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# Opportunities for Heat Integration of Biomass-based Fischer-Tropsch Crude Production at Scandinavian Kraftliner Mill Sites

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This paper investigates the potential for production of Fischer-Tropsch (FT) crude at a typical pulp and paper mill producing kraftliner. Heat integrated FT crude production, where excess heat from the FT crude process is used to produce steam for the mill's steam network, is evaluated for different levels of mill heat demand. The paper presents performance indicators, including wood fuel-to-FT crude efficiency, greenhouse gas (GHG) balances and production cost for FT crude, for co-located production of kraftliner and FT crude. These results are compared to corresponding performance indicators for FT crude production heat integrated with a mill producing fine paper, and stand-alone FT crude production, presented by the authors in a previous study. The results show that a typical kraftliner mill, in contrast to a typical fine paper mill, has a net steam demand even if large investments are made in steam saving measures. A kraft pulp and paper mill with an annual production of 417,000 ADt of kraftliner requires excess heat from an FT crude plant with 80–270 MW of wood fuel (LHV) input, depending on the heat demand at the mill. The wood fuel-to-FT crude efficiency, GHG emissions balances and production costs for FT crude are similar for heat integration in kraftliner and fine paper mills. The comparison of heat integrated and stand-alone FT crude production indicates higher wood fuel-to-FT crude efficiencies and lower production costs for heat integrated FT crude production. The reduction of GHG emissions is strongly affected by the assumed marginal electricity production technology, where heat integrated production benefits from low emitting electricity production technologies.

## 1. Introduction

Demand for second generation biofuels is projected to increase as part of reaching the 10 % renewable energy target for the European transport sector by 2020. According to the EU SET-Plan, biofuels based on lignocellulose have the potential to achieve improved environmental performance compared to first generation biofuels. FT fuels produced from gasified biomass can substitute fossil motor fuels in existing powertrains. The large generation of excess heat at high temperatures associated with gasification and syngas cleaning provides opportunities for heat integration of the production chain of FT fuels in pulp and paper mills, with a significant deficit of heat and with a constant year-round heat demand. However, the opportunities for heat integration of FT crude production will change over time as a result of strategic investment decisions affecting evolution of the mill process, affected by pressure from competing companies, policy instruments and market prices of feedstock and products. Heat integrated FT crude production at a typical Scandinavian pulp and paper mill producing fine paper has been investigated previously by the authors (Ljungstedt et al., 2013). The study showed that there are opportunities for heat integrated production of FT crude, but that the potential could disappear if the mill implements steam saving measures of 25 %. However, if a biorefinery concept such as lignin extraction is implemented simultaneously there is still a potential for heat integrated FT crude production. This paper investigates opportunities for heat integrated production of FT crude at a typical Scandinavian pulp and paper mill producing kraftliner. The results indicate the size of FT crude plants required in order to deliver excess heat to cover the part of the heat demand at a kraftliner mill that is not covered by combustion of black

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liquor. Different future developments at the mill are considered, such as implementation of steam saving measures and lignin extraction. The heat integrated production systems are evaluated based on their wood fuel-to-FT crude efficiency, GHG balances and production cost of FT crude. The performance of heat integrated production of FT crude at a kraftliner mill is compared with that of a fine paper mill. Kraftliner and fine paper mills represent the two main types of kraft pulp and paper mills in Sweden. In 2011, the annual paper production of these two mill types amounted to 1,300,000 and 350,000 t (Lundberg and Halvarsson, 2012). For comparison, the paper also presents an overview of results from Ljungstedt et al. (2013) concerning stand-alone production of FT crude.

## 2. The studied system

In this paper the production of FT crude is assumed to be co-located at a pulp and paper mill producing kraftliner. Further refining and upgrading of the FT crude at an oil refinery is not included. The investigated processes are presented briefly in this section. For more details, the reader is referred to Delin et al. (2005) and for the more recent work to Isaksson et al. (2012).

### 2.1 Pulp and paper mill

The mill is an integrated kraft pulp and paper mill producing 417,000 ADt/y (1305 ADt/24h) of kraftliner from softwood feedstock. Black liquor is combusted in the recovery boiler covering the main part of the mill’s steam demand and the remaining part is covered by falling bark and purchased wood fuel fired in the bark boiler. Data for the mill is presented in Table 1, based on data for a model mill representative of a typical Scandinavian kraftliner mill (Delin et al., 2005). For comparison, data for the fine paper mill mentioned above is included as well. All energy flows in this paper are based upon LHV of the fuel. As a consequence of higher pulp yield in the kraftliner mill, a larger share of the steam demand is satisfied by steam from the bark boiler requiring a larger import of wood fuel compared to for a fine paper mill. The kraftliner mill is however smaller, which makes the actual steam deficit similar to the fine paper mill.

