Chemical **L**ooping G**a**sification fo**r** Sustain**a**ble Production of Biofuels

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1. Introduction

This report provides the main results of the techno-economic analysis for the biomass-to-liquid plant investigated in the CLARA project, starting from biomass gasification to Fischer-Tropsch liquid fuel synthesis, as detailed in deliverable D1.2 [1].

The aim of the CLARA project is to develop and demonstrate a concept for the synthesis of liquid biofuels using the chemical looping gasification technique for the conversion of biogenic materials into biofuels. The project considers the complete biomass to fuel supply chain, i.e., biomass pre-treatment, chemical looping gasification, syngas cleaning and the fuel synthesis. According to the CLARA concept, waste biomass is pre-treated at the different decentralised locations and then transported to the centralised fuel synthesis plant. In the fuel synthesis plant the biomass is gasified in a CLG system having a scale of 200 MWth input. The scale of CLG is chosen as it was deemed the smallest scale to be economical and in-line with estimated biomass waste resource availability [2], [3].

The costs associated with transport and biomass processing (drying, pelletization and additive addition for the waste biomass feedstocks) for the chemical looping gasification unit were calculated and detailed in the Deliverable D7.1 report [4]. The average computed costs of €110.2 per tonne for pine forest residue and €67.9 per tonne for wheat straw pellets are used as input for the economic analysis presented in this report.

The analysis excludes subsequent fuel upgrading into transport fuels, per the project consortium agreement, assuming that fuel upgrading would be more economically advantageous if performed in large scale traditional oil refineries.

The technical modelling (mass and energy balance), previously reported in Deliverable D1.3 was replicated in ECLIPSE to be consistent with the models generated in ASPEN PLUS™ [1]. The technical modelling was repeated in ECLIPSE due to the software's ability to carry out a capital cost estimation and economic analysis using the results of the mass and energy balances.

The total project capital cost was estimated, along with operating and maintenance costs. The detailed cost estimation, including the cost of main components and installation was described in detail in Deliverable 7.2 and is briefly summarised in this report [5]. The operating and maintenance costs have also been reported in Deliverable 7.2 and are further discussed in the following section.

The reported costs are in 2020 EUROs and the economic analysis does not include any license fees for use of proprietary technology.

2. Techno-economic assessment study

The aim of the current study is to provide an economic analysis of the CLARA biomass-to-liquid plant based on the net present value concept.

The following steps were taken to produce this report:

- the mass and energy balance (technological models) were established in ECLIPSE for the two biomass scenarios: a. pelletised forest residue (PFR) and b. wheat straw (WS)
- the capital investment for individual components and equipment was then estimated using the specifications and operating conditions reported in Deliverable D1.3, while the calculation procedure and results were detailed in Deliverable D7.2 [1], [5].

- the individual equipment cost was further expanded by considering additional costs for installation and integration (piping, valves, instrumentation, and civil work), also detailed in Deliverable D7.2 [5]
- the fixed and variable operating costs are determined using the economic assumptions presented in Table 1.

Following these steps, the capital cost of the CLARA plant, the individual input streams and operation and maintenance (O&M) costs are used to calculate the annual cash flow and the breakeven selling price of fuels yielded for the two biomass resources considered in the report. Finally, a sensitivity analysis is carried out to investigate the effect of the most dominant parameters (electrical energy cost, feedstock price, plant capital investments and plant capacity factors) on the economic sustainability of the fuel synthesis facility.

2.1. Economic boundary conditions

The main economic assumptions and relevant conditions used in the techno-economic assessment are presented in Table 1.

Table 1. Economic boundary conditions

	Min.	**Baseline**	**Max.**	
Plant operating hours	6400	8000		hours
Discounted cash flow rate	4	6	8	%
Interest rate and other financing charges (during the construction period)		4		%
Construction period		3		years
Tax rate		0		%
Contingencies	10	15	20	% (EPC)
Working capital		5		% (EPC)
Commissioning cost		5		% (EPC)
Project life	20	25	30	years
Pelletised forest residues (PFR)	88.5	110.2	130.6	€/tonne
Wheat straw (WS)	64.7	76.9	86.6	€/tonne
Payment schedule				
Year 1		15		%
Year 2		50		%
Year 3		35		%
Average electricity price (business)	60	80	130	€/MWh
Plant salvage value		NO		
Insurance		1.5		% TCI
Maintenance		3.5		% TCI

The variations from the default values listed under the minimum and maximum columns in Table 1 are considered for the sensitivity analysis.

The labour requirements considered as part of the operation and maintenance (O&M) costs are presented in Table 2, resulting in an annual labour cost of €3.94 million.

Table 2. Labour cost assumptions

Labour cost (Technical personnel)	60,000	€/year
Number per shift	11	
Number of shifts	5[*]	
Total number of technical staff	55	
Labour cost (Admin personnel)	40,000	€/year
Number per shift	8	
Number of shifts	2	
Total number of admin. staff	16	

[*] Operating labour is assumed to work in a five shift pattern.

The raw material inputs and associated costs, together with the fees for waste disposal are presented in Table 3.

Table 3. Unit costs for the plant consumables

Material input/output	Unit price (€/tonne)
Fresh water	2
MDEA	1,500
Oxygen carrier (ilmenite)	300
Water-Gas Shift catalyst	16,000
Fischer-Tropsch catalyst	35,000
Wastewater discharge	4
Ash disposal	25

2.2. Technical results

The main technical results for simulation of the 200 MWth BTL plant using pelletised forest residue and wheat straw are summarised in Table 4. These results are extracted from the ECLIPSE simulation (i.e., a mass and energy balance) and compared against the ASPEN PLUS^{TM} simulation results, as presented in Deliverable D1.3. It should be mentioned that we assume that no design modifications are required for the two feedstock conversion scenarios, despite different characteristics of the pine residue and wheat straw pellets during the gasification process.

Table 4. Simulation results used for the estimation of operating costs

Material Stream	PFR	WS	Unit
Inputs			
Feedstock supply	40.07	41.94	tonne/hr
Oxygen carrier (make-up)	1.8	1.8	tonne/hr
Electricity	11.3	11.1	MWh/hr
Fresh water	86.8	86.4	tonne/hr
MDEA solvent	0.18	0.17	tonne/hr
Waste treatment			
Wastewater	64.9	64.5	tonne/hr
Solid residue disposal	2.3	5.3	tonne/hr
CO_2 capture			
Separated CO_2	31.7	32.1	tonne/hr
Raw FT products			
FT Naphtha fraction	2.718	2.479	m^3/hr
FT Middle distillate fraction	2.340	2.140	m^3/hr
FT wax	4.003	3.654	tonne/hr

It can be seen from Table 4 that with the PFR pellet the feedstock input is 40.07 tonne/hour and the raw naphtha, distillate and FT wax are 2.72 Nm^3/hour, 2.34 Nm^3/hour and 4.00 tonne/hour, respectively. When the WS pellet is used, with the same thermal input, the feedstock input is 41.94 tonne/hour, which is slightly higher than the PFR case. The raw naphtha, distillate and FT wax are 2.48 Nm^3/hour, 2.14 Nm^3/hour and 3.65 tonne/hour, respectively. The mass and energy balance shows that the consumption of catalysts, grid electricity and water is similar for both PFR and WS cases.

The simulation results also indicate that the use of PFR leads to an approximate 10% increase in FT products' yield, compared to the WS case.

2.3. Capital investment

The following main process units are modelled using the ECLIPSE process simulator:

- Chemical looping gasification system: composed of coupled fuel (where biomass is gasified) and air (in which the solid oxygen carrier is re-oxidised) reactor system, cyclones, ash handling system and a combustion air blower.
- Syngas cleaning and composition adjustment unit, including a raw gas cooling and water scrubbing system together with a syngas compression unit, a tar removal unit, and the partial water gas shift (WGS) reaction system.
- Acid gas removal system, a novel methyl diethanolamine (MDEA) based system, proposed, and demonstrated to reduce capital cost investment and energy expenditure in the CLARA concept plant

- Fischer- Tropsch (FT) synthesis unit, which includes a steam methane reforming unit

The calculation procedure is detailed in Deliverable 7.2, together with a comparison with other similar cost estimates for biomass gasification plants found in literature [6], [7]. The main equipment required for each of the main process units are listed, together with their corresponding cost, determined depending on the equipment type and size.

The total cost for the main process units, is illustrated in Table 5. This estimate also includes the integration cost, estimated as a percentage of the sum of all process equipment installed. The accuracy of the capital cost is estimated between ± 25 to 30 % [8]. It should be stressed that the total installed cost of the plant will be strongly dependent on aspects such as the location, the type of control system and the selection of service facilities.

Table 5. Total installed cost estimates for main process components of the CLARA plant

Main Process Units	**Installed Cost (€)**
Chemical Looping Gasification	68,619,778
Syngas Cleaning Unit + WGS unit	34,784,059
Acid Gas Removal Unit	40,209,784
Fischer-Tropsch Synthesis	49,932,803
Total installed cost	**193,546,424**
Buildings & other facilities	9,870,000
Total engineering, procurement and construction	**203,416,424**
Total capital cost (incl. working capital and fees)	**223,757,600**
Total capital investment (incl. contingency)	**254,270,650**
Total project investment (incl. interest charges)	**272,966,370**

The results show that the total installed cost of the BTL plant is €203.42 million, including buildings and other facilities. Considering the working capital, capital fees and commissioning cost, the total capital cost (TCC) of the plant is increased to €223.76 million. Further considering the construction, commissioning time and contingencies, the total capital investment increases to €254.27 million. Adding the loan repayment, the total project investment increases to €272.97 million.

