
Integration of Fischer-Tropsch fuel production with a complex oil refinery

Daniella Johansson* and Thore Berntsson

Department of Energy and Environment,
Division of Heat and Power Technology,
Chalmers University of Technology,
SE-412 96, Göteborg, Sweden
E-mail: daniella.johansson@gmail.com
E-mail: thore.berntsson@chalmers.se
*Corresponding author

Per-Åke Franck

CIT Industriell Energi AB,
Chalmers teknikpark,
SE-412 88, Göteborg, Sweden
E-mail: franck@cit.chalmers.se

Abstract: The oil refining industry is facing harder policies on renewable content in its products. One way to meet this is to produce diesel and gasoline from gasification of biomass via a Fischer-Tropsch (FT) synthesis. In this paper, heat integrating a biomass-to-FT syncrude process with a refinery is compared to a stand-alone biomass-to-FT syncrude process, in terms of the consequences for GHG emissions and energy balances. The upgrading of the FT syncrude is in both cases accomplished at the refinery, in the existing units or in new units. The studied system includes a circulating fluidised-bed biomass gasifier with a biomass input of 500 MW (50% moisture content) and a complex refinery with a crude oil capacity of 11.4 Mt/y. The integrated FT syncrude production shows the greatest potential for reductions in GHG emissions. Still, the GHG emission mitigation potential of using biomass for FT fuel production is smaller than co-firing biomass with coal in coal power plants.

Keywords: Fischer-Tropsch fuel; FT fuel; FT diesel; heat integration; system analysis; oil refinery; GHG emissions.

Reference to this paper should be made as follows: Johansson, D., Berntsson, T. and Franck, P-Å. (2014) 'Integration of Fischer-Tropsch fuel production with a complex oil refinery', *Int. J. Environment and Sustainable Development*, Vol. 13, No. 1, pp.50–73.

Biographical notes: Daniella Johansson received her MSc in Chemical Engineering (2008) from Chalmers University of Technology. She earned her PhD in Energy and Environment with specialisation in Industrial Energy Systems in 2013, Chalmers University of Technology.

Thore Berntsson earned his PhD in Heat and Power Technology at Chalmers University of Technology in 1976. In 1982, he became a Professor in Energy Technology in Process Industry, at Heat and Power Technology, Chalmers

University of Technology. His main research areas are industrial energy systems, process integration, new industrial energy technologies and biorefineries. He has been the Chair of three IEA Implementing Agreements; Pulp and Paper, Process Integration and Industrial Energy Related Technologies and Systems (IETS) and is now the Vice Chair of IETS. Through his research group, process integration developments have been applied in a large number of Swedish process industries.

Per-Åke Franck is the Managing Director in CIT Industriell Energi and he also works as an active consultant in projects for various clients. He is focused on various aspects of energy usage and thereby related environmental issues in the industrial sector. He has been involved in energy conservation projects, energy system and energy technology analyses projects in various industry branches ranging from the food industry to the steel industry. He has also worked for national governmental organisations in projects related to industrial energy usage and policy instruments and in international projects dealing with energy efficient technologies.

This paper is a revised and expanded version of a paper entitled 'Integration of Fischer-Tropsch diesel production with a complex oil refinery' presented at the SDEWES – the 7th Conference on Sustainable Development of Energy, Water and Environment Systems, Ohrid, Republic of Macedonia, 1–7 July 2012.

1 Introduction

The oil refining industry is a large fossil-fuel consumer. Today and in the future, harder regulations are to be imposed both on CO₂ emissions from the refinery process and on the refinery products. Since 2005, petroleum refineries within the EU have been part of the European Union Emission Trading System (EU ETS) (EU, 2009). The overall goal of the EU ETS is to reduce CO₂ emissions within the trading sector by 21% by 2020, relative to the 2005 levels (EUROPIA, 2011). In addition, the fuel quality directive requires the industry to reduce their life-cycle greenhouse gas emission (GHG) by 6% in 2020 (EC, 2009b). The fuel quality directive also includes sustainability criteria for biofuels, in which a fuel is only accounted as sustainable if GHGs savings compared to fossil fuels are 50% in 2017 for existing installations and 60% for installations built after 1 January 2018 (EC, 2009b). Many European countries have a quota regulation on the blending of diesel and gasoline, which requires a set level of renewable fuel production. However, the renewable energy directive endorses a mandatory renewable content of 10% in the transportation sector for all member states by 2020 (EC, 2009a), creating an incentive for the oil refining industry to increase its renewable fuel production.

One of several ways to increase the renewable content in refinery products and at the same time reduce CO₂ emissions is to produce fuels from forest residues. Gasification of residues from forestry via Fischer-Tropsch (FT) synthesis has received growing attention as an option for production of transportation fuels (e.g., Ekbom et al., 2005; Hamelinck et al., 2004; Tijmensen et al., 2002; Tock et al., 2010; Van Vliet et al., 2009). However, before the product from the FT synthesis (here after referred to as FT syncrude) can be used in today's car engines it needs further processing. In these steps, using the existing refineries has several advantages. The refinery structure offers a utility system already in place - process units in which the FT product can be co-processed along with crude oil, as

well as a long tradition and knowledge of producing transportation fuels. Heat integrating biomass gasification with existing refinery could potentially create synergy effects and reduce CO₂ emissions. The hot gas from the gasifier and the FT synthesis can provide heat for the refinery process, thus replacing imported fuel to the refinery. The production of FT crude could, theoretically, be integrated with any industry having a heating demand.

Several published studies have explored the system aspects of gasification for electricity or motor fuel production, (e.g., Isaksson et al., 2012; Joelsson and Gustavsson, 2012; Pettersson and Harvey, 2010; Wetterlund et al., 2011). These studies have mostly been focusing on biorefinery concepts integrated in the pulp and paper industry. Isaksson et al. (2012) have studied the CO₂ emission balance of integrating an FT syncrude production in an integrated mechanical pulp and paper mill. These authors found that the integration results in larger CO₂ savings compared to stand-alone operation in the case when electricity comes from coal power plants with carbon capture (CCS) or a natural gas combined cycle (NGCC) but not in the case when electricity is generated in coal power plants. Other studies deal with black liquor gasification in chemical pulp mills (Pettersson and Harvey, 2010) and forest residue gasification in Kraft pulp mills (Wetterlund et al., 2011). There are also studies investigating the integration of biomass gasification with district heating systems (Ekblom et al., 2008, 2005) and other industrial systems. For example, Walter and Ensinas (2010) have identified benefits when integrating gasification combined with FT production with a ethanol distillery. No system studies of FT production through biomass gasification in an oil refinery have been previously published to the authors' knowledge. Only studies investigating integration of coke gasification have been found (e.g., Navarro et al., 2005), and studies concerning production of FT intermediate and upgrading in existing refinery. For example, Ekblom et al. (2008) compared two configurations of biomass gasification to produce FT jet fuel. One plant produced jet fuel on site, while the other alternative was to produce an intermediate product, FT crude, to be further treated at a refinery. The authors conclude that the configuration with an intermediate product for further upgrade into bio-jet fuel would be economically competitive with energy market price levels at the time of the study (in 2008).

Studies focusing on the FT synthesis are well represented in the scientific literature. Most studies, however, focus on FT fuels produced from natural gas or coal (e.g., Dancuart et al., 2004; de Klerk, 2009; Dry, 2002; de Klerk, 2011; Kreutz et al., 2008; Leckel, 2009). Several coal-to-liquid and gas-to-liquid FT plants are running or are planned (Andrews and Logan, 2008), while biomass-based conversion for production of FT fuels is still far from commercialisation and only pilot plants are in operation (Damartzis and Zabaniotou, 2011).

In this paper, integration of FT syncrude production via biomass gasification with an oil refinery is investigated. In a complex refinery there are two possibilities for the upgrading of the FT syncrude; either using the existing refinery structure and co-feeding the FT syncrude with crude oil or investing in new units for the FT syncrude processing. In this study we evaluate both alternatives. The studied gasifier is a pressurised directly heated CFB gasifier based on modelling results reported by Isaksson et al. (2012) with a feed-to-fuel (C5+) efficiency of 52%, which is in conformity with other results reported in literature. The input to the biomass gasifier is 500 MW (50% moisture content), which is comparable with a large pulp mill. This size of biomass gasifier is considered feasible in terms of local resource supply and transportation possibilities and set as a maximum size

