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Case Study
Sölvesborgs Energi och Vatten, Sweden

WP3: Case studies for retrofitting

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1 Introduction to the case study

Conversion of the fossil oil boiler of Sölvesborgs Energi och Vatten in Sweden to the utilization of bio-oil or biodiesel.

Together with project partner Energikontor Sydost, the utilization of bio-oil in the existing central heating boilers of Sölvesborgs Energi och Vatten in Sölvesborg, Sweden, will be investigated. The two heating boilers have a capacity of 16 MW in total.

The base load of heat delivered to the district heat clients is excess heat from a nearby pulp mill. Sölvesborgs Energi och Vatten produce, on their own, exclusively heat from the two boilers for back-up and peak load.

Most of the heat in Sweden is produced by biomass, but the need of fossil fuel still remain for most of the heat delivery companies for back-up and peak-load production. Many of these companies have set the goal to reduce fossil fuel use in the district heating production to zero. Therefore, many district heating companies have, or will, retrofit the existing oil boiler to be able to burn bio-oils instead. Today, about 40 district heating plants in Sweden utilize bio-oils, in around 80 boilers. The total use is around 4,5 TWh, corresponding to around 450 000 tons of oil, and the use is increasing, also in other industry sectors. The largest part of this amount is pine pitch oil and used as fuel for transports.

2 Case study team

The case study will be conducted by the following partners:

Function	Organization name	Main staff
Case Study Team Leader	ESS – Energikontor Sydost AB (Sweden)	Göran Gustavsson (goran.gustavsson@energikontorsydost.se)
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3 Confidentiality issues

This report will be shared among the partners in the case study team only. However, in the course of the project, this report will also be used as the basis for deliverable D3.3, which will be – although confidential – shared with all the BIOFIT project partners. Therefore, any information within this report which should not be distributed to a larger group than the case study team must be clearly marked with "remove before creating the deliverable".

As the BIOFIT project will publish the results of the case studies it is important to also define which parts of the information should be kept confidential within the BIOFIT project partners. Any such information within this report must be clearly marked with "do not distribute".

4 Case study description

Three items will be described and discussed: the current situation, the suggested retrofit, and what the alternative would be when no retrofit takes place.

4.1 The current situation

Variations of feed-stock types and quantities historically in a Swedish context

This case study belongs to the industry sector for co-generation of heat and electricity. Figure 1 indicates original energy sources used for heat supplied into Swedish district heating systems. Fossil fuels dominated until mid 1980s. The most significant jump in Sweden's use of biofuels for production of district heating arose from the 1991 adoption of a carbon tax across industry, the service sector and households, which raised the cost of fossil fuels and made renewables competitive. Another driving force for renewables was the introduction of "green tax switch" 2001. In 2003 the green certificate system was introduced to support investment in new renewable power plants, leading to a rapid expansion of bioelectricity generation.

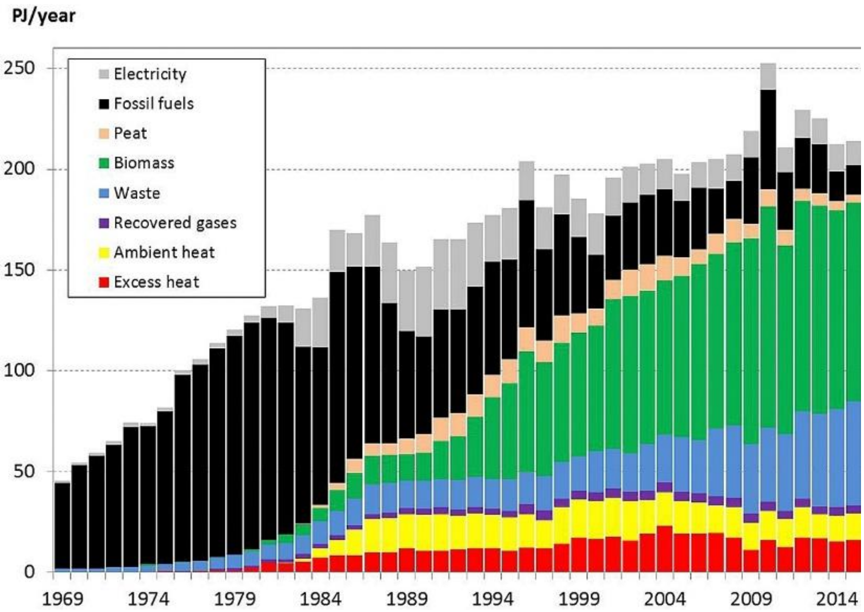

Figure 1: Original energy sources used for heat supplied into Swedish district heating systems (Statistics Sweden)

Market situation for the sector

Different factors affect the market for district heating, e.g.:

- Competition of the biomass from biofuel for vehicles production facilities. The use of biofuels for road transports has increased. It is a significant increase in Sweden.
- Energy efficiency actions in buildings. The foreseen decreased use of district heating in Sweden is significant as a result of energy efficiency actions. A similar focus on such actions are common across Europe.
- The development of incineration plants for household waste, appr 20 % of the produced heat for district heating in Sweden use household waste as feedstock.

- More individual independent energy solutions.
- The development of other renewable energies.
- The MCP-directive with more strict regulations for emissions, from small and middle-scaled heating plants.
- Public acceptance
- EU policies

The case study company

The company Sölvesborg Energi is owned by the municipality of Sölvesborg. The turnover is 17 MEURO. Th etotal number of employees is 41. One of the subsidiary companies concerns district heating, production and distribution. It´s turnover is 3 MEURO. The company was founded in 2003 when district heating was introduced in Sölvesborg and became a subsidiary company of Sölvesborgs Energi and Vatten AB in 2007. The vast part of the heat is not produced by themselves but bought as waste heat from the nearby pulp – and paper mill, owned by Stora Enso. The agreement with the base heat provider is ongoing with a notice period of three years.

Sölvesborg Energi owns two boilers, 10 + 6 MW, located to the central part of the city of Sölvesborg. These two boilers produced 4.3 GWh during 2017. The amount of produced heat from these boilers can vary a lot from one year to another. The company has, in addition to these two boilers, also an agreement with a company which use a boiler for steam production for their own production. According to the agreement, this boiler is available for Sölvesborg Energy as an extra back-up. This extra security has never been needed. According to the MCP Directive, the limits for emissions are taken into effect when the operation time of a boiler exceeds 500 h. The two boilers will be in operation more than 500 h normally.

Key features for district heating in Sölvesborg

- Heat deliveries from the pulp – and paper mill (Stora Enso): 51 GWh (2017)
- Heat deliveries from the back-up and peak load boilers owned by Sölvesborg Energi: 4,3 GWh (2017)
- Total installed capacity: 20 MW
- Two boilers, 10 MW and 6 MW, in Sölvesborg, feed-stock today: mineral oil
- One boiler, 4 MW in Mjällby, fossil liquid gas (back-up for the back-up – not used for several years)
- 1900 customers (560 connections)

The municipality has 17,000 inhabitants (9,000 in the society of Sölvesborg), with a total area of 1,100 km^2. The municipality is located to the southeast part of Sweden, in the region Blekinge. The pulp – and paper mill which provide the case study company with waste heat is located west of the city, in another region, Skåne.

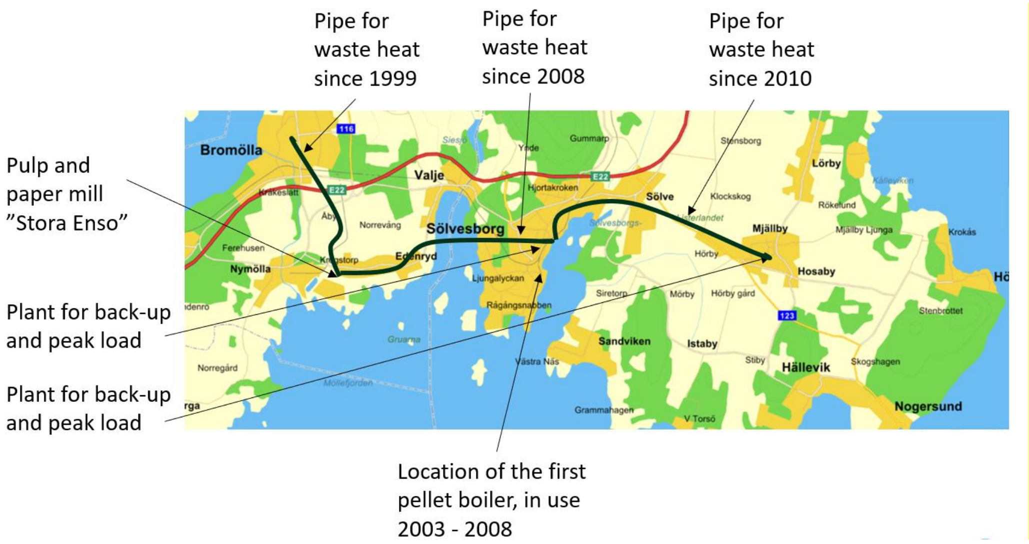

Figure 2: Location site details

The two facilities in Sölvesborg

Boilers:

DANSTOKER Global 11 (6,000 kW),

DANSTOKER Global 13 (10,000 kW)

The company Turboflame has delivered the burner for oil burning including automatic equipment and intermediate electrical installation

Figure 2: The two boilers for back-up and peak load.

Current situation of the plant

The case study company purchases waste heat from the pulp and paper mill of Stora Enso. A big heat exchanger is located at the site of the mill, from where the heat is pumped to the city of Sölvesborg for deliveries to their district heating clients. Sölvesborg Energi has back-up and peak-load boilers which they own on themselves, in order to secure heat deliveries to their clients. The two tanks for storage of the fuel is located inside the building, in a certain room for this purpose.

The annual heat production in the two oil boilers can vary greatly depending on, among other things, selected periods for maintenance at Stora Enso Nymölla pulp – and paper mill and thus absent heat delivery from there. The table below shows the annual use of mineral oil in the two boilers at Sölvesborg Energi, expressed in m^3.

Table 1: Heat production at the two boilers in Sölvesborg.

Year	2010	2011	2012	2013	2014	2015	2016	2017	2018
m3	54	267	46	264	12	403	157	483	48

Based on the figures above, the probable oil consumption in the oil boilers is typically estimated to be the average of the years reported above, i.e. about 200 m^3, which corresponds to about 2,000 MWh / year. This need is not significantly changed within the next 5-year period, based on available information. The plant has been in operation for 5,000 h since the start of operation in 2008, which corresponds to about 500 h / year.

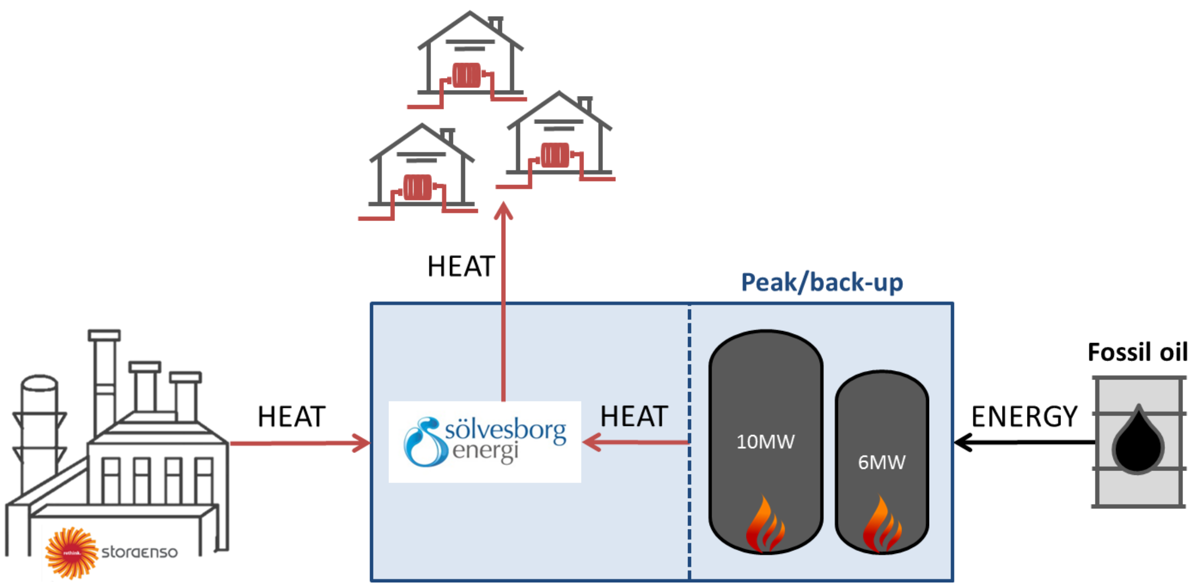

Figure 3: Current situation of the plant (Doris Matschegg)

4.2 Suggested retrofit

The suggested retrofit includes two cases:

- Retrofit the existing oil boilers to use cheaper bio-oils, (heavy bio-oils) which needs constant heating

- Retrofit the existing oil burners to use a more expensive fuel, light bio-oils (high quality bio-oils or biodiesel) which e.g. does not require constant heating

The prerequisites for converting from mineral oil to bio-oil are investigated, for e.g.

- Type of bio-oil
- Need of new burner
- Need of new pipes, containers and auxiliary equipment
- Need of heating system to keep the fuel warm

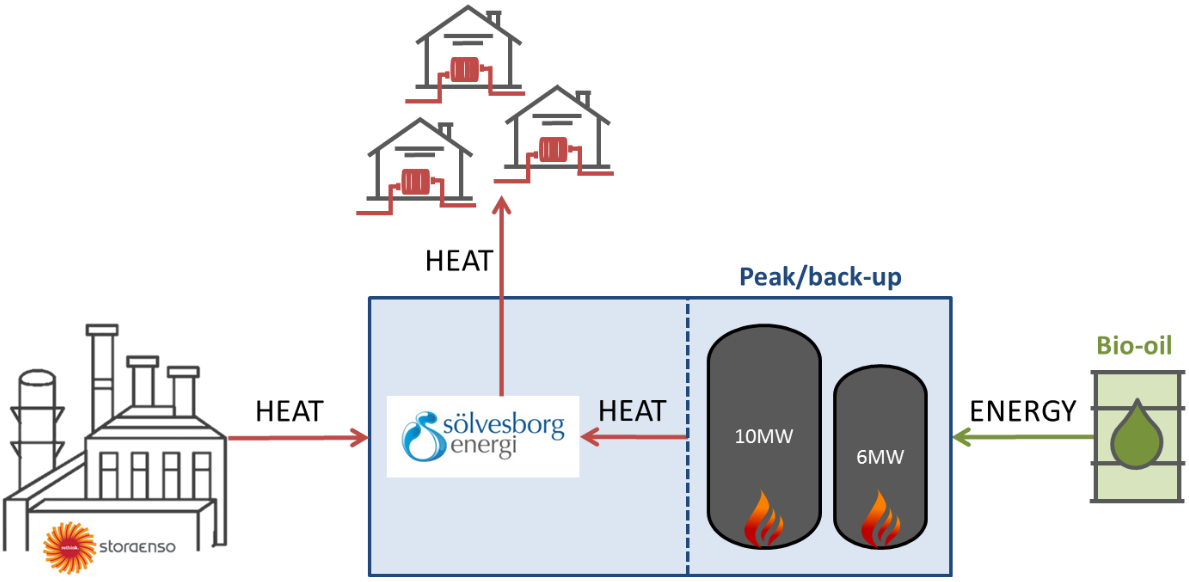

Figure 4: Suggested retrofit of the plant (Doris Matschegg)

The reason for the discussion on retrofit is primarily the company´s ambition to exclude the need of fossil fuels for the district heat production. The need of fossil fuel will be very close to zero, if the retrofit is carried out. The backup boiler for the backup will still be operated with fossil fuels, but on the other hand, the company has not used it the past ten years. By the help of the reports of the assessments, especially the techno-economic one with the pay-back period for the various options of biobased feedstocks estimated, the decision will be taken for retrofit or not. If a decision for a retrofit action is taken, the reports of the assessments will be one of the tools to choose the new feedstock.

Tentative timeline for the retrofit:

Dec 2018	ESS organise a first meeting with the case study company, the first of five meetings organised on a regular basis.

Feb 2019	Kick-off meeting for the case with the Case Study Team, in conjunction to the projects partner meeting in Jyväskylä, Finland, the first of four meetings organised on a regular basis.
Spring 2019	ESS meet suppliers of various types of liquid biofuels in order to get e.g. price, availability and experiences of handling and burning. ESS will collect experience of various bio oils from other companies which have carried out a conversion of the feedstock. ESS sends a compilation of their findings to Bioenergy 2020+ (BEST), CERTH and BTG.
Oct 2019	Written and oral report on findings from the sub-contracted consultant.
Dec 2019	Tecno-economic report from BTG and reports on environmental assessment (CERTH) and supply chain assessment (BEST).
Jan 2020	Presentation of reports from BEST, BTG and CERTH at Case study Team meeting #3. Insertion of the results from the three assessments, into this current report.
Mar 2020	Presentation from VTT about their digital tool and the implementation of the tool on the case, conjunction to the projects partner meeting in Karlshamn, Sweden.
May 2020	ESS organise the final meeting with the case study company.
Sep 2020	Final meeting for the case with the Case Study Team, where we discuss, among other, lessons learned and barriers for replication.
End of 2020	Decision of the board of Sölvesborgs Energi och Vatten on an investment, and later on a possible start of the process for purchase and installation.

4.3 Alternative to the retrofit

Sölvesborg Energi is dependent on supply of excess heat from the nearby pulp mill. Another municipal district heating provider, Bromölla Energi, is in the same situation, with a dependency on excess heat from the same pulp mill. These two municipalities are located close to each other with a common border. An alternative to the retrofit could be a joint owned new heat plant, where the existing boilers still could act as boilers to secure the heat deliveries as back-up and for peak-load. Such new facility could be considered investable if both of the district heating companies considered the risk for a termination of the agreement with the pulp mill, and hence an interruption of the heat deliveries, as high. There is, however, no plans for such a plant, and for that reason the only alternative to the retrofit is, for Sölvesborg Energi, to construct a new plant, a green-field scenario, to secure their own deliveries. This scenario is not realistic, since the capital expenditures are much higher in comparison to retrofit of the existing boilers. However, the green-field alternative is interesting in this report to give advice to policy makers about retrofitting in general of this kind of plants.

The capital expenditure for an investment according to the green-field scenario is roughly estimated. In general, the costs are approximately 90 – 110 EURO per kW. In this case, with

10 + 6 MW, the total expenditures should be close to 1.6 MEURO. Additional costs for adaptation to bio-oil are expected as marginal, probably less than 100,000 EURO. This applies to boilers that can be excepted to the regulation (2018:471) on medium-sized combustion plants, i.e. an annual time in operation of less than 1,000 h/a. Otherwise, investments have to be added to the figures, in order to secure to not exceed certain level of emissions of small particles. The cost for such filters, e.g. electrostatic precipitators are estimated to two times appr. 300,000 EURO, in total 600,000 EURO.