2.4. Estimation of operating and maintenance costs for the BTL plant

The annual plant operating costs (including raw materials, utilities, waste disposal, labour, maintenance and repair, insurance, etc.) are computed using the assumptions highlighted in Tables 1-3 and the simulation results presented in Table 4.

As highlighted in Table 1, in this study, the expected availability of the plant is 8000 hours during the operational years. Catalysts are assumed to be replaced every 3 years and, as such, catalyst costs are computed for a three-year period. The full annual costs of plant operation and maintenance for the proposed CLARA configuration are shown in Table 6.

Table 6. Annual O&M costs for the BTL plant

Feedstock type	Forest Pine Residue	Wheat Straw
Feedstock supply	€35,324,087	€25,800,301
Electricity	€7,231,667	€7,103,673
Water	€1,388,736	€1,382,336
Wastewater treatment	€2,076,704	€2,063,905
Solid waste disposal	€459,979	€1,059,951
Catalyst	€ 900,000	€ 900,000
Oxygen Carrier	€4,319,801	€4,319,801
MDEA solvent	€2,159,901	€2,039,906
Maintenance and repair	€7,117,370	€7,117,370
Operating labour cost	€3,944,160	€3,944,160
Plant insurance	€3,198,630	€3,198,630
Total O&M costs	**€68,121,036**	**€58,930,034**

2.5. Economic assessment results

Net Present value calculations were carried out to determine the break-even selling price (BESP) of produced FT products using the discounted cash flow analysis. Figures 1 and 2 illustrate the cost breakdown structure of BESP for the PFR and WS scenarios, where the consumables include costs of electricity, catalysts, solvents and waste disposal, while O&M costs refer to labour, maintenance and repair and insurance annual costs.

For the PFR scenario the total capital cost is estimated at €272.97M. If a PFR pellet cost of €110.2/tonne is assumed the annual cost of PFR pellets and other raw materials, such as the oxygen carrier and solvents is €53.86M, and the annual operating and maintenance costs (O&M) are €14.26M. For the plant to have a zero net present value over the project lifetime a break-even selling price (BESP) of €816/m^3 (raw syncrude) is required, which produces an annual income of €79.01M (including the FT wax sale).

For the WS scenario the total capital cost is estimated at €272.97M. If a WS pellet cost of €76.9/tonne is assumed the annual cost of PFR pellets and other raw materials, such as the oxygen carrier and solvents is €44.67M, and the annual O&M costs are €14.26M. For the plant to have a zero NPV over the project lifetime a BESP of €781/m^3 (raw syncrude) is required, which produces an annual income of €69.77M (including the FT wax sale). It is noted that the two BESP figures are based on an FT wax selling price of €1800/tonne. Comparing results with the project target (the projected fuel production cost is €700/m^3) we can see that the two BESPs are around 16% and 12% higher than the target price. However, the economics of plant performance can meet the target when the sale of by-products and carbon credits are considered during the assessment (see Chapter 3.9).

A breakdown of individual cost components of the two scenarios is given in Figures 1 and 2. Between the two scenarios, both feedstock charges and CAPEX dominate production cost of raw liquids generated, in comparison with other items. On the other hand, the income from FT wax sales which has a strong influence on cash flow, offsets the BESP significantly. A slightly lower BESP is found for the scenario using the WS pellets. This is because the WS price is lower than the PFR price.

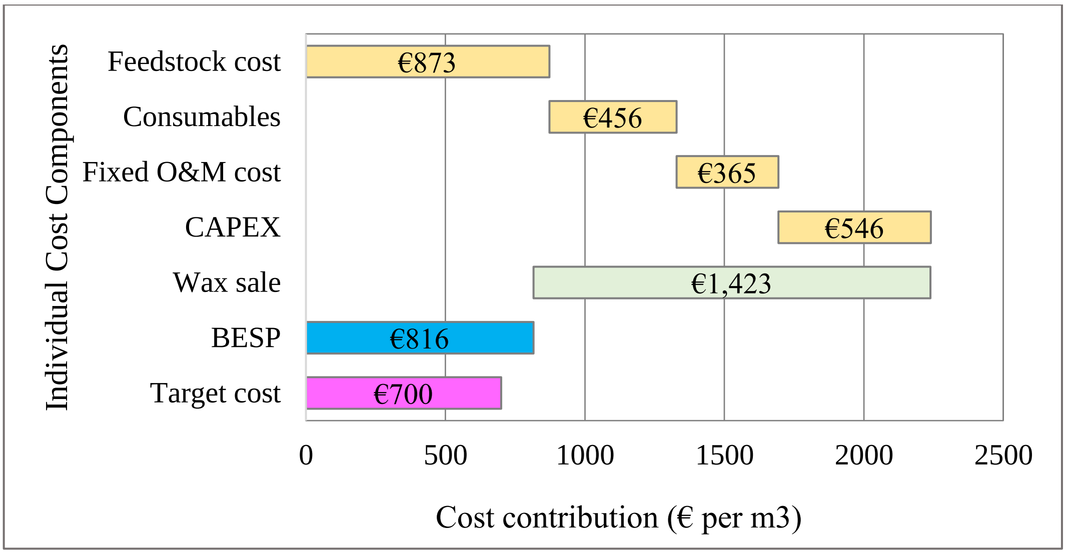

Figure 1 Contribution of cost components to the BESP of the raw FT fuel for the PFR scenario

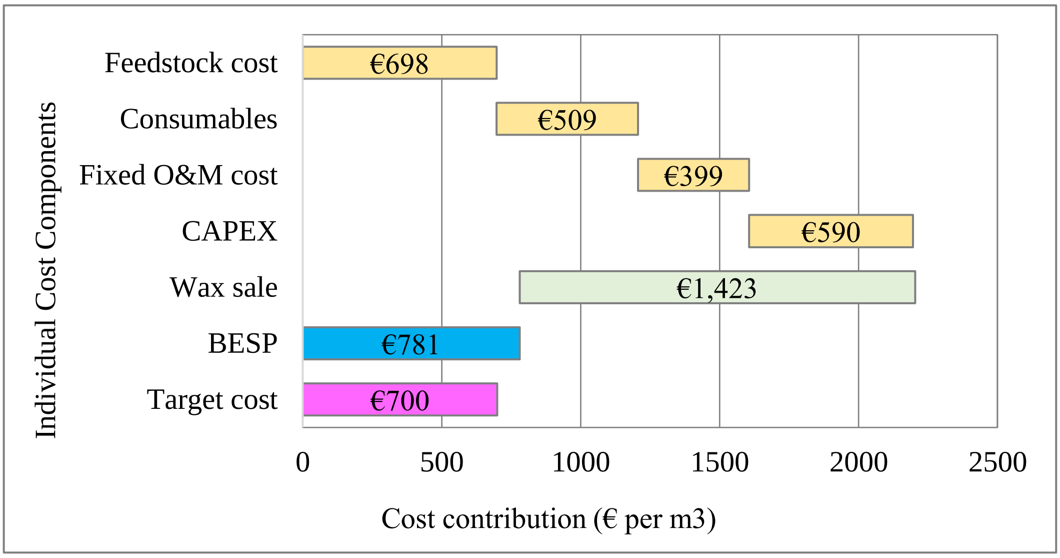

Figure 2 Contribution of cost components to the BESP of the raw FT fuel for the WS scenario

2.5.1. Influence of gas cleaning options on the BESP (MDEA vs. Rectisol)

As presented in Deliverable report 7.2, the total installed cost of the CLARA plant using the Rectisol configuration for syngas cleaning is estimated at €232.41 million. Considering the same economic condition as presented in previous chapters, the total project investment increases to €311.86 million. For comparison, the total project investment for the CLARA plant using the amine-based acid gas cleaning option was estimated at €272.96 million. The labour costs for each plant configuration are assumed equal, as are most operating costs (e.g., feedstocks, oxygen carriers and waste disposal), while the maintenance and insurance costs are increased in line with the increase in total capital investment.

Regarding the O&M cost associated with the energy consumption and solvent use there are some differences between the two scenarios. The Rectisol process uses methanol as a solution, which is a cheaper solvent than MDEA (the methanol market price is assumed €450/tonne [9] and the MDEA price is around €1500/tonne), resulting in lower operating costs. However, the methanol solution needs to be refrigerated during operation, the consumption of electricity in the Rectisol system is higher than in the MDEA system. For example, in the WS scenario the estimated electricity consumption is around 13.2 MWh/hr, while in the PFR scenario the consumption is 13.4 MWh/hr (compared to 11.1 MWh/hr and 11.3 MWh/hr, respectively in the MDEA configurations) [2].

The results from the Rectisol gas cleaning technology are presented in Figure 3. Compared with MDEA based gas cleaning, Rectisol based gas cleaning increases BESP from €816 to 925/m^3 for the PFR derived raw liquid fuel and from €781 to 901/m^3 for the WS derived raw liquid fuel. This gives an increase in BESP up to 15%.

