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NEGEM

Quantifying and Deploying Responsible Negative Emissions in Climate Resilient Pathways

# Comprehensive sustainability assessment of Bio-CCS NETPs

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# Executive Summary

Negative emission technologies and practices (NETPs) have a significant role in the Intergovernmental Panel on Climate Change's (IPCC) 1.5 °C and 2 °C climate change mitigation scenarios. In these scenarios, bioenergy production combined with carbon capture and storage (BECCS) has been the main negative emission technology used. BECCS can produce negative emissions when the carbon dioxide ($CO_2$) sequestered by growing biomass is stored to permanent geological storages. However, the total emission balance of the process needs to be evaluated, and e.g. possible climate impacts due to biomass production, transport and processing need to be assessed. Large scale production of bioenergy can also create pressure to other environmental impact categories, such as land and water use, and biodiversity. Thus, it is necessary to carefully evaluate the climate and environmental impacts of BECCS. Furthermore, it is important to understand the economic characteristics of BECCS technology to enable comparison with other NETPs and mitigation technologies.

In this deliverable, techno-economic evaluation (TEA) and life cycle assessment (LCA) were carried out for a biomass Fischer-Tropsch liquid (FTL) fuel concept combined with carbon capture and storage (CCS). A biofuel concept was selected to represent the BECCS technology as the limited biomass resources should be used in hard-to-abate-sectors, i.e. in applications where fossil products are challenging to replace by other means (e.g. aviation fuels, heavy transport). In addition, adopting CCS to FTL process would improve the $CO_2$ balance markedly and at low cost as more than half of the input carbon ends up as nearly pure $CO_2$ stream that could be transported and stored. Forest residues were selected as raw material as they are considered to have low risks related to climate and biodiversity impacts, when harvested according to good forest management practices. Analysis is focused on the situation in the Nordic countries (e.g. Finland and Sweden) which have a good potential for woody biomass due to large forest resources and forestry sectors but might lack $CO_2$ storage sites requiring $CO_2$ transport by ships to off-shore storage reservoirs.

In the analysis, two FTL plant capacities and two possible locations leading to different $CO_2$ transport chains were considered. FTL plant was assumed to be located either inland 100 km from the port or next to the port. In case the plant is located inland, $CO_2$ will be delivered by pipeline to the port. $CO_2$ is then liquefied at the port and loaded into the ships that will transport the $CO_2$ to the storage reservoir (1000 km one-way sea transport).

According to our study, the cost of Fischer-Tropsch (FT) crude without CCS is 125–147 €/$MWh_{LHV}$ (35–41 €/GJ), depending on the plant capacity. This is 2–3 times higher than the current fossil transport fuel prices without taxes and duties. The cost would be decreased by 25–34 €/$MWh_{LHV}$ (7.0–9.4 €/GJ) if capital costs could be reduced by 30% and by 10–15 €/$MWh_{LHV}$ (2.8–4.2 €/GJ) if the plant would also produce district heat.

The cost of CCS, which in the case of FTL plant equals $CO_2$ transport and storage costs, was 35–66 €/$tCO_2$ for the plants located inland and 31–46 €/$tCO_2$ for the plants located at the port. The costs are at similar level to $CO_2$ capture costs from flue gases with post-combustion capture showing that the transport and storage costs can be an important part of the total cost of CCS. The cost of CCS corresponded to 14–29 €/$MWh_{LHV}$ (3.9–8.1 €/GJ) increase in FT crude production costs. The transport and storage costs were found to be highly dependent on the transport chain capacities. Although the $CO_2$ transport and storage chains lead to significant cost differences, they had only a minor effect on the environmental performance of the whole FTL-CCS process.

The estimated levelised cost of stored $CO_2$ for the base cases (178–263 €/t$CO_2$) clearly indicates the better economic performance of larger capacity plants located as close as possible to the management and distribution centres of captured $CO_2$ (in this case the harbours where it is shipped to its final storage). Levelised cost of stored $CO_2$ is a metric that describes the cost of providing negative $CO_2$ emissions which takes into account the income from products (biofuel, electricity) but does not consider climate benefits arising from replacing conventional products with renewable ones. Production cost and the assumed market value of the product have a marked effect on the levelised cost of $CO_2$.

Today, there are no commercial plants producing FT fuels from biomass. The results suggest, that should FT fuel plants be built, it would be favourable to equip them with CCS, provided that negative $CO_2$ emissions can be credited and that sufficient $CO_2$ transport and storage infrastructure exists. The recognition of negative emission would improve the economics of FTL production and could speed up the commercial adoption of this technology. At the moment, the FT plants cannot benefit from providing negative $CO_2$ emissions through the EU Emission Trading Scheme (EU ETS) as the negative emissions are not yet recognized. If negative $CO_2$ emissions could be credited – through the EU ETS or other market mechanism–, the current EU emission allowance levels price level 50 €/t$CO_2$ (5/2021) would already make CCS feasible for most of the considered cases and would reduce production costs. For each 10 €/t of $CO_2$ credit, the production cost decreases by 4.4 €/$MWh_{LHV}$ (1.2 €/GJ).

Together with economic evaluation, the evaluated key performance indicators (KPIs) provide significant insights that highlight the strengths and weaknesses of the FTL-CCS technology and the different stages in its system, from the production and gathering of forest residues to the transport and sequestration modes for the captured $CO_2$. All scenarios studied presented almost identical carbon removal efficiencies regardless of their capacity or transport mode, indicating that the growth, harvest and transport of biomass and, most importantly, its processing in the FTL-CCS process are the main factors defining the total carbon removal efficiency. Therefore, efforts should be placed in these two sections of the system in order to improve its removal efficiency.

Compared to other negative emission technologies, BECCS processes such as the production of FT crude from biomass residues present the advantage of further reducing potential emissions by producing cleaner energy as electricity and fuels. These products then can be used to replace their conventional energy counterparts, avoiding the emissions embodied in their production.

The results obtained for the different 16 mid-point indicators highlight the trade-offs among different environmental dimensions, such as the balance between climate change impact reduction and impacts over the land use, a compromise typically present in biomass utilisation systems. Unlike most biomass sources, the use of forest residues significantly improves these balances, as there is no dedicated use of water or application of fertilisers for their growth.

The results obtained for the monetised end-point environmental impacts and the impact on human health, although different in nature, both indicate the overall beneficial impact of the considered FTL-CSS system on the environment and the society due to its carbon removal activity.

Key policy relevant messages:

- It is crucial to evaluate the overall sustainability of BECCS technologies to avoid unwanted impacts and trade-offs e.g. related to land use. Residual feedstocks are often considered to have lower risks on climate and biodiversity, when harvested according to sustainable management practises. Here residual woody biomass was studied as the raw material for a Fischer–Tropsch liquid process combined with CCS. Dedicated energy feedstocks are studied in NEGEM work packages 3 and 7.
- Production cost of FT biofuels without CCS is around 2–3 times higher than the price of fossil fuels.
- Adopting CCS to the FTL process would improve the $CO_2$ balance markedly and at low cost. More than half of the input carbon ends up as nearly pure $CO_2$ stream that just need to be compressed or liquefied for transportation and storage.
- The transport and storage costs are an important part of cost of CCS and they are highly dependent on the transport chain capacities. Even if a pure, concentrated stream of $CO_2$ is available from a process, the total costs of CCS can be high if the plant has an unfavourable location for transport and storage. Location becomes more and more important the smaller the plant is because transport costs are highly dependent on the scale. Thus, creating a shared transport and storage infrastructure is crucial to lower the costs and enable CCS also for the smaller plants.
- Although the $CO_2$ transport and storage chains lead to significant cost differences, they had only a minor effect on the environmental performance of the whole FTL-CCS process.
- At the moment there are no commercial plants producing FT fuels from biomass. Results suggest, that should such plants be built, it would be favourable to equip them with CCS provided that negative $CO_2$ emissions can be credited, and that sufficient $CO_2$ transport and storage infrastructure exists. The recognition of negative emission would improve the economics of FTL production and could speed up the commercial adoption of this technology.
- The main part of the environmental KPIs studied showed positive results for FTL-CCS process.
- Avoided electricity and fuel products represent a significant advantage over other BECCS technologies and NETPs, and should be promoted without causing instabilities in their respective markets that may cause a response opposite to the desired one.

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## Abbreviations

ASU = Air separation unit

bbl/d = Barrels per day

BECCS = Bioenergy production combined with carbon capture and storage

CAPEX = Capital expenses

CCS = Carbon capture and storage

CEPCI = Chemical Engineer magazine's Plant Cost Index

CRF = Capital recovery factor

DAC = Direct air capture

DALY = Disability-adjusted life years

GHG = Greenhouse gas

EU ETS = European Union Emission Trading Scheme

FT = Fischer-Tropsch

FTL = Fischer-Tropsch liquid

FTL-CCS = Fischer-Tropsch liquid combined with carbon capture and storage

IAMC = Integrated Assessment Modeling Consortium

IPCC = Intergovernmental Panel on Climate Change

KPI = Key performance indicator

LCA = Life cycle assessment

LHV = Lower heating value

LSMGO = Low sulphur marine gas oil

MWh = Megawatt hour

$MWh_{LHV}$ = Megawatt hour on lower heating value basis

NETP = Negative emission technologies and practices

O&M = Operation and maintenance cost

RED = Renewable energy directive

TEA = Techno-economic assessment

tkm = Tonne kilometer

WACC = Weighted average cost of capital

ZEP = Zero Emission Platform

# Introduction

Negative emission technologies and practices (NETPs) have a significant role in the Intergovernmental Panel on Climate Change's (IPCC) 1.5 °C and 2 °C climate change mitigation scenarios. Based on extensive recent scientific literature reviews on climate change mitigation scenarios, NETPs are needed to reach the 1.5 °C mitigation goal (Minx *et al.*, 2018). For achieving 2 °C target, the need for NETPs can be limited with ramping up the near-term ambition for mitigation. In these IPCC scenarios, bioenergy production combined with carbon capture and storage (BECCS) is the main negative emission technology used (Hilaire *et al.*, 2019). Also other NETPs, especially afforestation, direct air capture (DAC), and enhanced weathering are increasingly present in the scenarios. It is clear, that a portfolio of NETPs has lower sustainability risks than application of just one NETP technology (e.g. BECCS). The future need and realistic potential for NETPs significantly depends on the assumed future socio-economic conditions in the scenarios.

Based on the literature analysis made in NEGEM deliverable 8.1. (Koljonen *et al.*, 2021) the median estimates in the Integrated Assessment Modeling Consortium (IAMC) 1.5 °C Scenarios Database (Huppmann *et al.*, 2019) the median value for the need of BECCS in the 1.5 °C scenarios was above 3 $GtCO_2$/a in 2050 and nearly 11 $GtCO_2$/a in 2100 (Table 1). Fuss *et al.* (2018) have estimated that the sustainable potential for BECCS could be between 0.5–5 $GtCO_2$/year by 2050.

*Table 1 Summary of scenarios having each NETP active in the solution in the IAMC 1.5°C Scenarios Database. (Source: NEGEM D8.1)*

| NETP | Number of scenarios | Median value in 2050, $MtCO_2$/a | Median value in 2100, $MtCO_2$/a |
|---|---|---|---|
| BECCS | 266 | 3,300 | 10,840 |
| DAC-CCS | 8 | 50 | 6,420 |
| Afforestation | 51 | 3,790 | 4,740 |
| Enhanced weathering | 1 | 1,200 | 2,500 |
| Soil carbon / biochar | 1 | 3,600 | 3,500 |
| Total NETPs | 275 | 11,940 | 27,950 |

BECCS can produce negative emissions when the carbon dioxide ($CO_2$) sequestered by growing biomass is stored to permanent geological storages (Figure 1). However, the total emission balance of the process needs to be evaluated, and e.g. possible climate impacts due to biomass production and processing need to be captured (NEGEM D1.1.). These include also the possible climate impacts related to land use and e.g. on the soil and forest carbon stocks due to biomass use. Negative emissions are produced when more $CO_2$ is removed from the environment than it is emitted in the process. Thus, it is important to carefully study the total greenhouse gas (GHG) impacts of BECCS processes through life cycle assessment type of analysis. In addition, other environmental impacts than GHG emissions need to be evaluated, to avoid trade-offs.

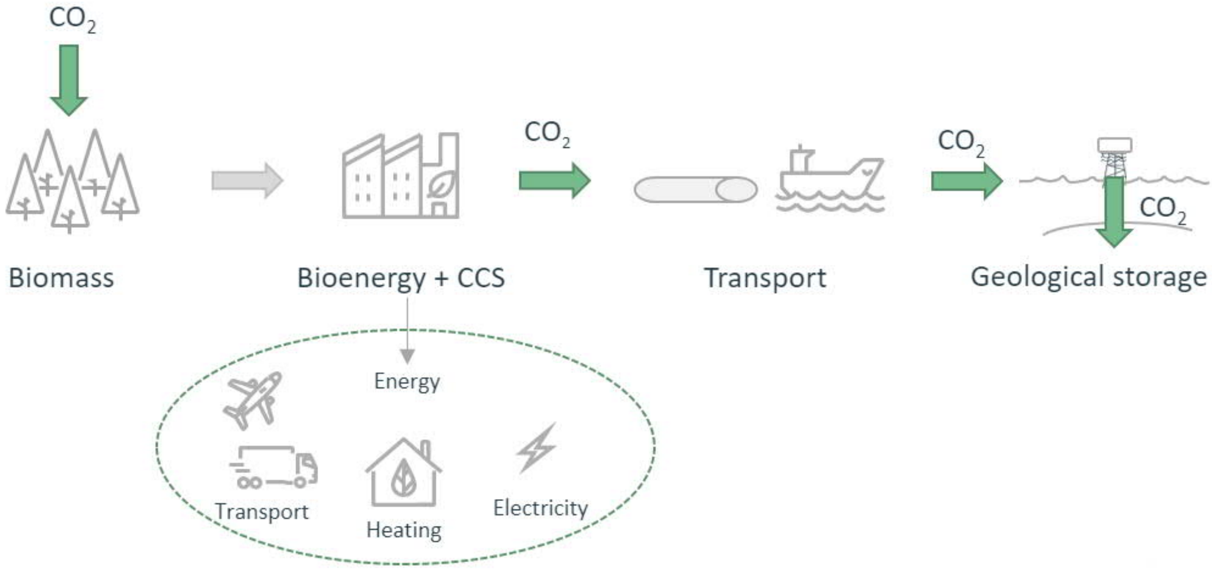


*Figure 1. BECCS principle.*

Several different bioenergy technologies and $CO_2$ capture processes can be applied for BECCS. For example, the bioenergy product can be electricity, heat, or a liquid biofuel. For combustion plants the CCS technology applied can be post-combustion, pre-combustion or oxy-fuel technology. In some biofuel production processes relatively pure $CO_2$ streams are already separated from the process and could be easily be compressed and stored. In NEGEM deliverable 1.1 (Cobo *et al.*, 2020) a selection of negative emission technologies and practices to be studied in NEGEM was made. The BECCS technologies were shortly reviewed, and Table 2 shows the scores based on the key performance indicators (KPIs) selected. The bolded technologies were chosen to be further studied in the project.

*Table 2. Deployment potential of BECCS technologies according to the calculated score and the selected KPIs (high potential: green cells, intermediate potential: yellow cells, low potential: red cells). NETPs in bold will be assessed in future tasks of WP1. (Modified from NEGEM D1.1)*

| NETPs | | TRL | Max CDR Gtonne·yr$^{-1}$ | Cost (2019€) €·tonne$^{-1}$ $CO_2$ | Score [-3, 3] |
|---|---|---|---|---|---|
| BECCS | Hydrothermal liquefaction | 5[1] | 0.5-5[2] | 210-294[h,3] | -1 |
| | Algal BECCS | 1-2[b] | 53[i,4] | n/a | 0 |
| | Anaerobic digestion | 8[b] | 2.8[5] | 139-313[j,6] | 0 |
| | Chemical looping combustion | 4[7] | 0.5-5 | n/a | 0 |
| | Oxy-combustion | 5[7] | 0.5-5[2] | 136[j,8] | 0 |
| | Combustion | 4-6[9] | 0.5-5[2] | 116[j,3] | 0 |
| | Pyrolysis | 7[10] | 0.5-5[2] | 136-387[j, 3] | 0 |
| | Gasification | 3-5[11] | 0.5-5[2] | 160-182[j, 3] | 0 |
| | Ethanol fermentation | 7[b] | 0.5-5[2] | 19-163[j, 2] | 1 |

[b]Authors' assessment, based on the reviewed literature.
[h]Net costs (revenues from liquid fuel accounted for).
[j]Gross costs, excluding revenues from electricity and fuels.
[1](*HyFlexFuel*, no date), [2](Fuss, William F. Lamb, *et al.*, 2018), [3](Baker, 2020), [4](N'Yeurt *et al.*, 2012), [5](Koornneef *et al.*, 2013), [6](IEAGHG, 2013), [7](Bhave *et al.*, 2017), [8](Cabral, Bui and Mac Dowell, 2019), [9](McLaren, 2012), [10](Carbon Neutral City Alliance, 2019), [11](Parkinson *et al.*, 2019)

Among the selected technologies are biofuel production technologies combined with CCS, namely ethanol fermentation and gasification. For this deliverable, biofuel production based on gasification and subsequent synthesis of liquid fuels combined with CCS was selected for further study with techno-economic (TEA) and life cycle assessment (LCA) approaches. The selection of biofuel production for further study on BECCS is justified with the idea that the limited biomass resources should be used in hard-to-abate-sectors, i.e. in applications where fossil products are challenging to replace by other means (e.g. aviation fuels, heavy transport). Further understanding on BECCS potential related to biofuel production was also considered important for future modelling work to be done in NEGEM WP8. The need for renewable fuels in transport sector is illustrated e.g. in the European Commission impact assessment (2020) for updated 2030 targets, where it was clearly indicated that all solutions are needed in the transport sector (electrification, biofuels, hydrogen and e-fuels).