5 Supply Chain

The definition of value chain encompasses the full range of interlinked, value-adding activities that are required to make a product available to customers. The term s**upply chain** refers to the integration of all activities involved in the process of sourcing, procurement, conversion and logistics.[1]

In this case study, the supply chain assessment involves feedstock, logistics and storage. The supply chain describes an increasing share of bioenergy. Annually, about 51 GWh (in 2017) of heat is delivered from a nearby pulp mill. Additionally, there is 4.3 GWh of heat produced in the company owned boilers. The pulp mill uses up to 100% bioenergy, whereas the boilers owned by Sölvesborg Energi uses mineral oil, therefore the current share of annual bioenergy is 92.2%. In scenario 1, the 4.3 GWh from the company owned boilers would be generated by using bio-oils. The share of bioenergy would increase to 100%. In scenario 2 all of the heat would be generated by using solid biomass in company owned boilers, therefore the share of bioenergy would also be 100%. The following supply chain assessment is focusing on scenario 1.

5.1 Feedstock type and costs

Two types of biofuels are available and used on the Swedish market to replace fossil oil in back-up boilers:

- Bio-oils from by-products and residues (most common: used cooking oil)
- Biodiesel (RME)

The bio-oils are available in different specifications and qualities, depending on e.g. ash or sulphur content.

<u>Bio-oils from residues or waste (e.g. used cooking oil)</u>

Bio-oils are renewable, selected residual-products which are extracted from residue and waste streams from the food industry, the oleo chemical industry or biodiesel production,

[1] https://keydifferences.com/difference-between-supply-chain-and-value-chain.html

for instance. The bio-oil origins from e.g.: sunflower, rapeseed, soy or oil palm. Instead of becoming a waste, the bio-oils are utilized for heat and power generation in Swedish district heating or industry boilers.

Typical collection methods for used cooking oil (UCO) are the establishment of public collection points in gathering places, such as schools, supermarkets, municipal buildings etc. or local restaurants. Also, a door to door collection is possible, but less likely. (Cocchi & Ugge, 2013)[2].

The following regulation and directives of the European Legislation must be followed in the collection of UCO (Tsoutsos & Stavroula, 2013)[3]

- REGULATION (EC) No1013/2006 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 14 June 2006 on shipments of waste.
- Council Directive 1975/439/EEC of 16 June 1975 on the disposal of waste oils (75/439/EEC). Council Directive 1991/689/EEC of 12 December 1991 on hazardous waste (91/689/EEC)
- Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste.
- Directive 2006/12/EC of the EUROPEAN PARLIAMENT and of the COUNCIL of 5 April 2006 on waste.
- Directive 2008/98/EC of the EUROPEAN PARLIAMENT and of the COUNCIL of 19 November 2008 on waste and repealing certain Directives.

Most companies offer bio-oils with different qualities, i.e. cold resistance, ash content, nitrogen content etc. The quality that is used in different boilers depends on burner, cleaning system and possibilities to heat the bio-oil. Heavy bio-oils require constant heating of bio-oil storage tank and pre-heating before the burner. Light bio-oils and biodiesel are more cold resistant and do not require constant heating. However, these bio-oils and biodiesel often cannot withstand temperatures below -10°C and must be stored in insulated tanks or inside, if temperature falls further. The price of the different bio-oil qualities increases with lower ash and nitrogen content as well as increased cold resistance.

<u>Biodiesel (RME)</u>

Biodiesel is a renewable diesel produced from vegetable oil (e.g. rapeseed or sunflower oil) or oil residues (e.g. UCO, animal fat). Rapeseed methyl ester (RME) is produced with rapeseed oil. To produce biodiesel, this rapeseed oil has to be trans esterified and subsequently purified

[2] Cocchi, M., & Ugge, C. (2013). *Guidlines for UCO collection, transport and promotion campaigns based on previous experiences.* ETA-Florence Renewable Energies.

[3] Tsoutsos, T., & Stavroula, T. (2013). *Assessment of best practices in UCO processing and biodiesel distribution.* Technical University of Crete.

and distilled. As by-products, glycerine and bio heating oil are formed. The figure below shows the production process of biodiesel.

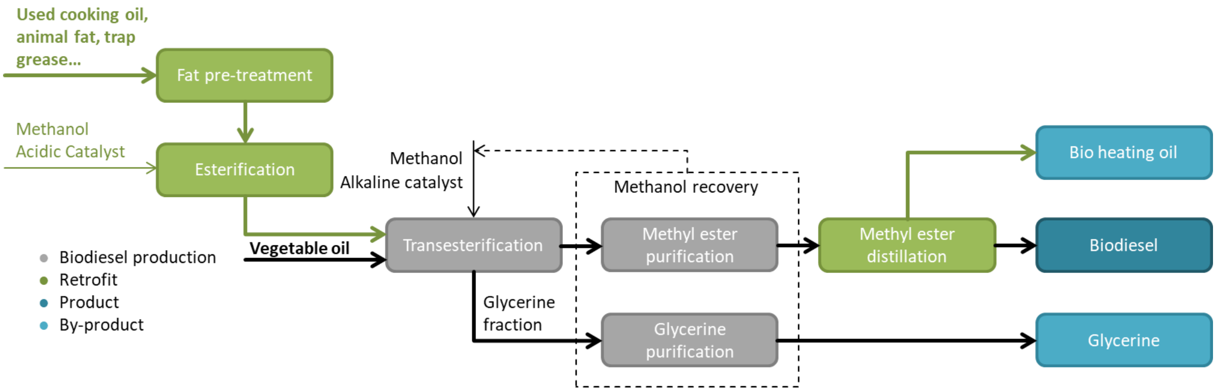

Figure 5: Biodiesel production process

The differences between bio-oils and biodiesel are that biodiesel has standardized characteristics (EN 14214) and has better quality regarding ash content and nitrogen. Biodiesel is more cold resistant than bio-oils and storage of biodiesel does not need constant heating in the storage tank. However, it is more expensive than all types of bio-oils.

Costs

In order to determine the costs of various bio-oils and RME, two regional suppliers were chosen: Vegoil for bio-oils and Ecobränsle for RME. The figures in the table below are indicative. They may differ within each categorized fuel. The indicative costs can be seen as an average figure over the last period of half a year. The rate of exchange from SEK to EURO is estimated to 1 EURO = 11.5 SEK. All prices are exclusive of VAT and refer to the net price, i.e. after any repayment of tax. The price of the different bio-oil qualities increases with lower ash and nitrogen content as well as increased cold resistance. Three bio-oils are given in the table below. The names are trademarks of the regional supplier. Bio 25 LAK has lower ash and nitrogen content compared to Bio 25. In addition, Bio 25 needs to be heated to 25 degrees. Bio -10 can handle a temperature down to minus 10 degrees. The bio-oils Bio -10, Bio 25 and Bio 25 LAK consist of 100% used cooking oil.

Table 2: Density, energy content and costs of various liquid fuels

Fuel	Density kg/m³	Energy content MWh/m³	Cost SEK/ton	Cost €/MWh
Mineral oil	840	9.94	11,300	83
RME	882	9.20	11,000	92
Bio -10	875	9.02	7,700	65
Bio 25 LAK	883	9.02	6,800	58
Bio 25	890	9.02	5,800	50

In the current situation, an annual average of 200 m³ of mineral oil (1,988 MWh/a) is used at Sölvesborg Energi. This corresponds to 216 m³ of RME and 220 m³ of bio-oil – see Table .

Table 3: Annual fuel utilization at Sölvesborg Energi

Fuel	Utilization m³/a	Utilization t/a
Mineral oil	200	168.0
RME	216	190.6
Bio -10	220	192.8
Bio 25 LAK	220	194.6
Bio 25	220	196.2

The boiler efficiency for all the fuels is estimated to be 95%.

Additionally, to the fuel price, the costs for fuel pre-heating, additional variable costs and yearly depreciation of the installations needed for the retrofit have to be considered. RME and Bio -10 do not need pre-heating and therefore no additional variable or heating costs have to be considered. Bio 25 LAK and Bio 25 need electricity for pre-heating with annual costs of about 1,700€. The costs [in €] for the annual fuel utilization are summarized in table 4.

Table 4: Annual fuel-related costs [€]

Fuel	Fuel costs	Ad. variable costs	Heating costs	Yearly depreciation*	Sum
Mineral oil	165,100	-	-	-	165,100
RME	182,300	-	-	3,880	186,180
Bio -10	129,200	-	-	3,880	133,080
Bio 25 LAK	115,100	9,100	1,700	11,330	137,230
Bio 25	99,000	9,100	1,700	11,330	121,130

**depreciation period of 15 years, interest not considered*

The cheapest fuel is Bio 25, even though there is a need for pre-heating. RME is the most expensive option and even more expensive than the current fuel. A more detailed calculation can be found in the techno-economic assessment.

5.2 Feedstock availability

<u>EU – Biodiesel trade</u>

Biodiesel is produced in nearly all Member States of the EU. Size and structure of the producers vary from farmers to multinational companies. The following table summarises production, import, export and consumption of biodiesel and HVO combined of the European Union. Production and export values stagnate whereas the import is increasing every year. Rapeseed oil is the most used feedstock for biodiesel and HVO production in the EU, accounting for 39% of total production in 2018. UCO (used cooking oil) is the second most important feedstock, making up 22% of total feedstock use in 2018.

Table 5: EU production, import and export of biodiesel and renewable diesel (HVO) in million litres (Flach, Lieberz, Bolla, & Phillips, 2019)

	2016	2017	2018	2019
Production	14,384	15,373	14,442	14,170
Import	629	1,097	3,366	3,400
Export	408	397	664	420
Consumption	14,610	16,020	16,854	17,380
Rapeseed oil use	6,587	6,848	5,652	5,435
UCO use	2,848	3,011	3,109	2,989
Consumption Sweden	1,613	1,772	1,674	1,610

Production and consumption of biodiesel in the EU nearly match. The import rates are comparably small but increasing since several years. The EU is not exporting biodiesel in a relevant magnitude.

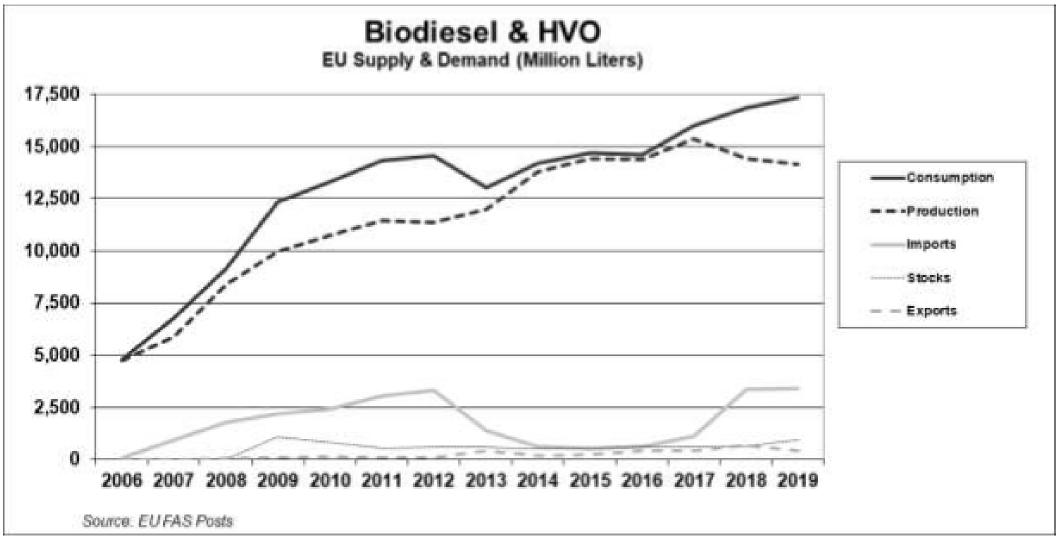

Figure 6: EU supply and demand of biodiesel and HVO (Flach, Lieberz, Bolla, & Phillips, 2019)

In 2018, the most important suppliers of biodiesel for the EU were Argentina, Indonesia Malaysia and China. Other suppliers, but with much smaller amounts are Norway, Taiwan, Bosnia & Herzegovina and India. (Flach, Lieberz, Bolla, & Phillips, 2019)[4].

[4] Flach, B., Lieberz, S., Bolla, S., & Phillips, S. (2019). *EU Biofuels Annual 2019.* USDA Foreign Agricultural Service.

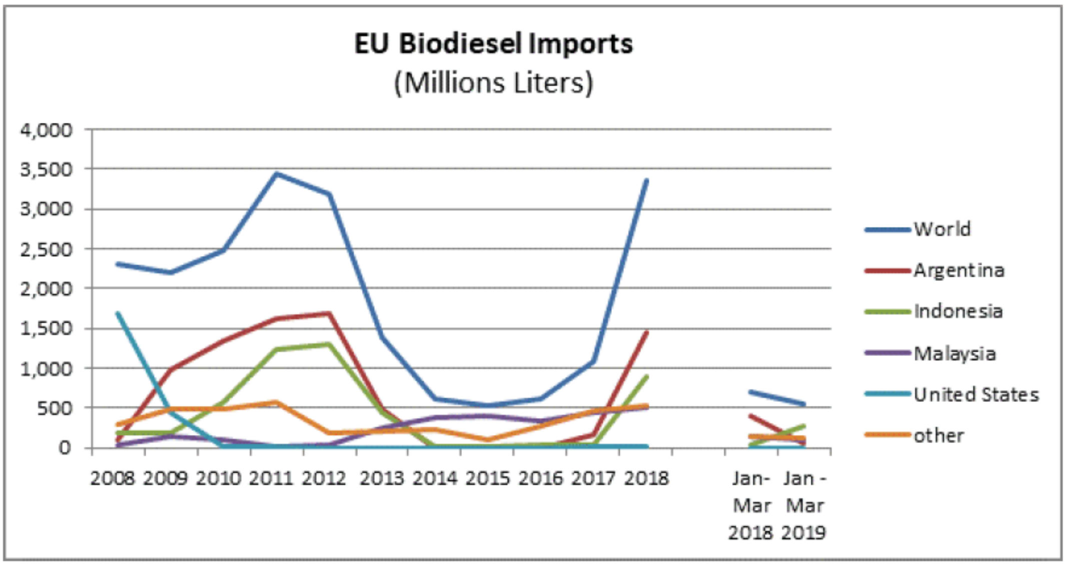

Figure 7: EU biodiesel imports (Flach, Lieberz, Bolla, & Phillips, 2019)

Sweden – Biodiesel and bio-oil consumption

There is a big variety of bio-oils and biodiesel available in Sweden and the import and export of these products for heating purposes exclusively is hard to estimate, since the biggest quantities are used as transport fuel. Sweden is using comparably high amounts of biodiesel and HVO (number 4 in the EU – see Table .), but is producing just a small amount of it. 85 % of the liquid biofuels used in Sweden for transportation or heat production are imported. Annually, about 4.5 TWh (450,000 tonnes) of bio-oils are consumed in Sweden, again primarily by the transport sector. There is a net exportation of bioethanol in Sweden.

Table 6: Biodiesel consumption

Table 10. EU Biodiesel/HVO Consumption Main Consumers (Million Liters)

Calendar Year	2011	2012	2013	2014r	2015r	2016r	2017r	2018e	2019f
France	2,624	2,653	2,658	2,931	2,954	2,954	2,954	3,025	3,025
Germany	2,756	2,874	2,581	2,752	2,483	2,498	2,522	2,644	2,600
Spain	1,921	2,563	941	1,036	1,091	1,293	1,546	1,979	2,275
Sweden	289	415	569	805	1,129	1,613	1,772	1,674	1,610
Italy	1,654	1,598	1,447	1,269	1,581	1,132	1,488	1,333	1,360
UK	1,034	493	863	839	736	724	750	1,100	1,200
Poland	1,079	837	843	730	795	909	954	966	970
Belgium	344	354	364	375	436	452	573	572	610
Austria	576	567	575	708	710	641	572	600	600
Finland	137	131	195	469	475	119	385	392	400
Others	1,949	2,072	2,064	2,587	2,329	2,275	2,504	2,697	2,730
Total	14,363	14,556	13,100	14,502	14,719	14,610	16,020	16,854	17,380

r = revised / e = estimate / f = forecast EU FAS Posts. Source: FAS EU Posts based on information collected in mt, then converted to liters using a conversion rate of 1 mt = 1,136 liters for biodiesel and 1,282 liters for HVO.

The biodiesel consumption in Sweden is expected to decrease in future, due to the abolition of tax waivers for biodiesel in connection with the introduction of a GHG reduction target for the diesel sector on July 1, 2018. The GHG reduction target pushes the use of UCO as a feedstock, yet the overall use of UCO will decrease due to decreasing amounts of biodiesel production. Additionally, local legislation cut the use of palm oil-based biofuels because of traceability issues. (Flach, Lieberz, Bolla, & Phillips, 2019)[5].

Sweden – Biodiesel and bio-oil suppliers

Several companies in Sweden supply the market with bio-oil in different qualities and quantities. Vegoil supplies several district heating companies with bio-oil close to Sölvesborg Energi. Vegoil is the company situated closest to Sölvesborg Energi, with storage tanks for bio-oil in Sölvesborg. The vegetable oil company AAK is situated in Karlshamn, 30 km from Sölvesborg. AAK sells small amounts of residues (bio-oil) from their vegetable oil production to e.g. district heating companies.

Some companies providing bio-oils on the Swedish market:

- Vegoil
- Energilotsen
- Wibax
- West energy
- Biofuel express
- AAK

There are four large companies providing standardised RME in Sweden. Ecobränsle is part of Energifabriken since the beginning of 2019. Ecobränsle and Adesso (former Perstorp) both produce and sell RME. Sthlm Biodiesel provides and sells biodiesel but is not a RME producer.

Companies providing biodiesel on the Swedish market:

- Ecobränsle (owned by Energifabriken since 2019)
- Energifabriken
- Sthlm Biodiesel
- Adesso

The biodiesel production at Ecobränsle is located in Karlshamn, only 30 km away from Sölvesborg. The biodiesel produced at Ecobränsle is of high quality and is mostly utilized and sold as transportation fuel. However, the biodiesel is also sold for heating purposes to several district heating companies, also close to Sölvesborg Energi.

[5] Flach, B., Lieberz, S., Bolla, S., & Phillips, S. (2019). *EU Biofuels Annual 2019.* USDA Foreign Agricultural Service.

5.3 Logistics

Vegoil is an important supplier of bio-oils in the region, and Ecobränsle is an important supplier of RME, thus these two will serve as examples, one for bio-oils and one for biodiesel.

Bio-oil

The bio-oil is delivered by suppliers of Vegoil by boat to a tank depot at the harbour in Sölvesborg, or to a rented tank near the customer. The bio-oils originate from different places around Europe. The tanks in the depot are fully optimized for bio-oils and consist of five tanks of a total volume of 10,000 m³. That indicates a continuous stock of different qualities. The tank depot is flexible and receives boat deliveries of 2,000 - 4,500 tonnes per boat load with several different kinds of bio-oils. The tanks are kept warm with three boilers (250 kW each), which are using their own bio-oil as feedstock since 2008. The distance between the tank depot at the harbour and the boiler of Sölvesborg Energi is approximately 2km.