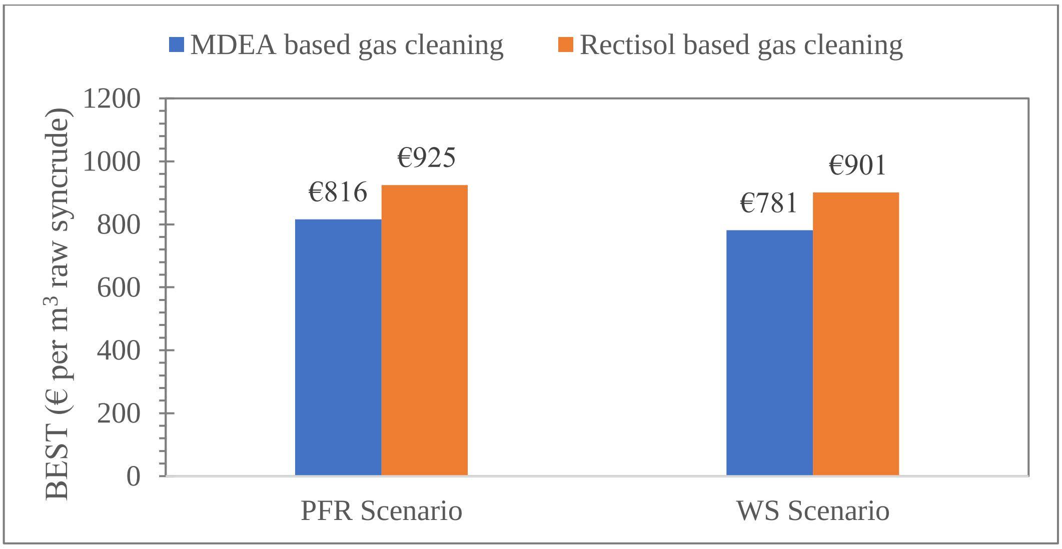

Figure 3 BESP vs Gas Cleaning Method for CLARA concept

3. Economic sensitivity analysis

A sensitivity analysis for the major economic parameters was performed to investigate the impact of several important economic attributes on the overall viability of the CLARA project and the competitiveness of the FT fuels in the synthesis fuel market.

The sensitivity parameters selected for the study include the plant total installed cost, plant availability, biomass feedstock price, electricity price, project lifetime, discounted cash flow rate, contingency value, and wax selling price.

3.1. Sensitivity of BESP to plant total installed cost

The total installed cost of the CLARA plant was estimated at €203.4 million, with a ±30% uncertainty. The sensitivity analysis investigates the influence of the corresponding ±30% variation in the total installed cost of the plant (from €145.36 to €261.4 million) on the BESP values (Figure 4).

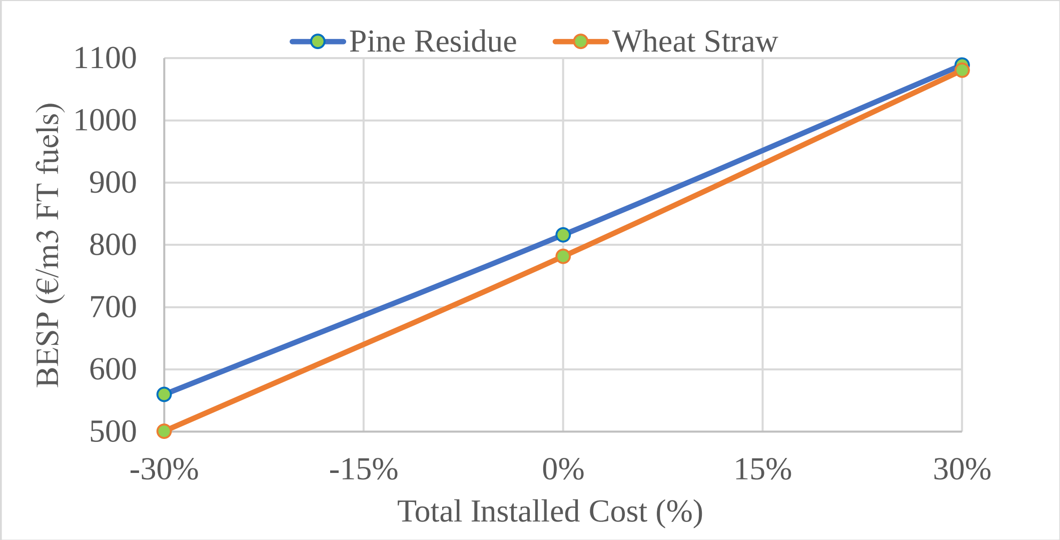

Figure 4 BESP vs. total installed cost for the CLARA concept BTL plant

The results show that the total installed cost has a major influence on the BESP of FT biofuels: the +30% variation in plant total installed cost leads to a +33.4% increase in the BESP for the pine forest residue case (up to €1089 per m^3 FT distillate and naphtha blend) and a +38.3% increase in BESP for the wheat straw case (to €1080 per m^3). The 30% decrease for the plant cost leads to a 31.4% decrease in FT biofuels' price in the pine forest residue case and a 36% decrease for the wheat straw derived fuels.

3.2. Sensitivity of BESP to biomass price

Figure 5 shows the BESP deviation if the biomass feedstock price is varied within the uncertainty ranges specified in the Deliverable D7.1 for wheat straw and pine forest residue [4].

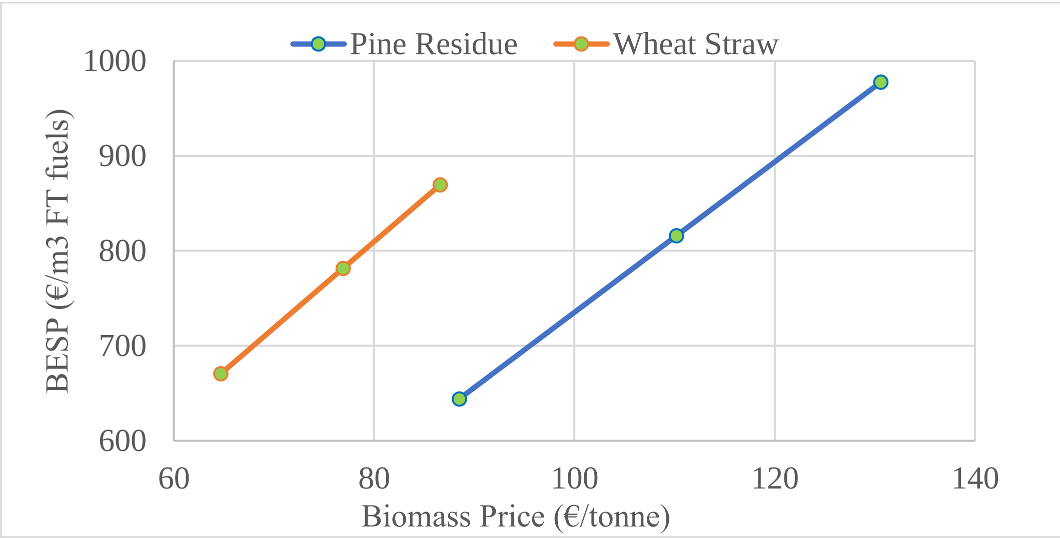

Figure 5 BESP vs. biomass price for the CLARA concept BTL plant

The FT fuels' BESP shows one of the greatest sensitivities to biomass price variations for the case of the pine forest residue: the lower limit biomass price represents a -19.7% variation from the base case, which leads to a 21% decrease in the BESP for the FT liquid fuels. The upper limit represents a 18.5% increase in feedstock price and results in a 19.8% increase in the raw FT products' BESP.

Comparatively, the BESP for the wheat straw pellets is less sensitive to feedstock price variations, ranging between €651.25 to €849 per m^3 of FT fuels. In fact, the 15.9% decrease in biomass price (from €76.9 to €64.7 per tonne) leads to a 14.2% decrease in BESP and a 12.6% increase in biomass price (from €76.9 to €86.6 per tonne) results in a corresponding 11.3% increase in FT crude's BESP.

3.3. Sensitivity of BESP to plant availability

The next important factor analysed was the plant availability, assuming that in the default scenario the plant was fully operational 8000 hours per year. Figure 6 illustrates the impact of plant availability on BESP of FT fuels for the two analysed scenarios.

Figure 6 BESP versus Plant Availability for the CLARA concept BTL plant

The results indicate that when plant availability is reduced to 6400 hours (20% decrease), the BESP for the PFR scenario will increase by 26.6% while the BESP for the WS scenario will increase by 30.4% compared to the default value.

3.4. Sensitivity of BESP to electricity cost

The cost of electricity is the smallest contributor to the BESP of FT fuels in the base case scenarios presented in the previous section. This can be explained as the use of the chemical looping gasification system and the MDEA based Acid Gas Removal unit reduces the electricity consumption of the plant.

The influence of the cost of electricity on the BESP for FT fuels is shown in Figure 7, assuming a minimum price of electricity of €60/MWh (which is the case in countries such as Sweden, Finland) and a maximum of €130/MWh (in Austria, Belgium) [10].

While the average EU/EEA electricity price for non-domestic consumers is €110/MWh (Spain, Portugal, the Netherlands), the baseline value chosen in our study for the price of electricity is €80/MWh, corresponding to prices reported in Norway and Denmark.

Using the selected boundary values for the price of electricity, the BESP for the FT fuels ranges between €771 and €928 per m^3 for the pine forest residue case and between €733 and €902 per m^3 for the wheat straw case.