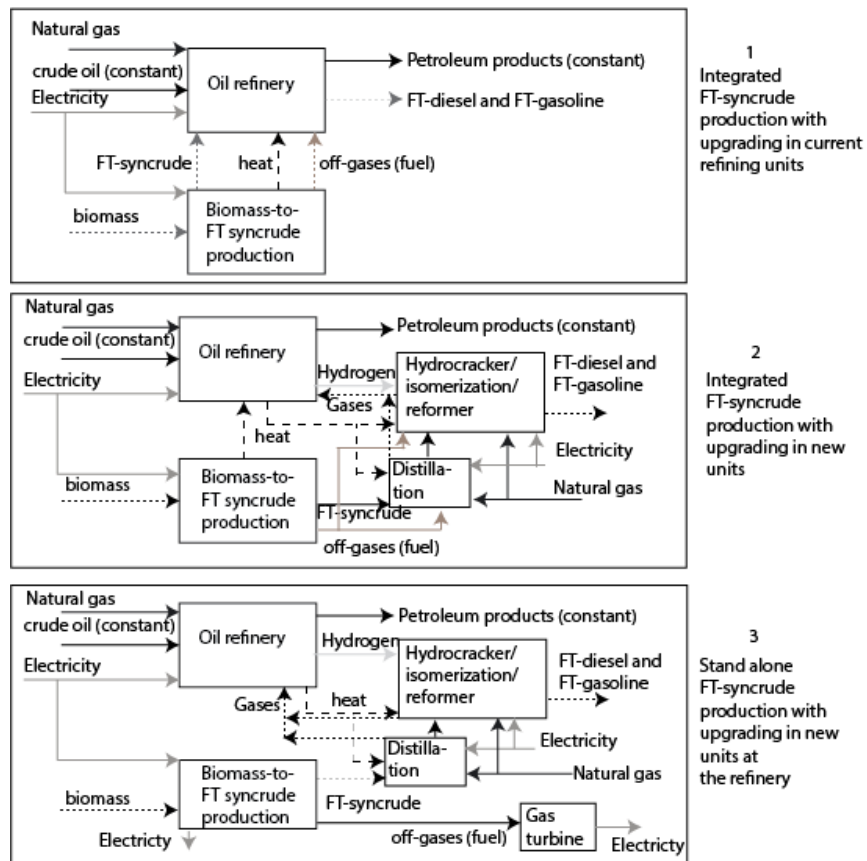
for the gasifier. A comparison with a stand-alone gasification plant with FT syncrude upgrading to FT fuels at the existing refinery is also included. This paper presents the impact of integration between the refinery, gasification process and upgrading units on the overall heat and mass balance, as well as the global GHG emission balance.

2 Objective and studied systems

The aim of this study is to investigate and compare the following alternatives for FT fuel production (see also Figure 1):

- *Case 1:* integration of a biomass gasification unit for FT syncrude production at an oil refinery including upgrading of the FT syncrude in existing refining process units
- *Case 2:* integration of a biomass gasification unit for FT syncrude production at an oil refinery including upgrading of the FT syncrude in new upgrading process units
- *Case 3:* a stand-alone biomass gasification unit for FT syncrude production with upgrading of the FT syncrude at the oil refinery in new upgrading process units.

Figure 1 Schematic picture of the three systems studied including the main energy streams



The analysis is made with respect to energy use and global GHG emissions. In addition, in this study the biomass is considered a limited resource and plausible alternative usage is co-firing of biomass with coal in coal power plants, as discussed by Axelsson and Harvey (2010). Therefore, a comparison between the GHG emission reductions that are obtained through FT fuel production and the GHG emission reductions gained by co-firing of biomass in coal power plants is included.

In order to reach the aim it is necessary to have detailed information on the existing refinery process, which in this study has been provided by an energy audit at the studied refinery (Andersson et al., 2012). There is a large heating demand at the refinery which cannot fully be covered with heat from a gasifier. Therefore the gasifier is limited to a reasonable size of 500 MW_{LHV}, which corresponds to the size of a large pulp and paper mill in Sweden.

Figure 1 shows the three studied systems and energy flows. The crude oil and the petroleum product flows for the studied refinery are constant. In Cases 1 and 2 the biomass-to-FT syncrude production is heat integrated with the refining processes, and hence replaces otherwise imported natural gas. In Case 1, the FT syncrude is upgraded in existing refinery processes and the off-gases from the biomass-to-FT syncrude process replace otherwise imported natural gas. It is assumed that there is enough spare capacity in existing units for co-processing the FT syncrude without any modifications, which is valid for the studied case-refinery (personal communication Christina Simonsson, Preem AB, November 2011-February 2012). In Case 2 the FT syncrude upgrading takes place in new process units (further described later) integrated with the refining process and the off-gases are used as fuel in these units and additional fuel is supplied by natural gas. Heat for these processes is supplied from the refinery and the net electricity demand is imported. The gas that is produced in the FT syncrude upgrading steps is in all cases used in the refinery, replacing otherwise imported natural gas.

Case 3 represents a stand-alone biomass-to-FT syncrude production process in which electricity is generated from the excess heat and from the off-gases. In this study no district heat delivery is assumed. The FT syncrude upgrading takes place in new upgrading process units at the refinery, with the same energy streams as in Case 2. The exception is the off-gas stream that in Case 2 is used as fuel in the upgrading process. Since the upgrading process in Case 3 is de-located from the gasification process the off-gases are instead used for electricity generation in a gas turbine.

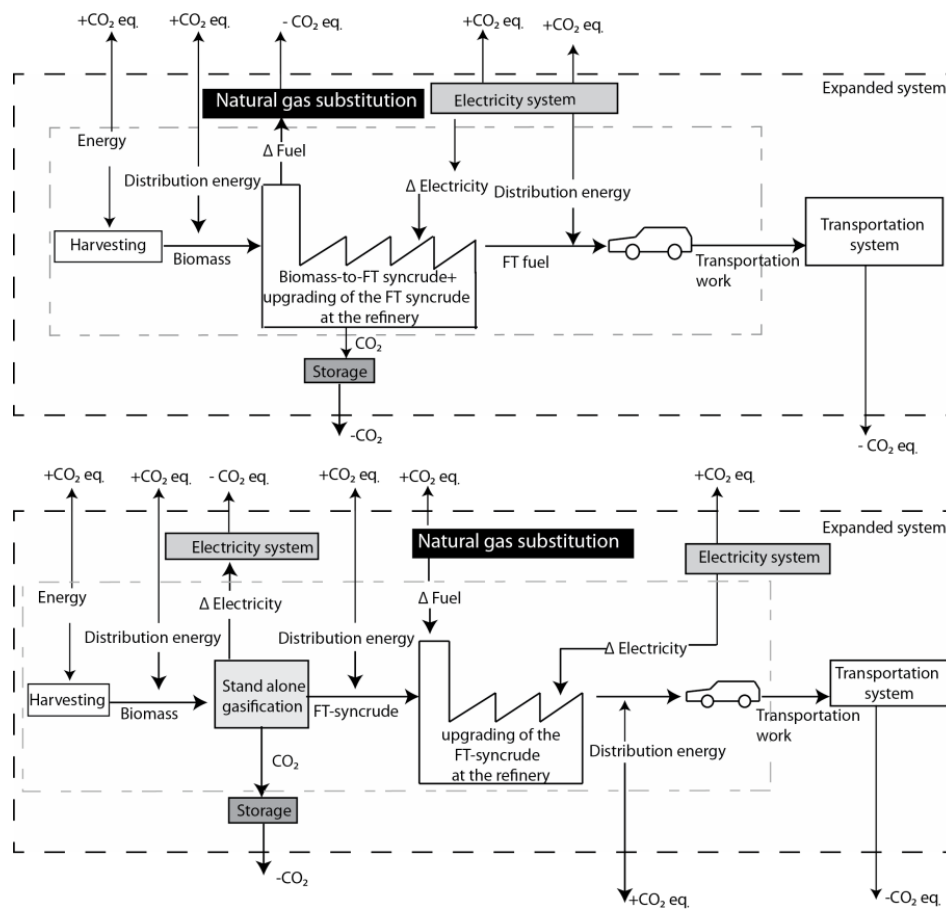
3 Methodology

In order to evaluate the heat integration possibilities for the biomass-to-FT syncrude process at a refinery and for the stand-alone biomass-to-FT syncrude facility the pinch analysis methodology has been used. The pinch analysis methodology was first developed by Linnhoff and colleagues in the late 1970s (Linnhoff and Flower, 1978). A thorough description of the methodology can be found in several editions; some of the most recently updated are (e.g., Kemp, 2007; Klemes et al., 2011; Smith, 2005).

In this paper, the GHG emissions are calculated as CO₂ equivalents (eq.), hence including also methane and nitrous oxide. The system boundaries for GHG emissions include harvesting of biomass to the combustion of the motor fuel (FT diesel and FT gasoline). The GHG emissions from the studied systems are evaluated in a life-cycle perspective using an expanded systems approach, more thoroughly described by

Pettersson (2011). It is assumed that the net energy and material streams entering or leaving the systems affect the surrounding system; see Figure 2. The net energy and material streams are the difference between the different cases and a reference case. The reference case is a sub-sector, energy-optimised refinery without FT fuel production (which is further described in the next section). All calculations assume a load factor of 0.91 for the studied system. The biomass used is forest residues (wood fuel) and the evaluation of GHG emissions is made from a European perspective.

Figure 2 GHG emission evaluation using system expansion



Notes: The upper figure represents Cases 1 and 2, while the lower figure represents Case 3. The CO_2 capture from the gasification process is optional in all cases. The + indicates an increase of CO_{2eq} , while - indicates a decrease of CO_{2eq} .