In most cases the bio-oil is delivered from the depot in Sölvesborg to the customer's tank by tank trucks from a nearby transport enterprise (Börjes tankservice). The bio-oil has a temperature between 45°C and 55°C when it is delivered to the client. It is filtered in automatic filters with a maximum of 0.2 mm size. Deliveries to clients with less consumption can also be made in containers of 1 m³. The trucks run on commercially available diesel fuel with a low proportion of biodiesel.

Vegoil is keen to act in a sustainable way, and so, for instance, all companies they hire for transport are certified according to ISO9000, ISO14001 and Euro5.

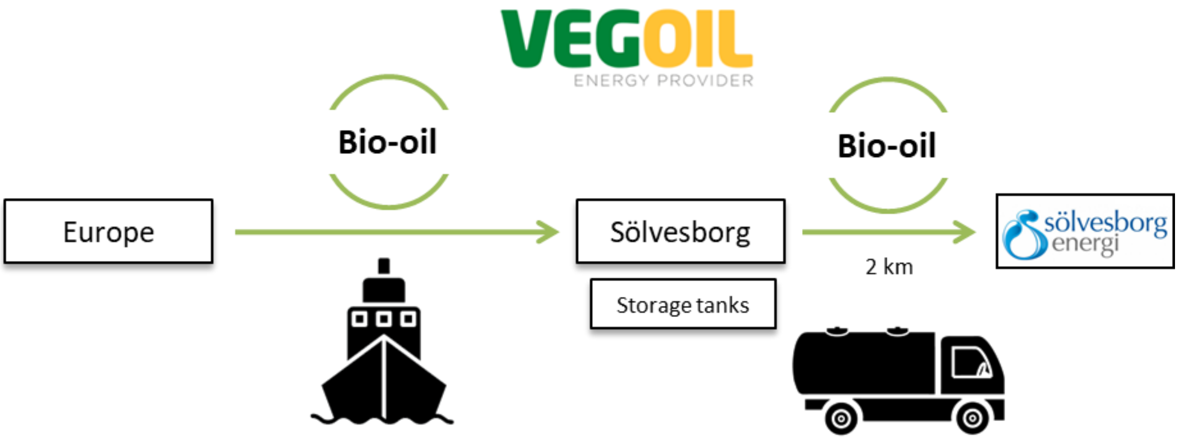

Figure 8: Vegoil logistics

<u>Biodiesel</u>

Most of the rapeseed for the biodiesel production is delivered from Norrköping, around 400 kilometres from Karlshamn, where both a rapeseed crusher and the biodiesel producer Ecobränsle are located. Karlshamn is about 30 km from Sölvesborg. Ecobränsle´s biodiesel production is linked to the largest rapeseed crushing plant in the Nordic countries, jointly owned by AAK and Lantmännen Energi. The rapeseed oil is supplied to the RME production via pipeline from the crusher. The crusher also provides the RME production with steam and heat, based on biofuels. RME produced in Karlshamn is transported to Sölvesborg by tank truck. The yearly production is 50,000 m³ RME. The by-product glycerol is sent to Denmark for use in biogas production.

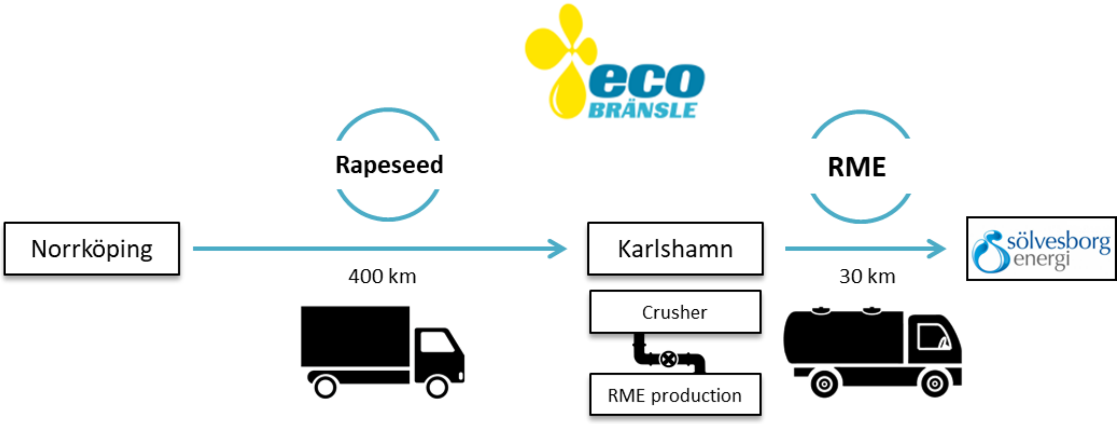

Figure 9: Ecobränsle logistics

5.4 Set up of the value chain

5.4.1 Bio-oil

To sum up, three different bio-oils with different qualities, made from UCO, are considered as resources. The producers of the bio-oils are unknown and vary; the supplier used as example here is the Swedish company Vegoil. UCO is collected in different European

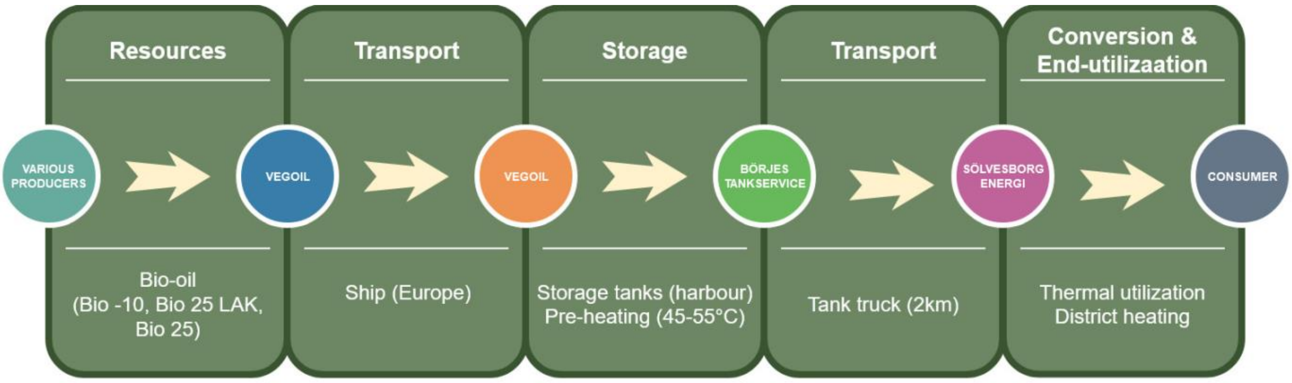

Figure 10: Overview value chain bio-oil

countries and shipped to Sweden. From the storage, where the heavy bio-oils need to be heated, it is transported to Sölvesborg Energi. At Sölvesborg Energi´s own storage additional investments are necessary for heating of the heavy bio-oil tanks. (See techno-economic assessment for more details) The bio-oil shall be burned in the back-up boiler of Sölvesborg Energi for thermal utilization. The generated heat of the back-up boiler will complement the heat delivery from a nearby StoraEnso pulp mill (51 GWh), when needed. The heat is transported through pipes (560 connections) to 1,900 costumers, in order to provide district heating. (See technical description for more details)

5.4.2 RME

To sum up, rapeseed is collected near Norrköping and delivered by truck 400km to a crusher close to Karlshamn. There, the rapeseed is transported through a pipeline to the RME producer Ecobränsle. The RME is further transported to Sölvesborg Energi by tank truck. RME does not need pre-heating. The RME shall be burned in the back-up boiler of Sölvesborg Energi for thermal utilization and subsequent district heating, as described above for the bio-oil value chain. (See technical description for more details)

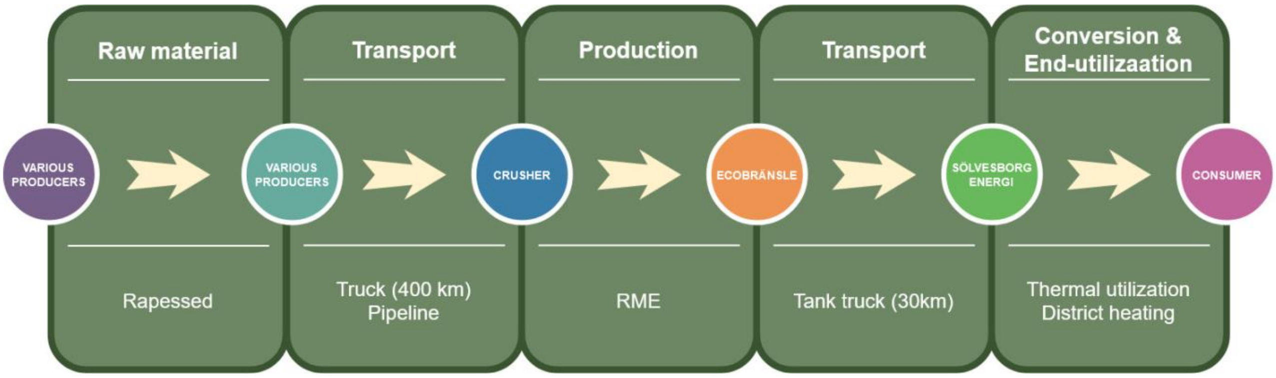

Figure 11: Overview value chain RME

5.4.3 Conclusion

In order to decide for a specific fuel, several aspects have to be considered. In this chapter bio-oils and RME are compared with respect to fuel costs, fuel availability, quality, legal framework and storability.

Heavy bio-oils (Bio 25 LAK, Bio 25) require constant heating, which include additional investment costs, but they are cheaper, compared to light bio-oils (Bio -10) or RME. Overall fuel-related costs are cheapest for Bio 25 (see Table).

Another important aspect is fuel availability. Generally, Sweden has a high import dependency regarding UCO and biodiesel.[6] The GHG reduction targets for the diesel sector in Sweden in 2018 pushed the use of UCO. But, due to a decreased biodiesel production in Europe, also the use of UCO, which is the second most used feedstock for biodiesel production, is expected to decrease.[7] If less UCO is needed, import rates will temporary fall and vice versa. This indicates a consistent availability for UCO based bio-oils. The availability for biodiesel, including RME, is expected to remain good, due to excess production capacity. The resulting price development is unsure for all of these fuels. Long-term contracts could enable security of supply and a certain price level for some time.

Generally, handling of RME and bio-oil is quite similar to each other. One difference is fuel quality standards. While the Standard EN 14214 ensures the quality of biodiesel, there is no standard for UCO based bio-oils. Using a waste stream and different collection methods could lead to quality issues. The survey undertaken by ESS indicates that heat suppliers in Sweden had experienced some quality issues when using bio-oil some years ago. Over recent years, these issues were mitigated and now the quality of bio-oils in Sweden is satisfactory.

The RED II includes GHG emission reduction targets, which will be regularly revised and updated. RME is a conventional biofuel and therefore in risk to not fulfil future targets. UCO however is listed as advanced biofuel source, because of using waste streams as fuels or feedstock. Therefore, UCO is to prefer, according to this aspect.

The required size of the storage tank depends on how often fuel is delivered. If the fuel is delivered only once a year the tank needs to have full capacity. If the fuel is delivered more often, the time of delivery is important to know, in order to ensure security of supply. One has to keep in mind that RME as well as bio-oils are perishable and should be used within one year. Therefore, the supply has to be planned carefully and a solution for eventual residues should be found beforehand for both resources.

From a supply chain point of view, bio-oil is to prefer over RME.

5.5 Market assessment

The conversion and the end-utilization is not changing in this case study, therefore a market assessment has not been conducted.

[6] https://www.greenea.com/wp-content/uploads/2016/11/Argus-2016.pdf

[7] https://apps.fas.usda.gov/newgainapi/api/report/downloadreportbyfilename?filename=Biofuels%20Annual_The%20Hague_EU-28_7-15-2019.pdf

6 Techno-economic assessment

6.1 Technical description

In this technical description, we first discuss the process characteristics of the current situation and each of the four retrofit options. In general, Sölvesborg Energi purchases waste heat from the pulp and paper mill of Stora Enso. Sölvesborg Energi has back-up and peak-load boilers, owned by themselves, in order to secure heat deliveries to their district heating clients. The major inputs and outputs are identified for each process and are described in figure 13.

The two heating boilers have a total capacity of 16 MW. The plant has been in operation for 5.000 hours since the start of operation in 2008, which corresponds to about 500 hours per year. There are two main sources for their electricity demand. The first source that requires electricity is the water circulation from the pulp mill. The pump is running continuously with a maximum capacity of 90 kW. The second source is the production of heat at the two boilers at Sölvesborg Energi, which requires a total of 5 MWh per year of electricity. The used electricity mix exists almost exclusively of non-fossil fuels (i.e. hydro and nuclear).

Currently, fossil oil is consumed in the two heating boilers. The oil consumption in the boilers is estimated at 200 m^3 per year. Taking the density of fossil oil (840 kg/m^3), this corresponds to 168 tonnes of fossil oil per year. The fossil oil is sent to the boilers and is converted into heat. Fossil oil has an energy content of 9,94 MWh/m^3. With a consumption of 200 m^3 fossil oil, this results in 1988 MWh per year. The heat produced by the boilers is sent to the district heating clients for back up and peak load. This fossil oil-based process is a benchmark to all four retrofits, showing that at least 1988 MWh of heat is required per year to secure heat deliveries.

There are two retrofitting options that use a lighter bio-oil in RME and Bio-10 (**Fehler! Verweisquelle konnte nicht gefunden werden.**B). RME has a higher density (882 kg/m^3) but lower energy content (9,2 MWh/m^3) compared to fossil oil. Consequently, more feedstock is required to produce the required 1988 MWh of heat per year. This holds true for Bio-10 as well, due to its higher density (875 kg/m^3) and an even lower energy content (9,02 MWh/m^3) than RME. Calculations show that 190,6 tonnes of RME and 192,8 tonnes of Bio-10 is required to achieve sufficient heat production. To realise a properly functioning process of combusting these bio-oils, adjustments to the boiler is required. Furthermore, the oil and ventilation system need to be reconstructed. As such, perforating a wall of the building is necessary to achieve this retrofit.

Finally, two heavy bio-oils, Bio-25 and Bio-25 LAK, could be used in the retrofit as well (Figure 13C). Both Bio-25 and Bio-25 LAK have a lower energy content (9,02 MWh/m^3) than fossil oil (9,94 MWh/m^3), which results in a higher amount of Bio-25 or Bio-25 LAK required to satisfy the energy demand. At least 196,2 tonnes of bio-25 and 194,6 tonnes of Bio-25 LAK is required to produce the required 1988 MWh per year. The same adjustments to the boiler and the reconstruction of the oil and ventilation system are required as for RME and Bio-10. Because the heavy bio-oils have to be preheated to 25°C, additional equipment needs to be installed. This is equipment such as an electricity supply for the heating of the fuel in the tanks and the pipes, as well as equipment for regulation and monitoring.

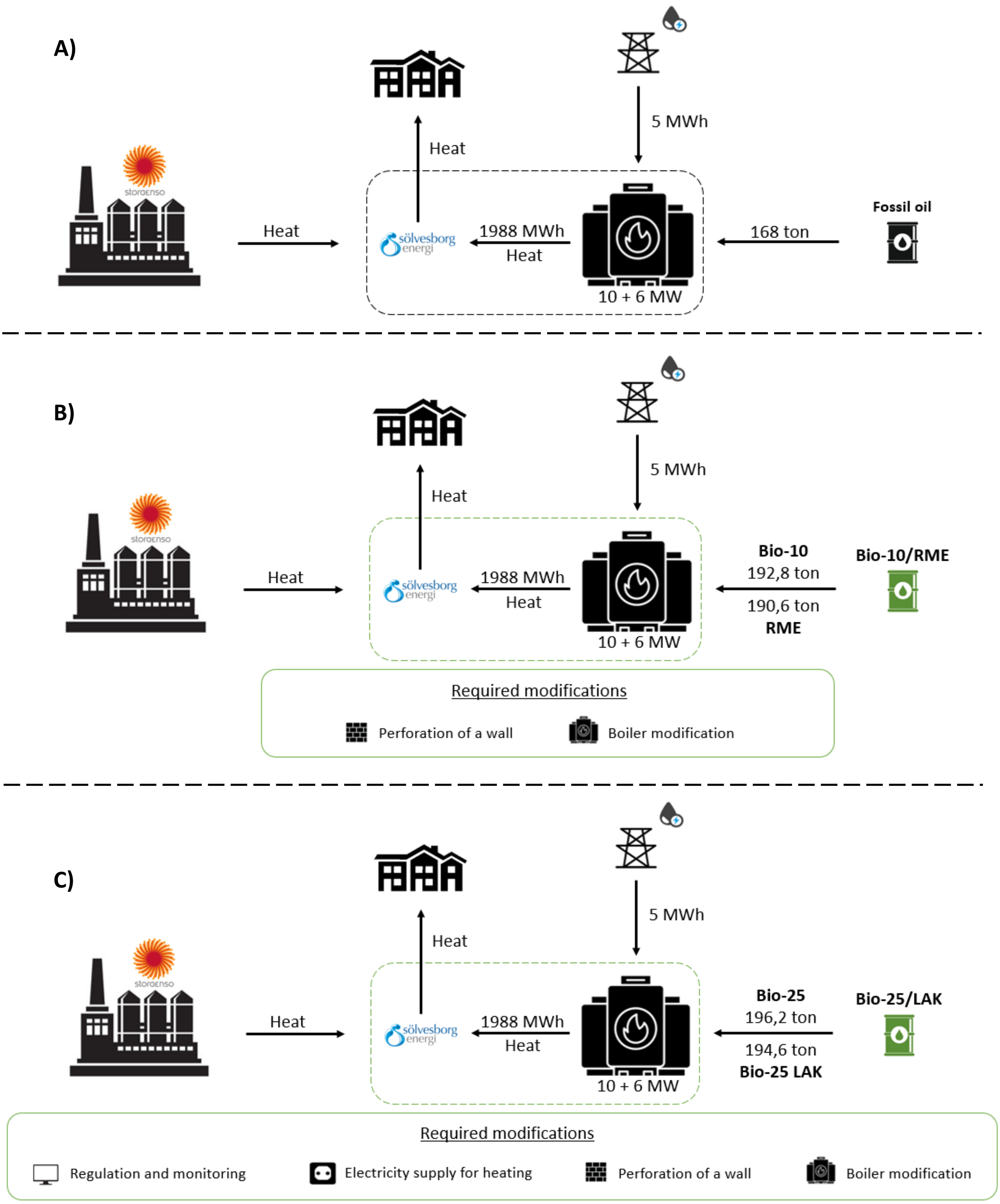

Figure 12: Technical overview of the current situation and the four potential retrofits. A) Current technical situation. B) Retrofit situation of Bio-10 and RME. C) Retrofit situation of Bio-25 and Bio-25 LAK.

