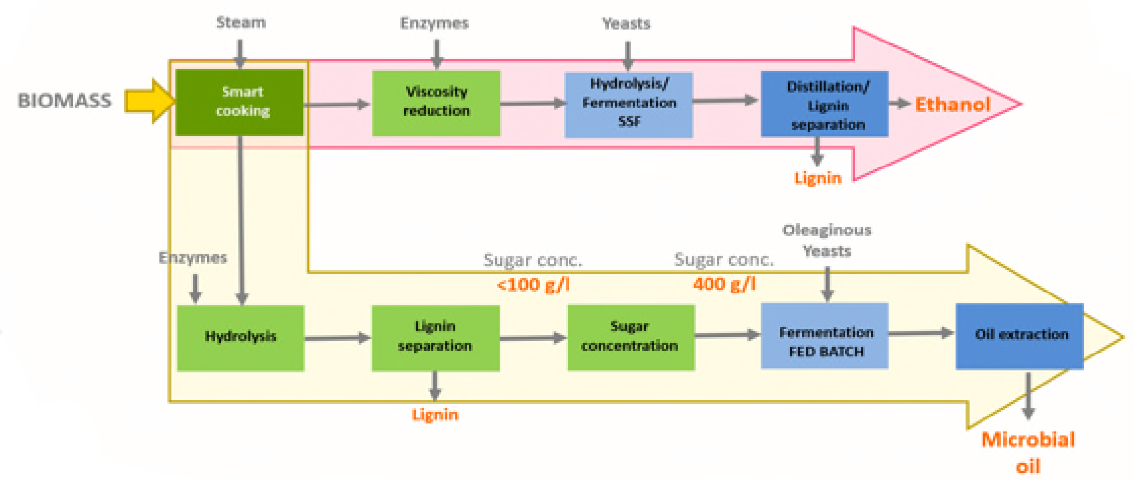

Figure 28: Slide extracted from MUSIC Deliverable D2.1, which describes the main differences between lignocellulosic ethanol (light red route) and microbial oil production processes (light yellow route).

In fact, the layout of the MO-IBC plant could still be considered quite similar to that of a commercial lignocellulosic ethanol plant, as the biomass pre-treatment and hydrolysis sections, shared under many aspects by the two processes, are among the more relevant part of the plant.

Due to its lower TRL status, few data is available on plants and production process with a scale higher than pilot. Amyris and Total process, Synthesized Iso-Paraffins from Hydroprocessed Fermented Sugar (HFS-SIP), is based on fermentation of lignocellulosic sugars to isoprenoids and it is one of the few that has reached commercial status, aiming at the production of Renewable Jet Fuel. Their first commercial plant in Brota, Brazil, has been operational since December 2012 and has the capacity to produce up to 50 ML of farnesene per annum (38.6 kt/y), with six reactors with 200 kL capacity each (Cortez et al. 2014). The facility has been certified by the Roundtable on Sustainable Biomaterials.

Total and Amyris' Biofene jet fuel has reached several milestones, such as having achieved ASTM certification and having in place a fuel purchase MoU been signed with an airline, thus is considered to have a FRL of 7, moving towards 8.

5.3.1 IBC plant overall description

The MO production plant model used for the Italian Strategic Case Study is based on information and data gathered through literature review on the topic, as well as from expert interviews. The main sources of information used are:

- the BIOLYFE Handbook (Chiaramonti et al. 2013) on Crescentino bio-ethanol plant (currently owned by VERSALIS), especially regarding the overall plant layout and the pretreatment and hydrolysis steps;
- the NREL report (R Davis et al. 2013) on a Renewable Diesel plant model, where MO is produced and used as IBC
- interviews and discussions with ENI partners, focusing on adapting the developed model to operating conditions similar to these occurring in their proprietary MO production process

Figure 29 provides a highlight of the overall structure of the MO production process as reported in the cited NREL report (R Davis et al. 2013). It has to be noted that the final product is HVO diesel, and the MO compares within the bioreactor broth stream, output of the A300 area and input for A500 one.

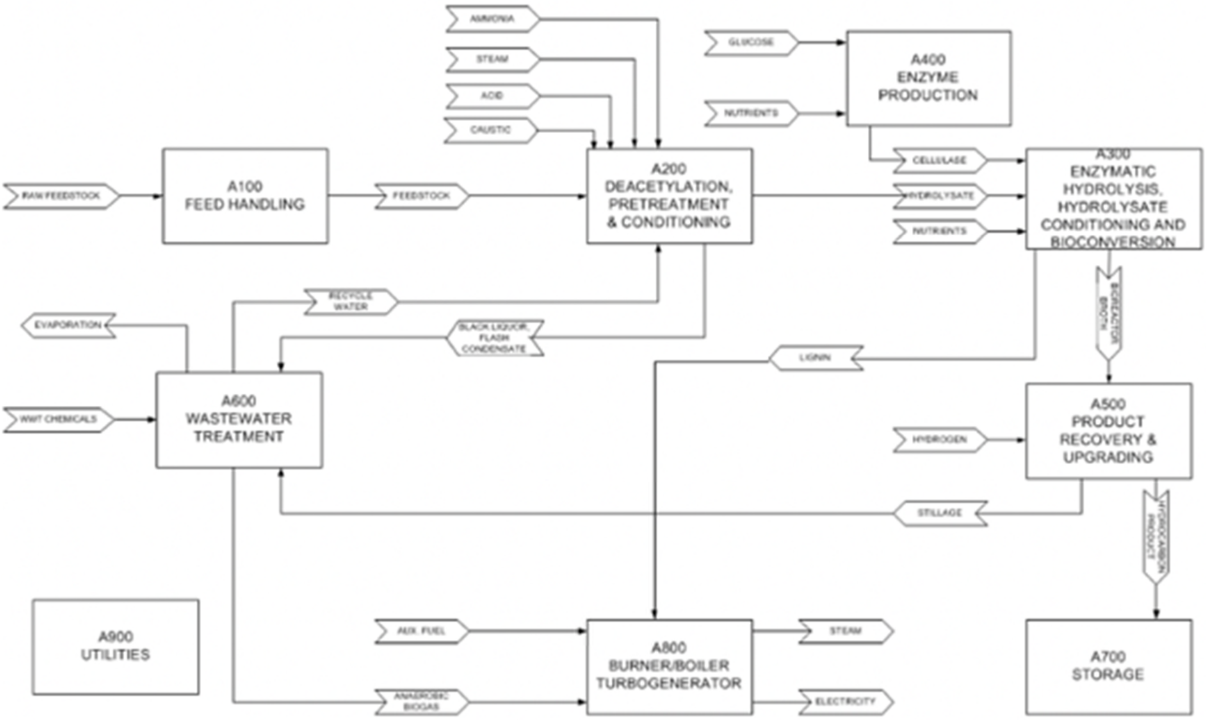

Figure 29: NREL MO-based HVO production plant layout

Figure 30 below instead provides an overview of Crescentino bio-ethanol production plant layout. With its 180 kt/a of biomass input and 40 kt/a of bio-ethanol output, it provides a reasonably scaled example for the MO production plant model used in the case study.

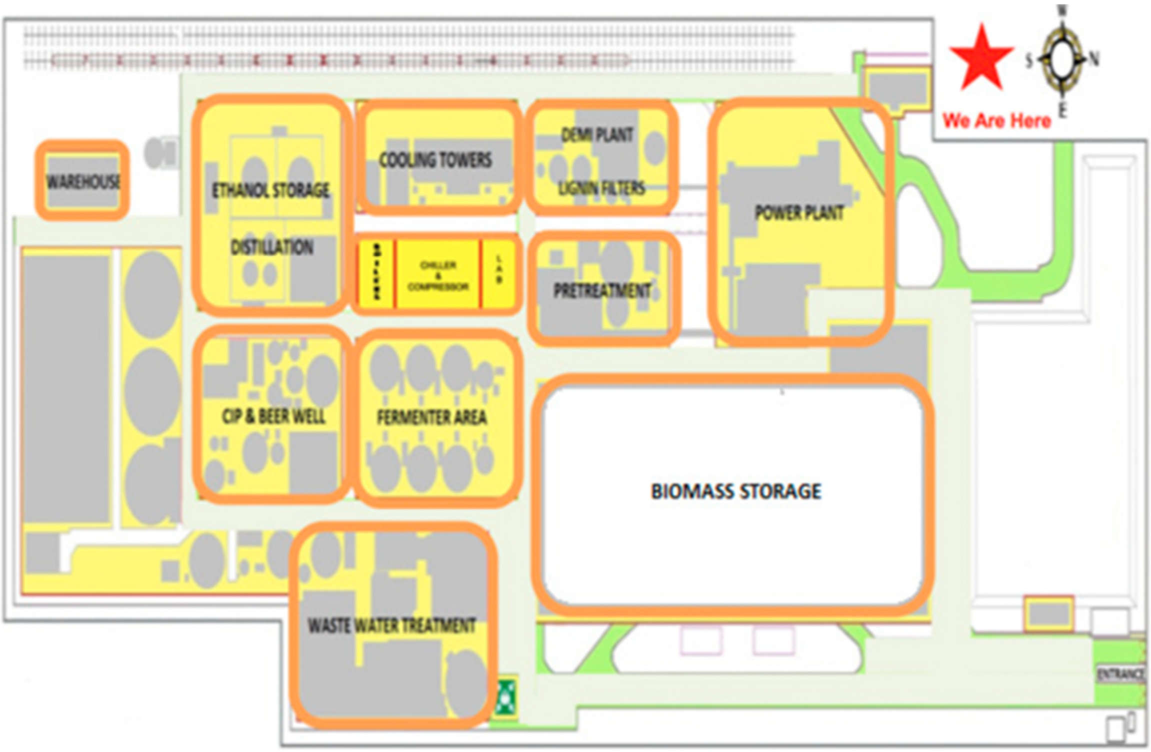

Figure 30: Crescentino bio-ethanol production plant overall layout (Chiaramonti et al. 2013)

The total target MO output of 100 kt/a is considered to be produced by two IBC plant in the centralized scenario, and four IBC plant in the decentralized one. The chosen overall layout of the plant is considered as modular; thus, the bigger plant is a scaled up version of the smaller one. The scale-up is mostly obtained through a doubling of the involved assets. In the followings, whenever not specified, the smaller plant of 25 kt/a of MO output is considered.

The IBC plant is articulated in interconnected macro-areas, as reported in Figure 31, spanning from feedstock handling to the storage of output product. A brief description of each of them is provided in the followings.

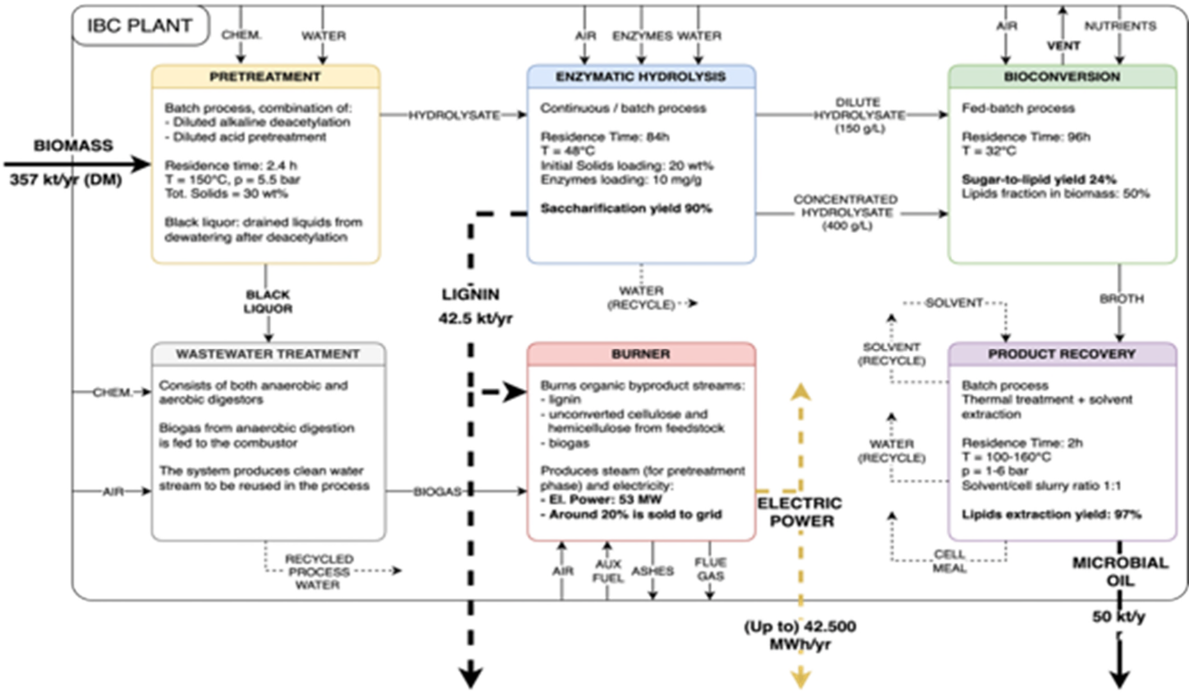

Figure 31: Overall IBC plant layout (Centralized, 50 kt/a MO output)

Feedstock storage and handling

This area deals with incoming biomass via trucks; thus, its facilities include truck unloading systems, dedicated hoppers and conveyors and finally a short-term storage of 72 hours (i.e., concrete domes). The storage domes are then connected to the pretreatment and conditioning area. Considering 7884 operating h/a, the hourly feedstock receiving rate is of 91 t/h (dry matter); having assumed the use of 8 t trucks, this means that the plant receives 11-12 trucks per hour.

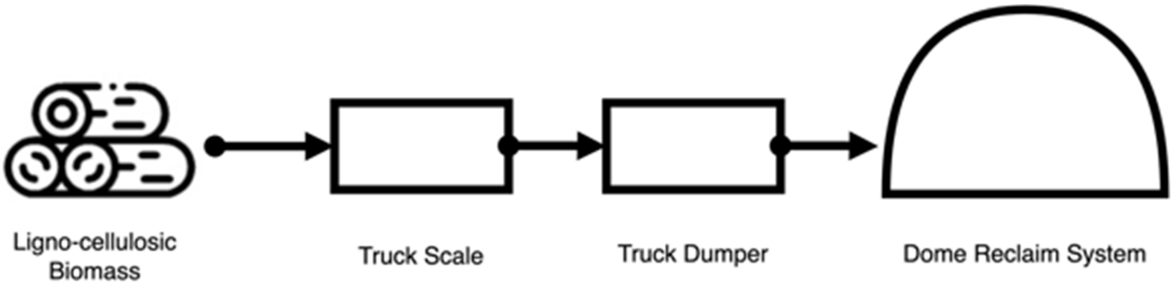

Figure 32: Feedstock storage and handling Area layout

Pretreatment and Conditioning

The primary role of biomass pretreatment for biofuel production is to disrupt the matrix of polymeric compounds physically chemically bonded within lignocellulosic biomass cell wall structures, including cellulose microfibrils, lignin, and hemicellulose. It has a significant impact on all downstream processing such as enzymatic hydrolysis and fermentation.

In the model design, pretreatment reactions are considered to be catalysed first using dilute sodium hydroxide, then using dilute sulfuric acid. After deacetylation, the black liquor is drained and sent to wastewater treatment area. The deacetylated biomass solid stream is charged with dilute sulfuric acid into a horizontal screw-feed reactor with a short residence time (5–10 minutes).

The **combination of both acid and alkaline pretreatment processes** minimizes the generation of inhibitory compounds derived from the dehydration of pentoses and hexoses in acidic media such as furan aldehydes, that may render enzymatic hydrolysis inefficient. This occurs at the cost of higher investments in equipment and longer processing time (R Davis et al. 2013).

Finally, the hydrolysate slurry is cooled by adding water and it is sent to a conditioning reactor, where ammonia is used to raise its pH, and then sent to the enzymatic hydrolysis area.

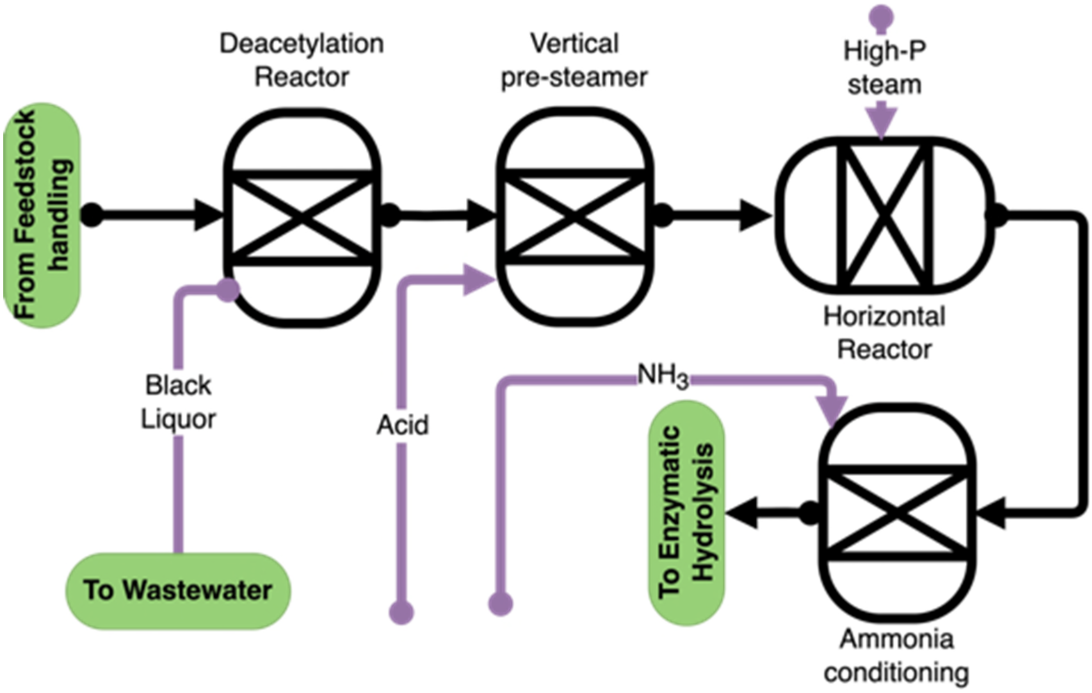

Figure 33: Pretreatment and conditioning area

Enzymatic Hydrolysis, Hydrolysate Conditioning, and Bioconversion

Scope of this process area is to convert cellulose to glucose using cellulase enzymes and then convert the sugars to lipids. The first process is known as enzymatic saccharification or enzymatic hydrolysis, where cellulose fibers are broken down into cellobiose and ultimately into glucose monomers. Two different reactors are disposed in series: the first one, the viscosity reduction tank, is a vertical tower designed to work with a high amount of dry matter (up to 40%). The retention time is set so to decrease the hydrolysate viscosity to a point that allows the transfer through a centrifugal pump. In the second reactor the enzymatic hydrolysis goes on leading to simpler oligomeric chains necessary for an efficient downstream conversion to lipids.

After hydrolysis is complete, the resulting glucose and other sugars hydrolyzed from hemicellulose are then conditioned to remove insoluble residual solids (primarily lignin) through a solid-liquid separation step where a vacuum filter press is used. This step is necessary to enable a more efficient gas-liquid mass transfer in the aerobic bioreactors downstream; it also carries a downside, since enzymes are removed together with solids, thus negating the additional hydrolysis activity that could take place during bioconversion. A further wash step is included to recover soluble sugars carried over into the solids fraction; the lignin-rich solids fraction is then sent either sent to the boiler for energy recover or prepared to be sold. The final step, where sugars are converted to hydrocarbon molecules using yeasts strains, occurs separately at lower temperature and in separate vessels, thus the entire process configuration can be referred to as separate hydrolysis and "fermentation" (SHF). The bioconversion step is carried out in fed-batch mode and it receives two different streams of hydrolysate materials: a first portion is sent directly from the filter press, while the majority of the stream is sent to an evaporator system to concentrate the sugars, then cooled and fed to the bioreactors as the conversion reaction proceeds through the batch cycle.

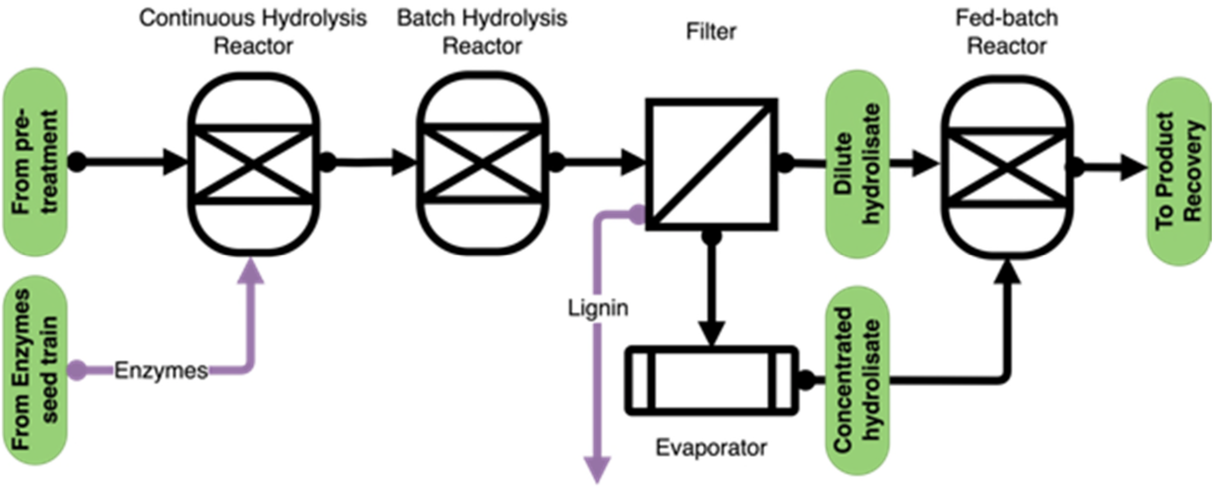

Figure 34: Enzymatic Hydrolysis, Hydrolysate Conditioning, and Bioconversion process flow

This process area, as modelled for the Strategic CS, differs from the NREL one (R Davis et al. 2013) in the fact that industrial lyophilized yeast strains are used, instead of using an inoculum seed train section. Seed train consisted in several reactors used to make a seed culture from the lab replicate and grow until ready for bioconversion. The implications related to this choice are three-fold: the process is faster, since it needs only the time for yeasts re-hydration, it reduces CAPEX and it avoids the need for diverting around 10% of hydrolysate material from bioconversion to sustain yeasts culture growth.

Cellulase Enzyme Production

Cellulase enzyme refers to a mixture of enzymes (catalytic proteins) and is used that is used in Enzymatic Hydrolysis area to hydrolyse cellulose into glucose. In the present design it is considered to be produced via submerged aerobic cultivation, using glucose and fresh water as feedstocks.

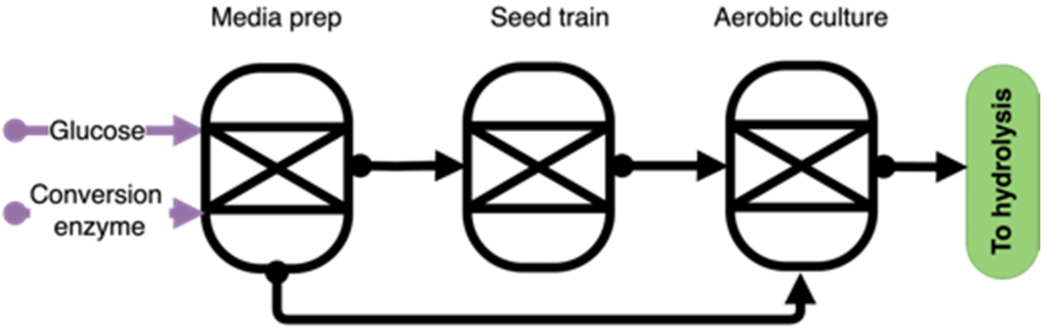

Figure 35: Cellulase enzyme production process flow

MO Recovery

Scope of this area is to separate the broth coming from the bioreactor into a hydrocarbon (MO) phase and an aqueous phase containing the biomass from the organism cells, some soluble solids including unconverted sugar and water. Here the suspended solid fraction is anyhow small, since lignin and other insoluble solids were already removed upstream in the process. The MO extraction is obtained with a batch process, composed by a thermal treatment under pressure for cells disruption, followed by solvent extraction of the lipid fraction.

Wastewater Treatment

This area gathers all the wastewater generated in the plant; it collects boiler and cooling towers blowdown, black liquor from deacetylation in the pretreatment area, and the aqueous phase from MO separation and recovery area. All these streams are processed by anaerobic and aerobic digestion, membrane filtration, reverse osmosis, evaporation, dewatering, and gravity belt thickening. The methane-rich biogas produced by the anaerobic digestion is directed to the combustor, as it is the dewatered sludge. The treated water produced is a relatively clean stream that can be reused in the process, i.e., as dilution water in pretreatment or enzymatic hydrolysis.

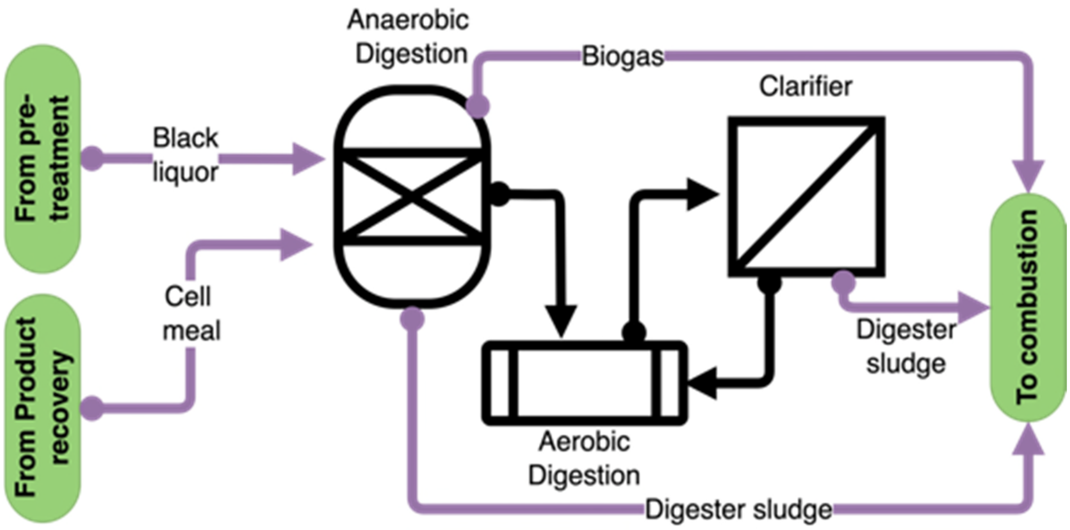

Figure 36: Wastewater treatment process flow

Combustor, Boiler, and power and steam generation

The purpose of the combustor (capable of handling the wet solids), boiler, and turbogenerator subsystem is to burn various organic by-product streams to produce steam and electricity and to reduce solid waste disposal costs. If all the byproducts are burnt, the plant energy needs are completely covered, and additional revenue could be generated through excess electricity sale. Combustible byproducts include e lignin and unconverted cellulose and hemicellulose from the feedstock, biogas from anaerobic digestion and biomass sludge from the wastewater treatment section.

As already explained in the introduction, in this model the lignin use changes depending to the considered scenario: it can be fully devoted to the internal energy uses (Baseline) or it can be sold on the market for other uses, following an economical optimum (Lignin). In either case, the electricity and heat production capacity are modulated taking into consideration the combustible feedstock availability; anyway, it has to be noted that the impact of lignin use on overall energy balance of this section is relatively small.

Other plant sections

Aside from the main operational areas described above, the model also comprehends a storage area for both the output product and the chemicals needed for the overall process and the utilities system needed across the plant, at least for CAPEX and OPEX calculation. The utilities system tracks cooling water, chilled water, plant and instrument air, process water, and the clean-in-place system that provides hot cleaning and sterilization chemicals to hydrolysis, bioconversion, and the enzyme production section.

5.3.2 IBC plant operational parameters

The main yields related to the various process sections are reported in Table 28 below; they specifically refer to the ENI MO production process. Since they slightly differ from the yields reported by the NREL report (R Davis et al. 2013), the involved mass flows and reactors sizing have been modified to take that into account. As an example, the difference in sugar-to-lipids yield (0.283 g/g for the NREL model) has an impact on the bioconversion section, where the vessels had to be scaled up to guarantee the same MO yield in the same process time. Moreover, also the upstream biomass collection, pretreatment and hydrolysis sections had to be scaled up to allow the use of higher volumes of biomass, proportionally to the NREL higher overall biomass-to-MO yield of 0.162 g/g.

Table 28: Main yields and process parameters

Yields and parameters	Value
MO/biomass DM (g/g)	0.14
MO lipids extraction (g/g)	0.97
Lipids fraction in cell biomass (g/g)	0.5
Lipids/sugars (g/g)	0.24
Sugars/biomass DM (g/g)	0.6

In the following part of this section, the main process parameters are reported and discussed, for each of the primary sections of the plant.

Feedstock storage and handling

Considering 7,884 operating h/a, the average hourly feedstock receiving rate is of 91 t/h (dry matter); since the moisture content ranges between 20% and 66%, depending on season and feedstock, the total biomass weight ranges between 109 and 151 t/h. Having assumed the use of 10 t trucks, this translates into 11-15 trucks that the plant receives per hour. The unloading time of a whole-truck unloader is reported at 7-10 minutes, so two truck dumpers are required to keep the receiving rate at the required level.

Biomass Drying

The moisture content of input biomass could vary significantly depending on feedstock, seasonality and geographical area, as reported in Table 32 in section 5.5.5, where the topic will be discussed in more detail. Of interest here is the fact that the overall drying power needed a 20% moisture content for the total biomass input of the IBC plant would range between 1.32 MW and 2.32 MW, with a yearly average need of 1.7 MW. Such heating power is provided by the thermal cascades of the power generation section.

Pretreatment and Conditioning

The deacetylation step has a total cycle time of 2.4 hours. The deacetylated material is dewatered by draining through screens at the bottom of the reactor. The drained liquor, often referred to as “black liquor”, is sent to the wastewater treatment area. It contains 20%–25% of the original dry biomass material, including all of the water extractives, 88% of the acetate, around 75% of soluble ash constituents, 50% of the sucrose, 20% of the lignin, 2% of the xylan that were originally present in the feedstock (dry basis). The remaining biomass solids are discharged from the deacetylation reactor and transported to the acid pretreatment reactor system, which has a cycle time of 15 minutes, at around 160°C, then the material is discharged to a flash tank.

After the flash, the hydrolysate whole slurry containing 30% TS is sent to conditioning, through neutralization by ammonia in stoichiometric quantities. The residence time for neutralization is 30 minutes; the slurry is diluted with water to slightly greater than 20 wt% TS and 16% IS to ensure miscibility through enzymatic hydrolysis and bioconversion; the dilution process also cools the slurry to 75°C.

Enzymatic Hydrolysis, Hydrolysate Conditioning, and Bioconversion

The enzymatic hydrolysis is initiated in a continuous, high-solids vertical tower reactor with the slurry flowing down the reactor by gravity, mixed with the cellulase enzyme at a 48°C temperature and with a 24 h residence time. This is required as the feed material at 20% solids (or more) is not pumpable until the cellulose has been partially hydrolyzed. After this point, the slurry is pumpable and is batched to one of the enzymatic hydrolysis vessels for another 60 hours, agitated at 48°C using a pump-around loop with cooling water heat exchange.

Once sugar production is complete, the hydrolysate is processed through a series of conditioning steps to purify and concentrate the sugars prior to conversion. The first conditioning operation is a solid-liquid separation step to remove lignin and other residual insoluble solids from the hydrolysate. At this point, the hydrolysate material has a 150 g/L sugar concentration; 50% of it is directly sent to the bioconversion vessels, while the other 50% is processed beforehand into an evaporator and its sugar concentrated up to 400 g/L (Bianchi 2019). The total process time for bioconversion accounts for 96h, comprising 24h for industrial lyophilized yeast re-hydration; the assumed MO volumetric productivity is of 1.3 g/L/h (R Davis et al. 2013).

MO Recovery

The MO extraction is obtained with a thermal treatment under pressure for cells disruption, followed by solvent extraction of the lipid fraction. The thermal treatment has a temperature range of 100-160°C, with high extraction efficiency starting from 140°C; the solvent extraction is batch-operated, with two consecutive batches and a solvent/cell slurry ratio of 1:1.

Combustor, Boiler, and power and steam generation

Figure 37 reports on the electricity usage of the various sections of the IBC plant. Hydrolysis and Bioconversion section has highly energy-intensive processes due to the use of pumps to feed oxygen into the hydrolysate and the bioconversion broth. It can also be noticed that lignin can account for up to 36% of the total energy inputs; anyway, in the Baseline scenario, 20% of the electricity produced is a surplus and it is sold to the grid.

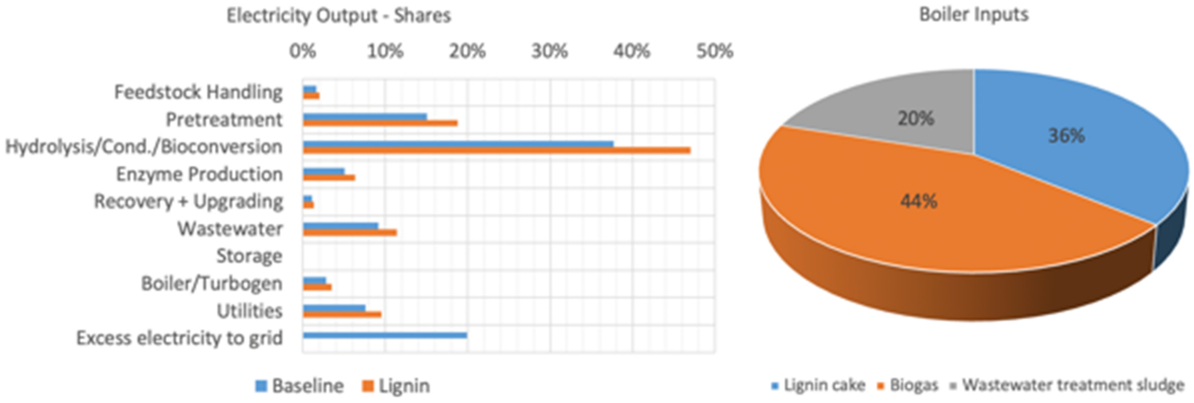

Figure 37: Electricity use shares for the various IBC plant areas (left). Boiler energy input streams - Baseline scenario (right)

5.3.3 IBC plant projected CAPEX and OPEX

The various inputs needed to evaluate CAPEX and OPEX of the model IBC plant discussed in this document mostly comes from the already cited NREL report (R Davis et al. 2013). There, an extensive bottom-up evaluation of all the components costs has been conducted, at a high level of detail. The same methodology has been applied for the plant conduction costs, related to chemicals, energy, personnel, insurance and others. All these costs have been actualized to 2021 values and converted to Euro.

These CAPEX and OPEX values have then been slightly modified to consider the variations of mass and energy flows related to the different process yields implemented in this model, as explained in Table 28. Moreover, CAPEX and OPEX were scaled down less than proportionally with the size of the plant: thus, the decentralized IBC plant with a nominal MO output of 25 kt/a doesn't account for half the CAPEX and OPEX of the centralized IBC plant with a nominal MO output of 50 kt/a. Finally, in both centralized and decentralized scenarios it has been evaluated the impact of selling lignin instead of using it for internal energy purposes. This choice has an impact on both CAPEX, since it allows to scale down the energy generation section, and on OPEX, since it reduces the revenues obtained from the sales of excess electricity, possibly up to the point of turning them into a net cost. Table 29 below provides a summary of total CAPEX for all the scenarios considered.

Table 29: Summary of total CAPEX cost for the IBC plant, for all the considered scenarios

	Centralized		Decentralized	
	Baseline	Lignin	Baseline	Lignin
CAPEX - single IBC plant	335,151,077 €	327,972,466 €	174,982,678 €	171,328,112 €
TOTAL CAPEX	670,302,154 €	655,944,931 €	699,930,713 €	685,312,449 €

Both the CAPEX related to the centralized and the decentralized scenario are higher than the NREL model (R Davis et al. 2013) CAPEX, respectively by 7% and 12%. This can be related to both the fact that one single plant is less expensive than two or four smaller ones of the same total nameplate capacity and to the fact that the MO-to-biomass yield used in this model is slightly lower than the one from NREL model. Moreover, the higher CAPEX in decentralized scenario, when compared to the centralized one, reflects the obvious economies in terms of land purchase and access to existing utilities that stem from deploying the IBC plant near to an existing bio-refinery such as the ones in Gela and Porto Marghera.

OPEX costs includes:

- **Personnel costs:** they are higher in the decentralized scenario, due to the fact that it is not possible to reduce the personnel units under a minimum level. Prices extrapolated from (R Davis et al. 2013)
- **Chemicals costs:** fixed across the scenarios. Prices extrapolated from (R Davis et al. 2013)
- **Lyophilized yeasts costs:** set at 350 €/1000m^3 hydrolysate (bioconversion reactors input)
- **Electricity costs:** electricity is considered as a net cost only in the scenarios where at least 44.5 % of total produced lignin is burnt. Below this threshold, electricity production covers all the plant needs and at least some electricity is sold to the grid generating profit. The price for electricity purchase is set at 108 €/MWh, which is the average for Italian industrial customers purchasing more than 70,000 MWh/a in (ARERA 2022).The average selling price of electricity is set instead to 50 €/MWh (GME 2022).
- **Biomass costs:** they depend on both the scenario (decentralized vs centralized) and on the geographical area (Veneto vs Sicily). The unitary cost ranges between 87 and 104.6 €/t, comprising biomass and logistics costs, as described in section 5.5.7.

Table 30 below reports a summary of the main OPEX costs.

Table 30: Summary of total OPEX cost for one IBC plant, for all the considered scenarios

	Centralized		Decentralized	
	Baseline	Lignin	Baseline	Lignin
Personnel Costs	2,806,605 €	2,806,605 €	1,591,358 €	1,591,358 €
Chemicals	10,910,441 €	10,910,441 €	5,455,220 €	5,455,220 €
Lyophilized yeasts	360,200 €	360,200 €	180,099 €	180,099 €
Electricity	- 2,259,300 €	3,795,137 €	- 1,129,650 €	1,897,569 €

Biomass	35,000,000 €	35,000,000 €	16,017,857 €	16,017,857 €
Other costs	5,502,128 €	5,502,128 €	2,829,361 €	2,829,361 €
OPEX - single plant	**52,320,075 €**	**58,374,512 €**	**24,944,245 €**	**27,971,463 €**
TOT OPEX	**104,640,149 €**	**116,749,024 €**	**99,776,979 €**	**111,885,854 €**

5.4 Markets and drivers

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

- MO sales, or, either, avoided cost for lipid feedstock purchase as HVO production process input
- Lignin sales, if not used for internal energy uses for the IBC plant
- Earnings from incentive schemes, as is the case for CIC schemes in Italy

The Italian Strategic CS specifically considers the advanced biofuels sector, where the MO IBC is directly used into a proprietary bio-refinery to produce advanced biofuels. There are several policy and market drivers that could foster this scenario: at the EU level, the RED II and, in perspective, the Fit for 55 packages, fosters the uptake of biofuels in transport sector. On the other side, the delegated act on high-ILUC risk feedstocks decided the palm oil gradual phase out to 2030; in such scenario, where biofuels targets are growing and some feedstocks are going to be removed from the playing field, MO, as well as other low TRL processes, could play a role on a medium-term perspective.

Finally, lignin is an important by-product of the process; it could become a new revenue stream if sold on the most appropriate market, taking into account its purity level.

5.4.1 Advanced biofuels market

The average energy share of renewables used in transport increased from 1.5% in 2004 to 8.3% in 2018 (Eurostat 2022) and total biofuel consumption was 17.0 Mtoe in 2018, compared to 15.4 Mtoe in 2017 (EurObserv'ER 2020). Within these figures, biodiesel's share was 82 %, in terms of energy content. As of 2019, 3.5 out of 4.8 Mtoe for EU28 is produced as Fatty Acid Methyl Ester (FAME) for biodiesel from waste fats and oils with only a small percentage from agricultural and forestry by-products such as tall oil and cellulosic feedstock oils (EurObserv'ER 2021). The blending of conventional biofuels is estimated at around 4%, well below the 7% cap set by the ILUC Directive (EP 2015) and RED II (EP 2018) while blending of advanced biofuels is estimated at 1.2% (Panoutsou et al. 2021).

Biodiesel production in the EU is dominated by only five Member States: Germany, France, Italy, Spain and the Netherlands (van Grinsven et al. 2020)

Vegetable oils (rapeseed, palm oil, soy) make for almost 80% of the feedstock used in EU For biodiesel production. Rapeseed oil has the largest share (36%), followed by palm oil (30%), which is mainly used for biodiesel production, with a 58% share of its EU imports dedicated to that, and soy (7%). Spain was the largest producer of palm oil biodiesel in 2020 (using 1.7 Mt), closely followed by the Netherlands (1.5Mt) and Italy (1.4 Mt). Moreover, in 2020 the EU consumed 2.6 Mt of used cooking oil (UCO) for biodiesel production, of which around 73% was imported from third countries, and 0,7 Mt of animal fats, with a 30% increase from 2019. Currently, the nominal capacity of FAME and HVO production are 20.3 Mt and 5.1 Mt respectively (Rangaraju 2021). Figure 38 below summarizes the EU27 biofuels consumption levels and the support from the various feedstock involved.

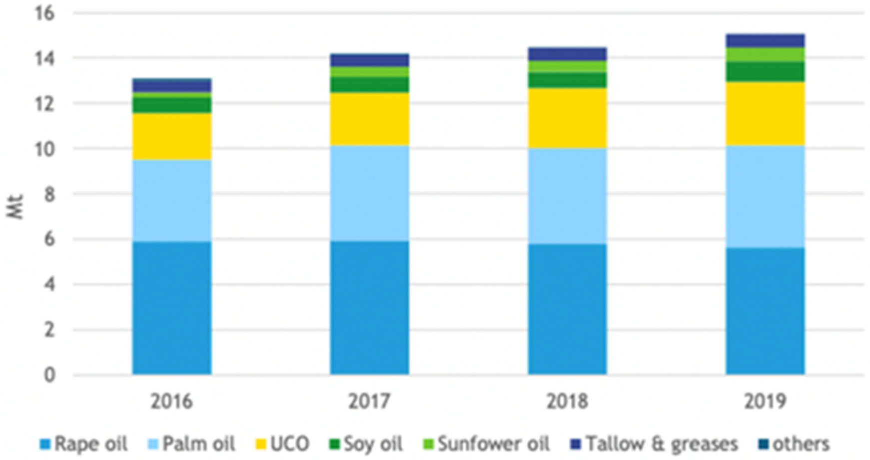

Figure 38: EU27 Biodiesel production and feedstocks shares (van Grinsven et al. 2020)

Worldwide, UCO is a relatively minor feedstock for biodiesel, be it FAME or HVO, accounting for 11% of global biodiesel consumption in 2019, mainly due to the US and EU. More important feedstocks are the various types of vegetable oil, such as palm oil, with 38.5% share, soy oil, with 25% share and rapeseed, with 14% share, of which 85% EU, all evaluated in 2019 (Bockey 2019).

UCO was priced at 885 USD/t in December 2021 and its price is growing, reaching an all-time high at 1,015 USD/t in February 2022 (ARGUS 2022). Similar trends are reported for Palm oil and Rapeseed oil, as shown in Figure 39: Rapeseed oil and palm oil price historical trends over the last three years (USD/t) below (Neste 2022).

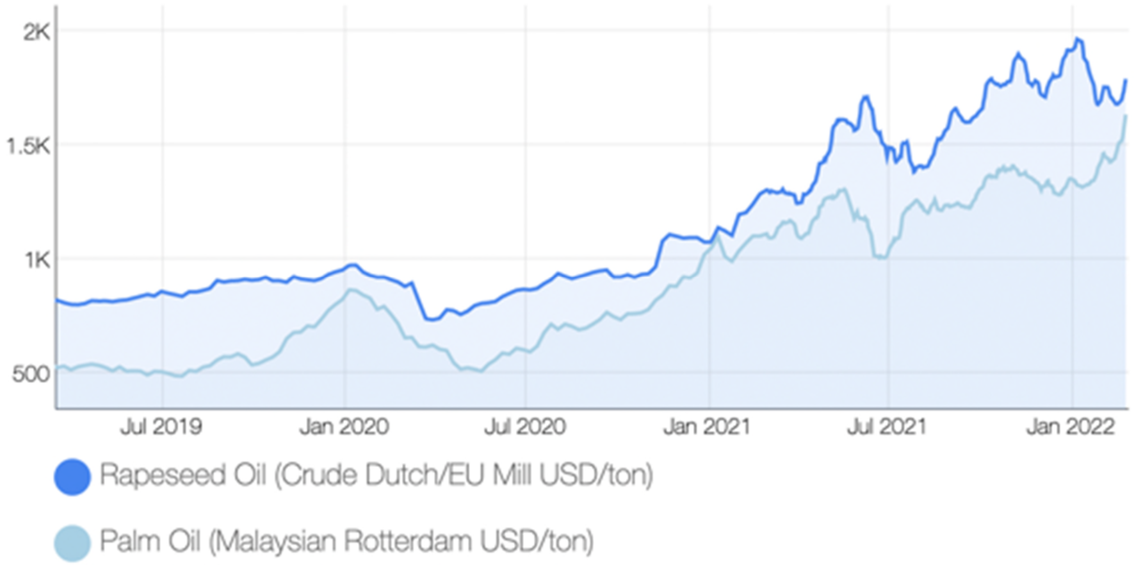

Figure 39: Rapeseed oil and palm oil price historical trends over the last three years (USD/t)

5.4.2 European-level policies

The Recast of the RED - usually referred to as REDII - was adopted in December 2018 (EP 2018) setting a new overall EU target for renewable energy consumption by 2030, and including subtarget for the transport sector. Transport is expected to operate with renewable energies for a minimum of 14% in road and rail transport by 2030; for the very first time, REDII contains measures to stimulate biofuels uptake also in maritime and aviation.

Within REDII 14 % RES-T target, over the 2020-2030 period there is a gradually increasing subtarget for biofuels produced from advanced feedstocks, as listed in REDII Annex IX, Part A. A minimum of 0.2% of transport energy is due by 2022, 1 % in 2025, and at least 3.5 % by 2030. Member States can double-count advanced biofuels towards both the 3.5 % target (thus 1.75 % actual volume) and the 14 % target. Other non-food/feed competing biofuels (listed in REDII Annex IX, Part B - e.g., used cooking oil and animal fat) can also be double-counted towards the 14 % target but are capped at 1.7 % in 2030 and are not eligible towards Advanced Biofuels obligations.

It is worth to remark that mandates in REDII are thus set for road transport only, while no obligations are set for aviation and maritime. Nevertheless, before the COVID-19 crisis, several MSs started to consider the possibility to implement mandates also for air transport: as an example, Norway announced that, starting from 2020, all jet fuel sold in the country have to contain a minimum 0.5 % content of advanced biofuels. Spain, in its new climate change law to come into force in 2025, is going to include a 2 % biofuel blending mandate for aviation; France is also developing a similar proposition. If confirmed in the coming years, this trend in policy will modify the existing market for sustainable feedstocks, in particular with regards to residual lipids, the reference sources for the major SAF route currently available in the market (HEFA biojet) (Chiaramonti et al. 2021).