Electricity produced or consumed in the studied system affects the marginal electricity production. Since the timeframe in the present study is relatively long, base load build margin rather than operating margin is considered. The base load build margin approach determines a likely type of electricity generation facility that will be built when new generation capacity is installed. It is assumed that the base load build margin electricity produced in the modelled time period will still occur in fossil-fuel-based technology

(Axelsson and Harvey, 2010). In this study, the build margin technologies are represented by three state-of-the-art fossil power generation technologies;

- 1 coal power (805 kg CO_{2eq}/MWh_{el}) (Gode et al., 2011)
- 2 coal power with CCS (259 kg CO_{2eq}/MWh_{el}) (Gode et al., 2011)
- 3 NGCC (376 kg CO_{2eq}/MWh_{el}) (Gode et al., 2011).

In this study it is reasonable to assume that the FT diesel and gasoline replace otherwise fossil-based diesel and gasoline with a 1:1 ratio (by energy content). The life-cycle GHG emissions from diesel are approximately 289 kg CO_{2eq}/MWh_{fuel} and from gasoline 286 kg CO_{2eq}/MWh_{fuel} (Gode et al., 2011). The fuel that can be saved due to the heat integration between the biomass-to-FT syncrude process and the refining processes is assumed to replace imported natural gas, with GHG emissions of 248 kg CO_{2eq}/MWh_{fuel}. The GHG emissions from distribution and dispensing of the final FT diesel and gasoline are assumed to be 2.7 kg CO_{2eq}/MWh_{fuel} (Edwards et al., 2011). There is a possibility to capture the CO₂ stream leaving the gasifier. It is assumed that this stream is compressed, with an electricity demand of 0.40 MJ/kg CO₂ (Sherif, 2010), and transported to storage by pipeline.

The gasification process needs substantial amounts of external biomass. The biomass could be transported either by truck or by boat, or both. As a worst-case scenario, it is assumed that all biomass is transported by truck. It is assumed that the logging area has a radius distance of 300 km from the refinery. The location of a future stand-alone plant is unsure, and will be defined by several parameters, e.g. space, location to raw material etc. In this study it is assumed that a stand-alone plant is located close to the raw material and hence, the average logging area radius for the stand-alone gasifier is assumed to be 100 km. The distance between the refinery and the gasifier is assumed to be 300 km. Further, it is assumed that an average truck needs 35 l diesel per 100 km (Isaksson et al., 2012) and that the logging of forest residues results in 3.4 kg of CO₂ per harvested MWh (Isaksson et al., 2012). It should be noted that all calculations are made on a LHV basis.

4 Studied system: refinery

The studied oil refinery is a complex refinery with a crude oil capacity of 11.4 Mt/y. This refinery, at present, produces mainly gasoline, diesel, propane, propene, butane and bunker oil. The hot utility demand in the refining process is, currently, satisfied mainly by furnaces using fuel gas from the refinery. Steam is also produced in process units and boilers. Table 1 shows some key parameters for the existing refinery.

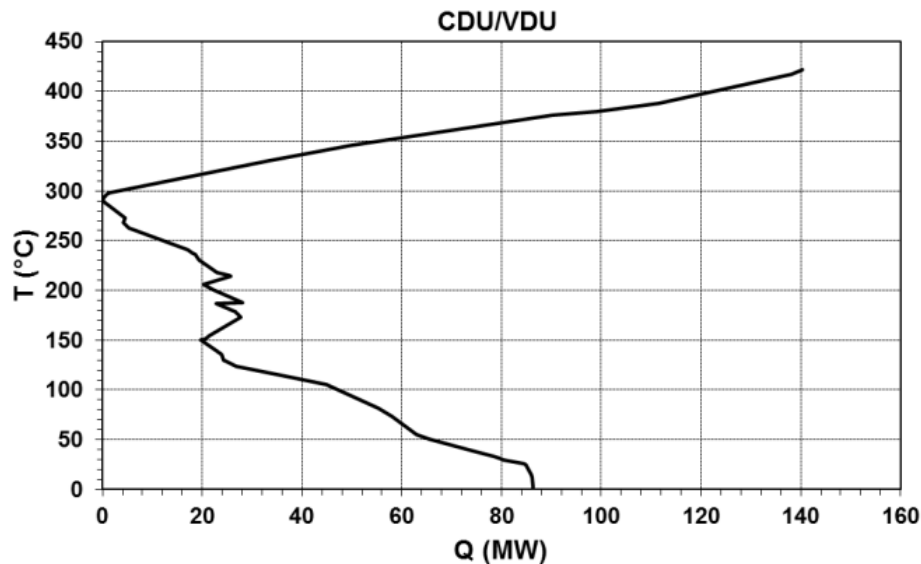
Table 1 Key parameters for the studied refinery before the retrofit

<i>Key factors</i>	
Crude oil capacity [kt/y]	11,400
Total CO ₂ emissions [kt/y]	1,800
Hot utility demand to process [MW]	409
Electricity import [GWh]	500
Diesel production [t/h]	540 t/h
Gasoline production [t/h]	340 t/h

However, the reference case in the present study is a future (theoretical energy optimised) refinery rather than the current case-refinery. The assumption is based on the fact that implementation of a large-scale biomass-to-FT syncrude process is unlikely to occur in the near future. It is therefore reasonable to assume that before such a radical implementation, extensive efforts will be put into making the existing refinery energy-optimised. Therefore, the reference case for this study is based on an energy audit performed at the current case-refinery (Andersson et al., 2012). In that study the theoretical heating and cooling requirements of each refinery sub-section are calculated. The theoretical heating requirements of the sub-sections are evaluated in a so called grand composite curve (GCC) of each subsection. These curves reflect the theoretical minimum requirement for each sub-sector. In (Andersson et al., 2012) all data, descriptions of the analysis, and constraints are thoroughly described.

The sub-section with both the largest heating requirements at high temperatures and the largest heat integration possibilities is the crude oil distillation unit/vacuum distillation unit (CDU/VDU). This sub-section is considered for heat integration with the new FT syncrude upgrading processes in Cases 2 and 3. Other refinery sub-sections with large heating requirements but at lower temperatures, which are included in the evaluation of the present study are: the isomerisation unit (ISO), the amine recovery unit (ARU) and the naphtha hydrotreater (NHTU). As an example, Figure 3 shows the minimum heating and cooling requirements for the CDU/VDU sub-section. The CDU/VDU is the only sub-section that can utilise the total amount of excess heat from the biomass-to-FT syncrude process (which is further described later).

Figure 3 GCC of the CDU/VDU in the studied oil refinery



In this study it is assumed that the fuel saved by heat integration between the biomass-to-FT syncrude process and the studied sub-sections will primarily replace shares of imported natural gas. It is further assumed that the fuel gas saved in the process furnaces will be used in the hydrogen production.

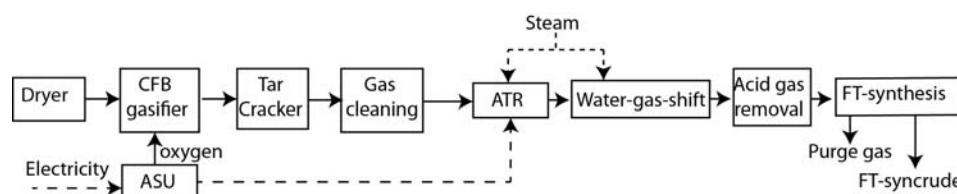
The studied refinery has a hydrocracker unit, in which vacuum gas oil (VGO) is hydro-cracked into mainly naphtha, diesel and unconverted oil. Currently, this unit is running below full capacity, which gives the refinery an opportunity to co-process FT wax along with the VGO without any production changes. However, the FT wax mainly consists of n-paraffins and no aromatics and no sulphur, which will affect the properties of the hydro cracking unit. Nevertheless, after discussion with experts at HaldorTopsoe (interview with Per Zeuthen, General Manager, HaldorTopsoe, February 2012) it is reasonable to assume that a 10% or less co-processing of FT wax, despite the different properties of the wax, will result in a constant product yield from the hydrocracker. The hydrogen demand will, however, change. The main purpose of the hydrogen in the hydrocracker unit is to remove sulphur and aromatics. Since the FT wax is both sulphur- and aromatic-free, less hydrogen will be needed for the FT wax fraction. On the other hand, the desulphurisation process heat is exothermic and, with less hydrogen provided, this will lead to a deficit of heat in the hydrocracker unit. After discussion with experts at HaldorTopsoe (interview with Per Zeuthen, General Manager, HaldorTopsoe, February 2012) it is realistic to assume that a 10% co-process with FT wax will lead to 8% less hydrogen consumption and 10% more primary energy use compared to hydrocracking of 100% VGO.

5 Studied system: Ft syncrude production

There is no full agreement as to which FT gasification system is the best, since it depends on how the system is evaluated and which parameters are considered most critical. For example, Tijmensen et al. (2002) found the oxygen-blown gasifier system to be the most efficient and economic one, while Tock et al. (2010) found the indirect gasifier system to be both more economic and more efficient. Several review articles and reports can be found describing the advantages and disadvantages of the different steps, including drying, gasification technology, cleaning, and upgrading of the syngas (e.g., Basu, 2010; Damartzis and Zabaniotou, 2011; Olofsson et al., 2005; Spath P.L and Dayton, 2003).

