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Report

GAFT - Economic viability assessment

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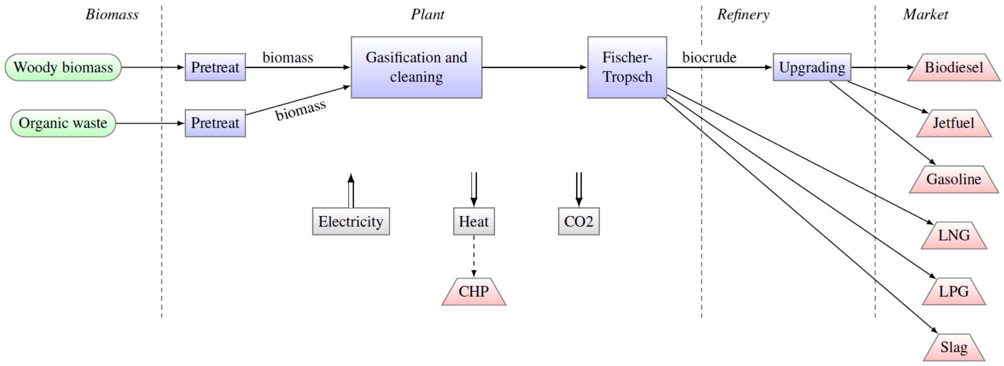

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ABSTRACT

This report presents the results of the economic viability assessments carried out as part of the GAFT project. A mathematical optimization model for optimal strategic and tactical planning of a biofuel plant is developed and its characteristics discussed. The model addresses the entire value chain of the plant using an integrated perspective and can be used for both investment analysis and tactical decisions for the operations of the supply chain. The model is used to analyse two business cases under Norwegian conditions based on data obtained in the GAFT project and a sensitivity analysis is carried out to evaluate the economic viability under different conditions. For both cases the results indicate that higher end product prices are required for an economically viable investment.

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Contents

1 Introduction

Task 4.2.3 in the GAFT project analyzed the business case(s) of the project using an economic optimization model. The analysis includes all costs, revenues and relevant constraints related to the business cases. The mathematical optimization model takes all information into account and calculates the best possible operation of the value chain for different scenarios. The mathematical model is based on related models developed and tested through several research projects.

This report describes the mathematical model developed, the input data that is used and the results of the business cases that were analyzed.

2 Model overview

This section gives a general description of the model framework, while the next section will give a detailed mathematical formulation.

The mathematical model is based on a network representation of the value chain from collection of resources to sale of final products. The nodes of the network represent activities and processes the products can undergo. The arcs between nodes are used to model flow of products between nodes. The planning horizon can be divided into timeperiods of chosen length (e.g. seasonal or yearly).

Decisions

When it comes to flow of raw materials, the model decides where and how much will be transported from the potential resource locations to the plant. Flow of products, both exchanged inside the plant, distributed further to refineries and sold to customers outside, will be decided upon. Additionally, the model will make decisions regarding different investment options. The list below states the most important decisions taken by the model:

- Where and how much raw material to collect of different types
- Transportation pattern for raw material
- Mix of resources used in the plant
- Overall plant size
- The size and investment time for pretreatment capacity
- Flow and transportation of products inside plant, from plant to refinery and to customers
- Sales of finished products to the different markets/customers

Optimization goal

The goal for the optimization model is to maximize profit (NPV) over a given planning horizon for the whole value chain. The objective function that is to be maximised consists of several terms:

- Cost of collecting/purchasing raw material
- Cost of transporting raw material
- Investment costs for the plant and pretreatment facilities
- Operational costs for the plant (and refinery)

- Income from sale of products
- Production fees (CO_2 fees)

Constraints

In order to ensure that the optimization model finds solutions that are applicable in real life, we have to include both physical and economic restrictions on what is possible and permitted. The most important restrictions are related to:

- Available raw material of different types at different locations
- Capacity of pretreatment processes
- Overall plant capacity
- Conservation of energy flows
- Minimum and maximum demand for the various products

The value chain network

Figure 1 shows how the general mathematical models looks at the different steps in the value chain. All arcs in the figure represents products flows determined by the model.
The green boxes to the left show the possible locations for raw material. Raw material from forestry, e.g. chips, goes into a pretreatment process at the plant. Raw material from waste or sewage is transported directly to the plant. Note that there are different pretreatment processes for raw material coming from forest and waste. After the pretreatment biomass proceeds to processing (gasification and cleaning followed by Fischer-Tropsch). Biocrude is transported to the refinery for upgrading to refined products, while excess heat can be sold to cumstomer(s) in the CHP market (typicall for district heating).