In March 2019, the EU adopted a delegated act that defines palm oil as a high-ILUC risk feedstock (European Commission 2019). As a result of this definition consumption of biofuels based on palm oil should be frozen at 2019 consumption levels until 2023 and gradually phased out by 2030; Member States can set more stringent requirements for the phase-out, if willing to. Currently, and especially in relation to the use of UCO, the question is what consequences the phase- out of high-ILUC palm oil will have, in terms of what feedstock will be used to replace it. Phasing out of palm oil, which is the cheapest feedstock, might lead to a shift to other non-EU vegetable oil feedstocks. Whether or not this will boost consumption of advanced biofuels strongly depends on developments in production facilities, both technologically and in terms of cost.

Several options for scenarios related to this phase-out can be identified:

- Increase in other food-based feedstocks under the food and feed biofuels cap (2020 consumption, with a maximum of 7%);
- Increase in low-ILUC certified biofuels (that could also be sustainable palm oil);
- Increase in UCO consumption (considering the 1.7% cap, and the lower availability);
- Increase in advanced biofuels production from feedstocks listed under Annex IX A.
- Increase in other renewable energy sources, such as renewable electricity.

On July 14th, 2021, the European Commission adopted the Fit for 55 package, containing:

- 8 revisions of existing legislation
- new legislation proposals

A RED II amendment has been proposed, with a new 40% overall RES 2030 target; moreover, it contains a proposal for double-counting removal for Adv. Biofuels, together with an increased subtarget: from at least 0.2 % in 2022 to 0.5% in 2025 and 2.2 % in 2030.

A new 2.6% sub-target for RFNBOs in 2030 has been proposed, together with further rules set on the sourcing of bioenergy, including to “minimise” the use of “quality roundwood” for energy production (a Delegated Act is expected to cover this topic). Under the REFuelEU proposal, SAF blending mandates have been proposed, together with specific ramp-up trajectories (see Figure 40). Such trajectories have to be fulfilled with biofuels from Annex IX part A & B feedstocks and RFNBO, using production process pathways already ASTM certified.

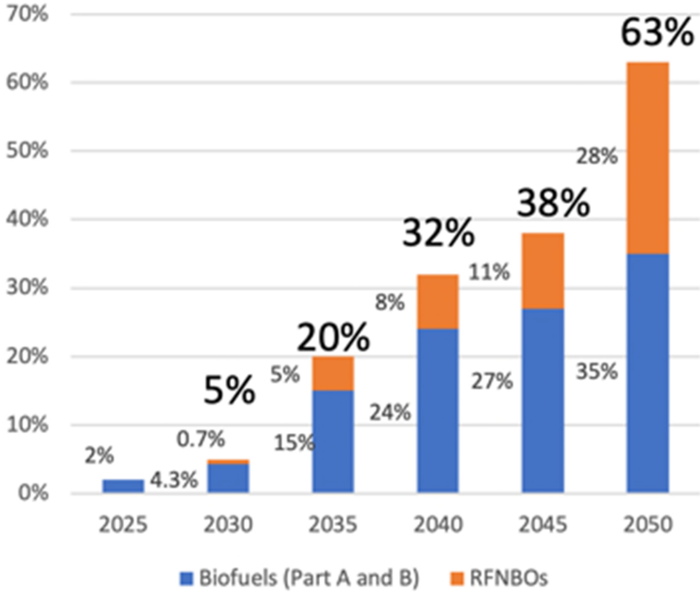

Figure 40: Proposed SAF blending mandates trajectories in REFuelEU

5.4.3 Italian case study policies and incentives in place

In 2006, the mandatory biofuels quota "obbligo di immissione in consumo" or Obligation to put into market was introduced to reduce CO_2 emissions in the transport sector. The obligated party are all subjects that feed gasoline or diesel for consumption in the system. This scheme defines the share of biofuels that fossil transport fuel suppliers need to include in their supply to the transport sector. Since 2018 transport fuel suppliers are requested to not only fulfil a general biofuel quota but also a quota of advanced biofuel. The quota is calculated using the trajectories defined in Art.11.1 of M.D. 02.03.2018 (MiSe 2018). For the time period from 2015-2022 the following quotas are foreseen:

- 2015: 5% biofuels, of which 0% advanced biofuels
- 2016: 5.5% biofuels, of which 0% advanced biofuels
- 2017: 6.5 % biofuels, of which 0% advanced biofuels
- 2018: 7% biofuels, of which 0,6% advanced biofuels
- 2019: 8% biofuels, of which 0,8% advanced biofuels
- 2020: 9% biofuels 2019: 8% biofuels, of which at least 0,9% of advanced biofuels
- 2021: 9% biofuels, of which at least 1,5% of advanced biofuels
- From 2022 on: 9% biofuels, of which 1,85% of advanced biofuels

More specifically, the quota for advanced biofuels is divided into two sub-categories, where advanced biomethane is accounted for 75% and other advanced biofuels for 25%. The respect of the quotas is monitored through a certificates system, and the amount for non-compliance with the obligation is fixed 750€ per certificate (Art. 1.2 M.D. 20.01.2015 [50]). Such certificates are the so-called "Certificates of release for consumption" or Certificati di Immissione in Consumo (CIC) in Italian. Every CIC corresponds to 10 Gcal of biofuels produced using conventional feedstock, or to 5 Gcal when advanced feedstocks are used, as defined by Article 5 of M.D. 02/03/2018 (MiSe 2018).

CIC are tradable on the market or can be gave back to the authority, in the latter case their value is set at 375 €. Such incentive has its duration set at 10 years, then other normative frameworks entry into force. Transport fuels suppliers are anyhow still obliged to purchase CIC certificates up to fulfilment of their mandatory quota of conventional and advanced biofuels to be put into market, in case they couldn't reach it.

Since MO is an IBC, CIC cannot be directly addressed to its production; instead, they have to be related to the production of the (advanced) biofuel that is put into market. In our case we considered HVO-diesel. Considering a LHV of 10.33 MWh/t for MO and 12.33 MWh/t for HVO and considering a conversion yield from MO to HVO of 96.7% on energy basis (around 81% on mass basis [51]), the 375 €/CIC becomes respectively 646 €/t MO and 779 €/t HVO.

5.4.4 Other possible uses of M.O.

As reported in section 5.2.1, many types of Single Cell Organisms are used for MO production, and each has a different output composition. Biofuels production is only one of the possible applications; basically, MO could replace vegetable oils in many industrial applications. Specific SCO could also be exploited for food applications, where MO could be seen as a valuable feedstocks, when it contains essential FAs (EFAs) (Rude and Schirmer 2009). Important EFAs include gamma linoleic acid (GLA), eicosapentaenoic acid (EPA), arachidonic acid (ARA), and docosahexaenoic acid (DHA). Poly-Unsaturated Fatty Acids (PUFAs) of the ω-3 and ω-6 families are essential for maintaining many functions in humans; oleaginous microorganisms can provide an alternative and economically feasible source of PUFAs, provided that most of the PUFAs occur in TGAs which is the preferred form to take lipids within the diet.

C3 commodity chemicals, currently produced from propylene in petrochemical processes, could have glycerol, produced as a by-product during lipid processing, as an alternative feedstock (Valdés, Mendonça, and Aggelis 2020; Subramaniam et al. 2010; Kosa and Ragauskas 2011; Jin et al. 2015). Fatty alcohols are used as feedstocks for the synthesis of antifoaming agents, cosmetics, detergents, pharmaceutical, surfactants and toiletries within the oleochemical industry. MO free fatty acids can be converted into various oleochemicals through a chemical process, i.e., through ozonolysis, monounsaturated free fatty acids can be converted into dicarboxylic acid, the intermediate for the formation of polyester and polyamide. Moreover, saturated free fatty acids can be utilized for the production of linear ω-unsaturated free fatty acids through steam cracking; then, the unsaturated fatty acids could further be used with alkanes for polyolefins synthesis. PUFA-rich oil can be utilized for the synthesis of epoxidized free fatty acid, which can be further used as UV-curable coatings and PVC stabilizers (Ahmad et al. 2019; Probst et al. 2015).

5.4.5 Lignin alternative markets and market prices

Coproduct generation in a lignocellulosic MO biorefinery is important, to try offsetting the processing cost of biofuels. Usually, lignin is intended to be burned, in order to supply energy for the SCO biorefinery. However, there is more scope for lignin to be valorised into fuels and chemicals, that can generate additional revenue for the biorefinery (Zakzeski et al. 2010). Opportunities that arise from the possible use of lignin fit into three categories (Holladay et al. 2007):

- **Power, fuel and syngas**, where lignin is used purely as a carbon source and aggressive means are employed to break down its polymeric structure (generally near-term opportunities)
- **Macromolecules**, where advantage of the macromolecular structure imparted by nature is retained in high-molecular weight applications (generally medium-term opportunities)
- **Aromatics and miscellaneous monomers**, where technologies are employed that would break up lignin's macromolecular structure but maintain the aromatic nature of the building block molecules (long-term opportunities)

The main products targeted to date are reported by to include:

- **Vanillin and vanillic acid:** Actually 80% of vanillin is produced from crude oil, and the remaining 20% from lignin. Vanillin from lignin and crude oil have similar prices and on the market their value is reported to be approximately 12 kUSD/t. As a comparison, natural vanillin price sets around 600 kUSD/t (Jablonsky et al. 2015).
- **Phenols:** important in plastics production and other materials. Main applications of phenols are in production of phenol-formaldehyde resins, polyurethane foams or polyurethanes for automobile industry. Today market value of phenol is approximately 1– 2 kUSD/t (Jablonsky et al. 2015).
- **Adsorbent:** Lignin has potential to adsorb heavy metals ions. Lignin’s adsorption has been studied against chromium, cadmium, lead, zinc, nickel, mercury and cobalt.
- **Activated carbons:** great adsorbents of organic and inorganic substances. Activated carbon used for water purification has price around 1,500 USD/t and can rise up to 2,500 USD/t

The multiple end products considered reflect the complexity of the starting material and its potential value in many applications. A broad range of conversion strategies and product targets are evaluated, with both physicochemical and biological pathways represented, including electrochemical approaches, improved and low-cost oxidation catalysts and engineered microorganisms with ability to funnel useable lignin monomers to specific chemicals (DOE and Office 2019).

One of the most rewarding - but also one the main challenge - in lignin application lies within high-value chemicals, such as benzene, toluene, and xylene (BTX) and phenols. The annual demand of BTX exceeds 100 million tons, and the average price for BTX is around 1,200 USD/t.

Phenols are another kind of important platform chemical in industry, which are of particular interest that can be produced from lignin. Current phenol production volumes amount to 8 million tons per year. Phenol market value is around 1,500 USD/t. It is also very promising to convert lignin to value-added materials, including carbon fiber, activated carbon, and composite materials (Liu, Jiang, and Yu 2015; H. Wang et al. 2019).

Price range for lignin starts with low purity lignin, with wide range 50-300 USD/t, and is closed with high purity lignin, which price can go up to 750-1,030 USD/t (Jablonsky et al. 2015; Poveda-Giraldo, Solarte-Toro, and Alzate 2021). Low purity lignin is reported to be used for Vanillin and Vanillic acid production, while high-grade lignin is used for BTX production (Poveda-Giraldo, Solarte-Toro, and Alzate 2021). Lignin obtained from enzymatic hydrolysis processes is expected to have lower level of purity (H. Wang et al. 2019).

5.5 Biomass supply chain

The IBC plants considered for the Italian strategic case study, for both the centralized and decentralized scenarios, are modelled to be deployed in two radically different regions of Italy: Veneto, one of the most rich, productive and developed in Europe, with high GDP and capillary transport infrastructures, surrounded by regions with similar features; Sicily, on the other side, is having poorly developed road and railway systems, and a below the average GDP on European scale. The first part of this section reports a brief overview of both areas, regarding agricultural sector and logistics infrastructures. Then, an overview of the overall value chain is provided, together with high-level information on the model developed for agricultural residues availability calculation. A detailed report on the methodology for optimal IBC plant location for the decentralized scenario is provided in the following section. The next two sections then summarize the hypothesis on biomass and logistics and report information on the related costs. Finally, the total biomass cost is calculated for the two subcases.

5.5.1 Porto Marghera subcase

The Veneto region alone holds the 10% share of the value of Italian agricultural production, after Lombardy and Emilia-Romagna, and its agriculture is specialized in some important sectors such as industrial crops, viticulture and meat livestock. The area considered in the Porto Marghera subcase thus represents about 20% of the total Italian agricultural production and is strongly characterized by cereal and industrial cultivation.

The profitability of the agricultural activity is strongly linked to the price trend of agricultural products and to the costs of production. This is particularly remarkable for cereal and industrial crops, which are more exposed to stock changes in the global market, while high value and cash crops are able to keep sales prices, thus less affected by the increase in production costs.

The areas that could be potentially cultivated for biomass production are increasing, but since the use of crop residues is currently still limited, there is no real incentive to increase the cultivation of industrial and biomass crops. At present, as far as tree crops are concerned, crop residues are generally buried (grapevine) or burned (olive tree), where it is still allowed. Currently, farmers burning crop residues (stubble, sarments, mowing or pruning) in the fields for the sole purpose of discarding them, to avoid more costly but legal methods, could be considered as pursuing an illegal waste management activity, which can be persecuted as article 256 of Italian Legislative Decree 152/2006. An exception could be a technically proven burning due, for example, to phytosanitary needs, even though local norms might explicitly forbid even these practices to limit particulate air pollution.

In recent years the cultivated areas have decreased, due both to the lower profitability and to the lower availability of agricultural manpower, with a subsequent, progressive increase of the uncultivated areas. On the other hand, the employment rate in farms cultivating high-value crops remains constant. However, the increase in marginal areas did not produce substantial changes in the distribution pattern of cultivated crops.

As regards the cultivation for the production of biomass, crops such as Arundo Donax, which have significant potential, are still perceived by farmers as weeds, thus more as a problem to be solved, than an opportunity. Thus, further studies will need to design and analyse scenarios that include the low social acceptability linked to the cultivation of marginal land with crops such as Arundo. The biomass prices were acquired either through market quotations for crop residues from cereals and wood chips for woody crops or based on quotations from sector studies for residues from crops such as maize, for which there is still no market consolidated.

Infrastructures

The road system of the Porto Marghera subcase area has good infrastructures for the circulation of heavy vehicles, with fast-flowing roads (for example about 400 km of motorways and 9,500 km of state and provincial roads in the Veneto Region, which is 18,345 square kilometers wide, which is about the 80% of the subcase total area). The cost of transport is thus relatively lower than in the Gela subcase, due to the shorter time required to move the biomass.
The transport costs were acquired from the price lists of the contractors for the transport of biomass (either bulk or round bales).

5.5.2 Gela subcase

The Sicily region coincides with the total area of the Gela subcase, and in recent years experienced deep structural changes in the primary sector: the total Utilized Agricultural Area (UAA) and the number of farms is significantly lower compared to the beginning of 2000. Today there are 219,680 farms in Sicily (13.6% of the total Italian farms) with an average size of 6.3 hectares, with approximately 1,387,520 hectares of UAA. However, it should be mentioned that more than 50% of the farms have an area smaller than 2 hectares. The most important agricultural productions in the region are the following: table grapes, pistachios, hazelnuts, almonds, citrus fruits, peaches, olives and olive oil, wine and cereals. The presence of several quality products (DOP - Designation of Origin / IGT - typical geographical indication and organic) is a remarkable strength of the regional agricultural sector.

The geographical location (the south of Italy suffers from water scarcity), combined with the lack of inefficient infrastructures for water distribution, hampers the cultivation of crops for biomass, and thus the use of crop residues from cereals; moreover, it has a negative impact also on the presence of tree crops such as vines and olive trees.

The fate of tree crops residues is generally the same as described in Porto Marghera subcase. However, it should be mentioned that in Sicily the fires risk is significantly higher due to droughts and water scarcity, therefore the practice of burning the residues is even more limited. As already mentioned for the other subcase, in Sicily also there has been a progressive abandonment of cultivated areas, both due to lower profitability and a constant demographic decline in rural areas.

Infrastructures

The regional road network is quite lacking and would significantly slow down the transport of biomass, mostly concentrated in the coastal part. The motorway network is limited to the connections of the most populous cities, and the road network, in poor conditions, consists of about 700 km of motorways and 3,500 km of state roads on a total area of 25,711 square kilometers.

5.5.3 The supply chain modelling

The Italian Strategic Case Study relies on ligno-cellulosic agro-residues such as olive and grapevine pruning, herbaceous agro-residues and energy crops, cultivated on marginal lands, such as *Arundo donax*. 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 *smells*, see Figure 16 below) representing (i) each soil type available in (ii) each climate cell (12km x 12km) within (iii) each province. The number of the simcells (2,177 for the Porto Marghera subcase, 617 for the Gela one) can be derived by the following formula:

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

Each of the 41,397 *single cells* (23,316 for Porto Marghera, 18,081 for Gela) was associated with the relevant simcell on the basis of the *meteo cell* and soil.

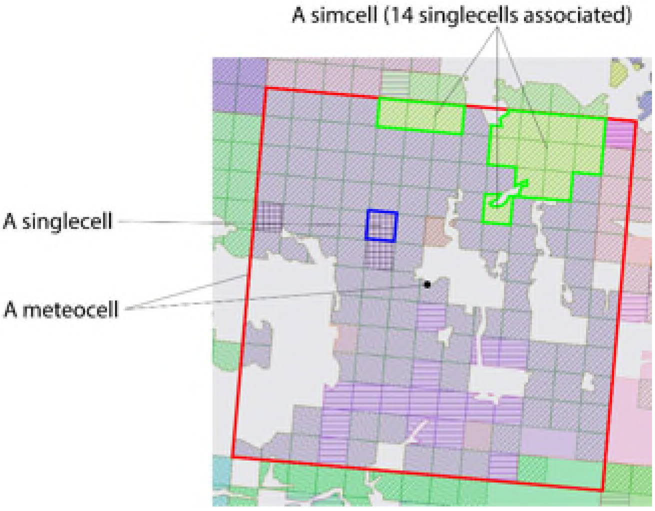

Figure 41: Meteo cells, simcells and single cells. Please notice that the purple simcell includes single cells with marginal land, arable land, olive groves and vineyards.

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. For the choice of the crops to be simulated in the INFER-NRG model as biomass supply for the IBC plants, we first selected, from the ISTAT dataset, the most cultivated ones in terms of area within each territory, filtering out those that cannot be reliably simulated with well-known and tested crop growth simulation. Then, we analysed, for each territory and selected crop, the suitability in a climate change perspective, within a scenario where the IBC plants are actually purchasing agro-residues. For example, grapevine and olive trees are among the most typical and traditional cultivations of Italy, and the Mediterranean, and they are part of traditional, well-established, and protected agricultural food chains, namely the ones producing wine and olive oil, which are not likely to disappear in the mid-term, even within climate change scenarios. Finally, we excluded the forage compartment, because of the lower woody content and efficiency, if compared with alternative crops, such as *Arundo donax*.

As a result, several crops and fruit trees were not considered in this study (e.g., orange production in Sicily) due to several reasons: first, we decided to include those crops that robust scientific literature proved simulation models are capable of faithfully reproduce in different climate scenarios. Second, we decided for a precautionary approach, which means that not all farmers could be willing to be involved in the studied residues supply chain, and therefore the total biomass of the present study is a smaller sub-section of the total potential biomass. Third, some agricultural compartments, such as the fruit production one, are still strongly affected by market prices fluctuations, which means that in some year farmers must significantly reduce their managements costs (e.g., pruning). However, it should be considered that, once in place, such a supply chain could significantly impact the market and the agricultural sector, stimulating more and more farmers to sell their residues, even if some initial investment could be required (e.g., purchase of shredding equipment). Furthermore, new laws, such as the recent one limiting or preventing the burning of the residues for environmental (air quality) or safety (fires) reasons, could also boosting the agricultural residues supply chain.

It should be mentioned that we intentionally, partially postponed some of the pruning operations on grapevine based on a recent trend, implemented by more and more farmers to delay the bud break. As a matter of facts, late frosts events are killing the buds, reducing grape production even by 70% in worst cases, and in a climate change perspective, the increase of these events is likely to continue. The use of maize residues for biofuels is currently limited to technical experiments, since generally the residues are currently buried at the end of the season. Therefore, the prices were hypothesized by analysing the process and then confirmed by quotes from sector operators working in maize production areas.

Finally, Table 31 below reports the average residues and energy crops yields used in the model for all the successive calculations.

Table 31: Average agricultural residues yield in t/ha/a in the two regional subcases for the two main climate scenarios

	Porto Marghera		**Gela**	
	rcp45	**rcp85**	**rcp45**	**rcp85**
Arundo Donax	75.38	82.03	63.40	74.38
Wheat	3.23	3.53	5.10	5.31

Maize	9.92	10.45	-	-
Barley	3.88	4.10	-	-
Rice	9.56	9.77	-	-
Sorghum	11.71	11.97	9.41	6.88
Triticale	6.02	6.55	5.59	6.72
Grapevine	1.91	2.04	1.31	1.29
Olive	-	-	2.31	2.34

5.5.4 IBC plant location optimization

In the decentralized scenarios, the IBC plants are deployed near to the biomass production areas, to take advantage of the densification obtained converting the starting biomass feedstock into the MO output (almost seven-fold) and optimize logistics costs. In order to locate the possible intermediate plants, first we extracted from the Corine Land Cover only the polygons (within both subcases) classified as industrial areas or other not-agricultural/not-urban/not-protected areas. Then, we selected only the polygons within a 5km radius from either highway exits or national roads and filtered out all polygons within a buffer of 5km from urban areas (Figure 42), so to simplify the hypothesis (the social acceptancy of the intermediate plant could be considered higher).

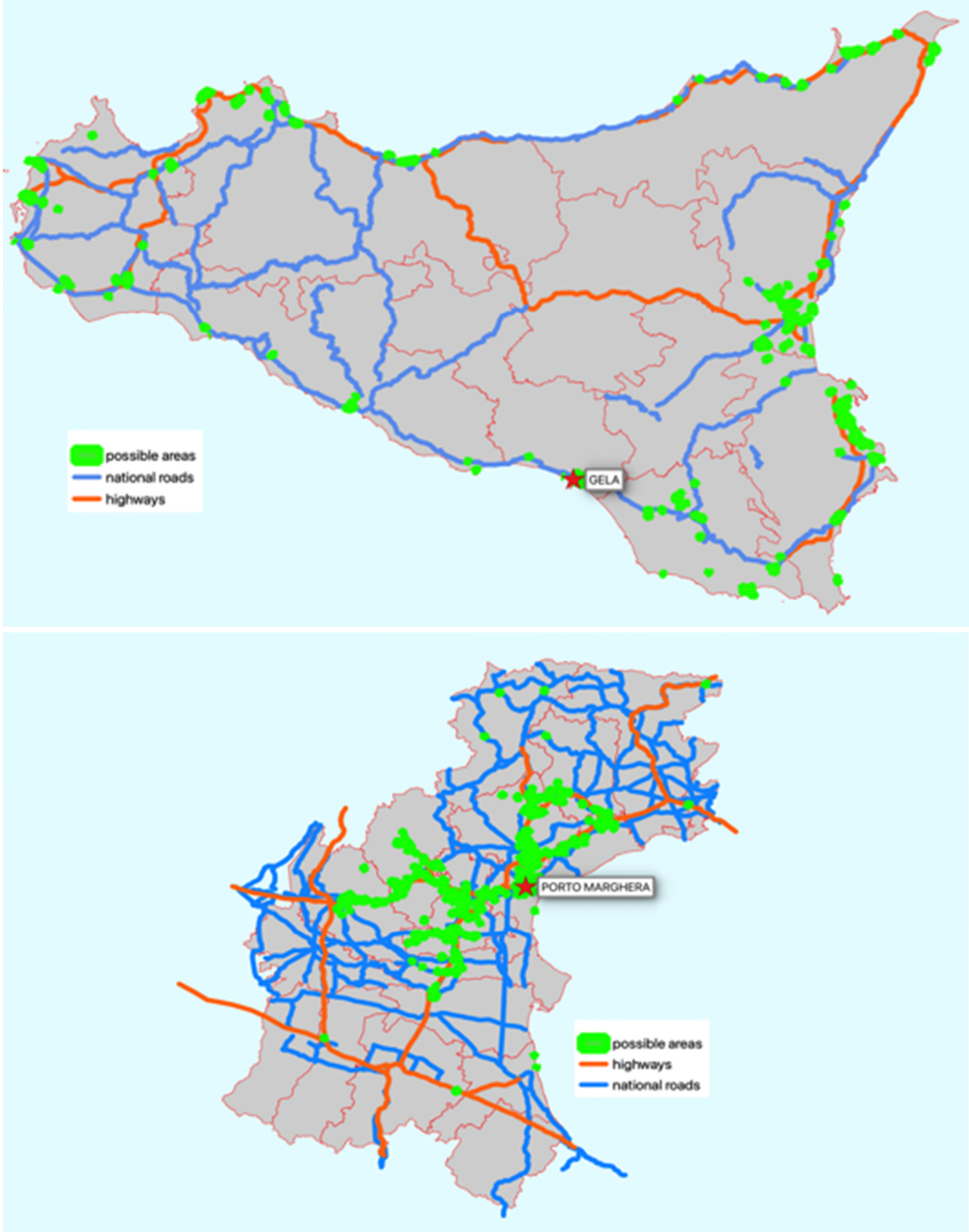

Figure 42: Possible areas and roads for Gela subcase (upper) and Porto Marghera subcase (lower)

Finally, we selected those areas surrounded by single cells that could provide residues in as many months as possible, so to minimize the inactivity of the plant and reduce/avoid the need of warehouses (Figure 43).

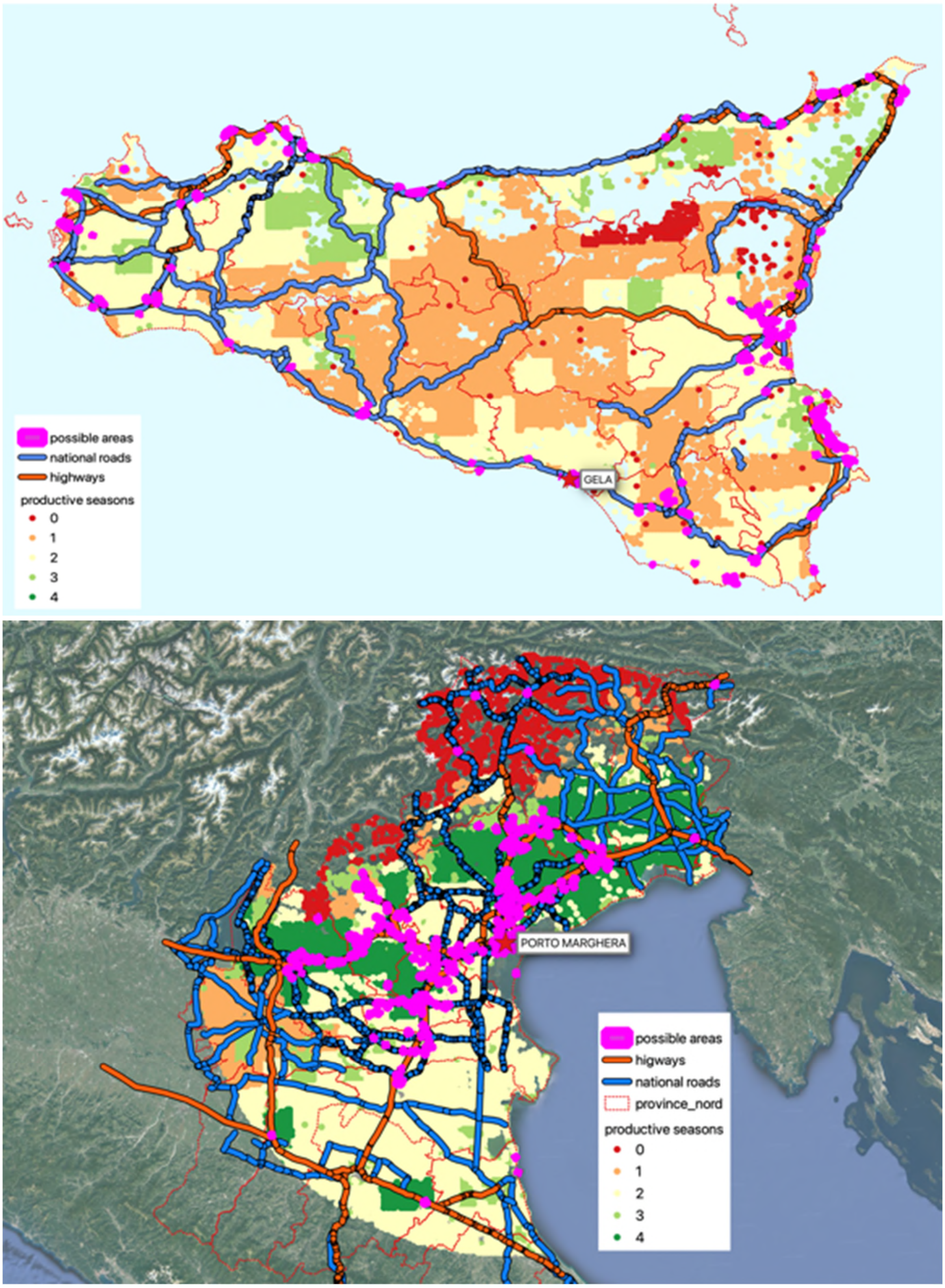

Figure 43: Possible areas, roads and number of productive seasons for Gela (upper) and Porto Marghera (lower)

Six intermediate plants were identified for the Gela subcase, namely (west to east) Castelvetrano, Ribera, Termini, Scicli, Sigonella and Siracusa. Given the wider territory, for the Porto

Marghera subcase we identified seven intermediate plants, namely (west to east) Modena, Verona, Ferrara Nord, Este, Imola, Portogruaro and Palmanova.

Subsequently, for both subcases, we obtained 271,698 directions, time of travel and distance from each singlecell to each intermediate plant (23,316 * 7 for Porto Marghera subcase, and 18,081 * 6 for the Gela one). We hypothesized a scenario with two intermediate plants for each subcase, pre-transforming half of the total biomass required by the main IBC plant into MO, and then sending the MO to the main IBC (with a 7/1 input/output biomass-to-MO ratio).
We calculated the biomass costs, using the same approach as for the centralized IBC plants, for each intermediate plant, and then we added, for each intermediate plant, the transport cost of the oil from to the main IBC, using standard tankers with a 30,000 liters capacity, corresponding to about 27,6 t of MO.

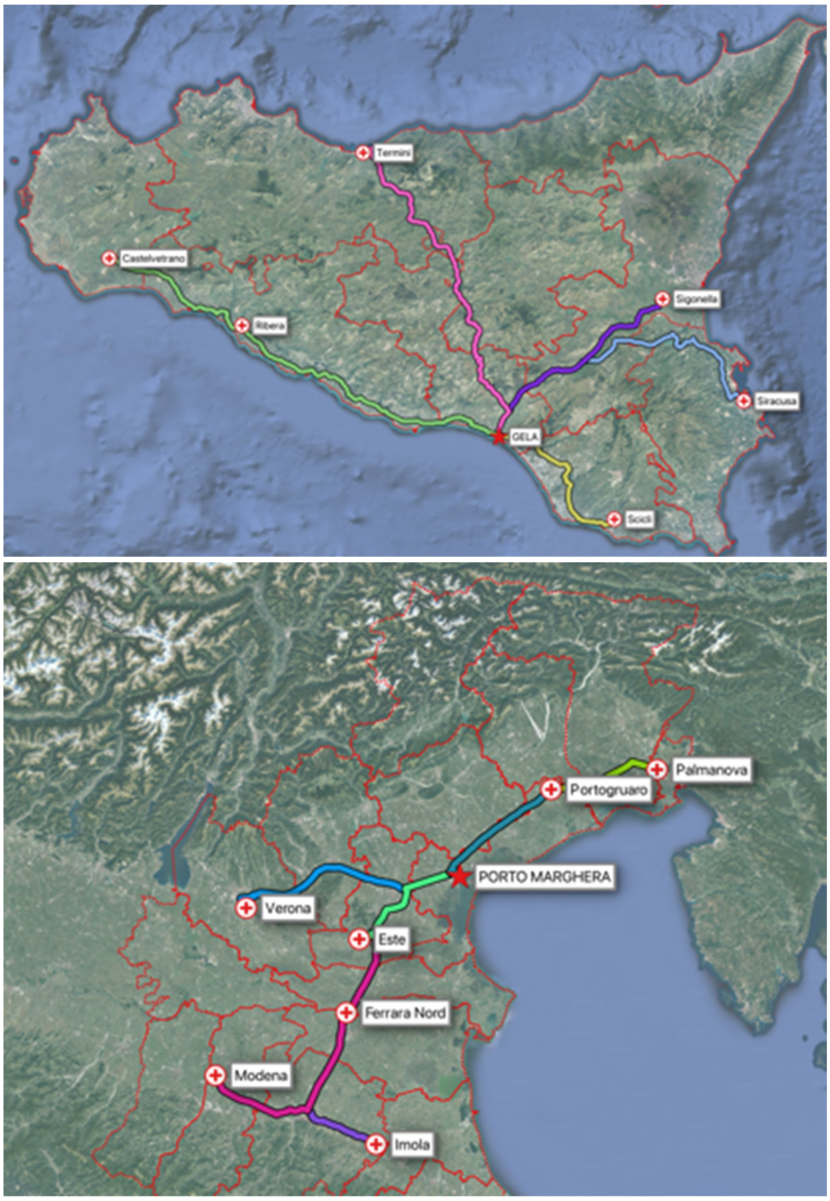

Figure 44: Decentralized IBC plants locations for Gela (upper) and Porto Marghera (lower) subcases, with relevant paths to the main bio-refineries

5.5.5 Biomass feedstocks availability and cost

As previously mentioned, the Italian Strategic Case Study relies on the use of ligno-cellulosic agro-residues such as olive and grapevine pruning, herbaceous agro-residues and 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's 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 wood logs 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 32 reports the average Moisture Content after harvesting for the various feedstocks (Mancini et al. 2008), while Table 33 reports their calendar availability

Table 32: Biomass feedstocks properties

#	Crop residues	Type	Moisture Content
G	Grapevine	Wood chips	40%
O	Olive		10%
S1	Wheat, triticale and barley	Straw (bales)	20%
S2	Rice		30%
SM	Sorghum and maize	Wood chips	66%
A	Arundo Donax		50%

Table 33:Biomass feedstock calendar availability for each subcase

	1	2	3	4	5	6	7	8	9	10	11	12
Porto Marghera												
S1					🟥	🟩	🟩	🟩				
S2					🟥			🟩	🟩	🟩	🟩	
SM					🟥			🟩	🟩	🟩	🟩	
G	🟪	🟪	🟪	🟪	🟥							
A	⬛				🟥						⬛	⬛
Gela												
S1						🟩	🟩	🟩				
SM								🟩	🟩	🟩	🟩	
O			🟧	🟧	🟧							
G	🟪	🟪										
A										⬛	⬛	⬛

The INFER-NRG model produced as an output a series of GIS-based maps reporting the monthly availability of each biomass type in the two subcase areas (see Figure 45). Such availability is included in a set of scenarios (see MUSIC 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 (Gela subcase only), 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).

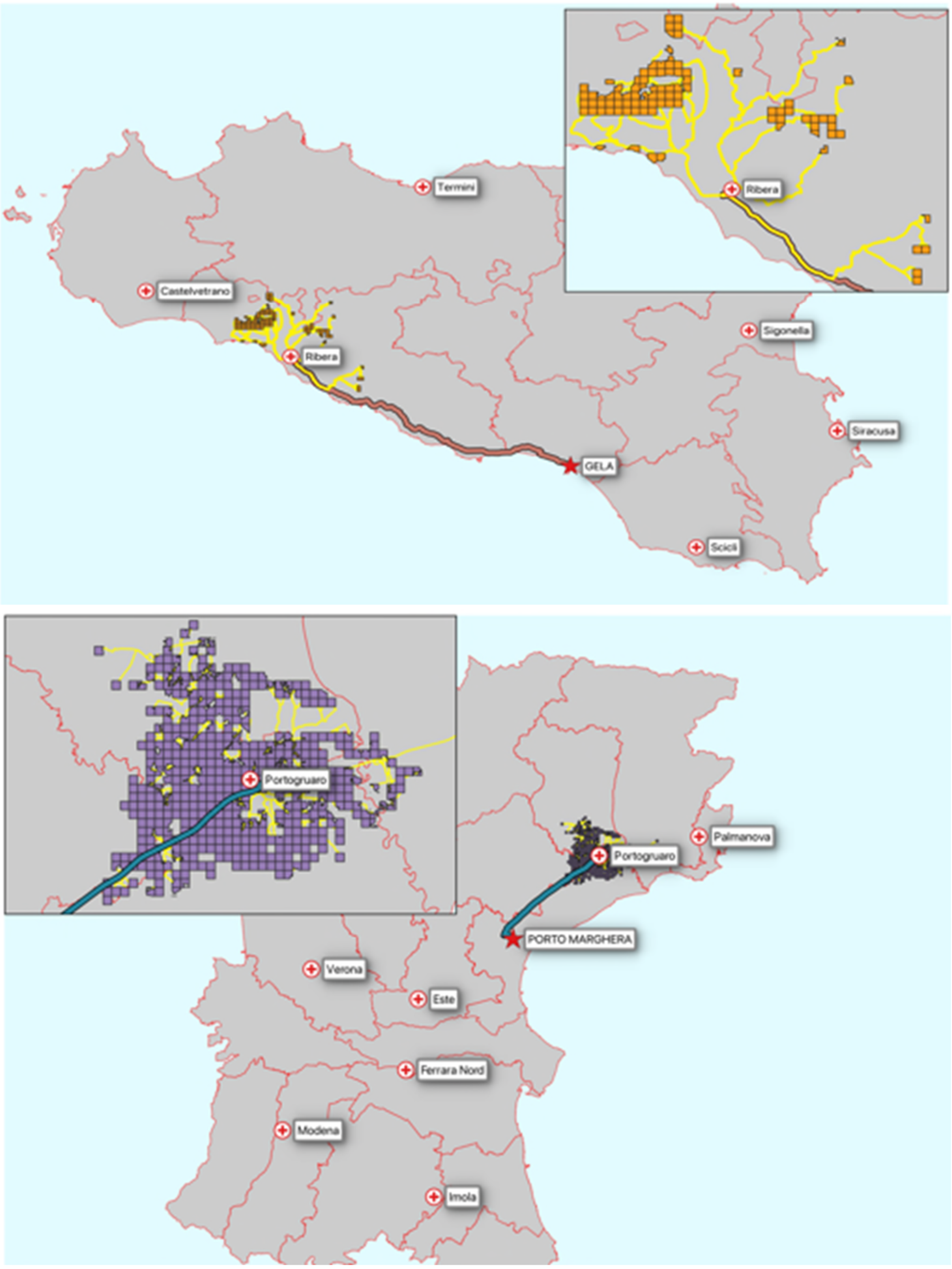

Figure 45: Single cells (orange) providing biomass to the intermediate plant in Ribera (yellow paths) from olive pruning in March, rcp85, subcase Gela (upper); single cells (purple) providing biomass to the intermediate plant in Portogruaro (yellow paths) from grapevine, subcase Porto Marghera

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 30 kt/month of dry biomass (therefore 15 kt/month for each plant of the decentralized scenario). 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., 30 kt/month for the main IBC, and 15 kt/month for each plant of the decentralized scenario). A higher threshold (45 kt/month for the centralized IBC, 22.5 kt/month for each plant of the decentralized scenario) has been successfully evaluated, as a safety measure to ensure a wider basin of availability in case of unfavorable events, such as reduced biomass availability. Figure 46 shows an example with minimum and safety supply areas, and road paths, for both subcases.

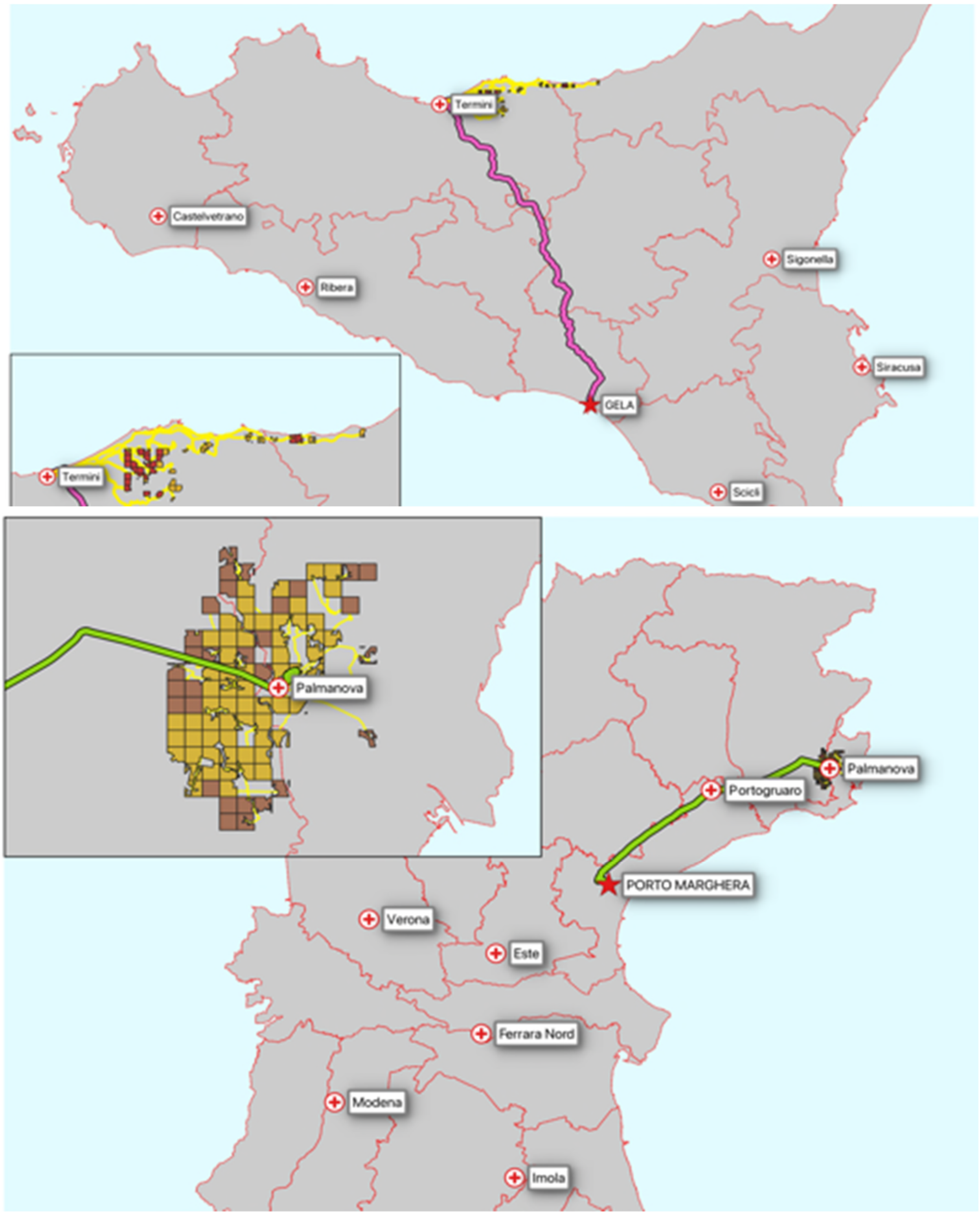

Figure 46: Minimum (red) and safety (pale brown + red) supply areas for Termini intermediate plant in August, RCP45 (upper), and minimum (pale brown) and safety (brown + pale brown) supply areas for Palmanova intermediate plant in July, RCP85 (lower)

Depending on the type of biomass available (see Table 33), the quantity of wet biomass needed to reach the monthly target varies. Table 34 and Table 35 below report the average yearly quantities for each biomass type (dry), respectively for Porto Marghera and Gela subcases, for each climate scenario.

Table 34: Average yearly quantities of produced biomass in the considered area of the Porto Marghera subcase, for both the centralized and decentralized scenario

PORTO MARGHERA (Centralized)							
scenario	Arundo	Wheat	Maize	Barley	Sorghum	Triticale	Grapevine
RCP45	196,678	41,615	165,421	71,798	136,414	144,876	225,216
RCP85	106,535	40,424	179,343	72,094	147,146	148,641	289,963
PORTO MARGHERA (Decentralized, average)							
scenario	Arundo	Wheat	Maize	Barley	Sorghum	Triticale	Grapevine
RCP45	81,163	75,345	89,954	32,897	61,749	70,744	130,762
RCP85	68,936	66,880	96,720	32,450	53,038	72,174	132,943

Table 35: Average yearly quantities of produced biomass in the considered area of the Geka subcase, for both the centralized and decentralized scenario

GELA (Centralized)						
scenario	Arundo	Wheat	Sorghum	Triticale	Grapevine	Olive Tree
RCP45	242,127	75,770	265,477	111,425	65,110	114,276
RCP85	511,853	79,395	271,242	109,539	63,950	115,855
GELA (Decentralized, average)						
scenario	Arundo	Wheat	Sorghum	Triticale	Grapevine	Olive Tree
RCP45	123,600	61,461	113,425	52,092	58,428	54,627
RCP85	122,021	46,370	72,963	55,711	57,666	55,351

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 (AIEL 2016).

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 36 summarizes the information.

Table 36: Biomass costs for the considered feedstock types (G: Grapevine, O: Olive, S1: Wheat, triticale and barley, S2: Rice, SM: Sorghum and maize, A: Arundo)

	G	O	A	S1, S2, SM
Fresh biomass price (market quotation)[8]	50* €/t	50* €/t	34** €/t	62* €/t

5.5.6 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. As best compromise between capacity, flexibility and representativeness we chose an 8 tons truck. Concerning the logistics for MO, standard tankers with a 30,000 l capacity were considered.

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.

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[8] * Based on prices of the Bologna Commodities exchange quotations for the North and Bari for the south of Italy (2021); ** Based on the estimated cost of production (Candolo, 2006)

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, we defined a cost of 50 €/hr for the loading, unloading and transport phases, using the 8 tons truck or the 30,000 l tankers.

Figure 47 below summarizes all the above-mentioned considerations, organizing them in successive logical steps.