The process layout used in the present study (see Figure 4) is based on work by Isaksson et al. (2012), which in turn is mainly based on literature data found in (Ekbom et al., 2008; Hamelinck and Faaij, 2001; Larsson et al., 2006; Spath et al., 2005). The initial biomass is assumed to have a moisture content of 50% and it is dried, with excess heat from the biomass-to-FT syncrude process, to 15%wt before entering the gasifier.

Figure 4 Schematic picture over the FT syncrude production route



The biomass gasification system consists of a pressurised oxygen-blown circulated fluidised bed gasifier (CFB). The CFB gasifier is feed-flexible and suitable for

large-scale production. It is also a proven technology that does not need advanced pre-treatment technologies. The gasifier is followed by a catalytic cracker, which gives a good gas yield and better tar reduction compared to thermal cracking (Basu, 2010). The gas cleaning consists of a cyclone and a bag filter to remove particles and alkali (Isaksson et al., 2012). The last cleaning step is a wet scrubber, which is a more well-known process than hot gas cleaning. The equipment cost for cold gas cleaning is cheaper since it does not need expensive high temperature resistant materials (Olofsson et al., 2005). Prior to the synthesis the gas is reformed in an autothermal reformer. Autothermal reforming is preferred to steam reforming since it is of simpler design (Hamelinck et al., 2004) and due to the fact that oxygen is already produced in the system. A hydrogen to carbon monoxide ratio of 2 is desirable for the FT synthesis. In order to achieve this, the H_2/CO ratio is adjusted in a water-gas-shift. To avoid poisoning of the FT reactor catalyst, all acid gases are removed in a Rectisol unit.

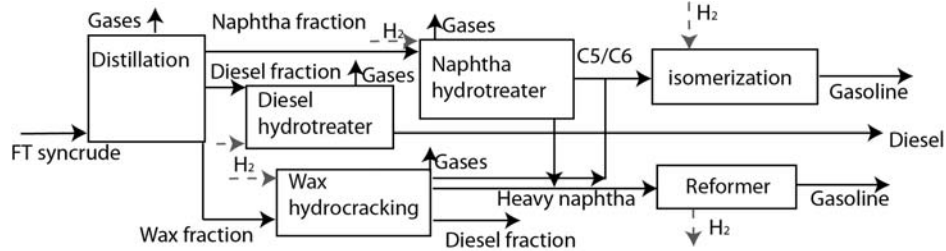
The FT-synthesis operates at low temperatures, which favours the production of high molecular weight linear waxes (>20 carbon atoms). The low-temperature FT (LTFT) synthesis is preferable for diesel production. Here, the FT synthesis occurs in a slurry phase reactor using a Co-catalyst. The Co-catalyst is more expensive than Fe-catalyst, but due to its higher activity and longer lifetime, it is the preferable LTFT catalyst (Kumar et al., 2009). A more detailed description of the studied biomass-to-FT syncrude process can be found in the work by Isaksson et al. (2012).

6 Studied system: Ft syncrude upgrading

The FT syncrude has inherently better properties than crude oil for fuel production (de Klerk, 2007). Distillate refining from FT syncrude and crude oil is of comparable complexity, but the separation complexity of syncrude is less than that of crude oil (de Klerk, 2007).

In Case 1, the calculation of the upgrading of the FT syncrude is based on detailed information from the existing refinery (personal communication Christina Simonsson, Preem AB, November 2011-February 2012) and in Cases 2 and 3 it is based on data from detailed study by Bechtel (1998) and from personal communication with Kramer (2012). Initially, light gases in the FT syncrude are separated from the liquid fraction. The syncrude is distilled to produce fractions of naphtha, diesel and wax. These fractions are processed through a series of refining steps, before the final products are produced. Figure 5 shows the upgrading steps in Cases 2 and 3. In Case 1, when only existing refinery processes are used, the structure of the upgrading is somewhat different from the picture below. In Case 1, the wax hydrocracker (previously described as hydrocracker) produces, in addition to the products seen in the picture, an unconverted fraction that goes to a fluidised cracker (not shown in the picture) in which mainly gasoline is produced. An additional difference is that the naphtha fraction from the hydrocracker goes to a naphtha hydrotreater before it is further refined, and no diesel hydrotreater is present.

Table 2 shows the difference in final distribution of the products in the case when existing refining structure is used compared to the case when new equipment is installed for the FT syncrude upgrading. The distribution of products from the upgrading steps is found in accordance with results reported by Sasol (Dancuart et al., 2004).

Figure 5 Schematic picture of the upgrading of the FT syncrude**Table 2** Final distribution of products for using existing refining structure versus new equipment (Case 1 versus Cases 2 and 3)

	Case	Gases	Gasoline (naphtha)	Diesel	Others
Existing structure [%]	1	3	25	63	8
New equipment [%]	2 and 3	6	15	77	3

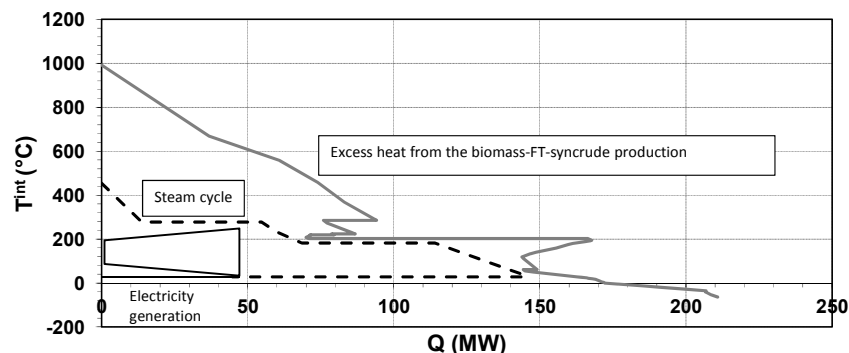
7 Heat integration possibilities in the stand-alone biomass-to-ft syncrude production

Figure 6 shows the GCC for the stand-alone biomass-to-FT syncrude process with a two-stage steam turbine. In order to maximise the electricity generation, the steam turbine cycle is arranged with two inlets for steam (at 60 bar and 10 bar). The biomass-to-FT syncrude production has no hot utility demand, but a cold utility demand of 210 MW. A known issue regarding the syngas from the gasifier is the appropriate temperature level for heat-exchanging. At high temperatures carbon will fall out, which will damage the metallurgy of the system. In this study the temperature level for superheating of steam is set to 450°C, which according to (Martellini et al., 2012) could be a feasible temperature. However, with other materials, higher temperatures are reported feasible (SpecialMetals, 2012). In the stand-alone alternative steam at 60 bar and 450°C is produced by heatexchanging with the hot gases from the gasification process, and is expanded in a first stage down to 10 bar. In the next stage, steam is expanded down to a reasonable value of 0.042 bar. In total, the steam turbine generates 43 MW electricity. The off-gas stream produced in the FT synthesis goes to a gas turbine that produces additional 1.8 MW electricity. Key data for the stand-alone case are found in Table 3.

Table 3 Key data for the stand-alone FT syncrude production

Biomass input (50% moisture content)	500 MW
Electricity from steam cycle	43 MW
Electricity from gas turbine	2 MW
Electricity demand	49 MW
<i>Net electricity demand</i>	<i>4 MW</i>

Figure 6 The GCC for the stand-alone FT syncrude production (solid line) with a two-stage steam cycle (dotted line)



8 Heat integration possibilities between the biomass-to-ft syncrude process and the refinery sub-sections

In the previous section a GCC for the biomass-to-FT syncrude process shows that there is around 75 MW of heat available above 200°C which in the stand-alone alternative is used to generate electricity. In Cases 1 and 2 this excess heat is instead used to cover part of the heating requirements in the refinery process. Figure 7 shows the background/foreground analysis of the FT process (grey curve) and the CDU/VDU sub-section (black curve). As the figure indicates, there is a theoretical opportunity to heat integrate the FT process with the CDU/VDU, and thereby save 77 MW_{heat}. With an assumed efficiency in the furnaces of 0.8, 96 MW_{fuel} could be saved. There are five more sub-sections at the refinery that have heating requirements at high temperatures which could have utilised the excess heat from the biomass-to-FT syncrude process. However, the CDU/VDU sub-section is the only section that alone can utilise the total amount of excess heat at high temperatures. The consequence of replacing the furnaces in this area is that the high pressure steam that is produced from flue gases in these furnaces has to be replaced. Today this steam is used to generate mechanical work in pumps and compressors. If the capacity in the furnaces is decreased due to the heat integration, 10 t/h steam is lost. This steam is assumed to be replaced by electricity in pumps, increasing the electricity demand in the refinery by 1 MW.

From Figure 7 it can be seen that after integration with the CDU/VDU area, still approx. 75 MW of heat are available below 210°C from the biomass-to-FT syncrude process. This heat could be used to cover heat demand at three areas; the ISO unit, the ARU and the NTHU. These three areas have together a total minimum hot utility demand below 180°C of 79 MW; see Figure 8. In total, the biomass-to-FT syncrude process could provide the refinery process with 152 MW heat, which could save 51% of the total hot utility demand (298 MW) in the reference (sub-sector energy-optimised) refinery.