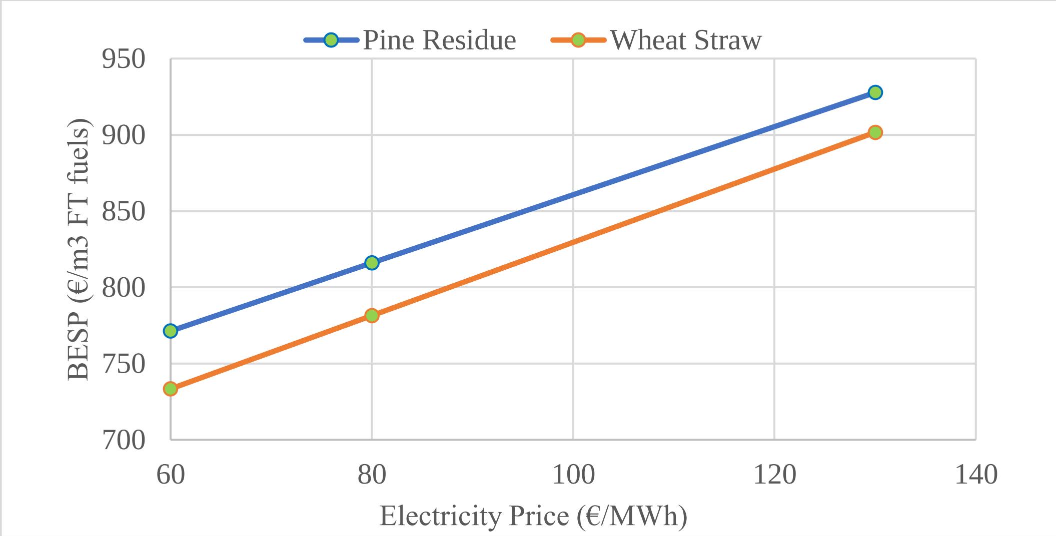

Figure 7 BESP vs. electricity price for the CLARA concept BTL plant

3.5. Sensitivity of BESP to plant lifetime

The influence of the plant operational lifespan on the BESP is presented in Figure 8, as this parameter is varied between 20 and 30 years, corresponding to a ±20% variation from the baseline plant lifetime of 25 years.

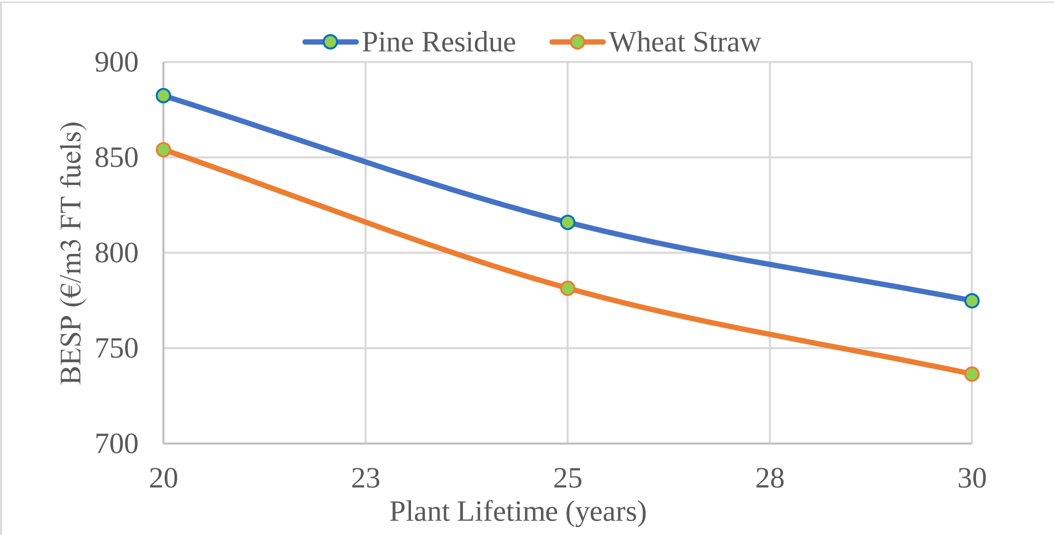

Figure 8 BESP vs. plant lifetime for the CLARA concept BTL plant

If the project life is extended to 30 years, this will lead to a reduction in the synthetic fuels BESP by 5% in the case of PFR and 5.8% in the case of WS, to values of €760 and €718 per m^3, respectively. Shortening the project lifespan to 20 years, the fuel BESP for the PFR scenario will increase by 8.1% (to €882 per m^3) and by 9.3% for the WS (to €854 per m^3).

3.6. Sensitivity of BESP to the discounted cash flow (DCF) rate

The influence of the DCF rate on the BESP is presented in Figure 9, as DCF is varied between 4 and 8% of the total capital cost of the biomass plant, corresponding to a ±33% variation from the baseline DCF rate, representing 6% of the Total Capital Cost. The BESP values varies between €712 and €930 per m^3 for the PFR case and between €668 and €906 per m^3 for the WS case.

The price of the wheat straw derived FT fuels is more sensitive to DCF rate variations, registering a 14.7% decrease and a 16% increase corresponding to the ±33% variation in DCF rates.

Comparatively, the BESP for the pine residue case varies by -12.7% (for 4% DCF rate) and by +14% (for 8% DCF rate) from the baseline value of €816 per m^3 of FT fuels.

Figure 9 BESP versus the DCF for the CLARA concept BTL plant

3.7. Sensitivity of BESP to the value of contingency

The influence of the contingency value on the BESP is presented in Figure 10, for a ±33% variation of the contingency (between 10 and 20% EPC).

Figure 10 reveals a low sensitivity of the BESP to this economic parameter, with the ±33% variation in contingency value registering a corresponding variation of only ±2.7% for the PFR case and ±3.1% for the WS case, respectively.

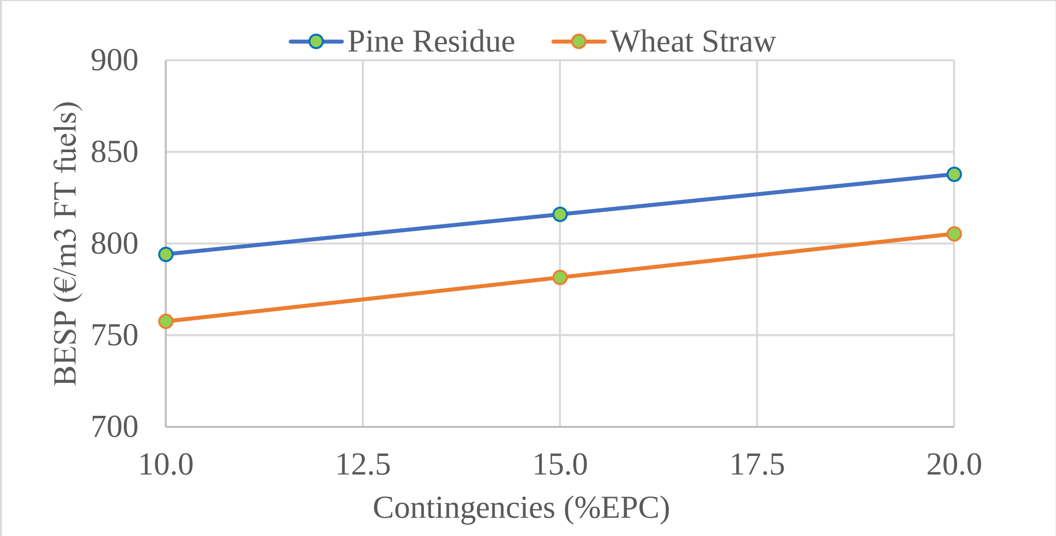

Figure 10 BESP vs. Contingency value for the CLARA concept BTL plant

3.8. Sensitivity of BESP to wax selling price

The wax selling is one of the main contributors to the final BESP and, as a result, we expect the BESP to have a high sensitivity to variations in the wax selling price.

For the sensitivity analysis, we varied the wax selling price ±11.1% from the default value of €1800/tonne. The results (Figure 11) show that the wax price is the most important economic parameter influencing the BESP value, as the ±11.1% variation produces a ±19.4% deviation in the pine forest residue case and a ±20.2% in the wheat straw case.

Figure 11 BESP vs. wax selling price for the CLARA concept BTL plant

3.9. Influence of by-products sales and CCS on production costs of FT products

The baseline case of the techno-economic analysis presented in this report does not consider indirect revenue, obtained from selling waste heat or from carbon credits, when the separated CO_2 from the AGR system would be further purified, compressed and stored.

3.9.1. Waste heat recovery

The CLARA BTL plant produces low- and medium-pressure excess steam that is classed as 'low grade' heat, with a flowrate of 28.9 tonne/h (for both scenarios considered). In order to valorise this excess steam, the CLARA plant should be located in close vicinity to another processing facility that has a net heat requirement, such as a kraft mill or an oil refinery [11], [12]. The latter would be also beneficial from the syncrude refining perspective, eliminating the transportation need for the syncrude produced. To estimate the impact of including this indirect revenue stream in the economic analysis on the BESP of FT fuels, we assume that the recovered waste heat from the plant can be sold at prices ranging from €5 to 15/GJ [13]. The simulation results show that the quantity of steam generated is 17.0 MWh/h or 61.2 GJ/h (at 30 bars, 300°C). Table 7 presents the resulting BESP values for the two scenarios.