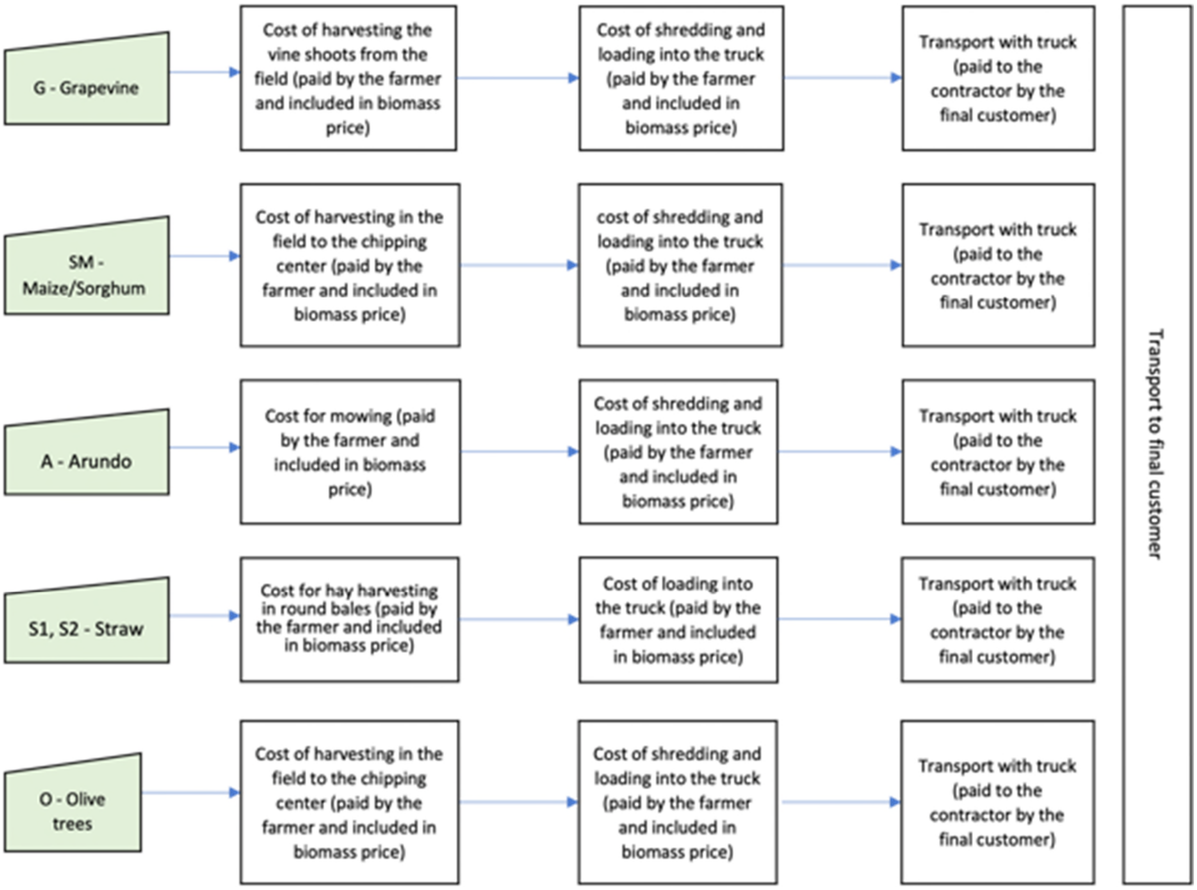

Figure 47: Pre-processing and logistics cost components based on crop types

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 48 reports the used iso-duration map; the solid line identifies the most used path, while the color scale represents the different travel times.

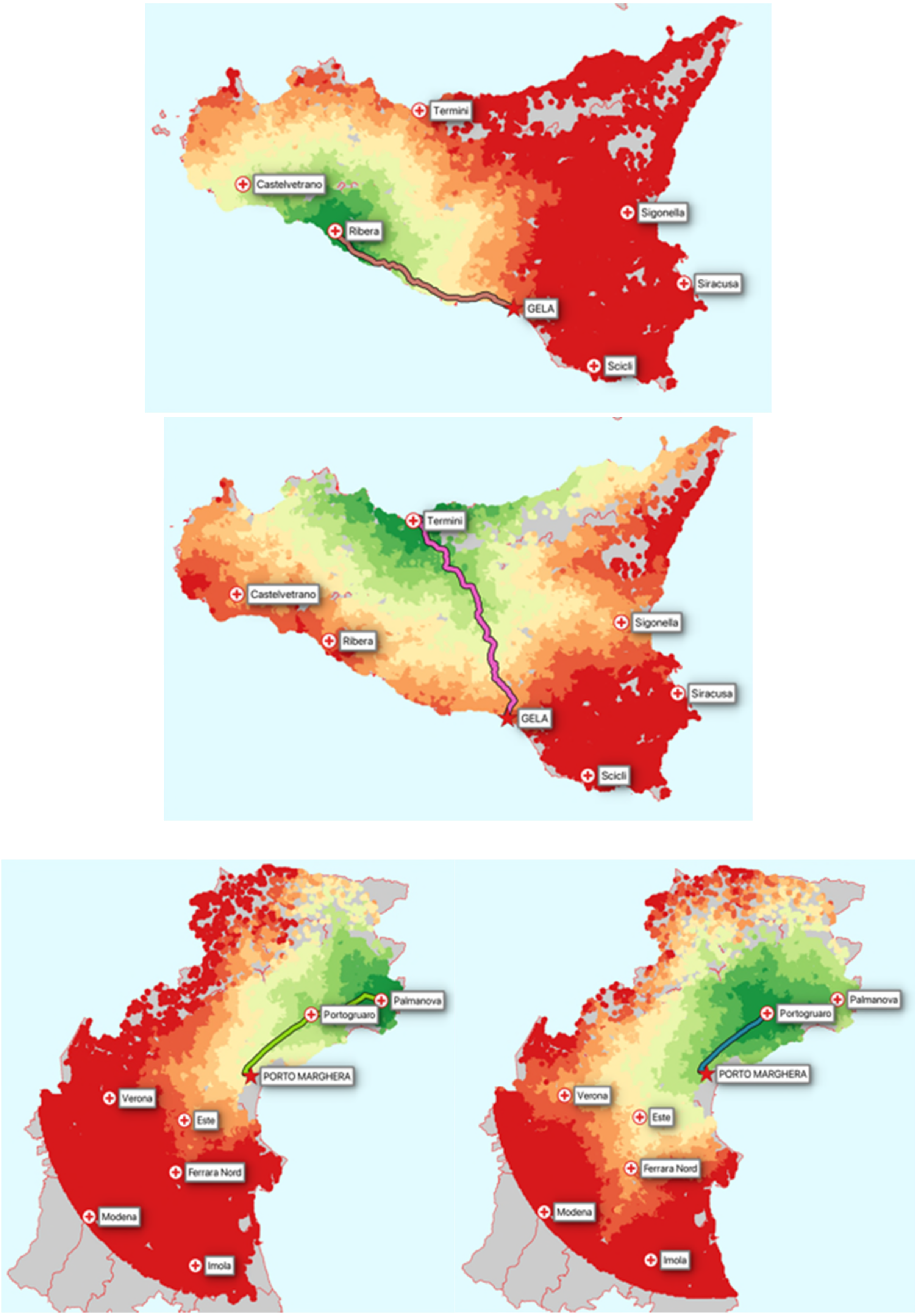

Figure 48: Trip duration from each singlecell to the selected intermediate plants. (green <= 30 minutes, red >= 2 hours and half; 15 minutes intervals).

5.5.7 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.

The total biomass cost value is made up by three different components:

- The **biomass feedstock cost**, as defined in Table 36
- The collection and **upstream logistics costs**, to transport the ligno-cellulosic biomass from the field to the IBC plant, be it centralized or decentralized
- The **downstream logistics costs** related to the transport of MO from the IBC plant to the biorefinery. Such costs are assumed not to occur in the centralized scenario, being the IBC plant in the same premises of the bio-refinery, and thus connected via pipeline.

Biomass feedstock costs are maintained constant across the scenarios, while upstream logistics costs could vary, since they are a function of the distance between each considered production cell and the IBC plant. Thus, depending on the cells productivity related to each climate scenario, there could be a variation in the number and geographical localization of the cells needed to produce sufficient input for the IBC plant. In turn, this have an impact on the number of travels needed to transfer biomass to the IBC plant, and on their duration and this finally converts into different logistics costs.

Finally, the downstream logistics costs are considered constant across all the scenarios, since the distance between each tentative decentralized IBC plant and the biorefinery is fixed as is the amount of MO monthly input. Figure 49 below reports the variability of the total biomass costs for the two subcases and the IBC location scenarios. It is immediately clear that the Porto Marghera subcase has quite lower prices for the biomass feedstock needed; moreover, it can be noticed that the overall price variability across the various climate scenarios is also much less pronounced.

Moreover, it emerges that in both the subcases, the decentralized scenario has an economic advantage in this area: in the northern subcase the centralized IBC plants has to pay almost 10% more for the biomass feedstock, when compared to the better decentralized solutions, and a similar situation is reported also for the southern subcase as well. Finally, the northern subcase shows great consistency across all the decentralized solutions, both in terms of average price and its variability across the climate scenarios. This situation cannot be found in the southern subcase, where the price variability is much higher as is the average price difference among the various solutions identified.

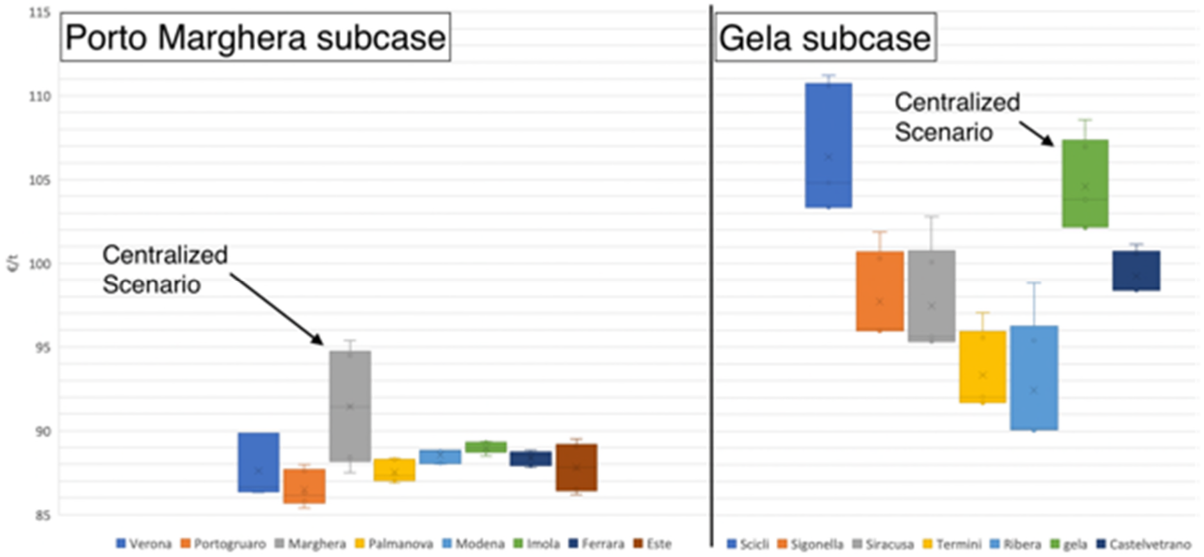

Figure 49: Boxplot graph reporting the variability of the total biomass cost as a function of the climate scenarios, for the two subcases and the two IBC location scenarios (centralized and decentralized)

Figure 50 below provides a possible explanation for the above-mentioned issue: it reports the variability of the share of total biomass costs related to the upstream transport and it can be noticed that it strictly resembles the overall total biomass cost variability. Thus, the higher variability of the southern subcase could be, for the most part, addressed to the lack of transport infrastructures that emphasizes in terms of costs the longer travels needed to gather enough biomass feedstock in the sub-optimal climate scenarios. This is less the case for the Porto Marghera subcase, given the better highway infrastructure of the area. It can be noticed as well how the centralized scenario suffers the most for this variability, independently of which subcase is considered. This is a direct consequence of the location constraint, not allowing for its geographical optimization with respect to the biomass production areas.

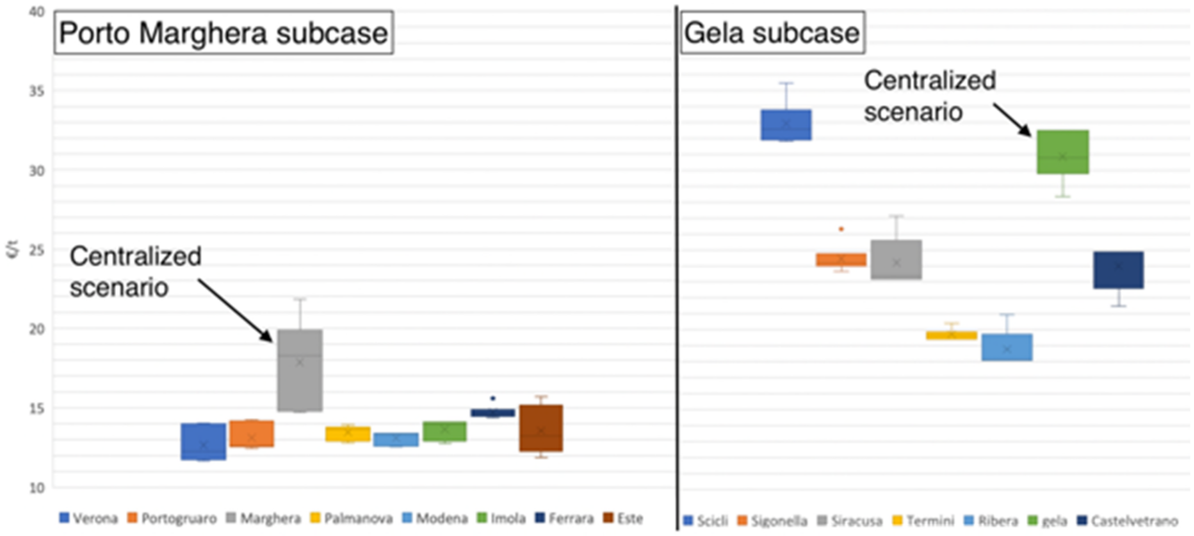

Figure 50: Boxplot graph reporting the variability of the biomass logistics costs as a function of the climate scenarios, for the two subcases and the two IBC location scenarios (centralized and decentralized)

Finally, it is worth pointing out that the MO transport phase from IBC plant to bio-refinery impacts for less than 2% of the total cost, ranging between 0.54 and 1.34 €/t for the northern subcase and between 0.8 and 1.84 €/t for the southern one.

5.6 Environmental assessment

The Strategic Case Study focuses on the production of 100 kt/yr. of Microbial Oil (MO) from biomass resources in 4 IBC plants (25 kt/yr. each) – 2 are located in the North (Veneto region) and 2 in the South (Sicily). The produced MO is either transported by trucks to biorefineries, in the Decentralized scenario, or by piping, which is the case of the Centralized scenario (where the IBC plants are deployed in the close proximity of the IBC plants) for further upgrade to an advanced biofuel (Figure 51).

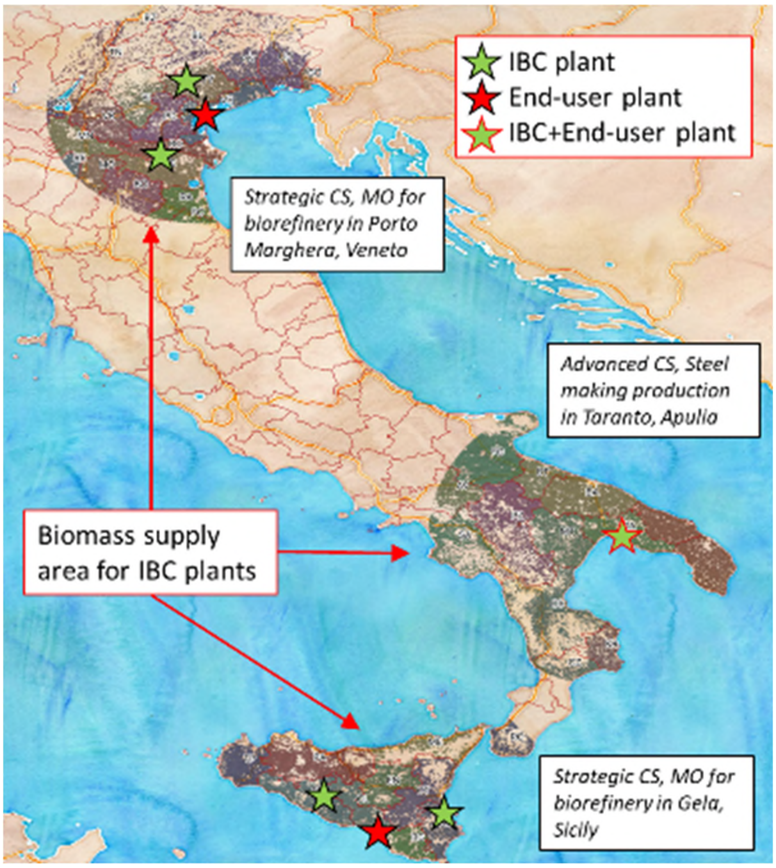

Figure 51. Map of Italy containing the position of the end-user plant (biorefinery) and the potential position of the IBC plants

The value chain concerning the production of MO, considers regionally available biomass, specifically, olive pruning, grapevine pruning, maize stalks, straws and Arundo. The needed biomass quantities are projected at local level, through GIS processing. A proper area is evaluated, on a monthly basis, with the target of providing 357 kt/yr. of dry biomass for the production of 50 kt/yr. of MO, in each biorefinery (Table 37).

Table 37. Available and used biomass, on a yearly basis, for the production of 50 kt/yr. of MO

Available biomass - Porto Marghera subcase (Average across scenarios)							
Scenario	Arundo	Wheat	Maize	Barley	Sorghum	Triticale	Grapevine
RCP45	81,163	75,345	89,954	32,897	61,749	70,744	130,762
RCP85	68,936	66,880	96,720	32,450	53,038	72,174	132,943
Available biomass - Gela Subcase (Average across scenarios)							
Scenario	Arundo	Wheat	Sorghum	Triticale	Grapevine	Olive Tree	-
RCP45	123,600	61,461	113,425	52,092	58,428	54,627	-
RCP85	122,021	46,370	72,963	55,711	57,666	55,351	-
Used biomass - Porto Marghera subcase (Average across scenarios)							
Scenario	Arundo	Wheat	Maize	Barley	Sorghum	Triticale	Grapevine
RCP45	53,399	49,571	59,183	21,644	40,626	46,544	86,032

RCP85	47,043	45,640	66,003	22,144	36,194	49,253	90,722
Used biomass - Gela Subcase (Average across scenarios)							
Scenario	Arundo	Wheat	Sorghum	Triticale	Grapevine	Olive Tree	-
RCP45	95,173	47,325	87,338	40,111	44,990	42,063	-
RCP85	106,226	40,368	63,518	48,500	50,202	48,186	-

The MO production process includes: (a) Pretreatment – deacetylation and dilute-acid pretreatment of biomass; (b) Enzymatic hydrolysis (saccharification) of the remaining cellulose; (c) Hydrolysate conditioning and bioconversion of the resulting hexose and pentose sugars to diesel-range fatty acids (MO). The process design also includes wastewater treatment (WWT), lignin and biogas combustion and required raw materials (Figure 52).

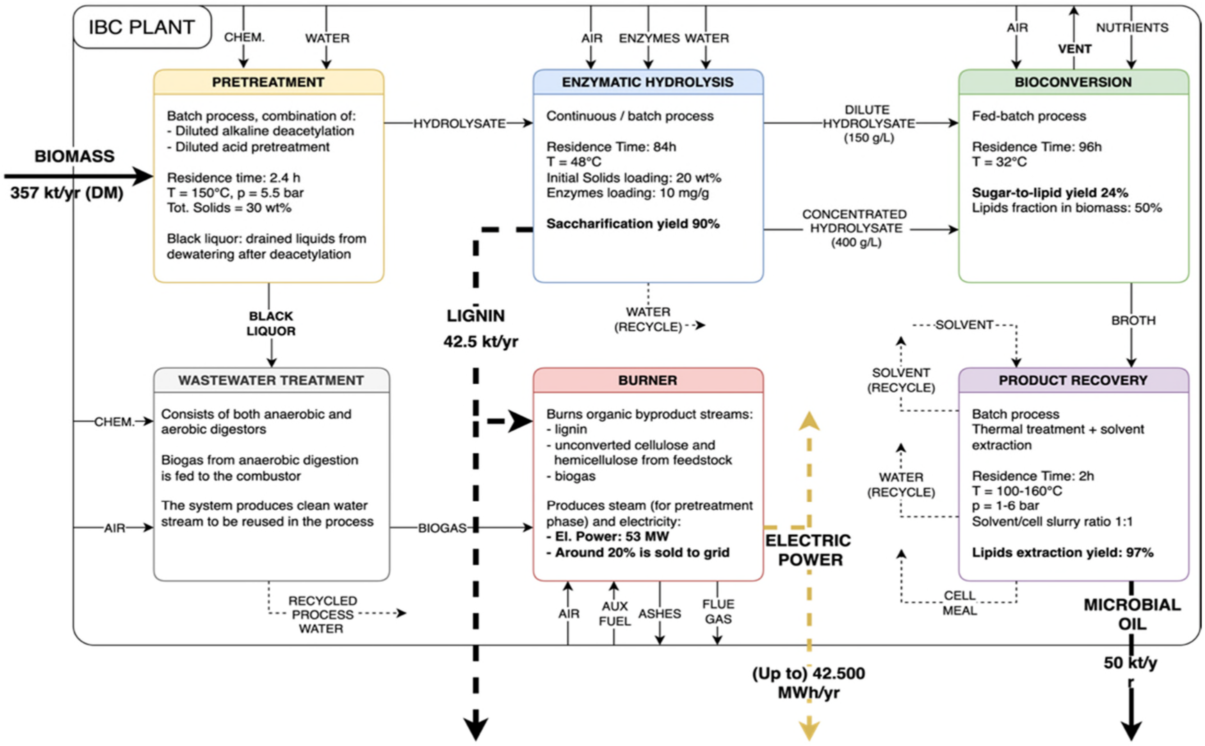

Figure 52. Process scheme of the IBC plants

The current analysis evaluates the total GHG emissions arising from the MO value chain up to the insertion to the biorefinery, in accordance with the principles and methodology given in Annex VI of the RED II. For convenience, as the IBC plants are identical regarding their operation and input/output flows, they will be treated as one – production of 50 kt/yr. of MO in the North and an equal amount in the South. Feedstock and MO logistics are the main differences between the two cases. In addition to MO, excess electricity is produced from the combustion of lignin – electricity production exceeds the IBC plant demand and it is assumed to be sold back to the Italian grid. As an alternative, lignin could be converted to value added products (chemicals and fuels). Therefore, two scenarios are evaluated and compared against:

Scenario 1: Lignin combustion – Excess electricity is sold to the grid.
Scenario 2: Lignin is sold for further conversion – Electricity is bought from the grid

Table 38 presents the feedstock and product flows for the IBC plants as well as the basic considerations of the scenarios.

Table 38. Major input/output flows and basic considerations of the scenarios

Biomass feedstock (dry matter)	357,000	[tn/a]
Microbial oil	50,000	[tn/a]
Lignin	42,500	[tn/a]
Scenario 1		
Excess electricity	45,186	[MWh/a]
Scenario 2		
Electricity purchase from grid	36,672	[MWh/a]

Numerous sustainability assessment tools have been developed such as Life Cycle Assessment (LCA), Substance Flow Analysis (SFA), Sustainability Impact Assessment (SIA), Environmental Risk Analysis (ERA), Multi-Criteria Analysis (MCA), Environmental Extended Input-Output (EEIO) Analysis and Cost Benefit Analysis (CBA).

LCA is the most widely used assessment tool to analyse the major environmental impacts of various products across their entire life-cycle, therefore, in this particular study the life-cycle of MO production scheme is examined with SimaPro v9.1 PhD LCA tool under the impact assessment method Greenhouse Gas Protocol adjusted to fit the methodology of the RED II, taking into account all relevant operational parameters and raw materials used. The system under investigation is considered to be geographically located in Italy, thus Italian-related data were used for the creation of the Life Cycle Inventory (LCI – input and output flows for a product system). Whenever this was not possible, data for Europe were used. Table 39 presents the raw materials used in an IBC plant for the production of 50 kt of MO per year.

Table 39. Input raw materials for MO production in IBC plant per process step – Production of 50 kt MO/yr.

Step	Raw material	Value	Unit
Pretreatment			
	Ammonia	960,804	[kg/a]
	Sulfuric acid	8,277,698	[kg/a]
	Caustic	5,195,734	[kg/a]
Enzymatic hydrolysis			
	Cellulase	1,452,293	[kg/a]
Bioconversion			
	Corn steep liquor	5,188,343	[kg/a]

	Diammonium phosphate	469,316	[kg/a]
	Corn oil antifoam	450,839	[kg/a]
	Sorbitol	66,517	[kg/a]
Burner			
	Lime	705,822	[kg/a]
Wastewater treatment			
	Ammonia	639,304	[kg/a]
	Polymer	11,086	[kg/a]

Besides the raw materials, the current analysis considers the direct emissions and waste flows from the IBC plant operation (Table 40).

Table 40. Major air emissions and waste flows of IBC plant operation

Air emissions	Value	Unit
Nitrogen	1,354,885,522	[kg/a]
Oxygen	526,180,759	[kg/a]
Carbon dioxide (biogenic)	377,769,759	[kg/a]
Methane	7,391	[kg/a]
Nitogen dioxide	280,850	[kg/a]
Carbon monoxide	247,592	[kg/a]
Sulfur dioxide	40,649	[kg/a]
Wastes	Value	Unit
Ash	16,784,511	[kg/a]
Wastewater	27,830,065	[kg/a]

The results of the environmental assessment of the overall MO production pathway for the Italian Strategic Case Study are presented in Table 41. GHG from the collection of biomass as well as from the transport of biomass and MO have been included in the assessment. 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, as an energy crop bears the emissions from the cultivation process.

Table 41. GHG of the overall MO value chain – North and South IBC plants

Step	North IBC plants	South IBC plants	Unit
Feedstock collection	**0.2511**	**0.2236**	[kg $CO_{2\,eq}$/kg MO]
Feedstock transport	0.0070	0.0220	[kg $CO_{2\,eq}$/kg MO]
Direct IBC plant emissions	0.0038	0.0038	[kg $CO_{2\,eq}$/kg MO]
Pretreatment	0.1990	0.1990	[kg $CO_{2\,eq}$/kg MO]
Enzymatic hydrolysis	0.1190	0.1190	[kg $CO_{2\,eq}$/kg MO]
Bioconversion	0.0346	0.0346	[kg $CO_{2\,eq}$/kg MO]
Burner	0.0004	0.0004	[kg $CO_{2\,eq}$/kg MO]
Wastewater treatment	0.0262	0.0262	[kg $CO_{2\,eq}$/kg MO]

MO transport	0.0611	0.0660	[kg $CO_{2\ eq}$/kg MO]
Scenario 1: Electricity credit	-0.379	-0.379	[kg $CO_{2\ eq}$/kg MO]
Scenario 2: Electricity bought	0.307	0.307	[kg $CO_{2\ eq}$/kg MO]
Total Scenario 1	**0.3231**	**0.3155**	[kg $CO_{2\ eq}$/kg MO]
Total Scenario 2	**1.0091**	**1.0015**	[kg $CO_{2\ eq}$/kg MO]

Carbon dioxide emissions from the combustion of biogas and lignin are biogenic and do not account for the GHG calculations. The contribution to GHG emissions from the IBC plant operation are mostly from the raw materials inputs and specifically from the chemicals for the pretreatment step and the enzymes for the hydrolysis. Feedstock collection has also a significant contribution to GHG emissions while MO and feedstock transport play a lesser role – even in the South IBC plants where biomass is transported for longer distances (an average of 42.7 km instead of 13.66 km). Excess electricity effectively offsets 0.379 kg $CO_{2\ eq}$/kg MO (46% reduction) while the purchase of electricity from the grid increases the total GHG emissions by 30%. However, in this case should also be accounted the displacement of products from the utilization of lignin.

Through the oxidation of lignin, phenolic aldehydes, and acids like vanillin/vanillic acid and syringaldehyde/syringic acid and dicarboxylic acids like malonic, succinic, and maleic acid can be produced. From these specific products, vanillin has significant global market demand and is regarded as the most valuable aldehyde (5 – 10 wt % yield for catalytic oxidation of lignin).

Today most vanillin is produced from the petrochemical raw material guaiacol (chemical synthesis) accounting 15.93 kg $CO_{2\ eq}$/kg vanillin produced while 15% of the world's production is produced from lignosulfonates, a by-product from the manufacture of cellulose via the sulphite process (wood-based vanillin) – 1.343 kg $CO_{2\ eq}$/kg vanillin produced.

The utilization of lignin from the production of MO could displace 0.0675 kg of vanillin produced from conventional methods per kg of MO produced, offsetting 1.075 kg $CO_{2\ eq}$/kg MO (chemical synthesis) and 0.09 kg $CO_{2\ eq}$/kg MO (wood-based vanillin). Consequently, the displacement of chemically produced vanillin could mitigate completely the effect of electricity to the production of MO and lead to negative GHG emissions while the displacement of wood-based lignin will have a minimum impact on the GHG emission of the entire MO value chain.

Ultimately, the results of the environmental assessments of MO production, revealed that MO in comparison with traditional feedstocks for biofuel production, like palm oil, coconut oil and soybean oil, presents significant GHG emission reductions (Figure 53).

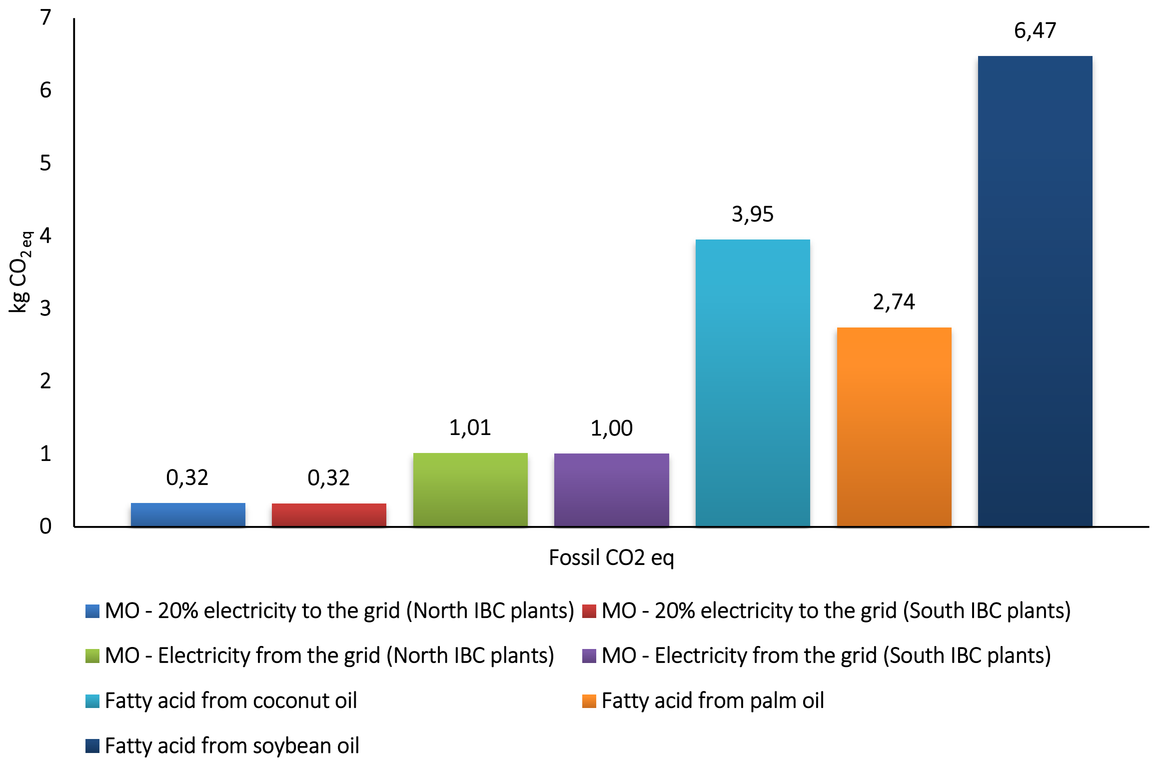

Figure 53. GHG emissions from the production of various fatty acids compared to microbial oil (MO)

5.7 Certification

5.7.1 Description of the value chain and identification of interfaces

In the value chain utilization of agricultural residues and energy crops is investigated. Specifically, prunings from grape vine and olive trees as well as straw will be used. Moreover, Arundo donax cultivated on marginal lands is considered. In the advanced case study, these feedstocks are converted into biochar and pyrogas to substitute coal and natural gas in the production of steel. As the product of the value chain is a material, it does not fall under the scope of the RED II and is not further assessed. In the strategic case study, the biomass feedstock is used to produce microbial oil as IBC. In a second conversion step, a biofuel is produced from the microbial oil. Two scenarios are researched. In one scenario, microbial oil production is integrated into the refinery. In the other scenario, microbial oil is produced decentralized and transported to the refinery for further processing.

Advanced biofuels are defined as being produced from feedstock listed in Annex IX of the RED II and with advanced technologies. They can be considered twice their energy content for the counting towards the minimum target of renewable energy in the transport sector. Straw is

specified in the list (e). Prunings and Arundo donax biomass are not listed by name but can be assigned to item (q) “other ligno-cellulosic material except saw logs and veneer logs”.
From the description above, the chain of custody interfaces displayed in the following figure can be identified. Based on these interfaces, the sustainability certification assessment will be provided in the following.

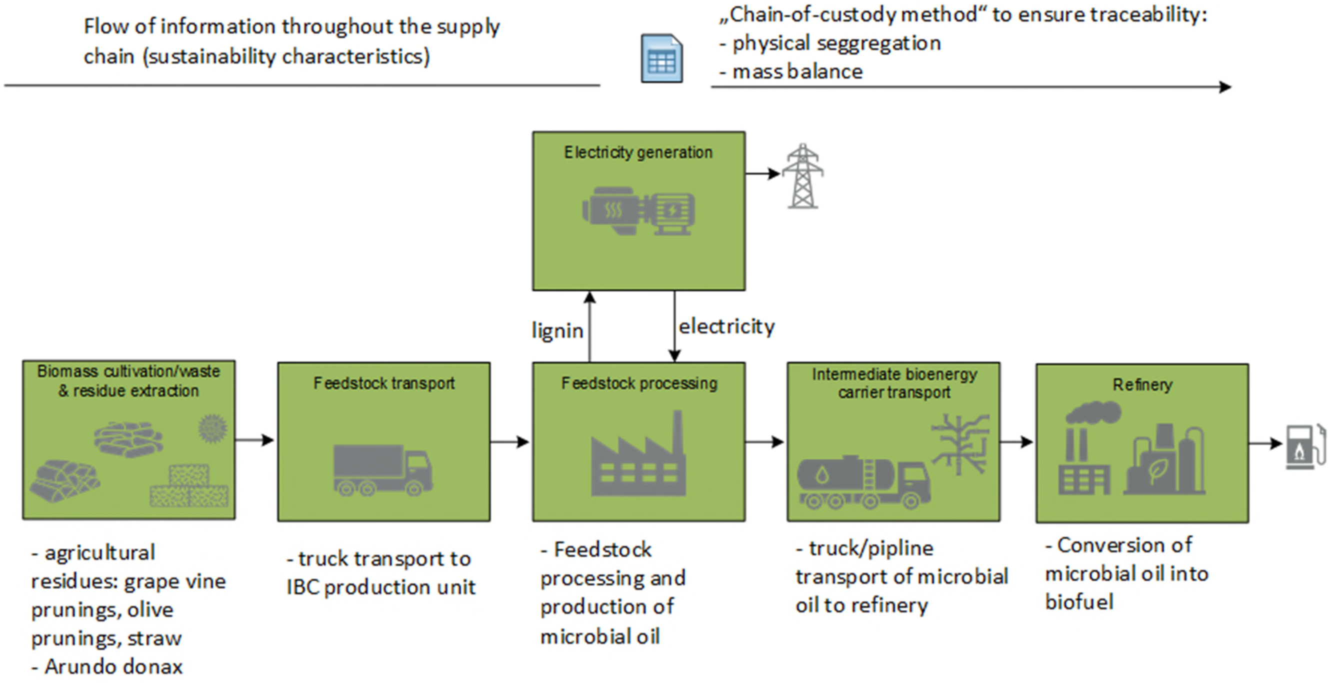

Figure 14: Interfaces along the value chain for the production of advanced biofuels based on microbial oil produced from agricultural residues and Arundo donax

5.7.2 Relevance for the value chain

As waste and residues as well as cultivated biomass are utilized, most of the criteria arising from the RED II (Table 16) apply, except the forest biomass criteria and eventually the efficiency criteria for electricity from biomass fuels. There is electricity generated in the process of microbial oil production from the by-product lignin and partially fed into the grid. The electricity could be considered part of the RED II scope under certain conditions. Installations with a total rated thermal input above 50 MW have to comply with efficiency criteria[9]. However, the major share of the electricity is used as process energy and only minor shares are fed into the grid. Therefore, the proportionate thermal input will likely be below 50 MW. More importantly, the lignin should be considered a biomass fuel to fall under the scope. But it is a by-product and not resulting from a dedicated fuel production process. If it would still be classified as a biomass

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[9] See Buffi et al. 2020 for further details

fuel, the electricity would have to meet the 70% GHG emission reduction threshold (compare 6.7).

For the advanced biofuel as final product, GHG emission reduction has been assessed using the methodology given in Annex V of the RED II. At least 65% GHG-reduction compared to the fossil reference must be achieved.

Table 16: Overview of RED II criteria and applicability to the Italian case study value chain

RED II reference	Criteria summarised	Applicability	Relevance for the case study
29(2)	Monitoring and management of impacts on soil carbon and soil quality	Wastes and residues from agricultural land	yes[1]
29(3)	Protection of land with high biodiversity value	Agricultural biomass for energy	yes[2]
29(4)	Protection of land with high carbon stock	Agricultural biomass for energy	yes[2]
29(5)	Protection of peatland	Agricultural biomass for energy	yes[2]
29(6)	Sustainable forest management	Forest biomass for energy	no
29(7)	LULUCF criteria	Forest biomass for energy	no
29(10)	GHG emission savings criteria depending on the staring date of the operation: at least 50% (< 2015-10-05) at least 60% (2015-10-06-2020-12-31) at least 65% (> 2021-01-01)	Wastes and residues agricultural biomass forest biomass	yes
29(11)	Energy efficiency criteria for electricity production from biomass fuels	Electricity generation	(yes)
30(1)	Mass balance system	Once sustainability and GHG emission savings criteria are to be verified	yes

[1] applies to Arundo donax only

[2] applies to straw and prunings

5.7.3 Protection of land with high value according to article 29(3)-(5)

In case of Arundo donax biomass, it has to be verified that biomass is not sourced from land with high biodiversity value, high carbon stock or peatland. Thereby the status of the land in or after January 2008 is crucial. Table 17 provides some examples for the land status. The three criteria were already part of the RED (2009/28/EC). Arundo donax shall be cultivated on marginal land areas, which amongst others includes grassland. Especially for these areas the land status has to be determined with consideration of the cut-off date 2008. If there is no clear documentation of the biodiversity value available, there might be an individual audit of a qualified specialist[10] required to determine if biomass from a plot in question is eligible as feedstock for biofuels claimed as sustainable.

There are overlaps between the criteria 29(3)-(5) and requirements for the direct payments (cross-compliance) in the EU. Under the previous certification under the RED, verification of the criteria was therefore mostly conducted based on existing documentations (e.g. communication on granting of direct payments).

Table 17: Cultivation area related sustainability criteria and relevant land status

Sustainability criteria	Land status
protection of land with high biodiversity value (29(3))	– primary forest and other wooded land, – highly biodiverse forest – designated areas (nature protection purposes) – highly biodiverse grassland
protection of land with high carbon stock (29(4))	– Wetlands – continuously forested area
protection of peatland (29(5))	– Peatland (with exceptions if drainage is not involved)

5.7.4 Monitoring and impacts on soil carbon and soil quality (29(2))

This criterion was evaluated within the assessment of the Greek case study. This assessment applies to the Italian case study, too. For details, please see section 6.7.3.

5.7.5 National implementation

On December 15th in 2021, the RED II was implemented into Italian law by the Legislative Decree 199/2021. From the national implementation no deviations are expected over the RED II directive (1:1 implementation). However, a set of implementing laws, especially on implementing models still have to be prepared, which calls for further attention.

5.7.6 Conclusions

The conformity of the examined value chain with the requirements of the RED II is achievable. However, there are few uncertainties with respect to ongoing processes and upcoming policies, which mostly concern the monitoring of soil carbon content and soil quality when using residues from agriculture.

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[10] in line with article 16 of the implementing regulation draft

Concerning the cultivation of Arundo donax, the type of land under consideration is crucial and should therefore be further assessed. Specifically, when grassland will be converted to cropland, the biodiversity value of the grassland is decisive. Biomass cultivated on land with (former) high biodiversity value will not be eligible as feedstock for biofuel production under the RED II framework.

5.8 Scenario Building and Optimization

Scope of the Techno-Economic Analysis (TEA) is the evaluation of the better solution in terms of plant location and by-product use, for the two geographical areas considered in the case study, which are located at the two opposite sides of Italy on the north-south axis, thus presenting substantial agricultural and infrastructural differences. Among the various financial and economical parameters considered in the analysis, the Minimum Fuel Selling Price (MFSP) plays an important role. MFSP is the cost break-even selling fuel price at which the future sales of transportation liquids and byproducts are equal to the present value of CAPEX and OPEX [62].
A set of two subcases and four scenarios for each subcase has been developed to capture the complexity of the evaluated situation:

- The two subcases (Porto Marghera and Gela) are related to the two different geographical areas of Veneto and Sicily.
- Within each subcase, two different scenarios are evaluated, regarding the IBC plant location, considering either one centralized plant or two decentralized plants, with respect to the central bio-refinery.
- Finally, for each location scenario, two scenarios regarding lignin use are defined: one where all lignin is burnt for internal IBC plant energy uses, and one where the economically optimal amount of lignin is burnt, and the rest is sold on the market for further uses.

Section 5.3 provided a thorough description of the IBC plant modelled for MO production, reporting the technical solutions together with information on all the main parameters impacting on the plant economics:

- Plant CAPEX and OPEX: these are mostly related with the technological choices related to the process needs; anyway, impacts on these parameters are accounted also on the choice of having a single centralized IBC plant rather than two smaller decentralized ones. This is related to both effects of scale and to the fact that the centralized IBC plant could benefit from the bio-refinery existing services and infrastructures.
- Biomass feedstock costs: this parameter varies depending on the geographical subcase, due to the different biomass availability as well as to the different logistics costs
- Electricity incomes or costs: the plant could either produce surplus electricity, up to the 20% of total production, and make an additional revenue from that, or could be in need for electricity from the grid to cover part of its consumption. These different situations are related to actual lignin use: if at least 44.5% of lignin co-product is burnt to produce electricity, the plant could still be considered as energetically self-sufficient and, for

higher shares of burnt lignin, surplus electricity is available for sale. Lower shares of lignin burnt for plant needs lead to the need of purchasing electricity from the grid.

- **Lignin price on the market:** on the other side, non-burnt lignin could be sold on the market to make additional profits. Obviously, the difference in revenues (and costs) between electricity and lignin sales has to be carefully evaluated so to not incur into net losses from this practice.
- **MO price on the market:** being the main output of the IBC plant, its market price has to be carefully considered. In the Italian Strategic CS, the MO is considered to be directly used in ENI's bio-refineries, substituting other non-advanced feedstock such as, i.e., palm oil. In this case, MO value could be considered as equal to the purchase cost avoidance of the non-advanced feedstock.
- **Biofuels incentives:** Italian legislation defined a subsidy scheme where, on one side, biofuels producers can access to the CIC certificates, valued 375 €/10 Gcal and doubled for advanced biofuels; on the other side, all the subjects that put fossil fuels on the market are obliged to put on the market also biofuels (conventional or advanced) for a predetermined quota. In case they couldn't put into market enough biofuels, they are either obliged to purchase enough CIC certificates or pay a 750€/10 Gcal fine. Thus, by producing MO, ENI avoids the cost of purchasing the corresponding amount of CIC certificates and this could be seen as a revenue. The specific value of this revenue depends on the *ex-ante* situation: if MO is used to substitute fossil fuels, subsidy value can be considered equal to 750€/10 Gcal of substituted fuel. Instead, if MO substitutes palm oil, the subsidy value can only be considered equal to 375 €/10 Gcal of substituted fuel, since this is the difference between 375 €/10 Gcal taken by palm oil (conventional feedstock) and 750€/10 Gcal taken by MO (advanced feedstock). In the followings, we will be considering the latter scenario, related to the substitution of a conventional feedstock

Table 42 below summarizes the main economic parameters used in the TEA.

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

	Centralized		Decentralized	
	Base	Lignin	Base	Lignin
Biomass price (dry)	91.4 (PM) / 104.6 (G) €/t[1]		86.9 (PM) / 92.9 (G) €/t[1]	
Electricity price	50 €/MWh (sold) – 108 €/MWh (purchased)			
Lignin price	300 €/t			
Incentives value	375 €/10 Gcal			
Palm oil price	700 €/t			
CAPEX (single plant)	335,151,077 €	327,972,466 €	174,982,678 €	171,328,112 €
OPEX (single plant)	52,320,075 €	58,374,512 €	24,944,245 €	27,971,463 €

[1] PM: Porto Marghera subcase, G: Gela subcase

Considering the electricity value (if sold) and cost (if purchased) defined in section 5.3.3 and defining a lignin electricity production capacity of 1.92 MWh_{el}/t, it is possible to define the price threshold for the usage of lignin for internal energy use or to be sold on the market. In fact, if electricity is sold to the grid for 50 €/MWh, lignin price on the market has to be higher than 96

€/t, otherwise it is more convenient to use it to produce electricity. Moreover, if electricity is purchased at 108 €/MWh, lignin price on the market has to be higher than 208 €/t to make it convenient enough to sell the lignin on the market and purchase electricity from the grid, instead of producing it using the same lignin. The actual lignin price used in the model is set at 300€/t, thus in the followings, when considering Lignin scenario, 100% of lignin is considered to be sold on the market.

A series of sensitivity analyses have also been conducted on several of the above-mentioned parameters, such as plant CAPEX, incentives value, biomass cost and lignin value. All these parameters value have been changed in the range of +/- 20% and the corresponding results evaluated.

Table 43 reports the standard values of the main technical and financial parameters that have been used together with MFSP 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 [63], [64].

Table 43: Financial parameters used for the techno-economic analysis

Depreciation	yr	10
Lifespan	yr	30
Discount Rate	%	5.0
Tax Rate	%	30

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:

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

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” [65], 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% [66].

5.9 Case study feasibility results

All the results reported in these sections are obtained by using the economic inputs from the above-mentioned Table 42 and
Table 43. Overall, the Porto Marghera subcase performs better when compared to Gela, as reported in Table 44 below. This can be mainly accounted to the lower biomass total cost, as reported in section 5.5.7.

Table 44: Summary of MFSP across the developed subcases and scenarios

Subcase	**Centralized**		**Decentralized**	
	Baseline	**Lignin**	**Baseline**	**Lignin**
Porto Marghera	1269 €/t	1127 €/t	1275 €/t	1133 €/t
Gela	1363 €/t	1221 €/t	1318 €/t	1176 €/t

In the followings, the two subcases are analysed separately; the impact on costs and revenues of the various economic parameters is evaluated, and a thorough sensitivity analysis is conducted. At first, the impact of the MO selling price on NPV, IRR and PBT of the IBC plant is evaluated; moreover, regarding the scenarios where lignin is modelled to be sold on the market, the impact of its market price is evaluated as well. Finally, the impact of all the other remaining parameters, such as biomass costs, CAPEX, electricity cost and CIC incentives on MFSP is evaluated as well.