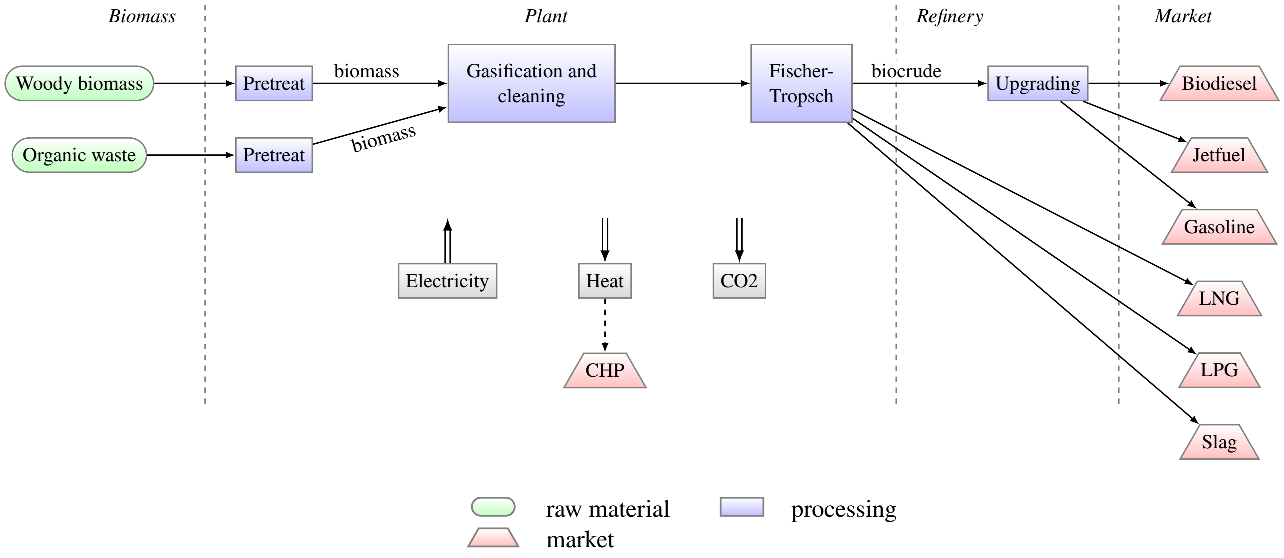


Figure 1: The overall value chain as represented in the mathematical model.

3 Mathematical description

3.1 Indexes, constants and variables

Indexes and sets

Index	Set	Description
t	T	All time periods, $t = 1, \ldots, \lvert T \rvert$
l	L	All resource locations
p	P	Pretreatment nodes
g	G	Gasification nodes
d	D	Plant designs
c	C	All commodities
	C^R	Raw materials

Data parameters

These data values are provided as user input to the optimization model and can be set individually for each business case being analysed.

Name	Description	Unit
$\text{MaxSupply}_{l,c,t}$	Upper limit for purchase of commodity c at location l	tons/year
$\text{Mix}_{c1,c2}$	The maximal ratio of $c1$ and $c2$ in the feedstock mix	> 0
$\text{MaxDemand}_{c,t}$	The maximum market demand for commodity	GJ/year
Moisture_{c}	The moisture content for commodity c	$[0, 1]$
Energy_{c}	The energy content for commodity c	MJ/ton
$\text{PreCap}_{p,k}$	The capacity for pretreatment line of type k	MJ/s
MaxCap_{d}	The maximum capacity for a plant with design d	MJ/s
ProdFunc_{c}	The production function for commodity c	MJ out/MJ in
$\text{PurchasePrice}_{l,c,t}$	The purchase cost at location l	NOK/ton
$\text{SalePrice}_{c,t}$	Sales price for commodity c	NOK/MJ
$\text{TranspCost}_{l,c}$	Transport costs from location l	NOK/ton
Discount_{t}	Discount factor for period t	$[0, 1]$
Depreciation	The depreciation rate for investments	$[0, 1]$
Inflation	The inflation rate	$[0, 1]$
TaxRate	The tax rate on revenues	$[0, 1]$

Variables

The table below provides an overview of the decision variables used in the model, together with a short description and the units used for the variable. Note the use of lowercase letters and an italic script for decision variables.