6.2 Economic description

Bioenergy is one of the pillars of the EU renewable energy transition towards a low carbon economy. One way in which bioenergy production can be increased is through retrofitting. In this specific case, the utilization of bio-oil in the existing central heating boilers of Sölvesborg Energi och Vatten will be investigated. This assessment addresses the economic feasibility of four different bio-oils, including biodiesel (RME), Bio-10, Bio-25 and Bio-25 LAK. The costs of such bio-oil based CHP plants will be compared to the costs of the currently operating fossil oil-based CHP plant. The total capital costs (CAPEX) and operating costs (OPEX) are required as input for the economical comparison between each retrofitting option.

The input data for the economic assessment are described in Table . As for the CAPEX, the costs can be divided into two categories. The first category represents "light" bio-oils, which do not require preheating (i.e. RME and Bio-10). Alternatively, the second category necessitates preheating the "heavy" bio-oils (i.e. Bio-25 and Bio-25 LAK). Retrofitting the first category involves modifying and/or exchange of the burner, parts of the oil system and pipes for filling. In addition, it involves the disassembly of old pipes for filling, the exchange of oil pipes between tanks and burner, insulation, tuning of new parts, and the installation of equipment for heating of the fuel in the tanks. These costs are combined into a single cost,

Table 7: Input data of light oils (RME and Bio-10) and heavy oils (Bio-25 and Bio-25 LAK) used for the economic assessment.

	Fossil	RME	Bio-10	Bio-25	Bio-25 LAK
Financing (CAPEX)					
Project Costs	€0	€17.400	€17.400	€17.400	€17.400
Modification costs boiler	€0	€36.500	€36.500	€139.600	€139.600
Retrofit heating equipment costs	€0	€0	€0	€3.500	€3.500
Costs for regulation and monitoring	€0	€0	€0	€2.600	€2.600
Perforation of a wall	€0	€2.600	€2.600	€5.200	€5.200
Incidental costs	€0	€1.700	€1.700	€1.700	€1.700
Financing (OPEX)[a]					
Costs for increased use of maintenance	€0	€0	€0	€6.500	€6.500
Costs for consumable materials	€0	€0	€0	€2.600	€2.600
Costs for heating of tanks and pipes	€0	€0	€0	€1.700	€1.700
Electricity costs	€142.812	€142.812	€142.812	€142.812	€142.812
(Bio)Fuel costs	€165.076,80	€126.124,13	€182.298,09	€98.930,88	€115.074,32
Fuel properties					
Density (kg/m^3)	840	882	875	883	890
Energy content (MWh/m^3)	9.94	9.2	9.02	9.02	9.02
Boiler efficiency	95%	95%	95%	95%	95%

referred to as "modification costs boiler". Furthermore, retrofitting for light oils requires the perforation of a wall of the building as a consequence of

[a] On a yearly basis

reconstructing the oil and ventilation system. As for the heavy oils, the above-mentioned costs also apply, but are significantly higher compared to the light oils. Due to the heavy nature of Bio-25 and Bio-25 LAK, there are additional investments required such as costs for electricity supply intended for heating of the fuel in the tanks and the pipes between the tanks and burner, and costs for regulation and monitoring of additional equipment. An estimation of the project costs (i.e. contracting) was given by Sölvesborg Energi and is similar for each retrofit. Besides the yearly utility costs and fuel costs, three additional OPEX items were identified for the heavy oils. These are costs regarding increased use of maintenance, additional consumable materials, and the heating of tanks and pipes.

Several values obtained from external sources are described in Table , with the fuel costs included separately in Table . The electricity price represents the price established for households in Sweden in March 2019. Furthermore, the discount rate was selected in accordance with the market stability, fluctuations in electricity price and the average inflation rate. For instance, the energy demand in Sweden for heating in households is expected to decrease significantly due to energy efficiency actions in buildings. This poses a risk for the district heating market stability. Because a nominal discount rate of 4-6% is often used for public actors in Sweden, and due to certain risks involved, the discount rate has been set to 7%. Financial benefits have been identified (i.e. Green Certificate System) for all bio-oils and the project lifetime is fixed to 12 years, operating 500 hours each year. The fuel costs were retrieved from Table 7 and are converted to euro per ton. The price of fossil oil is higher than all bio-oils. In addition, the price of the different bio-oils increases proportionate to the decrease in resistance to low temperature.

Table 8: Values extracted from other (external) sources

Item	Value
Electricity price	€0,18[8]
Discount rate	7%[9]
Project lifetime	12 years
Operational hours	500 h/year
Financial benefits	€25.000/year[10]

Table 9: Fuel costs

Item	Price (€/ton)
Fossil oil price	982,6
RME price	956,5
Bio-10 price	669,5
Bio-25 price	504,3
Bio-25 LAK price	591,3

6.3 Economic assessment

For each of the retrofitting options, a cash flow analysis was carried out. The metrics considered in this assessment are net present value (NPV), internal rate of return (IRR), and the payback period of the retrofit investment. The simple payback period (t_P), i.e. the

[8] https://www.globalpetrolprices.com/Sweden/electricity_prices/
[9] Bjorn Berggren, M. W. (2019). LCC ANALYSIS OF A SWEDISH NET ZERO ENERGY BUILDING – INCLUDING COBENEFITS
[10] https://blogs.dnvgl.com/energy/scandinavian-wind-without-subsidies

amount of time required to regain the value of the original investment, is calculated from the capital investment (C_0) and the annual cash flow (R_C):

$$t_p = \frac{C_0}{R_C}$$

NPV is an indicator of how much value an investment or project adds to the business. When the NPV is positive, the retrofit is feasible because value is added to the business. The NPV is determined by the sum of the future cash flows (C_t) generated by the investment over a series of time periods (t). The NPV is a function of the discount rate (i) and utilization period (n) of the investment:

$$NPV = \sum_{t=0}^{n} \frac{C_t}{(1+i)^t}$$

Finally, the IRR is the average interest rate paid per year. The IRR of an investment is the discount rate at which the net present value of costs of the investment equals the net present value of the benefits of the investment. In other words, IRR can be found when NPV equals zero. More profitable investments will have a higher IRR than investments of low profitability.

The results from the cash flow analysis are shown in Figure 14. Comments to the figure: Metrics of Bio-10: Net Cashflow; €60.952,67, Cumulative Cashflow[a]; €673.232,08, IRR[a]; 105%. Metrics of RME: Net Cashflow; €7.778,71, Cumulative Cashflow[a]; €35.144,55, IRR[a]; 8%. Metrics of Bio-25: Net Cashflow; €80.345,92, Cumulative Cashflow[a]; €794.151,03, IRR[a]; 47%. Metrics of Bio-25 LAK: Net Cashflow; €64.202,48, Cumulative Cashflow[a]; €600.429,73, IRR[a]; 37%. [a] Over a period of 12 years.
The orange bars represent the cumulative cashflow, determined by adding the annual net cashflow to the overall project investment. The blue bars represent the net cashflow, resulting from the annual profits gained from OPEX saving through retrofitting. The grey area represents the yearly internal rate of return, calculated for the project lifetime of 12 years.

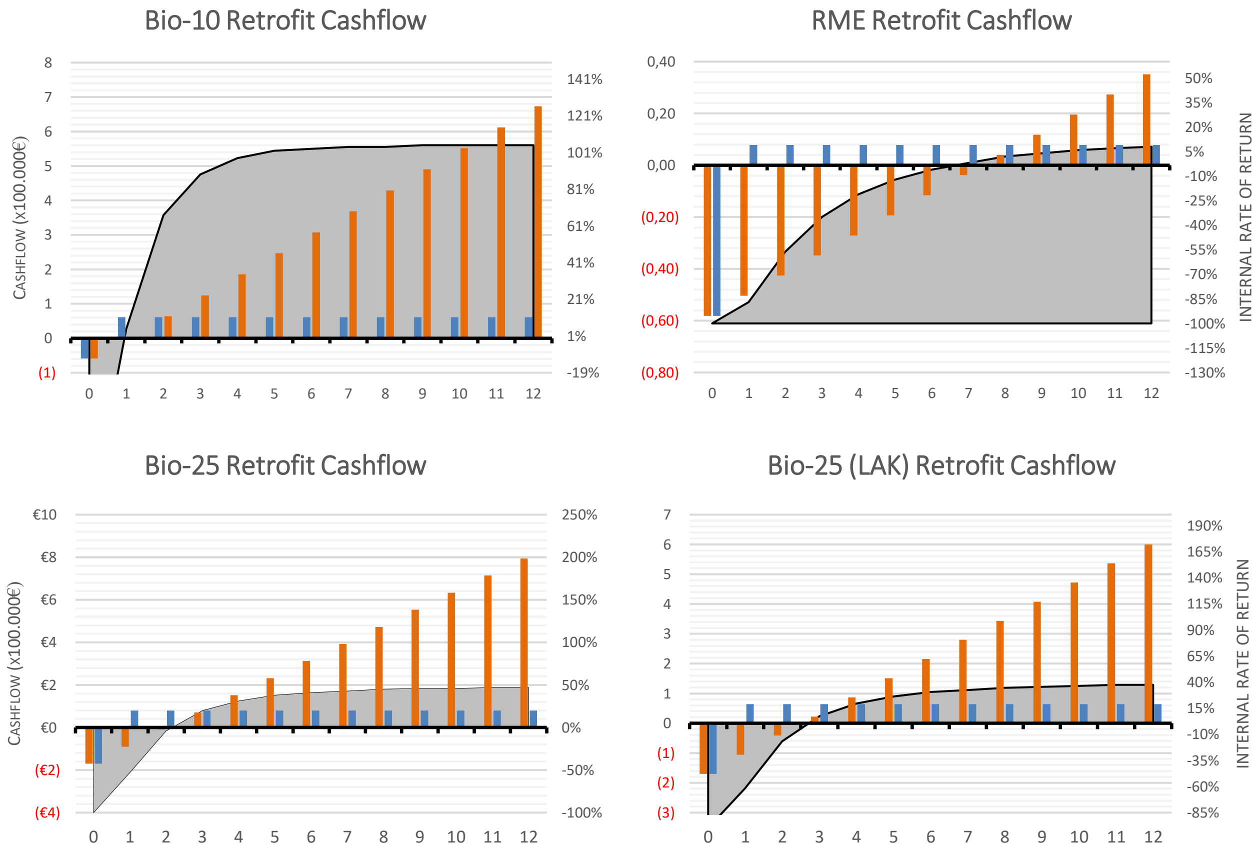

Figure 13: Cashflow charts of the four retrofits over a period of 12 years.

Here, the net cashflow is determined by the difference in OPEX between the specific retrofit and its fossil comparator. A positive net cashflow means lower OPEX requirements as opposed to fossil oil utilization. The yearly OPEX savings remain constant and thus identical cashflows are obtained each year. The increase in cumulative cashflow is the result of a constant positive net cashflow. The higher the cumulative cashflow, the more profit is earned over the project lifetime. For the IRR, a larger surface above the x-axis signifies a superior net return. Furthermore, the position where the line crosses the x-axis denotes the year where the total investment is regained. An analogous pattern can be observed for all retrofit cashflows. Year 0 denotes the time of investment and thus a negative cashflow is observed. Dependent on the OPEX difference between the specific retrofit and the current fossil situation, the net cashflow shows the yearly profit gained when implementing the retrofit. The yearly profit remains the same over the entire project lifetime, reflecting the constant net cashflow shown in Figure 14. The accumulation of these OPEX savings, beginning from the initial investment, is the actual cumulative cashflow of the project. The main, and most obvious difference is the IRR of each retrofit. The IRR is an important metric to determine the economic feasibility and will be further discussed in section 'Determining economic feasibility by means of IRR'.

Determining economic feasibility by means of NPV

A positive NPV indicates that the projected earnings generated through retrofitting, exceeds the anticipated investment. Only investments with positive NPV values should be considered. Figure 15 depicts the NPVs of the four retrofit options. The lowest NPV is observed for RME, with just over €3.000 added to the business. The NPV of the other retrofits are observed well above €300.000, where Bio-25 adds the most value to the business (€437.535). The low NPV for the RME retrofit is a reflection of the low IRR of the investment and can be attributed to the high feedstock costs. Although the Bio-10 retrofit option clearly results in the highest IRR, it does not result in the highest NPV. The main reason for this, is that the net cashflows of the Bio-25 retrofit is higher compared to the other retrofits. This ultimately results in a higher value of the project.

Determining economic feasibility by means of IRR

The economic feasibility is not only determined by using the NPV, but often collectively with the IRR of the project. The Bio-10, Bio-25 and Bio-25 LAK retrofits all show IRR values significantly higher than the discount rate with an IRR of 105%, 47% and 37% respectively

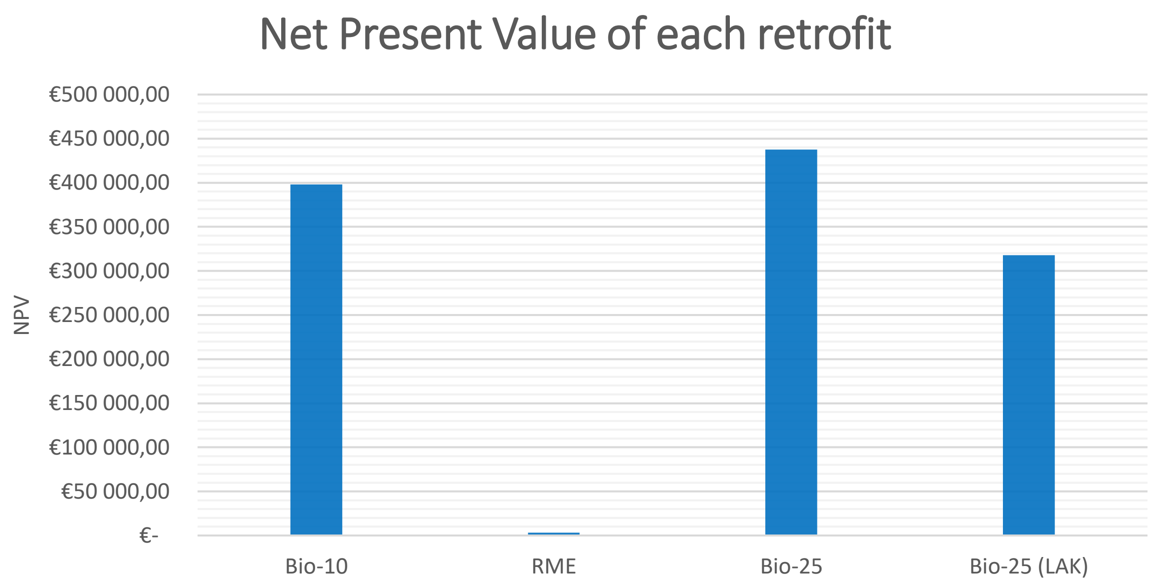

Figure 15: Net Present Value of each retrofit option. The determination of the NPV is the sum of the future cash flows (Ct) generated by the investment over a series of time periods (t). The NPV is a function of the discount rate (i) and utilization period (n) of the investment. NPV is calculated over a time period of 12 years, with a discount rate of 7%.

versus a discount rate of 7% per year, which indicates the economic viability of these three retrofitting options. This can be explained by the lower feedstock costs compared to fossil oil. The IRR of the RME retrofit is only 1% higher than the discount rate. This suggests that retrofitting RME is economically feasible, however, the viability of this retrofit greatly depend on the subsidy it entails. Without the green subsidy the project is economically infeasible. The reason that the IRR of the "heavy" bio-oils are lower than the IRR of Bio-10, is the total amount of the investment. However, it is important to mention that while the IRR of "heavy" oils are lower, the net cashflows and therefore the cumulative cashflows, are higher for these oils. This is due to greater OPEX savings resulting from lower feedstock costs (Table).

IRR sensitivity analysis

A sensitivity analysis was performed to test the robustness of the economic assessment. To understand the impact of fluctuations in the input values on the conclusions of the economic assessment, three main variables were considered: Feedstock costs, OPEX and CAPEX. A 10% variation was applied on the three variables. Figure 16 contains spider charts showing the impact of the three variables on the IRR of the four retrofits. The orange line represents the impact on OPEX change, the blue line represents the impact on feedstock costs fluctuations and the grey line represents the impact on CAPEX change. By looking at the spider charts, the nature of the relationship is readily observed. Figure 16 shows that all relationships are linear. In this way, the sensitivity towards a variable can be determined by the slope of the

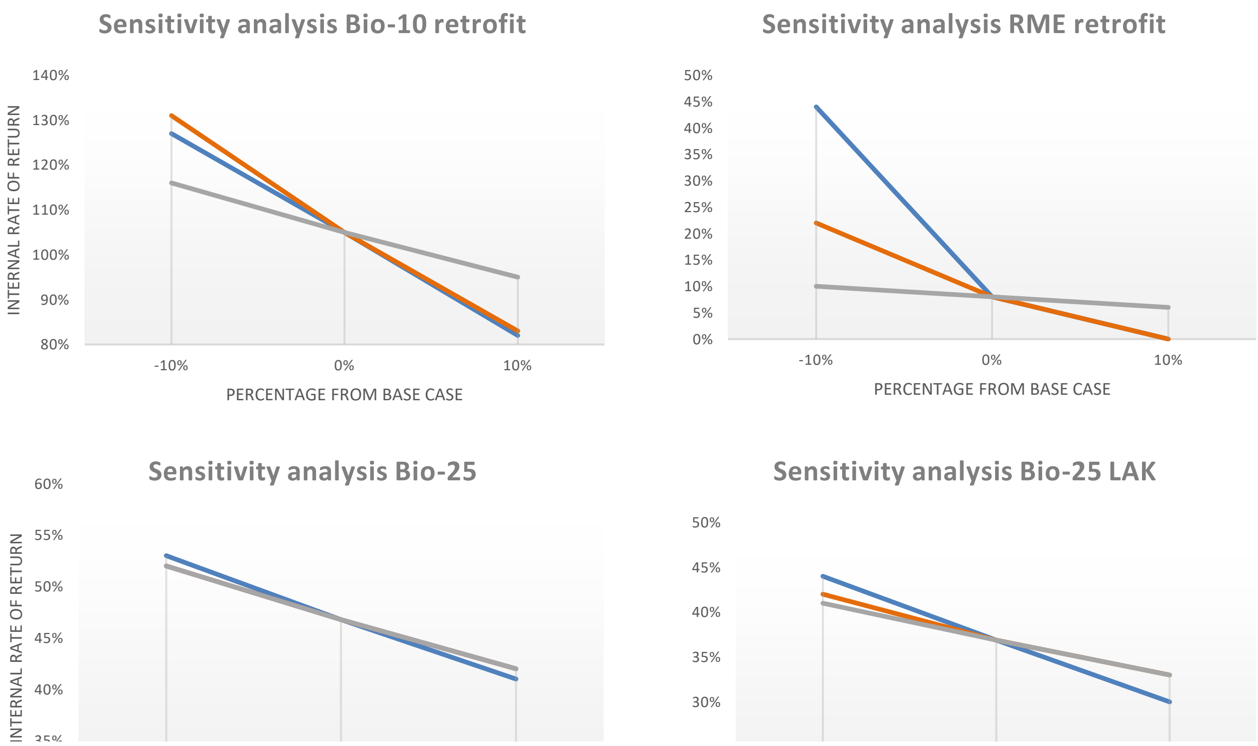

Figure 14: Sensitivity analysis for the impact of feedstock costs, OPEX, and CAPEX on the internal rate of return for all proposed retrofits. The orange line represents the impact on OPEX change. The blue line represents the impact on feedstock costs fluctuations. The grey line represents the impact on CAPEX change. The orange line in the Bio-25 sensitivity graph is not visible as it is covered by the grey which shows an identical sensitivity.

line (i.e. a steeper line implies greater sensitivity). As expected, there is a negative correlation with all three variables. The highest sensitivity is observed between feedstock costs and internal rate of return. The “heavy” bio-oils are less affected by changes in feedstock costs as opposed to the “light” bio-oils. For instance, a 10% increase in Bio-10 feedstock costs results in a 23% decrease in IRR, while a 10% increase in Bio-25 feedstock costs results in a 6% decrease in IRR. The difference in IRR reduction between RME and the “heavy” bio-oils after a 10% increase in feedstock costs is even larger. Because the Bio-10 and RME feedstocks are more expensive, the OPEX rises more significant than the “heavy” bio-oils. Consequently, the annual net cashflow drops proportionate to the OPEX elevation, causing the IRR to drop. In case of retrofitting RME, a mere 1,5% increase in feedstock costs renders this option economically infeasible. Changes in CAPEX does not significantly affect the IRR outcome. The grey line in Figure 16 generates the smallest slope of all three impact items. An increase in CAPEX impose minor effects on the net cashflow and thus the IRR value is only slightly affected.