Table 7. the impact of waste heat recovery on the BESP of FT liquids

	PFR Scenario	WS Scenario
BESP (if average heat price is €0/GJ) (baseline)	€816 per m^3	€781 per m^3
BESP (if average heat price is €5/GJ)	€756 per m^3	€715 per m^3
BESP (if average heat price is €10/GJ)	€695 per m^3	€649 per m^3
BESP (if average heat price is €15/GJ)	€635 per m^3	€583 per m^3

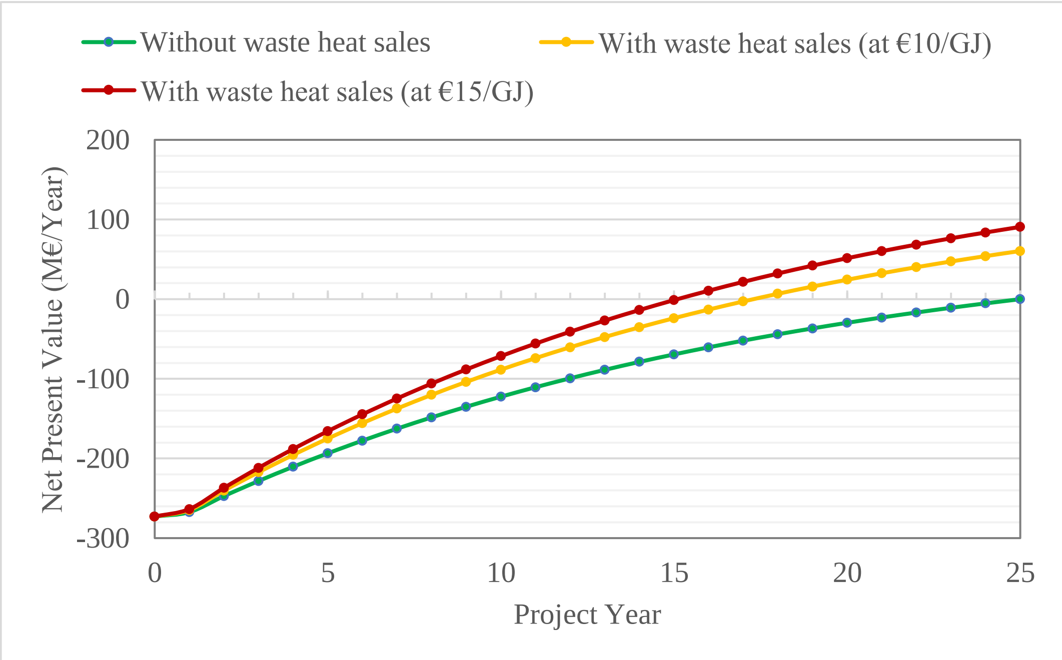

Figure 12 Influence of waste heat sales on the net present value of FT fuels for PFR

Figure 12 illustrates the influence of waste heat selling prices on the net present value of FT fuels when feeding pelletised pine forest residues. A similar trend can also be observed when using the pelletised wheat straw as the feedstock. Clearly, increasing income from by-product sales improves the profitability of biofuel production, shortening the simple payback period from 21.7 (without waste heat selling) to 13.7 years.

3.9.2. CO_2 taxes and credits

In recent years, many countries in Europe have taken measures to reduce carbon emissions, including instituting environmental regulations, EU Emissions Trading System, and carbon taxes [14]. If we introduce carbon taxes and carbon credits, these could make biofuel production profitable in the short term. As a feedstock in the biofuel production process, biomass is used to produce liquid fuels. Therefore, biomass would be exempt from paying carbon tax for fuel that is not combusted.

Generally, if grown in a sustainable manor, the use of biomass for biofuel production is considered to produce no net CO_2 emissions in its life cycle. When biomass CLG based FT synthesis process integrated with carbon capture is generally hailed as the prominent option for producing carbon negative fuels [15], [16]. Regarding the baseline of the CLARA project, the design and capital cost estimation did not include facilities for handling CO_2 compression and transportation. As a result, additional capital investment and operating and maintenance cost will be incurred when the negative CO_2 emission option is considered.

The ECLIPSE simulation package was used to estimate the cost of CO_2 capture and compression units for the CLARA BTL project. The total installed cost of the CCS plant is about €10 million. It is noted that the CO_2 capture cost refers to biofuel production with CO_2 capture facilities without pipeline and storage provisions in this study. This is because the capital investment cost of a pipeline installation, booster stations and CO_2 storage depends strongly on topography and socio-economic factors which is out of scope. However for the CCS plant, it is assumed that the operating and maintenance costs associated with CO_2 transport are about €6/tonneCO_2.

To better illustrate the impact of a carbon tax on the economics of biofuel production, we investigate the following scenarios:

Case 1: Biomass is not recognised as carbon neutral and biogenic CO_2 emissions have no carbon tax relief for biofuel production; the BTL plant is not fitted with CCS; no income from excess heat sales.

Case 2: Biomass is recognised as carbon neutral and biogenic CO_2 emissions have a carbon tax exemption for biofuel production; the BTL plant is not fitted with CCS; no income from excess heat sales.

Case 3: Biomass is recognised as carbon neutral; the BTL plant is fitted with CCS; no income from excess heat sales.

Case 4: Biomass is recognised as carbon neutral; the BTL plant is equipped with CCS; added income from excess heat sales (€10/GJ).

Table *7* Carbon dioxide balance over the CLG based FT bio-fuel production

	PFR Scenario	WS Scenario
Direct CO_2 input from feedstocks (tonne/h)	70.9	70.7
Indirect CO_2 emissions derived from grid electricity (tonne/h) [*] (without CCS)	3.1	3.1
Indirect CO_2 emissions derived from grid electricity (tonne/h) (with CCS)	3.8	3.8
CO_2 captured (tonne/h) [**]	31.7	32.1
$CO_{2\ eq.}$ to FT products (tonne/h)	23.0	22.5
CO_2 emissions from the SMR (tonne/h)	7.1	7.1
The rest of CO_2 (tonne/h)	9.1	9.1

[*] Regarding indirect CO_2 emissions associated with the purchase of grid electricity we assume that average CO_2 intensity in the EU is about 0.275 tonne CO_2/MWh.

[**] For Cases 3 and 4, the amount of CO_2 emitted from biogenic sources is captured and stored. Therefore the carbon credits for negative CO_2 emissions are given. The value of these negative CO_2 emission credits is assumed to be proportional to the carbon tax charged.

Figures 13 and 14 illustrate the sensitivity of the BESP of FT products using feedstocks of pine forest residue and wheat straw pellets to the CO_2 emissions' tax. Notably the impact of CO_2 emission tax on the BESP of FT products is significant when biogenic CO_2 emissions would not be considered as carbon neutral (Case 1). However, when biomass is given carbon tax exemption this influence tends to be negligible (Case 2). When the plant is fitted with CCS (i.e., negative CO_2 emissions), raising a carbon price on CO_2 emissions will reduce the cost of biofuel production, improving the economic performance of the FT plant greatly (Case 3). Furthermore if the recovered waste heat is sold to local businesses or communities the BESP will be further decreased (Case 4). It is also found that for the PFR scenario with CCS the required carbon price is much higher than that for the WS scenario to achieve the target for the CLARA project. This reflects that using wheat straw pellets is more economically advantageous compared to pine forest residues.