5.9.1 Porto Marghera Subcase

The Porto Marghera subcase involves a geographical area placed in the North-East of Italy; the transport infrastructure existing in this area are well-developed, as it could be expected, given the historical industrial vocation of the region. This in turn translates into lower biomass transport costs, and thus into lower total biomass costs. The main differences between centralized and decentralized scenarios lays into a lower CAPEX (and OPEX) for the former and a lower total biomass cost for the latter. In this subcase, the positive effects of a lower CAPEX and OPEX overcomes the opposite effects related to a higher biomass cost and this makes the Centralized scenario the best in terms of overall MFSP. It has to be noticed, anyway, that the differences proved almost negligible: this leaves to a wider range of possibilities, hindering neither an IBC plant deployment within the premises of the existing Porto Marghera bio-refinery, nor a more feedstock-barycentric one, as depicted in the decentralized scenario. Within each geographical scenario, quite a substantial difference is instead accounted to the choice of use made for the lignin co-product as shown in Table 45 below, selling lignin on the market instead of using it for internal energy uses (as defined in the Baseline scenario) makes for quite better overall economics for the process.

Table 45: MFSP value across the considered scenarios

Centralized		Decentralized	
Baseline	**Lignin**	**Baseline**	**Lignin**
1269 €/t	1127 €/t	1275 €/t	1133 €/t

Figure 54 below, provides an overview on the level of contributes of the various financial flows to both IBC plant costs and revenues, in each of the four considered scenarios. The highest yearly cost of the plant is accounted to the biomass feedstock; this obvious result also highlights the overall low process conversion yields, that turns into really big biomass input volumes.

Other cost lines comprehend the OPEX and the electricity costs, considered separately since they are present only in the scenarios where lignin is considered as sold on the market. Otherwise, electricity is accounted as a net revenue, since its production surplus is sold on the grid. It can also be noticed that electricity costs are almost twice the revenues: this is also related to the different payment and revenues schemes, the latter having a unitary cost almost two-fold than the former. Moving on to revenues composition, the bigger share comes from the MO valorisation; in this case, the unitary value is considered equal to the MFSP as reported in Table 45. Both CIC incentives and lignin sales also have a considerable impact on the overall results.

Figure 54: Breakdown of absolute costs and revenues figures regarding the four analysed scenarios

Figure 55 reports the same data, as share of the total costs and revenues. Total costs range between 102 and 112 M€/a and total revenues range between 164 and 171 M€/a, ante taxes. It can be noticed how biomass costs share is a little higher in the decentralized scenario, when compared to the centralized one, as already anticipated. The higher share of revenues coming from the MO sales in the Baseline scenarios, is instead related to the higher MFSP obtained when the additional revenues coming from lignin sales aren't available.

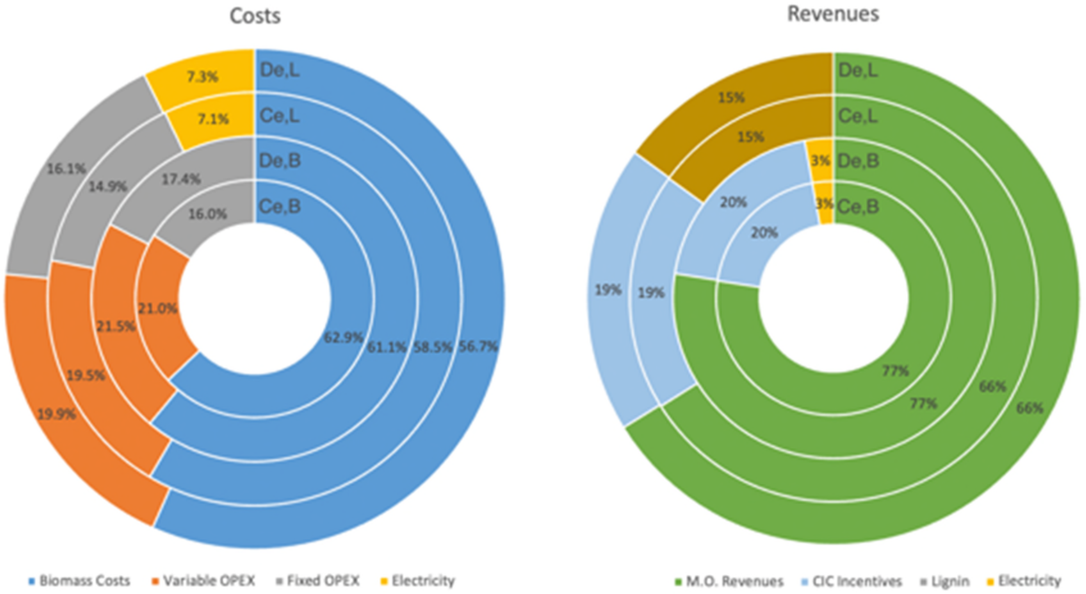

Figure 55: Breakdown of costs and revenues shares for the four considered Scenarios (Ce, B: Centralized, Baseline; De, B: Decentralized, Baseline; Ce, L: Centralized, Lignin; De, L: Decentralized, Lignin)

Figure 56 reports the result of a sensitivity analysis conducted on the scenarios where lignin co-product is sold on the market. In this analysis the parameters are variated, one by one, by +/-20% from the original values listed in Table 42 and the results are given in terms of MFSP. The biggest impacts are the ones related to CAPEX and biomass feedstock; both lead to a MFSP of around 1,000 €/t in the best case. Thus, improvements on plant technologies or upstream value chain optimization, i.e., through the set-up of framework contracts could lead to these results. Moreover, the IBC plant model is complex, and the economic results are affected by uncertainty, even if carefully evaluated; this sensitivity analysis could capture and highlight such uncertainty. CIC end lignin impacts follow with half the magnitude, while the impact of electricity cost and prices proves to be little.

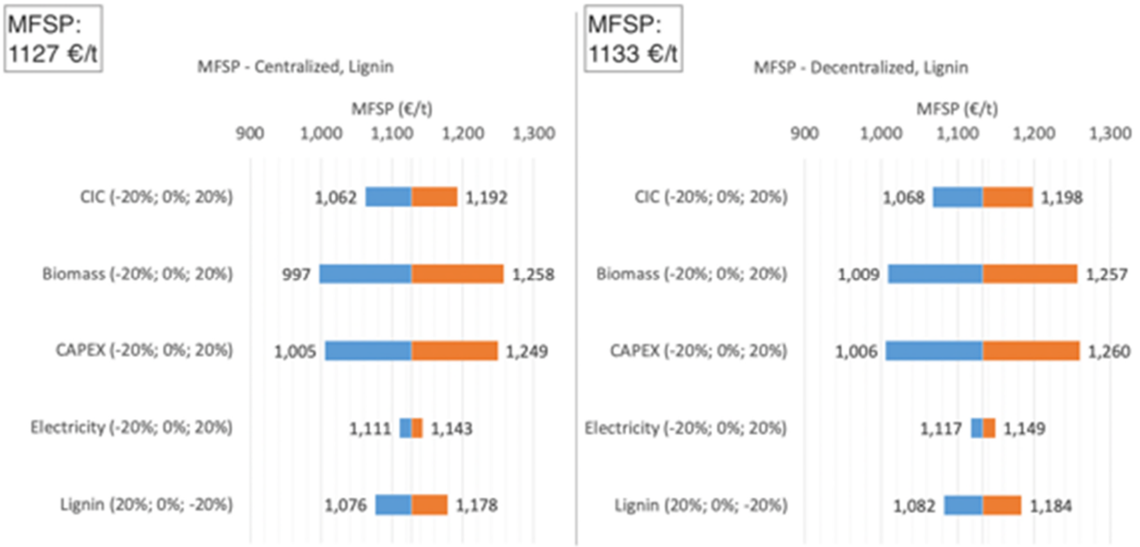

Figure 56: Tornado chart reporting the results of a sensitivity analysis on the effects of various economical parameters on the MO MFSP for the Centralized and Decentralized Lignin Scenario.

The final part of the techno-economic analysis focuses on the impact of MO FSP on the main economic parameters of the plant, such as NPV, IRR and PBT. The Baseline scenarios takes into account only MO price variability, while the Lignin ones consider lignin market price variability as well.

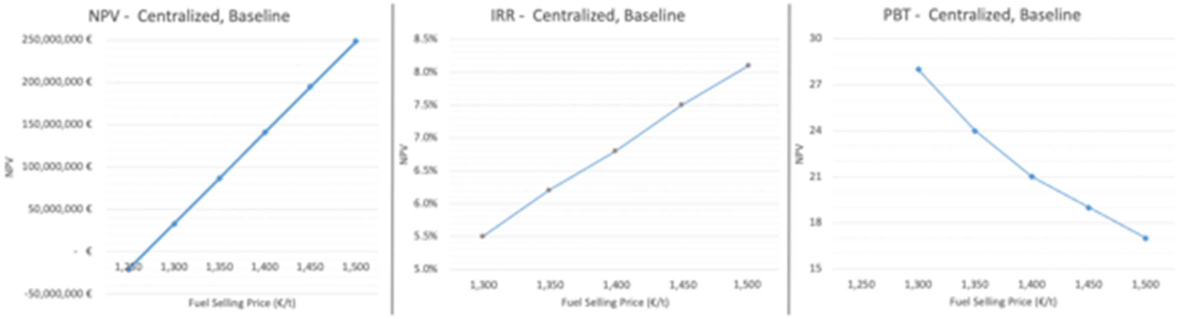

Figure 57: Summary of the main economic parameters (NPV, IRR, PBT) as a function of Fuel Selling Price and Lignin market price, in the Centralized, Baseline scenario.

Figure 57 and Figure 58 report an almost linear behaviour for NPV and IRR. In order to reach a 20 years PBT a MO FSP of 1,450 €/t is needed in the decentralized scenario; the corresponding NPV of the total investment is little shorter than 190 M€ over 30 years, and the corresponding IRR reaches 7.3%. The centralized scenario performs better: a MO FSP of 1,450 €/t leads to a 19 years PBT, around 200 M€ of NPV and to an IRR of 7.5%.

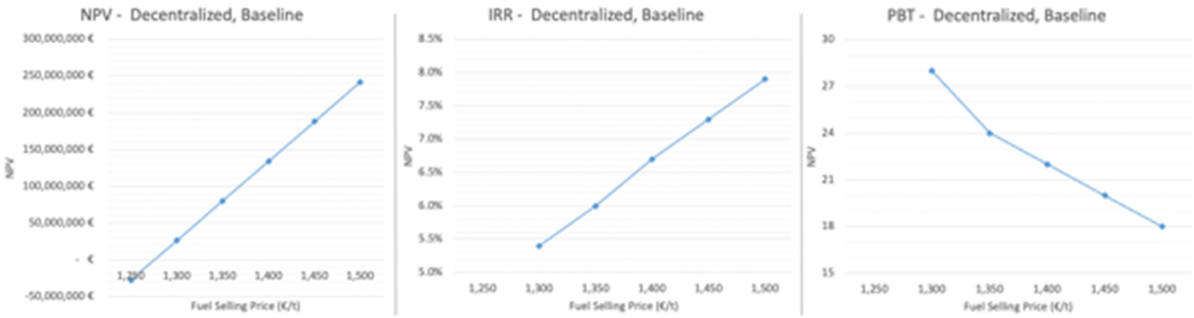

Figure 58: Summary of the main economic parameters (NPV, IRR, PBT) as a function of Fuel Selling Price and Lignin market price, in the Decentralized, Baseline scenario.

The Lignin scenarios perform better when compared to the Baseline ones: as reported by Figure 59 below, the centralized one reaches a 19 years PBT with a MO FSP of 1,300 €/t, with an IRR of 7.4% and an NPV over 190 M€ after 30 years. To be noted the strong impact that higher lignin market prices have on the MO MFSP: with a lignin price of 700 €/t, a MO MFSP of around 800 €/t is projected. Of course, this is a simplified analysis: reaching a high-level lignin purity cannot be taken for granted and it would in any case need further investments in plant technologies, reflecting in additional CAPEX that finally would increase again the MFSP. Anyway, this analysis further points out the importance of re-using lignin co-product in the most valuable way, to lower as much as possible MO MFSP.

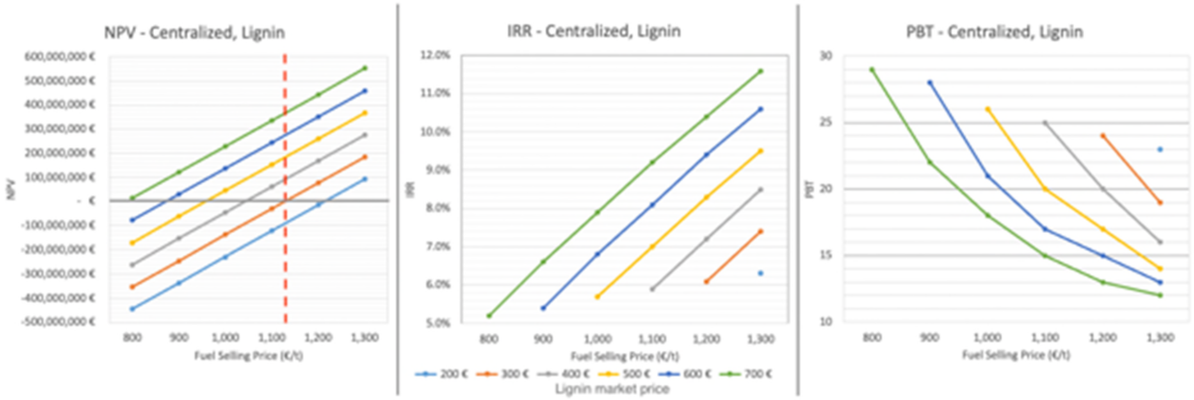

Figure 59: Summary of the main economic parameters (NPV, IRR, PBT) as a function of Fuel Selling Price and Lignin market price, in the Centralized, Lignin scenario. Red dashed line refers to MFSP as reported in Table 45

A really similar framework is reported by Figure 60 below, again pointing out the really subtle differences existing between Centralized and Decentralized scenario in the Porto Marghera subcase.

Figure 60: Summary of the main economic parameters (NPV, IRR, PBT) as a function of Fuel Selling Price and Lignin market price, in the Decentralized, Lignin scenario. Red dashed line refers to MFSP as reported in Table 45

5.9.2 Gela Subcase

When compared to the northern subcase, the area involved in the Gela subcase shows a quite less developed transport infrastructure. This clearly reflects in significantly different biomass transport costs and thus total biomass costs. Thus, in this case, the MFSP differences between Centralized and Decentralized scenario are greater, around 50 €/t in both the Baseline and the Lignin scenario. This leads to a clear preference for two decentralized IBC plants, as reported in Table 46 below.

Table 46: MFSP value across the considered scenarios

Centralized		Decentralized	
Baseline	**Lignin**	**Baseline**	**Lignin**
1363 €/t	1221 €/t	1318 €/t	1176 €/t

Figure 61 and Figure 62, reporting the detailed breakdown of costs and revenues, respectively with absolute figures and as shares of the total, presents an overall distribution really close to the one described in the Porto Marghera subcase. The only difference to be noticed is the higher share of costs related to the biomass feedstock, due to the higher unitary costs of the materials.

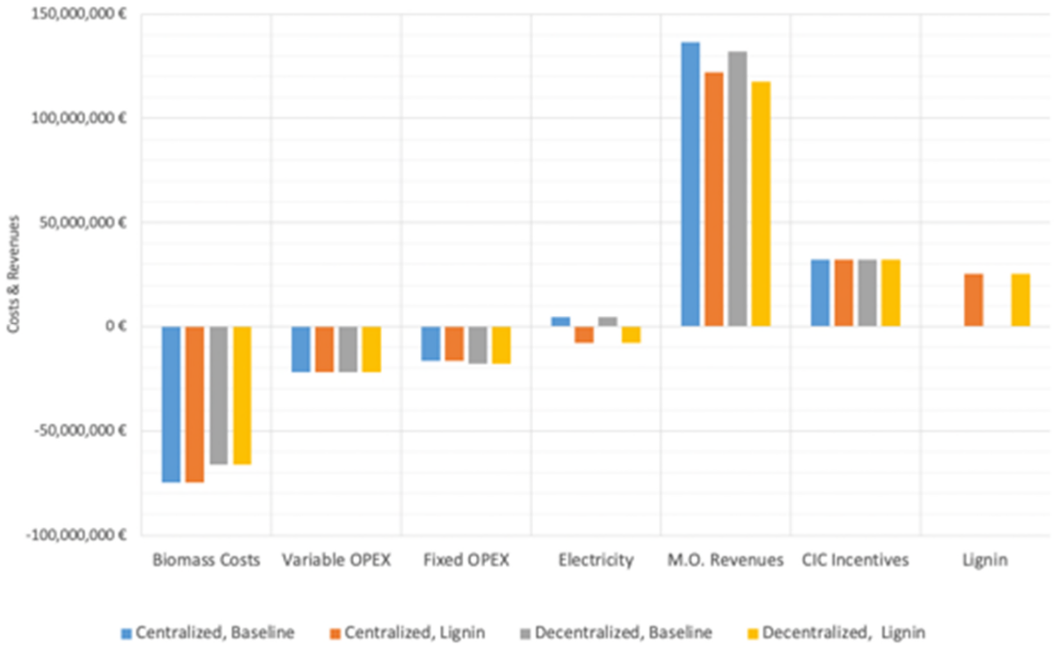

Figure 61: Breakdown of costs and revenue figures regarding the four analysed scenarios

In order to better understand the data reported by Figure 62, it is worth to know that in this subcase the total costs range between 106 and 121 M€/a and total revenues range between 159 and 179 M€/a, ante taxes. The wider spread, when compared with the northern subcase, can be related to the wider spread of biomass costs, that in turn influences the range of MFSP.

Figure 62: Breakdown of costs and revenue shares for the four considered Scenarios (Ce, B: Centralized, Baseline; De, B: Decentralized, Baseline; Ce, L: Centralized, Lignin; De, L: Decentralized, Lignin)

Figure 63 reports the result of a sensitivity analysis conducted on the scenarios where lignin co-product is sold on the market. In this analysis the parameters are variated, one by one, by +/-

20% from the original values listed in Table 42 and the results are given in terms of MFSP. The biggest impacts are the ones related to CAPEX and biomass feedstock; both lead to a MFSP of around 1,050-1,100 €/t in the best case. CIC end lignin impacts follow with half the magnitude, while the impact of electricity cost and prices proves to be little.

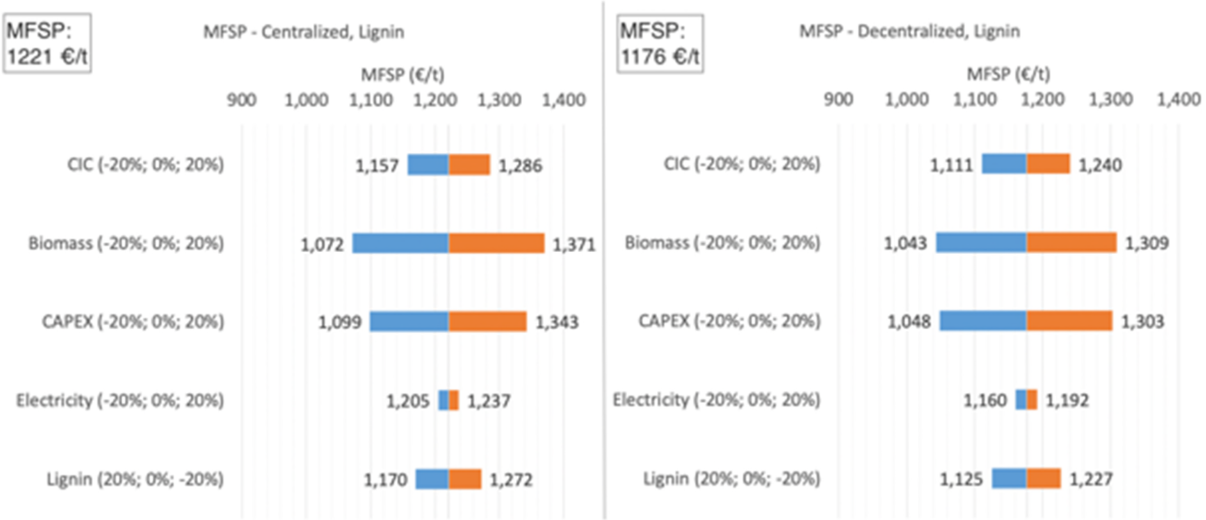

Figure 63: Tornado chart reporting the results of a sensitivity analysis on the effects of various economical parameters on the MO MFSP for the Centralized and Decentralized Lignin Scenario.

The final part of the techno-economic analysis focuses again on the impact of MO FSP on the main economic parameters of the plant, such as NPV, IRR and PBT. The Baseline scenarios takes into account only MO price variability, while the Lignin ones consider lignin market price variability as well.

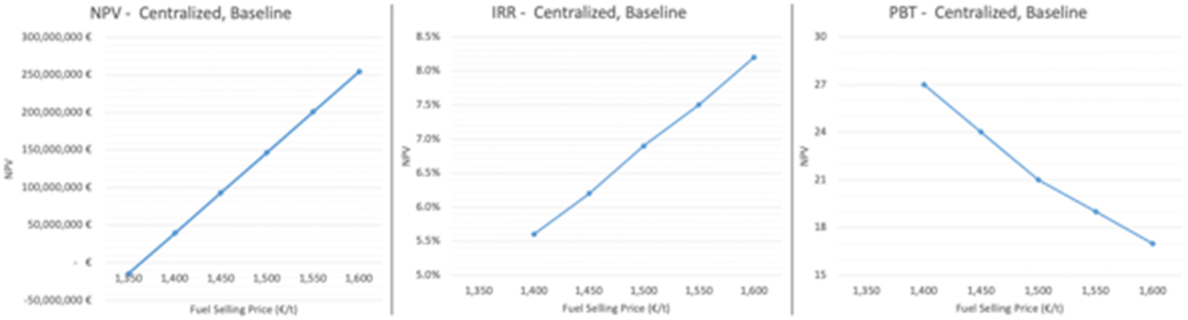

Figure 64: Summary of the main economic parameters (NPV, IRR, PBT) as a function of Fuel Selling Price and Lignin market price, in the Centralized, Baseline scenario.

Figure 64 and Figure 65 show an almost linear behaviour for NPV and IRR. In order to reach a 20 years PBT a MO FSP of 1,475 €/t is needed in the decentralized scenario; the corresponding NPV of the total investment is around 175 M€ over 30 years, and the corresponding IRR reaches 7.1%. The centralized scenario is worst performing: to reach a 20 years PBT a MO FSP of 1,525 €/t is needed, leading to around 170 M€ of NPV and to an IRR of 7.1-7.2%.

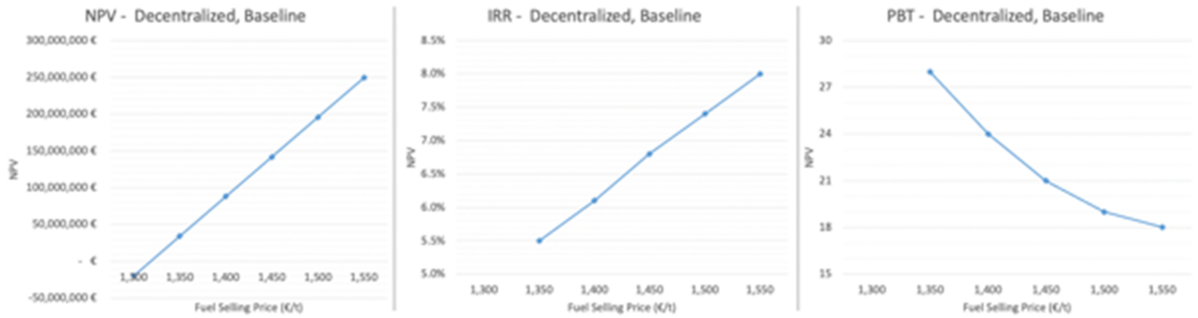

Figure 65: Summary of the main economic parameters (NPV, IRR, PBT) as a function of Fuel Selling Price and Lignin market price, in the Decentralized, Baseline scenario.

As expected, the Lignin scenarios perform better when compared to the Baseline ones: as reported by Figure 66 below, with the standard lignin price of 300 €/t, the centralized one reaches a 21 years PBT with a MO FSP of 1,350 €/t, with a similar IRR and an NPV over 140 M€ after 30 years. Again, to be noted, the strong impact that higher lignin market prices have on the MO MFSP: with a lignin price of 700 €/t, a MO MFSP of around 870 €/t is projected.

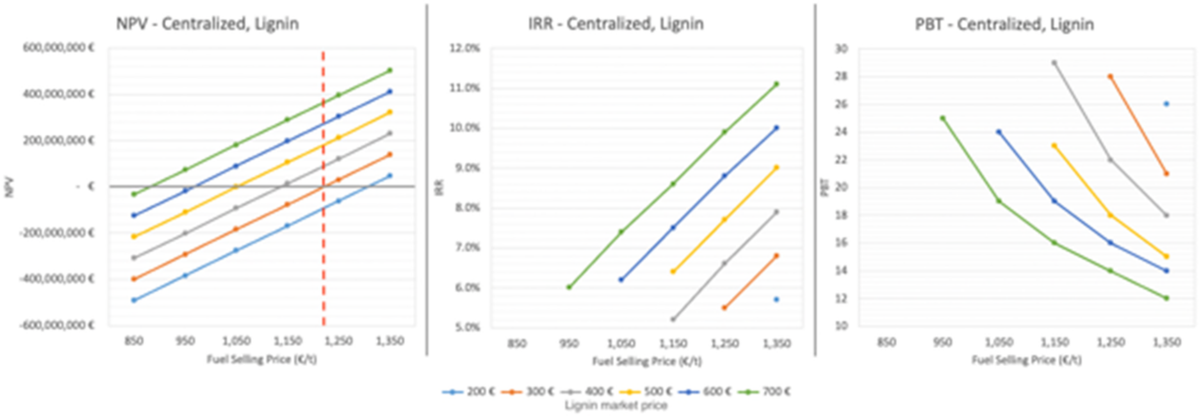

Figure 66: Summary of the main economic parameters (NPV, IRR, PBT) as a function of Fuel Selling Price and Lignin market price, in the Centralized, Lignin scenario. Red dashed line refers to MFSP as reported in Table 45

A similar framework is reported by Figure 67 below; in this subcase the differences existing between Centralized and Decentralized scenario are anyway quite bigger when compared to the ones reported in the Porto Marghera subcase. With the standard lignin price of 300 €/t, the decentralized Lignin scenario reaches a similar 22 years PBT with a lower MO FSP of 1,300 €/t, with a similar IRR and an NPV over 140 M€ after 30 years. A lignin market price of 700 €/t, leads here to a MO MFSP of around 825 €/t.

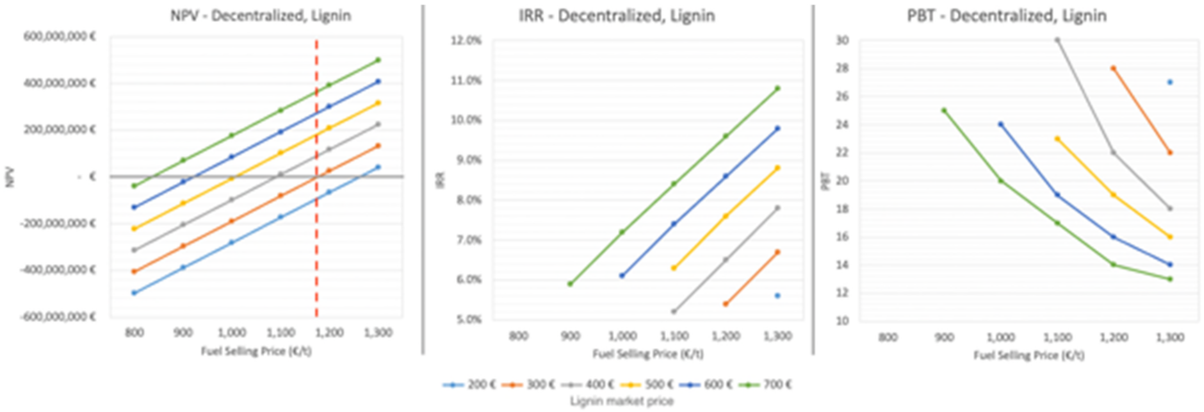

Figure 67: Summary of the main economic parameters (NPV, IRR, PBT) as a function of Fuel Selling Price and Lignin market price, in the Decentralized, Lignin scenario. Red dashed line refers to MFSP as reported in Table 45

5.10 Final remarks

The INFER-NRG model assessed that the areas considered for both Porto Marghera and Gela subcase 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 unfavorable 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 86.9 €/t to 104.6 €/t. Such variability is mostly related to the transport costs, which in turn are deeply affected by the existing transport infrastructure. From the analysis, it emerges that Porto Marghera subcase performs substantially better in this area.

In order to capture the complexity of the Case Study, related to the different geographical areas and to the possible techno-economical choices, four different scenarios for each subcase has been evaluated. Two scenarios regarded the alternative possibilities of either deploying a bigger IBC plant near the bio-refinery, optimizing CAPEX and OPEX, or deploying two smaller IBC plants near to the biomass production areas, taking advantage of biomass densification into MO and thus of the underlying logistics costs optimization. The other two considered scenario regarded the possibility of either use lignin co-product for internal energy uses rather than sell it on the market.

Overall, it resulted that selling lignin on the market gives an advantage in terms of final MO MFSP; it also resulted that IBC plants location has a bigger impact in the Gela subcase, while it is almost negligible in the Porto Marghera subcase. This can be explained by the narrower range of biomass costs that is obtained in the northern subcase, which in turn, as discussed, is related to the better transport infrastructure.

MO MFSP ranges between 1127 €/t and 1363 €/t; the conducted sensitivity analysis reported that the bigger influences on MFSP are related to CAPEX, biomass cost, Lignin sale price, CIC incentives and electricity cost, in order of importance.

Looking to the impact of the various parameters involved into the techno-economic evaluation, it can be noticed that improvements on plant technologies or upstream value chain optimization, i.e., through the set-up of framework contracts could lead to these results. Moreover, the IBC plant model is complex, and the economic results are affected by uncertainty, even if carefully evaluated; this sensitivity analysis could capture and highlight such uncertainty. Moreover, the importance of securing low biomass costs since the beginning of the project, for a successful business case, stands out clearly.

MO FSP of around 1,300 €/t, leads to IRR of around 7-7.4%, to NPV ranging across 140-190 M€ after 30 years and PBT of 19-21 years. It should be noted the strong impact that higher lignin market prices could have on the MO MFSP: with a lignin price of 700 €/t, a MO MFSP of around 800-870 €/t is projected across the scenarios. Of course, this is a simplified analysis: reaching a high-level lignin purity cannot be taken for granted and it would in any case need further investments in plant technologies, reflecting in additional CAPEX that finally would increase again the MFSP. Anyway, this analysis further points out the importance of re-using lignin co-product in the most valuable way, to lower as much as possible MO MFSP.

6 Torrefaction to replace lignite coal: the Greek case study

6.1 Introduction

Climate change and its progressively more frequent consequences that have been observed in recent years, such as heat waves, extreme storms, intense droughts etc., are directly linked to increasing greenhouse gas (GHG) emissions and in particular CO_2, which has been recognized as the main contributor to the greenhouse gas effect. Tackling the climate crisis requires the transition towards a Climate-Neutral economy, in respect of the circular economy principles "reduce, reuse, recycle" and away from the traditional concept "make, use, dispose". In this sense, moving away from a fossil-fuel dependent economy to a decarbonized one that will use renewable resources in a sustainable manner is a necessity. Understandably, this effort cannot be performed easily nor is a task that can be realized within a short-time period.

To this purpose, in September 2019, Greece announced the upcoming closure of all lignite plants in the country by 2028 at the latest, with most units – representing over 80% of current installed capacity – by 2023, signalling the beginning of Greece's transition to a differentiated mixture of power production that will not be based on lignite, a process that in fact has already started in the early 2010s with the gradual reduction of lignite-mining activities.

Decarbonization is expected to dramatically improve the country's environmental performance, promote competitive electricity generation methods, and diversify the production model. However, this decision is accompanied by two major challenges. The first concerns the way in which the lignite will be replaced in the electricity production mix and the second, the fair development transition of the lignite areas of Western Macedonia and Megalopolis.

Although there is a significant capacity (511 MW) installed in Megalopolis (SW Greece), Western Macedonia (NW Greece) has always been considered as the energy centre of Greece and the pillar which the industrialization of Greece was built upon (4.3 GW). Region's power plants, due to lignite, provided low-cost electricity to the Greek system and at the same time, as a counter-balance for the environmental degradation, affordable heat to local communities. The lignite-related activities have also had a huge impact on the regional economic development – the economy from 1950s onwards gradually transformed into one-dimensional – mainly focused on the energy sector and completely intertwined with Public Power Corporation (PPC), the utility company responsible for lignite power production. Notably, 45% of the region's Gross Value Added (GVA) is generated from the lignite sector, while, for each permanent staff position in the lignite mining and power production, 2.6 positions are created and maintained in the local labour market.

Within this economic context, Western Macedonia Region (WMR) is being led in a steep decarbonization path (Figure 68) and given the current situation of the Greek energy market and the somewhat aggressive renewables agenda, is stepping on to uncharted territories. Moreover, the energy transition plan creates unrest among the local population. It intensifies the fear about an upcoming energy insecurity/poverty, which they attribute to the implementation of renewable technologies and the increased energy cost.

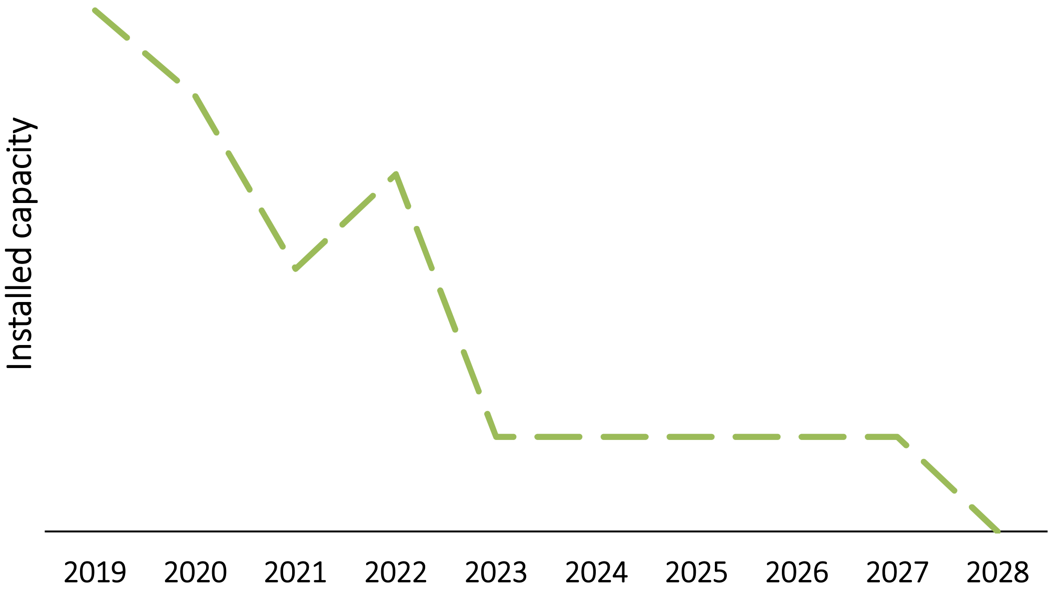

Figure 68. Western Macedonia's decarbonization path (spike in 2022 – operation of Ptolemaida 5)

Apart from the impact on the region's GVA and employment, the lignite phase-out could also deal a serious blow to the municipal district heating (DH) companies in the areas of Amyntaio, Ptolemaida and Kozani, which will be in a critical position if they do not adapt to this new reality. An impending threat for these DH companies is the discontinuation of their operation – dependent solely on cheap heat, generated by PPC's lignite-fired Combined Heat and Power (CHP) plants. Consequently, there is an immediate and pressing need for alternative energy sources for their uninterrupted operation.

Until 2021, DETIP (municipal district heating company of Ptolemaida) utilized up to 100 MW_{th} of heat, originating from PPC's Kardia Power plant, while, after the shutdown of this unit, installed two (40 MW_{th} each) electric boilers, an investment that cost 4 million € and is viewed with scepticism due to increased operating costs. DEYAK (municipal district heating company of Kozani) currently and until 2023, utilizes up to 137 MW_{th} of heat, generated by Agios Dimitrios Power Plant. The preferred solutions for the continuation of DEYAKs operation, beyond 2023 mainly revolve around natural gas, which according to current high prices could have a huge impact on DH pricing. On the other hand, DETEPA (municipal district heating company of Amyntaio), to face the closure of the local CHP plant, implemented a 30 MW_{th} biomass-fired DH plant to completely cover the demands of the approximately 4,000 residents of the area. As a consequence of this implementation, the price of the produced heat rose by 38%.

Therefore, it is particularly important to develop appropriate strategies and implement policy measures that can: (a) support the local economy; (b) enhance energy sustainability/security; (c) support the sustainable and equal growth of all production sectors (including the agricultural sector); (d) secure existing jobs and create new ones; and (e) increase rural income. Towards this purpose, the penetration of Renewable Energy Sources (RES) in power generation, heating and industrial applications as well as investments in technologies that utilize local natural resources, will play a critical role. In this way, the mitigation of the lignite phase-out consequences, could be ensured for the affected regions. A possible endogenous RES that can provide multiple benefits is the locally available biomass in case it could be mobilized in a sustainable and cost-effective manner.

In general, WMR presents a significant amount of biomass potential, especially in the regions of Kozani and Florina, due to the large agricultural activity (Figure 69).

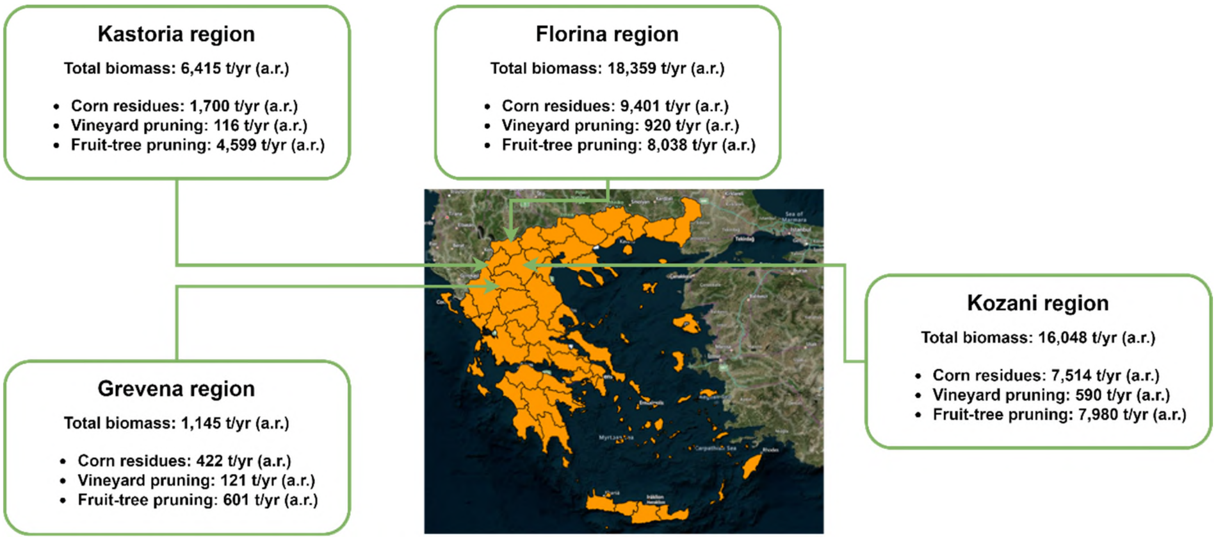

Figure 69. Biomass potential in WMR (GIS map from https://geodata.gov.gr/en/)

Apart from WMR, an even larger source of agricultural biomass is in the neighbouring region, Thessaly (Figure 70) and specifically in the Thessalian plain. Thessaly is a vital agricultural region for Greece, annual crops cover 81.1% of the total area and contributes more than 14% to the country's total agricultural production, especially in cereal grains (corn and wheat) and cotton production.

In both regions, biomass residues are widely available, though only a small fraction is collected and utilized – mostly as fodder – while the remaining amounts are usually burned or, to a lesser extent, incorporated in the soil. 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 of handling, transporting, and storing biomass and relevant residues.

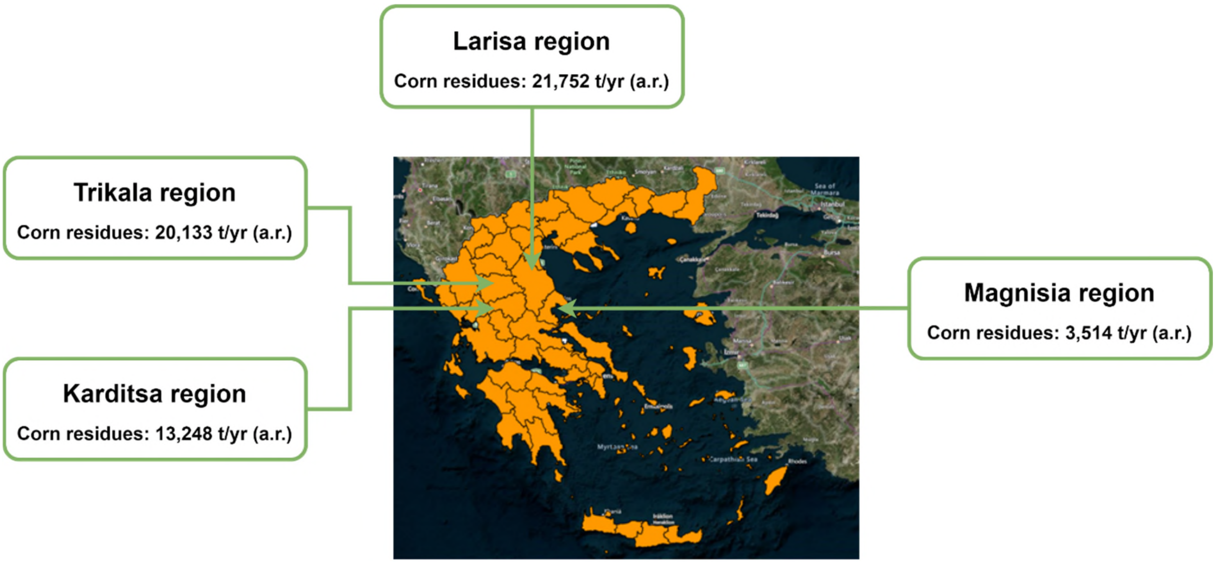

Figure 70. Biomass potential in Thessaly (GIS map from https://geodata.gov.gr/en/)

In this context, the Greek Case Study deals with the conversion of agricultural residues (corn residues, vineyard pruning and fruit-tree pruning) to Intermediate Bioenergy Carriers (IBCs) through torrefaction and their subsequent utilization – as alternative to lignite – in DH (DETEPA, DETIP, DEYAK) and electricity generation (Ptolemaida 5) and as a replacement of pet-coke in industrial applications (CaOHellas S.A., Grecian Magnesite S.A.). As IBCs are energetically denser, with analogous properties to coal, oil and gaseous fossil energy carriers, intermediate products, they are easier to transport, store and use than 'raw' – untreated - biomass residues.

The main goals for the creation and development of a biomass supply chain in the regions of Western Macedonia and Thessaly and consequently, of a torrefied biomass value chain in WMR, are the minimization of the cost of the individual supply stages and the continuous supply of biomass for the assurance of the energy adequacy of the end-users. These two conditions are particularly important for biomass to be considered as a fuel capable of replacing lignite, both in terms of price (current lignite market price – 17.36 €/MWh, without carbon price) and in terms of continuous and uninterrupted supply. The energy demands of the various end-users are continuous (and fluctuating during a heating season for the DH applications), while the harvesting of biomass takes place only during specific periods of the year. Thus, an effective planning of biomass supply and storage (both raw and torrefied) is an important part of the overall torrefaction production system.

The Greek Case Study focuses on the evaluation of the operability and cost of the most promising torrefaction schemes, in terms of torrefaction unit operational parameters, local biomass conditions (market and logistics), biomass physical and chemical properties, energy demand and infrastructural requirements. The investigation of the effect of the above-mentioned parameters on the final energy cost, is achieved through the development and implementation of a series of process modelling and optimization tools. In particular the conversion of agricultural residues to IBCs through torrefaction is examined with AspenPlus^{TM} process modelling tool, for diverse operating conditions. Furthermore, the subsequent utilization is optimized by employing a biomass supply optimization and cost minimization tool, which is based on non-linear programming techniques.

Ultimately, the ambition of this study is to develop the roadmap for large-scale implementation of IBCs at multiple applications (district heating, electricity generation and industrial fuel) on a regional or country level. The reasoning behind this is that through the introduction of IBCs, multiple benefits can be offered: (a) the organization of small biomass producers in larger, co-operative schemes; (b) the mobilization of unexploited quantities of biomass; (c) the creation of additional agricultural capital; (d) the development of the primary sector in regions where the other productive sectors decline; and (d) the prevention of energy poverty and the assurance of energy security.

6.1.1 Greek energy market status and main drivers

Electric power began to appear in Greece in 1889 in Athens, when the first power generation unit was built. In the following years and until the founding of PCC (1950), about 400 companies (municipally or privately owned) served almost an equal number of municipalities. Initially, the distribution was done with direct current, which limited the transmission distance – alternating current appeared after 1945.

PPC was founded in August 1950 with the aim to: (a) increase electricity production to a degree that meets growing demand; (b) expand and improve the networks in to supply power to all the municipalities in Greece, even the most remote ones; and (c) organize the distribution. Through a series of projects, which included the exploitation of lignite and the construction of thermal and hydroelectric power plants the electricity generation rose from 234 GWh in 1939 to 1,350 GWh in 1956 and 5,690 GWH in 1966. 41% of electricity came from lignite, 31% from hydroelectric plants and 28% from oil. Lignite continued to dominate the Greek electricity production mix and reached its peak in 1993 (74%) where its use gradually began to decline in favor of natural gas.

Greece, in December 2019, introduced the National Energy and Climate Plan (NECP), following a public consultation and a debate in the Greek Parliament. NECP aims to serve as the key tool for drawing up the national energy and climate policy in the next decade and set out a detailed roadmap regarding the attainment of specific energy and national climate objectives by 2030, which can be considered as more ambitious than the core EU objectives. Specifically:

a) Sets a higher objective for reducing GHG emissions, to enable the transition to a climate neutral economy by 2050
b) Increases the objective for RES penetration in Greek gross final energy consumption

c) Sets a more ambitious energy savings target, thus enhancing the energy efficiency improvement
d) Commits to a radical energy sector transformation by phasing-out lignite in power generation

The individual quantitative targets, which are deemed necessary for fulfilling these objectives, include the reduction of the total GHG emissions by at least 40% compared to 1990, the increase of the RES share in energy consumption (share in electricity should be at least 60% while for heating and cooling it must exceed 40% and 14 % in the transport sector) and the improvement of energy efficiency by 38%. Moreover, in respect to the improvement of energy efficiency, a key target is the increase of the direct use of natural gas in the final consumption sectors by at least 50% compared to 2017.

The promotion of natural gas in Greece is considered a top priority as it is expected to be the intermediate fuel for switching to a low GHG emissions model in all final consumption sectors and may also lead to both improved energy efficiency and lower energy costs compared to other conventional technologies. In combination with natural gas, Renewable Energy Sources (RES), are expected to make a significant contribution to the energy mix of the post-lignite era.