General discussion

The economic feasibility of the four retrofits was determined by using economic metrics, such as IRR and NPV. In addition, a sensitivity analysis was performed to understand the impact of variation in three variables on the economic feasibility. According to the metric values, RME appears to be economically feasible as it shows an IRR of 8% and an NPV of €3.349. Yet, this retrofit option can be declared infeasible if the costs of the bio-oil increase with 1,5%. The Bio-10 retrofit shows the highest IRR value. Because the investment is relatively low for the “light” bio-oils (€58.200), and the net cashflow relatively high (€60.953), an IRR value of 105% is obtained corresponding to a payback period of slightly less than 1 year. The NPV of this retrofit after a 12-year period is €398.064. These findings render this retrofit option attractive. Still, the sensitivity towards changes in feedstock costs must be considered as it affects the IRR value significantly. As the metric values already suggest, retrofitting Bio-25 is also feasible as it shows a positive IRR and an NPV of €437.535. Due to the relatively high investment for the “heavy” bio-oils (€170.000), and at the same time showing the highest net cashflow (€80.346), an IRR value of 47% is obtained corresponding to a payback period of 2,1 years. Since the net cashflow obtained through retrofitting is the highest observed for Bio-25, it also resulted in the highest NPV observed despite the relatively high investment. Finally, the Bio-25 LAK retrofit is also feasible considering the positive IRR value and an NPV of €317.701. As with the other “heavy” bio-oil, the relatively high investment in conjunction with a relatively high net cashflow (€64.202) results in a reasonable IRR value of 37%, corresponding to a payback period of 2,6 years.

Conclusion economic assessment

From the economic assessment it can be concluded that retrofitting Bio-10, as well as the “heavy” bio-oils are economically feasible. Retrofitting RME is only economically feasible due to the green subsidy it entails. On top of this, a mere 1,5% increase in feedstock costs renders this option economically infeasible. In this sense, although positive metrics values were obtained, this retrofit option is exposed to a high risk.

Bio-10 shows a superior IRR value combined with a payback period of less than 1 year. Such an option would be preferred when the project involves high risk and, as a consequence, necessitates quick payback of the investment. Ultimately, retrofitting bio-10 adds €398.064 to the business. Yet, Bio-25 adds more value to the business even though the initial investment is significantly higher compared to Bio-10. The period in which the investment is regained is marginally longer as opposed to Bio-10, however, is not of great concern considering the low risks involved. The Bio-25 LAK retrofit shows comparable metrics values to Bio-25 but is less profitable. This is mainly due to the difference in bio-oil costs. Nonetheless, retrofitting Bio 25 LAK is a viable option, especially in combination with its low sensitivity towards unforeseen changes in OPEX and CAPEX, and fluctuations in bio-oil costs. As such, from an economical point of view, Bio-25 would be the preferred option if there are no financial constraints. On the contrary, if certain boundary conditions are fixed (e.g. investment ceiling), Bio-10 would be the preferred option.

7 Sustainability assessment

7.1 Social aspects

The identified most important social aspects of the retrofit action are described. The proposed retrofit action has itself only small influence on social aspects, but on the other hand there are several similar plants throughout Europe with the possibility to convert from mineral oil, or other fossil fuels, to renewable light or heavy bio-oil, whether the retrofitted facility is the main facility for heat or combined heat and power production, or if it is a boiler for backup and peak load.

The combustion of bio-oil is a new experience for the company and for the technicians, hence there will be a learning for the staff. However, no formal training of the technicians or other staff members are necessary, because of the low grade of complexity, and in addition there are experience from this feed-stock at other district heating providing companies nearby, so the experience exchange will be secured by the networking with the technicians at these companies together with the bio-oil provider.

A decision for a retrofit investment will contribute to some different types of job opportunities. The retrofit action itself with e.g. efforts for project management, design, reconstruction and installation will create some job opportunities. Increased efforts from the technicians for operation and maintenance are foreseen, especially for the operation in the short run after the reconstructed facility has been taken into operation. However, for the current Case Study Company, it will not result in new job opportunities, but included in the tasks for existing staff, since the efforts are foreseen to be small. Various renewable feedstocks are pointed out as possible options for the conversion. The final choice of fuel will imply different possibilities for regional/national job opportunities. Bio-oil is, to a large extent, imported from other countries, e.g. Mid-Europe, while RME in general is produced in Sweden. Conversion to some sort of bio-oil will not have a significant impact on national or regional job opportunities, taken into consideration the extraction of the fuel. If, on the contrary, RME is chosen, new job opportunities along the value chain, both nationally and regionally, will appear, e.g. growers of rapeseed, collection, transport to the crusher in Karlshamn, processing rapeseed to RME, storage and finally transport to the plant in Sölvesborg.

The conversion of feedstock, either it is to bio-oil, RME or other biodiesel, implies increased possibility for national or EU-wide self-sufficiency of the fuel. From a national point of view, RME is preferable. The conversion strengthens national initiatives to import/extract renewable fuels for heat and combined heat and power production. The conversion to a renewable fuel is an act in se for increased security of supply, since the extraction/production is decentralised, in comparison to mineral oil.

The estimated pay-back period is short for some of the renewable feedstocks pointed out as possible options for the conversion. Hence, the Case Study Company may choose a fuel which will affect the local economy in a positive way. The company is fully owned by the municipality of Sölvesborg and the investment for conversion will consequently be able to affect the citizens' daily life.

Safety for technicians will not be affected by conversion of the feedstock, neither if the new feedstock is heavy nor light bio-oil. The emissions from the combustion process will be altered, when changing the feedstock from a fossil fuel to a renewable one. Except emissions of carbon dioxide, the content in the flue gases will be changed depending on many factors e.g. the content of various substances in the fuel. The concentration of e.g. small particles in the flue gases from bio-oil, in particular heavy bio-oil, are supposed to be higher in comparison to combustion of mineral oil. The concentration is dependent on combustion equipment e.g. the burner and, hence varies from one boiler to another. The conversion will not entail less concentration of all substances in the flue gases. The concentration of the most important substances needs to be measured on site, to get more precise data.

Traffic from trucks and other physical influence of the environment nearby the site of the plant as a result of the retrofit action are small. The number of trucks providing the plant with the feedstock will not be substantially affected, since the energy content in mineral oil and bio-oil is close to the same. The reconstruction phase is short and will not affect the physical environment significantly.

7.2 Policy issues: RED

As part of the EU2020 climate and energy package, the European Union passed a major directive on bioenergy and biofuels in 2009 "The Renewable Energy Directive (RED) (2009/28/EC)"[11]. The RED set targets for renewable energy consumption, including a sub-

[11] Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of

target mandating 10% of energy used in transport to be produced with renewable sources. This directive also introduced a set of sustainability criteria excluding biofuels produced on land with high biodiversity value or carbon stocks and fuels made from feedstocks originating from recently deforested land or drained peatland. Furthermore, biofuels were required to provide at least a 35% GHG reduction compared to fossil fuels in order to be accounted in the renewable energy target and to be eligible for public financial support.

In November 2016, the European Commission published a large package of measures in its "Clean Energy for all Europeans"[12] initiative. As part of this package, the Commission adopted a legislative proposal for a recast of the Renewable Energy Directive (RED II[13]). The European Parliament and the EU Council proposed amendments and a final compromise deal among the EU institutions was agreed on 14 June 2018[14]. This policy update provides an overview of the provisions relating to transport fuels in the final compromise document.

In RED II, the overall EU target for Renewable Energy Sources (RES) consumption by 2030 has been raised from the originally proposed 27% to 32%. The Commission's original proposal has been reintroduced in the final agreement for RES in the transport sector: Member states must require fuel suppliers to supply a minimum of 14% of the energy consumed in road and rail transport by 2030 as renewable energy. The exact trajectory to achieve these targets will be defined for each member states in the Integrated National Energy and Climate Plans. These plans will be designed by each member state following the guidelines set out in the Energy Union Governance Regulation[15].

Within the 14% transport target, there is a sub-target for advanced biofuels produced from feedstocks in Part A of Annex IX, including rape seed. These fuels must be supplied at a minimum of 0.2%[16] of transport energy in 2022, 1% in 2025 and increasing to at least 3.5%

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the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC, Official Journal of the European Union, L 140/16, April 23, 2009. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex%3A32009L0028

[12] "Clean Energy for All Europeans" DG Energy, European Commission, accessed March 7, 2018. https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/clean-energy-all-europeans

[13] Kristine Bitnere, The European Commission's renewable energy proposal for 2030, (ICCT: Washington, DC 2017). https://theicct.org/sites/default/files/publications/RED%20II_ICCT_Policy-Update_vF_jan2017.pdf

[14] General Secretariat of the Council of the European Union, Interinstitutional file, Proposal for a Directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources - Analysis of the final compromise text with a view to agreement, 21 June 2018. https://www.consilium.europa.eu/register/en/content/out?&typ=ENTRY&i=LD&DOC_ID=ST-10308-2018-INIT

[15] European Commission, DG Energy, 'Governance of the Energy Union'. Accessed on 07/03/2018. https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/governance-energy-union

[16] All percentages in this list refer to the total final energy consumed in the road and rail transport sector.

by 2030. Advanced biofuels will be double counted towards both the 3.5% target and towards the 14% target. Biofuels produced from feedstocks in Part B of Annex IX, including used cooking oils (UCO), will be capped at 1.7% in 2030 and will also be double counted towards the 14% target.

The maximum contribution of biofuels produced from food and feed crops will be frozen at 2020 consumption levels plus an additional 1% with a maximum cap of 7% of road and rail transport fuel in each member state. If the total share of conventional biofuels is less than 1% by 2020 in any member state, the cap for those countries will still be 2% in 2030. Further, if the cap on food and feed crops in a member state is less than 7%, the country may reduce the transport target by the same amount. Fuels produced from feedstocks with "high indirect land-use change-risk" will be subjected to a more restrictive cap at the 2019 consumption level, and will then be phased out to 0% by 2030 unless they are re-evaluated and certified as "low indirect land-use change-risk." "Low indirect land-use change-risk" feedstocks include those that are produced on land that was not previously cultivated.

7.3 Methodology: Environmental assessment

In line with the RED II, the following process steps should be considered in the life cycle analysis of bio-oil and biodiesel:

- ✓ cultivation/extraction of feedstocks;
- ✓ carbon stock changes caused by land use change;
- ✓ emissions from processing;
- ✓ emissions from transport and distribution;
- ✓ emissions from the liquid in use;
- ✓ emission savings from carbon capture and geological storage;
- ✓ emission savings from carbon capture and replacement; and
- ✓ use of the co-products.

It should be noted that all the aforementioned processes are directly linked to bio-oil and biodiesel production, while others outputs in the production phase, such as electricity and heat, are not taken into account.

A simplified approach for the LCA conducted in this work [17] is described in the RED II. According to the Directive, it is imperative to carry out the GHG emission analysis and quantify the GHG savings for each bioliquid brought in the EU market. The GHG emissions from both the production and utilization of bioliquid are calculated as (EU 2018):

$$E = e_{ec} + e_{l} + e_{p} + e_{td} + e_{u} - e_{sca} - e_{ccs} - e_{ccr} \ [\text{g } CO_{2eq}/MJ_{bioliquid}]^{18}$$

where:

E = total emissions from the use of the bioliquid;

e_{ec} = emissions from the extraction or cultivation of raw materials;

e_{l} = annualized emissions from carbon stock changes caused by land-use change;

e_{p} = emissions from processing;

e_{td} = emissions from transport and distribution;

e_{u} = emissions from the liquid in use;

e_{sca} = emission savings from soil carbon accumulation via improved agriculture management;

e_{ccs} = emission savings from carbon capture and geological storage; and

e_{ccr} = emission savings from carbon capture and replacement.

As stated in the Directive, the effect of machinery and equipment manufacturing is not investigated.

Including the energy conversion from the utilization of the bioliquid to produce heat, in case of energy installations delivering only heat, the total GHG emissions are calculated from the equation:

$$EC_h = \frac{E}{\eta}$$

where:

[17] A "full LCA approach" according to ISO 14 040 of transportation biofuels might result in most cases in a higher GHG emission and thus lower GHG saving compared to the simplified approach of REDII.

[18] The emission (E) can be negative if the emission savings (e.g. e_{ccr}) are higher than the emissions (e.g. e_{p}, e_{td}).

EC_h = total GHG emissions from the final energy commodity;

E = total GHG emissions of the liquid before end-conversion;

η = the heat efficiency, defined as the annual useful heat output divided by the annual fuel input, based on its energy content.

Since there is no energy loss, "η" is equal to 1.

According to RED II, the default percentage of GHG emission savings from the production of vegetable oil from waste cooking oil lies between 83 to 98%. Regarding the production of pure oil, as reported in part C of the Directive, in Annex IV, the default value for cultivation 'e_{ec}' is zero and the relevant value for processing 'e_p' is estimated to be 0.8 gCO_{2eq}/MJ. The corresponding value for transport and distribution 'e_{td}' is 1.4 gCO_{2eq}/MJ. The total emissions for all the aforementioned processes, i.e. cultivation, processing, transport and distribution, amount to 2.2 gCO_{2eq}/MJ. Similarly, as far as the production of hydrotreated oil is concerned, the relevant disaggregated default values for cultivation 'e_{ec}', processing 'e_p', and transport and distribution 'e_{td}' are 0, 14.3 and 1.7 gCO_{2eq}/MJ, respectively. The total emissions are estimated to be 16 gCO_{2eq}/MJ. It should be noted that the aforementioned values estimated (i.e. 2.2 gCO_{2eq}/MJ and 16 gCO_{2eq}/MJ) taking into account that the pure oil derives from waste cooking only after the purification process, and the hydrotreated oil is produced using steam and electricity. As expected, both purification process and heat/electricity consumption contribute to GHG emissions. These processes have been considered towards to achieve a fair comparison with current scenario in environmental terms. The processes are included in the process named "heat production from boilers" in the following environmental impact estimations. On the other hand, the default percentage of GHG emission savings from the production of rape seed biodiesel is 47%. The disaggregated default value for cultivation 'e_{ec}' is 32 gCO_{2eq}/MJ while the corresponding values for processing 'e_p' and transport and distribution 'e_{td}' are 16.3 gCO_{2eq}/MJ and 1.8 gCO_{2eq}/MJ, respectively. The total emissions for all the aforementioned processes, i.e. cultivation, processing, transport and distribution, are estimated at 50.1 gCO_{2eq}/MJ.

7.3.1 Boundaries of system

The system boundary of the process chain is shown diagrammatically in Figure 15 and Figure 16 for the current and the retrofit scenario, respectively. It involves: (i) the extraction of raw materials, (ii) their transport, (iii) their storage in tank and pre-heating before their processing, (iv) their processing to produce heat.

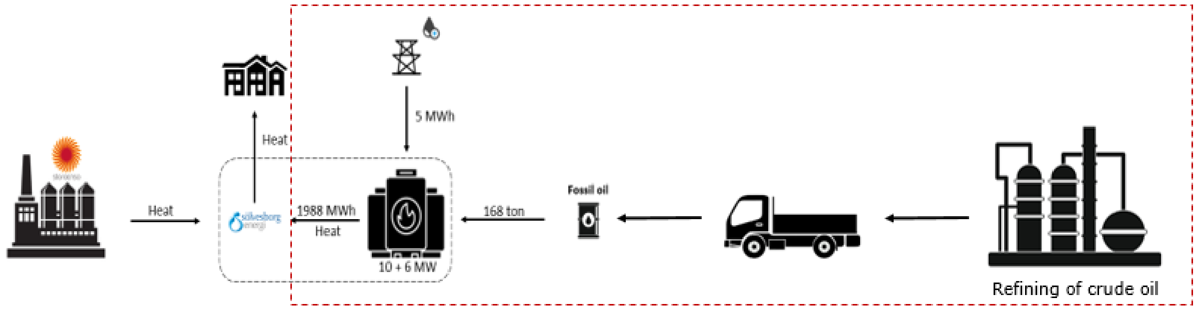


Figure 15: System boundaries for GHG calculation for the current scenario

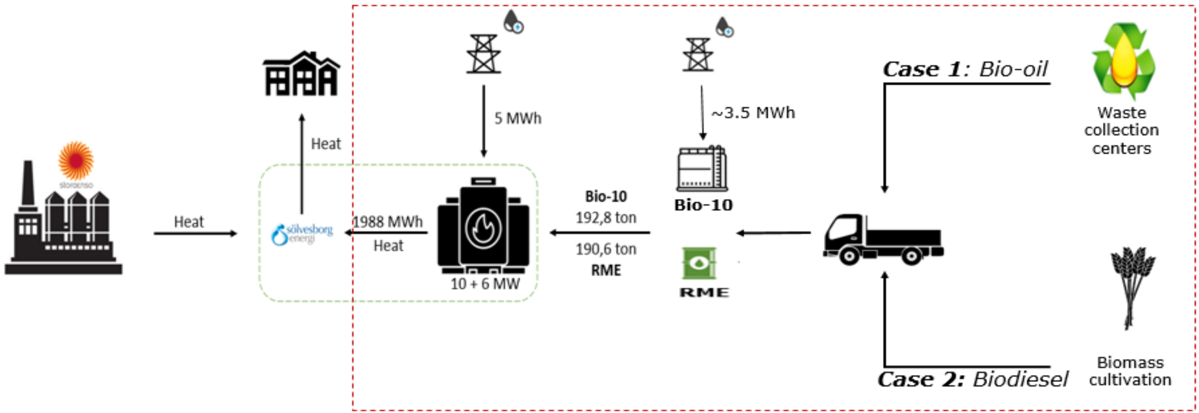


Figure 16: System boundaries for GHG calculation for each case study of the retrofit scenario

As reported in the RED II in ANNEX V, article 18, no life-cycle GHG emissions are associated with waste and residues (including agricultural residues directly from the field), as well as residues from processing, up to the process of their collection, irrespectively of whether they are processed to interim products before being transformed into the final product. With respect to this article, no life-cycle GHG emissions are associated with the UCO up to the process of collection. As a result, the emissions derived from the extraction/cultivation of raw material are not taken into account in the production process of the bio-oil up to the stage of collection (i.e. $e_{ec} = 0$ in the equation of total GHG emissions of bioliquids). Moreover, no carbon capture and geological storage are considered in the plant.