Figure 7 Background/Foreground curves for the biomass-to-FT syncrude process (grey line) and the CDU/VDU sub-section (black line)

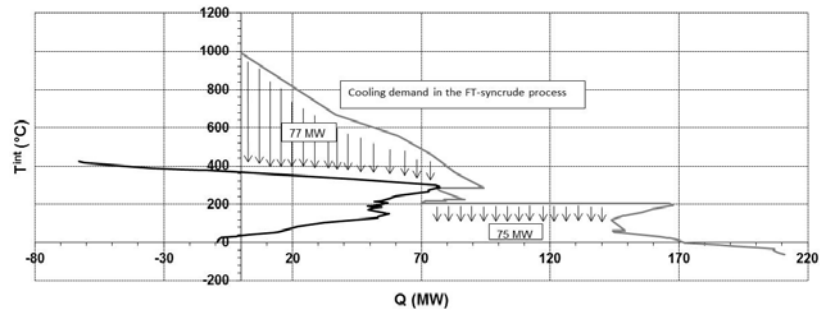
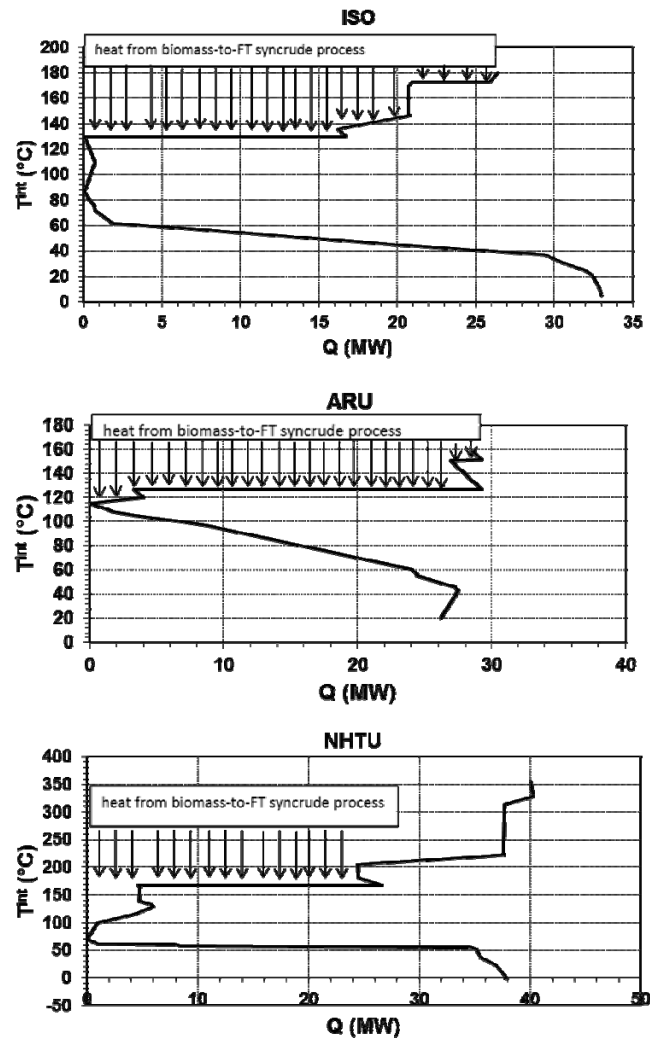
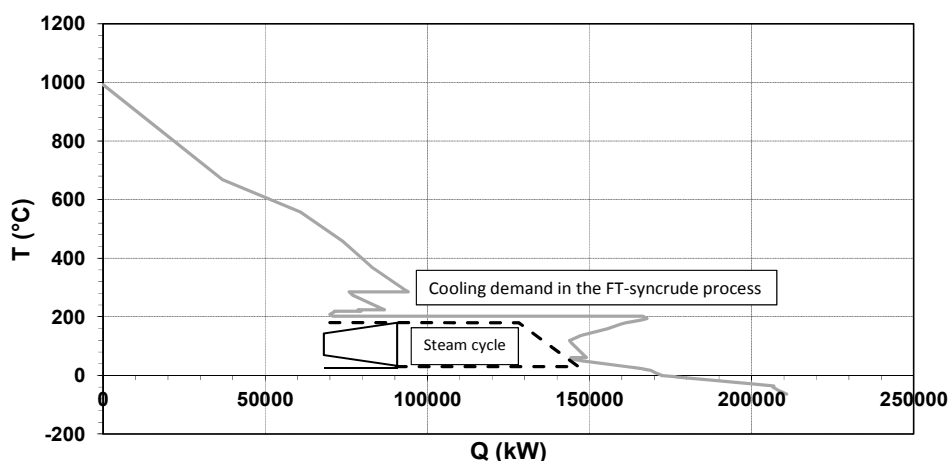


Figure 8 GGC for the ISO (upper picture), the ARU (middle picture) and the NTHU (the lower picture) subsections



The above stated savings, however, imply that the steam savings of 75 MW at low temperature actually replace steam generated in a boiler from (fossil) primary energy. This may not be the case for all refineries in general as the steam might as well be generated e.g. by heat recovery or steam extraction from a turbine. The assumption above, however, requires that the 75 MW of steam that is saved has been produced in boilers based on primary energy. The steam balance is different at different refineries and therefore it is not always that this steam originates from primary energy. Due to this uncertainty, alternative cases to Case 1 and 2 are studied. In these cases (here after referred to Case 1b and Case 2b), the excess heat at high temperatures from the FT process is heat integrated with the CDU/CDU units as previously described (as Figure 7 indicates). However, the excess heat at low temperatures is in these cases used for electricity generation in a condensing turbine (as Figure 9 shows). In the electricity generation, steam at 10 bar is expanded down to 0.042 bar, with an electricity efficiency of 0.25.

Figure 9 GCC for the FT process (solid line) with a two-stage steam cycle (dotted line)



9 Summary of resulting energy balances

Table 4 presents a summary of the main results for the three studied alternatives. The results show that the largest energy flows are in the gasification and synthesis part of the FT fuel production. An integrated FT diesel and gasoline production at the refinery could theoretically save 191 MW fuel in the refinery, which would decrease the natural gas import to the refinery. On the other hand, a stand-alone alternative could generate 45 MW power and minimise the amount of trucks with biomass to the refinery. The total yield of diesel could be improved if a new hydrocracker is built. The revenue difference between natural gas saving and electricity generation will probably define the most cost-effective alternative.

Table 4 Summary of energy balances for the three studied cases including CO₂ capture on the biomass-to-FT syncrude production

	<i>Case 1</i>	<i>Case 2</i>	<i>Case 3</i>
<i>Input biomass [MW]</i>	500	500	500
Number of trucks with biomass to refinery/day	160	160	10
FT syncrude [t/h]	22	22	22
FT wax [t/h]	8	8	8
FT gases ¹ [MW]	21	19	19
Off-gases [MW]	5	5	5
% wt of current hydrocracker load	2		
Δ Power consumption (including CO ₂ capture on the biomass-to-FT syncrude production) [MW]	55	55	9
Δ Power consumption (biomass-to-FT syncrude production) [MW]	49	49	5
Δ Power consumption (FT syncrude upgrading) [MW]	0.7	0.4	0.4
Δ Power consumption (compression of captured CO ₂) [MW]	4	4	4
Δ Power consumption (closure of furnace HS production) [MW]	1	1	0
Power generation (condensing turbine and gasturbine, stand-alone case)	-	-	45
Δ Fuel consumption for process heating [MW]	-191	-179	17
Δ Fuel consumption for process heating (biomass-to-FT syncrude production) [MW]	-195	-195	0
Δ Fuel consumption for process heating ² (FT syncrude upgrading) [MW]	5	9	9
Δ Hydrogen [kg/s]	-0.01	0.04	0.04
<i>FT diesel</i> ³ [MW]	163	200	200
wt% of current diesel production	2.5	3.1	3.1
<i>FT gasoline</i> ⁴ [MW]	60	38	38
wt% of current gasoline production	1.4	0.9	0.9
Efficiency [MW _{diesel} /MW _{biomass}]	0.33	0.40	0.40
<i>Efficiency</i> [MW _{diesel + gasoline}]/MW _{biomass}]	0.44	0.48	0.48

Notes: ¹ 44.1 MJ/kg [30], ² Includes fuel for hydrogen production, ³ 43.0 MJ/kg [30], ⁴ 43.7 MJ/kg [30]

The hydrogen demand is negative in Case 1, which is due to the assumption (discussed earlier) that co-processing of wax with VGO in existing hydrocracking unit uses less hydrogen than the VGO processing. The effect of this assumption is a larger H₂ production flow from the reformer compared to the H₂ demand in the cracking and isomerisation processes.

9.1 Alternative to cases 1 and 2

In these cases (Case 1b and Case 2b), the excess heat from the FT-process at low temperature ($\sim 200^{\circ}\text{C}$) is used to produce electricity in a condensing turbine. The difference compared to Case 1 and Case 2 is that instead of saving 96 MW of natural gas the refinery saves 19 MW of electricity import.