Apparently, the main focus for RES penetration is on the electricity production, with a share exceeding 60% of the gross final electricity consumption. Overall, the aim is for RES to be the major domestic source of power by the middle of this decade. Wind farms and photovoltaics are considered the dominant applications in electricity generation, while for heating and cooling a significant increase in the role of heat pumps, thermal solar systems and geothermal energy is expected.

Despite the projections and commitment to the decarbonization of the energy sector, lignite is still an integral part of the Greek electricity production mix (Figure 71).

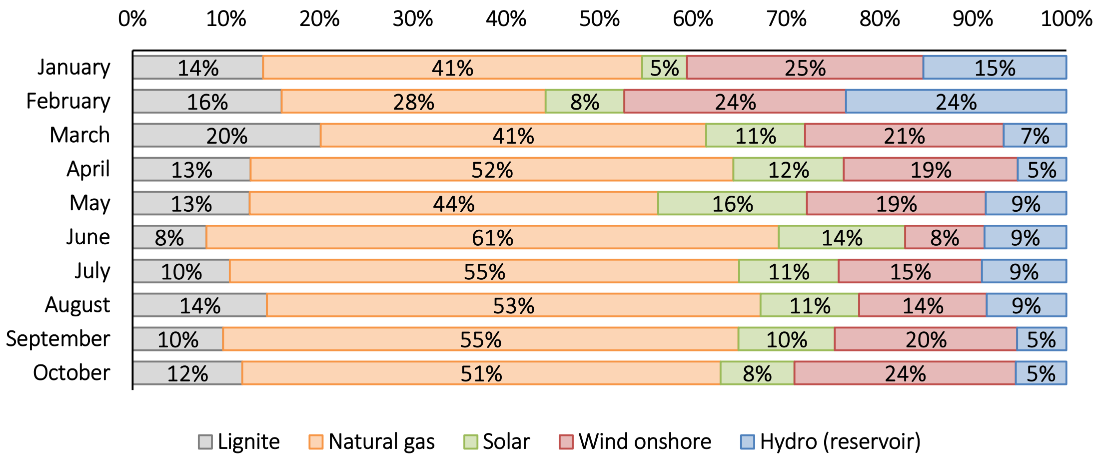

Figure 71. Greek electricity production mix (2021)

Currently, the RES in the electricity mix doesn't exceed 35%, while further penetration poses new challenges. The stochastic nature of solar and wind power generation requires the integration of energy storage applications into the RES power generation sector in to avoid the extensive cut-offs of renewable energy generation (during night-time for instance) and the uneven production during the day. Without the necessary investments in energy storage technologies, wind and solar energy cannot serve as a base-load.

At the same time, the emergence of natural gas as the dominant fuel for the decarbonization period, is proving to being, besides controversial, a problematic strategy. The high dependency on this imported fuel creates additional risks for energy security – natural gas supply is highly susceptible on geopolitical instabilities, while the recent significant price rise (275%) intensifies the fear for upcoming energy poverty. These facts reinforce the belief that lignite needs to be substituted by an endogenous energy source.

Compared to the availability of residual biomass in Greece, the use for energy generation is limited – the absence of certification of the raw materials, obstructs the further promotion. However, in the following years biomass is expected to have a steady, albeit slightly decreasing, use for space heating. In order to promote biomass for energy production, a series of measures are proposed in the NECP, where, among others: (a) priority should be given in the use of agricultural/forestry residues and wastes, as well as in the biodegradable fraction of urban waste and sewage; and (b) the sustainability certification scheme for biofuels, bioliquids and solid fuels should be maintained and extended to ensure that only sustainable biofuels, bioliquids and solid fuels are used in the Greek territory. These two measures are particularly important and can act as major enabling factors for the promotion of IBCs from agricultural residues in the energy sector.

NECP can be described as an overly ambitious plan, especially the gradual phasing-out of lignite use in power plants and the cease of operation of the existing PPC-owned lignite units by 2023, except for the under-construction Ptolemaida 5 unit (which will be closed in 2028), essentially requires the re-organization of the country's industrial production and the radical transformation of the national energy model, in a coordinated and fair manner for the under-transition areas of WM and Megalopolis.

To meet the above challenges, Greece, in addition to the NECP, introduced in September 2020 the Just Transition Development Plan of lignite areas (JTDV), which is based on three pillars: (a) employment protection; (b) mitigation of the socio-economic impacts of the decarbonization; and (c) energy self-sufficiency of lignite areas and the country in general.

According to the JTDV, the vision for the "next day" in WMR is based on five principles:

- Create new employment opportunities in the local community by emphasizing labour-intensive areas.
- Utilize the inherent advantages of WMR, including the high technical level of existing workforce, the large green energy potential (solar, biomass), the proximity to large urban areas, the prospects of smart agriculture based on the strong primary sector, etc.
- Ensure a quick transition, built on solid foundations and focusing on realistic solutions.
- Promote social and environmental sustainability, emphasizing on sustainable development.
- Promote innovation and integrate modern technology.

These five principles highlight the country's need to reduce GHG emissions and diversify the regional economy through decarbonization, while maintaining and creating new jobs in productive sectors. Promoting the goal for lignite phase-out and the commitment to a carbon-free energy supply can offer an opportunity to restart WM's economy based on strong productive sectors, such as smart agricultural production – the necessary modernization of agricultural production if linked to the organized utilization of the produced biomass for energy production, can improve energy security and create employment opportunities in both agriculture and clean energy, without putting any additional burden on energy consumers. Consequently, the implementation of IBC schemes can open up the energy market for currently unexploited biomasses, like agricultural residues, that have currently unacceptable conditions and properties, further increasing the sustainability of the agricultural sector.

6.2 Torrefaction technology

6.2.1 Torrefaction process

A possible medium for the successful utilization of agricultural residues is their conversion to IBCs. Generally, IBCs are produced from various biomass sources – like forest biomass, cultivated biomass (energy crops), biomass residues – under different conversion routes, namely, thermo-chemical, physical-chemical and bio-chemical. These intermediate products have upgraded properties (analogous to fossil fuels) and higher energy density than in their raw format, enabling their transport and long-term storage.

Torrefaction is a biomass conversion process that falls into the thermo-chemical conversion category, where raw biomass is heated in an inert atmosphere at temperatures between 250 and 320 °C (the temperature depends on the feedstock characteristics) to generate an upgraded high-quality solid biofuel with far greater energy density and calorific value than the original feedstock, providing significant benefits in logistics, handling and storage, as well as opening up a wide range of potential uses.

During torrefaction, three products are generated:

1. A stable, homogenous solid biomass (brown to black colour), 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 by-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 72). The amount and calorific value as well as the chemical composition of the torr-gas depend on the feedstock and on the degree of torrefaction (torrefaction temperature). Typically, a torrefaction unit is aimed to operate in a self-sufficient manner (autothermal operation).

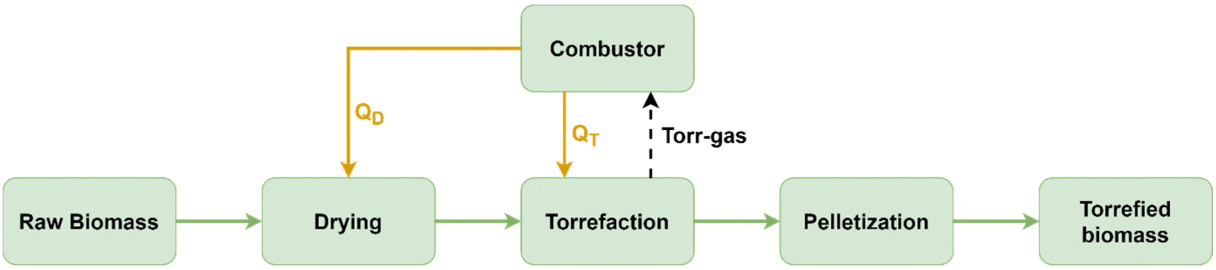

Figure 72. Simplified schematic of torrefied biomass production

The torrefaction process can be divided into the following 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 free water evaporates under constant temperature.

3. **Post-drying.** The temperature is increased up to 250 °C. The residual water (present in the 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 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 (Table 47), residence time, heating rate, biomass composition and reactor type.

Table 47. 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		

For the purposes of the Greek Case Study, the effect of temperature and biomass composition were examined, while the other parameters were considered constant for all cases.

The solid torrefied products show relatively similar characteristics as coal (Table 48). Torrefaction combined with densification provides an energy dense fuel of 19 to 24 GJ/tn, in the form of pellets (by roller pressing or extrusion) or briquettes (by piston or roller briquetters or extruders), in line with ISO TS 17225-8 requirements in mechanical durability and fines content.

Table 48. Indicative properties of torrefied wood pellets, different biomass types and coal-based fuels.

Parameter	Wood	Wood pellets	Torrefied wood pellets	Charcoal	Coal
Moisture content (% a.r.[11])	30-45	7-10	3-8	1-5	10-15

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[11] a.r. = as received, relating to 'raw' biomass without pre-treatment

Net Calorific value a.r. (MJ/kg)	9-12	15-16	19-24	30-32	23-28
Volatiles (% d.b.[12])	70-75	70-75	55-65	10-12	15-30
Fixed carbon (% d.b.)	20-25	20-25	28-35	85-87	50-55
Bulk density (tn/m^3)	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	Hydrophilic	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 consistency	Limited	High	High	High	High
Transport cost	High	Average	Low	Average	Low

Evidently, torrefied biomass has superior characteristics over raw biomass and similar to fossil fuels, while torrefaction, as a technology, possesses feedstock flexibility, opening up the energy and biocarbon market for agricultural by-products, grassy crops and other underutilized biomasses with unacceptable, under current conditions, properties. Consequently, the implementation of torrefaction in WMR, can be a possible solution for the utilization of agricultural residues in energy and industrial applications, depending, though, on the economics of the overall value chain – the additional capital and operating expenses of the torrefaction unit should be offset by savings in the raw biomass supply chain (logistics, storage, handling) and higher energy densities.

6.2.2 Torrefaction technology status

There are enough torrefaction reactor options to cover any potential application. Different reactor configurations (Table 49), 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. 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.

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[12] d.b. – 'dry basis'

Table 49. Torrefaction reactor configurations

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	+	+	+

Torrefaction is a mature technology; however, its applicability has only been proven on a research or demonstration scale, large-scale industrial proof is still being worked on. Torrefaction units with capacities of 100,000 tn/a or higher are currently under construction or in permitting phase (Table 50).

Table 50. Indicative list of torrefaction units

Location	Status	Commisioning	Capacity	Intended Net Calorific Value	Product form
Austria	In operation	2013	8,000 tn/a	22-23 GJ/tn	Briquette
Belgium	In operation	Expected in 2022	30,000 tn/a	22-28 GJ/tn	Powder
Ireland	In operation	Not available	10,500 tn/a	Not available	Not available
Portugal	In operation (not at full capacity)	Q4 2020	120,000 tn/a	18-22 GJ/tn	Pellet
United Kingdom	In operation	Not available	30,000 tn/a	21 GJ/tn	Pellet
Canada	In operation	2016	15,000 tn/a	22 GJ/tn	Pellet
United States	In operation	2012	75,000 tn/a	25-30 GJ/tn	Pellet
United States	In operation	2019	90,000 tn/a	21-23 GJ/tn	Pellet, briquette
Estonia	Under construction	Q4 2020	157,000 tn/a	21 GJ/tn	Pellet

Russia	In permitting phase	Q4 2021	80,000 tn/a	21-25 GJ/tn	Pellet
Canada	In permitting phase	Q1 2021	100,000 tn/a	21 GJ/tn	Pellet
United States	In permitting phase	2022	400,000 tn/a	25-30 GJ/tn	Pellet
Ethiopia	In final negotiation	2023	60,000 tn/a	22-23 GJ/tn	Briquette
Finland	In final negotiation	2023	60,000 tn/a	22-23 GJ/tn	Briquette

The development of the torrefaction industry is similar to that of the wood pellet industry in its infancy years. Despite the fact that torrefied biomass has superior characteristics over raw biomass and similar ones to fossil fuels, end-users are reluctant to rely in this technology – requiring proof of continuous operation in an industrial scale before signing a purchase and supply contract. Project developers, on the other hand, require supply agreements with end-users before investing in a large-scale torrefaction unit. Therefore, the torrefaction industry was on a standstill for quite some time and only these days (and to cope with the decarbonization objectives) several large-scale projects emerged.

6.2.3 Potential applications

Originally, torrefied biomass was intended for use in thermal power plants, substituting coal partially or completely. However, the pursuit of climate-neutral economy and the increasing price for carbon emissions, have opened the door for torrefaction products to find application to a wide range of diverse markets and industrial sectors (**Figure 73**).

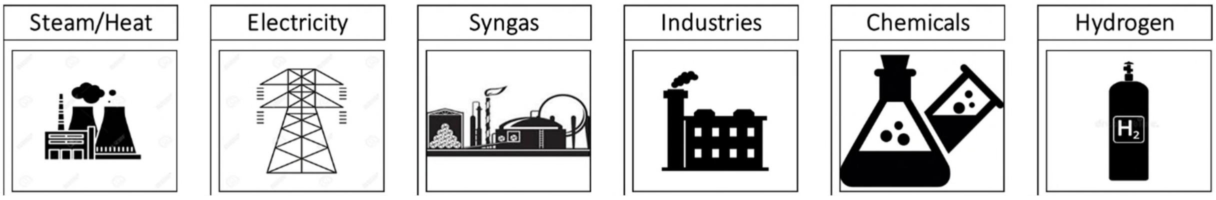


Figure 73. Torrefaction products potential applications

Upgraded properties and high-quality, make torrefied biomass the most promising biomass fuel for use in: (a) electricity and heating sector; (b) energy-intensives industries; and (c) additional non-energy related sectors such as the mining and metallurgical industry, the non-metallic mineral industry (glass, ceramic materials, and cement), or the chemical and petrochemical industries.

The main focus of the Greek Case Study is the introduction of torrefied biomass in district heating applications, electricity generation and energy-intensive industries.

6.3 Advanced case study results

6.3.1 Municipal district heating company of Amyntaio

DETEPA was established in 1997 to administrate the municipal DH system. From 2005 until 2020, it received its heat capacity from Amyntaio CHP (7 €/MWh for the excessive heat). As the post-lignite era is approaching rapidly, DETEPA implemented the first DH plant that uses locally available biomass on a large scale in the region, to completely cover the heating demands of the approximately 4,000 residents of the area, upon the insertion of up to 100% of biomass in the fuel mix. The total capital investment cost was approximately 12,000,000 €. The DH plant has the following general characteristics: (a) two combustion boilers of a nominal capacity of 15 MW each (i.e., medium scale) are installed to meet the needs of DH; (b) a mixture of lignite and biomass is used as fuel; (c) the used biomass consists of corn residues and wood-chips – the latter are used to partially cover the biomass demand until the supply chain of corn residues is developed; and (d) the residual biomass is in principle collected by farmers.

Although DETEPA (30 MW_{th}), is the smallest of the three DH companies in WMR (DEYAK peak load, 171 MW_{th}, DETIP peak load, 140 MW_{th}), acted first and ensured, to a large extent, the continuation of its operation and at the same time became a pioneer of biomass utilization, having the opportunity to upgrade its status and grow into a key player in a potential biomass market.

Thermal energy consumption from DH stood at **42,732 MWh** in 2015 and **44,220 MWh** in 2016, while, during the first year of operation (October 2020 – May 2021), DETEPA utilized **30,000 MWh** of lignite and approximately **36,000 MWh** of biomass (wood-chips), a relatively large amount to mobilize, especially in an underdeveloped biomass supply market. As a result of the partial transition to biomass-based fuels, the produced heat selling price rose approximately by 38% (to 56.8 €/MW_{th} from 41.3 €/MW_{th} in 2019).

In this context, the advanced case study dealt with the conversion of corn residues, to IBCs through torrefaction and their subsequent utilization – as alternative to lignite – in the DH plant of DETEPA.

6.3.2 Implementation in municipal district heating

The torrefaction schemes that were analysed and compared concern applications in the DH plant of DETEPA in WMR. Two options were examined, regarding the torrefaction unit operating time, **Option 1** concerns six months of operation, while, **Option 2**, 12 months of operation. These options differ mainly in the size of the torrefaction reactor required and secondarily in the storage needs for raw and torrefied biomass. Both options cover the monthly fluctuations of the thermal energy demand. Additionally, as DETEPA mainly utilizes lignite and wood-chips, the replacement of the lignite part (50% - energy based) of the fuel-mix, was considered for both options.

The economic feasibility of the two stand-alone torrefaction concepts were studied in terms of: (a) seasonal biomass availability; (b) seasonal biomass procurance costs; (c) storage costs; (d) logistics costs; (e) capital expenses; (f) operational costs; (g) energy demand; and (h) optimal capacity of the torrefaction reactor.

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, based on non-linear programming, was used to determine the optimal use of biomass for each torrefaction scheme and minimize the cost through optimal time planning for biomass procurement and maximum torrefaction unit capacity.

Table 51 presents the comparison between the total cost in €/MWh of the different fuel-mixes, after the biomass supply optimization and cost minimization of the individual torrefied biomass supply chains.

Table 51. Comparison of fuel-mix cost (including then and current carbon price)

Fuel	Lignite (33€/tn carbon price)	Lignite (85€/tn carbon price)	Torrefied biomass (Option 1)	Torrefied biomass (Option 2)	Wood-chips
Fuel demand (tn)	18,510	18,510	6,384	6,384	7,600
Fuel price (€/tn)	35.00 €	35.00 €	240.61 €	214.73 €	89.00 €
Fuel price (€/MWh)	19.00 €	19.00 €	45.06 €	40.21 €	19.84 €
Fuel cost €	647,729 €	647,729 €	1,536,039 €	1,370,818 €	676,365 €
Carbon cost (€)	415,364 €	1,069,877 €	-	-	-
Fuel cost (€/MWh)	31.18 €	50.38 €	45.06 €	40.21 €	19.84 €
Fuel mix	Lignite/Wood-chips	Lignite/Wood-chips	Option 1/Wood-chips	Option 2/Wood-chips	
Fuel-mix cost (€/MWh)	25.51 €	35.11 €	32.45 €	30.03 €	

For DETEPA the current fuel-mix (50% wood-chips, 50% lignite) has a total cost of 25.51 €/MWh of fuel, including the carbon price for the CO_2 emissions from the use of lignite (33 €/tn), while, after the implementation of torrefaction, the total cost increases to 32.45 €/MWh for Option 1 and 30.03 €/MWh for Option 2. However, taking into account a carbon price of 85 €/tn, torrefied biomass, for both options, is proving to be cheaper than lignite.

Although the implementation of torrefaction does not appear to be financially advantageous for DH applications, this could be misleading. The feasibility analysis of the torrefied biomass value chain was performed under the limitations provided by the underdeveloped local agricultural residues market. At the same time, the large fluctuations in demand between months and dependence on weather conditions make it necessary to install a torrefaction reactor with a larger capacity than a unit that doesn't follow the thermal heat demand, thus, the capital cost and ultimately the overall cost are greatly increased. Additionally, carbon price over 72 €/tn erode the financial advantage of lignite. For carbon price above this level, torrefied biomass become a more competitive alternative to fossil fuels.

6.3.3 Environmental footprint

In the considered torrefied biomass value chain of the Advanced Case Study, corn residues are collected in WMR. This feedstock is transported by truck to a torrefaction unit. Subsequently, the torrefied biomass is fuelled – to substitute lignite – in DETEPAs DH plant. The produced heat is then fed into the DH network and used by households for space heating. The GHG emissions of the overall chain as well as the emission savings have been assessed using the methodology given in Annex VI of the RED II. The calculations revealed that they are emitted **8.9 gr CO_2 eq per MJ of heat** produced from torrefied biomass, resulting in an **88.9% GHG emission savings** in the case of lignite substitution.

6.3.4 Lessons learned

Biomass is an alternative fuel source, that can partially or completely replace heavily polluting fossil fuels and facilitate the reduction of emitted CO_2. Nevertheless, is accompanied by significant additional requirements that can increase the energy production cost. This can be attributed to the seasonal availability, the physical and chemical properties of biomass that implicate its acquisition, as well as the transport and storage stages of the overall supply chain.

The major issues that DH companies face in view of large-scale biomass utilization, concern handling/firing biomass feedstocks with diverse characteristics, especially agricultural residues, the lack of cooperation between DH plants and local farmers, leading to unexploited biomass quantities, the difficulties in entering into contracts with biomass suppliers (because of the inconsistent properties) and finally the seasonal variability in quantities and properties that create an insecurity of supply. All of the above render DH plants unable to fully utilize the potential capacities of local biomass and force the procurement of standardized biomass fuels. These raw materials (wood chips) are usually imported, which actually moves jobs abroad instead of creating them in the local labour market. In this context, it is particularly important to develop appropriate strategies that could facilitate the establishment of biomass supply chains in regions under rapid decarbonization to overcome all obstacles regarding the utilization of biomass in a local level. In this way, it will be possible for the agricultural sector to develop and fill the gap left by the cessation of fossil fuels, while increasing the energy security through the use of raw materials from local, endogenous biomass sources.

This prospect requires the transformation and upgrading of the regional biomass supply chains, in a way that they can offer the opportunity to produce a homogenized product that can be utilized by multiple end-users without further processing. The purpose of this upgraded value chain should be the exploitation of the untapped biomass capacities, the valorisation of agricultural residues (determination of the actual market price), the generation of additional agricultural income (this revenue has the potential to be channelled into the internal market, sustaining the employment in the local tertiary economic sector), the minimization of the overall supply chain cost, the improvement and uniformization of the chemical and physical properties of the various biomass feedstocks for utilization by a diverse range of end-users and ultimately the enhancement of region’s energy sustainability and security.

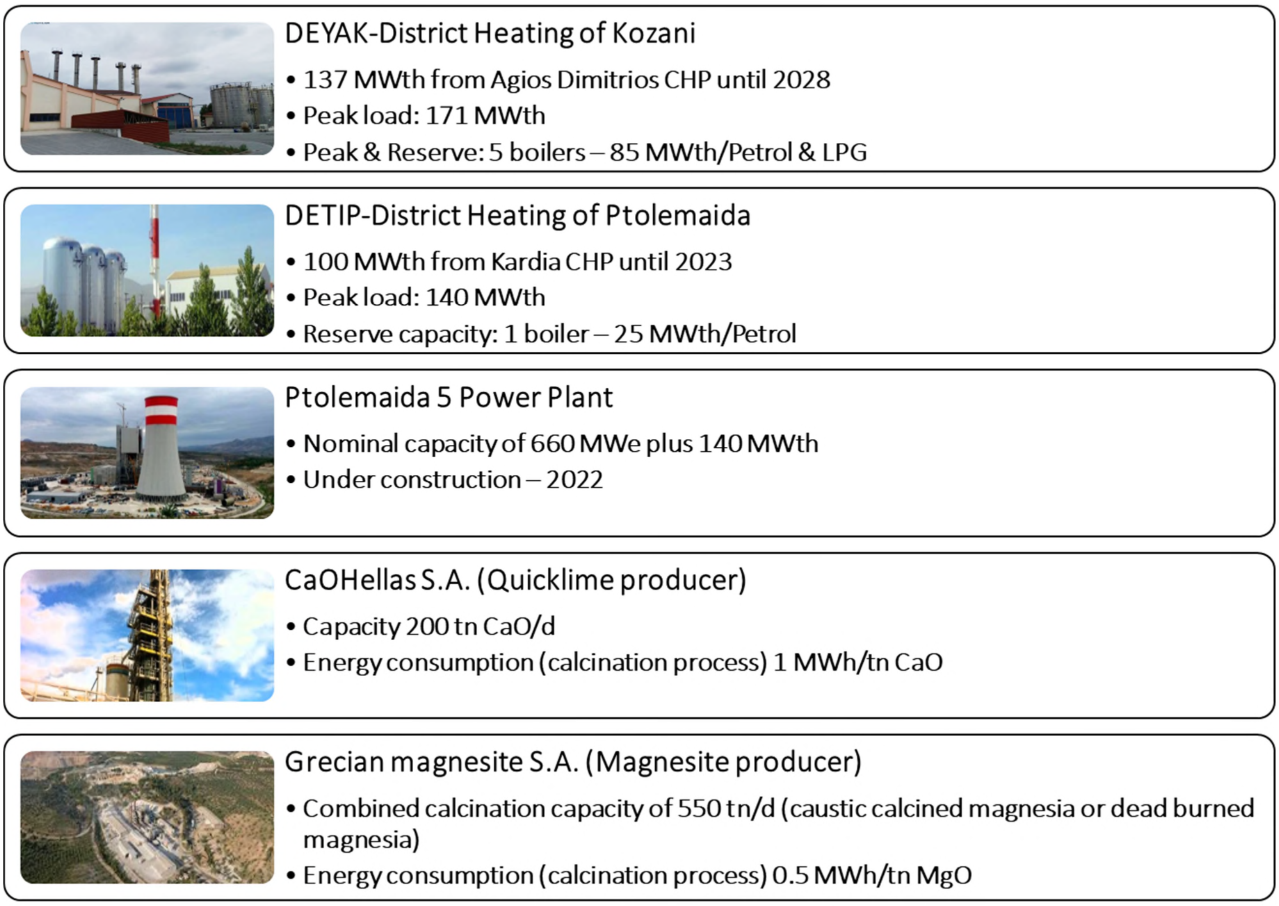
Key points of the Advanced Greek Case study:

- DETEPA can handle woody biomass without issues. Torrefaction could solve the handling problems of non-woody biomass.
- Enough biomass is widely available in WMR. There is no need for long-distance transport.
- Biomass procurement costs are inextricably linked to the existence of an established biomass market.
- DETEPA can mitigate the torrefaction unit capital cost in case it expands its activities. DETEPA can act both as a DH company 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.
- The lignite phase-out is a huge challenge for Western Macedonia. The region’s GDP is deeply intertwined with PPCs activities. An industry that will exploit the experienced work-force 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 drives to the discovery of the applicability (technologically and economically) of a torrefied biomass value chain supplying the DETEPA plant. Consequently, this endeavour constitutes the roadmap 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.

6.4 Strategic case study concept

The Strategic Case Study builds upon the torrefied biomass value chain supplying the DETEPAs 30 MW_{th} DH plant in the Amyntaio area and investigates the large-scale implementation of torrefaction at multiple applications in WMR (Figure 74).



DEYAK-District Heating of Kozani
- 137 MWth from Agios Dimitrios CHP until 2028
- Peak load: 171 MWth
- Peak & Reserve: 5 boilers – 85 MWth/Petrol & LPG

DETIP-District Heating of Ptolemaida
- 100 MWth from Kardia CHP until 2023
- Peak load: 140 MWth
- Reserve capacity: 1 boiler – 25 MWth/Petrol

Ptolemaida 5 Power Plant
- Nominal capacity of 660 MWe plus 140 MWth
- Under construction – 2022

CaOHellas S.A. (Quicklime producer)
- Capacity 200 tn CaO/d
- Energy consumption (calcination process) 1 MWh/tn CaO

Grecian magnesite S.A. (Magnesite producer)
- Combined calcination capacity of 550 tn/d (caustic calcined magnesia or dead burned magnesia)
- Energy consumption (calcination process) 0.5 MWh/tn MgO

Figure 74. Potential end-users of torrefied biomass

The main goal is to explore the economic viability of various torrefaction schemes, which concern applications in DH (DEYAK, DETIP), electricity generation (Ptolemaida 5) and energy-intensive industries (CaO Hellas, Grecian Magnesite), by comparing the total torrefied production costs of the different implementation scenarios with the current market prices of lignite and wood-chips.

The feedstock for the torrefaction units is provided in the form of agricultural residues. Specifically corn residues, fruit-tree pruning and vineyard pruning. These biomass types are collected within WMR and transported by truck firstly to central storage points and subsequently to a torrefaction unit. To expand the current biomass capacity and enable large-scale implementation, the import of corn residues from the neighbouring region of Thessaly was considered. Truck transport from several central storage points within Thessaly, was also employed.

Torrefied biomass is fuelled – to substitute lignite – in the DH plants of DEYAK and DETIP for the production of heat, as well as in Ptolemaida 5, for electricity generation purposes. In CaO Hellas and Grecian Magnesite the torrefied biomass is considered as a replacement of pet-coke used in the calcination process.

The torrefaction process was simulated through a modelling tool, set for autothermal operation under variable feedstock properties. While the biomass procurement planning and torrefied biomass production optimization was carried out by a biomass supply optimization tool, over a set of variables and conditioned to the satisfaction of a system of constraints.

6.5 Biomass supply chains

6.5.1 Biomass availability

Despite the fact that WM's economy is dominated by lignite-related activities, the primary sector, including agriculture, forestry, farming and livestock activity, plays a key role in the region's GVA (7%), employing more than 20% of the local workforce. The arable plains of WMR (40% of them are irrigated) are cultivated intensively, producing several (apples, peaches, corn etc.) agricultural products.

Thessaly, located in central Greece (neighbouring region of WM), is sometimes referred to as the "breadbasket" of Greece. The region is the fifth largest in terms of land area and has some of the most fertile agricultural lands in Greece. Thessaly is a major food producer, while the region's economy depends strongly on agriculture as a relatively high percentage of the population is partly or fully employed in agriculture – the share of the primary sector in regional GVA was 12.3%, topping the ranks of all other regions in Greece.

This kind of agricultural activity leads to the production of significant amounts of agricultural residues in both regions, a biomass source that remains mostly unexploited. Annually in WMR there are available 19,037 tn of corn residues, 21,218 tn of fruit-tree pruning and 1,747 tn of vineyard pruning, while in Thessaly 58,646 tn of corn residues are annually available, especially in Larisa and Karditsa (Figure 75).

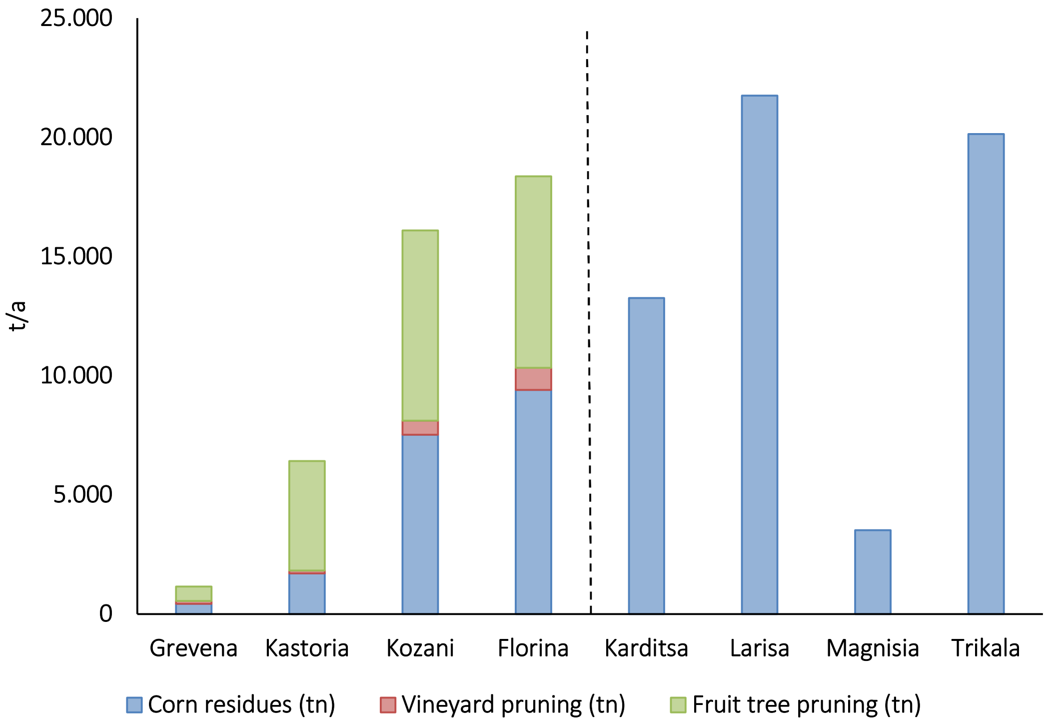


Figure 75. Biomass availability in WMR (left) and Thessaly (right)

Historically, these materials have been used for animal bedding, burned, or left on fields. However, agricultural residues can be an important energy source if the biomass inherent problems can be solved. Biomass is usually associated with: (a) inconsistent physical and chemical properties during the year; (b) special handling requirements; (c) storage difficulties due to the biological degradation; (d) higher transport cost; and most importantly (e) seasonal availability, which creates uncertainty regarding the continuous and uninterrupted supply.

The seasonal availability issue is best illustrated in Figure 76, where the monthly availability of corn residues, fruit-tree pruning and vineyard pruning in the regions of WM and Thessaly is presented.

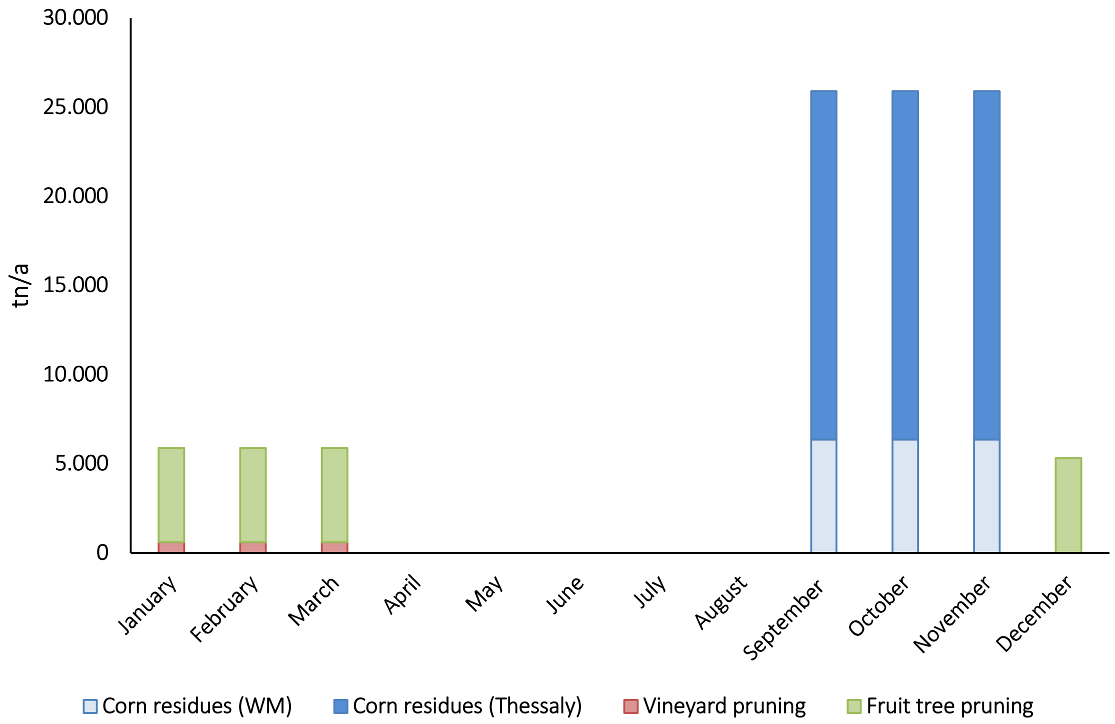


Figure 76. Biomass availability per month and type

Agricultural residues are available (in varying quantities) in both regions from September to March, while, during the late spring and summer months, there is a lack on biomass availability, which, in case of utilization for energy applications must be covered by additional infrastructural requirements (storage facilities), increasing the specific energy cost and the mass loss due to biological degradation. Consequently, there is a need to effectively improve the agricultural residues properties, for better handling and storage, while the production of a homogenized and stable product can open up a diverse range of markets that agricultural residues can find application for. This further demonstrates the importance of implementing torrefaction in WMR.

Finally, biomass torrefaction 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 is essential to the successful biomass mobilization in WM.

6.5.2 Collection procedures - Analysis and cost

An important aspect of agricultural residues economics is the supply chain and especially the collection procedures. As biomass supply chains have a completely different structure compared to the lignite one, even supply chains of different biomass types present great disparities. Therefore, a thorough and extensive investigation of the various stages, comprising the overall supply chain is needed, specifically in WMR, where 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. The regional agricultural production scheme has as main purpose food or feed production; agricultural residues are not considered as part of this production system. Therefore, farmers tend to overlook the vast economic potential of this biomass type and consequently, current agricultural management practices jeopardize the provision of biomass resources for energetic use. Synergy between primary product cultivation and residual biomass collection is essential for the development of new bio-based products and the accurate assessment of their market opportunities.

Figure 77 presents the collection cost of the raw biomass types considered for the Greek Case Study. Actual, on-field data and collection parameters (biomass quantity, collection time, diesel fuel consumption, equipment needed, workforce, techniques and hindrances), were recorded and analysed. The scope was to investigate, stage by stage, the cost of the biomass value chain and identify any problems and obstacles about the physical supply chain, affecting the mobilization of these locally available biomass resources and ultimately their utilization for energy purposes.

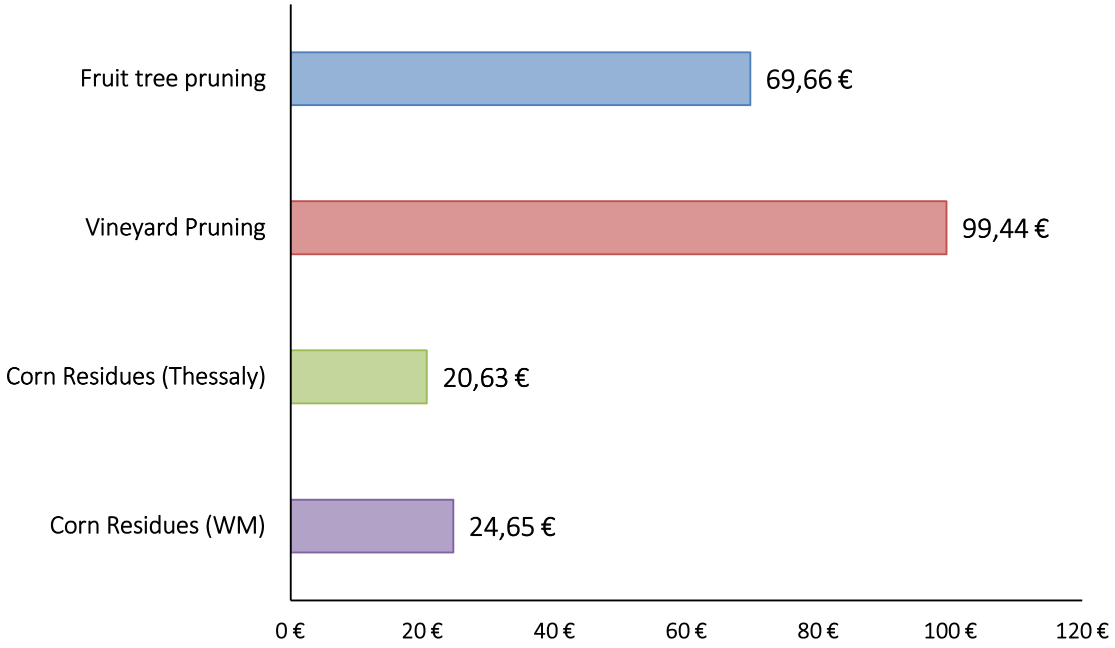


Figure 77. Collection costs (€/tn) for the raw biomass types under consideration

The data analysis of the different biomass types collection procedures revealed that corn residues are the cheapest feedstock. The total collection costs are approximately 21 €/tn for corn residues from Thessaly, while in WMR the same type costs around 25 €/tn. The different techniques followed, and the machinery used during the collection in these two regions, affect significantly the total cost (Table 52).

Table 52. Collection cost of corn residues by stage, WMR and Thessaly

Stage	Corn residues – WMR	Corn residues – Thessaly
Mulching (€/tn)	5.73 €	3.99 €
Windrowing (€/tn)	3.32 €	-
Baling (€/tn)	8.44 €	11.31 €
Loading (€/tn)	5.37 €	3.60 €
Unloading (€/tn)	1.78 €	1.73 €
Total cost (€/tn)	**24.65 €**	**20.63 €**

Common sense among the local farmers, the transporters and the end-users, is that the transport cost is the inhibiting factor for mobilizing corn residues, based on the premise that the relatively low levels of energy density (energy per volume unit) have the tendency to increase the overall cost and the complexity of the supply chain. However, based on the observations from the collection procedures, it can be concluded that the equipment used can have a similar effect. Unsuitable, modified, agricultural tractors, that also may have a higher engine power than needed, increase the total collection cost. Therefore, a standardization and homogenization of the collection procedures is essential to the successful and cost-effective mobilization of corn residues. Moreover, bales, the form which the corn residues are extracted from the field, require careful handling by experienced staff. Careless handling leads to unbundling of the bale and to biomass losses, re-bundling is possible, but it increases costs.

Apart from the economic aspect, but in direct relation to it, large unexploited quantities of corn residues were observed in both regions. A limited part is used as fodder while the remainder is usually left on field or even worse, burned, making it difficult to specify the actual market value of this biomass feedstock.

The total collection costs for vineyard pruning are the highest among the examined biomass types (99.4 €/tn), mainly due to the low yield – 0.85 tn/ha, compared to 2.6 tn/ha for corn residues. Yield depends on the variety grown, the primary product (wine or grapes for consumption), cultivation practices and various soil, weather and environmental factors that affect agriculture as a whole. The overall low availability in WMR (1,747 tn/a), as well as the high collection costs, make this biomass resource non-viable for energy purposes, from an economic perspective in a possible biomass supply chain. However, for the purposes of the cost analysis, it is considered as a part of IBC value chain, to investigate the effect of high feedstock cost to the total torrefied biomass production cost.

Fruit-tree pruning is the largest biomass source in WMR (21,218 tn/a), presenting, at the same time, the highest yield (4.3 tn/a). Nevertheless, due to the non-fully mechanized collection procedures, the overall biomass supply cost is significantly higher than for corn residues (69.66 €/tn). Labour costs make up 87% (60.3 €/tn) of the total cost, rendering this biomass type – like vineyard pruning – an expensive source for torrefied biomass production.

In summary, corn residues are considered the most economically (feedstock cost-wise) viable option for biomass torrefaction. The availability in WMR is significant but can’t support large-scale implementation in WMR alone – corn residues import from regions where availability is even higher (like Thessaly) is necessary. In any case, collection procedures standardization is imperative to minimize and stabilize the collection cost. Fruit-tree pruning is an immense biomass resource in WMR and elsewhere – fully mechanized collection procedures are important for the improvement of the economic efficiency of the supply chains. Vineyard pruning present high collection cost and low availability and yield; therefore, they can be excluded from a potential torrefied biomass value chain.

6.5.3 Torrefaction unit location and logistics

Logistics refers to the overall process of managing the efficient and cost-effective flow and storage of resources, from the point of origin until the transport to their final destination, in accordance with end-user’s requirements. Proper logistics planning reduces the risk of incurring problems that may lead to additional costs and delays. In this sense, the prospect of multiple storage options, to facilitate the effective flow of raw biomass to the various torrefaction schemes, is explored.

WMR is divided into four regional units (Kozani, Florina, Kastoria, Grevena), while Thessaly is divided into five (Larisa, Karditsa, Trikala, Magnisia and Sporades). As Sporades are islands, they are considered outside of this assessment. The torrefaction units for the different implementation options are considered to be co-located with the respected application. In each regional unit of the two regions, a central storage point is considered. Therefore, for the case where the biomass feedstock originates only from WMR, four central storage points are taken into account, while in the case of importing corn residues from Thessaly the total number of storage points, increases to eight. Furthermore, an extra scenario explores torrefaction of corn residues only from Thessaly. A central torrefaction unit in Larisa is being considered and the raw biomass is being transported from the four storage points of this region.

The required biomass for the different torrefaction schemes can be found in a circular area around each central collection point. 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. The average transport distance from the collection points to the central storage points is 21 km for WM and 36 km for Thessaly. The average transport distance from the central storage points to the torrefaction unit is 54 km for WM and 147 km for Thessaly. For the additional scenario, the average transport distance from the central storage points is 46 km and from the torrefaction unit to end-users, 115 km.

The transport distances are input variables of the biomass supply optimization tool, minimizing the total torrefied biomass production cost according to the location of the biomass collection points, central storage points and torrefaction units.

6.6 Conversion to Intermediate Bioenergy Carrier

6.6.1 Implementation scenarios

For the purposes of the case study, the feasibility of twenty-two torrefaction schemes, divided into two scenarios, were investigated. Table 53 summarizes the main characteristic of the cases considered. The torrefied biomass demand corresponds to the complete satisfaction of energy needs for each specific case. **Scenario 1** accounts only biomass collected within WMR and **Scenario 2** adds corn residues from Thessaly.

Table 53. Implementation scenarios and demand coverage

	Torrefied biomass demand (tn)	Scenario 1: “Only biomass from WMR” (%)	Scenario 2: “Corn residues import from Thessaly” (%)
50% DETEPA	5,888	100%	100%
100% DETEPA	11,776	100%	100%
50% DETIP	17,993	100%	100%
100% DETIP	35,987	60%	100%
50% DEYAK	35,097	62%	100%
100% DEYAK	70,194	31%	73%
2% Ptolemaida 5	45,596	48%	100%
5% Ptolemaida 5	113,990	-	-
10% Ptolemaida 5	227,979	-	-
CaO Hellas	13,850	100%	100%
Grecian Magnesite	18,836	100%	100%

All torrefaction schemes are designed for torrefied pellet production at varying mass rates (based on the feedstock properties), while they are considered to be co-located with the respected application, sharing the storage space and handling equipment. Co-location will result in benefits for feedstock logistics. The heat demand of drying and torrefaction is covered by the combustion of torr-gas.

For each DH unit, two different implementation schemes, were considered: (a) 50% fulfilment of thermal demand; and (b) 100% fulfilment. The thermal demand of DETIP corresponds to a new 140 MW_{th} DH unit and of DEYAK, to a new DH unit of 180 MW_{th}. Biomass capacities of WMR (**Scenario 1**) could only cover up to 21,764 tn of torrefied biomass demand, while **Scenario 2**, boosts up the production to 50,972 tn. Ptolemaida 5, due to its immense size (660

MW$_e$), substitution rates of under 1% could be achieved for Scenario 1 and just over 2% for Scenario 2. The demand of CaO Hellas and Grecian Magnesite could then completely be fulfilled by both scenarios.

6.6.2 Torrefaction process simulation

For the simulation of the torrefaction process the AspenPlus^{TM} modelling tool was employed. The overall torrefaction model consists of three subsystems (Figure 78), namely: (a) drying; (b) torrefaction; and (c) off-gas utilization, with each system represented by AspenPlus^{TM} unit operation models, coupled with FORTRAN calculators and design specs.