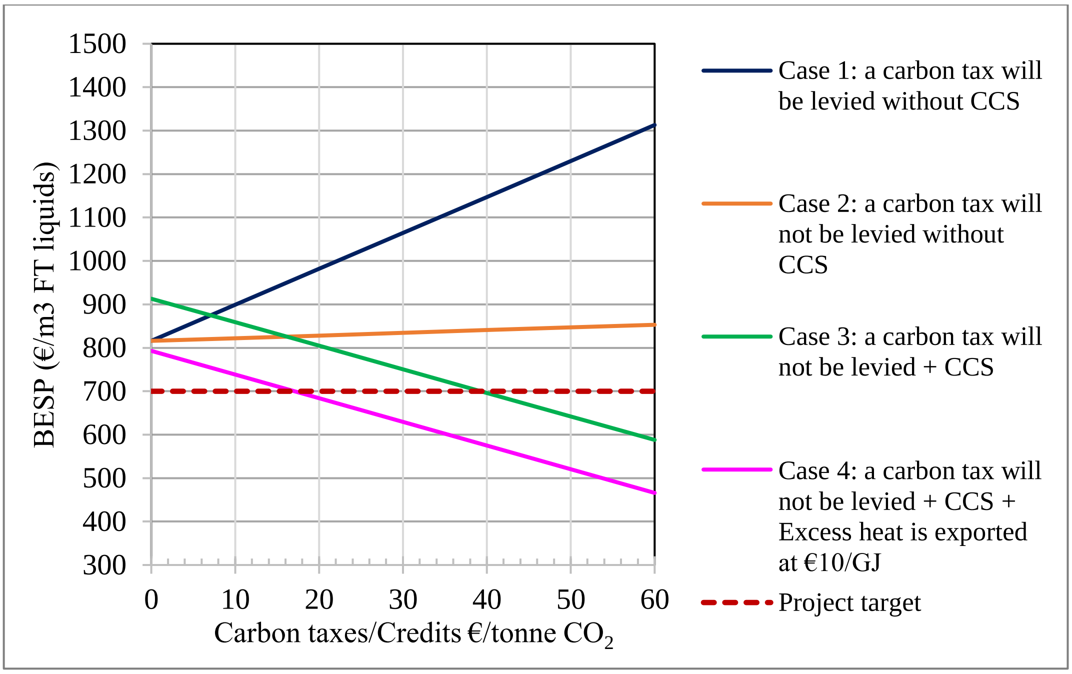

Figure 13 Impact of CO_2 tax/credits on BESP of FT fuels for the PFR scenario

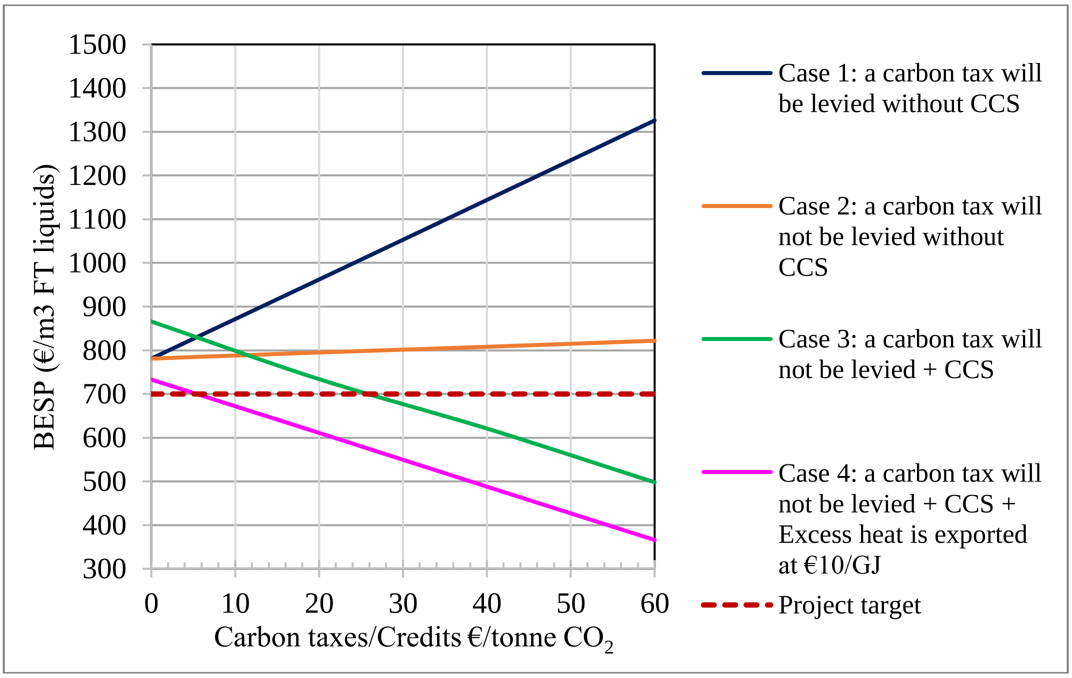

Figure 14 Impact of CO_2 tax/credits on BESP of FT fuels for the WS scenario

Figure 15 illustrates the impact of carbon credits on the net present value of FT products when feeding pelletised pine forest residues. Including carbon credits improves the profitability of biofuel production, reducing the simple payback period from 21.7 years (without carbon credits) to 11.2 years.

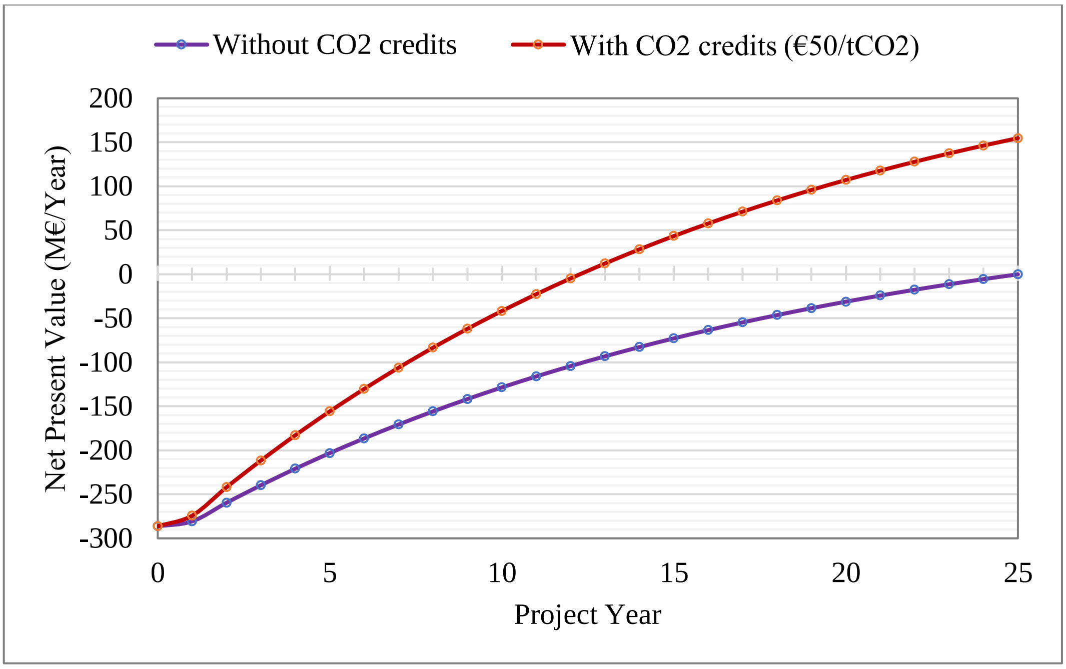

Figure 15 Impact of carbon credits on the net present value of FT products for biofuel production

The economic viability of the CLARA plant was examined using the internal rate of return in connection with different economic assumptions. At the default values (base case), the IRR is equal to DCF (in this case 6%) indicating that no profits or losses have been made. A higher IRR than 6% is required in order to achieve profits. Figure 16 shows the impact of waste heat sales and carbon credits on the internal rate of return biofuel production. Including the revenue from by-product sales and carbon credits improves the profitability of biofuel production, increasing the IRR from 6% to 13%.

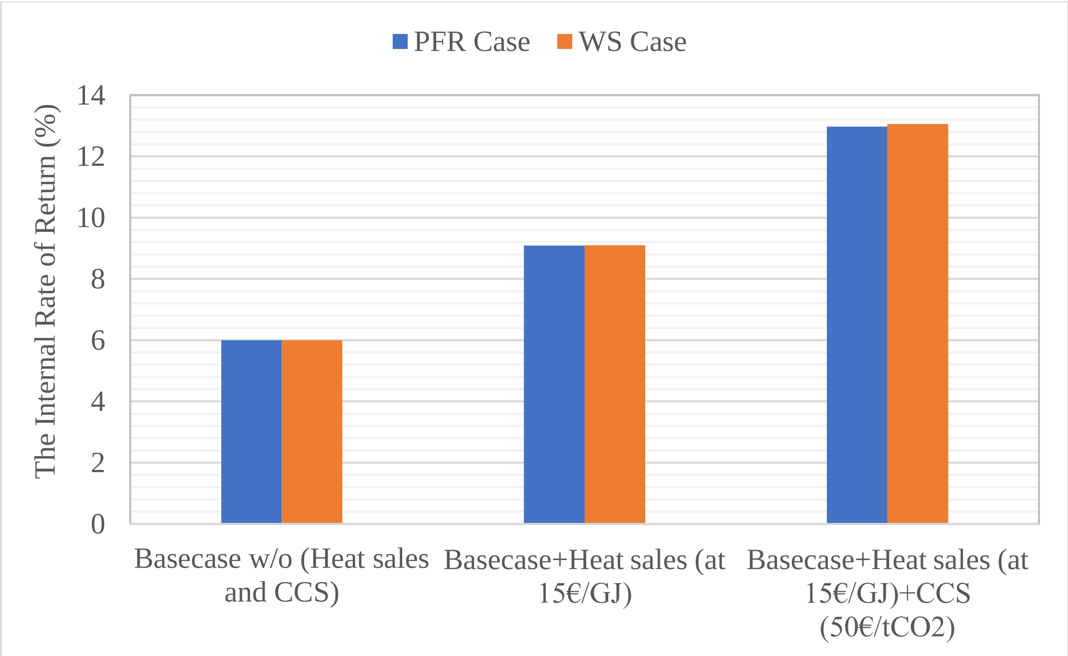

Figure 16 Impact of by-product sales and CCS on the internal rate of return

3.9.3. CO_2 avoidance cost

If grown in a sustainable manor, the use of biomass for biofuel production, which is considered to produce no net CO_2 emissions in its life cycle, and as a replacement for fossil fuels in energy or power generation systems is one of the most effective ways of reducing CO_2 emissions. If the BtL plant is equipped with a CCS facility, negative CO_2 emissions will be achieved.

The CO_2 avoidance cost is calculated according to the following equation [17]:

$$€/_{t\ CO_2\ avoided} = \frac{€/_{MWh-bioFT} - €/_{MWh-fossil}}{t_{CO2-fossil}/MWh - t_{CO2-bioFT}/MWh}$$

Where $€/_{MWh}$ is the BESP or market price of FT Syncrude and diesel/gasoline respectively, expressed with respect to the energy content; and $t_{CO2-fossil/bioFT}$ are the emissions (tonne of CO_2) corresponding to 1 MWh of fossil fuels or FT Syncrude, respectively.

The net CO_2 emission values for both PFR and WS scenarios, equipped with CCS are presented in Table 8.

Table 8 CO_2 emissions' inventory for the production of 1MWh of FT Syncrude [*]

	Fine Forest Residue	Wheat Straw
Indirect CO_2 emissions derived from onsite electricity consumption (tCO_2/MWh)	0.079	0.086
Indirect CO_2 emissions derived from electricity consumption (feedstock pre-treatment plant) (tCO_2/MWh)	0.027	0.025
CO_2 emissions derived from feedstock transport (tCO_2/MWh)	0.0047	0.0053
CO_2 captured (tCO_2/MWh)	0.661	0.725
Net CO_2 emissions (tCO_2/MWh)	-0.551	-0.609

[*] the average calorific value of the FT Syncrude is around 9.7 MWh/m^3.

To estimate the CO_2 avoidance cost for fuel switching we assume that an average carbon intensity of petrol and diesel of 0.338 tCO_2/MWh (or 94 gCO_2 equivalent per MJ), specified by the RED II.