Name	Description	Unit
$outflow_{l,c,t}$	The outflow of commodity c from location l	tons/year
$inflow_{c,t}$	The inflow of commodity c to the plant	tons/year
$invest_{p,k,t}$	Investment in pre-treatment lines with capacity type k in year t	0/1
$design_{d}$	Investment in a plant with design size d	0/1
$sale_{c,t}$	Sales of commodity c to the market	*/year
$prod_{c,t}$	Production of commodity c in the plant	*/year
$energy_{p,t}$	Energy inflow to pretreament node	MJ/second
$flow_{i,j,t}$	Energy flow from node i to node j	MJ/second
$process_{t}$	Energy processed in plant	MJ/second

3.2 Constraints

Feedstock supply

The flow of feedstock into the plant should balance the outflow from all locations for each commodity and period

$$\sum_{l \in L} outflow_{l,c,t} = inflow_{c,t}, \text{ for all } c \in C, t \in T.$$

The flow of feedstock out of a location can not exceed the maximum available

$$outflow_{l,c,t} \leq \text{MaxSupply}_{l,c,t}, \text{ for all } l \in L, c \in C, t \in T.$$

There may be restrictions on feedstock mix, i.e. the ratio of commodity $c1$ and commodity $c2$ must be below a given value $\text{Mix}_{c1,c2}$

$$inflow_{c1,t} \leq \text{Mix}_{c1,c2} \cdot inflow_{c2,t}, \text{ for all } t \in T.$$

Investment

The model can select at most one design size for the overall plant

$$\sum_{d \in D} design_d \leq 1.$$

Invest in at most one new pretreatment line per period and pretreatment node

$$\sum_{kinK} invest_{p,k,t} \leq 1, \text{ for all } p \in P, t \in T.$$

Demand

The sales for each commodity should not exceed the maximal demand

$$sale_{c,t} \leq \text{MaxDemand}_{c,t}, \text{ for all } c \in C, t \in T.$$

The sales for each commodity should not exceed the production

$$sale_{c,t} \leq prod_{c,t}, \text{ for all } c \in C, t \in T.$$

Plant operation

The inflow to each pre-treatment node is adjusted for moisture level to get the energy inflow

$$energy_{p,t} = (1 - \text{Moisture}_{c(p)}) \cdot \text{Energy}_{c(p)} \cdot inflow_{p,t}, \text{ for all } p \in P, t \in T,$$

where $c(p)$ is the commodity associated with pretreatment node p.
The plant must have invested in sufficient pre-treatment capacity to handle the energy inflow

$$energy_{p,t} \leq \sum_{t' \in T : t' \leq t, k \in K} \text{PreCap}_{p,k} \cdot invest_{p,k,t'}, \text{ for all } p \in P, t \in T.$$

The flow of energy is conserved through gasification and cleaning

$$\sum_{p \in P} energy_{p,t} = \sum_{g \in GC} flow_{p,g,t}, \text{ for all } t \in T,$$

and similar conservation for the flow into the Fischer-Tropsch process

$$\sum_{g \in GC} flow_{g,FT,t} = process_t, \text{ for all } g \in G, t \in T.$$

The outflow (production/consumption) of commodities depends on the total energy processed

$$prod_{c,t} = \text{ProdFunc}_c \cdot process_t, \text{ for all } t \in T.$$

Note that ProdFunc can be negative for some commodities, e.g. electricity, denoting an inflow of the commodity. The production functions are based on other work carried out in the GAFT project and are further described in Appendix A.

The overall plant size must accomodate the total energy processed

$$\rho \cdot process_t \leq \sum_{d \in D} \text{MaxCap}_d \cdot design_d, \text{ for all } t \in T,$$

where ρ is an adjustment factor for energy losses in the processing. A value of $\rho = 1.04$ was used throughout the analyses.

3.3 Objective function

The overall objective function to maximize is the net present value of the plant, taking into account all relevant costs and incomes from the operation of the plant. The following sections provide details on the components that are part of the objective.

Feedstock cost

The purchase cost of supplied raw materials for each location and period

$$purchasecost_{c,t} = \sum_{l \in L} \text{PurchasePrice}_{l,c,t} \cdot outflow_{l,c,t}, \text{ for all } c \in C^R, t \in T.$$

In addition there are costs for purchasing electricity that must be adjusted for the operational hours of each period

$$purchasecost_{El,t} = \text{PurchasePrice}_{El,t} \cdot prod_{El,t} \cdot \text{Ophours}, \text{ for all } t \in T.$$

Cost on inflow from all locations (typically transport costs)

$$transpcost_t = \sum_{l \in L} \text{TranspCost}_{l,c} \cdot outflow_{l,c,t}, \text{ for all } t \in T.$$

Investment cost

Similar to the approach in Kempegowda et al. (2015), we adjust all investments costs with a factor γ to account for other costs (site, projecting, etc.). A value of 1.378 was used for γ in the model runs.