In this deliverable, TEA and LCA are made for a Fischer-Tropsch (FT) crude concept combined with CCS. This concept was recognised promising in a previous study by Hannula & Melin (2020) which compared different biofuel production concepts combined with CCS. The cost of CCS (€/t$CO_2$ stored) was the lowest among the studied technologies (pyrolysis, 1st and 2nd gen. bioethanol, bio-hydrogen). It was shown that $CO_2$ could be captured at low cost also from the 2nd gen. ethanol plants. However, a significantly higher share of input carbon was found to end up as concentrated $CO_2$ in FTL plants compared to 2nd generation bioethanol plants. This translates into higher potential for negative emissions and benefits of "economies of scale" in transport and storage of $CO_2$ for the FTL plants. In addition, ethanol blending limits could limit the demand of 2nd generation ethanol. Also, thermochemical processes tend to be more forgiving with regards to feedstock heterogeneity than biochemical processes meaning there is more potential feedstocks available. Thus, FTL-CCS was selected also for this study. In this deliverable, a specific focus is also put to the techno-economic evaluation of the $CO_2$ transport and storage.

The biomass raw material studied is forestry residues, which are available as a side stream of forest industries. Forest residues from forest industry (e.g. saw dust, bark) or harvest residues (e.g. slash) can be considered to have low risks related to climate and biodiversity impacts, when harvested according to good forest management practices (Camia *et al.*, 2020).

We first describe the scope of the study with case descriptions and the methods used. Then further details on the FTL and CCS processes are given, followed by the TEA and LCA results. Finally, key findings and policy relevant messages are provided.

## 1 Scope of the study

This study focuses on TEA and LCA analysis of FTL-CCS concept, and builds on study by Hannula & Melin (2020) by extending the analysis for certain parts and switching the focus from the US to the EU. $CO_2$ transport and storage costs were not evaluated in detail previously. In the study by Hannula & Melin (2020), a constant transport and storage cost of \$15/t$CO_2$ was applied regardless of the scale. Analysis was based on 100 km transport distance via a pipeline and storage in an onshore reservoir, which is a representative case for the US. In this study, transport costs are analysed in more detail and using logistics chains relevant for the Europe.

Analysis is focused on the Nordic countries that have a good potential for woody biomass, due to large forest resources and established bioenergy and forest industries. However, for example in Sweden and

Finland there are no suitable onshore reservoirs and thus, $CO_2$ would be most likely transported via ships to offshore reservoirs, for example in the North Sea, which contains the largest storage capacity for $CO_2$ in the North West Europe (de Kler *et al.* 2016, Pedersen *et al.* 2009). Transport by ships provides flexibility and could enable application of CCS also to smaller scale projects having low $CO_2$ capture costs but too small scale for pipelines, and to $CO_2$ sources located far away from storage sites. Furthermore, onshore storage of $CO_2$ has faced difficulties both with health and safety regulators and public acceptance (Brunsting *et al.* 2011). Thus, ship transportation is considered in this study as the main transport method. The analysis is kept on a generic level rather than specifying the exact location of the FTL plant or the storage site. The effect of location, plant and delivery chain capacities are studied by varying case configurations. Figure 2 presents a simplified illustration of the BECCS process studied.

This study provides a detailed LCA that encompasses a wide selection of environmental indicators, grouped into Key Performance Indicators (KPIs). Primarily, LCA provides as a result the global emission inventories for the analysed system, describing, among others, the total $CO_2$ emissions, which can be used to evaluate the global carbon removal efficiency of the system (KPI-1). The functional unit here is per $CO_2$ ton sequestered by biomass whereas Hannula & Melin (2020) studied the $CO_2$ emissions per MJ of FT crude produced. The selection of functional unit was made to highlighting the negative emission aspect and enable comparison with other NETPs in further NEGEM work.

The emission inventories are then used to characterize the impacts caused by the system, either being mid-point impact indicators (KPI-3) such as Climate change impact or Water consumption, or end-point indicators, which describe the impacts on human health and ecosystems. The latter can be monetised and aggregated into global environmental metrics (KPI-5). In addition to these, indicators such as avoided emissions (KPI-2) or total impact to human health (KPI-6) are directly estimated from the LCA results. Altogether, these indicators enable the characterization of both negative and positive environmental impacts in the FTL-CCS process and its supply chain, presenting a clearer picture of their advantages and weaknesses.

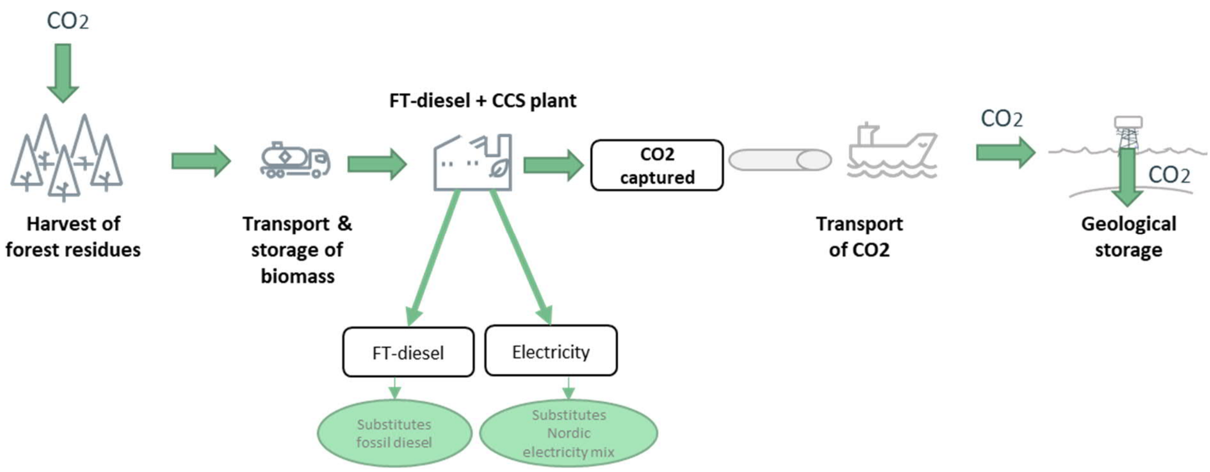


*Figure 2. A simplified illustration of the FT crude + CCS concept studied.*

## 2 Case descriptions

In this study, two different capacities for the FTL-CSS plant are considered. The smaller capacity represents first-of-a-kind plant described in Hannula & Melin (2020) having a capacity of 1000 bbl/d (petrol equivalent) which corresponds to biofuel output of 59 MW (lower heating value, LHV) and 208 kt/a of $CO_2$ captured. A larger plant with 2400 bbl/d capacity corresponding to 142 MW biofuel output and 500 kt/a of $CO_2$ is also considered to study the effect of scale on the feasibility.

Two possible locations for the FTL plant are considered leading to different $CO_2$ transport chains (Figure 3). FTL plant is located either inland 100 km from the port (Cases A1–A3) or next to the port (cases B1–B3). In case the plant is located inland, $CO_2$ will be delivered by pipeline to the port. $CO_2$ is then liquefied at the port and loaded into the ships that will transport the $CO_2$ to the storage reservoir (1000 km one-way sea transport).

In addition, both dedicated (A1, A2, B1, B2) and shared transport infrastructure cases (A3, B3) are studied as CCS typically involves one magnitude higher $CO_2$ flow than could be captured from the assumed FTL plants. In the dedicated infra cases pipeline, liquefaction and sea transport capacities match the $CO_2$ output from the FTL plant (208 or 500 kt/a). In the shared infra cases, pipeline, port and shipping are assumed to serve several $CO_2$ sources with a total capacity of 2.5 Mt/a. In both cases, the storage reservoir is assumed to have a 5 Mt/a injection rate because establishing an off-shore storage is feasible only on a large scale and thus also in real life a storage site would likely serve more than one $CO_2$ source.

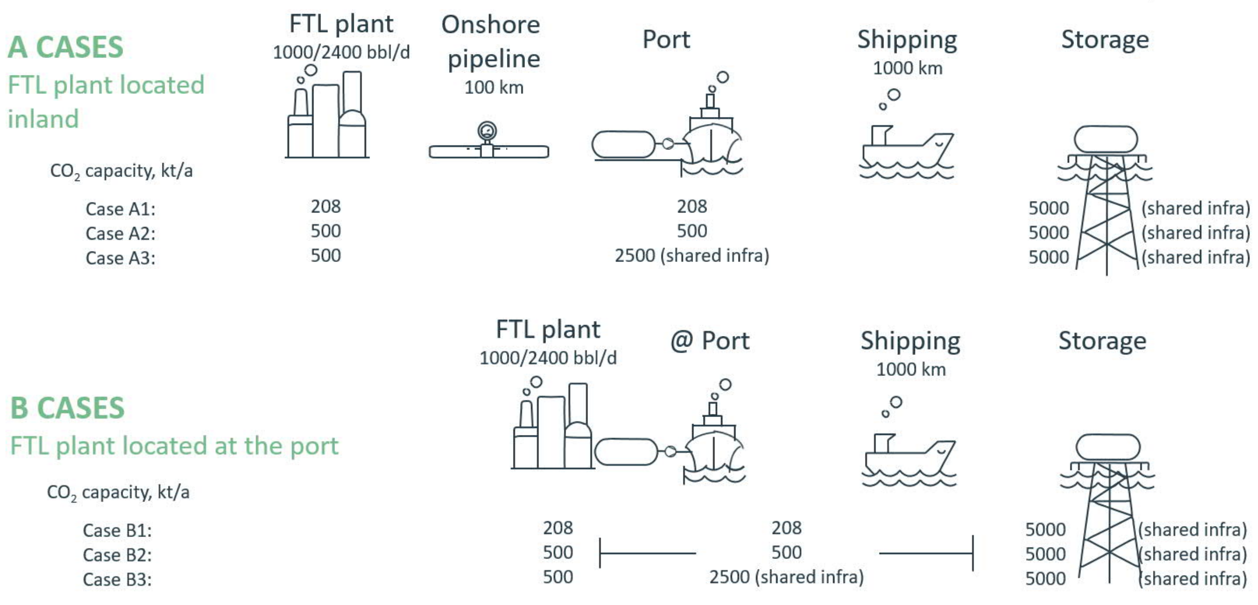


*Figure 3. Considered cases.*

Transport and storage steps together with the selected TEA system boundary are shown in Figure 4. Costs related to reservoir itself were left outside the boundary and were not evaluated in detail.

For cases A1–A3, $CO_2$ is first pressurized to the pipeline transport pressure and delivered to the port where it is then liquefied. Liquefaction processes differ for cases A and B. In A $CO_2$ is already pressurised whereas in B starts at atmospheric pressure and thus requires compressing. After the liquefaction, the rest of the chains are similar. Liquefied $CO_2$ is stored in a temporary buffer storage from where it is loaded onto the ships. The ships unload their cargo at the storage site and $CO_2$ is then pressurized and heated to conditions required for the injection into the reservoir. The process steps and related assumptions are described in more detail in chapter 4.

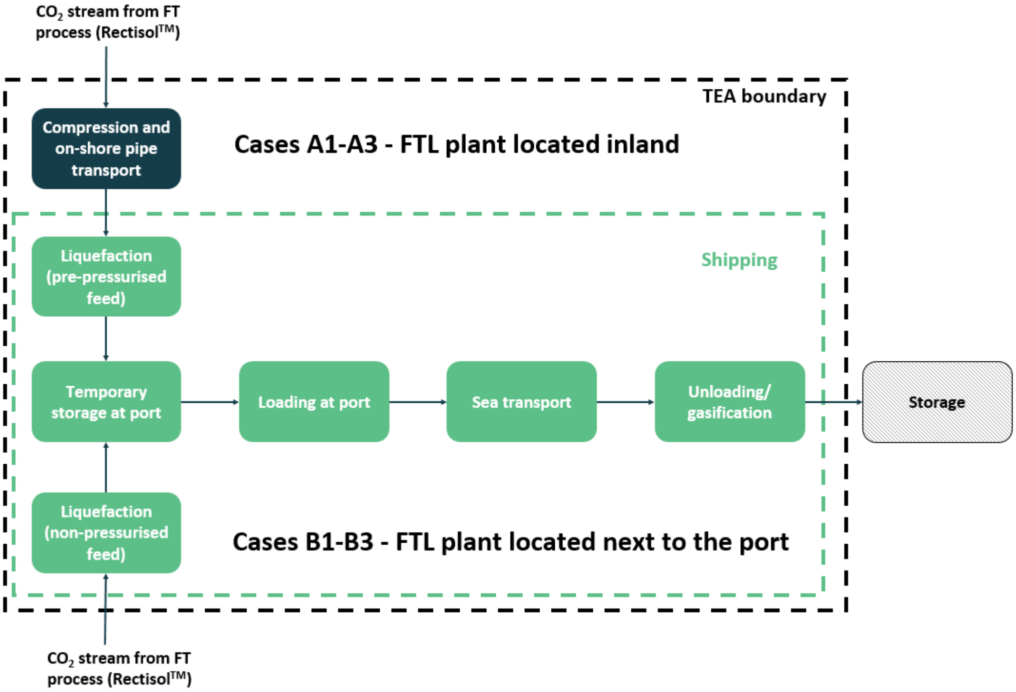


*Figure 4. Considered transportation chains and the system boundary of the techno-economic analysis of transport and storage of $CO_2$.*

# 3 Methods

## 3.1 Techno-economic evaluation

The main metrics of the techno-economic evaluation are the production cost of FT crude with and without CCS (€/MWh LHV) and the cost of CCS (€/t$CO_2$ stored). In addition, we analyse how different negative $CO_2$ emission credit price levels would affect the cost of FT crude.

The FT crude production costs were calculated using Eq. 1:

$$FT\ crude\ production\ cost\ = \frac{CAPEX\ \ +Biomass+O\&M+Electricity+Fuel}{Annually\ produced\ FT\ crude} \quad (1)$$

where

CAPEX = total annualised investment cost

Biomass = annual biomass feedstock costs

Electricity = annual electricity costs/incomes

Fuel = annual fuel cost for $CO_2$ transport

O&M = annual operation and maintenance costs.

The cost of CCS describes the additional costs for each tonne of $CO_2$ stored for adding CCS to FTL plant and is related to production costs of FT crude with and without CCS according to Eq. 2:

$$Cost\ of\ CCS = \frac{C_{FT\ w/CCS} - C_{FT\ without\ CCS}}{Annually\ stored\ CO2} \quad (2)$$

where $C_{FT}$ is the annual production costs of FT crude.

In this case, where no additional $CO_2$ capture process is needed (see Chapter 4), the cost of CCS equals the transport and storage costs of $CO_2$ (Eq. 3):

$$Cost\ of\ CCS = \text{Transport and storage costs of } CO_2 = \frac{CAPEX_{CCS} + Electricity_{CCS} + Fuel_{CCS} + O\&M_{CCS}}{Annually\ stored\ CO_2} \quad (3)$$

where the cost components now relate only to the $CO_2$ transport and storage.

The performance and investment cost data for the considered processes was obtained from the literature. As larger plants typically have lower specific investment costs ("economies of scale"), the investment costs were scaled to the considered capacities using Eq. 4:

$$Investment\ cost = Reference\ investment\ cost \times \left(\frac{Capacity}{Reference\ capacity}\right)^{Scale\ factor} \quad (4)$$

The scaled investment costs were then annualized using the Capital Recovery Factor (CRF) method (Eq. 5). CRF was calculated weighed average costs of capital (WACC) of 8% and process specific lifetimes (n, years) using Eq. 6.

$$Annualised\ investment\ cost = CRF \times Investment\ cost \quad (5)$$

$$CRF = \frac{WACC \times (1+WACC)^n}{(1+WACC)^n - 1} \quad (6)$$

Currency exchange rates and Chemical Engineer magazine's Plant Cost Index (CEPCI) were used to escalate all costs to €2018.

The FTL plant was assumed to be operated 8000 h/a on full load hour basis (Hannula&Melin 2020). For the 1000 bbl/d plant, biomass price was assumed to be 20 €/MWh (LHV) while the cost for the larger plant was assumed to be 23 €/MWh. The higher costs are due to the larger supply radius and the necessity to use more expensive biomass assortments (Hannula & Kurkela 2013). It was assumed that the ships will need to travel also in the Baltic Sea. Thus, low sulphur marine gas oil (LSMGO) with a cost of 432 €/t (Ship and Bunker 2021) was chosen as the ship fuel due to the strict sulphur emissions regulations in the Baltic Sea. Price of electricity was considered to be 50 €/MWh.