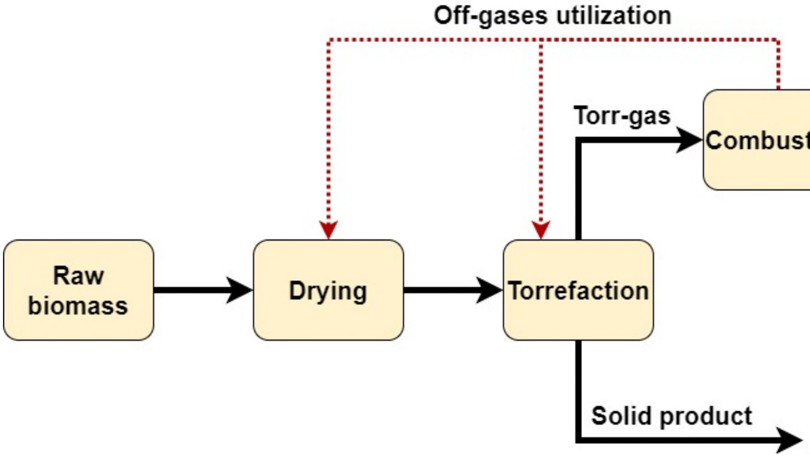


Figure 78. Process scheme of biomass torrefaction model

The biomass streams were treated as non-conventional components and used as a basis for mass balance calculations, while the torrefaction yields and characteristics are based on correlations derived from real experimental data. For each system and operating conditions, the collected/required heat was calculated. An important aspect of the model is that the torr-gas should cover the energy requirements for drying and torrefaction.

The developed tool is flexible in term of studied operating conditions and could be accurately utilized for the calculation of the mass and energy balances, the product yields and the thermal characteristics of the process. Moreover, it can be utilized for diverse capacities, variable torrefaction conditions and different heat utilization schemes. Some general results of the torrefaction simulation model are shown in Table 54.

Table 54. Results of the biomass torrefaction process simulation

Parameter	Corn residues	Fruit-tree pruning	Vineyard pruning
Energy efficiency (% d.b.)	89	87	86
Mass Yield (% d.b.)	71	77	74
Feedstock moisture content (%)	30	34	34
Product moisture content (%)	3	3	3
Feedstock energy content (LHV)	3.07 MWh/t	3.23 MWh/t	3.08 MWh/t

Product energy content (LHV)	5.79 MWh/t

6.6.3 Supply optimization and cost minimization

In this study a tool has been developed for a torrefaction unit that accounts for biomass procurement under realistic availability conditions, storage and torrefied biomass production for a set of operating conditions, provided by the AspenPlus^{TM} torrefaction simulation model and the subsequent utilization at various applications, taking into consideration the actual monthly energy demands (Figure 79).

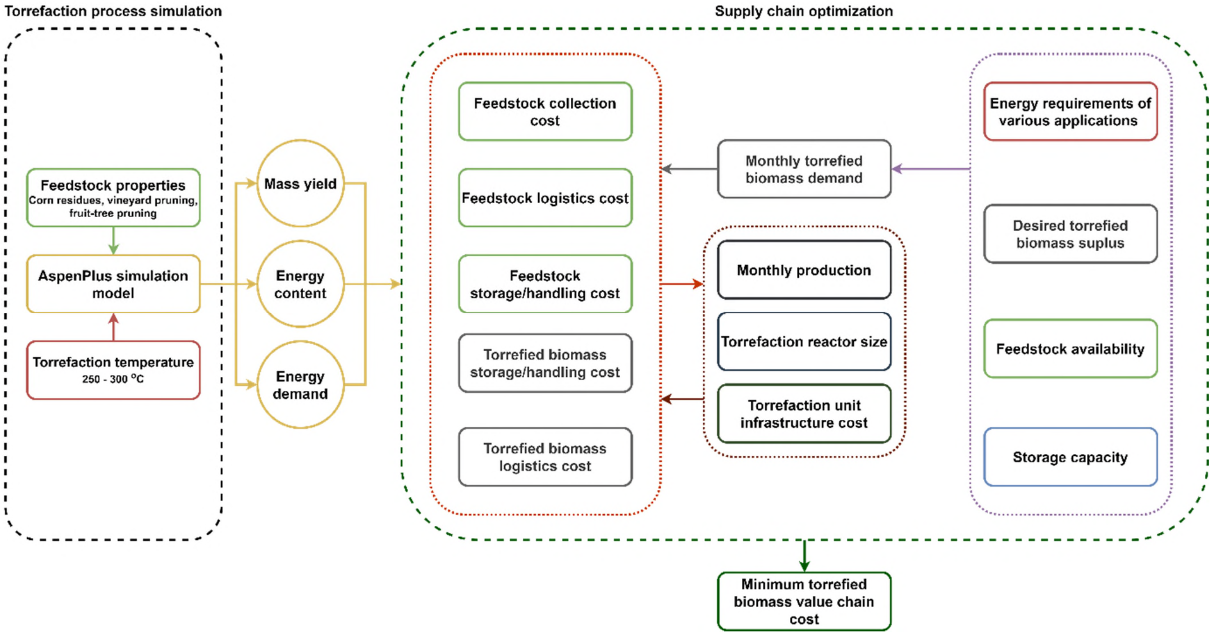


Figure 79. Supply chain optimization tool: process flow

Specifically, a non-linear programming (NLP) problem is developed for the calculation of the optimal schedule of biomass procurement, torrefied biomass production and utilization based on the minimization of the overall costs. The biomass supply optimization tool determines the optimal use of biomass for each operational option and minimizes the cost of the different case scenarios. The model provides an optimal solution over a twelve-period planning horizon, by minimizing the non-linear objective function over a set of variables and conditioned to the satisfaction of a system of equalities and inequalities (constraints). The variables for the specific tool concern the following:

- the quantities of biomass feedstock bough
- the quantities of feedstock stored for conversion during periods where biomass availability is low,
- the quantities of utilized feedstock in the torrefaction reactor
- the quantities of produced torrefied biomass
- the quantities of torrefied biomass stored, for subsequent use

A set of constraints ensure that the torrefied biomass demand is met at all times. The objective function consisted of procurement, transport and storage cost for raw biomass, storage and transport for the torrefied biomass and capital costs of the torrefaction unit. The duration of a single time period for the simulation is selected as one month. A series of pre-defined values, derived from real local agricultural residues collection procedures and literature review, as well as the mass and energy balances, the thermal characteristics of the torrefaction process and the product yields of the torrefaction unit operating set-up from the AspenPlus^{TM} modelling tool results, were integrated into the developed biomass supply optimization tool, providing the minimum costs of the overall torrefied biomass value chain for the selected cases.

6.6.4 Value chain cost analysis

This part of the Case Study had as main goal calculating the total IBC value chain costs per MWh, in the case of replacing lignite with torrefied biomass as fuel under the effect of seasonal biomass availability, seasonal biomass collection cost, biomass source, storage cost, logistics cost, capital investment, thermal energy demand, and capacity of torrefaction unit reactor.

The total IBC value chain costs depend on two major cost components: production and operating expenses. The production costs refer to the capital investment needed for the construction of the torrefaction unit, like equipment, buildings, engineering and supervision, contingencies in case of an unexpected event occur, etc. Operating expenses include, among others, the biomass collection cost, the truck transportation cost (raw and torrefied biomass) and the storage cost (raw and torrefied biomass). Regarding the biomass feedstock cost, the equipment (machinery used for the collection) ownership costs are also taken into consideration. Unlike the capital expenses which are one-time expenses (paid during the construction phase) and have to be repaid over the entire life-time of the torrefaction unit (20 yrs. in this particular case), operating expenses are calculated on a yearly or a monthly basis.

Table 55 presents the base case for the torrefaction unit total capital investment estimation. The base case refers to a torrefaction unit with a capacity of 79,200 tn of torrefied biomass per year and the equipment costs are estimated based on similar equipment costs from literature.

Table 55. Base case for the total torrefaction capital investment estimation

Capacity (tn/year)	79,200
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 exchangers	538,500 €
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 €**
Start-up 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 €**

Additionally, based on the torrefaction unit capacity of the different torrefaction implementation scenarios, the costs should be scaled up or down, by applying an appropriate scaling factor:

$$\frac{Cost_{base\ case}}{Cost_{scaled}} = \left(\frac{Size_{scaled}}{Size_{base\ case}}\right)^{n}$$ with n, being the scaling factor.

Based on literature findings, a scaling factor of 0.7 is considered as appropriate for the torrefaction unit capital expenses estimation.

Both capital and operating expenses are key inputs of the developed biomass supply planning optimization and cost minimization tool. Furthermore, for the purposes of the IBC value chain cost analysis, two basic feedstock source scenarios have been examined (Table 53), **Scenario 1**, which considers biomass originating only from WMR and **Scenario 2**, which adds corn residues from Thessaly to the biomass quantities of **Scenario 1** (Table 56).

Table 56. Available biomass quantities for the IBC value chain cost calculation scenarios

	Corn residues (tn)	Vineyard pruning (tn)	Fruit-tree pruning (tn)
Scenario 1	19,037	1,747	21,218
Thessaly region	58,646	-	-
Scenario 2	77,684	1,747	21,218

In total, 42,002 tn of biomass is annually available for **Scenario 1** that leads to a maximum production of 21,764 tn of torrefied biomass. The produced torrefied biomass can cover entirely the demand from DETEPA, DETIP, CaO Hellas and Grecian Magnesite while it could cover only the 31% and 1% of DEYAK and Ptolemaida 5 respectively.

The total torrefied biomass production cost is compared against the current prices of the most common biomass fuel – wood-chips (16.74 €/MWh), lignite (17.36 €/MWh) and pet-coke (for CaO Hellas and Grecian Magnesite – 11.13 €/MWh, 20.92 €/MWh with carbon price). Current high carbon price (89 €/tn – 32.42 €/MWh), result in a combined cost of just over 50 €/MWh for lignite– far greater than the total production cost of any torrefaction scheme examined in this cost analysis and essentially excludes lignite from the comparison. Either carbon price should not exceed 59 €/tn or the lignite price to decrease to 6.5 €/MWh, for lignite to be considered as a competitive (price-wise) fuel. Ultimately, the main competitor and comparison measure for torrefied biomass are wood-chips. Torrefied biomass is a biomass fuel, so the total production cost should not exceed the price of a competitive biomass fuel per unit of energy, even if it possesses superior properties.

Figure 80 illustrates the total cost in €/MWh for the different cases, after the biomass supply optimization and cost minimization under **Scenario 1**. The green area represents the total torrefied biomass produced in each torrefaction scheme (right vertical axis).

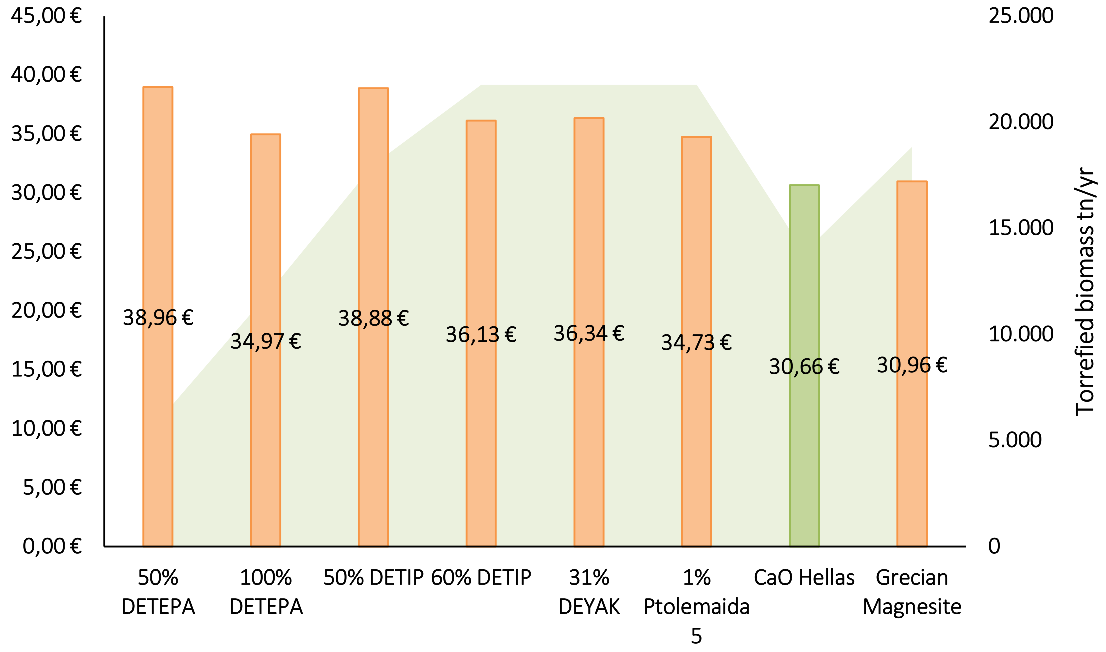


Figure 80. Total cost in €/MWh for the "Only biomass from WMR" – Scenario 1

In all cases the total cost is well above the current price for wood-chips and pet-coke, especially for DH and electricity applications (more than twice). This is due to two factors: (a) the large fluctuations during the heating season increase the capital expenses – larger torrefaction reactor is needed to compensate the increased demand during the most severe winter months and (b) the immense capacity of Ptolemaida 5 requires the use of all of the available biomass quantities, including fruit-tree prunings (almost thrice the price of corn residues) and vineyard pruning (fourfold the price), while for the other two industries, CaO Hellas and Grecian Magnesite, the steady demand counterbalances the increased feedstock costs, leading to the lowest total costs of the **Scenario 1** cases, they are, however, higher than the price for pet-coke (around 10 €/MWh). Carbon price should be at the range of 36 €/tn for lignite price to be equal to the lowest production costs case (CaO Hellas).

The above conclusions are best illustrated in Figure 81 which shows the cost breakdown of the selected case for torrefaction implementation. The total cost has been divided into four sub-costs: (a) Biomass cost; (b) Transport cost; (c) Storage cost; and (d) Capital cost.

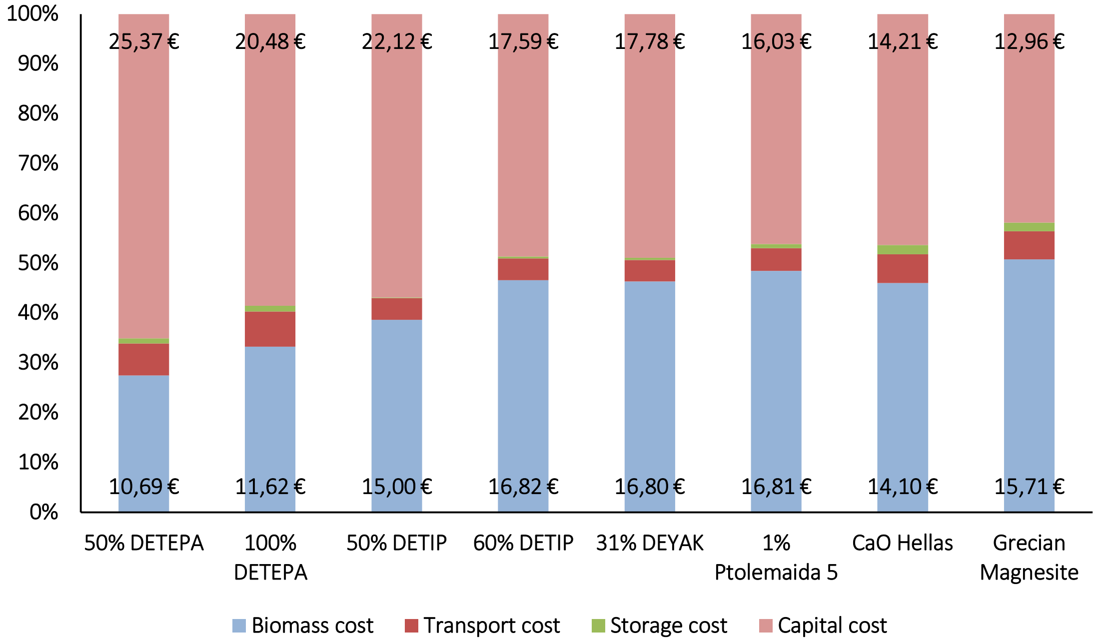


Figure 81. Cost breakdown for the "Only biomass from WMR" – Scenario 1

As can be seen, for the DH applications, the annualized capital costs are higher than the biomass cost, leading to increased total cost, while for Ptolemaida 5, even though the annualized capital costs are lower than the biomass cost, the expensive biomass feedstocks that had to be utilized keep the total cost well above 34 €/MWh. In contrast, for the two calcination industries, the combination of mainly cheap biomass use (corn residues) and stable demand during the year, results in the total cost being the lowest among the cases by **4 to 8 €/MWh**.

Overall, the results of **Scenario 1**, highlight the importance of finding cheap and sufficient quality biomass available. For this purpose, **Scenario 2** has been developed. In this scenario the import of corn residues from the region of Thessaly and the subsequent use along with the biomass from WMR has been assessed. The corn residues from Thessaly have the comparative advantage that they cost 4 €/MWh less than those of WMR, however they incur higher transport costs – average transport distance to a WMR-based torrefaction unit, 148 km compared to 54 in Scenario 1.

In Thessaly, 58,646 tn of corn residues are available annually. These quantities, when added to the 42,002 tn of WMR, can produce 50,972 tn of torrefied biomass, a quantity capable of fully meeting the demands of DETEPA, DETIP, CaO Hellas and Grecian Magnesite, 73% of DEYAK and 2.2% of Ptolemaida 5. In both scenarios the torrefied biomass produced can only cover a small fraction of Ptolemaida's 5 capacity. Therefore, either the introduction of very large quantities of biomass or the application of CO_2 capture technologies should be considered in order for Ptolemaida 5 to operate in an environmental-friendly manner.

Figure 82 shows the total costs in €/MWh for the different cases, after the biomass supply optimization and cost minimization under Scenario 2. Again, the green area represents the total torrefied biomass produced in each torrefaction scheme (right vertical axis).

As can be seen, the total costs of the IBC value chain are 2 to 7 €/MWh lower than Scenario 1, depending on the case.

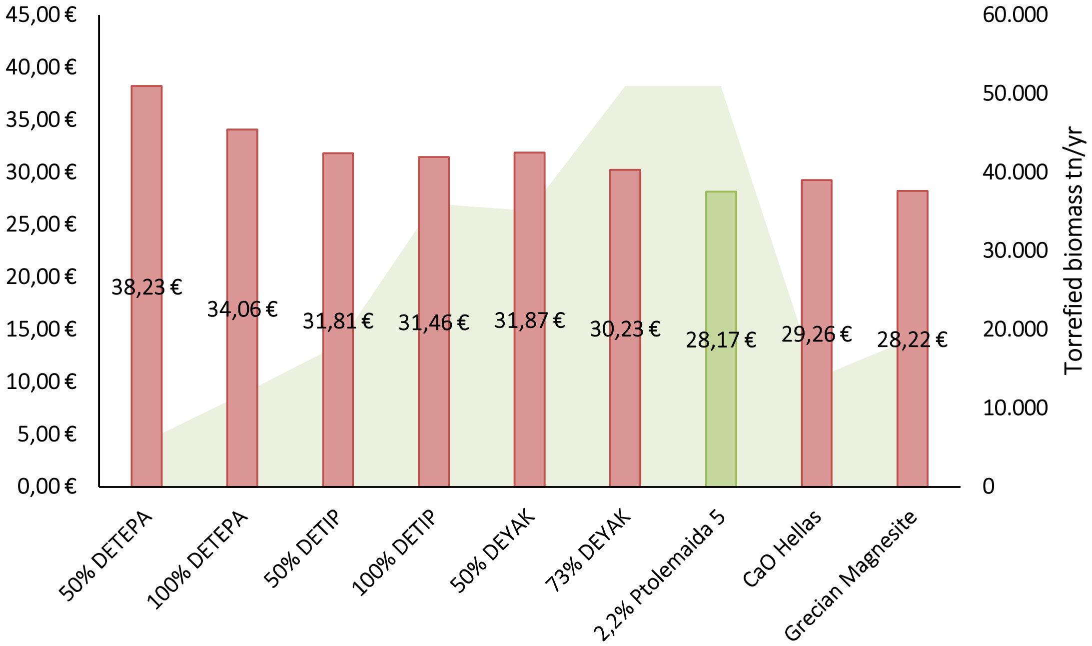


Figure 82. Total costs in €/MWh for the "Import from Thessaly" – Scenario 2

Taking also under consideration the results of the cost breakdown, illustrated in Figure 83, and in combination with Figure 81, it is apparent that the biomass feedstock price and the capital costs have the highest effect on the total cost.

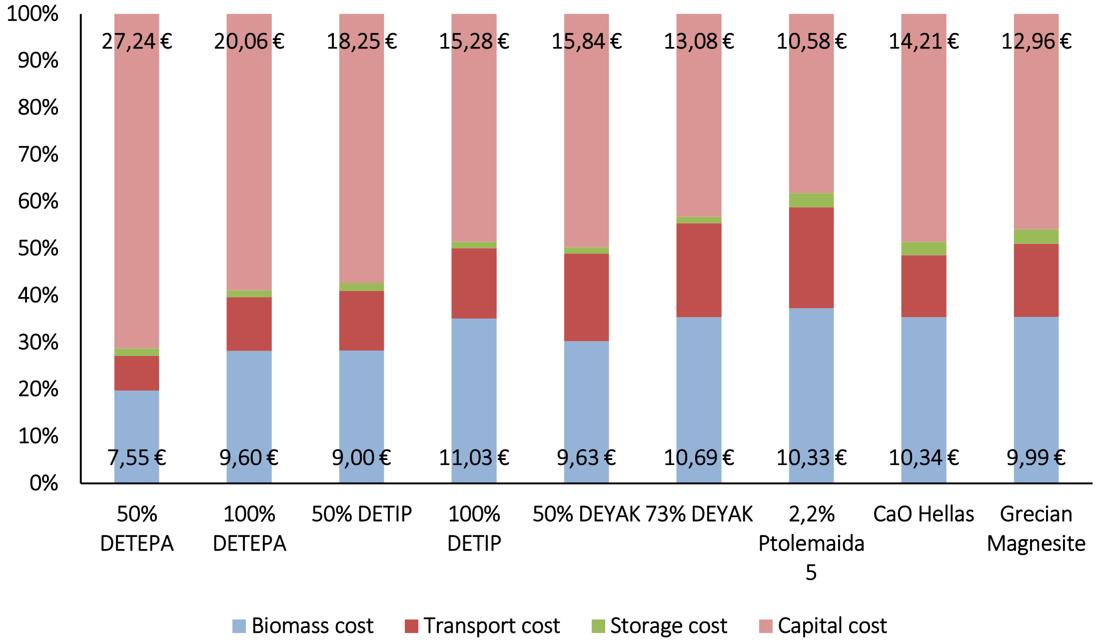


Figure 83. Cost breakdown for the "Import from Thessaly" – Scenario 2

Generally, the capital costs of Scenario 2 cases are lower than those of the Scenario 1, except for the 50% DETEPA case (which are higher) and the CaO Hellas and Grecian Magnesite cases (which are equal). The capital costs are greatly affected by the seasonal availability of biomass. In the above cases, their capacity can be mostly covered by the corn residues in WMR and to a lesser extent by the corn residues in Thessaly. Corn residues (in both regions) are available from September to November, therefore, the torrefaction reactor should have the appropriate capacity to operate and produce the necessary torrefied biomass during these months, this effect is negated in the CaO Hellas and Grecian Magnesite cases due to the economy of scale, while the lower corn residues price in Thessaly is offset by the higher transport cost. The same applies and to the other cases. As in Scenario 1, the total costs remain higher compared to competing fuels.

Overall, Scenarios 1 and 2 show an interaction between torrefaction unit size, biomass price and demand fluctuations that significantly affect the total costs. In order to find the optimal correlation between the feedstock price and the size of the unit and achieve the lowest total IBC value chain cost, under the current biomass market conditions in WMR and Thessaly, two secondary scenarios were investigated, where the torrefaction unit has stable production during the year (Table 57).

Table 57. Scenarios description for the optimal torrefaction unit size

Scenario	Feedstock source	Description

3	WMR	Investigation of optimal torrefaction unit capacity when only biomass from WMR is used. Torrefied biomass production is independent of the various applications
4	WMR and Thessaly	Investigation of optimal torrefaction unit capacity when biomass from WMR and Thessaly is used. Torrefied biomass production is independent of the various applications

Figure 84 and Figure 85 show the total cost in €/MWh and the cost breakdown for Scenario 3.

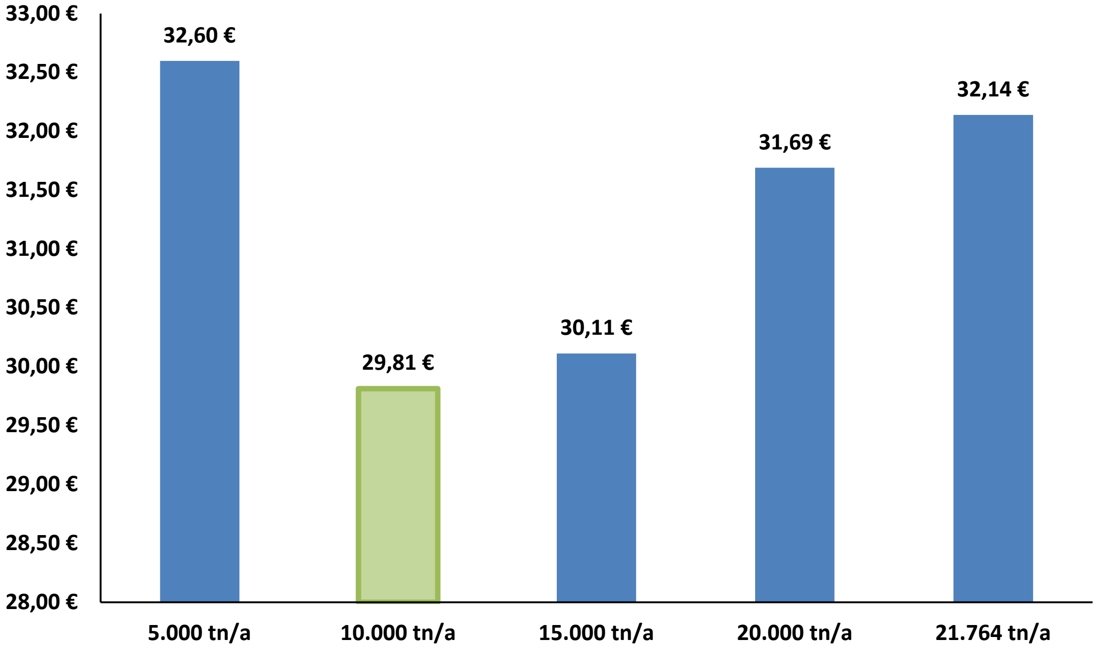


Figure 84. Total cost in €/MWh for the "Only biomass from W. Macedonia" – Scenario 3

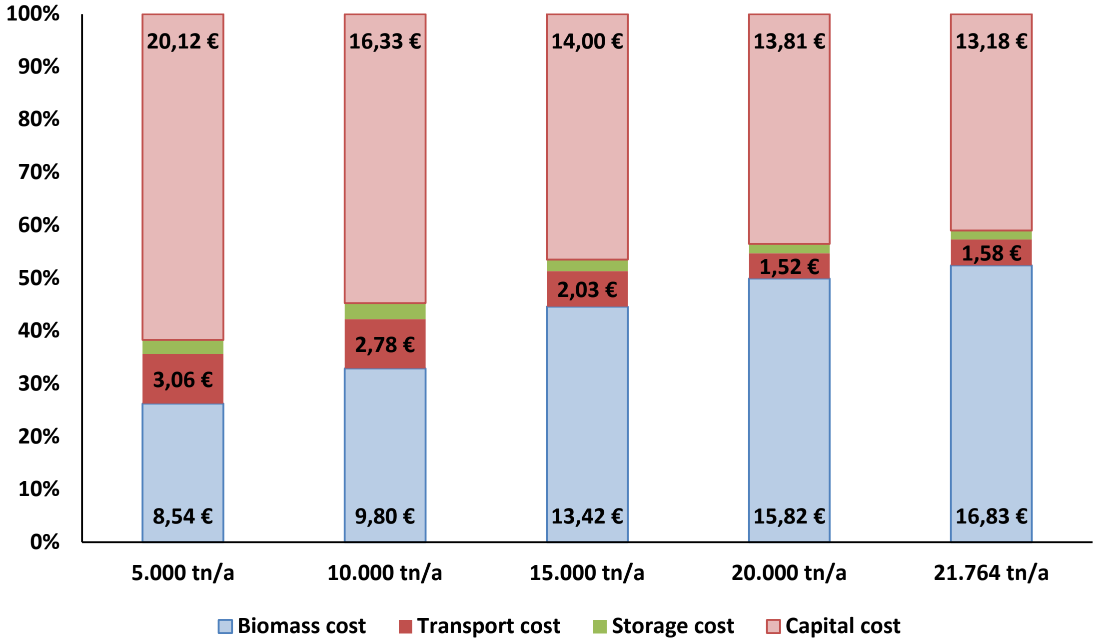


Figure 85. Cost breakdown for the "Only biomass from W. Macedonia" – Scenario 3

In total, 5 cases regarding the torrefaction unit size were investigated: (a) 5,000 tn/a; (b) 10,000 tn/a; (c) 15,000 tn/a; (d) 20,000 tn/a; and (e) 21,764 tn/a – maximum production of torrefied material according to the available biomass. As can be seen, the 10,000 tn/a case presents the lowest total cost, this can be attributed to the fact that the cheapest type of biomass, corn residues (24.65 €/MWh), is mainly used, while when the size of the torrefaction unit increases and a decrease in the total cost is expected due to economy of scale. This does not happen as biomass at a very high price is incorporated in the feedstock mix, specifically fruit-tree prunings (69.66 €/MWh) and vineyard prunings (99.44 €/MWh). Ultimately, based on the current biomass price conditions in WMR, a torrefaction unit of 10,000 tn/a capacity can produce the cheapest torrefied biomass, in price though, significantly higher than wood-chips and pet-coke (78.1% and 28.81% respectively).

In **Scenario 4**, where corn residues from Thessaly are added to the available biomass in WMR, 10 cases regarding torrefaction unit size were investigated: (a) 15,000 tn/a; (b) 20,000 tn/a; (c) 21,764 tn/a; (d) 25,000 tn/a; (e) 30,000 tn/a; (f) 35,000 tn/a; (g) 40,000 tn/a; (h) 45,000 tn/a (i) 50,000 tn/a; and (j) 50,972 tn/a – maximum production according to the available biomass.

Figure 86 and Figure 87 illustrate the results of the total IBC value chain cost and the cost breakdown for **Scenario 4**.

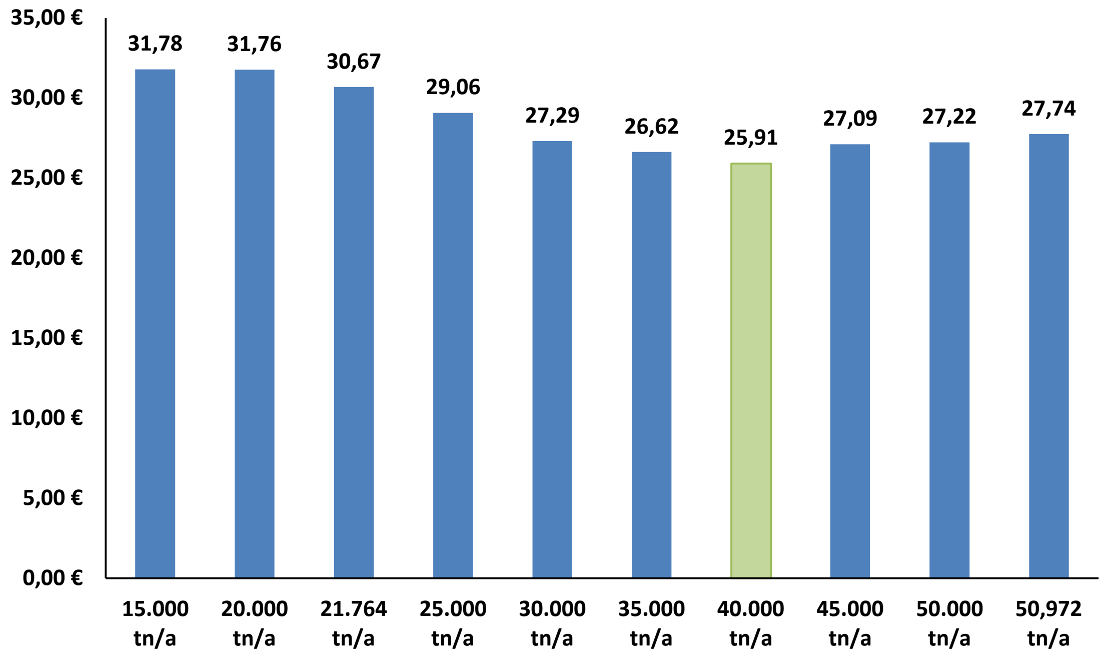


Figure 86. Total cost in €/MWh for the "Import from Thessaly" – Scenario 4

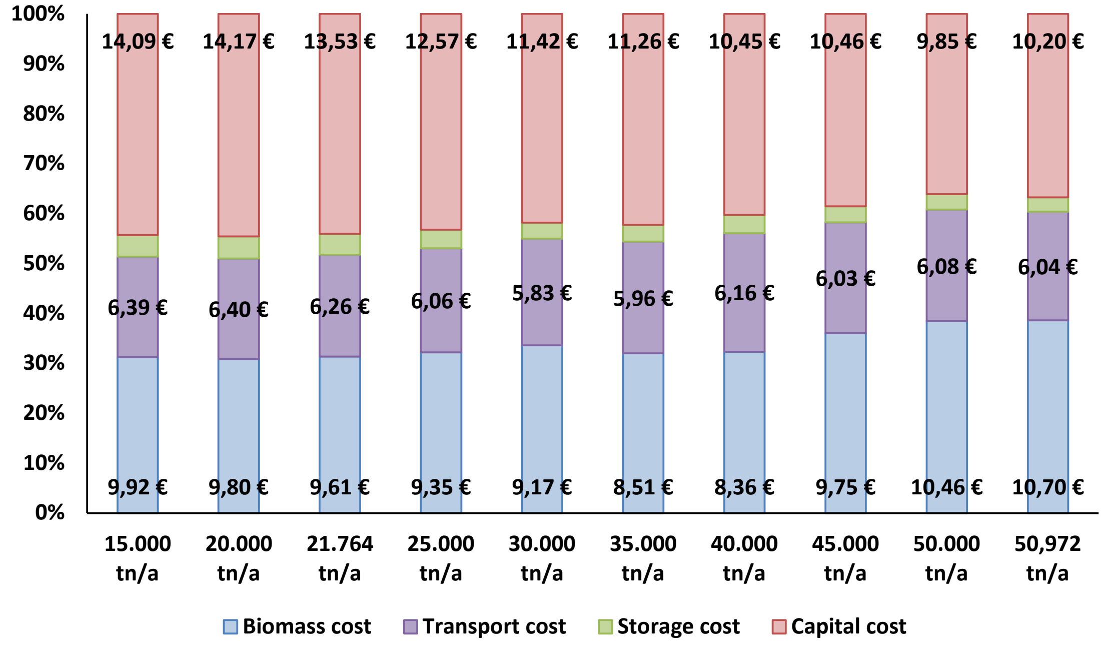


Figure 87. Cost breakdown for the "Import from Thessaly" – Scenario 4

For this scenario the optimal torrefaction unit size is 40,000 tn/a, which offers torrefied biomass at a price of 25.91 €/MWh – cheaper by 3.9 € than in Scenario 4 and 2.26 € than the cheapest price observed during the analysis of the basic scenarios (Scenario 2), it is however 24% higher than pet-coke, which makes torrefied biomass incapable of replacing fossil fuels in magnesite and quicklime production from an economic perspective. On the contrary, carbon price must not exceed 23 €/tn, for lignite to compete this price. In this particular scenario, the higher transport costs of raw biomass negate the cheaper biomass price – 20.63 €/MWh and the lower capital costs.

This can best be observed in Scenario 5, where the difference between the transport of raw and torrefied biomass from Thessaly is examined and compared (Figure 88).

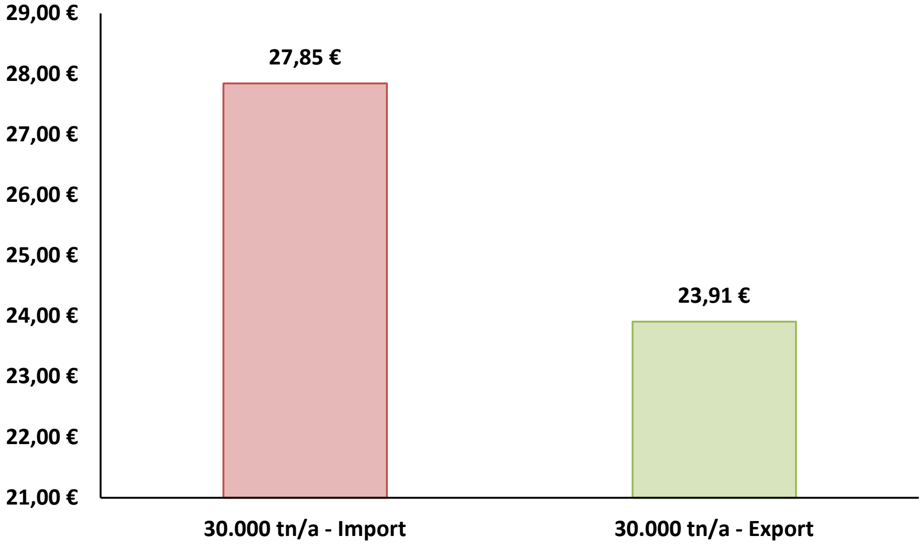


Figure 88. Total cost in €/MWh – Scenario 5. Left bar: Total cost for a torrefaction unit in WMR importing raw biomass from Thessaly. Right bar: Total cost for a torrefaction unit in Thessaly, exporting torrefied biomass in WMR

In this scenario a torrefaction unit of 30,000 tn/a (maximum production according to the available biomass in Thessaly) capacity has been considered, which in the case of raw biomass is located in WMR and in the case of torrefied biomass is located in Thessaly. The transport distance for both cases is set at 115 km.

The results of the analysis indicate that the transport of torrefied biomass is significantly cheaper than the transport of raw biomass (3.94 €/MWh lower). However, even in this case where the cheapest feedstock is used exclusively, the total cost is 14.2% higher than pet-coke, mainly due to the scale of the torrefaction unit.

The impact of the torrefaction unit scale is illustrated in Figure 89, which shows how the total IBC value chain cost is affected by the torrefaction unit capacity, when the cheapest type of feedstock is used (corn residues from Thessaly).

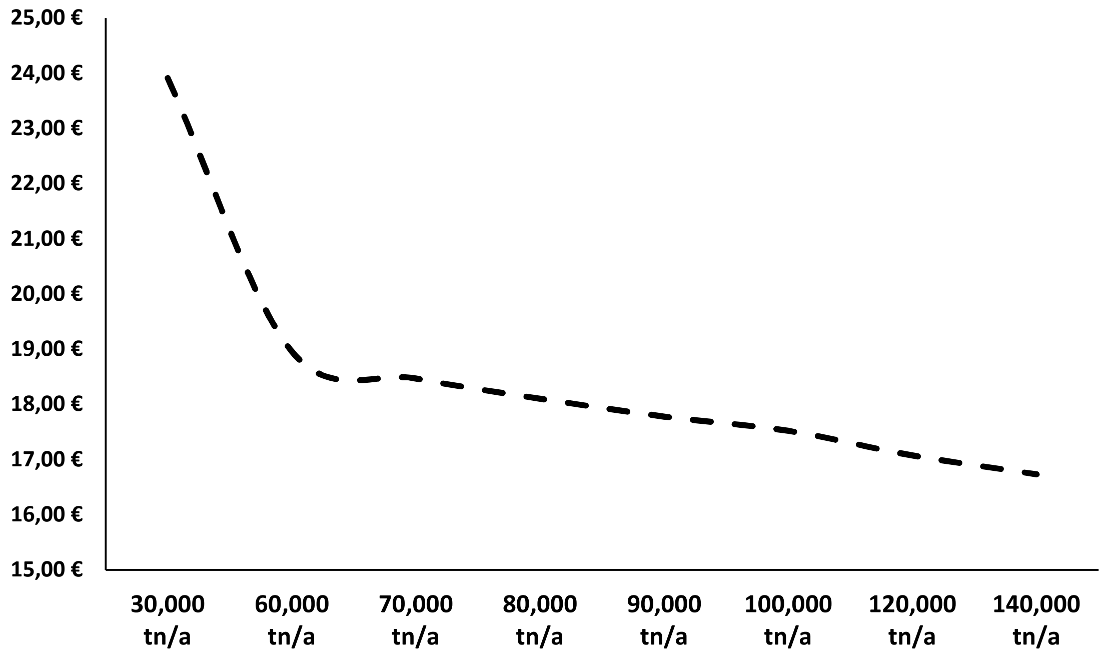


Figure 89. Influence of torrefaction unit capacity on total production cost

For lower torrefaction unit capacities, the total costs reach 24 €/MWh whereas for capacities of 70,000 tn/a, the total costs could reach 18.47 €/MWh. For capacities over 70,000 tn/a total costs could decrease to 16,73 €/MWh, however the rate of reduction is significantly reduced.

Ultimately, as shown in Figure 90, the optimal torrefaction unit capacity under the current biomass market conditions in Thessaly is 140,000 tn/a, which requires 272,904 tn/a of corn residues. Nevertheless, such quantities of corn residues are not available in Thessaly.

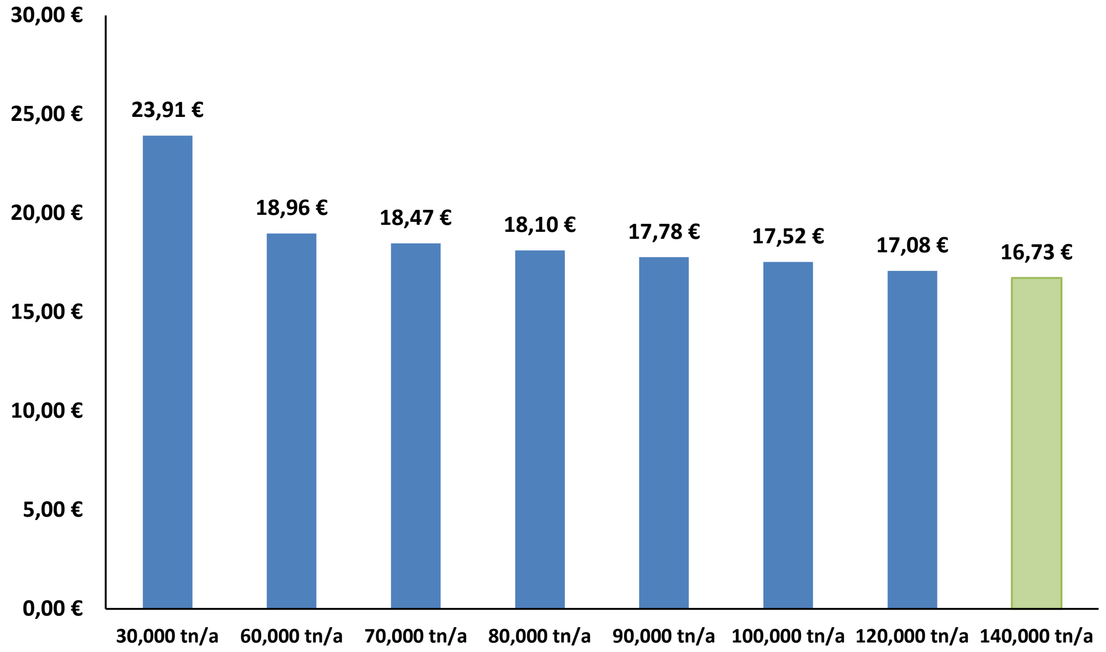


Figure 90. Optimal torrefaction unit capacity where total cost of torrefied biomass equals wood-chips price (16.74 €/MWh)

At this capacity, the final total costs of torrefied biomass are the same as the price of woodchips, while a torrefaction unit of under 60,000 tn/a (approximately 117,000 tn of corn residues) is sufficient for the production of cheaper torrefied biomass than pet-coke.

In summary, to have an economic benefit (other than environmental) from the use of torrefied biomass, the required balance between the costs of biomass, the size of the torrefaction unit and the costs of transport must be found. In general, what was reflected from the analysis of the various scenarios (both basic and secondary) is that torrefied biomass production should not be linked to the demand of a particular application when it presents large fluctuations throughout the year, large-scale torrefaction units have better economic performance than small-scale, raw biomass cost effects considerably the total cost of IBC value chain, only locally available biomass should be considered economically suitable for torrefaction and any long-distance transport should only take place for torrefied biomass.

6.6.5 Sensitivity analysis

A Sensitivity analysis is necessary to identify how and in what extent changes in certain key aspects of the IBC value affect the total torrefied biomass production cost. Therefore, in Figure 91, certain economic parameters are varied to illustrate a price range of the torrefied biomass. Note that the base case refers to 40,000 tn/a torrefaction unit shown in Scenario 4 (25.91 €/MWh).

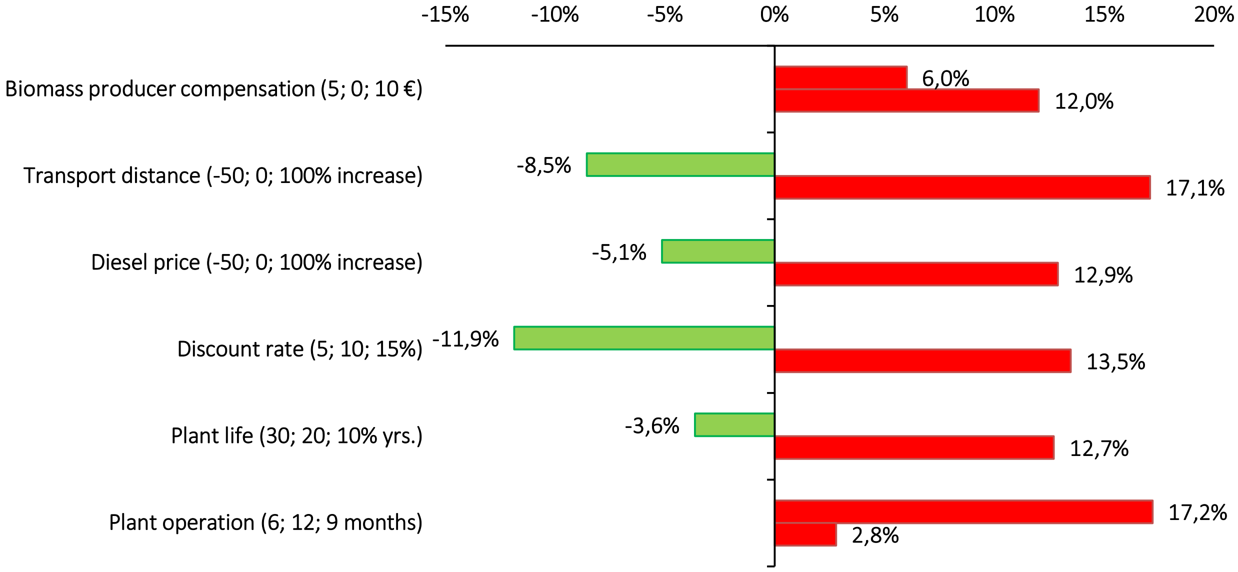


Figure 91. Economic sensitivity and its effect on the total production cost

It can be seen that the biomass producer compensation can impact negatively the biomass torrefaction scheme, increasing the total production cost. This is understandable as the biomass price would increase. While it makes perfect sense for the biomass producer to receive direct compensation, this would have a huge impact on the overall production cost and an indirect "reward" system should be examined – discount in electricity or heating bills, municipal tax relief etc.