10 GHG emissions balances

As described in the methodology section, the GHG emissions are evaluated in an expanded system (see also Figure 2). Table 5 shows the life-cycle GHG emissions related to the production of FT fuels, as well as the corresponding GHG emission savings for replacing fossil fuels.

Table 5 GHG emissions from the production of FT fuels and the replacement of fossil fuels

	Case 1 [kt CO _{2eq} /y]	Case 2 [kt CO _{2eq} /y]	Case 3 [kt CO _{2eq} /y]
Harvesting	14	14	14
Transportation to refinery/to gasifier	29	29	10
Transport of FT syncrude to refinery	-	-	2
Replacing fuel consumption in refinery (natural gas)	-419	-392	-4
<i>Power import (three different alternatives):</i>			
1 Power import (power plant)	355	353	59
2 Power import (power plant with CCS)	114	113	19
3 Power import (NGCC)	166	165	28
Distribution of FT diesel and gasoline	5	5	5
Replacing diesel	-376	-462	-462
Replacing gasoline	-137	-87	-87
CO ₂ captured from the biomass-to-FT syncrude production	-322	-322	-322

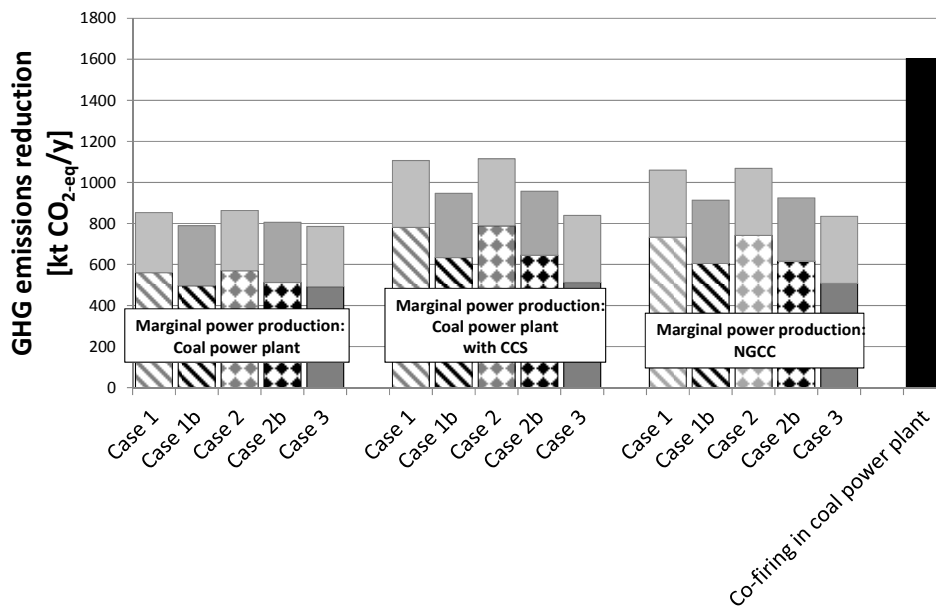
Notes: Including CO₂ capture on the biomass-to-FT syncrude production.

The hashed bars in Figure 10 show the potential for reduction in GHG emissions for the studied cases (in absolute numbers). The grey-coloured bars on top of the hashed bars in each case represent the additional reduction which can be achieved if the almost clean CO₂ stream from the gasifier is captured. As can also be seen in Figure 10, the choice of capturing the relatively clean CO₂ stream from the gasifier has a significant impact on the GHG emissions reduction.

There is no noticeable difference between the two integrated cases (1 and 2). This stresses the fact that the largest energy flow is related to the gasification process. There is, however, a noticeable difference between Case 1 and Case 1b, and Case 2 and Case 2b. The b cases represent a scenario where part of the excess heat from the FT-process is used for electricity generation. Figure 10 shows that, from a GHG emission point-of-view, integration of an FT-process with a refinery process that result in natural gas savings is preferable compared to an alternative with a combination of electricity

generation and natural gas savings. However, the difference between the integrated cases (in which heat is supplied to the current process and natural gas thereby is saved) and the stand-alone case (which generates electricity) is significant but varies depending on assumptions about the marginal electricity generation technology. Cases 1 and 2 are, regardless of marginal electricity, GHG-beneficial compared to a stand-alone alternative. Case 1b and Case 2b have greater potential for reductions in GHG emissions than a stand-alone case, when the marginal electricity producer is a coal power plant with CCS or an NGCC.

Figure 10 The GHG emission reduction potential for the studied cases per year



Notes: The grey-coloured bar in each case represents the additional reduction which can be achieved if the almost clean CO₂ stream from the gasifier is captured. The black bar on the left hand side represent the GHG emissions saved if the same amount of biomass is instead used for co-firing in coal power plants.

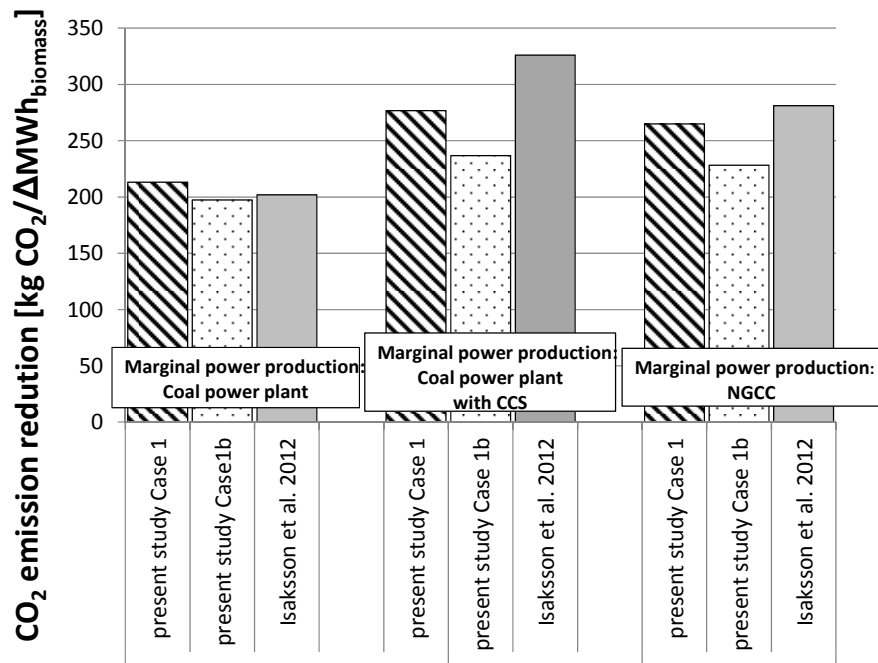
In order to look at the GHG emission reduction from a broader perspective, a comparison with the corresponding GHG emission reduction from co-firing of biomass in coal power plants is also shown in Figure 10. In this study it is assumed that biomass will become a limited resource in the future, thus additional demand of biomass to the gasification process will lead to increased use of fossil fuels elsewhere in society. The figure shows that the production of FT fuels will not offset the negative effect of having to supply more coal to coal power plants if the biomass to the FT production is replacing biomass otherwise used as co-firing in coal power plants.

Based on information from Figure 10 and the FT diesel and gasoline production in Table 4 the specific GHG emission reduction per total diesel and gasoline production (kg/MWh_{diesel + gasoline}) can be calculated. The GHG emission reduction varies between the different cases from 258 kg CO₂eq./MWh_{diesel+gasoline} to 437 kg CO₂eq./MWh_{diesel+ gasoline}, and if CO₂ from the biomass-to-FT syncrude process is captured, the GHG emission

reduction varies between 430 kg CO_{2eq}/ MWh_{diesel+ gasoline} and 621 kg CO_{2eq}/ MWh_{diesel+ gasoline}. The reduction per total diesel and gasoline production is not calculated for Cases 1b and 2b, but the resulting GHG emission reductions would be lower compared to Cases 1 and 2 (as Figure 10 indicates).

The present paper shows that an FT syncrude production, integrated with the refinery process has greater potential for reductions in GHG emissions than a stand-alone alternative in most cases. However, the FT syncrude process could be heat integrated with other industries, which have a deficit of heat at suitable temperatures. Isaksson et al. (2012) have investigated the integration potential of an FT syncrude production with an existing thermo-mechanical pulp mill and showed similar results as in the present study. FT syncrude integration with a pulp and paper mill also showed larger potential for reductions in CO₂ emission potentials than a stand-alone alternative, for scenario when the marginal electricity is coal with CCS and an NGCC, but lower emission reduction compared to co-firing of the same amount of biomass in a coal power plant. As stated in the introduction, there are other studies that investigate the integration of an FT process with different industries and district heating networks. However, since the same data for the FT syncrude process is used in both the present paper and in Isaksson et al. (2012), a proper comparison with focus on heat integration in different industries is possible. Figure 11 shows the results of the comparison between heat integration of an FT syncrude process with a refinery or with a pulp mill. To be able to compare the two studies, the emissions from the present study are changed from CO₂ equivalents to CO₂ emissions only and the level of emissions from electricity generation is the same as the one used by Isaksson et al. (2012).