## 3.2 LCA

Life cycle assessment (LCA) (Guinée *et al.*, 2002; ISO 14040, 2006) was applied to the FTL-CCS system to assess several technical, environmental, and social indicators, providing a more holistic characterization of the considered BECCS process. In particular, the LCA was conducted on an attributional model of the FTL-CCS process and the most significant echelons of its supply chain, encompassing the growth, harvest, and transport of biomass, the gasification, synthesis and emission capture processes, and the transport and final storage of the captured $CO_2$.

Unlike other types of biomass, the forest residues here use are obtained as a by-product of the thinning or final fellings in timber production. Because of that, only positive environmental impacts caused during the growth of trees are allocated to these resources (e.g. carbon sequestration or improvements in land use change), allocating them by mass to the biomass residues. Negative environmental contributions of the forest biomass growth (such as consumption of water or impacts on the soil) are completely allocated to the main product (i.e. wood products) and therefore are not accounted for in this analysis. The environmental contribution of the harvest and transport of forest residues is also accounted for in this analysis, as these may differ significantly from the gathering and management of main wood products.

Due to the potential competition of different sectors for some of the inputs (i.e. biomass residues) and products (e.g. FT crude generated), the performance of the considered system may be affected by complex interactions with related sectors and markets at a regional level. With the considered scope focusing on the generic Nordic country scenarios, the lack of detail would add excessive levels of uncertainty to the estimated interactions. To avoid these potential uncertainties, the process is modelled following an attributional approach, assuming no response of sectors and markets to the operation of the system analysed.

The generated FT crude and electricity products are modelled as avoided products, assuming that these would only replace the contribution of producing their conventional counterparts (i.e. fossil-based diesel and average Nordic electricity mix). Therefore, the inventories and environmental impacts avoided from these products are subtracted from the total, also circumventing the use of a particular allocation method. This product substitution implies the assumption that the use of both FT crude and electricity would be identical to their conventional counterparts. At the same time, these fuel and energy products can be used in a wide variety of processes, making it difficult to properly model the environmental contributions of their use phase. The uncertainty that these uses would add to the LCA results is here prevented by excluding the use phase from the scope of the LCA here considered, encompassing the activities and inventories from the extraction of raw materials from nature to the production of the FT crude and electricity products (i.e. cradle-to-gate approach for these products).

The modelling of the system has been assumed to remain constant at different capacities, as relative input and output flows to and from the process (i.e. the most significant factors in the estimation of inventories and impacts in LCA) are assumed to remain constant at different capacities. Only infrastructure-related inventories are significantly affected by changes to the production capacity, but these generally play a very marginal role in industrial processes such as the one here considered. Here, emissions due to infrastructure are not included in the analysis.

Following these considerations, scenarios A1 to B3 are modelled accordingly, only modifying the energy and material input and output flows while disregarding the effects of infrastructure capacity (e.g., when comparing scenarios A1 and A3).

Under these considerations, the FTL-CCS system can be modelled using the technical process and scenario information provided throughout sections 4 and 5, characterising the particular process flows (i.e. inputs from other human activities) and emissions of the system. All the estimated process flows and LCA results are calculated for 1 tonne of sequestered $CO_2$ by biomass (i.e. Functional unit = 1t Seq$CO_2$), highlighting the negative emission aspects and efficiencies of the system here considered. This measure directly characterises the negative emission efficiency of the process, defining how much of the carbon initially sequestered is stored and removed from the environment. An additional advantage of this definition is its applicability to any type of negative emission technologies (e.g. Direct Air Capture or even terrestrial NETPs such as afforestation or soil carbon sequestration), enabling the direct comparison of significantly different negative emission technologies and strategies.

To this end, it was assumed that 1 kg of biomass forest residues delivered to the FTL-CCS process present a net removal (i.e. net amount of $CO_2$ removed from the atmosphere accounting for the emissions in the growth, management and transport of residues) of 1.81 kg of $CO_2$ (Swiss Centre For Life Cycle Inventories, 2020). Since a fraction of the net $CO_2$ removed by the biomass is emitted in the FTL-CCS process, this will be referred as sequestered $CO_2$ in biomass growth throughout this report. Note that this should not be confused with the final amount of $CO_2$ geologically stored.

The environmental characterization of the process flows and emissions was done through LCA software SimaPro (Pre' Consultants, 2014) and using information from the EcoInvent v3.7 (Swiss Centre For Life Cycle Inventories, 2020) database.

The results of the LCA analysis directly correspond to some of the considered KPIs of the system, evaluating its effect on several environmental dimensions. Total $CO_2$ emissions are directly obtained from the inventory data (i.e. prior to impact characterization) and provide direct insight into the negative-emission performance of the system. These emissions are then used to estimate the $CO_2$ removal efficiency (KPI-1) as well as the emissions avoided from the avoided products (KPI-2). The characterization of the obtained inventories is divided into two groups: mid-point environmental impacts (i.e. direct effects on specific environmental aspects), and end-point indicators (i.e. total impact on the three areas of protection: human health, ecosystems, and availability of resources). Mid-point indicators (KPI-3) were estimated using the Environmental Footprint v3 methodology (Fazio *et al.*, 2018), and encompass impacts to 16 different environmental aspects such as climate change, particulate matter formation, acidification, or land and water use. In contrast, end-point indicators, here evaluated through the ReCiPe 2016 (Huijbregts *et al.*, 2016) methodology, aggregates different mid-point indicators into the three areas of protection, providing a more concise characterization of the total environmental performance.

These end-point indicators are further aggregated into a single economic indicator using the monetization methodology proposed by Weidema *et al.* (2013), obtaining a monetized indicator of the environmental externalities of the process (KPI-5). The monetization methodology here considered applies a price value for each of the end-point impact categories previously defined (particularly to human health and ecosystems indicators, since availability of resources is often expressed as cost equivalent values). In this case, the prices used are based on the cost required to compensate the loss of life quality and expectancy due to each end-point impact indicator.

These environmental indicators together with the economic values provided later in the report, cover two of the three pillars of sustainability. The remaining social sustainability pillar was characterized through the Human Health endpoint indicator (KPI-6) previously described and without monetization, allowing a direct measure of the potential effect of the process on society. Although other, more complete, and detailed indicators exist for the characterization of social sustainability, their assessment depends on the particular characteristics of specific existing systems, which is incompatible with the general northern European scope here considered.

In addition to the mentioned KPIs, the economic performance of the FTL-CCS process is also evaluated through the levelised cost of stored $CO_2$ (KPI-4), directly obtained from the main economic indicators of the process and unrelated to the LCA.

Altogether, the performance of the FTL-CCS process system is evaluated through a set of six KPIs, divided into three categories technical, environmental, economic, and social, as listed in Table 3.

*Table 3*. Key performance indicators considered

| Type | KPIs | |
|---|---|---|
| Technical | KPI-1 | $CO_2$ removal efficiency |
| | KPI-2 | Avoided emissions |
| | | |
| Environmental | KPI-3 | Mid-point indicators |
| | | |
| Economic | KPI-4 | Levelised cost of stored $CO_2$ |
| | KPI-5 | Monetised end-point environmental impacts |
| | | |
| Social | KPI-6 | Impact on human health |

## 4 FT crude production

Producing liquid transport fuels from biomass is a multistep process where biomass is first converted into syngas via gasification and syngas is then converted into a mixture of hydrocarbons with varying chain lengths in a Fischer-Tropsch process. The main product of the plant is FT crude, which is defined here as hydrocarbons having five or more carbon atoms (C5+). Syncrude resembles a mixture of liquid fuels but it requires further refining to marketable liquid biofuels. The final refining is assumed to take place in a conventional refinery process and is excluded from the analysis in this work. The process is energy self-sufficient, covering the process heat needed and with some excess electricity produced.

The process model for producing FT crude from biomass from Hannula & Melin (2020) is used in this study. Only a short description of the process model is given here. More details can be found from Hannula & Melin (2020) and Hannula & Kurkela (2013). The process starts with the drying of biomass residues from their initial moisture of 50 wt-% to 8 wt-% with a belt dryer (Figure 5). The assumed feedstock is woody biomass residues typical for Nordic countries (Appendix A). The dried biomass is then fed to a fluidized bed gasifier operated at 880 °C and 4 bar with a mixture of steam and oxygen. Oxygen is produced in a cryogenic air separation unit, ASU.

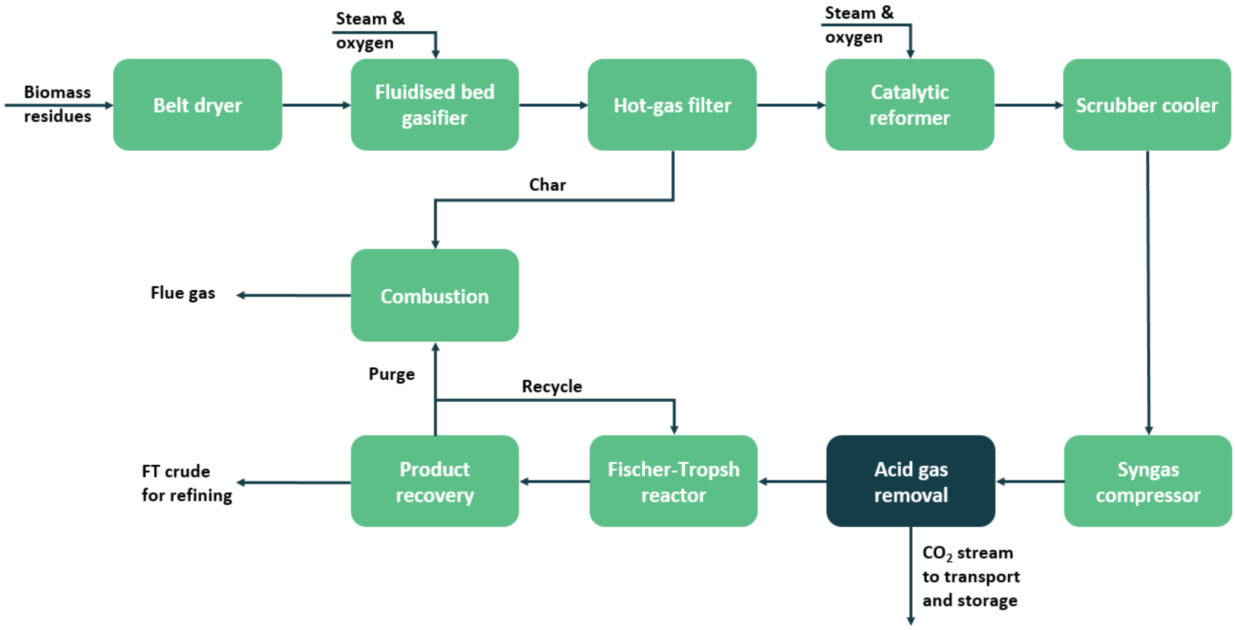


*Figure 5. Process step for producing Fischer-Tropsch liquids from biomass. (Adapted from Hannula&Melin 2020)*

During gasification, the residues are converted to product gas containing CO, $H_2$, $CO_2$, $H_2O$, $CH_4$, small amount of higher hydrocarbons and tars. The gas is cooled down to 820 °C to facilitate removal of entrained dust by ceramic filter elements. Gas then enters a catalytic reformer, where tars and hydrocarbons are converted to light gases. The tar-less gas exits the reformer at around 950 °C and is cooled down to 200–300 °C while recovering sensible heat to generate steam.

The shifted gas is then cooled to 200 °C with heat recovery and fed to a two-stage water scrubber where it cools down to 60 °C while recovering sensible heat for feedstock drying. Finally, the gas is cooled down to 30 °C to remove syngas moisture. The dried gas is compressed and cooled down to enable removal of acid gases ($CO_2$ and sulphur species) from syngas. Syngas is scrubbed with chilled methanol (Rectisol process) that absorbs $CO_2$ (and $H_2S$). $CO_2$ is then released from methanol at reduced pressure and elevated temperature. The separated stream of $CO_2$ is either vented or transported and stored while methanol is recycled to absorption process.

The ultra-clean synthesis gas is converted to Fischer-Tropsch syncrude using cobalt-based catalysts in a boiling-water reactor. The reactor is operated at 200 °C and 25 bar and and reaction exotherm is recovered as saturated steam. The alpha value is set to 0.90 and selectivity to C5+ is 92%. A small amount of the recycle flow is continuously purged to prevent accumulation of inerts and sent for combustion.

The oil fraction and wax (syncrude) is sent for “mild hydrotreating” to convert the waxes to lower chain length hydrocarbons after which this fuel related product is sent for final refining to commercial liquid fuels in a conventional oil refinery. The aqueous product (reaction water) is treated as wastewater.

Char from gasification and purge gas from FT synthesis are burned in an auxiliary boiler that produces superheated steam at 500 °C and 93.5 bar, which is used to generate electricity in a steam turbine. Steam required for process is extracted at two intermediate pressure levels (25 and 5 bars). Waste heat recovery from process steps (mainly syngas cooling) is also integrated into the steam cycle. Low temperature heat suitable for biomass drying is recovered from gasification inland and syngas scrubber while of the rest of the heat demand is met by hot water generated from low pressure steam (0.8 bar). The steam turbine is equipped with a condensing tail and the process can produce more electricity than it requires.[1]

Only 31% of the input carbon ends up in the syncrude (Figure 6). 54% is separated as $CO_2$ in the acid gas removal process (Rectisol) while 2% is lost in the process. The remaining 14% is emitted into atmosphere as $CO_2$ as part of the auxiliary boiler's flue gases. $CO_2$ needs to be separated from syngas before FT synthesis regardless of what happens to $CO_2$ afterwards. Thus, no additional $CO_2$ capture process is required for this stream. Additional $CO_2$ could be recovered from flue gases but this was not considered here due to the relatively low amount of additional $CO_2$ and higher capture costs. Capturing $CO_2$ from flue gases would require e.g. an amine based post-combustion capture system.

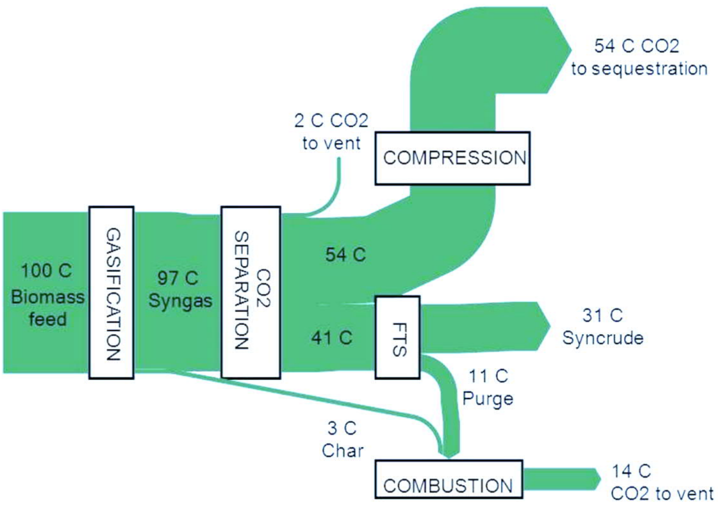


*Figure 6. Carbon flows for biomass-FTL process. (Hannula&Melin 2020)*

The key performance metrics derived from the Aspen model from Hannula&Melin (2020) are summarized in Table 4 together with economic assumptions. For the 1000 bbl/d plant, biomass price was assumed to be 20 €/MWh while the cost for the larger plant was assumed to be 23 €/MWh. The higher costs are due to the larger supply radius and the necessity to use more expensive biomass assortments (Hannula & Kurkela 2013). The costs are typical for woody biomass in Nordic countries. Detailed electricity and steam balances can be found in Appendix B.

*Table 4. Key performance and cost metrics for the FTL plant*

| Parameter | Value | Source |
|---|---|---|
| FT syncrude production efficiency, syncrude/biomass to dryer (LHV) | 50.8% | Hannula & Melin 2020 |
| Specific electricity production, $kW_e/MW_{syncrude}$ | 60.5 | |
| Specific $CO_2$ capture rate, $tCO_2$/tonne of dry biomass | 1.052 | |
| | | |
| Biomass price, €/MWh (LHV) | 20 (1000 bbl/d plant)<br>23 (2400 bbl/d plant) | Own assumption |
| | | |

[1] In case the plant would be designed to produce also district heat, condensing tail would be bypassed and the steam from the back-pressure turbine would be sent to a district heat exchanger. In this mode, process would require electricity from the grid.

| | | |
|---|---|---|
| Specific investment, M€/$MW_{syncrude}$ (LHV) | 6.2 | Hannula & Melin 2020 |
| *Reference scale, $MW_{syncrude}$ (LHV)* | 59.1 | Hannula & Melin 2020 |
| *Scaling factor* | 0.67 | Hannula & Melin 2020 |
| | | |
| Fixed O&M, of CAPEX | 4 % | Hannula & Melin 2020 |
| | | |
| Lifetime, years | 20 | Hannula & Melin 2020 |

# 5 $CO_2$ transport and storage

## 5.1 Pipeline delivery to port (A cases only)

For the pipeline delivery $CO_2$ is compressed to 150 bar similar to assumption made by Hannula and Melin (2020). The $CO_2$ stream from the acid gas removal process (Rectisol™) is first compressed to 80 bar in an inter- and after-cooled multistage compressor and then the pressure is increased to delivery pressure with a high-pressure pump. The assumptions related to compression are listed in Table 5.