*Table 1: Data for integrated pulp and paper mills; for fine paper and kraftliner production.*

| Characteristics | Kraftliner mill | Fine paper mill |
|---|---|---|
| Paper production (ADt/24h) | 1,305 | 1,570 |
| Black liquor (MW) | 134 | 242 |
| Falling bark/Imported wood fuel (MW) | 16/95 | 32/62 |
| Steam generated in recovery/bark boiler (MW) | 109/62 | 191/56 |
| MP steam (11 bar, 200°C) demand (MW) | 74 | 30 |
| LP steam (4.5 bar, 200°C) demand (MW) | 67 | 170 |
| Power generated on site (MW) | 30 | 44 |
| Total power consumption (MW) | 50 | 67 |

The paper accounts for possible steam saving measures (SSM) of up to 40 MW, corresponding to 28 %, using currently available technologies, as presented by Axén (2010). The options are divided into two groups of totally 30 MW (21 %) and 40 MW (referred to as SSM-low/high). Lignin extraction is considered as an example of biorefinery concept that could be implemented simultaneously at the mill, resulting in decreased steam production in the recovery boiler. Lignin extraction is an emerging technology that has not been tested in full scale and there exists uncertainties regarding e.g. the amount of lignin that it is possible to extract. Therefore, two levels of lignin extraction are considered; 0.15 and 0.27 t/ADt (29 and 52 MW, referred to as LE-low/high). The lignin extraction increases the consumption of electricity (0.4/0.8 MW) and steam (2.5/4.3 MW). Table 2 presents the 7 cases studied, resulting from combinations of levels of steam saving measures and lignin extraction.

*Table 2: Level of steam saving measures; SSM-low/high (30/40 MW) and lignin extraction; LE-low/high (0.15/0.27 t/ADt) for the cases studied*

| Mill configuration/case | 1 (BAU) | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| Steam saving measures (SSM) | - | low | high | low | low | high | high |
| Lignin extraction (LE) | - | - | - | low | high | low | high |

### 2.2 Fischer-Tropsch crude production

Data for the FT crude process used in this study was generated using an ASPEN model and presented in more detail by Isaksson et al. (2012). The process includes a pressurized, oxygen and steam blown circulating fluidized bed gasifier operating at 25 bar and 850 °C, a slurry phase FT-reactor operating at 23 bar and 210 °C, using cobalt as catalyst, as well as integrated drying of the feedstock from 50 wt-% to 15 wt-% moisture content. The biomass-to-FT crude efficiency is 52 % and the electricity demand is approximately 90 kW/MW of biomass input. The spectrum of final products depends on the refining process, for example the product mix in a refinery maximizing FT diesel yield from FT crude feedstock is 29 % FT diesel, 38 % motor gasoline and 33 % jet fuel on an energy basis (de Klerk, 2011).

## 3. Methodology

To quantify the size of an FT crude plant required to cover the mill's heat demand, the mill heat demand is determined for each case. To quantify the amount of excess heat available from the FT crude production plant, Pinch Analysis (Linnhoff and Flower, 1978) with individual temperature differences of 4–16°C (Isaksson et al., 2012) is used. The excess heat is used to generate HP (61 bar) and MP (11 bar) steam that is fed into the mill's steam network. The resource flows considered for co-located production of FT crude are the incremental flows of the mill with FT crude production, compared to the mill without production of FT crude.

As a performance indicator for the different cases, wood fuel-to-FT crude efficiency is used (amount of FT crude produced in relation to incremental use of wood fuel and electricity). The incremental use of electricity is valued as wood fuel, based on an assumed value of wood fuel-to-electricity efficiency. Sensitivity analysis is performed with respect to this parameter.

Net GHG emissions ($CO_2$-equivalents using GWP100 values) are estimated applying a life cycle perspective to determine the emissions associated with the incremental resources imported to or exported from the site. For the resulting GHG emissions balances, the usage of FT crude is also included within the system boundaries of this study. It is assumed that FT crude replaces fossil feedstock in an oil refinery. The avoided emissions of fossil GHGs are calculated based on the amount of "green" $CO_2$ released during complete combustion of the FT fuel, corresponding to 255 kg $CO_2$-eq./$MWh_{fuel}$ (Isaksson et al., 2012) to which 23 kg $CO_2$-eq./$MWh_{fuel}$ are added, corresponding to the extraction of fossil crude oil (Gerdes and Skone, 2009). Emissions of GHGs connected to transport of FT crude to the oil refinery and distribution of motor fuels to customers are assumed to be the same as for the fossil feedstock and fossil motor fuel it replaces, i.e. not affecting the GHG balance. The GHG emissions associated with increased import of wood fuel to the mill consist of emissions from logging and transporting of the wood fuel, i.e. well-to-gate emissions; 9 kg $CO_2$-eq./$MWh_{wf}$ (Isaksson et al., 2012). The results are presented as GHG emissions reduction per unit of wood fuel used as a function of the GHG emissions associated with marginal electricity production (base load build margin). Production cost of FT crude is determined using investment cost data presented by Johansson (2013) and Pettersson (2011). It is assumed that the kraftliner mill is about to replace the old bark boiler and is facing a choice between investing in a new bark boiler and investing in a production plant for FT crude. Thus, it is the incremental investment cost compared to investing in a new bark boiler that is considered. All the results are presented in 2010 year money value. The capital recovery factor is set to 0.1. Investment costs include equipment and installation costs, balance of plant costs and indirect costs. The annual operation and maintenance costs are assumed to be 4 % of the total investment cost. The production cost for FT crude is calculated as the sum of the annually incremental costs including capital cost, operation and maintenance costs, cost of electricity and wood fuel usage, divided by the amount of FT crude produced annually. Revenue from a policy instrument promoting production of renewable electricity is assumed to be 20 €/$MWh_{el}$, representing an average level for Sweden. Wood fuel-to-FT crude efficiencies, GHG balances and production costs for the kraftliner mill are compared to the corresponding results for the fine paper mill. In addition, the results for stand-alone (SA) FT crude production plants are also included, based on similar assumptions but assuming that excess steam is used for power generation in a condensing steam turbine unit.