The flow diagram of transport of raw material in both the current and retrofit scenarios are shown analytically in Figure 17 and Figure 18, respectively. In the current scenario, the transportation route begins in Gothenburg (Sweden). Then, the raw material is transported by boat to the harbor of Malmö or Helsingborg (Sweden) and lastly by truck to the plant.

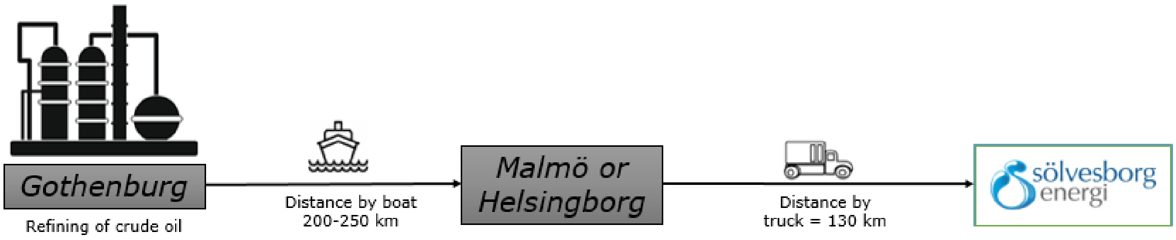


Figure 17: Transport connection of mineral oil from extraction to distribution to plant

Regarding the retrofit scenario, two cases are investigated. In the first case, the bio-oil is collected in Europe, transported by boat from the harbor of Amsterdam or Rotterdam to the harbor of Sölvesborg and, then, transferred by truck to the Sölvesborg plant. In the second case, the rapeseed crop is collected in Norrköping and transported by truck to Karlshamn where RME biodiesel is produced. It is assumed that a mass percentage of 40% oil is contained in the seed. The final product is transported by truck to the plant.

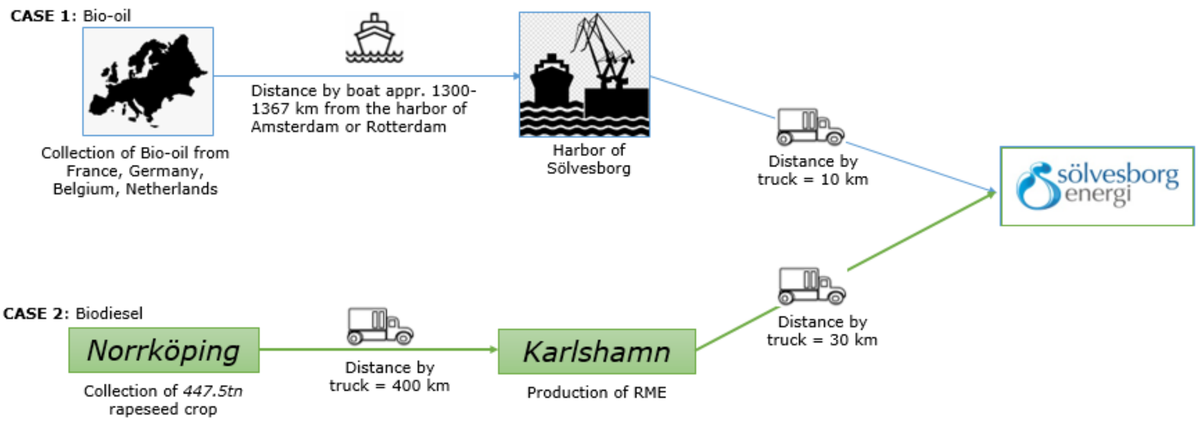


Figure 18: Transport connection of bio-oil/ biodiesel from collection to distribution to plant for each case study

7.3.2 Functional Unit

The functional unit provides the reference to which all other data in the product systems are normalised. Based on the RED II, the functional unit can be defined and quantified as follows (EU 2018): "*Greenhouse gas emissions from bioliquids, EC, in terms of grams of CO_2-equivalent per MJ of final energy commodity (heat), gCO_{2eq} /MJ* ".

The GHG emission savings from bio-oil or biodiesel are calculated as (EU 2018):

$$SAVING = (EC_{F(h)} – EC_{B(h)}) / EC_{F(h)}$$

where:

EC_B = total emissions from the bio-oil or biodiesel in [g CO_{2eq}/MJ]

EC_F = total emissions from the fossil fuel comparator in [g CO_{2eq}/MJ]

In RED II (Annex V, part B in paragraph 19) referred that:

"*For bioliquids used for the production of useful heat the fossil fuel comparator $EC_{F(h)}$ shall be 80 gCO_{2eq}/MJ*. "

The GHG emission savings from using bioliquids for producing electricity, heating and cooling should be at least (i) 70 % for installations that will start to operate after 1 January 2021, and (ii) 80 % for installations that will start to operate after 1 January 2026. An installation is expected to operate after starting the physical production of bioliquids, alongside heating, cooling, and electricity for biomass fuels.

7.4 Results

The environmental performance of both the current and the retrofit scenarios employing the SimaPro software is presented in the following sections. For the life-cycle environmental analysis, the IMPACT 2002+ methodology was implemented. Note that all processes assumed are in accordance with the database Ecoinvent v3 of SimaPro software. The Life Cycle Impact Assessment methodology IMPACT 2002+ represents a combined mid-point/ damage-oriented approach; it links all types of life cycle inventory results throughout 14 mid-point categories to four damage categories, i.e. (i) human health, (ii) ecosystem quality, (iii) climate change and (iv) resources.

7.4.1 The current situation

Regarding the current scenario, all input data compilation of materials, energy flows and environmental releases of the analyzed process (see Figure 15) are included in the environmental analysis. More specifically, the system boundaries include:

- The extraction process of crude oil (from the Gothenburg of Sweden), including the energy used for the conversion of unrefined crude oil to refined oil;
- The transportation of raw material from the extracted point to the processing plant (see Figure 17), including the fuel used in each mean of transport;
- The electricity from Swedish national electricity grid required for the operation of boilers;
- The heat that produced from the boilers, including the used fuel oil and the electricity needing for the proper operation of the boiler.

The total annual amount of GHG emissions is calculated to 670 $tnCO_{2eq}$. The contribution of the emissions of each stage of the process with respect to the Global Warming impact category is illustrated in Figure 19. It can be observed that boilers perform worst in terms of GHG emissions (>95%). This is largely associated with the pollutants released (PM10, PM2.5, NO_x, PAH, CO, SO_x) from the combustion process. On the other hand, the process related to the extraction of crude oil has minor environmental impact (<4%) in the global warming impact category. This is mainly due to the releases of some toxic substances to the environment during the mining process. Moreover, GHG emissions associated with the transportation stage are almost negligible. This is, perhaps, attributed to the fact that emissions from shipping include mainly nitrogen and sulfur oxides, instead of CO_2 emissions. Last, but not least, electricity consumption is nearly free of GHG emissions (<1%), mainly because the Swedish electricity generation mix is dominated by renewable energy resources.

Table 1: Emissions in each stage of current process

Processes	**Emissions ($tnCO_{2eq}/a$)**
Crude oil extraction	25
Heat production from boilers	643
Electricity utilization	0.141
Transport of crude oil from the extraction point to plant	1.703
Total	**669.844**

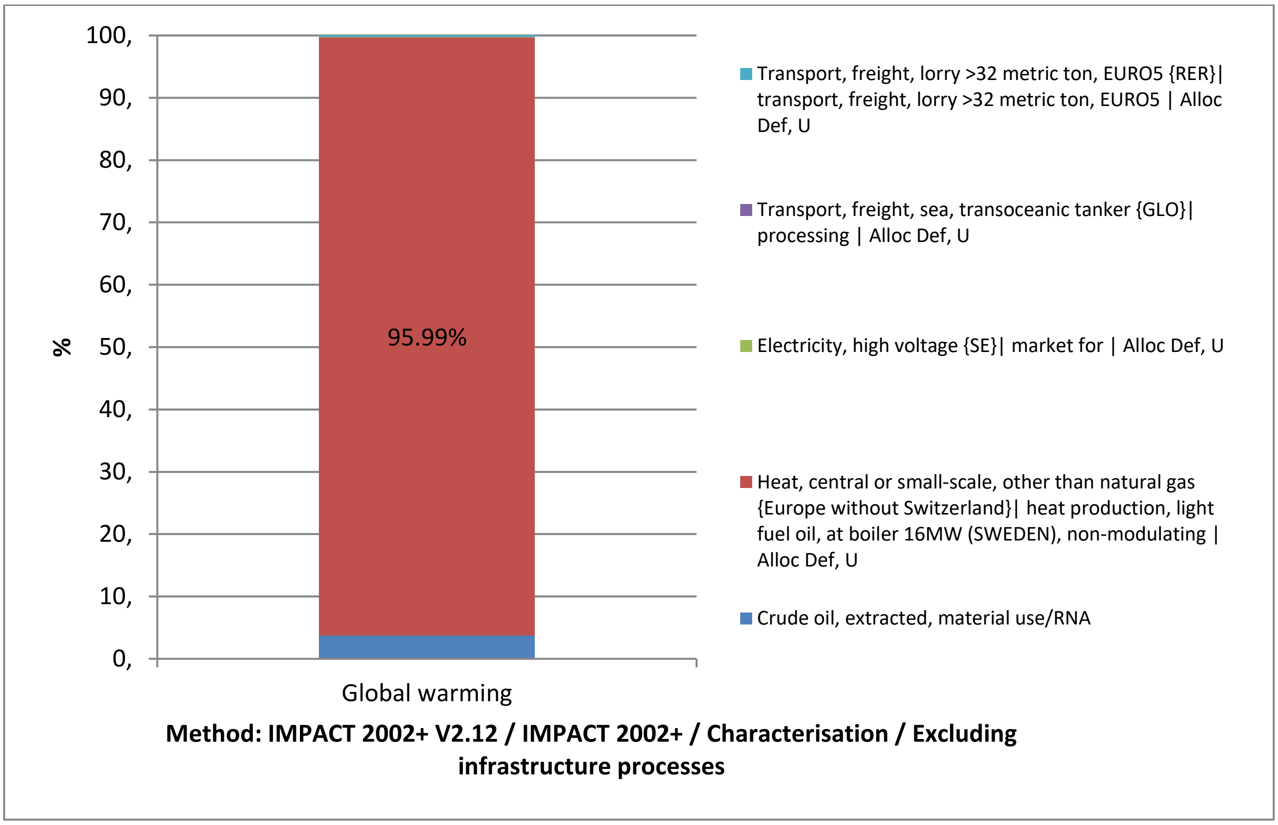
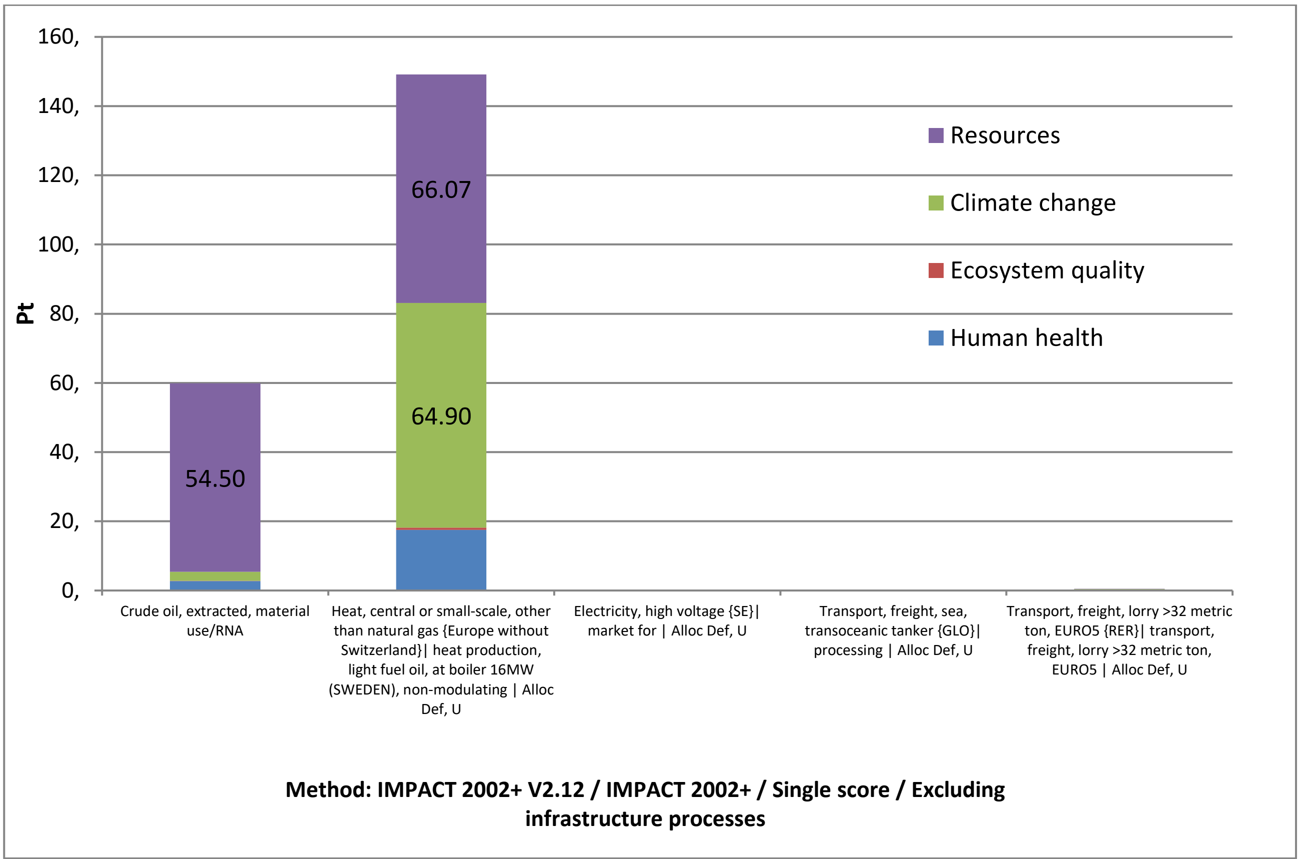


Figure 19: Characterization

The following figures illustrate the environmental impact of process steps in four damage-oriented impact categories, namely, (i) human health, (ii) ecosystem quality, (iii) climate change and (iv) resources. More specifically, Figure 20 creates a single score for the environmental impact of each stage. It is evident from this figure, that the extraction/utilization process of crude oil accounts for high contribution (<50%) in the category of mineral resources. The extraction process is associated with the energy surplus required for further mining of the resource in the future. Boilers are significant contributor to life cycle impacts in climate change and resources. As already mentioned, the environmental impact of boilers is associated with the high carbon-intensive combustion of mineral oil. Furthermore, as expected, it has a considerable impact (approximately 20%) on human health due to the pollutants (chloroethylene, PM2.5, CFC, ethylene etc.) emitted in the stage of fuel combustion. On the other hand, both the transportation stage and the electricity consumption are nearly free of environmental impacts.



[19] The Eco-indicator point (Pt) is a dimensionless value; it corresponds to one thousandth of the yearly environmental load of one average European inhabitant.

Figure 20: Single score

7.4.2 Suggested retrofit

In retrofit scenario, all inputs and outputs of the system boundary presented in Figure 16, for both bio-oil and bio-diesel case, encompass:

- The collection of raw material. In case of bio-oil, two cases are investigated: (i) the collection and refining of UCO into bio-oil and (ii) the collection of UCO without further refining. Regarding biodiesel, the cultivation of rapeseed crop as well as the relevant energy required for the formative process to biodiesel are also considered in the analysis;
- The transportation of raw material from the collection point to plant (Figure 18) including the fuel used in each mean of transport;

- The electricity from Swedish electricity grid required for the operation of boilers; in the case of bio-oil, it is also required for the storage;
- The heat output, including the used biofuel and the electricity needing for the proper operation of the boiler.

The results are presented individually for the utilization of each bioliquid (i.e. bio-oil and biodiesel).

7.1.1.1 Case 1: Bio-oil

For the environmental analysis, four different scenarios are conducted in order to estimate the impact of collecting the different amounts of bio-oil from the European countries under investigation. It is worth noting that for transporting the biofuel among 4 European countries, namely, France, German, Belgium and Netherlands, the optimal route (i.e. fewer kilometers) was taken into investigation. Thus, the fuel collection begins in France, is turn it transfers to Germany and Belgium, and ends in the Netherlands, where the bio-oil is transported by sea to the harbor of Sölvesborg.

Table 2 shows the distance between the countries and the amount of bio-oil transported on each route. More specifically:

- In **Scenario 1**, (i) half amount of the bio-oil produced is transported through the highest kilometers route, while (ii) the less amount of bio-oil produced is transported through the shortest route.
- In **Scenario 2,** (i) half amount of the bio-oil produced is transported through the shortest kilometers route and (ii) the less amount of bio-oil produced is transferred through the highest route.
- In **Scenario 3,** (i) almost the entire amount of bio-oil produced is transported through the highest kilometers route and (ii) the corresponding minimum one through the shortest route.
- In **Scenario 4,** (i) nearly the entire amount of bio-oil is transported through the highest kilometers route, whilst the corresponding minimum one through the highest route.