The investment cost will have contributions from investments in pretreatment lines and the overall plant. For the pretreatment investments there are yearly contributions depending on investment decisions

$$invcostpre_t = \gamma \sum_{p \in P} \text{PreInvCost}_{p,k} \cdot invest_{p,k,t}, \text{ for all } t \in T.$$

The investment cost of the plant will depend upon both the design selected and the maximum capacity required for each pretreatment process

$$invcostplant = \gamma \sum_{d \in D, p \in P} \text{InvFixedCost}_{p,d} \cdot energymax_{d,p}.$$

where $energymax_{d,p}$ is the maximum energy processesed

$$energymax_{d,p} \geq denergy_{d,p,t}, \text{ for all } d \in D, p \in P, t \in T.$$

The overall investment profile will be a combination of the above

$$invcost_t = \begin{cases} invcostplant + invcostpre_1, & \text{for } t = 1, \\ invcostpre_t, & \text{for } t > 1. \end{cases}$$

The production functions are based on other work carried out in the GAFT project and are further described in Appendix B.

In addition there are depreciation effects that needs to be accounted for when calculating plant value. The total value of the plant at the end of period t adjusted for depreciation is equal to

$$plantvalue_t = invcost_t + (1 - \text{Depreciation})/(1 + \text{Inflation}) \cdot plantvalue_{t-1}, \text{ for all } t \in T,$$

where $plantvalue_t = 0$ for $t = 0$. Based on the plant value we can calculate the depreciation for each period

$$depreciation_t = \text{Depreciation} \cdot plantvalue_t, \text{ for all } t \in T.$$

Operational cost

The operational cost of the plant can depend on the choice of design size and the mix of input products

$$opcost_t = \sum_{d \in D, c \in C^R} \text{OpUnitCost}_{d,c} \cdot denergy_{d,c,t}, \text{ for all } t \in T,$$

where $denergy_{d,c,t}$ is the input energy of raw material c associated with design size d. This variable can be non-zero only for the selected plant design

$$denergy_{d,c,t} \leq \text{MaxCap}_d \cdot design_d, \text{ for all } d \in D, c \in C^R, t \in T,$$

and should equal the sum of energy inflow to all pretreatment nodes handling the input product

$$\sum_{d \in D} denergy_{d,c,t} = \sum_{p \in P : c(p) = c} energy_{p,t}, \text{ for all } c \in C^R, t \in T.$$

The production functions are based on other work carried out in the GAFT project and are further described in Appendix C.

Sales income and production fees

The sale of final products will generate an income based on the sales price for the commodity in each period

$$saleincome_t = \sum_{c \in c} \text{SalePrice}_{c,t} \cdot sale_{c,t}, \text{ for all } t \in T.$$

In addition there can be fees on some of the produced commodities, typically this is used for fees on CO_2 emissions

$$CO2cost_t = \text{Fee}_{CO2,t} \cdot prod_{CO2,t} \text{ for all } t \in T.$$

Overall objective

The overall objective is to maximize the net present value of the investment, discounting to the first year and accounting for tax effects and depreciation of the investment

$$npv = \sum_{t \in T} \mathrm{Discount}_t \cdot [revenue_t \cdot (1 - \mathrm{TaxRate}) + depreciation_t \cdot \mathrm{TaxRate} - invcost_t],$$

where the total yearly revenue is calculated as

$$revenue_t = saleincome_t - purchasecost_t - transpcost_t - opcost_t - CO_2cost_t, \quad \text{for all } t \in T.$$

4 Business case description

We have analysed two business cases. The main assumptions and differences for the cases are listed in the table below.

	Case 1	Case 2
Feedstock	Mix of wood and organic waste	100% Wood
Capacity	Up to 600 MW (Base case: Max org.waste capacity 100 MW)	250-600 MW
Heat infrastructure	No heat market	District heating
Supply	Wood and sludge delivered at site (Base case: Wood: 550 NOK/tonn; Org.waste: 0 NOK/tonn)	Wood delivered at site (Base case: 550 NOK/tonn)
CO_2 handling	No CO_2 capture; Emission costs	CO_2 capture; No emissions costs. CO_2-credits and CO_2 train investment

For both cases we have the following financial assumptions:

Parameter	Value
Return rate	5%
Inflation	2%
Depreciation	10%
Tax rate	28%
Exchange rate, USD - NOK	8.5
Time period	25 years

The end products that can be sold to the market are the three main products from the bio upgrading - biodiesel, jetfuel and gasoline. In addition we get LNG, LPG, heat, and also slag and CO_2 (which could have both negative and positive value in the market.)