*Table 5. Assumptions for $CO_2$ compression for pipeline delivery*

| Parameter | Value | Source |
|---|---|---|
| Electricity demand, kWh/kg$CO_2$ | 0.105 | Hannula&Melin 2020 |
| Specific investment, k€/(t$CO_2$/h) | 125 | |
| *Reference scale, t/h* | 26.0 | |
| *Scaling factor* | 0.67 | |
| Fixed O&M, % of CAPEX | 4% | |
| Lifetime, a | 20 | |

A suitable pipeline diameter for each annual $CO_2$ flow is selected based on earlier models developed by Kujanpää *et al.* (2011). Large enough diameter is selected so that no intermediate pumping stations are required. Cost assumptions are listed in Table 6.

*Table 6. Assumptions for onshore pipeline from the FTL plant to the port*

| Parameter | Value | Source |
|---|---|---|
| Pipeline investment cost, €/km | 354*e^(0.00176*diameter (mm)) | Chandel *et al.* (2010) |
| Fixed O&M, % of CAPEX | 0.25% | Own assumption |
| Lifetime, a | 30 | Own assumption |

## 5.2 Liquefaction

To increase the density, $CO_2$ needs to be liquefied for ship transportation. $CO_2$ cannot be liquefied below its triple point (5.1 bar, -56.6 °C) pressure. $CO_2$ is transported at 6–7 bar pressure and temperature of around -50 °C, which are the most commonly suggested (Brownsort 2015) conditions. These conditions include a sufficient margin from the triple point to avoid risk of solid $CO_2$ formation in normal operation. In addition, the density of $CO_2$ is the highest at the triple point. Higher pressures would allow transporting of $CO_2$ at higher temperatures with less heat leakage. However, the cost of pressure vessels increases with the pressure and thus lower pressures are preferred.

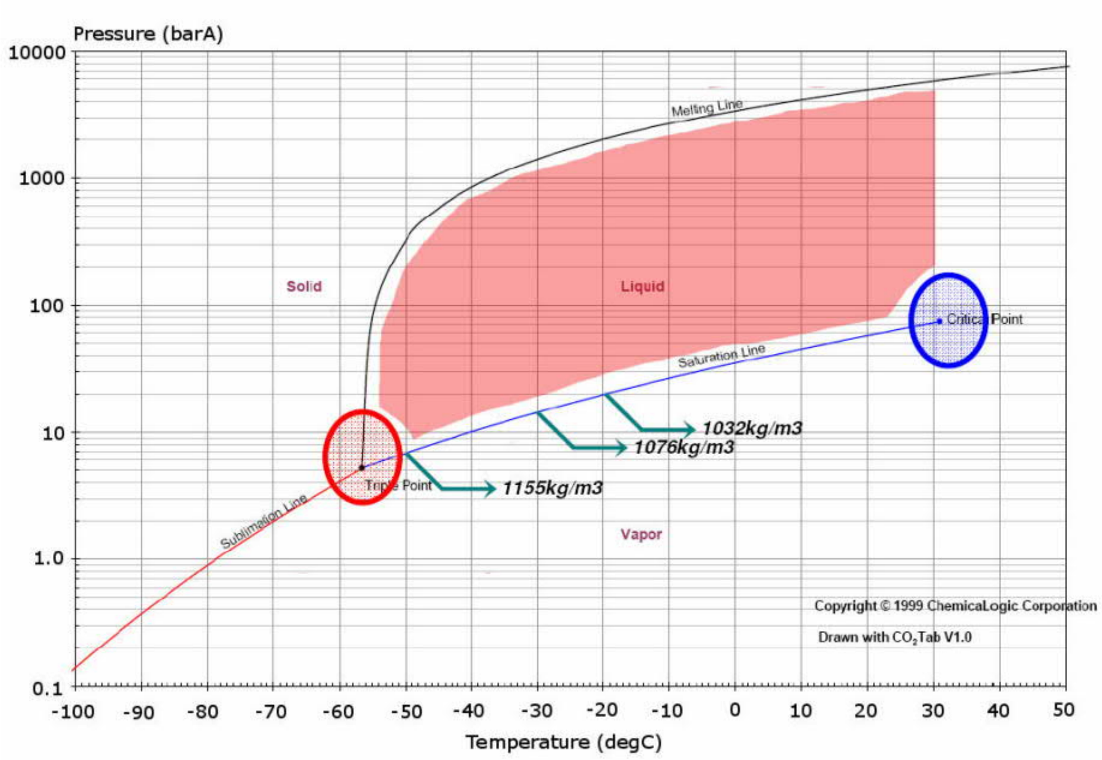


*Figure 7. Phase diagram for $CO_2$. (Melin 2011)*

Various process concepts have been designed for liquefaction of $CO_2$. Open cycle liquefaction processes involve multi-stage compression to around 60–100 bar, cooling with water and expansion to the liquid delivery pressure. Expansion leads to cooling and partial liquefaction of $CO_2$ stream. The $CO_2$ that flashes off during expansion is recycled to the appropriate pressure stage in the multistage compressor. Water is removed first by condensation between first compressor stages by cooling and then by a regenerative adsorption beds at intermediate pressure. Water needs to be removed to prevent freezing. Also, if non-condensable gases (e.g. nitrogen) are present, they can be removed by flashing at a suitable pressure.

In case an external refrigeration circuit is utilised, lower pressure is adequate. In an example design $CO_2$ is compressed to 20 bar and cooled to liquefaction temperature using an ammonia-based refrigeration system. Energy consumption for the two main liquefaction processes is similar.

In this study open cycle liquefaction process is considered. The design of the liquefaction process depends markedly on the initial pressure of $CO_2$. In case $CO_2$ is delivered by pipeline to the liquefaction plant (cases A1-A3), initial compression steps can be avoided and thus both investment cost and electricity demand are lower compared to the case where liquefaction starts from 1 atm $CO_2$. The assumed values for the non-pressurised and pre-pressurised liquefaction processes are listed in Table 7. More detailed description of the processes can be found from Yoo *et al.* 2013.

*Table 7. Assumptions for the liquefaction of $CO_2$*

| | Value<br>Non-pressurised | Value<br>Pre-pressurised (100 bar) | Source |
|---|---|---|---|
| Electricity demand, kWh/kg$CO_2$ | 106.4 | 17.3 | Yoo *et al.* 2013 |
| Specific investment, k€/(t$CO_2$/h) | 193 | 97 | Element Energy 2018 |
| *Reference scale, t/h* | 125 | 125 | Element Energy 2018 |
| *Scaling factor* | 0.67 | 0.67 | Own assumption |
| Fixed O&M, % of CAPEX | 4% | 4% | Own assumption |
| Lifetime, a | 20 | 20 | Element Energy 2018 |

## 5.3 Temporary storage

While $CO_2$ capture and liquefaction are continuous processes, shipping occurs in discrete deliveries. Thus, an intermediate buffer storage is required at the port. The storage is continuously filled while the ship(s) are at the sea. The required capacity of the temporary storages is typically assumed to be 1–1.5 times the capacity of the ship. For this study, a factor of 1.2 is considered similar to Yoo *et al.* 2013.

Temporary storages are typically modular. They consist of several cylindrical heat insulated steel tanks in which $CO_2$ is stored at shipping conditions. The considered maximum capacity of a single storage tank in literature is 3 000–6 000 t$CO_2$ (Apeland *et al.* 2011, Element Energy 2018, Yoo *et al.* 2013). Even in the cases with the smallest required storage capacities, the required capacity is in the same range as the maximum capacity of a single storage vessel. Thus, storage costs are assumed to be linearly dependent with capacity (scaling exponent is 1).

Boil-off due to heat leakage into the insulated storage vessels is assumed to be negligible similar to other studies (Jakobsen *et al.* 2017, Element Energy 2018, Kjärstad *et al.* 2016). In practice, if boil-off gas needs to be vented to reduce pressure in the tanks, it could be sent back to the liquefaction plant. The additional energy demand compared to total liquefaction energy demand is considered negligible.

*Table 8. Assumptions for temporary $CO_2$ storage at the port*

| | Value | Source |
|---|---|---|
| Specific investment, €/(t$CO_2$) | 545 | Element Energy 2018 |
| *Reference scale, t$CO_2$* | 12 310 | |
| *Scaling factor* | 1.0 | |
| Fixed O&M, % of CAPEX | 5% | |
| Lifetime, a | 20 | |

## 5.4 Loading

Liquid $CO_2$ from the buffer storage is transferred to the ship through an insulated pipe via a loading arm. Pressure in the storage tanks is kept constant while filling or emptying tanks. When discharging liquid $CO_2$, gaseous $CO_2$ is added to prevent pressure from dropping. Similarly, when storages are filled, gaseous $CO_2$ is removed to prevent pressure increase. Thus, while liquid $CO_2$ is transferred to ship, gaseous $CO_2$ from ship's storage tanks is simultaneously transferred to intermediate buffer storages (or to liquefaction) via a parallel gas return arm. (Brownsort 2015) Costs of loading equipment is show in Table 9. It is assumed that port does not require any other modifications to enable $CO_2$ shipping. The electricity consumption of the liquid $CO_2$ transfer pumps is negligible.

*Table 9. Assumptions for loading of $CO_2$ from the port to the ship*

| Parameter | Value | Source |
|---|---|---|
| Specific investment, €/(t$CO_2$/a) | 1.58 | Element Energy 2018 |
| *Reference scale, kt$CO_2$/a* | 3000 | |
| *Scaling factor* | 0.67 | |
| Fixed O&M, % of CAPEX | 3% | |
| Lifetime, a | 20 | |

## 5.5 Ship transport

Ship transport takes place using tanker ships having cruising speed of 15 nautical miles per hour (27.8 km/h) and capacities between 3 000–40 000 t$CO_2$. Today, $CO_2$ is already transported in medium pressure (10-20 bar) conditions with relatively small tankers (<2000 t/$CO_2$) for merchant use (e.g. beverages). For CCS applications where the $CO_2$ flows are much higher, low pressure conditions are more suitable and they could allow tankers with capacities over 10 000 t.

The number of ships required depends on the ship capacity, annual $CO_2$ throughput (Mt/a), ship transport distance and the availability of the ships. One ship is adequate for every studied case as the maximum assumed ship capacity is not exceeded. Thus, the ship capacity is chosen so that a high utilization factor is achieved.

Ship transport costs consist of ship investment costs, fixed operation and maintenance costs, fuel costs and harbour fees. Specific fuel consumption (tonnes of fuel required per hour for a tonne of cargo) depends on the ship capacity. An average scaling factor for LPG and LNG carriers (0.544) is adopted from NTN (n.n.) to describe the better fuel economy of the larger ships. Fuel consumption during loading, unloading, maneuvering is assumed to be on average 15% of fuel consumption during cruising. Low sulphur marine gas oil (LSMGO) is assumed to be used as the fuel due to strict sulphur emissions regulations in the Baltic Sea.

It is assumed that boil-off gas does not have to vented as pressure can be allowed to increase a couple of bars before gas has to vented (e.g. de Kler *et al.* 2016). According to Apeland *et al.* (2011) a pressure increase of 1 bar is likely to allow operation for 7 to 10 days without the need to release any $CO_2$. In the studied cases the trip times with cargo are clearly shorter than this.

The ship transport related assumptions are summarized in Table 10.

*Table 10. Assumptions for ship transport*

| Parameter | Value | Source |
|---|---|---|
| Max ship capacity, $tCO_2$ | 50 000 | Element Energy 2018, Kler *et al.* 2016 |
| | | |
| Specific investment, M€/($tCO_2$) | 31 | Element Energy 2018 |
| *Reference scale, t/$CO_2$,* | 10 000 | Element Energy 2018 |
| *Scaling factor* | 0.55 | Element Energy 2018 |
| Fixed O&M, % of CAPEX | 5% | Element Energy 2018 |
| | | |
| Lifetime, a | 20 | Element Energy 2018 |
| | | |
| Transport distance (one-way), km | 1 000<br>(500 and 2 000 as sensitivity) | |
| Cruising speed, nm/h | 15<br>(27.8 km/h) | Element Energy 2018 |
| | | |
| Cruising time, h | (2*Transport distance / Cruising speed) | Element Energy 2018 |
| Loading time, h | 15 | Element Energy 2018 |
| Unloading time, h | 15 | Same as loading (unloading to temporary storage at the platform) |
| Port entry/exit, h | 2 | Element Energy 2018 |
| Offshore connection, h | 4 | Element Energy 2018 |
| | | |
| Maximum availability | 95% | Element Energy 2018 |
| | | |
| Fuel consumption for a reference ship during cruising, MW (LHV) | 12 | Kjärstad *et al.* 2016 |
| Reference scale, $tCO_2$ | 11 500 | Kjärstad *et al.* 2016 |
| Scaling factor | 0.544 | NTN (n.n.) |
| Fuel consumption during manouvering, loading, unloading | 15% of cruising | In line with de Kler *et al.* 2016 |
| | | |
| Low sulphur marine gas oil price, €/t | 432<br>(36 €/MWh LHV) | Ship&Bunker 2021 |
| | | |
| Harbour fees, €/$tCO_2$ | 1.3 | de Kler *et al.* 2016 |

### 5.6 Unloading / gas conditioning / injection

At the storage site $CO_2$ needs to be brought from the ship transport conditions to the conditions suitable for the injection into the well, which depends on the storage site characteristics. $CO_2$ could be injected directly from ships via a flexible hose to well or via an offshore platform that can also include a temporary storage. If $CO_2$ is injected directly from ships, conditioning of $CO_2$ has to take place in the ship while platform concept enables conditioning to take place partly on the platform. In case a platform includes also a temporary storage, no on-board condition is required. Platform with storage enables also significantly faster unloading times and thus more efficient shipping as discharging liquid $CO_2$.

The platform with storage concept is considered here as it was also shown to lead to lowest cost (de Kler *et al.* 2016). Liquid $CO_2$ is first discharged from ship into a temporary offshore storage from which it is pumped to injection pressure, heated to required temperature (~5–10 °C) and injected into the well. $CO_2$ is assumed to be stored in a saline aquifer and 300 bar based on de Kler *et al.* 2016. Electricity required for pumping is assumed to be produced by internal combustion engines running on same fuel as ships and having an efficiency of 40% (based on lower heating value). The heat required for gasification is assumed to be taken from seawater and excess heat from engines similarly to de Kler *et al.* 2016.

Assumptions related to offshore gas conditioning are summarized in Table 11. These include only the equipment related to gas conditioning (pumps, heat exchangers, engines). The cost of platform itself is considered as a part of the storage cost component. The gas conditioning equipment is assumed to serve whole storage site and not only the FTL plant studied.

*Table 11. Assumptions for the unloading and gas conditioning for injection*

| Parameter | Value | Source |
|---|---|---|
| Electricity demand*, kWh/kg$CO_2$ | 10.3 | de Kler *et al.* 2016 |
| Engine efficiency, kWhe/kWhfuel, LHV | 40% | Own assumption |
| Specific investment, k€/(t$CO_2$/h) | 7.6 | de Kler *et al.* 2016 |
| Reference scale, t/h | 3.8 | de Kler *et al.* 2016 |
| Scaling factor | 0.67 | Own assumption |
| Fixed O&M, % of CAPEX | 5% | Element Energy 2018 |
| Lifetime, a | 20 | Element Energy 2018 |

*provided by internal combustion engines having efficiency 40% (LHV) leading to a fuel demand of 25.8 kWh/kg$CO_2$ demand

## 5.7 Storage reservoir

$CO_2$ is assumed to be stored in an offshore saline aquifer. The storage costs were estimated from a study by Jakobsen et al (2014). The $CO_2$ storage costs in their model, which is based on the Zero Emission Platform (ZEP) methodology, consist of six components: 1) Pre-Financial Investment Decision Costs 2) Platform, 3) Injection wells, 4) Operating, 5) Monitoring, Measurement and Verification (MMV) 6) Close-down.

Based on the data, storage cost in an offshore saline aquifer can be estimated using equation

$$\text{Specific } CO_2 \text{ storage Cost } (€/tCO_2) = 173.26x^{-0.33}$$

where x=annual $CO_2$ injection rate in kilotonnes. The resulting cost graph is illustrated in Figure 8.

The main storage cost components for offshore saline aquifers are Pre-FID costs and injection well drilling costs (ZEP 2011). The costs do not include gas conditioning so double counting is avoided.