The transport distance for raw biomass has a considerable effect on total production cost and the same applies for diesel price (affects both transport and biomass cost) – long-transport distances or expensive fuel could skyrocket the cost and render the whole torrefaction scheme as unviable. In general, the biomass feedstock price plays a major role on the final production cost. Cheap and closely available biomass can decrease the total cost, while expensive biomass in wider radius could raise the cost significantly.

The discount rate refers to the interest rate used in discounted cash flow (DCF) analysis to determine the present value of future cash flows and affects the capital recovery factor – higher discount rate raises the capital cost throughout the torrefaction unit life. In particular, a 5% discount rate will reduce the production cost by 11,9% while a 15% discount will increase it by 13,5%.

The plant life affects the capital recovery factor, which in turns affects the yearly capital costs. Shorter plant life means that the capital investment has to be repaid within a shorter period of time, raising the total production cost.

The plant operation refers to the torrefaction reactor capacity. This factor directly affects the capital expenses of the torrefaction unit, since a shorter operation time will require a larger torrefaction reactor to achieve the required torrefied biomass production.

6.7 Environmental footprint of the potential value chains

6.7.1 Greenhouse gas emissions and savings

According to the Renewable Energy Directive 2018/2001/EC the greenhouse gas (GHG) 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 various torrefaction schemes considered for the Strategic Greek Case Study fall under the point d) of the above paragraph, therefore the GHG emission savings should be at least 70%.

For the calculation of the GHG emissions, the cases of **Scenario 1** and **Scenario 2** were considered and include the GHG emissions from the: (a) biomass collection; (b) biomass transportation (raw and torrefied); (c) torrefied biomass conversion; (d) storage and handling: and (e) the conversion to electricity or heat produced. GHG emission reduction has been assessed using the methodology given in Annex VI of the RED II (Figure 92).

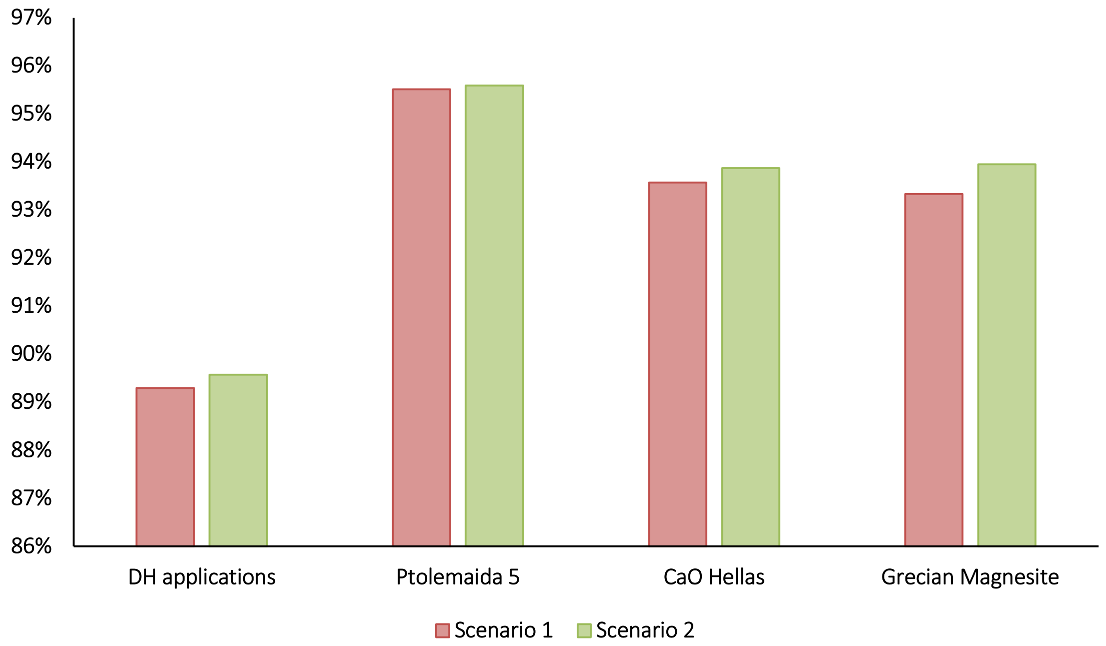


Figure 92. GHG emission savings of the various IBC implementation options

The GHG emission calculations revealed that the Ptolemaida 5 case presents the higher emission reduction in both scenarios (95.51 and 95.59%), while the DH applications have the lowest reduction (89.29 and 89.57%), though differences are small. This is due to the fact that the GHG emission savings of the various IBC value chains are calculated against specific and different fossil fuel comparators:

- 183 g CO_2 eq/MJ for electricity production.
- 80 g CO_2 eq/MJ for heat production or 124 g CO_2 eq/MJ for heat production from direct physical substitution of coal.

Furthermore, the emission reductions in both scenarios are almost equal. In Scenario 2 biomass is transported for longer distances (from Thessaly to WMR), however the higher emissions from transport are offset by the fact that more corn residues are used – they have lower emissions during their collection compared to the fruit-tree prunings (32.4 kg CO_2 eq/tn and 92.1 kg CO_2 eq/tn respectively).

Overall, the results indicate that the RED II GHG emission savings criteria can be fulfilled, as for each case of both scenarios GHG reductions above 70% were calculated.

6.8 Certification

6.8.1 Description of the value chain and identification of interfaces

In the considered value chain of the advanced case study, agricultural residues are collected in a region within Greece. Specifically, residues from corn production (corn straw) is under investigation. This feedstock is transported by truck to a torrefaction unit. The torrefied product is used as fuel to substitute lignite in a district heating plant. The produced heat is fed into a district heating network and used by households for space heating purposes. The strategic case study builds up upon the advanced case study. Besides the above mentioned feedstocks, the utilization of fruit tree prunings and vineyard prunings is investigated. The following three applications are researched:

- District heating: municipal district heating with torrefied biomass
- Combined heat and power production: use of torrefied biomass in the fuel mix
- Industrial application (quicklime, magnesite): substitution of pet coke with torrefied biomass

The torrefaction process will be located very close to or even integrated into the production of the final products of the different value chains, to avoid an additional truck transport of the torrefied material.

From the description above, the chain of custody interfaces displayed in Figure 93 can be identified. Based on these interfaces, the sustainability certification assessment will be provided in the following.

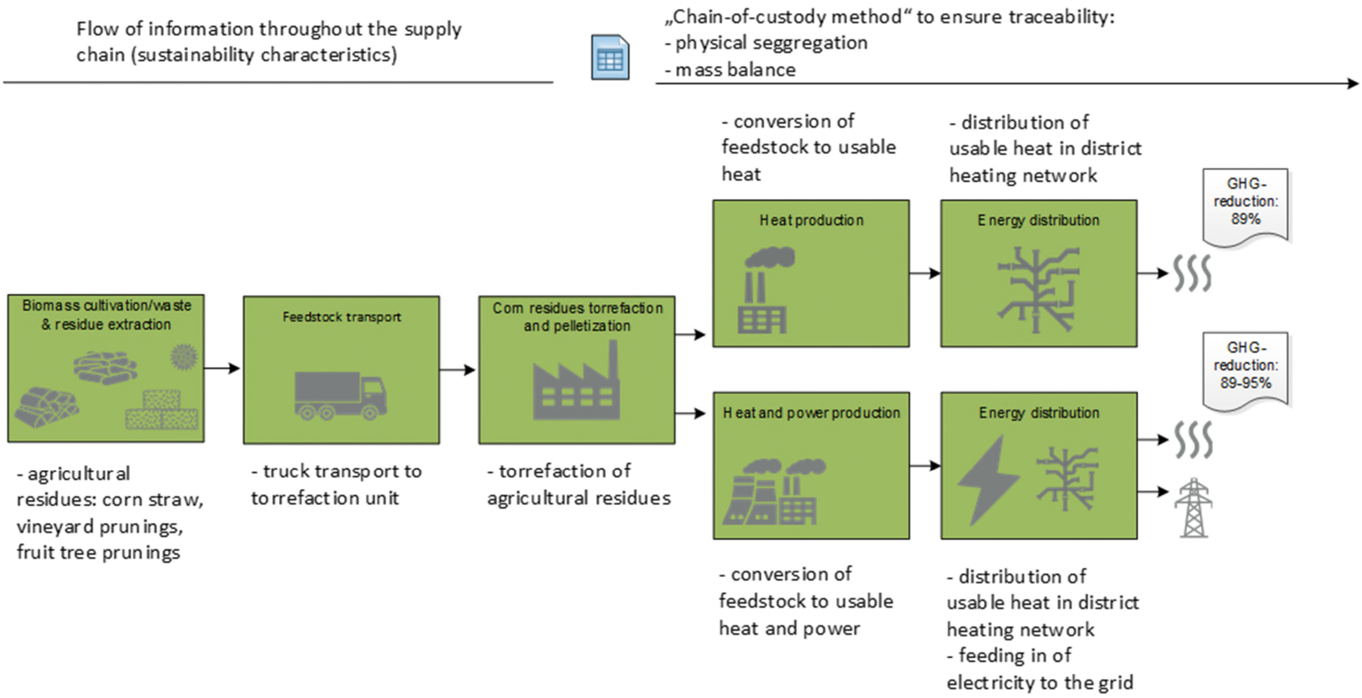


Figure 93: Interfaces along the value chain to produce heat and power from torrefied bio-mass in different cases

6.8.2 Relevance for the value chain

The RED II specifies sustainability criteria and criteria for GHG emission reduction in Article 29. Which criteria apply for a certain case depends largely on the type of biomass, the type of biomass fuel, the sector in which energy is used, the capacity of installations and the date on which an installation starts operation. Installations producing heat from solid biomass fuels with a total rated thermal input equal to or exceeding 20 MW have to proof compliance with the criteria.

As only waste and residue feedstock is used in the value chain, the criteria excluding biomass from land to be excluded from biomass harvesting do not apply (Table 58). GHG emission reduction has been assessed using the methodology given in Annex VI of the RED II. Thereby, different cases were calculated to allow to differentiate if direct substitution of coal is realized or not. The results indicate that the GHG emission savings criteria can be fulfilled, as for both cases GHG reductions above 80% were calculated. In general, the GHG reduction depends on the starting date of operation[13]. For installations which started operation before 2021-01-01, a GHG emission reduction does not have to be proven. Corn straw as well as vineyard and fruit tree prunings are considered residues from agriculture. Therefore, negative impacts of soil carbon and soil quality have to be avoided. This must be ensured and proven with a monitoring system.

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[13] According to RED II Article 29(10), an installation is considered in operation once the physical production of heating and/or electricity from biomass fuels has started

Table 58: Overview of RED II criteria and applicability to the Greek case study value chain

RED II reference	Criteria summarised	Applicability	Relevance for the case study
29(2)	Monitoring and management of impacts on soil carbon and soil quality	Wastes and residues from agricultural land	yes
29(3)	Protection of land with high biodiversity value	Agricultural biomass for energy	no
29(4)	Protection of land with high carbon stock	Agricultural biomass for energy	no
29(5)	Protection of peatland	Agricultural biomass for energy	no
29(6)	Sustainable forest management	Forest biomass for energy	no
29(7)	LULUCF criteria	Forest biomass for energy	no
29(10)	GHG emission savings criteria: dependent on the staring date of the operation: at least 70% (2021-01-01 – 2025-12-31) at least 80% (> 2026-01-01)	Wastes and residues agricultural biomass forest biomass	yes
29(11)	Energy efficiency criteria for electricity production from biomass fuels	Electricity generation	no
30(1)	Mass balance system	Once sustainability and GHG emission savings criteria are to be verified	yes

6.8.3 Monitoring and impacts on soil carbon and soil quality (29(2))

The assessment above shows, that the criterion laid down in Paragraph 2 in Article 29 of the RED II applies to the investigated value chain(s). Providing information on how to show compliance with this requirement is challenging for two reasons: On the one hand, this criterion has been newly added to the RED II and there is no previous experience from the certification of biofuels under the former RED available. On the other hand, at the time conducting this assessment, there is a situation in which the specifications in terms of an implementing regulation are not finalized yet. For that reason, further details or guidance is very limited.

Technical input for the development of guidance to ensure compliance with 29(2) was provided by the REDIIBIO project (Guidehouse et al. 2021). A draft implementing regulation[14] was published in July 2021 and the adoption by the EU Commission was planned in 2021. The regulation includes specific rules for wastes and residues in Article 21 and particularly for waste and resi-

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[14] on rules to verify sustainability and greenhouse gas emissions saving criteria and low indirect land-use change-risk criteria

dues from agriculture in the paragraphs 6 and 7. Based on the mentioned sources some implications on how conformity can be demonstrated, and verification can be carried out are given in the following.

According to Article 21(6) of the implementing regulation draft, negative impacts on soil quality and soil carbon content resulting from feedstock extraction can be avoided if a set of essential soil management and monitoring practices are applied. A non-exhaustive list of examples of essential management practices to promote and monitor soil carbon sequestration and soil quality is given in Annex VI of the draft regulation (Table 59). There is no further guidance given in the implementing regulation draft. However, the list can be interpreted in a way that practices can be excluded if they are not relevant (e.g., in case a respective soil is not acidic), which would have to be justified

Table 59: Examples of essential soil management practices to promote soil carbon sequestration and soil quality (Source: Draft implementing regulation Annex VI)

Requirement	**Soil quality parameter**
At least a 3-crop rotation, including legumes or green manure in the cropping system, taking into account the agronomic crop succession requirements specific to each crops grown and climatic conditions. A multi-species cover crop between cash crops counts as one.	Promoting soil fertility, soil carbon, limiting soil erosion, soil biodiversity and promoting pathogen control
Sowing of cover/catch/intermediary crops using a locally appropriate species mixture with at least one legume. Crop management practices should ensure minimum soil cover to avoid bare soil in periods that are most sensitive	Promoting soil fertility, soil carbon retention, avoiding soil erosion, soil biodiversity
Prevent soil compaction (frequency and timing of field operations should be planned to avoid traffic on wet soil; tillage operation should be avoided or greatly reduced on wet soils; controlled traffic planning can be used).	Retention of soil structure, avoiding soil erosion, retaining soil biodiversity
No burning of arable stubble except where the authority has granted an exemption for plant health reasons.	Soil carbon retention, resource efficiency
On acidic soils where liming is applied, where soils are degraded and where acidification impacts crop productivity	Improved soil structure, soil biodiversity, soil carbon
Reduce tillage/ no tillage - Erosion control – addition of organic amendments (compost, manure, crop residues) – use of cover crops, rewetting Revegetation: planting (species change, protection with straw mulch, and phosphate fertilization) - landscape features – agroforestry	Increase soil organic carbon

This selection of management practices is based on the REDIIBIO results. The authors of the REDIIBIO project highlight that the list applies to non-perennial crops and that an equivalent list applicable to perennial crops should be developed. The implementing regulation draft does not mention any limitations. In case of fruit tree and vineyard prunings the approach is therefore not entirely clear. However, from the logic of the differentiation between different biomass feedstocks, the requirement is applicable to these biomass types, as they originate from agricultural land. To ensure that soil quality and soil carbon is adequately monitored, Annex VI lists examples of monitoring practices (Table 60).

Table 60: Examples of monitoring practices for soil quality and carbon mitigation impacts (Source: Draft implementing regulation Annex VI)

Monitoring approach	Method of verification/demonstration
Risk assessment	Identifying areas with high risk of soil quality decline helps prevent these risks and focus on areas with the greatest impact.
Soil organic matter analysis	Consistent sampling of soil organic matter improves monitoring so that this matter can be maintained or improved.
Soil organic carbon analysis	Soil organic carbon is seen as a good marker for wider soil quality.
Soil conditioning index sampling	A positive value indicates the system is expected to have increasing soil organic matter
Soil erosion assessment	Ensures that erosion is below a tolerable level, i.e., USDA Agricultural Research Service ‘t’ levels.
Nutrient management plan	A plan outlining nutrient strategy (focusing mostly on N, P, K) and fertilizer regimes can prevent nutrient imbalances.
Regular soil pH analysis	Monitoring pH helps identify imbalances in pH.

Comparable with the requirements for forest biomass, a two-tier approach (“risk-based approach”) was laid down for the verification. This means that compliance can be demonstrated on national level or on the level of the economic operator (sourcing area level). In the former case, evidence must be provided, that the fulfilment of the criteria is already covered by applicable law in the country in which waste and residues from agriculture are sourced (Tier 1). If such evidence is not available, the verification must take place on sourcing area level (Tier 2).

There are existing requirements for agricultural operators receiving direct EU payments (cross-compliance). Amongst others, operators must maintain a good agricultural and environmental condition of land, which includes to maintain soil organic matter and soil structure[15]. This implies that for cross-compliance operators, the requirement might already be considered fulfilled. However, there is no official statement known confirming this assumption. Due to the common agricultural policy (CAP) it seems unlikely that verification of the requirement on sourcing area level will be relevant for EU member states.

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[15] https://ec.europa.eu/info/food-farming-fisheries/key-policies/common-agricultural-policy/income-support/cross-compliance_en

6.8.4 National Implementation

The RED II has not been implemented into Greek law yet. With respect to the threshold of 20 MW total rated thermal input of energy installations, results from interviews conducted by Bioenergy Europe indicate that a lower threshold will not be implemented in Greece. With respect to potential additional sustainability criteria, there is no information available so far, but an identical implementation of the sustainability criteria seems likely.

6.8.5 Conclusions

With respect to the application of torrefied biomass in quicklime and magnesite production, the value chains would not directly be subject to the requirements of the RED II, as a material is produced. However, if the production sites would have to be part of the EU ETS, biomass-fuels utilized in the production process might also have to be in conformity with RED II.

Generally, the conformity of the examined value chain with the requirements of the RED II is achievable. GHG emission savings criteria can be complied with for present and future installations (from 2026 on). However, there are few uncertainties with respect to ongoing processes and upcoming policies which have been outlined in detail.

The threshold of 10 MW might change in future. According to the proposal for a revised RED II, sustainability and GHG emission reduction criteria might apply to installations with lower capacities (5 MW). This implies that in future more installations and supply chains might become subject to certification. However, as few sustainability criteria apply to the value chain (due to the focus on waste and residue feedstock), the consequence of this potential development seems to have a limited impact on the further development of the value chain.

6.9 Final remarks

The Greek Case Study dealt with the conversion of agricultural residues (corn residues, vineyard pruning and fruit-tree pruning) to IBCs through torrefaction and their subsequent utilization – as alternative to lignite – in DH (DETEPA, DETIP, DEYAK), electricity generation (Ptolemaida 5) and industrial applications (CaOHellas S.A., Grecian Magnesite S.A.).

The economic analysis of the IBC value chain revealed, besides the viability of the proposed torrefaction schemes, the overall challenges regarding the decarbonization of energy and industrial sectors.

In general, the lignite phase-out is a huge challenge for Greece and especially WMR – the regional economic activity and development is mainly focused on the energy sector, therefore, decarbonization and the resulting closure of the lignite-fired power plants, will constitute a huge blow on region’s economy and employment. Apart from that, the significant price-rise of natural gas – which emerged as a transitional fuel – due to geopolitical instabilities, intensifies the fear about an upcoming energy insecurity/poverty among the local population. Consequently, appropriate strategies should be developed for a just and sustainable energy transition and support employment.

Amid the current energy price turmoil, biomass, a widely available endogenous material, could arise as a possible energy source that can provide multiple benefits (increase of rural income, enhancement of energy sustainability and mitigation of lignite phase-out consequences) in case it could be mobilized in a sustainable and cost-effective manner.

Biomass and specifically agricultural residues are characterized by seasonal availability and diverse properties, while they are associated with high transport and storage costs, making their supply, handling, processing and use, challenging.

Torrefaction, which is a mature technology, can homogenize diverse biomass feedstocks, extend their period of storage and minimize transport/storage cost. Torrefied biomass has superior characteristics over raw biomass and comparable to fossil fuels. The production cost – depending on the scale of the torrefaction unit – is similar with white pellets as long as the biomass feedstock supply chain is running in an efficient manner. Overall, torrefaction can transform the regional biomass supply chains, facilitate biomass procurement, contracting and stabilize market prices, while the implementation of torrefaction in energy and industrial applications depends on the cost minimization of the IBC value chain – local agricultural practices play a key role in the biomass feedstock costs. Therefore, their assessment could lead to a better understanding of the associated costs. Simultaneously, the synergies between the relevant stakeholders (farmers, transporters, end-users) could enable the mobilization of unexploited biomass quantities and secure uninterrupted supply.

To conclude, under the current energy and carbon market conditions, the energy and industrial sectors suffer from significant increases in production costs. Decarbonization can offer substantial environmental benefits but should not be at the expense of energy security and equitable access to energy. Lignite still is an integral part of the Greek energy mix (8 to 20%) and depending on the carbon prices, remains the most economic option, however there is uncertainty regarding its availability beyond 2025. As wind and solar energy cannot serve as a base-load, biomass can emerge as a potential substitute for fossil fuels, however the underdeveloped biomass supply chains (especially those of agricultural residues) and the inherent characteristics of biomass, act as a roadblock towards large-scale utilization. Torrefaction can solve the biomass properties issues, nevertheless the need for organizing effective biomass supply chains, remains. The tools developed during the Greek Case study (biomass torrefaction process simulation tool and biomass supply optimization and cost minimization tool) can facilitate that.

The results of the different scenarios and under the current local biomass market conditions, indicate that the total torrefied biomass production cost is between **24 and 39 €/MWh** – far greater than the **16.74 €/MWh** for wood-chips and **20.92 €/MWh** for pet-coke (current market price with carbon price) – a torrefaction unit of 140,000 tn/a, not further than 115 km is required for the total production cost to be equal with wood-chips price (or a torrefaction unit of 60,000 tn/a in the case of pet-coke). Lignite price (50.1 €/MWh) at this point cannot compete with any torrefaction scheme examined in this case study, as it is greatly affected by the current carbon price. Torrefaction unit capacity, biomass price, biomass location (transport cost) and demand fluctuations affect significantly the total IBC value chain cost.

Key points of the Greek Case study:

- WMR suffers both energetically and economically from the decarbonization.
- Natural gas is emerging as the transitional fuel – fears for an upcoming energy poverty due to the significant increase in prices and/or geopolitical instability.
- There is a need to substitute lignite with an endogenous energy source – Wind & solar power cannot serve as base-load.
- IBCs can homogenize diverse biomass feedstocks and minimize transport/storage cost.
- The National Energy and Climate Plan supports RES, further steps and actions needed for biomass.
- There is a need for effective biomass supply chains – the tools developed during the Greek Case Study can facilitate that.
- Torrefaction possesses feedstock flexibility, opening up the energy and biocarbon market for agricultural by products, grassy crops and other underutilized biomasses with – under current conditions - unacceptable properties.
- There is a wide range of diverse markets that torrefaction products could find application for.
- Torrefied biomass has superior characteristics over raw biomass and similar ones to fossil fuels.
- The economics of torrefaction, depending on the scale, are similar with white pellets as long as the biomass supply chain is running in an efficient manner.
- Torrefaction capital costs are mainly affected by the torrefaction reactor capacity (43% of the capital expenses).
- The analysis of key aspects of IBC value chains on a regional level is necessary for the optimization of torrefied biomass supply chain and the minimization of the total production cost.
- There are a lot of enabling factors regarding biomass utilization in the Greek Case, however, the legal framework and the lack of large-scale pilot plants are major hindrances.

7 Torrefaction for steel production: the international case study

In Europe, only a few plants producing torrefied biomass (TB) at significant scale are in operation or being developed today. One of these concerns the TORERO waste wood torrefaction plant that is under development at the Arcelor Mittal (AM) steel mill in Ghent (Belgium). 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 biomass fraction of SRF and RDF). 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 TB made from a range of different feedstocks for use at a range of AM steel mills including e.g. facilities in Belgium, North/South France, North Spain, North Germany, Poland & Italy, and potential rest of the world.

7.1 Technology and markets

The steel industry is one of the biggest industrial emitters of CO2, accounting for ~7% of anthropogenic emissions globally, with 102 M tonnes/year in EU-28. If the EU 2030 targets are to be met, demonstration of low-carbon technologies (SET-plan) and generation of new value chains and cross-sectorial partnerships is needed. Implementation of renewable approaches allow to massively decrease CO2 emissions in industrial processes. More specifically, the demonstration of innovative technologies incorporating biomass or (bio)waste in steel production will decrease CO2 emissions by replacing fossil coal in the blast furnace of an integrated steelmaking process. While also the assimilation of the C-H reductants from waste into steel or ethanol contributes to the circular economy. By limiting coal consumption and the transformation thereof, would make the EU less dependent on raw materials and more sustainable. Moreover, by having raw materials near the steel mills, and also optimizing the type of waste selected, further decreases CO2 emissions. This creates new partnerships and value chains that will result in a new source of socio-economic benefits.

There are several options to substitute fossil carbon with biogenic carbon in the integrated steel mill route; from the literature have identified that substitution of coal by biomass in the pulverized coal injection (PCI) 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 in blast furnace. The core of the process in 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 in steelmaking are coke, heavy oil, pulverized coal, natural gas and hot reducing gases. Coke is the primary fuel and reducing agent in blast furnace process, ranging around 350 - 400 kg/t of hot metal in modern blast furnaces. The main function of coke in the blast furnace are: i) acting as reducing agent, ii) supplies energy to the process and is a support medium to the burden material. Pulverized coal is the most widely used auxiliary fuel in blast furnace, and hence it can reduce significantly 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 a total of 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 US). 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 provides a suitable reducing atmosphere in the furnace conditions, without compromising blast furnace efficiency nor increasing coke rate feed. The low energy density of 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. Note that, in order to inject the biomass into the modern blast furnaces the woody biomass must be upgraded for utilization in blast furnaces 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 BF can be summarized as follows:

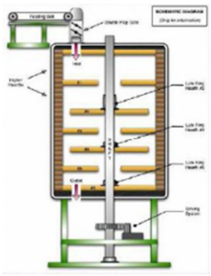
- Lower calorific value of biomass products compared to coal require efficient pre-treatment and pyrolysis.
- Difficulties in biomass injection at a high rate due to the porous nature which require optimization for the injection process.
- Wider particle size distribution of biomass after grinding which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

According to the literature, injection of charcoal in blast furnace can be up to 200 kg/ton hot metal. However, this is considered for charcoals with high carbon content and low ash content. Charcoal from wood-based 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. In Torero, it has been identified that 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.

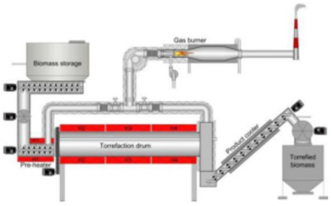
A number of technologies have been investigated by ArcelorMittal to be used for the production of biocoal, or related alternative coals. Starting point was the IEA Bioenergy Task 32 report performed in 2012 (Cremers et al. 2015). Technologies and related companies evaluated were:

- Rotating drum; CDS (UK), Torr-Coal (NL), BIO3D (FR), EBES AG (AT), 4Energy Invest (BE), BioEndev/ ETPC (SWE), Atmosclear S.A. (CH), Andritz, EarthCare Products (USA)
- Screw reactor; BTG (NL), Biolake (NL), FoxCoal (NL), Agri-tech Producers (US)
- Herreshoff oven/ Multiple Hearth Furnace (MHF); CMI-NESA (BE), Wyssmont (USA)
- Torbed reactor: Topell (NL)
- Microwave reactor: Rotawave (UK)
- Compact moving bed: Andritz/ECN (NL), Thermya (FR), Buhler (D)
- Belt dryer: Stramproy (NL), Agri-tech producers (USA)
- Fixed bed: NewEarth Eco Technology (USA)

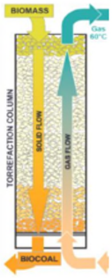
After due diligence with still active technology providers and plant visits (where possible) the rotating drum technology was selected. The rotating drum is a continuous reactor and can be regarded as proven technology for various applications. For torrefaction applications, the biomass in the reactor can be either directly or indirectly heated using superheated steam of flue gas resulting from the combustion of volatiles. The torrefaction process can be controlled by varying the torrefaction temperature, rotational velocity, length and angle of the drum. The drum rotation causes particles in the bed to mix properly and exchange heat, however the friction on the wall also increases the fine fraction. Rotating drums have a limited scalability, therefore higher capacities would require modular setup (Cremers et al. 2015).



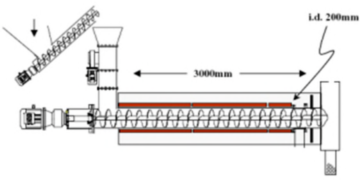
Multiple hearth furnace



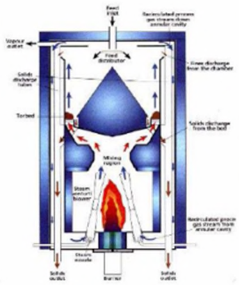
Rotary drum reactor



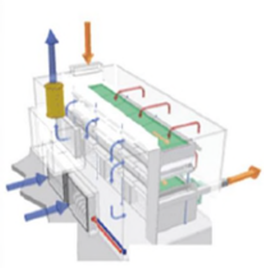
Moving bed reactor



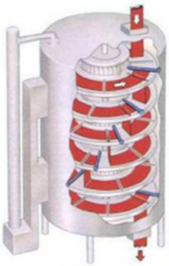
Screw conveyor reactor



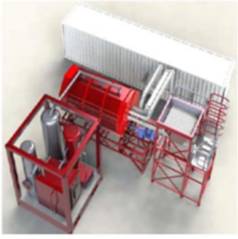
Torbed reactor



Oscillating belt reactor



TurboDryer



Microwave reactor

A collaboration was set-up with TorrCoal and Renewi in the Torero[16] project, with the aim to construct a Torrefaction demonstration plant at the Steel plant in Gent, Belgium and inject the produced biocoal in the blast furnace.

7.2 Advanced case study results

7.2.1 Torrefaction demonstration plant at ArcelorMittal in Gent, Belgium

The conceptual design of the Torero plant has been completed and the future location determined. After evaluating a number of alternatives, the initial idea of integration with the sinter plant was retained. The currently bio-coal production with the demonstration reactor will be within a range of 30 000 ton/year to 50 000 ton/year. The ARM engineering team estimates that the most likely production at start-up of one reactor will be 37 500 ton/year. The basic

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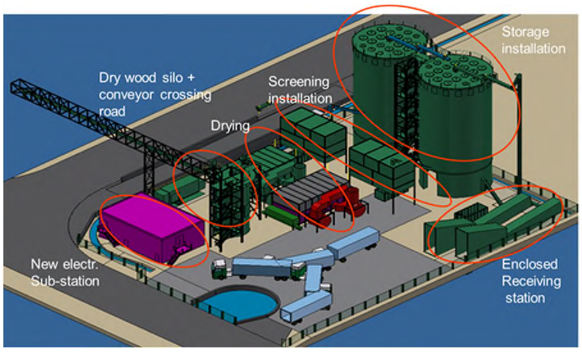
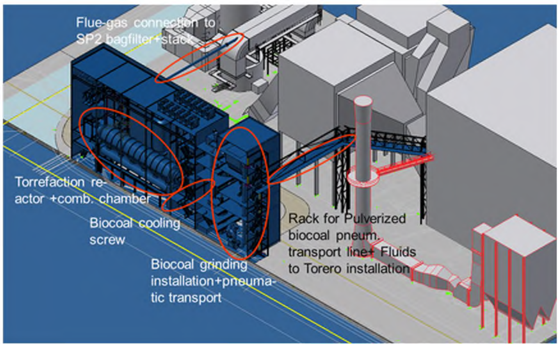
[16] TORERO has received funding from the European Union's Horizon 2020 - Research and Innovation Framework Programme (H2020-EU.3.3.3. - Alternative fuels and mobile energy sources). Project ID: 745810

engineering of the plant has been completed. Below 3D-view of the pre-handling, torrefaction and grinding installation.





Wet-B-Wood will be received in an enclosed receiving station over- and undersized wood will be removed there. The wood is transported via a bucket elevator and chain conveyor to a wet silo (2000 m^3). At the bottom of the silo via an internal screw the wood is brought to the ferro and non-ferro metals screening installation. After that the wood is brought to the continuous belt dryer to dry the wood. The dry wood is stored in a small dry wood silo and extracted at the bottom. Then it 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, torrgas is produced. 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 for dryer. 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 in the grinding installation pulverized. The pulverized biocoal is stored in a pulverized biocoal silo and send via pneumatic transport to Blast furnace.

The construction of the demonstration plant was started in 2020. Due to COVID significant delay occurred in the works, but in February 2022 a milestone was reached with the installation of the rotating drum reactor on site.

Figure 94: Progress of Torero plant construction works

Figure 95: Rotating Drum installation in February 2022

7.2.2 B-wood torrefaction at TPC Dilsen stokkem, BE

7.2.2.1 Introduction

In 2021, 3 torrefaction runs at industrial scale have been performed with B-wood as feedstock, at TPC, Dilsen Stokkem (Belgium). The below mentioned information gives a quick overview of the main results obtained during these production runs.

7.2.2.2 Production information

B-wood has been torrefied at a mass temperature of about 295°C (max. mass temperature during about 15 minutes at the end of the torrefaction process in the last section of the rotary kiln) with a mass loss of about 50 % on dry base.

Around 50 tons of torrefied B-wood have been produced. This means an input of dry feedstock into the reactor of about 100 tons was needed to produce 50 tons.

7.2.2.3 Photos

Figure 96: Photo of B-wood (a.) and of torrefied B-wood (b.)

7.2.2.4 **B-wood** and bio-carbon (torrefied bio-carbon) characterizations

Table 61: Average values - Characterisation of feedstock (B-wood) and torrefied product (Bio-carbon)

	B-wood	Bio-carbon
Moisture %	16,26	3,77
Ash %_dry	2,08	4,27
Vol mat %_daf	80,93	52,48
Fixed C %_dry	18,69	45,66
Fixed C %_daf	19,08	47,52
Gross Cal Val_daf GJ/t	19,99	26,72
Net Cal Val GJ/t cV As re-ceived	15,00	23,96
H %_daf	6,11	5,33
C %_daf	51,38	69,10
N %_daf	2,47	1,90
S %_daf	0,07	0,08
O %_daf	39,96	23,59
H %_dry	5,97	5,10
C %_dry	50,32	66,12
N %_dry	2,42	1,79
S %_dry	0,07	0,08
Cd mg/kg_dry	1,88	1,26
Pb mg/kg_dry	105,76	225,08
As mg/kg_dry	1,90	11,14
Mo mg/kg_dry	0,85	0,48
Hg mg/kg_dry	0,01	0,00
K mg/kg_dry	807,70	1788,20
Ca mg/kg_dry	2962,50	5842,20
Mg mg/kg_dry	465,65	700,14
Ti mg/kg_dry	491,65	472,60

Mn mg/kg_dry	97,80	214,82
Ni mg/kg_dry	6,15	5,88
Co mg/kg_dry	1,00	1,39
Cl mg/kg_dry	210,00	224,00
F mg/kg_dry	0,00	23,10
V mg/kg_dry	3,90	0,90
Sn mg/kg_dry	1,90	4,58
Si mg/kg_dry	2466,50	5833,20
P mg/kg_dry	180,00	329,00
Na mg/kg_dry	774,80	775,98
Sb mg/kg_det	1,03	2,25
Fe mg/kg_dry	990,00	1140,40
Cr mg/kg_dry	22,35	54,84
Cu mg/kg_dry	15,25	42,46
Zn mg/kg_dry	160,90	318,92
Al mg/kg_dry	490,35	1113,38

The composition of B-wood is rather inhomogeneous and therefore sampling can strongly influence the final analysis result. To get a good picture of the composition and its variation, more analyses are undoubtedly necessary.

The main challenge is related to the presence of metal pieces among the wood particles in the B-wood. This metal pieces have led to some blockages at the grinder system which have been easily solved. Another challenge which has been overcome is the high HCl and SO2 concentrations emitted during B-wood torrefaction which have been kept below the authorized limits thanks to the fume cleaning system using Sorbacal. Torrefaction of B-wood has been performed successfully at industrial scale. With the future torrefactions runs, we will definitely acquire even more data to draw more conclusions on the B-wood torrefaction at industrial scale.

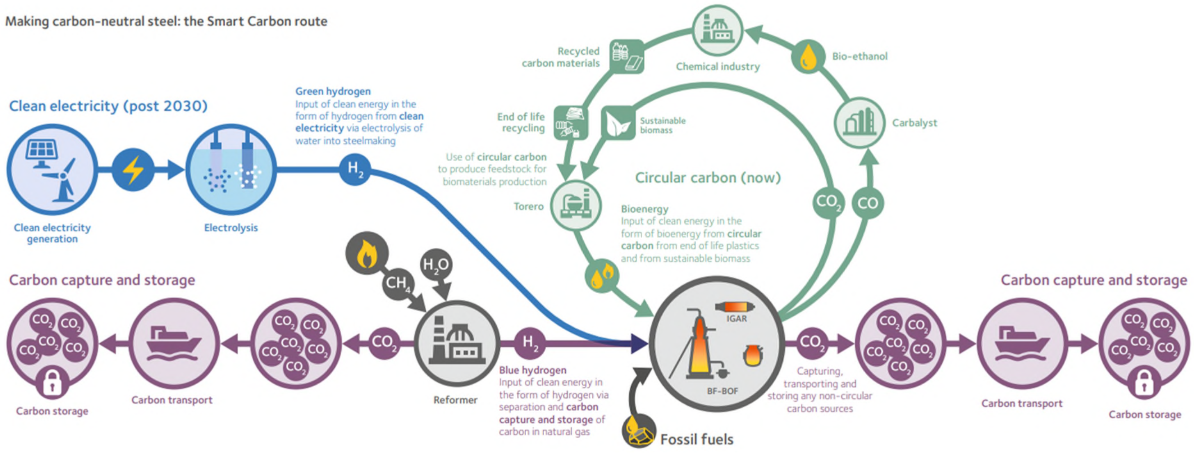
7.2.3 Replacement of coal by SRF pellets in the ArcelorMittal cokeplant

The LIFE SMART project aims to reduce GHG emissions by replacing fossil resources by renewable resources. In the project, the replacement of fossil coal for use in the coking plant, and in a second phase the torrefaction plant, by SRF pellets is studied. The SRF pellets are made of a mix of non-recyclable waste consisting of plastics, textiles and biomass (> 30% biomass).
Currently, industrial feasibility tests are ongoing to test the optimal replacement ratio for coking coal. The test interval is between 2 and 4 wt% of pellets in the coal blend, a higher replacement ratio leads to a loss of quality and as such, an optimal replacement ratio is sought. The replacement ratio is estimated to amount to between 30 and 60 kton SRF pellets per year. This replacement would save an estimated 23 to 46 kton of fossil CO_2 emissions per year for the coking plant.

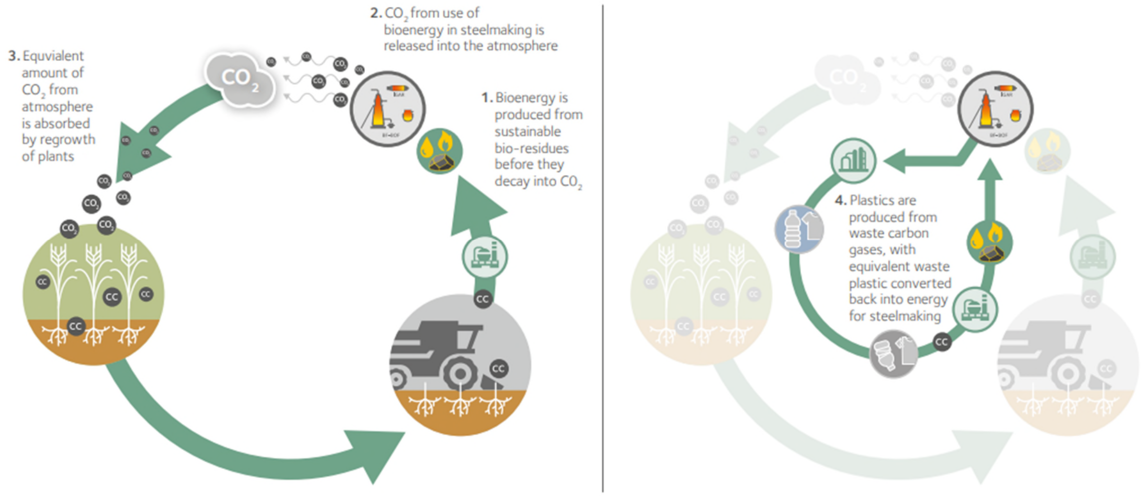
Figure 97: SRF pellet feeding during industrial tests in the coking plant

7.3 Strategic case study concept

ArcelorMittal is committed to reaching net-zero on a global basis by 2050. We have now adopted an ambitious set of carbon targets with which to lead our sector: by 2030, we are targeting a 25% reduction in our CO2e emissions intensity across our global steel and mining operations, with an increased European target of 35% (up from 30%). Both targets cover both scope 1 and 2. These targets create the milestones we need to achieve in order to meet our long-term target of net-zero by 2050 and are set against our 2018 baseline. ArcelorMittal has identified two viable decarbonisation technology pathways for steel: Innovative DRI and Smart Carbon, and a third pathway, direct electrolysis, which is promising but not yet mature. We have done a lot of work developing technologies for the two viable routes since the publication of our last report. While these technologies are still far from being commercially competitive, this work has reinforced the potential that both pathways have to produce net-zero steel. In Europe, the policy environment has enabled ArcelorMittal to accelerate plans to decarbonise steel. EU policy combined with support for significant projects to kickstart the development of hydrogen infrastructure in Europe and reduce the costs, alongside ambitious national commitments to deliver abundant supplies of clean energy and provide funding support for decarbonisation, make it possible to envision zero carbon-emissions steelmaking in first-mover countries across scope 1 and 2 emissions within the next five years: as set out in our detailed plan for our Sestao plant in Spain. As renewable and low-carbon electricity becomes increasingly available, the production of affordable, industrial-scale green hydrogen becomes a possibility and the prospect of zero carbone missions steel made via the green hydrogen– DRI–EAF route becomes viable. In Europe, our strategy is largely focused on the Innovative DRI pathway. This reflects the commitment in Europe to prioritise the availability of green hydrogen at competitive prices. Given the significant variation across countries and regions in existing CO2 policy frameworks and in the availability and cost of the clean energy, we will continue to develop our Smart Carbon route. This combines bio-energy, carbon capture and utilisation – all technologies that the International Energy Agency (IEA) and the UN Intergovernmental Panel on Climate Change (IPCC) see as critical to achieving net-zero by 2050. Crucially, Smart Carbon gives us flexibility to adjust our carbon emission reduction plans to local steelmaking conditions.



Circular carbon uses carbon-based energy that does not add carbon to our biosphere. It can be in the form of bioenergy from the natural carbon cycle, such as waste from sustainably-sourced construction wood, agriculture and forestry residues, where regrowth of managed forests and crops will recapture the CO2 emitted from the bioenergy used. Circular carbon uses carbon-based energy that does not add carbon to our biosphere. It can be in the form of bioenergy from the natural carbon cycle, such as waste from sustainably-sourced construction wood, agriculture and forestry residues, where regrowth of managed forests and crops will recapture the CO2 emitted from the bioenergy used. Circular carbon uses carbon-based energy that does not add carbon to our biosphere. It can be in the form of bioenergy from the natural carbon cycle, such as waste from sustainably-sourced construction wood, agriculture and forestry residues, where regrowth of managed forests and crops will recapture the CO2 emitted from the bioenergy used.



There are several options to substitute fossil carbon with biogenic carbon in the integrated steel mill route. Studies from the literature have identified that substitution of coal by biomass in the pulverized coal injection (PCI) 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 in blast furnace. The core of the process in 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 in steelmaking are coke, heavy oil, pulverized coal, natural gas and hot reducing gases. Coke is the primary fuel and reducing agent in blast furnace process, ranging around 350 - 400 kg/t of hot metal in modern blast furnaces. The main function of coke in the blast furnace are: i) acting as reducing agent, ii) supplies energy to the process and is a support medium to the burden material. Pulverized coal is the most widely used auxiliary fuel in blast furnace, and hence it can reduce significantly 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 a total of 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 US). 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 provides a suitable reducing atmosphere in the furnace conditions, without compromising blast furnace efficiency nor increasing coke rate feed. The low energy density of 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. Note that, in order to inject the biomass into the modern blast furnaces the woody biomass must be upgraded for utilization in blast furnaces 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 BF can be summarized as follows:

- Lower calorific value of biomass products compared to coal require efficient pre-treatment and pyrolysis.
- Difficulties in biomass injection at a high rate due to the porous nature which require 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 before utilization to avoid its negative impact on the refractory materials.

According to the literature, injection of charcoal in blast furnace can be up to 200 kg/ton hot metal. However, this is considered for charcoals with high carbon content and low ash content. Charcoal from wood-based 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. In Torero, it has been identified that 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.

The LIFE SMART project investigates the replaceability potential of coking coal with SRF pellets (see section 7.2.3). The most important limit on the replacement of coal with SRF pellet is the decrease in quality. Pilot scale trials have shown that the physical properties of the coke, as expressed by the CSR parameter (Coke Strength after Reaction), begin to decline around a 2 wt% SRF pellet addition in the coal blend. These results are now being verified in an industrial setting. The figure below shows the addition of different weight percentages of SRF pellets (AlterCoal pellets) and of different types of pellets. A lower CSR may be compensated by increasing the quality of the coal blend, which induces a higher cost for the coal blend. As such, the replacement ratio of the coal blend with SRF pellets is constrained by economical parameters.

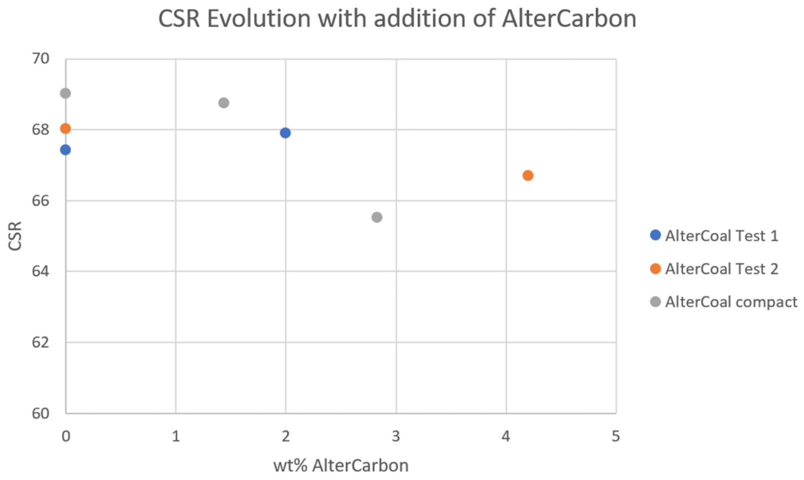


Figure 98: Test results of SRF pellet addition to coking blend

A second important factor to be considered in the replacement of fossil resources by renewable resources is the conversion factors in the process. The coking process is a dry distillation which has as goal to remove the volatiles from the coals and to produce a porous, hard, slowly reaction product: metallurgical coke. During the conversion process, a wide range in reactions occurs, ranging from decomposition reactions to condensations reactions, effectively resulting in a sort of 'chemical rearrangement' of the participating molecules. The SRF pellets, consisting of biomass, textiles and plastics undergo this range of reactions but do not have the same conversion selectivity as the coking coals due to their different composition, as shown in Error! Reference source not found.. It can be seen that the use of SRF pellets will yield less coke and more liquid and gaseous byproducts. These byproducts are valorised in the steel plant, however, the loss in coke production will have to be compensated by adjusting the production target or by sourcing external coke. This represents an important restraint on the economics of this process.