In 2019, the average EU price (excluding taxes and tariffs) of diesel was €0.61 per litre, while that of gasoline was €0.56 per litre. In 2020, the average EU price of diesel dropped to €0.48 per litre, while that of gasoline was €0.45 per litre. In 2021, the average EU diesel price increased to €0.65 per litre and that of gasoline reached €0.64 per litre. Making a similar mix of diesel and gasoline as the one in the FT Syncrude produced, therefore we assume that the average fossil fuel price ranges from €46.6 to 64.5 per MWh for the reference fuel.

When the CCS system is installed on the BtL plant and biomass feedstocks are recognised as carbon neutral, the specific CO_2 emission intensities are -0.551 tCO_2/MWh for the PFR scenario and -0.609 tCO_2/MWh for the WS scenario. When the price of the mix of diesel and gasoline (excluding taxes and tariffs) is €46.6 per MWh, the CO_2 avoidance costs are €74.4/tCO_2 for the PFR scenario and €61.3/tCO_2 for the WS scenario. If the price of the mix of diesel and gasoline goes up to €64.5 per MWh, the CO_2 avoidance costs are reduced to €46.6/tCO_2 for the PFR scenario and €35.8/tCO_2 for the WS scenario.

3.10. Fischer–Tropsch product upgrading for biofuel production

Since the raw FT product cannot be directly used as fuel, it needs to be upgraded through distillation to split it into fractions for making the liquid fuel blend. Typically the primary FT product mixture consists of significant amount of high molecular weight waxes, higher boiling middle distillate and naphtha. To make high quality liquid fuels for commercial use, high molecular weight waxes are needed to crack to low molecular weight hydrocarbons, utilising hydrogen. Considering that the focus of this program is to develop an efficient technology for the production of liquid fuels based on chemical looping gasification (CLG) of biogenic residues and there is no detailed technical and economic information associated with the upgrading process, we decided to model this scheme as a black box using published data sources [18-19]. The simplified process diagram for the upgrading component is shown in Figure 17.

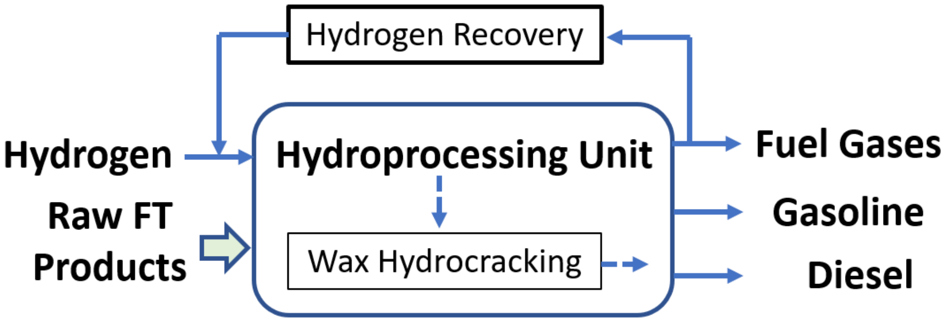

Figure 17 the hydroprocessing scheme for the raw FT products

Table 9 Mass and energy balance of the hydroprocessing process

Feedstock type	Pine Forest Residue	Wheat Straw
Raw FT products, tonne/h (dry basis)	7.99	7.30
Hydrogen consumption, tonne/h	0.06	0.05
Light fuel gases, MWh/h	29.57	27.00
Bio-gasoline, m^3/h	4.14	3.78
Biodiesel, m^3/h	5.08	4.64

The plant produces approximately 73,760 and 67,360 cubic meters of the refined bio-oil blend per year, together with fuel gases (a mix of methane and propane) of 851,760 GJ and 777,600 GJ per year for PFR and WS scenarios, respectively. These products are illustrated in Table 9. The fuel gases produced from the upgrading process are assumed to have a market value of €10/GJ (in year 2020).
The total capital cost for the upgrading process is estimated at €15.6M, which is about 8% of the total BtL plant capital investment. The estimated operating and maintenance cost associated with FT product upgrading amounts to about €0.96 million per year, including labour, consumable and maintenance costs.
Using the net present value analysis, the computed BESP of upgraded bio-fuel blends for the feedstock of pine forest residues is €1.08 per litre, and €1.06 per litre for the feedstock of wheat

straw. If expressed with respect to the energy content of the refined fuel blend, the BESP becomes €137.4 per MWh and €134.9 per MWh for pine forest residue and wheat straw, respectively. Figure 18 illustrates the influence of the upgrading process on the BESP of refined biofuels. Compared with BtL plan without hydroprocessing, the upgrading process increases BESP from €816 to 1080/m^3 for the PFR scenario and from €781 to 1060/m^3 for the WS scenario. This gives an increase in BESP up to 36%.

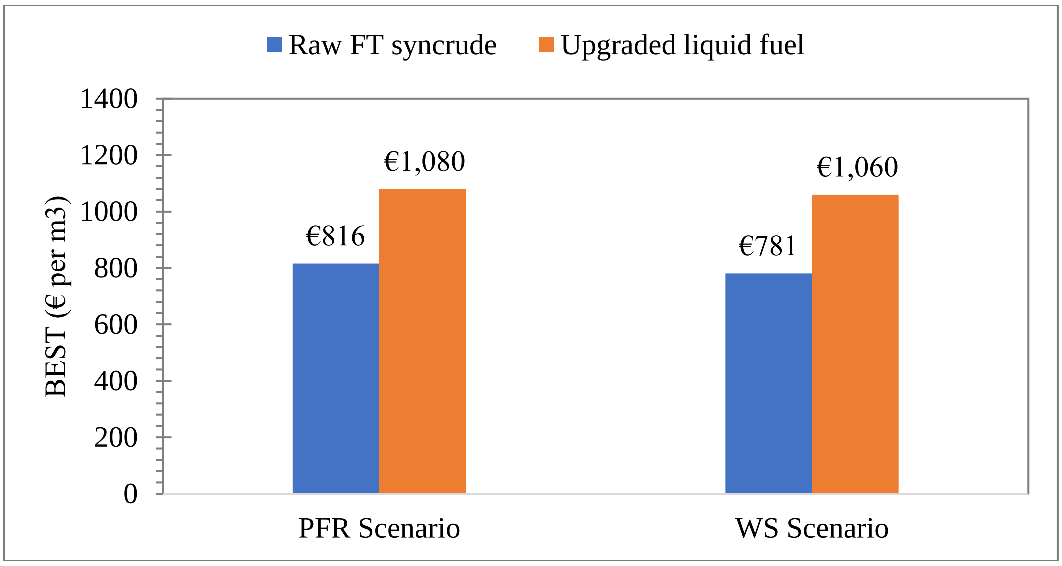

Figure 18 Influence of the upgrading of FT products on the BESP

3.11. Discussion

The results of the techno-economic analysis are summarised in Figures 19 and 20 for the pine forest and wheat straw scenarios, respectively. Figure 19 highlights the conditions in which the CLARA target price for the diesel and naphtha fractions can be reached (lower plant capital investment, lower discount cash flow rate, higher wax selling price and lower biomass feedstock prices) for the case of pine forest residues.

The results underline that, in favourable economic conditions (in terms of borrowing costs, inflation and depreciation – reflected in a low value of the discounted cash flow rate), the CLARA plant can reach its target price to produce competitive transport fuels.

The analysis also reveals the most significant economic parameters: wax selling price, plant availability, plant total cost and feedstock price.

The production ratio between FT fuels (naphtha and diesel fractions) and wax specified in the CLARA concept plant design is 1:1 (on a weight basis). Thus, the selling price of wax is an important economic parameter, with the BESP showing the highest sensitivity to variations in wax selling price.

The plant availability is generally recognised to be a key parameter to achieve competitive biofuel prices, as high productivity leads to higher revenues and allows faster capital cost recovery.

In the previous section, the feedstock price was revealed to be the most important OPEX component influencing the BESP values. The sensitivity analysis also confirms that the biomass price has a high impact on the FT biofuels' prices.

The results also show that the plant capital cost is an important cost parameter and plant optimization for capital cost reduction can lead to significant decreases in the BESP values.

Despite highlighting the important role of the discounted cash flow rate, the sensitivity analysis reveals it has only a moderate influence on the BESP of the FT fuels. Similarly, the price of electricity and the project lifetime also have a moderate impact on BESP values.

The considered contingencies and interest rates' variations have the smallest influence out of all the economic parameters investigated in this study, with high uncertainties in their values producing only a slight variation in the FT fuels' BESP.

For the case of wheat straw derived fuels (Figure 20), the sensitivity analysis groups the same parameters as high impact (total plant cost, plant availability, feedstock, and wax price), moderate impact (discounted cash flow rate, project life and electricity price) and low impact (contingency value and loan interest rates) as in the case of pine forest residues.