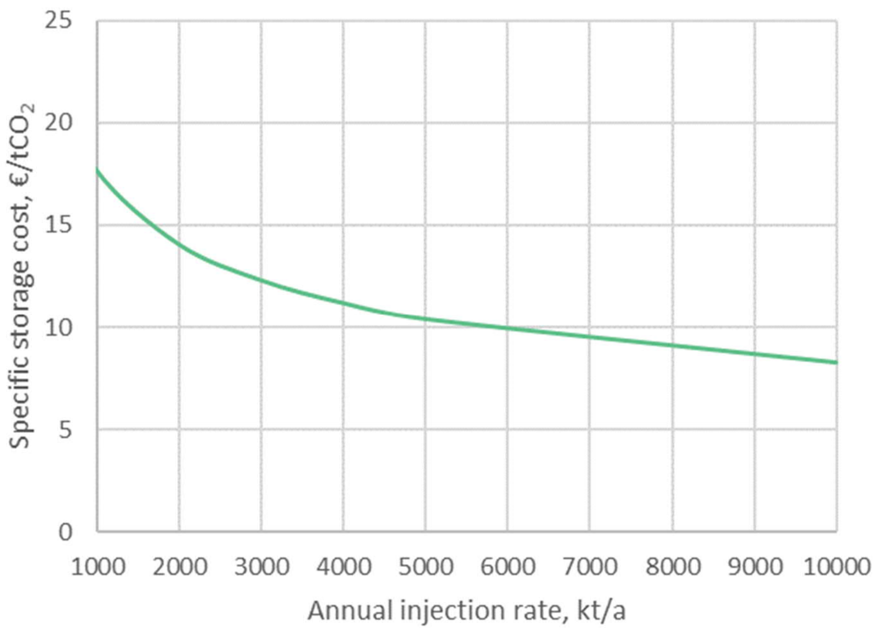


*Figure 8. Specific storage cost in offshore saline aquifers as a function of annual injection rate of $CO_2$. Costs do not include conditioning of the $CO_2$ (from transport state to conditions required for injection). (Derived from Jakobsen et al 2014)*

# 6 Results

## 6.1 Production cost of FT crude without CCS

Production cost breakdowns of FT crude without CCS are shown in Figure 9. For the 1000 bbl/d (59 $MW_{FTcrude}$) plants (A1 and B1) the total production cost is 147 €/$MWh_{LHV}$ (40.8 €/GJ). Increasing the plant capacity to 2400 bbl/d (142 $MW_{FTcrude}$) decreases the costs to 125 €/ $MWh_{LHV}$, (34.7 €/GJ). Due to the high capital intensiveness, the lower specific investment of the larger plant more than compensated the assumed higher cost of biomass (20 vs 23 €/MWh). The location of the plant was not considered to affect the biomass price: even though the biomass supply area is a half-circle for the plant at the port, biomass could also be transported by ships. Biomass accounts for ¼ and 1/3 of the total cost for the smaller and larger plant, respectively.

The cost of producing FT crude would decrease by 34 and 25 €/MWh for 1000 and 2400 bbl/d plants, respectively if investment costs could be reduced by 30% e.g. through wider adoption of the technology.

In the base case, it was assumed that the FT plant uses excess steam to produce electricity. Especially for the Nordic countries, it would be feasible to run the steam cycle of the FT plant on combined heat and power mode if there is district heat demand at the vicinity of the plant. This would make the FT plant a net consumer of electricity but a significant amount of heat suitable for district heating would be produced. If excess heat would be valued at 30–40 €/MWh, the costs would decrease by ~10–15 €/MWh (2.8–4.2 €/GJ). In addition, utilising FT plants for district heating would free biomass from the existing district heat boilers, which could improve biomass availability for the biofuel production.

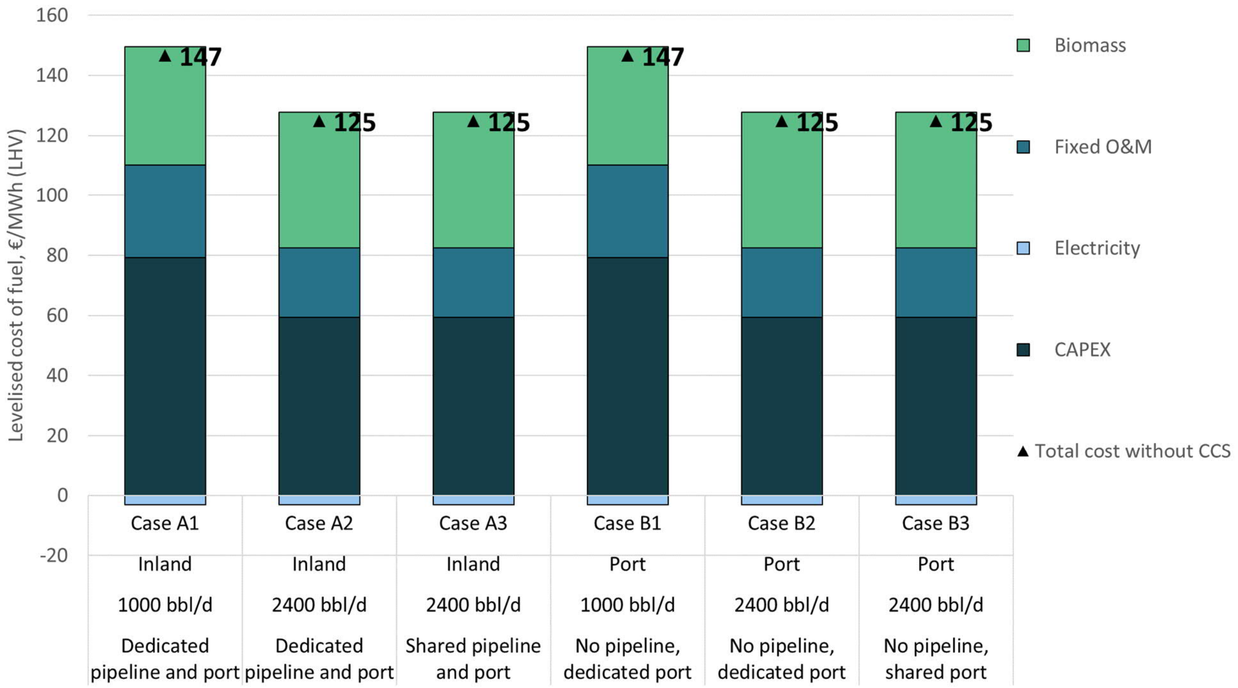


*Figure 9. FT crude production cost breakdown without CCS, depending on plant capacity.*

The costs are similar to the recently reported costs. IEA Bioenergy (IEA 2020) reports a cost range of 75–144 €/MWh for a plant with 200 MW (3400 bbl/d) biofuel output. If the larger plant from this study would be scaled to same capacity, the cost would be ~110 €/MWh which is in the middle of the indicated range. Analysis by IEAGHG (IEAGHG 2018) indicates FT crude production cost of 86 €/MWh for 260–290 MW biofuel output. At same capacity the model used in this study would lead to a cost of 105–108 €/MWh. The cost difference is mainly due to significantly higher biomass price used in this study.

The costs are around two times higher[2] than the current fossil transport fuel pump prices when taxes and duties are excluded. In 2019 the average price of petrol and diesel in the EU were 62 and 63 €/MWh, respectively (Statista 2021). There are no public price quotations for advanced biodiesel. According to estimation by Sipilä *et al.* (2018), the price of advanced biodiesel was around 100 €/MWh in 2018 and could increase to around 150 €/MWh by 2030 due to the supply limited market. In a supply limited market, the price of advanced biofuels will be determined by the fees laid down for not being able to comply with the biofuel blending obligation set by the Renewable energy directive (RED). This suggests that producing biofuels through FTL, could become feasible if no other cheaper alternatives emerge.

### 6.2 $CO_2$ transport and storage costs (cost of CCS)

The calculated transport and storage costs are 35–66 €/t$CO_2$ for the plants located inland and ~31–46 €/t$CO_2$ for the plants located at the port (Figure 10). The costs represent the situation where CCS has been widely adopted. The costs for the first-of-a-kind projects could be significantly higher.

The results show that:

- Shared transport infrastructure would reduce costs markedly. In the case of dedicated transport and storage chains, the costs increase markedly as $CO_2$ conditioning (compression/liquefaction),

[2] It should also be noted that the FT crude would require additional refining.

ship transportation and especially pipeline construction benefit highly on the economies of scale. Building 100 km pipeline for 200 kt$CO_2$ capacity would not likely be realistic case in practice.

- At lower $CO_2$ throughputs, shipping costs are higher than the $CO_2$ conditioning costs while in shared transport infra cases, conditioning and shipping costs are similar.
- Temporary storage costs and loading and unloading costs represent only a small fraction of the costs.

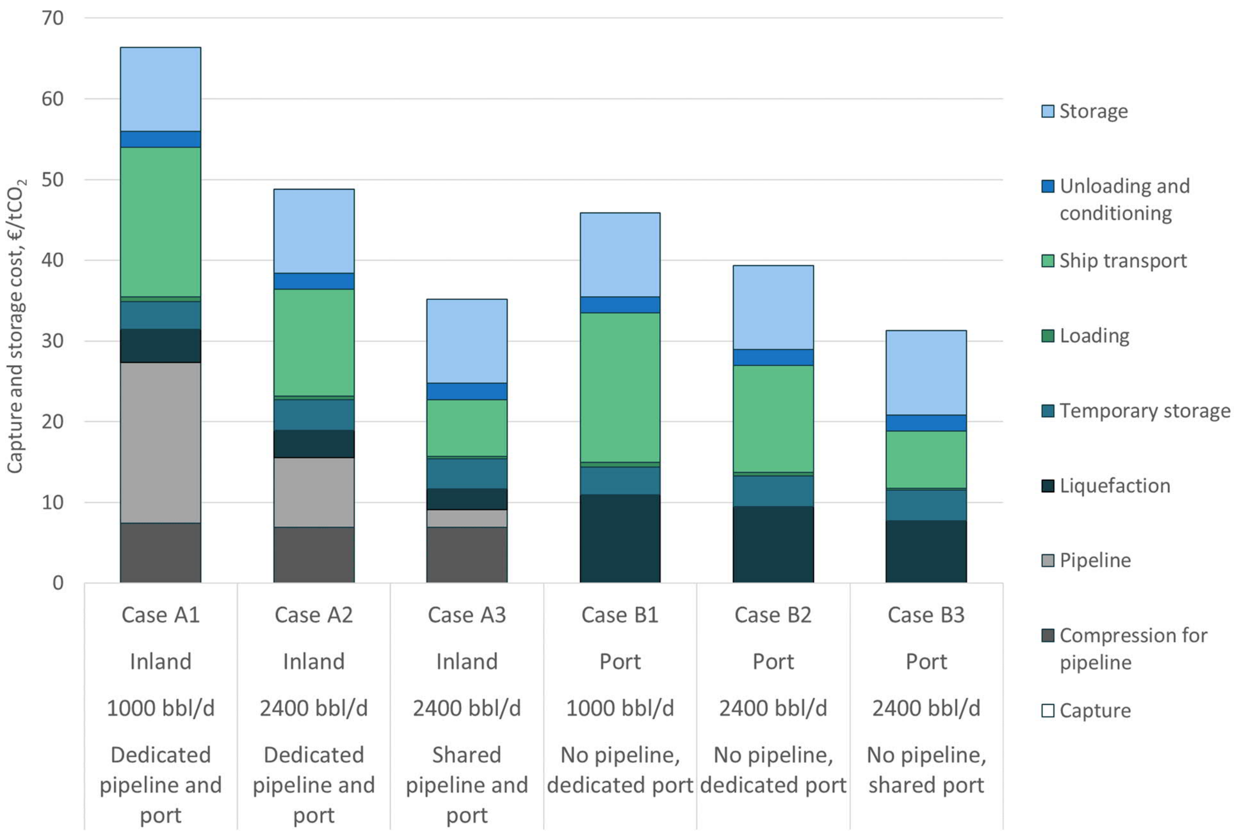


*Figure 10. Breakdown of $CO_2$ transport and storage costs by transport chain step. The storage costs are equal for each case as a large shared storage reservoir was considered for each case. Capture costs are zero as $CO_2$ is already separated from the process even without CCS.*

Figure 11 shows cost category breakdown of transport and storage costs revealing the high capital cost intensiveness. The reservoir related storage costs were not divided into the different cost categories as they were outside the boundary limits. The reservoir related storage costs are mainly CAPEX.

At smaller $CO_2$ throughputs ship fuel and harbour fees are higher than the electricity costs but due to improved fuel economy of larger ships, electricity costs are higher in the dedicated transport infra cases. The effect of $CO_2$ throughput on the shipping costs is further illustrated in Figure 12 showing the benefits of using larger, more fuel-efficient ships.

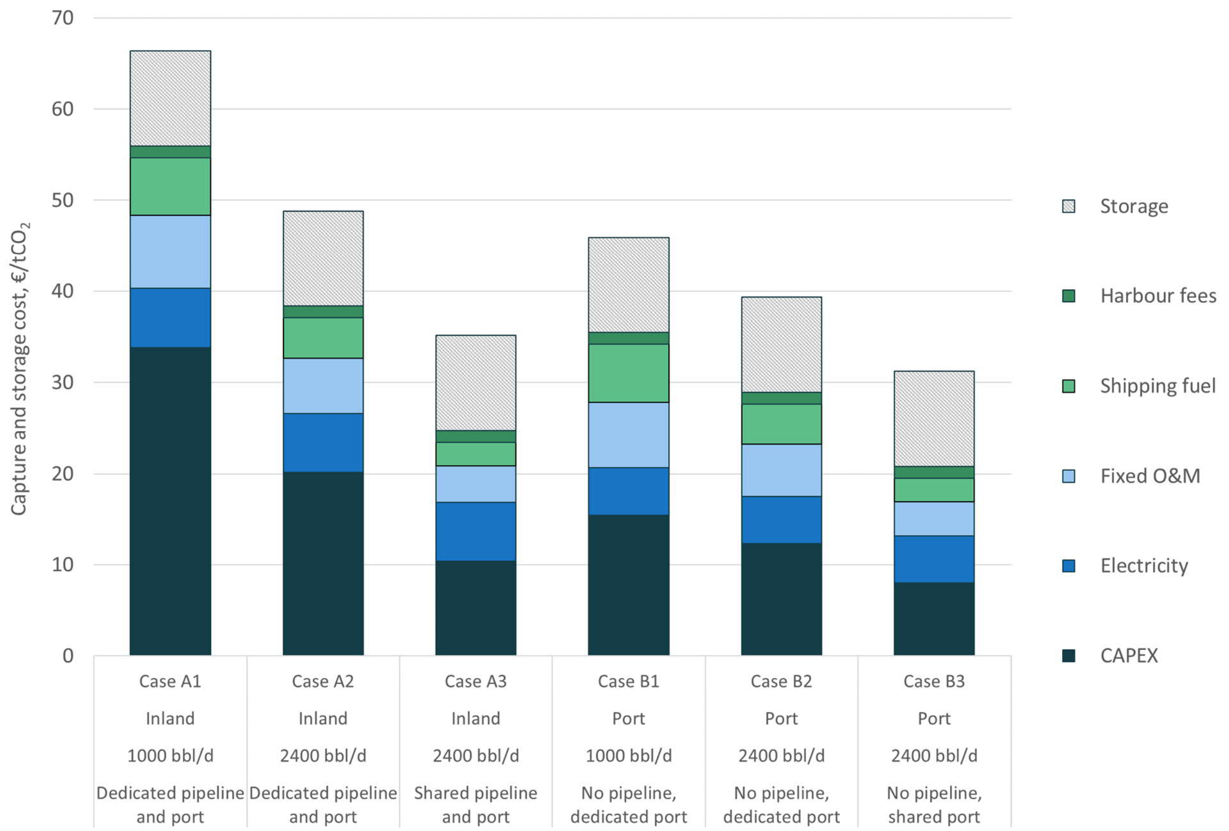


*Figure 11. Breakdown of $CO_2$ transport and storage costs by cost type. (Storage costs where not broken down but are given as a lump sum. Storage costs are mainly CAPEX).*

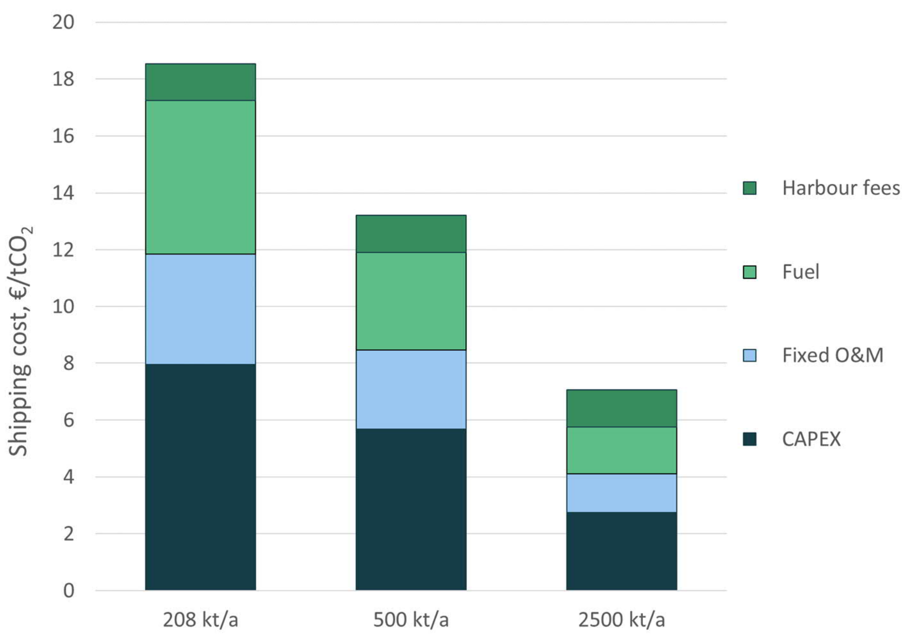


*Figure 12. The effect of $CO_2$ throughput (kt/a) on the shipping costs.*

Shipping distance has a relatively low impact on the total transport and storage costs (Figure 13). For 500 $ktCO_2/a$ cases, the shipping cost decrease only ~3 €/$tCO_2$ if transport distance is halved from 1000 to 500 km while doubling the transport distance increases costs by ~4 €/$tCO_2$. Compared to the total transport and storage costs 40–50 €/t, Figure 10), these are minor increases.