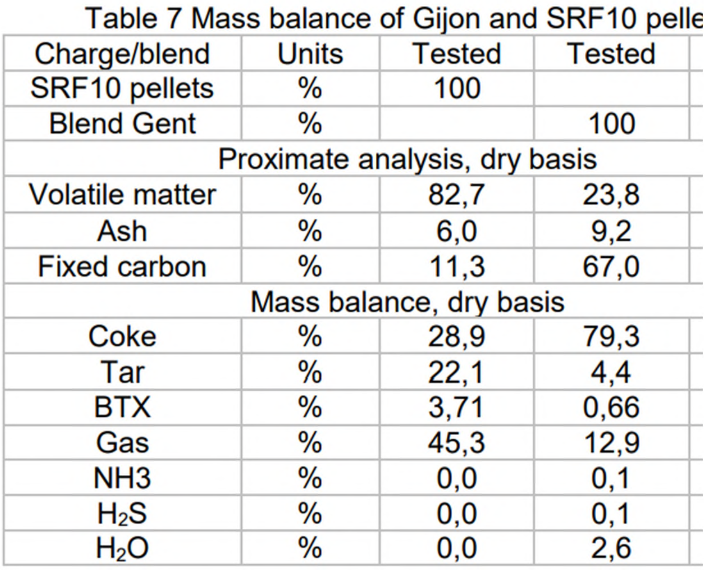


Table 7 Mass balance of Gijon and SRF10 pelle

Charge/blend	Units	Tested	Tested
SRF10 pellets	%	100	
Blend Gent	%		100
Proximate analysis, dry basis			
Volatile matter	%	82,7	23,8
Ash	%	6,0	9,2
Fixed carbon	%	11,3	67,0
Mass balance, dry basis			
Coke	%	28,9	79,3
Tar	%	22,1	4,4
BTX	%	3,71	0,66
Gas	%	45,3	12,9
NH3	%	0,0	0,1
H_2S	%	0,0	0,1
H_2O	%	0,0	2,6

Figure 99: Mass balances for coal blend and pellet conversion

The production of biocoal and alternative coal will provide a new use (bio)waste for production of feedstock for renewable ethanol and other base chemicals. The blast furnace is (besides the steel production) used as a gasification unit and will lead through existing fermentation technology to the production of ethanol or other chemicals. The waste gases that result from iron and steelmaking are composed of the same molecular building blocks – carbon and hydrogen – used to produce the vast range of chemical products our society needs. Today most waste gas is incinerated, resulting in CO2 emissions. With the partner LanzaTech, supported by the EU Horizon2020 Steelanol project, ArcelorMittal is building the first large-scale plant to capture the waste gas and biologically convert it into ethanol, the first commercial product of our Carbalyst® family of recycled carbon chemicals. Thanks to a lifecycle analysis study, we can predict a CO2 reduction of up to 87% compared with fossil transport fuels, so this ethanol can be used to support the decarbonisation of the transport sector as an intermediate solution during the transition to full electrification. In the future, we will expand the family of Carbalyst® products to other chemicals. Construction started in 2019 and once completed end 2022, the facility will capture around 15% of the available waste gases at the plant and convert them into 80 million litres of ethanol per year.

Figure 100: Steelanol plant under construction at ArcelorMittal Gent

As it is part of the ArcelorMittal climate action plan Smart Carbon pathway will be roll-out in operational plants in Europe and rest of the world.

Figure 101: Integrated Steel Plants (BF-operated) in EU

The steel industry is important in the EU, divided in 500 production sites in 23 EU 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 this project, replacing part of the fossil fuel by torrefied wood powder, can be easily translated to other steel plants. In theory, all existing steel plants in the EU can benefit from this innovation technology and lower their greenhouse gas emission.
- In the demonstration plant, a yearly capacity of 100,000 ton type B wood is targeted, the equivalent of 50,000 tons of torrefied material. At full commercial scale, this capacity will be higher and the investments will decrease as the number of plants grows in the EU. The feed stock 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 is large supply

ArcelorMittal has made an assessment on the feasibility of implementing the Torero technology in their production facilities as part of the Carbon Action Plan. ArcelorMittal Europe has committed to reduce CO2 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 (DRI) operations across seven countries, AM has a significant role to play in contributing to the EU's green ambitions. To transform our operations to become carbon neutral, we need 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). AM will reduce our European Scope 1 CO2 intensity by 30% by 2030, over a 2018 baseline.

AM has committed around €300 million towards carbon-neutral technology, leveraging our 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.

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. These include Torero (turning waste wood into bio-coal to replace coal as a reductant in ironmaking); IGAR (making synthetic gas from waste CO2 as a replacement for fossil fuels); and Carbalyst® (converting off-gases into bio-ethanol).

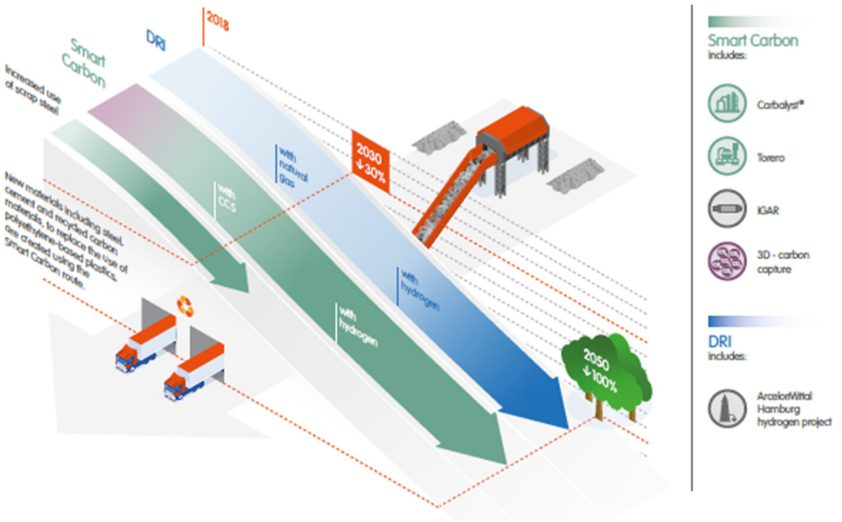


Figure 102: ArcelorMittal Europe Carbon Action Plan

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The Torero technology thus has an important contribution to the path to carbon neutrality by 2030. An implementation plan has been developed for Torero plants in EU taking into account local feedstock conditions.

Figure 103: ArcelorMittal production plants in Europe

The total BF production Europe is estimated at 31,5 Mt0n. Based on the average coal consumption of a blast furnaces the total

- Coal consumed is 16,4 Mton (522 kg/ton hot metal), resulting in total Coke 11 Mton (350 kg/ ton hot metal)
- PCI (powder coal for injection) 4,7 Mton (150 kg/ ton hot metal)

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.

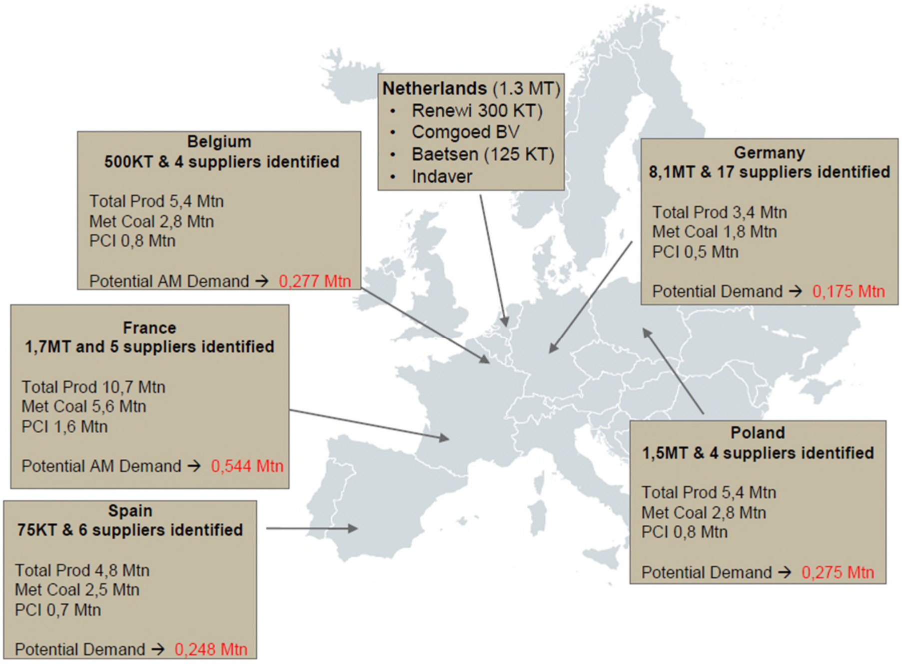

Figure 104: Potentials (Source: EU funded BioReg Report 2018)

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 50Mton. 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%).

7.4 Biomass availability and plant siting

7.4.1 Different types of waste biomass

Main biomass waste types are green waste, food waste, wood, paper and cardboard, some textiles, organic sludges, filter cakes of organic sludges and various organic residues from industrial activities (food and beverage industry).

Most of these wastes are among the list of wastes that have to be collected separately in many EU countries. Residual waste should not contain much of such waste. They are collected as mono-stream which is clearly beneficial for the quality and the potential for reuse or recycling.

However, there is still a lot of bio-mass in the residual waste fraction. It is sometimes difficult to set up or organise separate collection for small volumes. Such smaller volumes often end up in the residual waste. Another reason is the quality of a specific biomass stream. Acceptation criteria of the waste streams that are collected separately indicate what is not acceptable. For example, not all paper-based products can be recycled.

Green waste

Green waste is the compostable part of organic waste. It consists of leaves, branches, trunks, roots, grass clippings and plants. Green waste is sent to composting plants and converted in to certified compost. Composting is considered as recycling. Other recycling or reuse application are mulch material as ground cover. For the latter, in theory, only wood can be used, not the leaves, grass or other plants. In order to maintain a good composting process, a minimum amount of wood is needed. For example, an equal amount of wood and grass is needed for good composting of grass. Big pieces of wood are screened out at the end of the composting process.

Green waste needs to be collected separately. There is a landfill and combustion ban on green waste. Only the excess of wood can be sent to a combustion plant for energy recovery.

Food Waste

Food waste can be food scrap, kitchen waste, packed and unpacked food. Food waste is often wet but can be solid and dry are completely liquid. Food waste has a low calorific value. It has a negative impact on the recycling quality of other waste materials if mixed. More and more, also food waste needs to be collected separately. Food waste when mixed with green waste can be used to make compost. However, food waste is generally used to feed anaerobic digestors. The anaerobic digestor generates bio-methane gas and a liquid residue called digestate. Digestate is a liquid organic containing substance. The direct application on land is not possible everywhere due to the high content of nitrogen. Several technologies do exist for the further treatment of digestate and the use of the thick and thin fraction of the digestate separation. One of the options is drying and combustion with energy recovery or the use of the dry pellets as animal bedding or organic fertilizer.

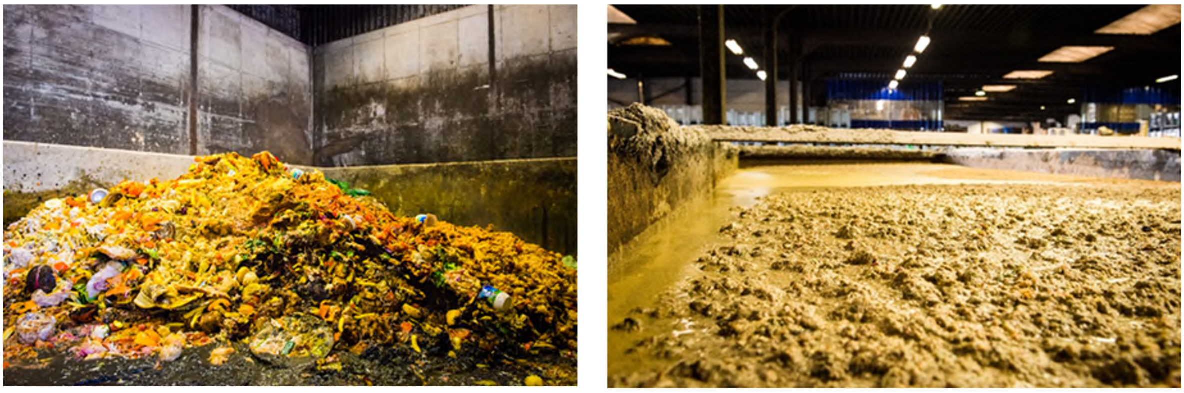

Figure showing food waste before and after pre-treatment to make an energy mix for digestion plants.

Wood Waste

Wood waste is the biggest volume of solid biomass waste. Wood waste consists of untreated wood or treated wood. Treated wood can be contaminated (railway sleepers, chemically treated wood) or non-contaminated wood (painted, varnished or glued such as in panel board, strand board, plywood, MDF). Contaminated treated wood is dangerous waste and as such indicated in the EURAL waste list. The types of wood waste are often indicated with the letters: A-wood for untreated wood; B-wood for non-contaminated treated wood; C-wood for contaminated treated wood. For the treatment of C-wood, a permit to treat dangerous waste is required.

Figure showing examples of a waste wood pile.

Paper and cardboard

Paper and cardboard is also one of the biggest available biomass wastes. Paper and cardboard is collected separately for the same quality reason as indicated earlier. Paper and cardboard is an important raw material of paper mills. The European Paper Recycling Council promotes and monitors recycling. The targets set earlier for 2020 was 74% recycling and obtained in time. There are several qualities of paper products. Not all paper and cardboard waste can be recycled to every quality. Like for wood, also for paper, several qualities are used linked with the market value and the potential application. There is still paper and cardboard in residual waste. The latest sorting at source regulation in Flanders (as an example) came in to force on the first of September 2021. Waste collectors of industrial residual waste need to control the composition of residual waste and inform the client (waste producer) if the residual waste still contains one of the 24 streams that need to be collected selectively. Packaging material including paper and cardboard are one of the main streams for which non-conformities need to be made.

Textiles

The circular economy of textiles gets a lot of attention because of the high environmental (including micro plastics) and social impact of textile production. Europe is a big consumer of textiles. Production together with its environmental and social impact are elsewhere. Most textile waste clothes are shipped abroad for reuse. Collection systems in many countries operate separate from the other wastes. The two main types of textile waste are those made with natural fibres and those made with synthetic fibres. Several industrial textiles and several clothes are a combination of several fibres making recycling more difficult. A lot of textiles if not reused or recycled as industrial rags, insulation, furniture padding are still incinerated are used in cement kilns. New upcoming is the spinning of yarn from recycled textiles and the chemical recycling of synthetic textiles.

Organic sludges, filter cakes from organic sludges

Organic sludges are produced in many wastewater treatment facilities such as in the facilities that treat domestic waste waters. Not all organic sludges can be used in agriculture. Its use is strongly regulated in the EU and can depend on the use of the land (to grow food crops, to feed cattle, …. Several documents and admissions indicating the amount and the moment in the year are required to use organic sludges on agricultural land. The amount of sludge that can be used in agriculture depends on the nitrogen content of the sludge and the nitrogen content of the land. To guarantee continuity, alternatives for the use on land, are needed. One of the alternatives is combustion and drying before combustion.

Organic residues from industrial processes

The food and beverage industry generates various biomass containing residues that are used in agriculture, as feed for digestors, for composting or combustion. The direct use in agriculture is often the cheapest option but as indicated above, strictly regulated.

Another organic waste stream from industrial processes is digestate mentioned in the paragraph of food waste. Digestate is also dried and if not used in agriculture, it is used in digestors or combusted.

7.4.2 Availability of biomass

The Eurostat database provides following data for 2018, as listed in this table.

Table 62: Available biomass waste material in the EU-28 (data from 2018)

	EU – 28 in tonne
Wood wastes	56.290.000
Paper and cardboard	53.200.000
Textile wastes	2.370.000 (not all is biomass based)
Animal and mixed food waste	26.920.000
Vegetable waste	58.450.000
Animal faeces, urine and manure	13.160.000
Sludges and liquid waste from waste treatment	10.200.000 (not all is biomass based)
Industrial effluent sludge	13.400.000 (not all is biomass based)

In the European Commission's Knowledge Centre for Bioeconomy, Brief on biomass for energy in the European Union (biomass_4_energy_brief_online_1, publications.jrc.ec.europa.eu/JRC109354) is indicated that 12.4 % of the EU biomass supplies for energy purposes comes from waste which represents 17 Mtoe. Wood is a main source of biomass for energy production. A lot of waste wood is used in biomass power plants for power and heat production. The value of waste wood increased at the end of 2021 and the beginning of 2022. The market value of waste wood is followed by indexes such as the EUWID index. The graph below shows the sharp rise of the wood value. The index reflects the price the power plant needs to pay to get wood. The index is used in delivery contracts for waste wood. Contracts often use the EUWID index and a factor. The index itself is not equal to the price.

Figure EUWID index used for waste wood showing data until February 2022.

Climate change mitigating policy and high energy prices because of high prices for the traditional energy carriers (gas, fuel, …) increased the appetite for biomass. The demand for waste wood is strongly increased as is reflected by the strong rise of the EUWID index for the German market. The price levels completely shifted. Some months ago, biomass power plants were paid to treat waste wood. Now, biomass power plants can easily pay for feedstock. Wood from The Netherlands and Belgium is exported to Germany and Scandinavia. Several new biomass projects in Belgium will reduce the export of wood. The planned capacity even requires an import of waste wood in Belgium. This shift in market conditions together with the high demand for wood in Germany and Luxembourg effects strongly effects the price levels during the first months of 2022. Price levels are currently (February 2022) changing every week and are clearly not stable yet. The changes in price levels mean that the collectors gate fee are under pressure. It is easy to get rid of waste wood and collection fees (gate fees for collection) are dropping.

7.4.3 Availability of biomass

Common steps before or during the process of using biomass are size reduction, screening and sorting. The process of making compost out of green waste consists of shredding and screening. Food waste is turned in to an energy rich slurry from which packaging is removed.
Wood waste for recycling can be made out of A-wood or B-wood. C-wood is generally combusted.

A-wood consists of packaging material such as pallets and untreated construction wood. Pallets are collected separately or sorted out for reuse. As wood becomes more expensive, the interest in damaged pallets of all kind and wood planks increases. Damaged pallets are repaired making use of new or old planks. The market for reuse of wood in construction is still small but growing. More and more second-hand marketplaces and shops provide construction wood for reuse.

If wood is used for recycling in panel board, strand board, animal bedding or combustion, it needs to be size reduced. Most small biomass power plants may only use untreated wood (A-wood). The bigger power plants, having a full gas cleaning system, can use B-wood. The size specification for biomass power plants differs from plant to plant and can be 0-300 mm (pre-crushed), 0-200 mm or 0-150 mm (chips). Some smaller installation can only accept material with particles smaller than 100 mm. In general, the smaller the size, the higher the cost to make it. Also, wood for recycling needs to be size reduced. The size depends on the application. Roughly speaking, 0-100 mm is a common size limit for recycling. Specification for recycling are in general more extensive than specification for biomass power plants. The content of fines, the moisture content, the amount of unacceptable material (such as MDF or pieces of panel board) are examples of criteria for wood for panel board production. The size of wood for making cat litter, bedding material or wood pellets for combustion are much smaller. Because not all wood is acceptable for recycling, sorting is needed to take out metals, MDF, pieces of panel board, other non-acceptable wood and all non-wood. Sorting can be automated or by hand. Several preparation steps for using waste wood can be performed in the panel board or strand board plant.

The same technologies are used to prepare wood for feeding Torrefaction technology. The specified particle size is smaller than the standard size for panel board or strand board production. For the production of particles with a small size at high capacity, fast turning shredders are needed. Such fast turning shredders have the disadvantage of making more fine material and dust for which an alternative outlet is needed if it cannot be put back in the product material. Paper and cardboard are collected in different qualities and baled. A sorting step can be included to clean for example the paper stream prior to baling. Size reduction and pulping is performed at the paper mill. Except for confidential paper for which the size reduction is performed in a controlled environment. Dry pulping can be used to increase the value and the off-take options of recycled paper and carboard but the dry pulping process still seems to have a high risk of fire. Shredding, screening and sorting are common technologies in waste wood preparation and biomass preparation in general. Drying is less common and limited to sludge and digestate treatment. An upcoming technology for the treatment of organic sludges is Hydrothermal Carbonization. The technology claims to generate a carbon rich concentrate from wet biomass streams so that it can be used as energy carrier.

Advanced recycling plants intent to increase the number of recyclable materials with post sorting from residual waste. Eurostat data indicate more than 40 million tons of mixed and undifferentiated waste, 165 million tons of household and similar waste (excluding separately collected waste fractions) and more than 100 million tons of sorting residues (all European Union – 28 countries data). These data show that there is still room for improved sorting (sorting at source + post sorting). Wood, textiles, paper and cardboard sorted from this waste are probably too low in quality for recycling but it can be an interesting source for biomass applications. If it is required to get 100% pure biomass, advanced sorting will help to get such pure biomass mix. Size reduction, drying and pelletizing or briquetting allow to make a biomass pellet or briquette.

Figure 105: examples of paper and cardboard containing residual waste

In Figure 105 examples of paper and cardboard containing residual waste are shown. Post sorting can recover this biomass.

Figure 106: Mixed Renewi pellets (left) and wood pellets (right)

7.5 Logistical overview and alternatives

In several countries or regions, wood needs to be collected separately. Regulation does not oblige to collect the different types of wood separately however, C-wood is hazardous waste and needs to be collected following the transport regulations of hazardous waste. Wood is collected most often with metal waste containers. Smaller volumes of wood can be combined with other waste materials as long as post sorting is sufficiently efficient. The main driver to sort waste wood at source is the lower treatment fee. The fee is significantly lower than the fee to collect residual waste. The waste producers can bring waste wood to the collection site instead of renting a container. Most wood comes from container parks, packaging material of industrial customers, and building and construction waste. Most wood arrives unbroken at the collection site in 20 up to 40 m^3 containers. Depending on the size of the wood chips and the size of the container, the containers only contains 4 to 10 ton wood.

Wood that arrives at the collection site is treated at the collection site or shipped to centralised and specialised wood treatment sites. Transport from collection site to treatment site is done with walking floors or by boat. Walking floors of 90 m^3 can take 20 to 25 tons if well loaded. Loading and unloading walking floors takes approximately 15 minutes. Walking floors is until now the cheapest and most flexible (drive from loading to unloading position) way of transport for short distances. Boat transport is preferred for longer distances. Loading, unloading and last distance costs depend on the connection to the quay. If possible, transport by waterway is preferred but until now costs are higher and it requires more space for wood storage at both the loading and unloading point. High amount of storage are often in conflict with fire safety standards. Fire safety standards limit the size of the heaps and the height of the heaps (for example 4 meter max).

Renewi can deliver wood for Torrefaction at ArcelorMittal Gent from various sites by walking floor or by boat. Most wood will come from the Renewi Gent site which is just across the road of ArcelorMittal. Transport will be done by walking floor.

7.6 Greenhouse gas emission

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 (Biermann et al. 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 example of an integrated steel mill (blast furnace route). The potential for CO2 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 CO2 emissions between the cogenerated steel, ethanol, and electricity.

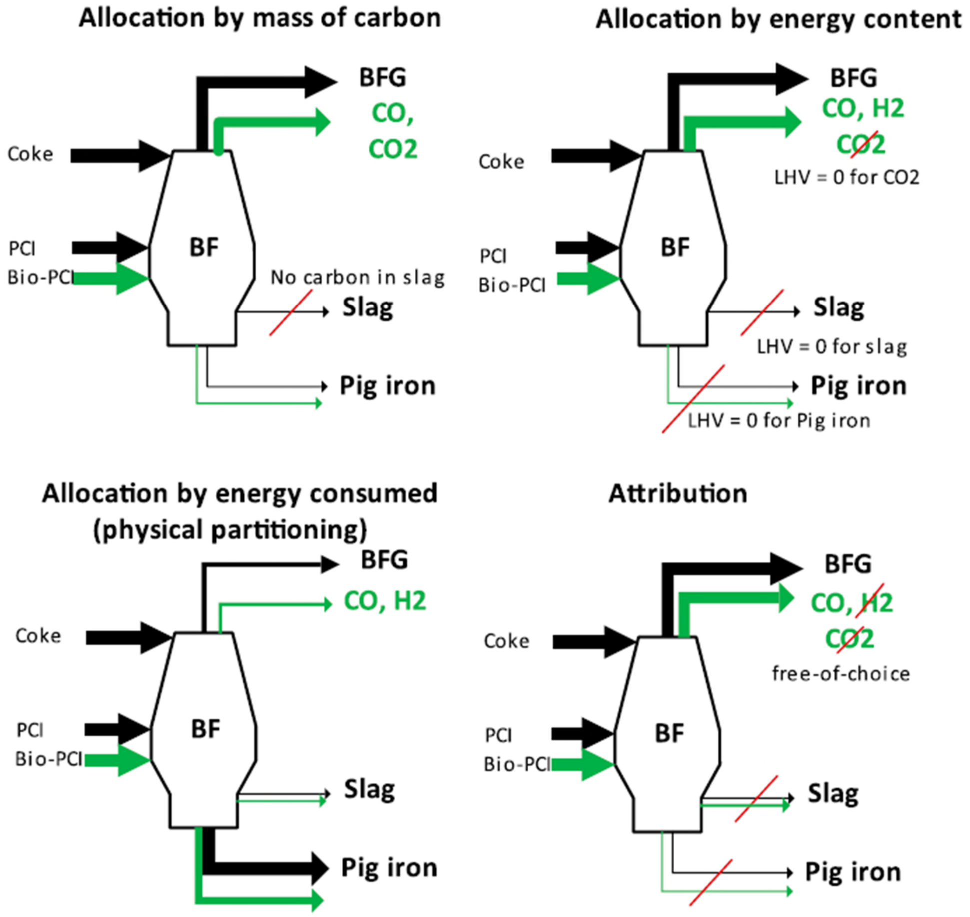

Figure 107: Biomass allocation schemes

Carbon allocation 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 ktCO2 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 H2 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. They recommend that policymakers consider the emerging relevance of co-processing in non-refining facilities. Provided there is no double-accounting of emissions, policies should contain 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.

The overall emissions in ETS are illustrated (diamond symbols) in figure below, together with the share of these emissions that each product system receives. The injection of biochar reduces the overall emissions by 2.5% and 3.5% in C2 and C3, respectively, when producing either electricity or ethanol. The application of CCS (C4) reduces emissions by 26.6%. The distribution of emissions varies as a function of the steel mill configuration and the carbon allocation scheme, although the steel product emissions clearly dominate due to the large differences in product volume. Note that the carbon allocation scheme does not affect the total emissions. The following three paragraphs consider each product system in detail.

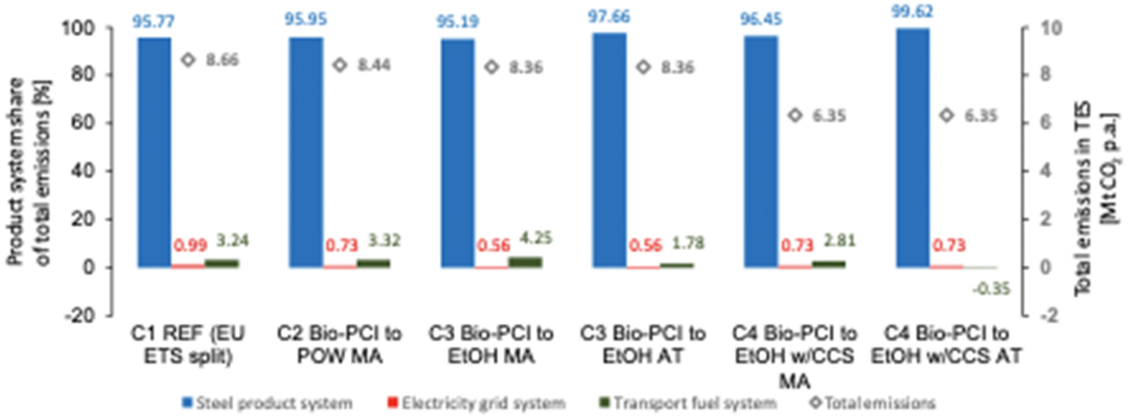

Figure 108: Total emissions in TES

In Figure 108 the total emissions are shown. Total emissions in TES and their distribution into the three product systems for the studied steel mill configurations C1–C4 depending on allocation by mass (MA) or attribution (AT). The grid intensity is 295.6 gCO2/kWh (EU average). EtOH, ethanol production via fermentation of blast furnace gas; POW, electricity export; REF, reference mill with electricity export.

The CO_2 emission intensities of the steel product that results from reductions of CO_2emissions through mitigation are shown in figure below. The emission intensity of steel produced in the reference mill (2,073 kgCO_2/t HRC) is reduced in all configurations, C2–C4, when biochar is introduced. Allocation by mass provides a large share of biogenic carbon to the steel product, *ca.* 50 kgCO_2/t HRC, which is more than the emission reduction achieved by co-generating electricity in the reference case (C1). Attribution allocates all the biogenic carbon to ethanol and, thus, renders higher carbon emissions to the steel than allocation by mass. The co-generation of ethanol (fossil + biogenic) has a similar effect on the steel-related emissions as the introduction of biochar (see C3 configuration with free attribution). The co-generation of electricity (C2, mass allocation) is less-beneficial than co-generation of ethanol with respect to the emissions from the steel product. As expected, CCS (C4) has the strongest impact on the emission intensity of steel, reducing it by 24%–26%. Note that allocation of the CO_2 emissions avoided (due to CCS) follows the allocation by mass principle also for the C4 configuration with free attribution. Thus, 93% of the avoided CO_2 emissions from CCS are allocated to steel.

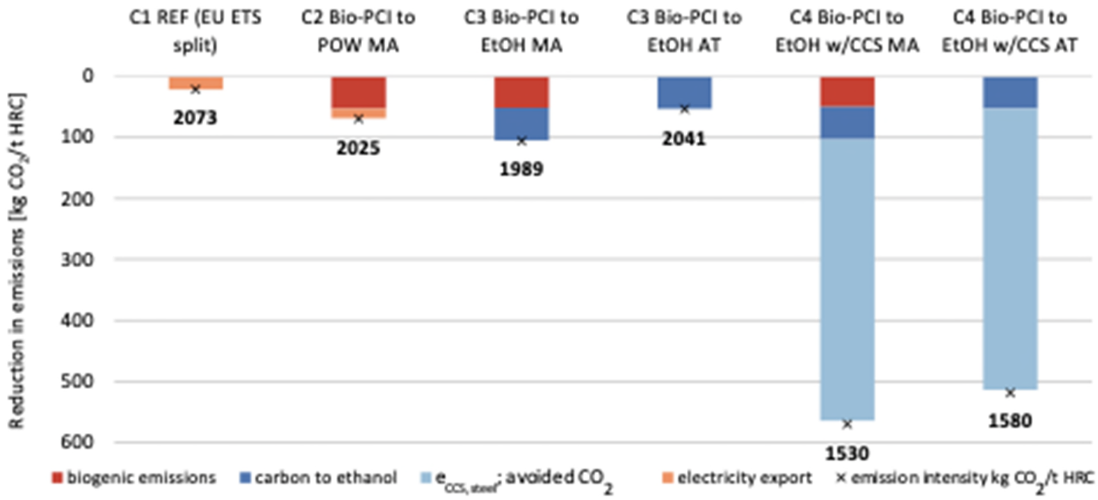

Figure 109: Emissions compared to the reference mill and the resulting emission intensity

This figure shows the emissions compared to the reference mill and the resulting emission intensity of the steel product, depending on the steel mill configuration and allocation scheme, i.e., allocation by carbon mass balance (MA) and free attribution (AT), which maximizes the amount to biogenic carbon assigned to the ethanol production. The allocation of CO2 avoided (CCS) is 93:7 (steel:ethanol) based on mass allocation. The grid intensity is 295.6 gCO2/kWh (EU average).

The CO_2 emission intensities of the produced ethanol are illustrated in figure below. The C1 and C2 configurations do not produce ethanol, and the emission intensity of the transport product system is the same as that of the fossil comparator, 94 gCO_{2eq}/MJ. In C3, the co-generated ethanol has a higher emission intensity than the fossil comparator with mass-based allocation. Free attribution reduces the emission intensity, although the biofuel target is not met. Note that a large share of the ethanol emission intensity is related to the electricity demand caused by the diversion of BFG to the syngas fermentation plant (displaced electricity). If these emissions were allocated to the steel product instead, leading to an increase of 27 $kgCO_2$/t HRC, C3 with mass allocation would perform better than the fossil comparator and C3 with free attribution would fulfil the biofuel criterion, i.e., 65% emission savings compared to the fossil comparator.

Configuration C4, with syngas fermentation and CCS, requires the importation of NG to cover the heat demand. Since the heat is generated in the CHP plant, co-generation of electricity increases, and this reduces the number of emissions from the imported and displaced electricity. Despite this, the CO_2-avoided from CCS allocated to ethanol does not compensate for the fossil share of the ethanol when allocating based on mass. With free attribution, however, CCS may lead to negative emissions in the transport product system. The value of -7 gCO_{2eq}/MJ in Figure 22 is based on a CO_2-avoided allocation of 93:7 between steel and ethanol (allocation by mass). The emission intensities would be +56 gCO_2eq/MJ and - 624 gCO_{2eq}/MJ for the extreme (steel:ethanol) ratios of 100:0 and 0:100, respectively. This attribution of avoided emissions to a product beyond the zero-line (0 gCO_{2eq}/MJ) is unnecessary and should be avoided, unless the associated negative emissions can somehow be valorised by a robust, consumer-based, offsetting mechanism.

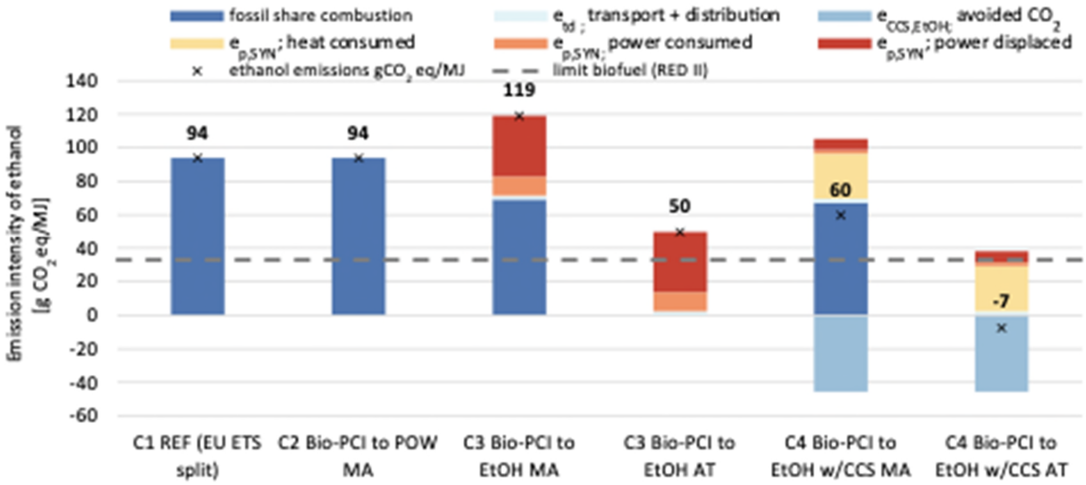

Figure 110: Emission intensities of the ethanol product

This figure shows the emissions intensities of the ethanol product depending on the steel mill configuration and allocation principles: Allocation by carbon mass balance and free attribution maximizing the biogenic carbon to ethanol production. The allocation of CO2 avoided (CCS) is 93:7 (steel:ethanol) based on mass allocation. The grid intensity is 295.6 gCO2/kWh (EU average).

The absolute CO_2 emissions in the electricity grid system change when implementing mitigation technologies. For C1 and C2, electricity is exported, whereas for C3 and C4 electricity is imported. The indirect CO_2 emissions from the imported electricity are passed through to the co-generated products (indicated by the bars cancelling out each other). The indirect emissions derived from the electricity required for CCS are considered in the CO_2 avoidance calculation. In C3 and C4, only the electricity previously exported from the steel mill (C1, C2) must be generated elsewhere, causing emissions corresponding to the grid intensity (assuming that the existing capacities of power-generating facilities suffice). Since the default grid intensity (EU average of 295.6 gCO_2/kWh) is lower than the emissions intensities of the electricity in C1 and C2

(546 gCO_2/kWh and 384 gCO_2/kWh, respectively), C3 and C4 cause net-lower emissions than C1 and C2. For grid intensities higher than the generated electricity's intensities in C1 and C2, the configurations C3 and C4 cause an increase in emissions in the electricity grid system.

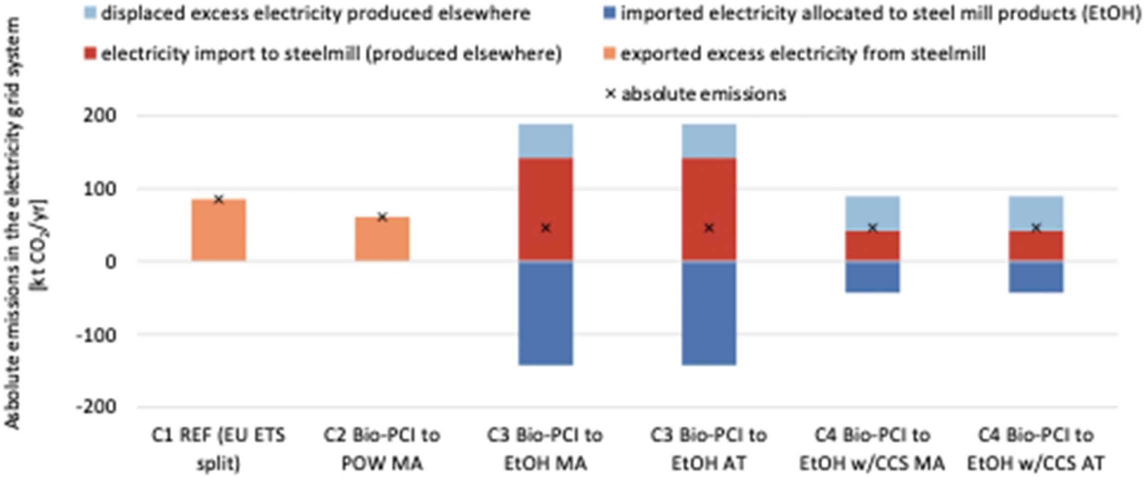

Figure 111: Absolute emissions in the electricity grid system due to interaction with the steel mill (4 Mt HRC per year) depending on the steel mill configuration and allocation principles: allocation by carbon mass balance and free attribution

Taking into account the results of intensive study on the impact of allocation scheme of the Torero biogenic carbon from the bio-coal to ethanol of steel product. The preferred allocation scheme for the Torero-Steelanol process is 'free attribution' since most beneficial for production of advanced biofuel. The impact of planned implementation of the Torero plant reactors (capacity and optimization) and allocation scheme on the production of advanced ethanol is illustrated in below table. The wood will be supplied from 4 sites of Renewi in the wider area of the AM Gent plant: Gent (65000 ton), Evergem (30000 ton), Puurs (80000 ton).

Table 63: Carbon allocation scheme Torero

Approximate year	Waste wood used Tons/year (Renewi supply sites)	Biocoal produced/consumed Tons/year	Ethanol produced Tons/year	% adv. ethanol	Allocation basis
Torero scope 2022	87 500 (Gent 65 kt Evergem 20 kt Puurs 0 kt)	37 500	64 000	68 % BIO (32 % RCF)	100 % bio-C allocation to ethanol
Torero scope 2024	175 000 (Gent 65 kt Evergem 30 kt Puurs 80 kt)	75 000	64 000	100 % BIO	73 % bio-C allocation
Torero scope post 2026 (optimised process)	233 000 (Gent 65 kt	100 000	64 000	100 % BIO	55 % bio-C allocation

	Evergem 30 kt Puurs 80 kt TBD 58 kt)				

7.7 Certification

7.7.1 Description of the value chain and identification of interfaces

In the case study value chain, ethanol production takes place as part of an integrated steel production process in which biobased and non-biobased torrefied material is utilized to substitute pulverized coal in a blast furnace, where exhaust gases are captured and fed into a microbial fermentation process.

To assess the relevance of the sustainability criteria arising from RED II, primarily from Article 29, the different interfaces of the value chain are examined which are illustrated in a simplified manner below (Figure 112). Among the MUSIC case studies, the international case study is special due to the input of biomass and (non-biobased) waste feedstocks as well as the overall complexity.

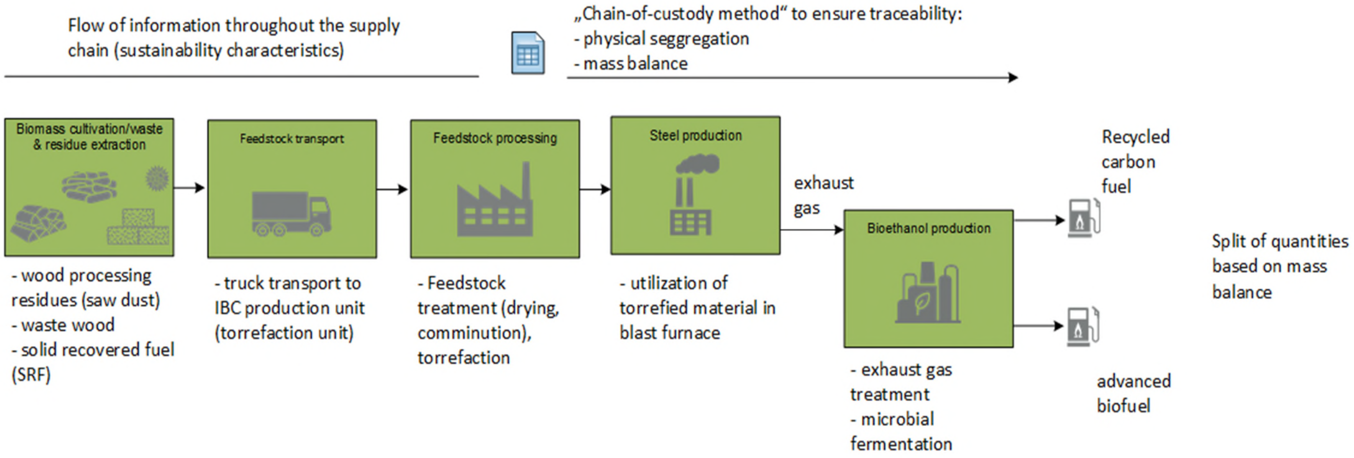

Figure 112: Interfaces along the value chain to produce bioethanol and/or recycled carbon fuel from torrefied biomass and SRF in an integrated steel production process

7.7.2 Relevance for the value chain

Applicability of the criteria depends largely on the type of biomass, the type of biomass fuel, the sector in which energy is used, the capacity of installations and the date on which an installation starts operation. In value chains for the production of liquid biofuels used in transport, criteria apply independently from the capacity of the production facilities (as it is the case for electricity and heat from biomass fuels).

RED II allows to mix consignments with different sustainability characteristics. In the present case at the point of torrefaction, material flows are no more separated and the intermediate bioenergy carrier biochar consists of a mix of biobased and fossil carbon. However, the precise ratios are not determined yet, as an assessment of the suitability of different fuel mixes has not been completed so far. Application of conversion factors in the mass balance for each of the feedstocks in use allows tracking the share of intermediate produced from biomass. This approach is applied along the entire supply chain. As a result, the product flow (bioethanol) can be split into different classes in line with RED II.

The proportion of ethanol made from biomass is classified as biofuel. In the present case more specifically as advanced biofuel as the feedstock is part of Annex IX Part A and can be assigned to item (q) “other lignocellulosic material except saw logs and veneer logs”. As a result of waste and residue utilization, sustainability criteria do not apply. However, a 65% GHG emission reduction compared to the fossil fuel comparator has to be realized and verified (Table 64).

Table 64: Overview of RED II criteria and applicability to the international case study value chain

RED II reference	Criteria summarised	Applicability	Relevance for the case study
29(2)	Monitoring and management of impacts on soil carbon and soil quality	Wastes and residues from agricultural land	no
29(3)	Protection of land with high biodiversity value	Agricultural biomass for energy	no
29(4)	Protection of land with high carbon stock	Agricultural biomass for energy	no
29(5)	Protection of peatland	Agricultural biomass for energy	no
29(6)	Sustainable forest management	Forest biomass for energy	no
29(7)	LULUCF criteria	Forest biomass for energy	no
29(10)	GHG emission savings criteria: dependent on the staring date of the operation: at least 50% (< 2015-10-05) at least 60% (2015-10-06-2020-12-31) at least 65% (> 2021-01-01) 70% for recycled carbon fuels[1]	Wastes and residues agricultural biomass forest biomass	yes

29(11)	Energy efficiency criteria for electricity production from biomass fuels	Electricity generation	no
30(1)	Mass balance system	Once sustainability and GHG emission savings criteria are to be verified	yes

[1] Indication from RED II amendment proposal

From the proportion of ethanol assigned to SRF, only the biomass fraction of SRF can be considered a biofuel. The remaining fraction can be classified as recycled carbon fuel (RCF) according to the definition given in RED II Article 2 (35): "Recycled carbon fuels" means liquid and gaseous fuels that are produced from liquid or solid waste streams of non-renewable origin, which are not suitable for material recovery in accordance with Article 4 of Directive 2008/98/EC; or from waste processing gas and exhaust gas of non-renewable origin, which are produced as an unavoidable and unintentional consequence of the production process in industrial installations.

RCFs do not fall under Article 29. Even though not being a biofuel, RCFs may be considered eligible for contribution to the GHG reduction target in the transport sectors according to Article 25 (but optional for the EU member states). The threshold for GHG emission reduction is not specified in the RED II. Article 25 refers to a delegated act planned to be published in January 2021, which includes a threshold as well as a methodology specifying GHG emission calculation rules for RCF. The delegated act has not been published at the time writing this report. In the proposal for an amendment of the RED II[17], which was published in July 2021, Article 29a includes a minimum GHG emissions saving criterion for RCFs of 70%. As RCF are not biofuels, it remains unclear if the GHG emission savings criteria will have to be verified via a voluntary or national scheme or in a different way.

7.7.3 National implementation

As the steel production plant investigated in this case study is located in Belgium, the Belgian legislation was considered. However, at the time preparing this report, available information indicated that the implementation has not been completed yet (Cancian 2021).

7.7.4 Conclusions

The applicability of sustainability criteria arising from RED II is limited, as the criteria do not apply to waste and residue feedstocks which are foreseen in the value chain. There are uncertainties with respect to RCFs, due to an outstanding delegated act. It seems likely that RCFs will have to comply with a 70% GHG reduction. Currently it seems not to be possible to credit RCFs,

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[17] https://ec.europa.eu/info/sites/default/files/amendment-renewable-energy-directive-2030-climate-target-with-annexes_en.pdf

due to unclear GHG emission savings criteria. Eligibility of RCFs can deviate between EU member states, therefore policy development on national level needs to be followed continuously.

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