The market prices (in the base case) are assumed to be as follows (based on other work carried out in the GAFT project):

End product	Price
Biodiesel	22.02 USD/GJ
Jetfuel	34.05 USD/GJ
Gasoline	8.28 USD/GJ
LNG	9.67 USD/GJ
LPG	7.09 USD/GJ
Heat	13.89 USD/GJ
Slag	20 USD/tonn
CO_2 emissions	7.24 - 80 USD/tonn
CO_2 credits	50 USD/tonn

Initially, the CO_2 emission cost in the studies performed in the GAFT project was set to 7.24 USD per tonn. By assuming a Norwegian CO_2 tax of 500 NOK/tonn in addition to the CO_2 quota price we get a CO_2 emission cost of 80 UDS/tonn. In the case analyses we have performed analyses with both these values.

The economic viability and best possible design and operation for different assumptions and scenarios are analysed for the business cases. We have investigated the following variations (sensitivites) in order to analyse economic viability:

- Feedstock price: Price decrease
- End product price: Multiplier 1.0 - 2.0
- Maximum ratio of organic waste: Up to 50% sludge mass ratio in the feeedstock
- CO_2 emission costs: 7.24 USD/tonn; 80 USD/tonn
- CAPEX and OPEX: Cost decrease

5 Results

5.1 Case 1

By using the base case values as given above, no investments are made. The first parameters that are adjusted to see effects on investment are feedstock prices. By decreasing the price of logwood to 300 NOK/tonn, and introducing revenues for using organic waste (- 500 NOK/tonn), investment in the biorefinery is profitable.

The second sensitivity that is investigated is the end product price. (The feedstock prices are as in base case). The result is that aprroximately 50% increase in the end prices are required to get profitability and, with that, investment. The resulting design is a 400 MW capacity in pretreatment of wood, and 250 MW pretreatment capacity of organic waste (And a capcity of the biorefinery of 600 MW). By setting maximum organic waste capacity to 100 MW, the profitability of the plant decreases, but is still profitable at a 50% increase in end price. If the plant will get revenues (500 NOK/tonn) for handling and converting the organic waste (keeping the logwood price equal), an end product price increase of 20% is sufficient for a profitable investment. By increasing the CO_2 emission costs up to 80 USD/tonn, an increase in price of 76% is necessary to get a profitable investment.

The results of these different sensitivities and variations are illustrated in Figure 2.
The resulting flow, and key financial numbers for the case with 100% end product price increase and maximum organic waste treatment capacity of 100 MW are shown in Figure 4.
The last sensitivities are decreases in CAPEX and OPEX. Keeping the base case assumptions but lowering the CAPEX costs does not result in a profitable investment. The sales price are to low and/or operational costs and feedstock costs too high. Lowering the operational costs to 15% (keeping the feedstock prices as in the base