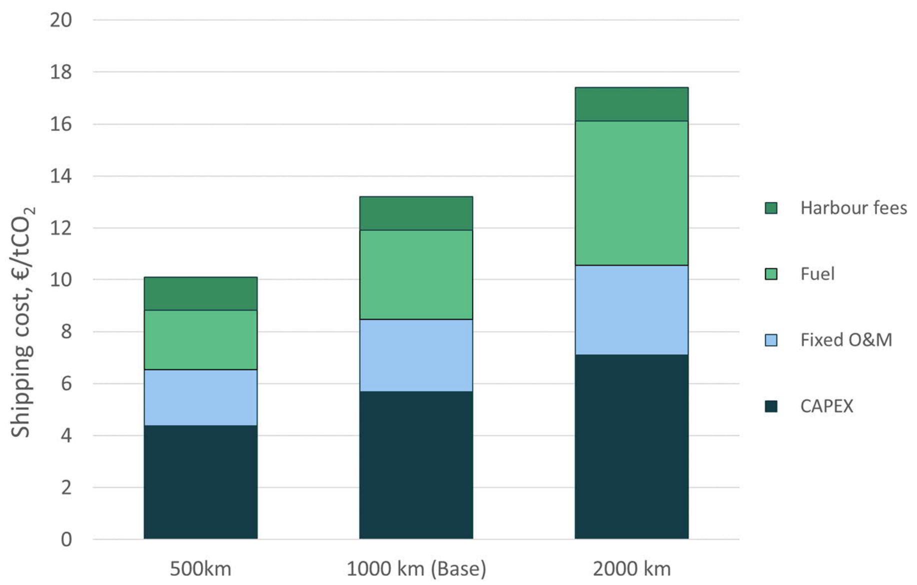


*Figure 13. The effect of shipping distance on shipping costs for 2400 bbl/d (500 $ktCO_2/a$) plant located at the port.*

## 6.3 The effect of CCS and negative carbon credits on the production cost of FT crude

Adopting CCS increases the cost of FT crude by 14–29 €/$MWh_{LHV}$ (3.9–8.1 €/GJ) (Figure 14). This corresponds to 11–20% increase on costs.

At the moment, the FT plant could not benefit from providing negative $CO_2$ emissions through the EU Emission Trading Scheme (EU ETS) or other EU policy as the EU does not recognize negative emissions. Figure 15 shows how the production costs would be affected if negative $CO_2$ emissions could be credited with 50 €/t which corresponds to the current price (5/2021) of the EU emission allowance. This shows that CCS would be feasible at current emission allowance prices in the all the cases except A1. However, the costs reported here correspond to a situation where $CO_2$ transport and storage chains have already been established.

The effect of negative $CO_2$ credits is further illustrated in Figure 16, which compares the production cost of FT crude with and without CCS. For each 10 €/t of $CO_2$ credit, the production cost decreases by 4.4 €/$MWh_{LHV}$ (1.2 €/GJ).

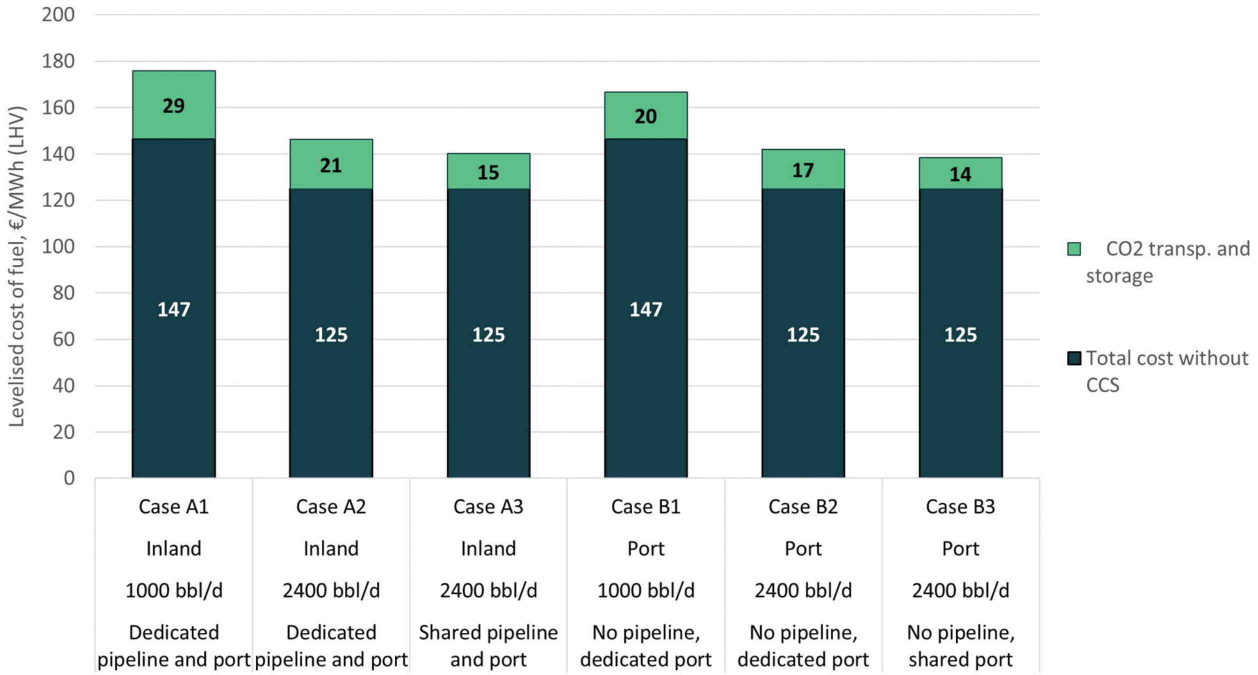


*Figure 14. Production cost of FT crude with and without CCS.*

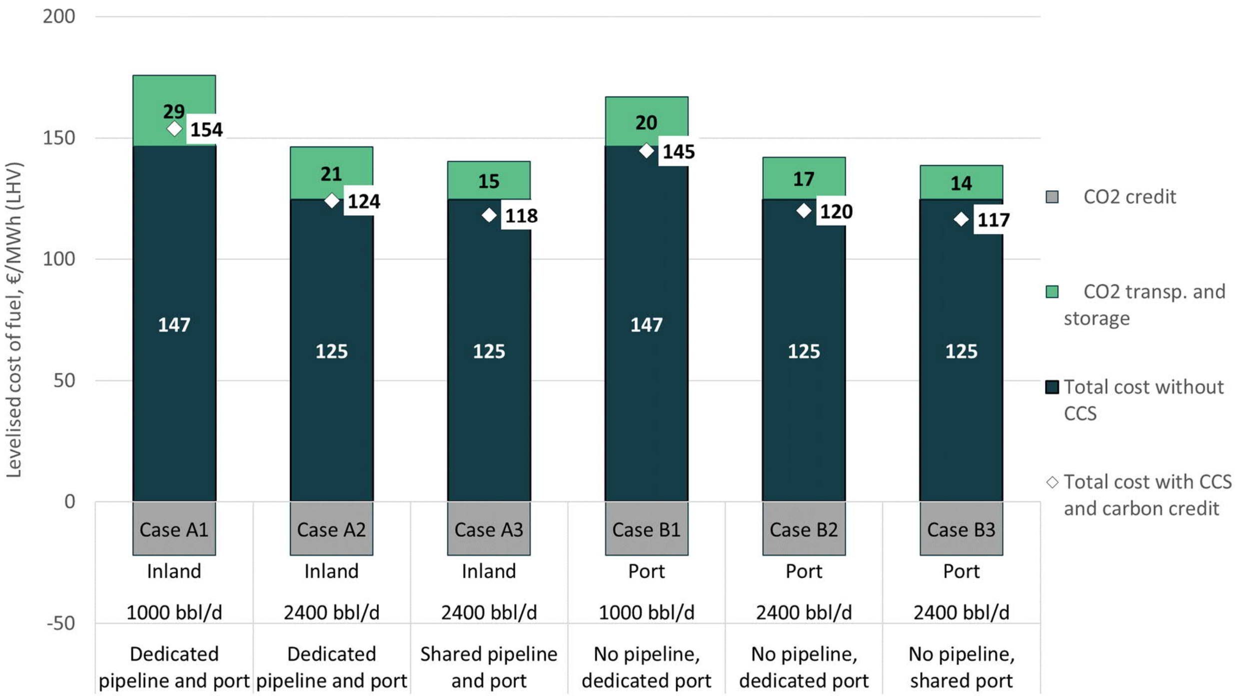


*Figure 15. Production cost of FT crude with and without CCS when negative $CO_2$ emissions are credited @ 50 €/t.*

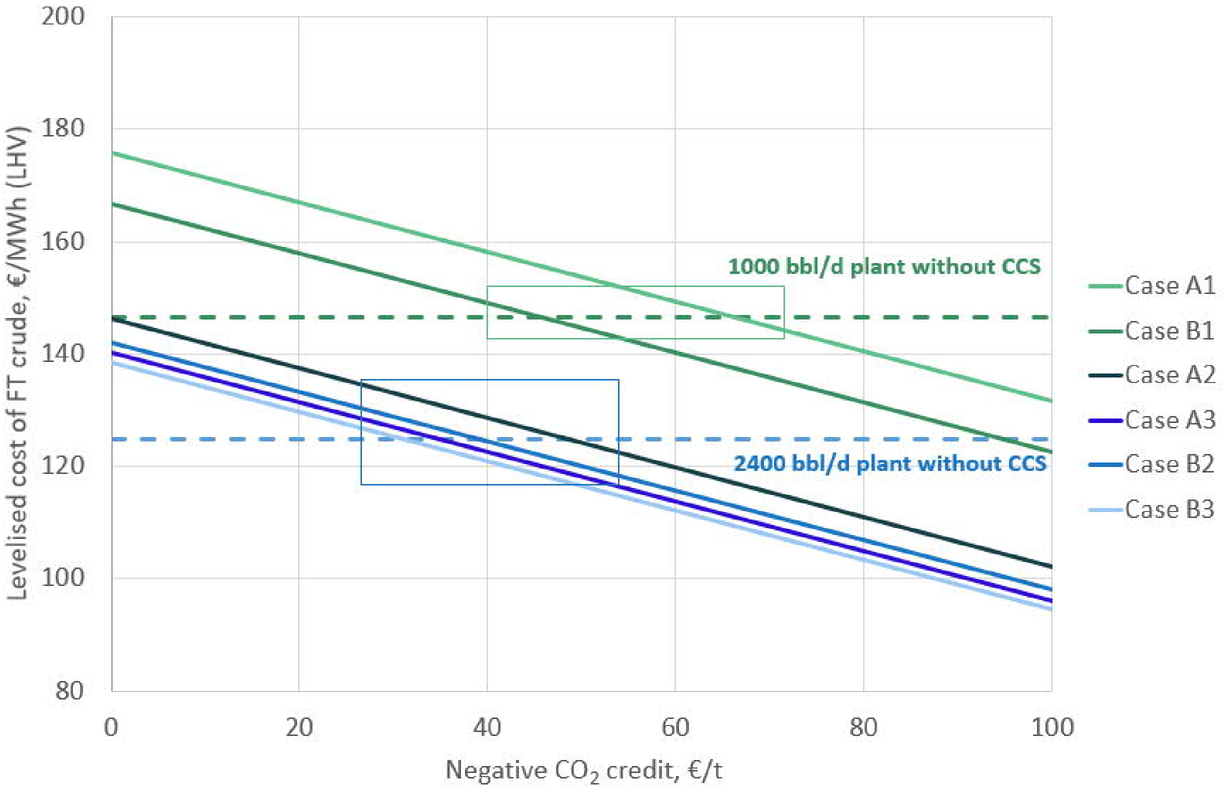


*Figure 16. Effect of negative $CO_2$ credit on the production costs of FT crude. The intersections show the break-even $CO_2$ credit prices compared to production without CCS. The break-even prices correspond to $CO_2$ transport and storage costs shown in Figure 10.*

## 6.4 KPIs

The life cycle inventory model for FTL-CCS process can be found in Table 12 for both scenarios A1-3 and B1-3. The results for the several KPIs studied based on the inventory, are presented in this section.

*Table 12.* FTL-CCS LCA inventory model

| | | Flow | Values | | Source for emission inventory data |
|---|---|---|---|---|---|
| Product (Functional Unit) | | Sequestered $CO_2$ in biomass growth | 1 | tonne | |
| Co-Products (avoided Products) | | FT Crude | 107.82 | kg | Ecoinvent 3 (as Diesel) |
| | | Electricity | 79.74 | kWh | Ecoinvent 3 (as average Nordic mix) |
| Input flows | Biomass growth, harvest & transport | Biomass forest residues | 552.08 | kg | Ecoinvent 3 (as dry wood chips) |
| | | Biomass lorry transport | 110.42 | tkm (tonne x km) | Ecoinvent 3 |
| | FTL-CCS Process | Water | 1816.04 | kg | Ecoinvent 3 |
| | | Methanol | 1.08 | kg | Ecoinvent 3 |
| | $CO_2$ transportation & storage | Pipeline $CO_2$ transport | A1-A3: 56.53<br>B1-B3: 0 | tkm | Custom model (based on Wildbolz, 2007) |
| | | Shipment Operation | 580.59 | tkm | Ecoinvent 3 |
| | | Electricity requirements | A1-A3: 75.24<br>B1-B3: 60.50 | kWh | Ecoinvent 3 |
| | | Low-sulfur fuel requirements | A1,B1: 140.05<br>A2,B2: 108.96<br>A3,B3: 80.29 | MJ | Custom model (based on fuel oil no.2 combustion) |
| Direct emissions (from FTL process) | | $CO_2$ | 172.03 | kg | From FTL-CCS process |

Note that the life cycle inventories for the different scenarios only change in the pipeline, electricity and ship fuel requirements for the captured $CO_2$ transport and storage. Inventories in all other major sections of the supply chain (i.e. biomass growth, harvest and transport, and FTL-CCS process) have been assumed to be independent from the process capacity, therefore presenting the same values for all 6 scenarios. This assumption aligns, as indicated in the LCA methodology description section, with the capacity independence of results in most LCA analyses.

### 6.4.1 KPI-1 and KPI-2, $CO_2$ removal efficiency and Avoided emissions

The $CO_2$ removal efficiency of the system (KPI-1) is evaluated as the ratio between the final carbon stored and the carbon initially sequestered in the growth of biomass. This measure directly characterises the negative emission efficiency of the process, defining how much of the carbon initially sequestered is stored and effectively removed from the environment. An additional advantage of this definition is its applicability to any type of negative emission technologies, enabling the direct comparison of significantly different negative emission technologies and strategies. Because of these properties, KPI-1,2,3,5 and 6 are expressed with the same functional unit.

In addition to this measure, avoided emissions (KPI-2) for the produced electricity and FT crude also contribute to the total emission reduction of the process. These avoided emissions are also evaluated as the ratio between the avoided carbon emission and the carbon initially sequestered in the growth of biomass. Note that avoided emissions are not considered in KPI-1. Figure 17 provides the obtained results for the previously defined LCA scenarios A1 to B3 for KPI-1 and KPI-2.

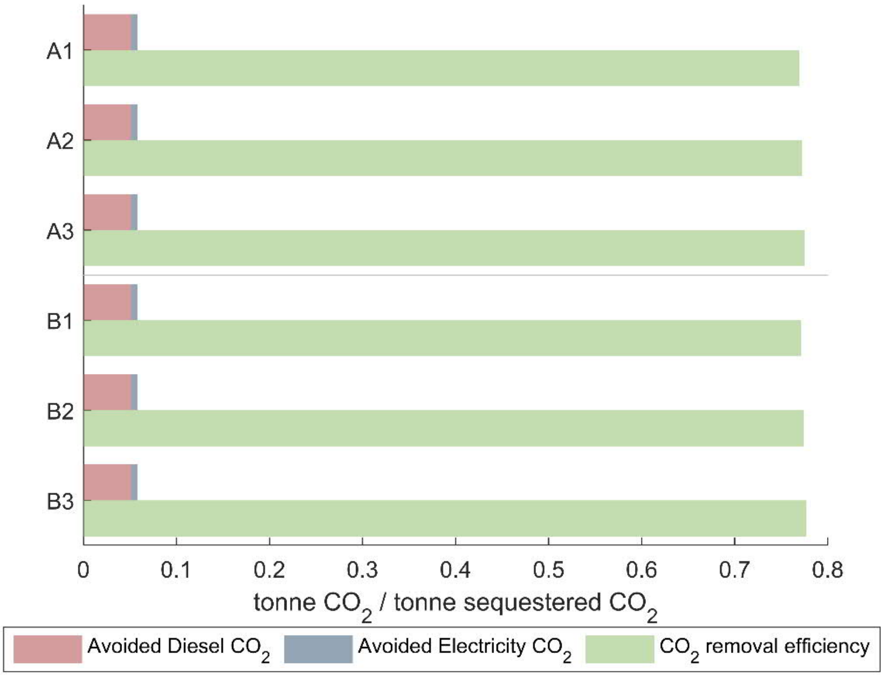


*Figure 17.* KPI-1, $CO_2$ removal efficiency, and KPI-2 Avoided emissions results.