Figure 11 Comparison of CO₂ emission reduction when integrating an FT syncrude production in a refinery and a pulp mill



As can be seen in Figure 11, the results from Isaksson et al. (2012) shows a larger CO₂ reduction per extra biomass input compared to this study for two of the marginal electricity alternatives. For the refinery the extra biomass input is the same as the biomass required in the FT syncrude process. In the pulp mill, however, the extra biomass is less than required in the FT syncrude process, since part of the biomass demand is utilised from saved biomass due to the integration with the FT plant, see (Isaksson et al., 2012).

11 Discussion

The present study and the generated results are based on a complex case-refinery that in prior to integration with a biomass gasifier is energy optimised. In practice, however, all refineries are different with respect to process units, operation, size, crude oil and products. In this study the biomass-to-FT syncrude process has been heat integrated with an energy-optimised refinery, which assumes a theoretical minimum heating demand. In practice, all energy measures may not be economic or practical to realise. However, a less energy optimised refining process would have larger heating requirements, and thus, not significantly affect the results of this study.

In this study the refinery is located quite close to the forest residues. If the study is performed in a country with less forest resources, the transportation distance would increase. However in that case it is more likely to assume that the biomass will be transported by boat, which has lower GHG emissions than transportation by truck. The reason to why we in this study assumed transportation by truck is to calculate a 'worst case scenario'. A duplication of the transportation distance would decrease the GHG reduction potential by only a few percentages (3-4%), which indicates that the transportation distance has a relatively small impact on the final results.

In summary, the results of the present study could be regarded as fairly general for complex refineries in Europe. Regarding the upgrading of the FT syncrude, data for existing refinery units were used in combination with conceptual studies of FT syncrude upgrading for data of the new upgrading units. The level of detail in the studies and data used varies, and a number of assumptions on process performance have been made. One main uncertainty is that the data used for the FT upgrading are not adjusted for the exact composition of the resultant FT syncrude from the simulation model.

In this study, it is assumed that the heat from the gasification process replaces heat that currently is supplied by process furnaces in the CDU/VDU area. This heat integration could practically be solved by direct heat integration or through a heat transfer system. Since the temperature levels are above the normal steam upper limit, organic fluids or molten salt fluids must be used in the practical heat transfer system. Furthermore, there is uncertainty whether the syngas from the gasification process can be used at very high temperatures without first being quenched, due to reduced atmosphere in the syngas. However, there is ongoing research to resolve this issue. Moreover, we have assumed that heat from the FT-synthesis part (heat around 200°C) can be used to cover the heat demand in refinery process at the refinery or to produce steam in the stand-alone case. But there is also uncertainty about the appropriate temperature difference in the cooling of the FT synthesis, which is not yet resolved.

Generally, only a few of a refinery's subsections are heat-integrated with each other, which is mainly due to process constraints such as different running times, safety reasons, and diverse sensitivity to capacity loss. This is also why the pinch analysis has been

conducted on subsections instead of the total refinery, which would have given larger heat-saving potentials. These issues must be resolved also when integrating with the biomass-to-FT syncrude process. An integrated biomass-to-FT syncrude production would increase the complexity of the refinery. Moreover, a biomass-to-FT syncrude production has a lower load factor than a typical refinery and, therefore, a backup system is needed (e.g. furnaces with spare capacity must exist) which can be turned on quickly. At the studied refinery the experience with such complex integration is limited, and before the potential heat integration can be realised all safety and process technical aspects must be investigated along with the construction of an appropriate back-up system.

To evaluate which system is the best, an economic analysis must be performed and evaluated together with the results from this study.

In this study it is shown that a gasification plant with the same order of biomass import as a large pulp mill only produces renewable diesel and gasoline corresponding to around 3% of the current diesel and gasoline production at a large oil refinery. Therefore, it is unrealistic to assume that the current production of diesel and gasoline can be replaced with biomass gasification to FT diesel and gasoline on-site. A more possible future is that the refinery may have one FT syncrude production plant at the refinery and if it wants to produce more FTfuels it must import FT syncrude.

12 Conclusions

In this study, heat integration of FT fuel production with an existing refinery has been evaluated and compared to a stand-alone FT syncrude production facility with regard to potential for global GHG emission reduction. Conclusions that can be drawn from the results are:

- In general, the results show that an FTfuel production that is heat integrated with a refinery generates larger GHG emission savings than corresponding stand-alone alternative.
- Upgrading of the FT syncrude in existing or new units has marginal effect on the global GHG emissions. The diesel production, however, can be maximised if new upgrading units are built.
- In the case where the process is heat integrated with the refinery, larger GHG emission reduction potential is obtained if excess heat from the FT-process replaces natural gas. The difference from a case where both natural gas is replaced and electricity is generated is significant. However, the GHG emission reduction is still larger than the stand-alone case for all scenarios, except when the marginal electricity producer is coal power plants.
- The possibility to capture CO₂ from the FT process significantly increases the GHG mitigation potential.
- As also indicated by e.g. Isaksson et al. (2012) the specific GHG mitigation potential for using biomass for FT fuel production is smaller compared to the use of biomass for co-firing in coal power plants.

- The results of the present study show a lower CO₂ mitigation potential compared to the alternative where a similar process is heat integrated with a mechanical pulp mill, when the marginal electricity is coal with CCS and an NGCC.

Acknowledgements

This work has been carried out within the Energy Systems Programme, which is primarily financed by the Swedish Energy Agency. The work has also been co-financed by Preem AB. The authors would like to thank Preem AB, and especially Christina Simonsson, for valuable inputs during the work. The authors would also like to acknowledge Eva Andersson at CIT Industriell Energi AB for collecting and gathering the stream data for the refinery process and Johan Isaksson for sharing the gasification model.

References

- Andersson, E., Franck, P.-Å., Åsblad, A. and Berntsson, T. (2012) *Pinch Analysis at Preem Lyr*, Report, Chalmers University of Technology, Göteborg, Sweden.
- Andrews, A. and Logan, J. (2008) *Fischer-Tropsch Fuels from Coal, Natural Gas, and Biomass: Background and Policy*, RL34133, CRS Report for Congress, USA.
- Axelsson, E. and Harvey, S. (2010) *Scenario for Assessing Profitability and Carbon Balances of Energy Investment in Industry*, The AGS Pathway Report, Göteborg [online] <http://www.publications.lib.chalmers.se/cpl/record/index.xsql?pubid=98347> (accessed 27 March 2012).
- Basu, P. (2010) *Gasification Theory and Modeling of Gasifiers. Biomass Gasification Design Handbook*, Academic Press, Boston.
- Bechtel (1998) *Aspen Process Flowsheet Simulation Model of a Battelle Biomass-Based Gasification, Fischer-Tropsch Liquefaction and Combined-Cycle Power Plant*, US Department of Energy (DOE), Pittsburgh, Pennsylvania.
- Damartzis, T. and Zabaniotou A. (2011) 'Thermochemical conversion of biomass to second generation biofuels through integrated process design – a review', *Renewable and Sustainable Energy Reviews*, Vol. 15, No. 1, pp.366–378.
- Dancuart, L.P., de Haan, R. and de Klerk, A. (2004) 'Chapter 6 Processing of primary Fischer-Tropsch products', in André, S. and Mark D. (Eds.): *Studies in Surface Science and Catalysis*, Vol. 152, pp.482–532, Elsevier.
- de Klerk, A. (2007) 'Environmentally friendly refining: Fischer-Tropsch versus crude oil', *Green Chemistry*, Vol. 9, No. 6, pp.560–565.
- de Klerk, A. (2009) 'Can Fischer-Tropsch syncrude be refined to on-specification diesel fuel', *Energy Fuels*, Vol. 23, No. 9, pp.4593–4604.
- de Klerk, A. (2011) 'Fischer-Tropsch fuels refinery design', *Energy & Environmental Science*, No. 4, pp.1177–1202.
- Dry, M.E. (2002) 'The Fischer-Tropsch process: 1950–2000', *Catalysis Today*, Vol. 71, Nos. 3–4, pp.227–2241.
- EC (2009a) *DIRECTIVE 2009/28/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the Promotion of 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.