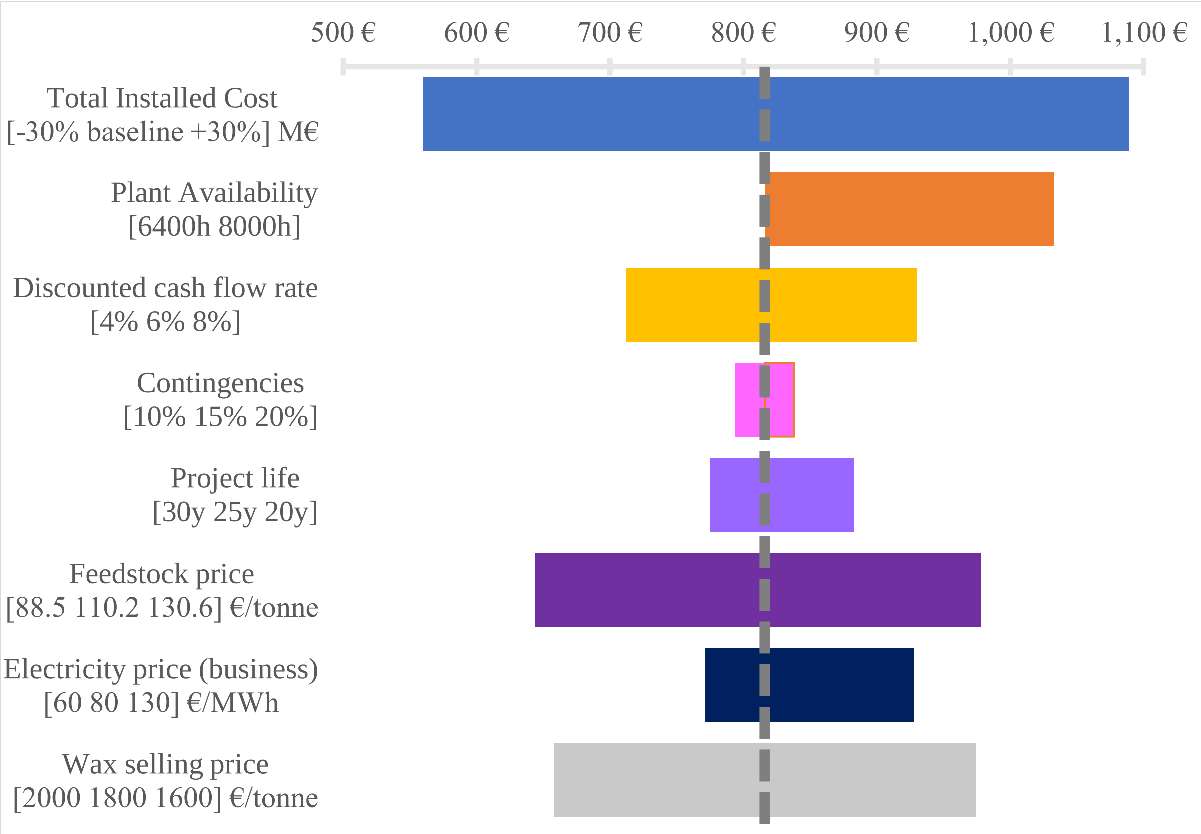

Figure 19 Sensitivity analysis of different economic parameters for PFR derived FT fuels

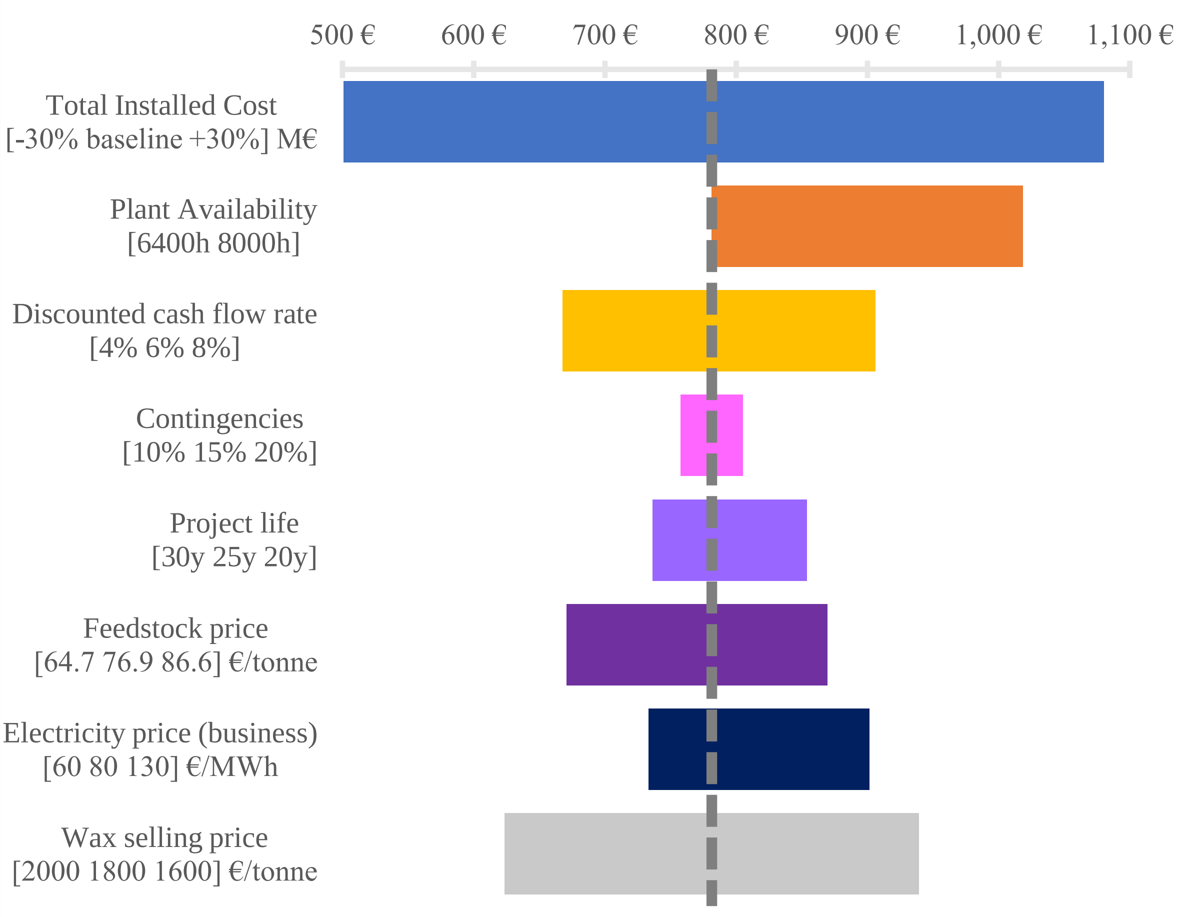

Figure 20 Sensitivity analysis of different economic parameters for WS derived FT fuels

4. Conclusions

In this report, we perform a techno-economic analysis to estimate the break-even selling price of the Fisher-Tropsch biofuels derived from wheat straw and pine forest residues in the framework of the CLARA concept plant. Following the capital investment and operational cost estimation presented in Deliverable 7.2, the discounted cash flow methodology is used to perform the economic analysis and estimate the break-even selling price of fuels obtained in the CLARA biomass-to-liquids (BTL) concept plant.

A sensitivity analysis is also performed to examine the impact of the main economic parameters on the fuel price and competitiveness of the CLARA plant.

In addition to the sensitivity analysis, we also analyse the case of selling the excess steam produced and the possible obtaining of carbon credits, following carbon dioxide separation, storage, and utilisation.

The following conclusions are drawn:

- For the PFR scenario without CCS, the break-even selling price (BESP) of raw FT fuels was estimated at €816 per m^3
- For the WS scenario without CCS, the BESP of raw FT fuels was estimated at €786 per m^3. Compared with the PFR scenario, the use of WS reduced the BESP by about 3.6%.

- When installing the CCS system on the BtL plant the BESP of raw FT fuels was increased by €97 per m^3 (about 11.8%) for the PFR scenario and €80 per m^3 (about 10.1%) for the WS scenario without carbon taxes/credits.
- The revenue obtained from selling the wax and by-product is off setting the relatively high capital and operational expenditures, while the FT fuels' BESP is most sensitive to the wax selling price. Thus, maximizing wax selling prices will be critical in ensuring the success of the CLARA concept.
- Plant optimisation and the reduction of capital investment and operating costs are essential to achieving low BESP values for the produced liquid fuels
- Ensuring high plant availability and minimizing outages and operational downtime is one of the most important tasks for achieving cost competitiveness in the liquid fuel market
- Compared with MDEA based gas cleaning, Rectisol based gas cleaning increases 13.4% of BESP for the PFR derived raw liquid fuel and 15.4% of BESP for the WS derived raw liquid fuel
- Biomass feedstock price (including harvesting, transport, upgrading and storage costs) has a significant influence on the fuel BESP, while feedstock cost is the most important cost contributor to the final BESP values
- Favourable economic conditions are needed to reach the CLARA target price of €700 per m^3, but the discounted cash flow rate (which includes depreciation, interest rates, inflation) has a moderate impact on BESP values
- The value of carbon tax and credits is essential for negative CO_2 emissions ensuring that additional capital and operating investment costs related to the CCS operation can be recovered. To achieve the project target, for the PFR scenario, the required carbon taxes will be €22 and €50/tonneCO_2 eq. with or without the income from waste heat sales, respectively. For the WS scenario the required carbon taxes will be €7 and €35/tonneCO_2 eq. with or without the income from waste heat sales, respectively.
- Replacing of fossil liquid fuels with biofuel produced gives negative CO_2 emissions when the CCS system is installed and biomass is recognised as CO_2 neutral. As a result, the specific CO_2 emissions are -0.551 tCO_2/MWh for the PFR scenario and are -0.609 tCO_2/MWh for the WS scenario. When the reference fuel price ranges from €46.6 to 64.5/MWh, the CO_2 avoidance costs are reduced from €53.4 to 33.3/tCO_2 for the PFR scenario and from €45.1 to 26.2/tCO_2 for the WS scenario.
- Integrating the hydroprocessing process into the FT plant increases the BESP of refined bio-fuel blends to €1.08 per litre, equivalent to 32.4% increase for the feedstock of pine forest residues, and €1.06 per litre, equivalent to 34.9% increase for the feedstock of wheat straw if compared with the base case.

5. Disclaimer

The content of this deliverable reflects only the author's view, and the European Commission is not responsible for any use that may be made of the information it contains.

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