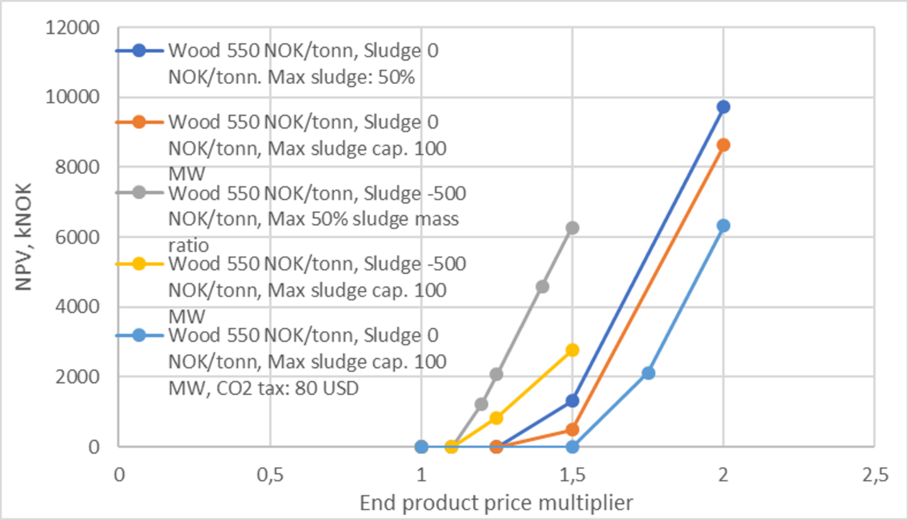


Figure 2: Sensitivity of NPV with regard to end product prices, case 1

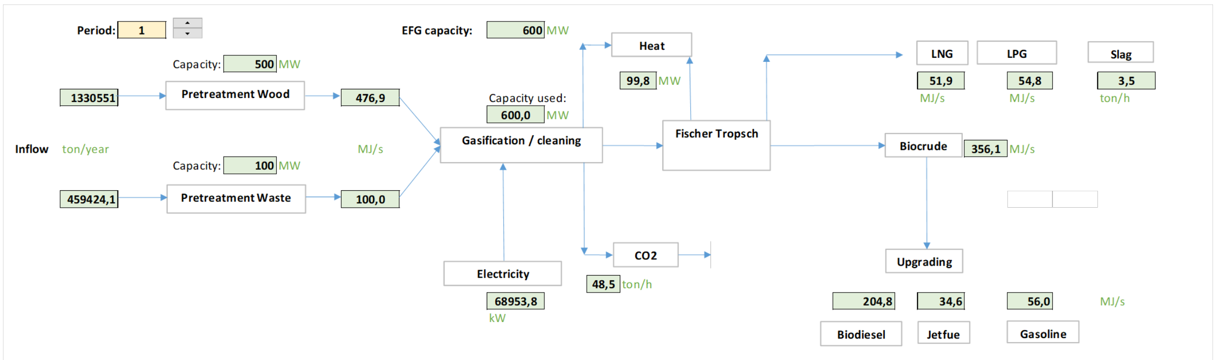


Figure 3: Flow diagram with material inflow and energy flow for Case 1 (Year 1).

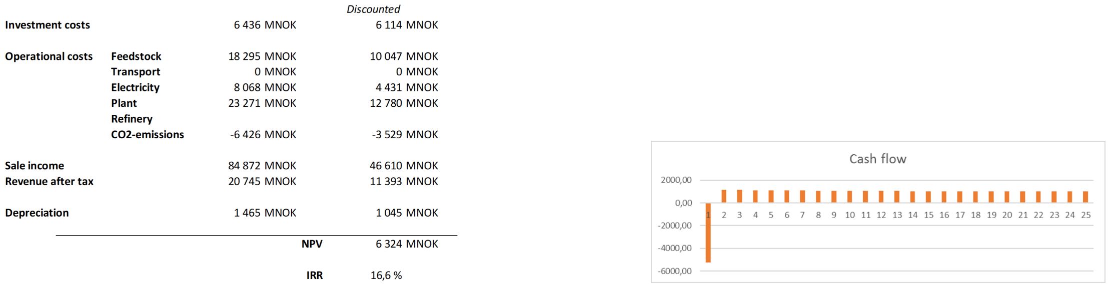
case) results in a profitable investment. The result (that maximises the NPV for this case) is a plant with 200 MW pretreatment capacity of wood and 100 MW pretreatment capacity of organic waste.

5.2 Case 2

The main differences for case 2 to case 1 are first, that we assume CO_2 capture, secondly, there is a district heating infrastructure and market, and thirdly, the refinery can only take logwood (no organic waste). CO_2 capture implies both extra income and extra costs. Capture of CO_2 gives the refinery CO_2 credits. But also, there is an extra investment costs related to the capture and compression train. Logwood only as a feedstock implies other feedstock costs (in total), and also slightly other conversion factors from biomass to end products.

The first sensitivity analysed in this case is the end price sensitivity. For this case profitable investment occurs when the price of end products are increased with 75%. Resulting NPV is substantially lower than case 1. The reasons for this are mainly higher investment costs (CO_2 capture and compression train), and higher feedstock costs. Figure 5 compares the two cases for the base case assumptions.

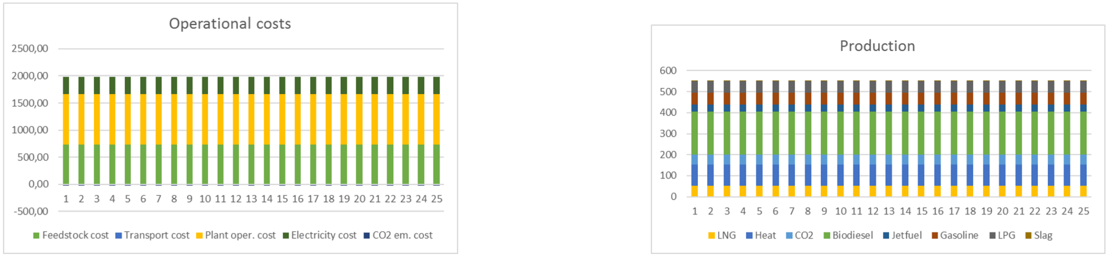
The resulting flow, and key financial numbers for case 2 with 100% end product price increase are shown in Figure 7.