Table 2: Different scenarios investigated

	Transportation		Scenario 1		Scenario 2		Scenario 3		Scenario 4	
No	Route	(km)	% w/w	Mass (tons)	% w/w	Mass (tons)	% w/w	Mass (tons)	% w/w	Mass (tons)
1	France - Germany	816	50%	96.4	20%	38.56	70%	134.96	10%	19.28
2	Germany - Belgium	426	30%	57.84	30%	57.84	20%	38.56	20%	38.56
3	Belgium – Netherlands	190	20%	38.56	50%	96.4	10%	19.28	70%	134.96
Sum		1432	100%	192.8	100%	192.8	100%	192.8	100%	192.8

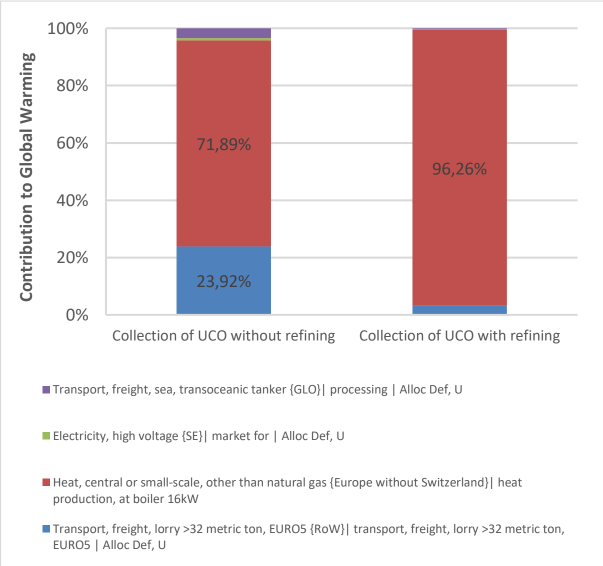
In Scenarios 1 & 3, the greater amount of bio-oil is transported between France and Germany. As it can be seen in Table 2, both scenarios correspond to the highest kilometers route. On the other hand, Scenarios 2 & 4 investigate the case of transporting the less quantity of bio-oil through the highest kilometers route. Calculated results regarding GHG emissions are presented in Figure 21 for both cases investigated (i.e. with or without further refining of UCO). Interesting trends concerning these results are summarized as following:

- For the case of further refining UCO into bio-oil, for all scenarios investigated, the GHG emissions derived from the transportation stage (i.e. bio-oil truck) are significantly lower than the corresponding GHG emissions derived from the operation process of boiler. More specifically, the contribution of boiler to the Global Warming Category ranges between 96-98%. These high percentages are expected considering the relatively higher releases of toxic substances to the environment during the operation stage of boilers (combustion process, in particular). On the other hand, electricity consumption was found to be free of environmental burden. This is attributed to the electricity system of Sweden, which is almost entirely decarbonized.

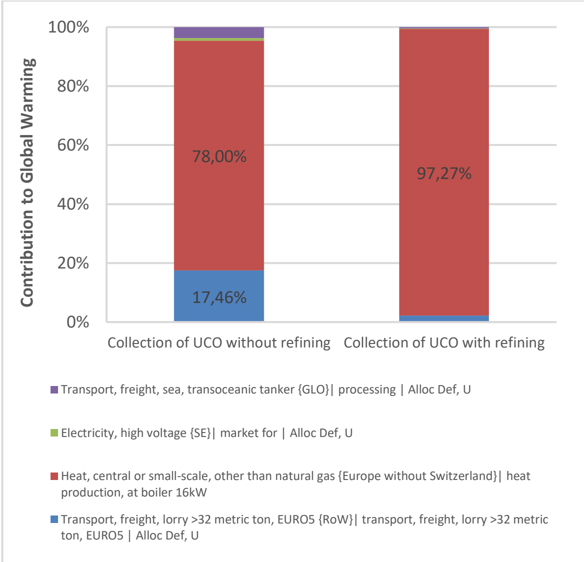
- Results without considering the refinery process of UCO exhibit a similar behavior. For all scenarios investigated, the major contribution to GHG emissions is the heating process, followed by the transportation stage. More specifically, the contribution of the transportation phase to GHG emissions varies from 14.11% (Scenario 4) to 27.01% (Scenario 3). The electricity consumption stage has nearly negligible influence on the category of Global Warming.

- Regarding the production process of bio-oil, it can be argued that the main, environmentally adverse, impact is associated with the transesterification of vegetable oil to bio-oil (accounting for up to 94%), in case of no refinery, and with the operation of boiler (accounting for up to 90.42%), in case of refinery (see Figure 22).

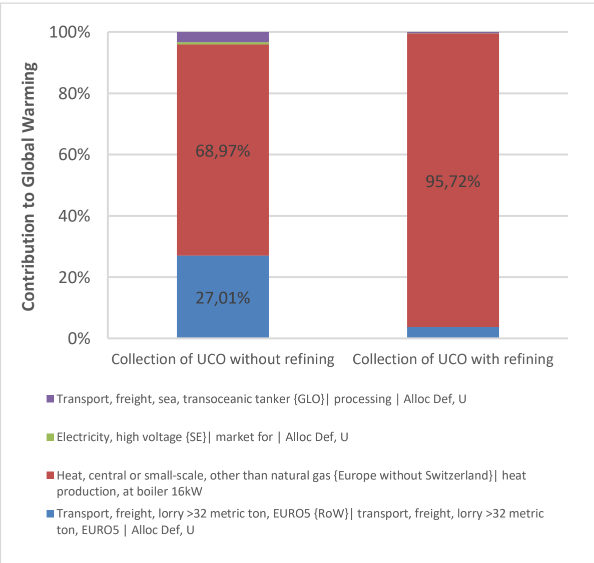
- For the different scenarios analyzed, it is worth mentioning that fluctuations of the contribution of the transportation stage to the overall GHG emissions, vary, in turn, the corresponding contribution of the bio-oil production process to global warming category. As expected, the transportation of bio-oil through higher kilometers route lead to a decrease to GHG emissions derived from the bio-oil production process.



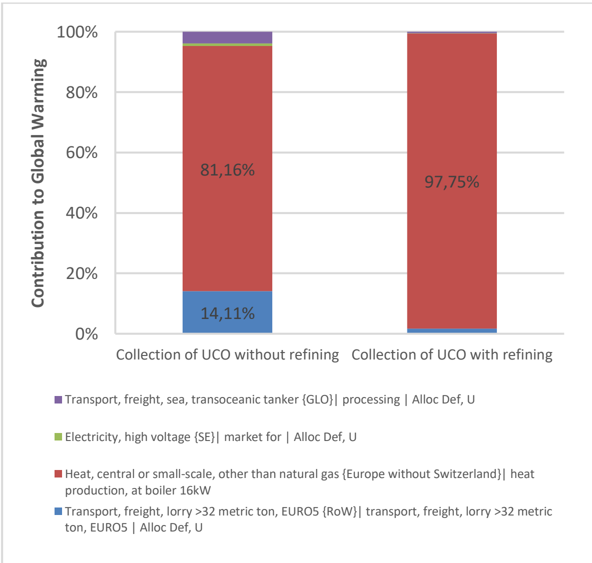
(a) Scenario 1



(b) Scenario 2

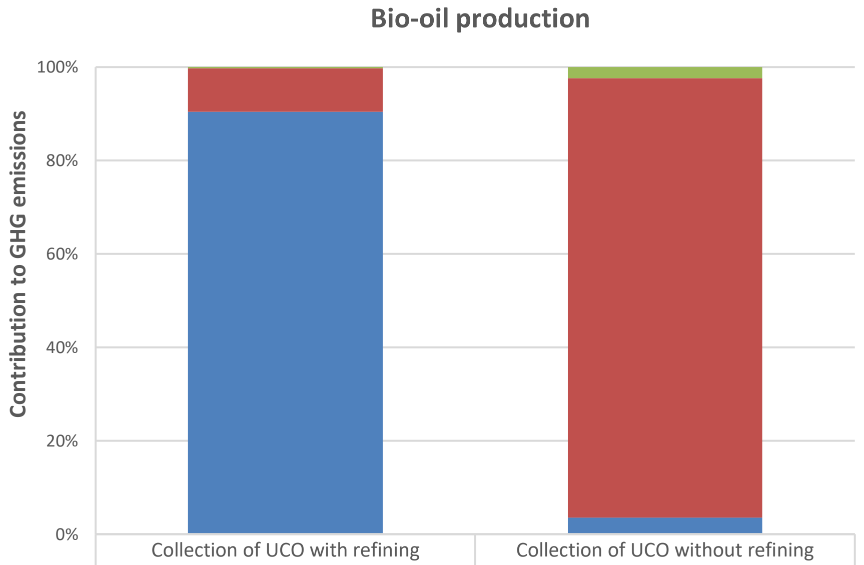


(c) Scenario 3



(d) Scenario 4

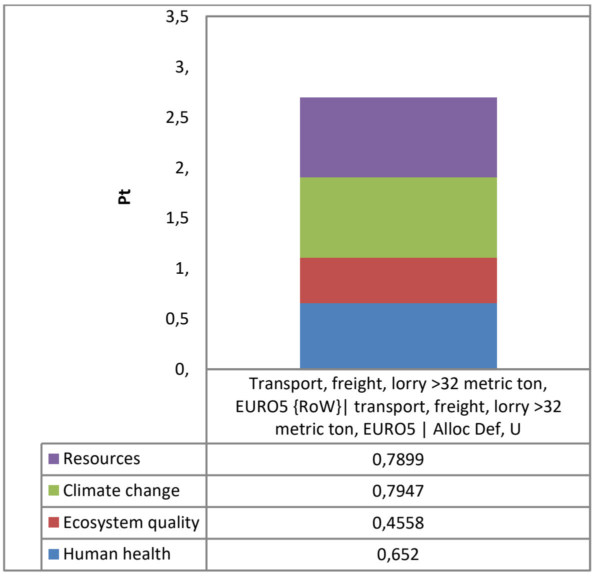
Figure 21: Characterization (Method Impact 2002+, V2.12 / Impact 2002+/Characterization/Excluding Infrastructure Processes)



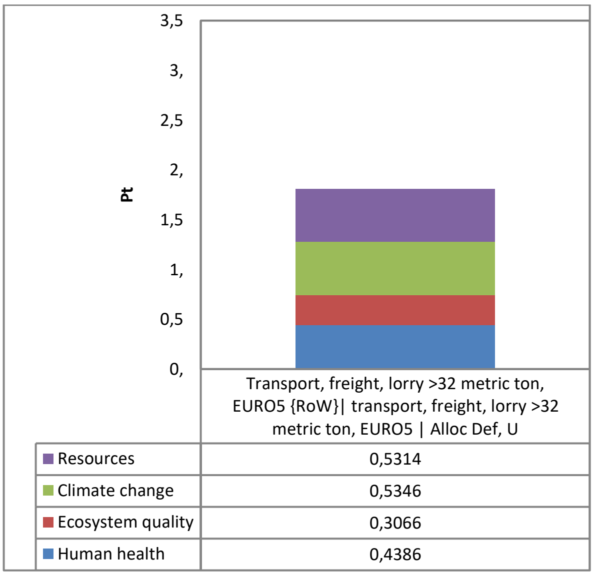
	Collection of UCO with refining	Collection of UCO without refining
Electricity, low voltage {SE}| market for | Alloc Def, U	0,23%	2,35%
Vegetable oil methyl ester {FR}| treatment of waste cooking oil, purified, REDII - SWEDEN esterification | Alloc Rec, U	9,35%	94,11%
Heat, central or small-scale, other than natural gas {Europe without Switzerland}| heat production, at boiler 16 kW	90,42%	3,55%

Figure 22: Characterization (Method Impact 2002+, V2.12 / Impact 2002+/Characterization/Excluding Infrastructure Processes)

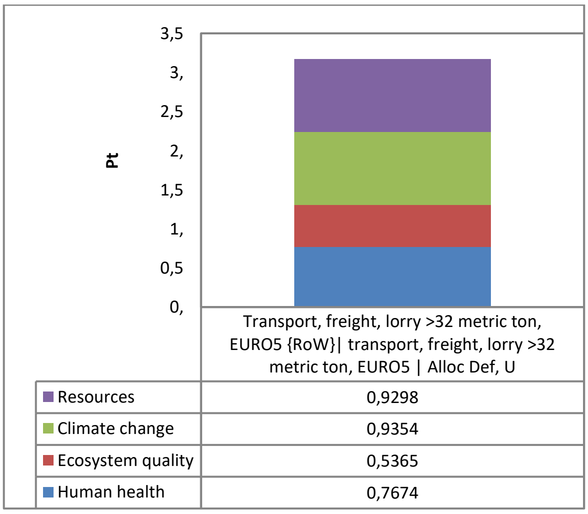
Figure 23 illustrates the environmental impact of the transportation stage for each scenario investigated in the four damage-oriented impact categories, namely, (i) human health, (ii) ecosystem quality, (iii) climate change and (iv) resources. It can be observed that Scenarios 1 and 3 have a greater influence in all impact categories. It is evident that the higher the kilometers route and the amount of the fuel transported, the worst the environmental performance. Therefore, Scenario 4 seems to have the less impacts on all impact categories, followed by Scenario 2.



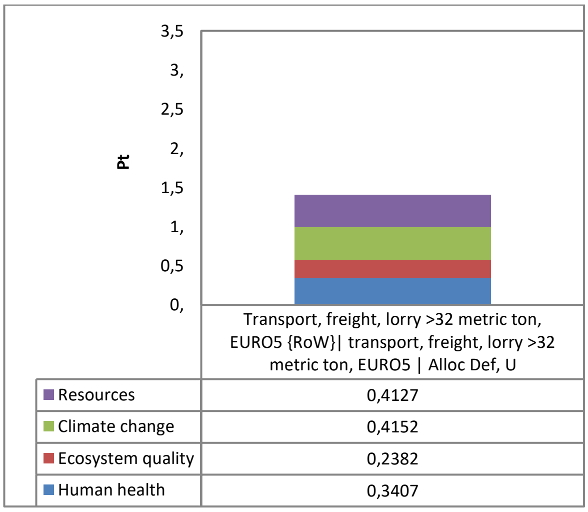
(a) Scenario 1



(b) Scenario 2



(c) Scenario 3



(d) Scenario 4

Figure 22: Single score (Method Impact 2002+, V2.12 / Impact 2002+/Single Score/Excluding Infrastructure Processes)

7.7.4.1.1 Summing-up

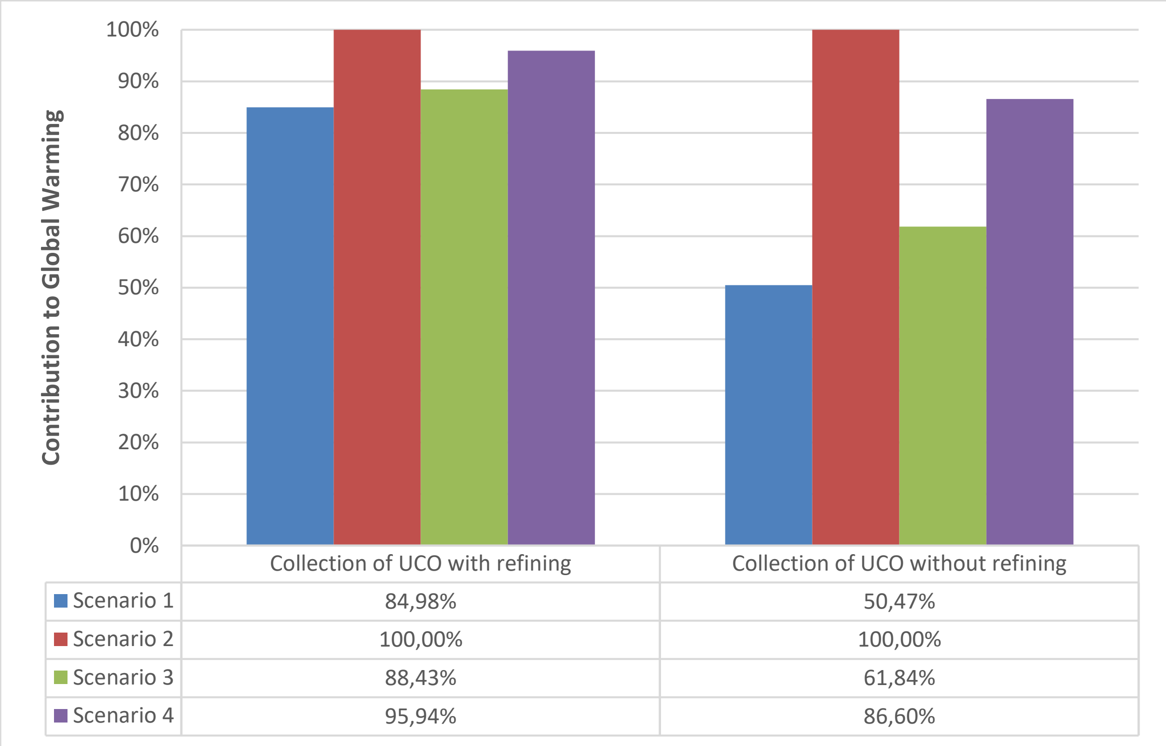
An integrated comparison of the different scenarios is presented in Figure 23 and Figure 24, as well as, in Table 3. It should be mentioned that Figure 23 reflects the relative contribution of each scenario to the environmental impact, quantifying how much impact has each scenario in the collection of UCO. It is worth mentioning that Scenario 2 reaches 100% contribution in both cases (with or without refining); this percentage has been estimated as a result of the comparative assessment of the highest impact (worse scenario) on the global warming category.

The results show that the main, environmental-wise adverse, impact in terms of GHG emissions is associated with the boilers. In the case of utilization refined UCO, this is mainly attributed to the processes evolved in the esterification plant, which is energy-intensive with the required energy being generated via natural gas-fired power plant (high methanol emissions releases). Furthermore, as it can be seen from Figure 24, the case of further refining UCO into bio-oil has great influence on the category of climate change, because of the toxic emissions derived from the operation process of boilers. On the contrary, in case of no refining, transesterification of vegetable oil to bio-oil has high impact on the categories of resources and human health. This significant environmental-wise adverse contribution to both categories comes from the transesterification of vegetable oil to bio-oil. Negligible (<1%) life cycle GHG emissions come from the electricity consumption in both cases.

The environmental performance is slightly affected by the kilometers route and the amount of the fuel transported; the higher the kilometers route and the amount of the bioliquid transported, the worst the environmental performance. It can be argued that, in both cases of refined and unrefined UCO, Scenarios 1 & 3 present higher environmental impact compared to Scenarios 2 & 4.