The results for all 6 scenarios present almost identical avoided emission and, most importantly, removal efficiencies. This similarity indicates the marginal emission differences from the pipeline transport of captured $CO_2$ and the different shipment conditions when compared to the total emissions in the FTL process and the other direct process contributors such as electricity mix or methanol production and distribution.

All scenarios present removal efficiencies very close to 0.77 tonne $CO_2$ stored / tonne sequestered $CO_2$ (less than 1% difference among all scenarios), with the remaining 0.23 tonnes of $CO_2$ sequestered either being released as emissions (in the FTL process or from the related processes) or transformed into FT crude (assumed as diesel for environmental characterization). In turn, the replacement of diesel with FT crude would avoid the emission of 0.05 tonne $CO_2$ (for each tonne of $CO_2$ sequestered) in its production stage. As described in the definition of the LCA approach here applied, the combustion of the produced fuel (i.e. the use phase of this product) is not considered in the scope of the LCA, and therefore the emissions generated in use phase and their contribution to different environmental impacts are not accounted for in any of the considered KPIs. Furthermore, the surplus of electricity produced in the FTL process would avoid the emission of 0.007 tonne $CO_2$. The amount of generated excess electricity is low compared to the biofuel output. In addition, due to the relatively low emission level of the considered average Nordic electricity mix, the corresponding electricity avoided emissions are low. Correspondingly, the implementation of this technology in other geographical context (with more carbon intensive average electricity mixes) may yield better avoided emissions from the production of clean electricity. In total, the combined carbon removal efficiency of the whole FTL-CCS system (with avoided emissions) would reach a total $CO_2$ removal efficiency of 0.83 tonne $CO_2$ per 1 tonne of $CO_2$ sequestered for all scenarios.

### 6.4.2 KPI-3, Mid-point indicators

In total, the Environmental Footprint v3 method characterized 16 different indicators, as listed in Table 13.

*Table 13.* Mid-point indicators from Environmental footprint v3 characterization method

| Mid-point | Unit | Mid-point | Unit | Midpoint | Unit |
|---|---|---|---|---|---|
| Climate change | kg $CO_2$ eq | Human toxicity, cancer | CTUh | Land use | Pt |
| Ozone depletion | kg CFC11 eq | Acidification | mol H+ eq | Water use | m3 depriv. |
| Ionising radiation | kBq U-235 eq | Eutrophication, freshwater | kg P eq | Resource use, fossils | MJ |
| Photochemical ozone formation | kg NMVOC eq | Eutrophication, marine | kg N eq | Resource use, minerals and metals | kg Sb eq |
| Particulate matter | disease inc. | Eutrophication, terrestrial | mol N eq | | |
| Human toxicity, non-cancer | CTUh | Ecotoxicity, freshwater | CTUe | | |

Among all the mid-point categories, Climate change indicator appears as one of the most critical for negative emission technologies such as the FTL-CCS process. The results for this indicator are presented in Figure 18, providing the contribution of the different main sections of the analysed system: biomass growth, harvest and transport, FTL-CCS process, $CO_2$ transport and storage, and avoided products.

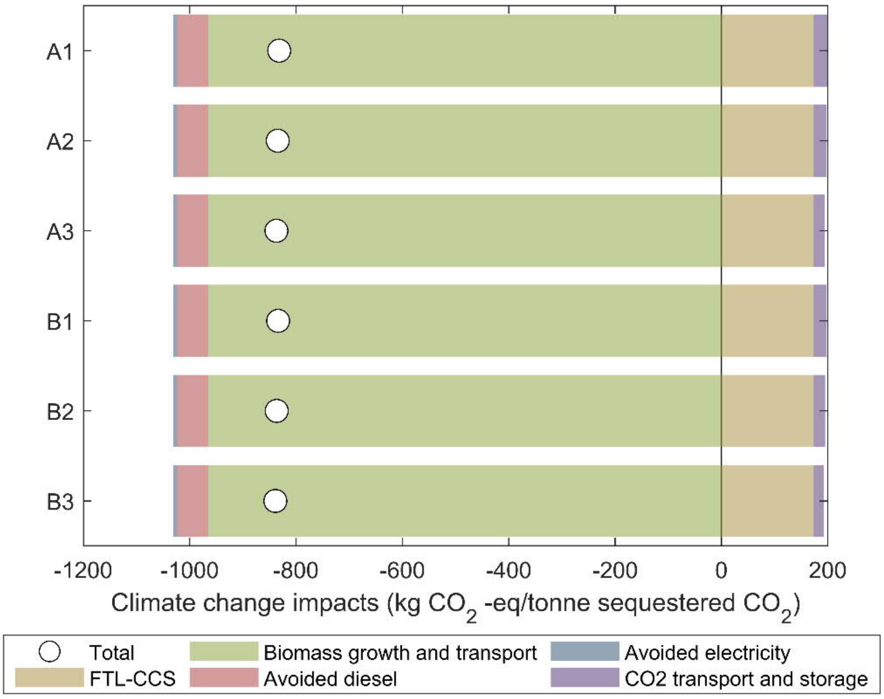


*Figure 18.* KPI-3, Global warming potential mid-point indicator results.

As in the results for KPI-1 and KPI-2, the Climate change results and the contributions of the different sections is almost identical through scenarios A1 to B3, a pattern also seen in all other mid-point indicators. Furthermore, the total climate change impact indicator aligns with the carbon removal efficiency, indicating the overall negative global warming effect on the environment, approximately reducing an average of 836 kg $CO_2$-eq/tonne of $CO_2$ sequestered, with less than 0.5% relative difference between scenarios.

By sections, FTL-CCS presents the highest positive contribution to climate change (174 kg $CO_2$-eq/tonne of $CO_2$ sequestered in all scenarios) mainly due to the direct emissions of non-captured $CO_2$ and, in a minor degree, to the embodied life cycle emissions of the required water and methanol inputs. Captured $CO_2$ transport and storage climate change contribution, although marginal when compared to FTL-CCS section, presents also positive values ranging from 19 kg $CO_2$-eq /tonne of $CO_2$ sequestered in scenario B3 to 26 kg $CO_2$-eq /tonne of $CO_2$ sequestered in scenario A1, indicating the higher climate change impact of $CO_2$ pipeline transport and smaller ship transport capacities.

On the other side, the combined contributions of growth, harvest and transport of biomass represents the major driver to achieve negative emissions, reducing 966 kg $CO_2$-eq/tonne of $CO_2$ sequestered. Note that only biomass growth can contribute to the reduction of the climate change impact, with both the harvest and transport stages of this section being active emission sources and contributing to the increase of the climate change impact. As previously mentioned, due to the small output and low emission profile of the considered average Nordic electricity mix, avoided emissions from the produced electricity only contribute 8 kg $CO_2$-eq /tonne of $CO_2$ sequestered. In contrast, the avoided FT crude product presents a significant contribution to the total climate change reducing 58 kg $CO_2$-eq/tonne of $CO_2$ sequestered in all scenarios.

The results for the remaining 15 mid-point indicators are presented in Figure 19, also providing the contribution of the different sections of the system analysed.

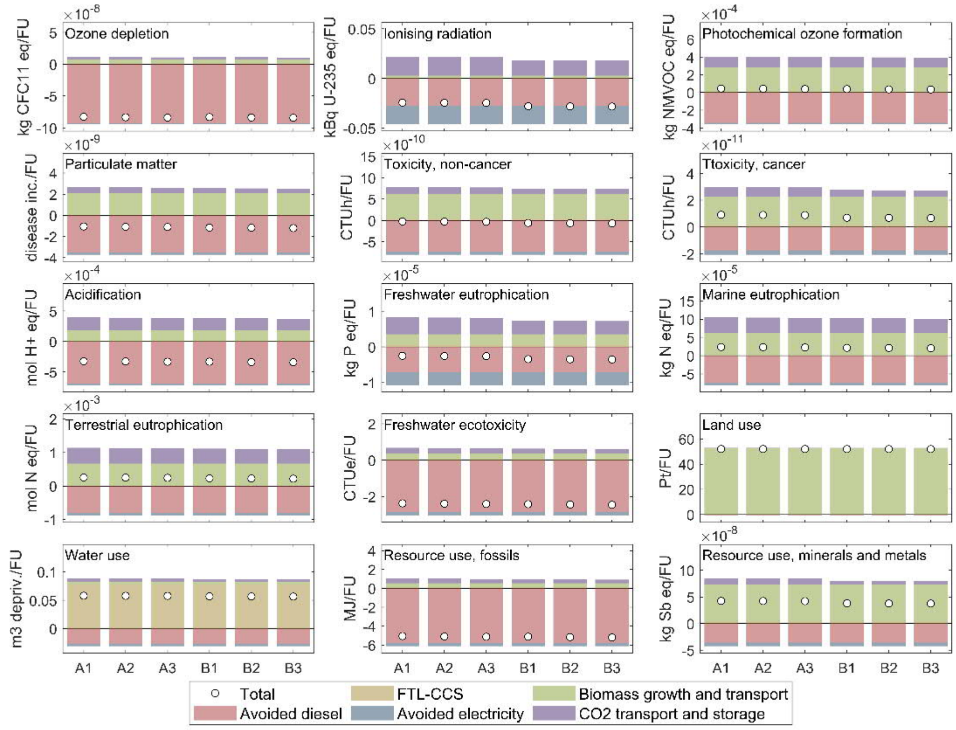


*Figure 19.* KPI-3 Mid-point indicator results (except Global Warming Potential) as characterized through Environmental Footprint v3 method. FU = Functional unit = 1 tonne sequestered $CO_2$

Out of the 16 mid-point indicators analysed, 9 present negative total values, indicating a generally positive environmental prospect for the FTL-CCS system, mainly due to the substitution of conventional diesel (and in a minor part electricity) with cleaner FT crude and electricity. The remaining 7 mid-point indicators present positive total values, indicating a particular level of impact on a particular environmental aspect. As could be expected, most of these positive contributions are mostly due to the growth, harvest and transportation of biomass, as these activities have a direct impact on forest soil (causing Land use and Marine and Terrestrial eutrophication) and involve fossil-fuel powered machinery, contributing to Photochemical ozone formation and Carcinogenic toxicity (both from the generated emissions), to Mineral and metal resource depletion (from the machinery assembly). In some cases, emissions and impacts associated to biomass residues are completely allocated to the main economic product (in this case, the production of wood), only accounting for the most beneficial factors such as the sequestration of $CO_2$ and associating them with the residues. This approach, however, fails to capture the impact of activities that only involve biomass residues, assuming these equal to those carried out for the main products. For this particular case, it has been assumed that harvesting and transport of residues is distinct from that of the main wood products, and therefore their contributions to emissions and impacts should be properly characterised being proportional to the amount of forest residues used in the FTL-CCS process.

In contrast, Water use mid-point indicator presents a significant positive value due to the water requirements of the FTL-CCS process to generate intermediate steam and the production of electricity as well as for the FT crude synthesis and the carbon capture process. For this same mid-point indicator, biomass growth, harvest and transport section presents a positive although very small contribution, highlighting the low requirement of water resources for forest residues resources when compared to crop-based biomass.

### 6.4.3 KPI-4, Levelised cost of stored $CO_2$

In contrast with the other KPIs considered, the Levelised cost of stored $CO_2$ is purely based on the economic results described in sections 6.1– 6.3, instead of results from LCA applied to the FTL-CCS system. Unlike the economic results previously presented, this KPI provides the cost for the removal (through biomass growth), capture (in FTL process) and storage of 1 tonne of $CO_2$ from the environment, considering the potential economic benefits obtained from the produced electricity and fuel products but disregarding the emissions avoided, as these are clearly indicated by KPI-1. The effect of these products is considered in the Levelised cost of stored $CO_2$, as they can provide a significant revenue that directly contributes to the economic efficiency of the FTL-CCS technology. While the potential revenue from electricity production has been reported in Figure 9, the revenue of FT crude has been estimated to be 60 €/MWh assuming it to have the same market price as conventional diesel in Europe (Statista 2021). The obtained results are presented in Figure 20.

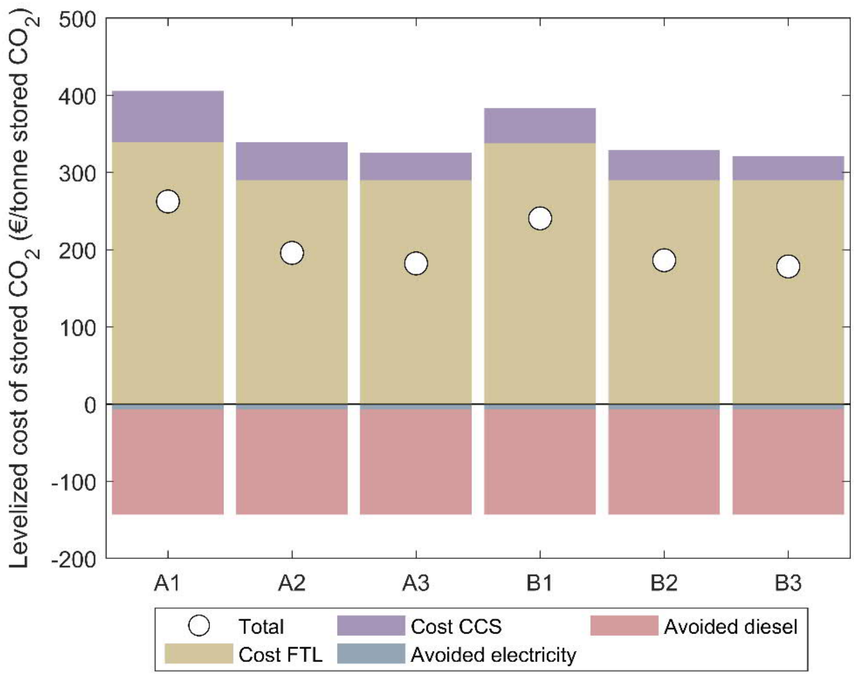


*Figure 20.* KPI-4, Levelised cost of stored $CO_2$.

The obtained levelised costs of stored $CO_2$ range from 263 €/tonne $CO_2$ (scenario A1) to 178 €/tonne $CO_2$ (scenario B3), further highlighting the impact of structural decisions of the FTL-CCS process on its total economic efficacy as a negative emission technology. Furthermore, the cost of the FTL process (without CCS) corresponds to the major contribution to the total cost, with capture, transport and storage of $CO_2$ only representing from 16% (scenario A1) to 10% (scenario B3) of the total cost.

The predominant role of FTL process on the Levelised cost of stored $CO_2$ explains the similar behaviour of the results obtained for KPI-4 with the Levelised costs of fuel presented in Figure 14.

### 6.4.4 KPI-5, Monetised end-point environmental impacts

The monetization and aggregation of end-point environmental indicators significantly simplify the overall environmental evaluation of the analysed FTL-CCS system, providing a single economic indicator representing the economic cost caused to the environment. The obtained results are expressed in €2019 and presented in Figure 21, comparing the effect of avoided products in the total environmental performance.

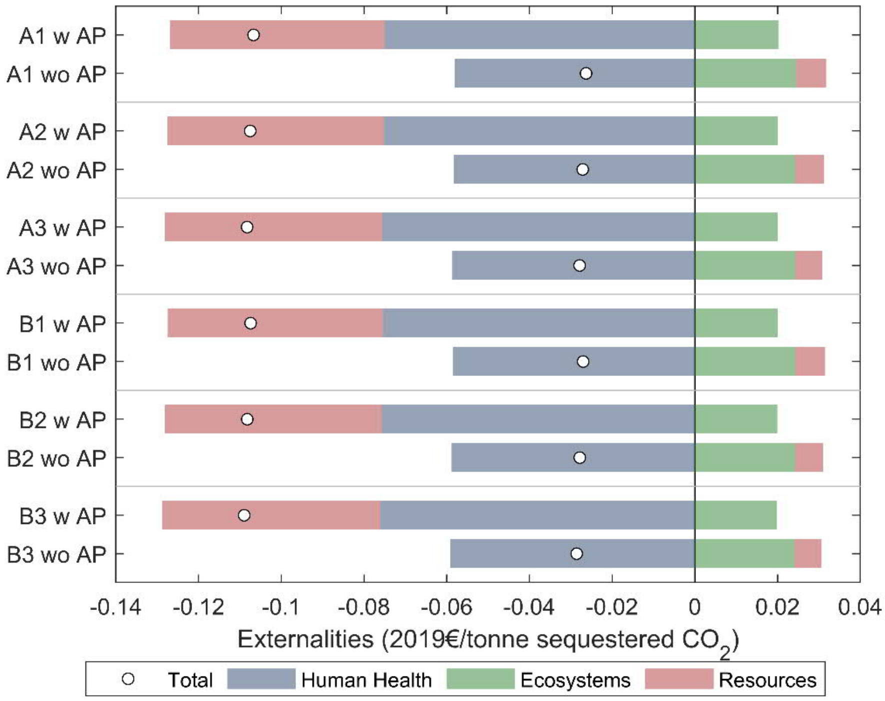


*Figure 21.* KPI-5, Monetised end-point environmental impact indicators. Results are provided for scenarios A1 to B3, with avoided products (w AP) and without (wo AP).