			Discounted
Investment costs		6 436 MNOK	6 114 MNOK
Operational costs	**Feedstock**	18 295 MNOK	10 047 MNOK
	Transport	0 MNOK	0 MNOK
	Electricity	8 068 MNOK	4 431 MNOK
	Plant	23 271 MNOK	12 780 MNOK
	Refinery		
	CO2-emissions	-6 426 MNOK	-3 529 MNOK
Sale income		84 872 MNOK	46 610 MNOK
Revenue after tax		20 745 MNOK	11 393 MNOK
Depreciation		1 465 MNOK	1 045 MNOK
		NPV	6 324 MNOK
		IRR	16,6 %

(a) Key economic figures for the planning period, Case 1.

(b) The cash flow for the planning period, Case 1.



(c) Yearly OPEX, Case 1.

(d) Yearly production in tons, case 1.

Figure 4: Illustrations of solution for Case 1 with 100% increase in end product price

By lowering CAPEX or OPEX, keeping the other parameters as in base case, no investments are profitable for Case 2. Lowering both CAPEX and OPES to 40% of original values gives a profitable investment.

5.3 Discussion of results

In general, economic viability of the plant with the base case assumptions is not present. The NPV results of a plant is clearly sensitive to end products prices. The analyses also show that capture of CO_2 is costly and increases the costs significantly. However, with increasing CO_2 emission costs, this can still be more economically than no capture.

6 Conclusion

A mathematical optimization model is developed to analyse business cases in the GAFT project and find optimal design for different cases. This report describes some analyses for two different cases, and the required assumptions in order to get profitability.
The model can be used to perform further analyses. Relevant analyses include price development over time, cost development over time (for instance a decrease du to lerning effects), increases in CO_2 emissions costs and/or required CO_2 capture. It could also be relevant to include the possibility to make investments in different time periods (for instance increasing capacity, adding pretreatment equipment for different feedstocks, adding CO_2 capture etc).

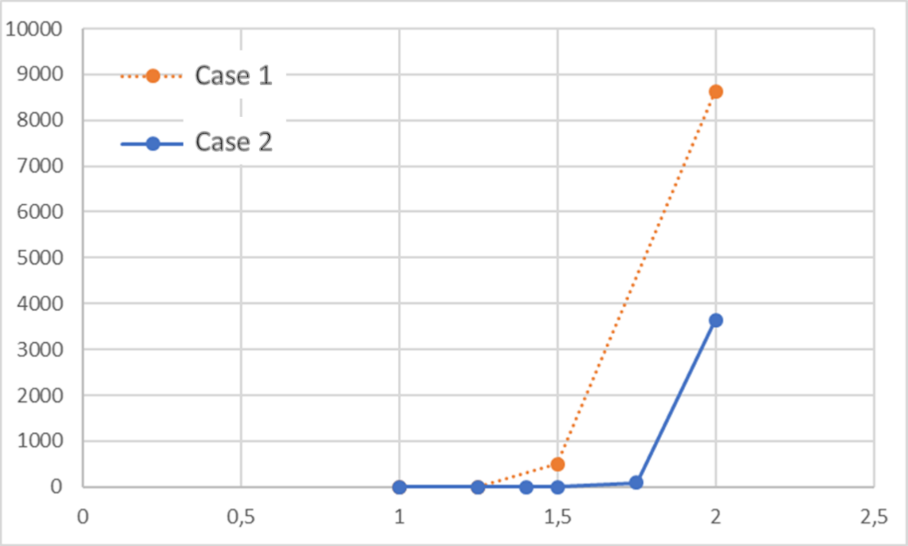


Figure 5: Sensitivity of NPV with regard to end product prices for Case 2, compared with Case 1.