- EC (2009b) *DIRECTIVE 2009/30/EC OF THE EUROPEAN PARLIMENT AND OF THE COUNCIL Amending Directive 98/70/EC as Regards the Specification of Petrol, Diesel and Gas-Oil and Introducing a Mechanism to Monitor and Reduce Greenhouse Gas Emissions and Amending Council Directive 1999/32/EC as Regards the Specification of Fuel Used by Inland Waterway Vessels and Repealing Directive 93/12/EEC*, Official Journal of the European Union.
- Edwards, R., Larivé, J-F. and Beziat, J-C. (2011) *Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context – WTT APPENDIX 1*, European Commission, Joint Research Centre, Institute for Energy and Transport, EUR 24952 EN-2011 [online] ies.jrc.ec.europa.eu/uploads/media/WTT_App_1_010307.pdf (accessed 27 March 2012).
- Ekbom, T., Hjerpe, C., Hagström, M. and Hermann, D. (2008) 'Pilot study of Bio-jet A-1 fuel production for Stockholm- Arlanda Airport', *Värmeforsk service AB*, Stockholm [online] <http://www.varmeforsk.se/rapporter> (accessed 2 November 2011).
- Ekbom, T., Ingman, D., Larsson, E. and Waldheim, L. (2005) *Biomass Gasification for Co-Generation – Integration with the Rya CHP Plant. Part 1 (Biobränsleförgasning för kraftvärme respektive energikombinat – integration med Rya kraftvärmeverk Göteborg – del 1: konceptstudie av processalternativ)*, TPS and Nykomb Synergetics (In Swedish), Nykomb Synergetics AB, Stockholm, Sweden.
- EU (2009) *Directive 2009/29/EC of the European Parliament and of the Council of 23 April 2009 Amending Directive 2003/87/EC so as to Improve and Extend the Greenhouse Gas Emission Trading Scheme of the Community*, Directive 2009/29/EC of the European Parliament and of the Council (Issue), Official Journal of the European Union.
- EUROPIA (2011) *2030–2050 Europa Contribution to EU Enrgy Pathways to 2050*, The European Petroleum Industry Association, Brussels, Belgium.
- Gode, J., Martinsson, F., Hagberg, L., Öman, A., Höglund, J. and Palm, D. (2011) *Estimated Emission Factors for Fuels, Electricity, Heat and Transport in Sweden (Miljöfaktaboken 2011)*, Värmeforsk service AB, Stockholm, No.1183 (In Swedish) [online] <http://www.varmeforsk.se/rapporter> (accessed 27 March 2012).
- Hamelinck, C.N. and Faaij, A.P.C. (2001) *Future Prospects for Production of Methanol and Hydrogen from Biomass*, Report NWS-E-2001-49, Utrecht University, Utrecht, the Netherlands.
- Hamelinck, CN., Faaij, A.P.C., den Uil, H. and Boerrigter, H. (2004) 'Production of FT transportation fuels from biomass; technical options, process analysis and optimisation, and development potential', *Energy*, Vol. 29, No. 11, pp.1743–1771.
- Isaksson, J., Pettersson, K., Mahmoudkhani, M., Åsblad, A., Berntsson, T. (2012) 'Integration of biomass gasification with a Scandinavian mechanical pulp and paper mill – consequences for mass and energy balances and global CO₂ emissions', *Energy*, Vol. 44, No. 1, pp.420–428.
- Joelsson, J.M. and Gustavsson, L. (2012) 'Reductions in greenhouse gas emissions and oil use by DME (di-methyl ether) and FT (Fische-Tropsch) diesel production in chemical pulp mills', *Energy*, Vol. 39, No. 1, pp.363–374.
- Kemp, I.C. (2007) *Pinch Analysis and Process Integration – A User Guide on Process Integration for the Efficient Use of Energy*, 2nd ed., Elsevier, Oxford, UK.
- Klemes, J., Friedler, F., Bulatov, I. and Varbanov, P. (2011) *Sustainability in the PROCESS INDUSTRY*, The McGraw-Hill Companies Inc., USA.
- Kramer, S.J. (2012) E-mail, December 2011 and February 2012.
- Kreutz, T.G., Larson, E.D., Liu, G. and Williams, R.H. (2008) *Fischer-Tropsch Fuels from Coal and Biomass*, Princeton University: Princeton Environmental Institute, Princeton, USA [online] <http://www.wem.mit.edu/mitei>.
- Kumar, A., Jones, D. and Hanna, M. (2009) 'Thermochemical biomass gasification: a review of the current status of the technology', *Energies*, Vol. 2, No. 3, pp.556–581.

- Larsson, E.D. Consonni, S., Napoletano S., Katofsky, R.E., Iisa, K. and Frederick, J. (2006) *A Cost-Benefit Assessment of Gasification-Based Biorefining in the Kraft Pulp and Paper Industry - Volume 2- Detailed Biorefinery Design and Performance Simulation*, Final Report, U.S. Department of Energy, DE-FC26-04NT42260.
- Leckel, D. (2009) 'Diesel production from Fischer-Tropsch: the past, the present, and new concepts', *Energy and Fuels*, Vol. 23, No. 5, pp.2342–2358.
- Linnhoff, B. and Flower, J.R. (1978) 'Synthesis of heat exchanger networks: I. Systematic generation of energy optimal networks', *AIChE Journal*, Vol. 24, No. 4, pp.633–642.
- Martellini, E., Nord, L.O. and Bolland, O. (2012) 'Design criteria and optimization of heat recovery steam cycles for integrated reforming combined cycles with CO₂ capture', *Applied Energy*, Vol. 92.
- Navarroa, C., Shang, Z. and Wei, H. (2005) 'Optimisation of integrated gasification combined cycles in refineries', *European Symposium on Computer-Aided Process Engineering-15, 38th European Symposium of the Working Party on Computer Aided Process Engineering*, Special issue, Vol. 20, pp.205–210.
- Olofsson, I., Nordin, A. and Söderlind, U. (2005) *Initial Review and Evaluation of Process Technologies and Systems Suitable for Cost-Efficient Medium-Scale Gasification for Biomass to Liquid Fuels*, Report, Energy Technology & Thermal Process Chemistry, University of Umeå and Department of Engineering, Physics and Mathematics, Mid Sweden University, ETPC Report, 1653-0551, 05-02 [online] <http://www.swepub.kb.se/bib/swepub.oai:DiVA.org:miun-5992?tab2=abs> (accessed 27 March 2012).
- Pettersson, K. (2011) *Black Liquor Gasification-Based Biorefineries – Determining Factors for Economic Performance and CO₂ Emission Balances*, PhD thesis, Department of Energy and Environment, Chalmers University of Technology, Göteborg, Sweden [online] <http://publications.lib.chalmers.se/cpl/record/index.xhtml?pubid=140328> (accessed 26 July 2012).
- Pettersson, K. and Harvey, S. (2010) 'CO₂ emission balances for different black liquor gasification biorefinery concepts for production of electricity or second-generation liquid biofuels', *Energy*, Vol.35, No. 2, pp.1101–1106.
- Sherif, A. (2010) *Integration of a Carbon Capture process in a Chemical Industry*, Master's thesis, Department of Energy and Environment, Chalmers University of Technology, Göteborg, Sweden [online] <http://studentarbeten.chalmers.se/publication/131163-integration-of-a-carbon-capture-process-in-a-chemical-industry-case-study-of-a-steam-cracking-plant> (accessed 26 July 2012).
- Smith, R. (2005) *Chemical Process – DESIGN AND INTEGRATION*, John Wiley & Sons Ltd., West Sussex, England, Chichester.
- Spath, P., Aden, A., Eggeman, T., Ringer, M., Wallace, B. and Jechura, J. (2005) *Biomass to Hydrogen Production Detailed Design and Economics Utilizing the Battle Columbus Laboratory Indirect – Heated Gasifier*, National Renewable Energy Laboratory [online] <http://nrelpubs.nrel.gov/Webtop/ws/nich/www/public/SearchFormalable> (accessed 27 March 2012).
- Spath, P.L. and Dayton, D.C. (2003) *Preliminary Screening – Technical and Economic Assessment of Synthesis Gas to Fuels and Chemicals with Emphasis on the Potential for Biomass – Derived Syngas*, National Renewable Energy Laboratory (NREL) [online] http://www.osti.gov/bridge/product.biblio.jsp?osti_id=15006100 (accessed 26 July 2012).
- Special Metals (2012) *INCOLOY® Alloy 330* [online] <http://www.specialmetals.com/products/incoloyalloy330.php> (accessed 14 February 2012).
- Tijmensen, M.J.A., Faaij, A.P.C., Hamelinck, C.N. and Van Hardeveld, M.R.M. (2002) 'Exploration of the possibilities for production of Fischer Tropsch liquids and power via biomass gasification', *Biomass and Bioenergy*, Vol. 23, No. 2, pp.129–152.

- Tock, L., Gassner, M. and Maréchal, F. (2010) 'Thermochemical production of liquid fuels from biomass: thermo-economic modeling, process design and process integration analysis', *Biomass and Bioenergy*, Vol. 34, No. 12, pp.1838–1854.
- Van Vliet, O.P.R., Faaij, A.P.C. and Turkenburg, W.C. (2009) 'Fischer-Tropsch diesel production in a well-to-wheel perspective: a carbon, energy flow and cost analysis', *Energy Conversion and Management*, Vol. 50, No. 4, pp.855–876.
- Walter, A. and Ensinas, A.V. (2010) 'Combined production of second-generation biofuels and electricity from sugarcane residues', *Energy*, Vol. 35, No. 2, pp.874–879.
- Wetterlund, E., Pettersson, K. and Harvey, S. (2011) 'Systems analysis of integrating biomass gasification with pulp and paper production – effects on economic performance, CO₂ emissions and energy use', *Energy*, Vol. 36, No. 2, pp.932–941.

Abbreviations

ARU	amine recovery unit
ETS	emission trading system
Eq.	equivalents
FT	Fischer-Tropsch
CDU	crude oil distillation unit
CFB	circulated fluidized bed
GCC	grand composite curve
GHG	Green House Gas emissions
ISO	isomerisation unit
LHV	lower heating value
LTFT	low temperature Fischer Tropsch
NGCC	natural gas combined cycle
NTHU	naphtha hydrotreater unit
VDU	vacuum distillation unit
VGO	vacuum gas oil.