As most of the previously analysed mid-point indicators, the aggregated monetised end-point indicators present negative values, indicating the overall improvement of environmental conditions when applying the FTL-CCS system. The obtained results clearly highlight the fundamental contribution of the generated cleaner FT crude and electricity as avoided products, decreasing the total cost of externalities 0.08 €2019/tonne sequestered $CO_2$ in all scenarios. While the improvement of avoided products takes place in all three end-point indicators, it is particularly significant the contribution of avoided fossil diesel in the Resources area of protection, more than compensating the impacts on this area caused by the FTL-CCS system.

Impact on the Ecosystems area of protection, however, presents positive costs in all considered cases, as it is directly caused by the negative effects of the growth and harvest of biomass on its environment (e.g. soil quality decrease, water eutrophication…).

The results obtained for the Human health area of protection consistently present negative cost of externalities, as these fundamentally depend on the total contribution to the climate change and related mid-point indicators from KPI-3, all of which present beneficial improvements from the FTL-CCS system.

### 6.4.5 KPI-6, Impacts on human health

The end-point impact on human health is here considered as a proxy of the social impact of the analysed system, as it is the only environmental measure that presents a direct effect on the population. The results obtained for this indicator are presented in Figure 22.

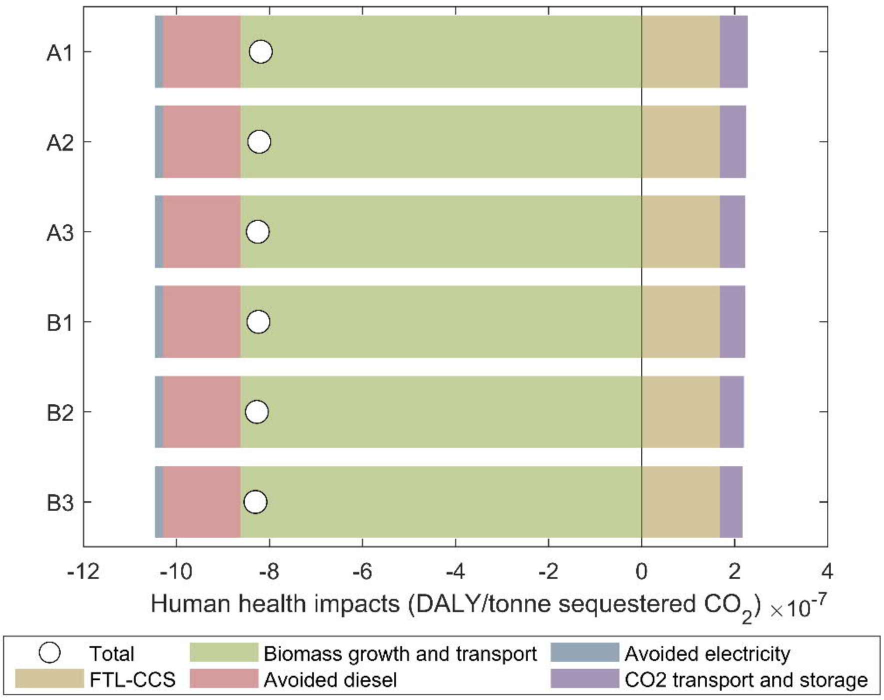


*Figure 22.* KPI-6, Impact on Human health

As previously mentioned, the impact on human health for the considered system is fundamentally caused by the impact on climate change and related mid-point indicators. This explains the similar contribution patterns presented in Figure 22 and those presented for the climate change impact in KPI-2 for all scenarios. As in that case, the total impact on human health appears to be negative, indicating an improvement of 8.24 $\cdot 10^{-7}$ Disability-adjusted life years (DALY) / tonne sequestered $CO_2$. Similar to the impact on climate change indicator, the main contributor to this beneficial environmental profile are the negative emissions generated in the growth of biomass, reducing the negative effects of global warming and the emission of particles and therefore diminishing the probability of developing health issues related to these factors.

Together with the carbon removal from biomass, the production of cleaner electricity and diesel alternatives further improve the overall impact of the FTL-CCS system on human health.

## 7 Key findings and policy relevant messages

According to our analysis, the cost of FT crude without CCS is 125–147 €/MWh$_{LHV}$ (35–41 €/GJ) depending on the plant capacity. This is 2–3 times higher than the current fossil transport fuel prices without taxes and duties. The cost would be decreased by 25–34 €/MWh$_{LHV}$ (7.0–9.4 €/GJ) if capital costs could be reduced by 30% and by 10–15 €/MWh$_{LHV}$ (2.8–4.2 €/GJ) if plant would also produce district heat.

Adapting CCS to FTL plants is straightforward as concentrated $CO_2$ is already separated from the process. This stream just needs to be compressed or liquefied for transport and storage. The transport and storage costs were found to be highly dependent on the transport chain capacities. The calculated costs were 35–66 €/t$CO_2$ for the plants located inland and 31–46 €/t$CO_2$ for the plants located at the port. The costs are at similar level to $CO_2$ capture costs from flue gases with post-combustion capture and they correspond to 14–29 €/MWh$_{LHV}$ (3.9–8.1 €/GJ) increase in the production costs of FT crude. Thus, even if a pure, concentrated stream of $CO_2$ is available from a process like in the case of FTL plants, the total costs of CCS can be high if the plant has an unfavourable location for transport and storage. Location comes more and more important the smaller the plant is because transport costs are highly dependent on the scale. Thus, creating a shared transport and storage infrastructure is crucial to lower the costs and enable CCS also for the smaller plants. Although the $CO_2$ transport and storage chains lead to significant cost differences, they had only a minor effect on the environmental performance of the whole FTL-CCS process.

Today, there are no commercial plants producing FT fuels from biomass. Results suggest, that should FT fuel plants be built, it would be favourable to equip them with CCS provided that negative $CO_2$ emissions can be credited and that sufficient $CO_2$ transport and storage infrastructure exists. The recognition of negative emission would improve the economics of FTL production and could speed up the commercial adoption of this technology. At the moment, the FT plants cannot benefit from providing negative $CO_2$ emissions through, for example, the EU Emission Trading Scheme (EU ETS) as the negative emissions are not yet recognized in the EU policy. If negative $CO_2$ emissions could be credited, the current EU emission allowance levels price level 50 €/t$CO_2$ (5/2021) would already make CCS feasible for most of the considered cases and would reduce production costs. For each 10 €/t of $CO_2$ credit, the production cost decreases by 4.4 €/MWh$_{LHV}$ (1.2 €/GJ).

Together with economic evaluation, the evaluated KPIs also provide significant insights that highlight the strengths and weaknesses of the FTL-CCS technology and the different stages in its system, from the production and gathering of forest residues to the transport and sequestration modes for the captured $CO_2$.

KPI-1, $CO_2$ removal efficiency

As observed in the results for KPI-1, all scenarios present almost identical carbon removal efficiencies regardless of their capacity or transport mode, indicating that the growth, harvest and transport of biomass and, most importantly, its processing in the FTL-CCS process are the main factors defining the total carbon removal efficiency. Therefore, efforts should be placed in these two sections of the system in order to improve its removal efficiency. On one hand, more efficient harvest and transport of biomass (e.g., through the promotion of electric vehicles for the gathering and transportation of residues) can have a minor although noticeable impact on the carbon removal efficiency. This may be particularly significant in processes located at greater distances from the biomass production centres. On the other hand, the overall removal efficiency can be mostly affected by improvements on the FTL-CCS system, such as the reduction in the consumption of utilities like process water or methanol, or by extending the application of carbon capture to all the emissions of the process and not just the major sources. While these modifications may improve the overall carbon removal efficiency, these may also require additional energy inputs to the process, which can counter the emission improvements depending on the carbon intensity of the mix used. For the Nordic scenario here considered, electricity mixes present a relatively low carbon intensity, favouring the application of extended carbon capture process to FTL and other process with direct emissions.

KPI-2, Avoided emissions

Compared to other negative emission technologies, BECCS processes such as the production of FT crude from biomass residues present the advantage of potentially further reducing emissions by producing cleaner energy as electricity and fuels. These products then can be used to replace their conventional energy counterparts, avoiding the emissions embodied in their production. Despite their benefits, the introduction of these products in their respective markets can cause unexpected negative effects, such as the increase in the average cost of energy and the increase in use of cheaper less environmentally friendly alternatives. Because of that, policies and economic incentives should be applied over the integration of these alternative cleaner products on their markets, ensuring the overall improvement of the environmental profile of energies without causing significant increases or variations in their cost, availability and demand to avoid causing a negative or even damaging response of both producers and consumers. In any case, carbon removal efficiency of processes such as the FTL-CCS system should be prioritised, as avoided emissions (production of electricity and fossil diesel) for the considered process only represent a relatively small contribution (0.058 tonne $CO_2$ avoided/tonne $CO_2$ sequestered by biomass) when compared to the net $CO_2$ removed by biomass growth (0.769 to 0.777 tonne $CO_2$ removed /tonne $CO_2$ sequestered by biomass).

KPI-3, Mid-point indicators

The results obtained for the different 16 mid-point indicators highlight the trade-offs among different environmental dimensions, such as the balance between climate change impact reduction and impacts over the land use, a compromise typically present in biomass utilisation systems. Unlike most biomass sources, the use of forest residues significantly improves these balances, as there is no dedicated use of water or application of fertilisers for their growth.

Furthermore, of the few midpoint indicators where biomass growth and transport represent a major contributor (e.g., photochemical ozone formation or use of mineral and metal resources), only the harvest and transport stages of biomass contribute to the system, and not so the growth and development of biomass resources. This highlights the benefits of using forest or other kinds of biomass residues as raw materials for BECCS technologies, indicating the necessity of a well preserved and managed forest and vegetation system from which obtain in a controlled manner much more globally beneficial biomass resources.

KPI-4, Levelised cost of stored $CO_2$

Together with all the economic analysis provided in the results section, the estimated levelised cost of stored $CO_2$ clearly indicates the better economic performance of larger capacity plants located as close as possible to the management and distribution centres of captured $CO_2$ (in this case the harbours from where it is shipped to its final storage). These characteristics correspond to scenario B3 which presented the lowest estimated levelised cost of stored $CO_2$ at 178 €/tonne of stored $CO_2$.

KPI-5 and KPI-6, Monetised end-point environmental impacts and Impact on human health

The results obtained for the monetised end-point environmental impacts and the impact on Human health, although different in nature, both indicate the overall beneficial impact of the considered FTL-CSS system on the environment and the society due to its carbon removal activity. These benefits are even more relevant when accounting for the avoidance of conventional fuels and electricity, reducing the estimate monetised cost of environmental externalities almost threefold when compared to the FTL-CCS system alone. Overall, these results highlight the sometimes overlooked benefits of BECCS technologies for their combined role of negative emission technologies and producers of cleaner energy products, obtaining objectively environmentally and socially better processes and products.

Policy relevant messages:

- It is crucial to evaluate the overall sustainability of BECCS technologies to avoid unwanted impacts and trade-offs e.g. related to land use. Residual feedstocks are often considered to have lower risks on climate and biodiversity, when harvested according to sustainable management practises. Here residual woody biomass was studied as the raw material for a Fischer–Tropsch liquid process combined with CCS. Dedicated energy feedstocks are studied in NEGEM work packages 3 and 7.
- Production cost of FT biofuels without CCS is around 2–3 times higher than the price of fossil fuels.
- Adopting CCS to the FTL process would improve the $CO_2$ balance markedly and at low cost. More than half of the input carbon ends up as nearly pure $CO_2$ stream that just need to be compressed or liquefied for transportation and storage.
- The transport and storage costs are an important part of cost of CCS and they are highly dependent on the transport chain capacities. Even if a pure, concentrated stream of $CO_2$ is available from a process, the total costs of CCS can be high if the plant has an unfavourable location for transport and storage. Location becomes more and more important the smaller the plant is because transport costs are highly dependent on the scale. Thus, creating a shared transport and storage infrastructure is crucial to lower the costs and enable CCS also for the smaller plants.
- Although the $CO_2$ transport and storage chains lead to significant cost differences, they had only a minor effect on the environmental performance of the whole FTL-CCS process.
- At the moment there are no commercial plants producing FT fuels from biomass. Results suggest, that should such plants be built, it would be favourable to equip them with CCS provided that negative $CO_2$ emissions can be credited, and that sufficient $CO_2$ transport and storage infrastructure exists. The recognition of negative emission would improve the economics of FTL production and could speed up the commercial adoption of this technology.
- The main part of the environmental KPIs studied showed positive results for FTL-CCS process.
- Avoided electricity and fuel products represent a significant advantage over other BECCS technologies and NETPs, and should be promoted without causing instabilities in their respective markets that may cause a response opposite to the desired one.

# 8 Further steps

The study presented in this deliverable sets a framework that enables analysing varying BECCS technologies and enables comparison with other NETPs. For example, the selection of the functional unit or the LCA analysis has been made to enable comparison with other NETPs. Other NETPs are studied in NEGEM deliverables 1.2, 1.3 and 1.5 with similar methods.

The results of this study will be used in further NEGEM research, e.g. in WP7 and WP8 NEGEM scenario modelling activities.

For preparing this report, the following deliverable/s have been taken into consideration:

| D# | Deliverable title | Lead Beneficiary | Type | Dissemination level | Due date (in MM) |
|---|---|---|---|---|---|
| D1.1 | Justification of NETPs chosen for the NEGEM project | ETH | R | CO | M6 |
| D8.1 | Stocktaking of scenarios with negative emission technologies and practices - Documentation of the vision making process and initial NEGEM vision | VTT | R | P | M8 |

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# Appendix A - Properties of the biomass

*Table A1. Properties of the woody biomass used in the Aspen model*

| | Value | Source |
|---|---|---|
| Proximate analysis, wt%, dry basis | | Hannula&Melin (2020) |
| Fixed carbon | 25.3 | |
| Volatile matter | 70.8 | |
| Ash content | 3.9 | |
| Ultimate analysis, wt%, dry basis | | |
| C | 53.2 | |
| H | 5.5 | |
| N | 0.3 | |
| S | 0.04 | |
| O (as difference) | 37.06 | |
| Ash | 3.9 | |
| | | |
| Lower heating value (LHV), MJ/kg, dry basis | 19.34 | |
| Moisture content, wt%, as received | 50% | |
| Lower heating value (LHV), MJ/kg as received | 8.45 | |

# Appendix B - Electricity and steam balances for 1000 bbl/d (petrol equivalent) FTL plant without CCS

*Table A2. Electricity balance for a 1000 bbl/d (petrol equivalent) FTL plant when is $CO_2$ vented into the atmosphere*

| | Value | Source |
|---|---|---|
| Electricity demand, MW | -12.5 | Aspen Plus simulation model used in Hannula&Melin (2020) |
| Oxygen production&compression | -4.2 | |
| Feedstock drying&feeding | -1.0 | |
| Syngas compression | -4.8 | |
| Acid gas removal | -1.0 | |
| Synthesis | -0.3 | |
| Power island | -0.4 | |
| Misc | -0.7 | |
| Gross production, MW | 15.9 | |
| Steam turbine (back pressure) | 11.5 | |
| Condensing tail | 4.4 | |
| | | |
| Balance, MW | 3.4* | |

*in CHP mode (=without condensing tail) plant would require 1 MW of electricity from the grid

*Table A3. Steam balance for a 1000 bbl/d (petrol equivalent) FTL plant*

| | Value | Source |
|---|---|---|
| On-site consumption, kg/s | 8.2 | Aspen Plus simulation used in Hannula&Melin (2020) |
| Gasifier | 2.9 | |
| Reformer | 0.9 | |
| WGS | 0.6 | |
| AGR solvent regeneration | 1.2 | |
| Deaerator | 1.2 | |
| HP feedwater pre-heater | 1.5 | |
| Turbine extractions, kg/s | 2.7 | |
| HP steam (25 bar / 333 °C) | 1.5 | |
| IP steam (5 bar / 179 °C) | 1.2 | |
| Gross production, kg/s | 23.4 | |
| Gasification plant (93.5 bar / 500 °C) | 9.2 | |
| Auxiliary boiler (93.5 bar / 500 °C) | 6.9 | |
| Admission steam (14 bar / 195 °C, saturated) | 7.3 | |