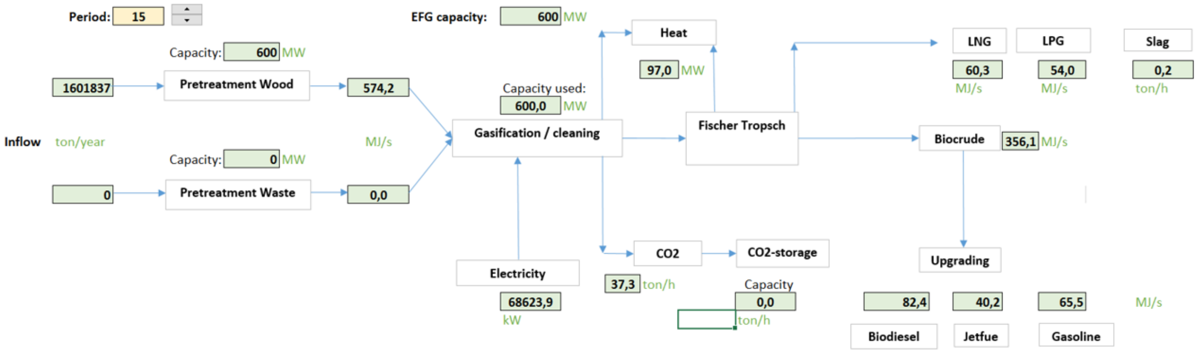
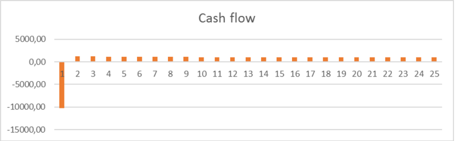


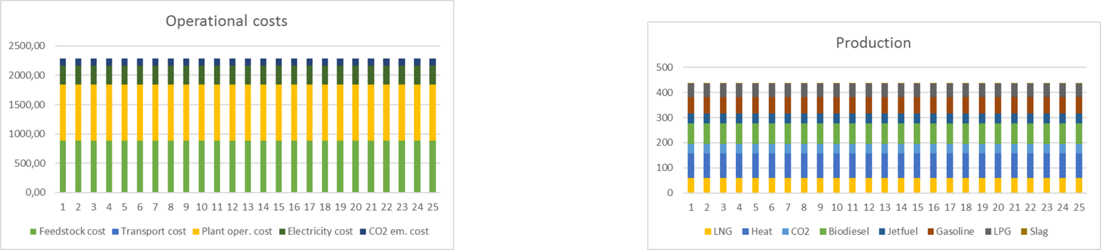
Figure 6: Flow diagram with material inflow and energy flow for Case 2 (year 15 as an example).

			Discounted
Investment costs		11 542 MNOK	10 965 MNOK
Operational costs	**Feedstock**	22 025 MNOK	12 096 MNOK
	Transport	0 MNOK	0 MNOK
	Electricity	8 029 MNOK	4 409 MNOK
	Plant	24 078 MNOK	13 223 MNOK
	Refinery		
	CO2-emissions	3 093 MNOK	1 699 MNOK
Sale income		83 243 MNOK	45 716 MNOK
Revenue after tax		23 187 MNOK	12 734 MNOK
Depreciation		2 627 MNOK	1 875 MNOK
		NPV	3 644 MNOK
		IRR	9,1 %

(a) Key economic figures for the planning period, Case 2.



(b) The cash flow for the planning period, Case 2.



(c) Yearly OPEX, Case 2.

(d) Yearly production in tons, Case 2.

Figure 7: Illustrations of solution for Case 2 with 100% increase in end product price

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Appendices

A Production functions - Product conversion multipliers

The conversion factors for the commodities are given in the table below. The factors are based on calculation and work as described in Del Alamo et al. (2017) and Kempegowda et al. (2015). The factors are calculated based on energy output / energy input, and an average for all the simulated cases (mixed feedstock and different capacities) (Except for CO_2, which is measured in ton/h out / MW energy input)

End product	Conversion factor, mixed input	Conversion factor, 100 % wood
Biodiesel	0.355	0.414
Jetfuel	0.060	0.07
Gasoline	0.097	0.114
LNG	0.090	0.105
LPG	0.095	0.094
Heat	0.173	0.169
Slag	0.006	0.0003
CO_2 emissions	0.084	0.065
Electricity	119.5	119.5

B CAPEX

The capex multipliers are given in the table below. The multipliers are based on calculation and work as described in Del Alamo et al. (2017) and Kempegowda et al. (2015).

Biorefinery capacity (MW)	Capex org.waste multiplier, mixed input	Capex wood multiplier, mixed input	Conversion factor, 100 % wood
150	1.798	1.869	1.95
300	1.071	1.648	1.744
450	0.794	1.530	1.633
600	0.620	1.452	1.560

C OPEX

The opex multipliers are given in the table below. The multipliers are based on calculation and work as described in Del Alamo et al. (2017) and Kempegowda et al. (2015).

Biorefinery capacity	Opex org.waste multiplier	Opex wood multiplier
150	0.2751	0.2374
300	0.1881	0.2116
450	0.1540	0.1973
600	0.1540	0.1973