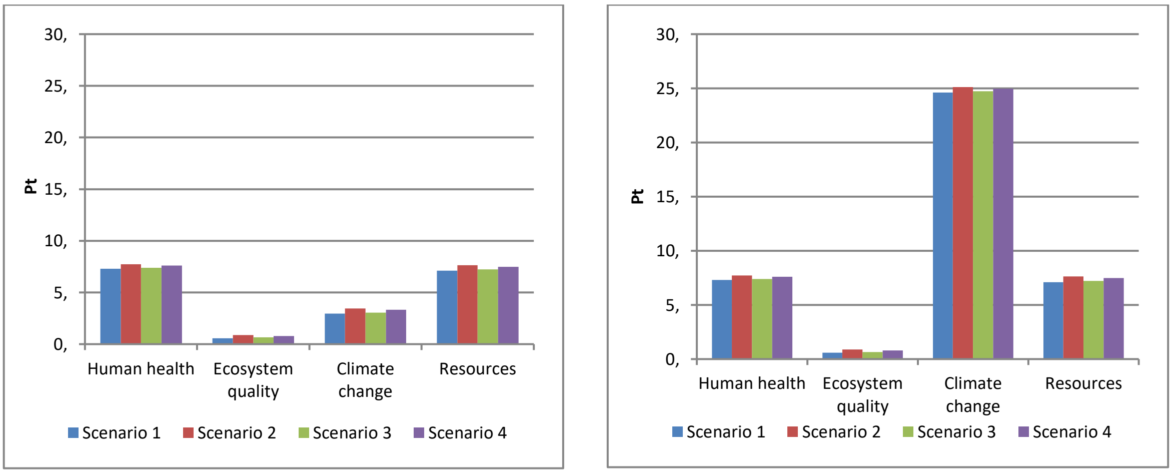
Table 3: Emissions in each stage of bio-oil process

Processes	**Emissions ($tnCO_{2eq}/a$) of each Scenario**			
	1st	**2nd**	**3rd**	**4th**
Heat production from boilers (refined UCO)	238	238	238	238
Heat production from boilers (unrefined UCO)	23.65	23.65	23.65	23.65
Electricity utilization	0.24	0.24	0.24	0.24
Transport of UCO and bio-oil from the collection point to plant	9.01	6.43	10.37	5.25
Total (refined UCO)	**247.25**	**244.67**	**248.61**	**243.49**
Total (unrefined UCO)	**32.90**	**30.32**	**34.26**	**29.14**



	Collection of UCO with refining	Collection of UCO without refining
Scenario 1	84,98%	50,47%
Scenario 2	100,00%	100,00%
Scenario 3	88,43%	61,84%
Scenario 4	95,94%	86,60%

Figure 23: Comparative characterization of transportation effect for each scenario



(a) Collection of UCO without refining (b) Collection of UCO with refining

Figure 24: Comparative single score of transportation effect for each scenario

7.1.1.2 Case 2: Biodiesel

In case of bio-diesel, total annual emissions amount to 345 $tnCO_{2eq}$. It is evident from Figure 25 and Figure 26 that bio-diesel exhibits a similar behavior to bio-oil; boilers have the highest environmental GHG emissions (>96%), while the transportation stage and the electricity consumption are nearly free of GHG, even from a whole life cycle perspective. Regarding the transportation stage, the freight lorry that transfers 447.5 tons of rapeseed crop seems to have minor environmental impact (<4%) in Global Warming category. This small percentage is associated with the emissions of gaseous pollutants (CO, HC, and NO) from the truck.

Table 4: Emissions in each stage of biodiesel process

Processes	**Emissions ($tnCO_{2eq}/a$)**
Heat production from boilers	331
Electricity utilization	0.141
Transport of rapeseed crop and biodiesel from the collection point to plant	13.107
Total	**344.248**

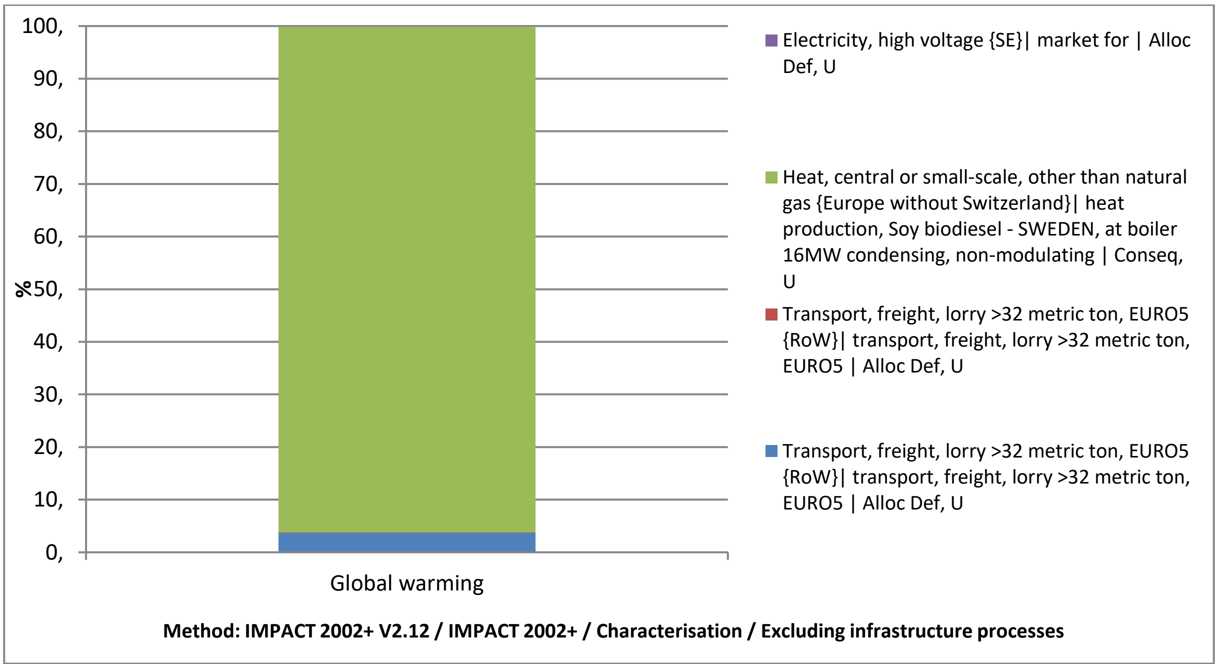


Figure 25: Characterization

The following figures show that the utilization of biodiesel has a negative impact on the ecosystem quality, simply because biodiesel is produced from crops. All processes investigated have negligible environmental impacts in the categories and resources.

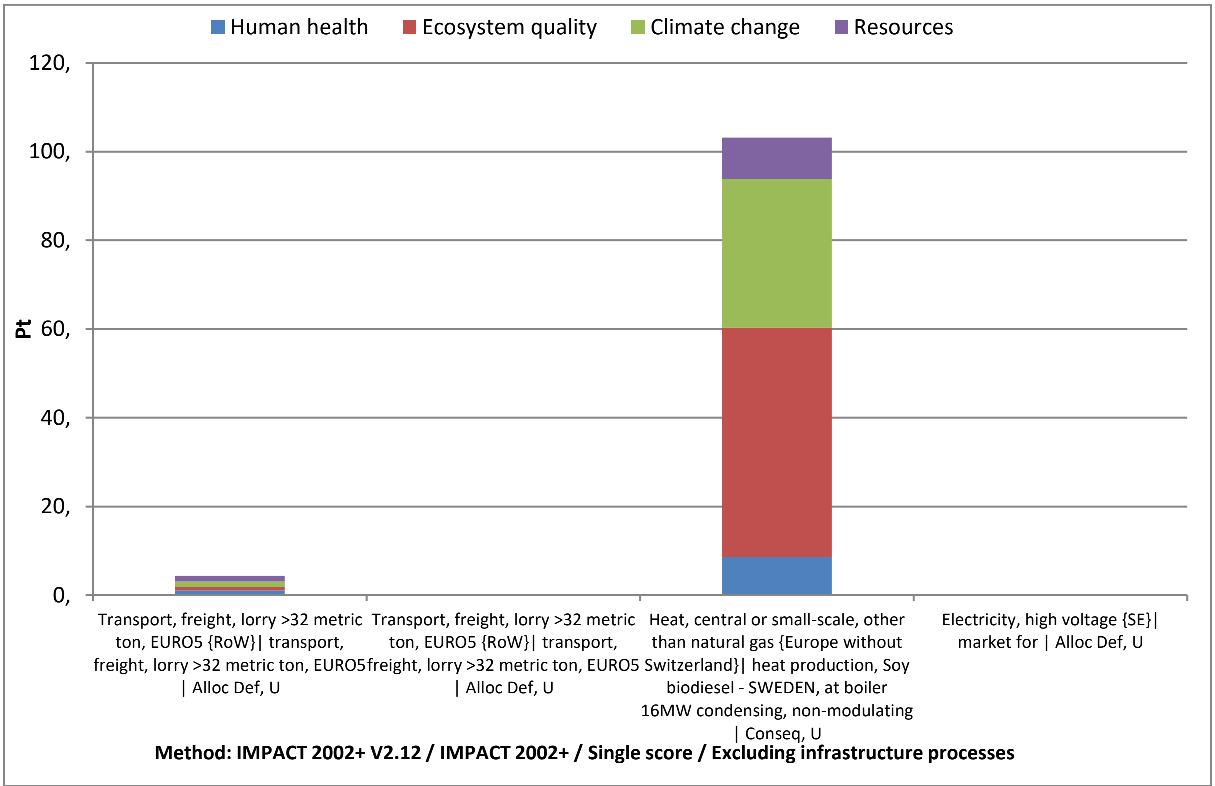


Figure 26: Single score

7.8 Conclusion

A rigorous life-cycle analysis was carried out in order to assess the environmental impact associated with the production and utilization of conventional fossil fuels and biomass fuels for heating purposes. Particular emphasis was given to the evaluation of the GHG emissions that arise from the production and utilization of (i) conventional crude oil ('current scenario') and (ii) bio-oil and biodiesel ('retrofit scenario'). In the case of bio-oil, it was investigated the utilization of UCO with and without refining. The environmental benefits of using the aforementioned biomass fuels were also examined by calculating the GHG emission savings to be incurred by the replacement of conventional crude oil.

The detailed results presented in this work indicated that both scenarios exhibit a similar environment behavior in most damaged-oriented impact categories. This is largely attributed to the fact that the mainly, environmentally adverse impact, is associated with the operation of boilers. As expected, boilers contributed the most to Global Warming impact category, due to pollutants emitted from the combustion process. The other process steps, i.e. crude extraction/mining, transportation and electricity consumption, were found to have very small environmental burden. The total emissions for the production of 1,988 MWh_{th} from crude oil amount to 669 $tnCO_{2eq}/a$. This value is significantly higher than the corresponding of (i) bio-oil, which lies between 244 - 249 $tnCO_{2eq}$/a in case of utilizing refined UCO and 29 - 34 $tnCO_{2eq}$/a in case of utilizing unrefined UCO, and of (ii) biodiesel, which is estimated at 345 $tnCO_{2eq}$/a.

In order to provide comparable results with the fuel comparator determined by RED II (amounted to 80 gCO_{2eq}/MJ), the GHG emissions savings, defined as the emissions avoided from the production of bioliquids, have been calculated per MJ of produced energy. It was found that no GHG emissions savings are associated with the current scenario (crude oil utilization). On the contrary, the GHG emissions savings that arise from the production of bioliquids (i) lie between 56-58% in case of using bio-oil from refined UCO (33.1 – 34.8 gCO_{2eq}/MJ) and 95-97% in case of using bio-oil from unrefined UCO (4.2 – 4.9 gCO_{2eq}/MJ), and (ii) reach 40% (48.2 gCO_2eq/MJ) in case of using biodiesel. These values are comparable with the ones reported in the relevant literature, estimating GHG emissions savings in the range of 28-70 gCO_{2eq}/MJ [20]. Therefore, the utilization of biomass fuels seems to be the most appropriate, environmental-wise way of producing useful heat. However, it is perhaps interesting to note that bio-oil presents a more promising, environmental-friendly, alternative to biodiesel for heating purposes, due to emissions released from the cultivation and collection of rapeseed crops, in contrast to zero emissions during the collection of UCO. Additionally, the utilization of bio-oil from unrefined UCO attains the best environmental performance saving GHG emissions compared to fossil fuel use.

A summary of the results of the environmental analysis are collectively presented in Table 5.

Table 5: Overview results of environmental assessment

Inputs (in SimaPro software)	**Outputs (from SimaPro and RED II)**
Crude oil	
- 168 tons fossil oil transported 200-250 km by ship & 130 km by truck - 5MWh electricity input in boiler - 1988 MWh heat production	**670 $tnCO_{2eq}$/a** Shares of emissions by each stage: 96% *by boiler, 3.73% by extraction of crude oil, 0.25% by transport 0.02 % by electricity*
	93.5 gCO_{2eq}/MJ
	No saving according to REDII
Bio-oil	

[20] https://www.epa.gov/sites/production/files/2018-03/documents/emission-factors_mar_2018_0.pdf
https://post.parliament.uk/research-briefings/post-pn-0523/

	Collection of UCO with refining	*Collection of UCO without refining*
- 192.8 tons bio-oil transported 1300-1367 km by ship & 1442 km by truck in total - 5MWh electricity input in boiler - 1988 MWh heat production	**244 - 249 $tnCO_{2eq/a}$** Shares of emissions by each stage: 95.6-*97.5% by boiler, 2.4-4.3% by transport, 0.06-0.1 % by electricity*	**29 - 34 $tnCO_{2eq/a}$** Shares of emissions by each stage: 69-*81.2% by boiler, 18-30.3% by transport, 0.7-0.82 % by electricity*
	33.1 – 34.8 gCO_{2eq}/MJ	**4.2 – 4.9 gCO_{2eq}/MJ**
	56 - 58% saving according to REDII	**95 - 97%** saving according to REDII
Biodiesel		
- 447.5 tons crop transported 400km by truck - & 191 tons biodiesel transported 30km by truck - 5MWh electricity input in boiler - 1988 MWh heat production	**345 $tnCO_{2eq/a}$** Shares of emissions by each stage: *96% by boiler (including the pretreatment process of biodiesel from crops), 3.9% by transport, 0.1% by electricity*	
	48.2 gCO_2eq/MJ	
	40% saving according to REDII	

* The savings are calculated according to the equation in page 40.

8 Risks

In order to make a decision on investments, the risks need to be assessed and ranked on importance.

8.1 Risk assessment for the retrofit

A list of risks has been made. Only the risks directly related to the retrofitting and retrofitted situation has been taken into account. Probability and consequence of each risk has been determined. The risks have been divided in two categories, the first table (13) concerns risks related to their situation in general, with their dependence on waste heat deliveries from the pulp – and paper mill, the second one is about risks related to their possible new situation after the conversion to a biobased liquid biofuel, independently on whether it is bio-oil or biodiesel. Most of the risks in the first table concern interruption of heat deliveries either from the pulp – and paper mill or from their own boilers. Worst case scenario is an interruption of the waste heat supply wintertime, from the mill and in the meantime from their own boilers. However, it´s not financially motivated to construct new facilities to decrease this risk.

Table 13: Risks associated with the comanies security of heat deliveries in general

Risk	Probability (1 – 4)	Consequence (1 – 4)	Total risk (1 – 16)
Longstanding interruption of waste heat deliveries from the pulp mill, wintertime	2	3	6
Decision from the pulp mill to permanently stop the waste heat deliveries, announced less than one year in beforehand	2	3	6
Longstanding interruption of heat deliveries because of technical problem at one of their own boilers	2	2	4
Longstanding interruption of heat deliveries because of technical problem at both of their own boilers	1	4	4
Longstanding interruption of waste heat deliveries from the pulp mill, not wintertime	2	2	4
Unforeseen decision from the pulp mill to permanently stop the waste heat deliveries	1	4	4

The total risk is estimated to be ranked as biggest for the situation where the emissions exceed the limits for emissions set by regional, national or EU authorities. This risk is possible to influence, but not to eliminate. However, there are other heat providing companies with the experience of combustion of various types of liquid biofuels to facilitate their choice of fuels, but in the end of the day the specific burner and auxiliary equipment at the plant in Sölvesborg, and how these are operated, will decide the levels of emissions.

Table 14: Risks associated with the conversion of feed-stock

Risk	Probability (1 – 4)	Consequence (1 – 4)	Total risk (1 – 16)
The emissions exceed the limits for emissions set by regional, national or EU authorities	2	4	8
Lack of relevant liquid biofuel on the Swedish market and hence significantly raised prices	2	2	4
Lack of relevant liquid biofuel because of unforeseen problems for the fuel supplier	1	3	3
Decreased attraction from clients to buy district heating, because of conversion of fuel	1	1	1

9 Key Performance Indicators (KPI)

The following items are defined as the KPIs for the business cases in order to evaluate the different cases. The KPIs can also be aggregated to obtain overall numbers for the BIOFIT project. The KPIs should not be used as a comparison between the case studies or as a ranking tool, since the KPIs will quickly result in unfair comparisons between the different scenarios.

Each KPI will be calculated separately and even though some KPIs may be interconnected (such as biomass use and bioenergy production), they will all be independently evaluated and discussed.

For the KPIs determined by the CST, a fill-in form is available in order to guarantee identical calculation methods. For the remainder of the KPIs, the project partner responsible for the calculation will ensure a single method is used for the KPI determination.

Technical KPIs (CST leaders)

The following technical KPIs are defined:

- **Increase in biomass converted per year**

The increase in biomass conversion for the retrofit compared to the current situation should be determined. This can be determined by taking the yearly biomass input (on dry weight) for the retrofitted situation and subtracting an averaged yearly biomass input for the current situation. The same should be done for the alternative case, where the same amount of product is made.

- **Increase in bioenergy or biofuel generated per year**

A net increase of bioenergy or biofuel production should be determined for the retrofitted situation and compared to the current situation. This can be calculated by taking the LHV energy value of the yearly produced bioenergy or biofuel and subtracting the yearly average of the current situation.

Economic KPIs (CST leaders and BTG)

The following economic KPIs are defined:

- **Internal rate of return; IRR (BTG)**

Based on the data provided by the economic assessment from the CST, the internal rate of return will be determined.

- **CAPEX reduction compared to alternative (CST leaders)**

The CAPEX reduction can be calculated by subtracting the CAPEX required for the retrofit from the CAPEX required for the alternative scenario. The obtained CAPEX reduction should *then be normalised on the annual capacity of the main product. This will result in a reduced CAPEX per GJ/yr added capacity.*

Environmental KPIs (CERTH)

Environmental KPIs will be determined by CERTH, indicative environmental KPIs are:

- **Carbon dioxide Equivalent Emission Reduction of supply chain and operation**

Greenhouse Gases (GHGs) are gases in the atmosphere that absorb infrared radiation that would otherwise escape to space; thereby contributing to rising surface temperatures. There are six major GHGs: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6). Emissions of other gases can be converted to CO_2 equivalents through specific methodologies. Since the main sources for CO_2 emissions are combustion processes related to energy generation and transport, CO_2 emissions can therefore be considered a useful indicator to assess the contribution of retrofitting on climate change.

- **Increased efficiency of resources consumption**

Percentage and mass reduction in non-renewable material consumption of the project. As proposed in the "Clean Energy for All Europeans", the target for renewable energy consumed should reach 32%. Through assessing the specific KPI, the renewable share of energy will be monitored and thus the expectation will be met. ["Clean energy for all Europeans | Energy." [Online]. Available: https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/clean-energy-all-europeans. [Accessed: 22-Jan-2019].]

KPI	value
Increase in biomass converted per year	2 GWh
Increase in bioenergy or biofuel generated per year	n/a
Internal rate of return; IRR	RME: 8 % Bio -10: 105 % Bio 25: 47 % Bio 25LAK: 37 %
CAPEX reduction compared to alternative	RME and Bio -10: 1.6 MEURO Bio 25 and Bio 25 LAK: 1.5 MEURO
Carbon dioxide Equivalent Emission Reduction of supply chain and operation	RME: 48.5 % Bio-oil (refined): 62.8 – 64.6 % Bio-oil (unrefined): 95 – 95.7 %
Increased efficiency of resources consumption	100 %

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