## 4. Results and Discussion

Table 3 presents the resulting energy balances for heat integrated FT crude production at the kraftliner pulp and paper mill compared with the mill without production of FT crude.The increased electricity import is mainly a result of the demand connected to the FT crude processes, but also a result of loss of electricity production compared with the mill without production of FT crude. Figure *1* presents the sizes of FT crude plants that would be needed to deliver enough heat to cover the heat demand at the kraftliner mill and the fine paper mill, for the different cases considered.

*Table 3: Energy balances for heat integrated FT crude production at the kraftliner pulp and paper mill.*

| Δ (Incremental energy flows) | 1 (BAU) | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| Wood fuel input to FT plant (MW) | 227 | 120 | 81 | 206 | 271 | 168 | 233 |
| Wood fuel import (MW) | 142 | 75 | 50 | 129 | 169 | 106 | 145 |
| Electricity import (MW) | 28 | 15 | 10 | 25 | 34 | 21 | 29 |
| FT crude export (MW) | 117 | 62 | 42 | 106 | 140 | 87 | 120 |

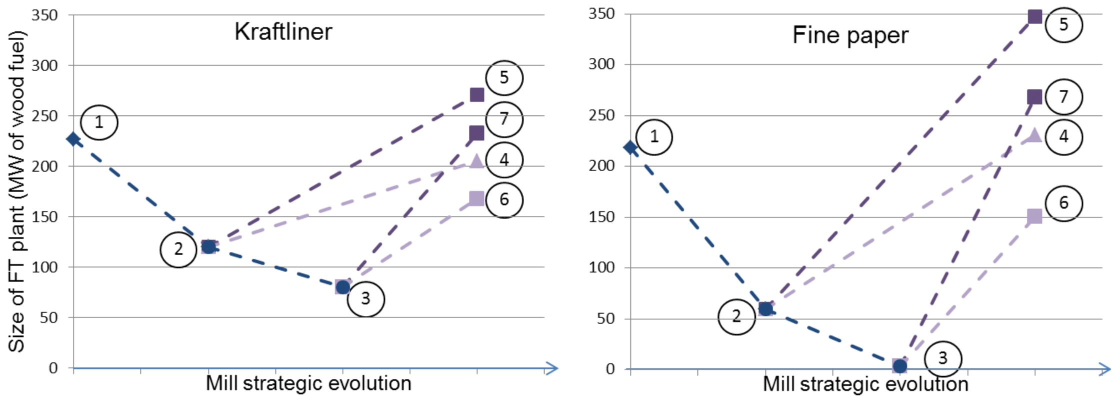


*Figure 1: Potential size of an FT crude plant co-located with a pulp and paper mill, Cases 1-7.*

The FT crude plants in cases 2 and 3 are assumed not to be large enough for the mill to make the investment, due to high specific investment cost (Thunman et al., 2007). However, if another biorefinery concept is implemented at the mill (Cases 4 – 7), increasing the net steam demand, the required size for the heat integrated FT plant increases to 170 – 270 MW of wood fuel input. Corresponding results for the fine paper mill are 150 – 350 MW of wood fuel input. The amount of lignin extracted in the different types of mills corresponds to the same share of the total energy content of the black liquor. The larger amounts of lignin extracted in the fine paper mill (54/94 MW) result in larger heat demands and consequently a need for larger FT crude plants heat integrated with the mill. The fine paper mill has a larger possibility to be self-sufficient in terms of heat supply, while the kraftliner mill, with a higher specific heat demand, will not have that possibility even with large investments in steam saving measures. The kraftliner mill is therefore more likely to be interested in investing in new, alternative heat sources. However, as for the fine paper mill, lignin extraction is required in order to achieve sufficient sizes.

Figure 2 presents the wood fuel-to-FT crude efficiency for the heat integrated and stand-alone production of FT crude.

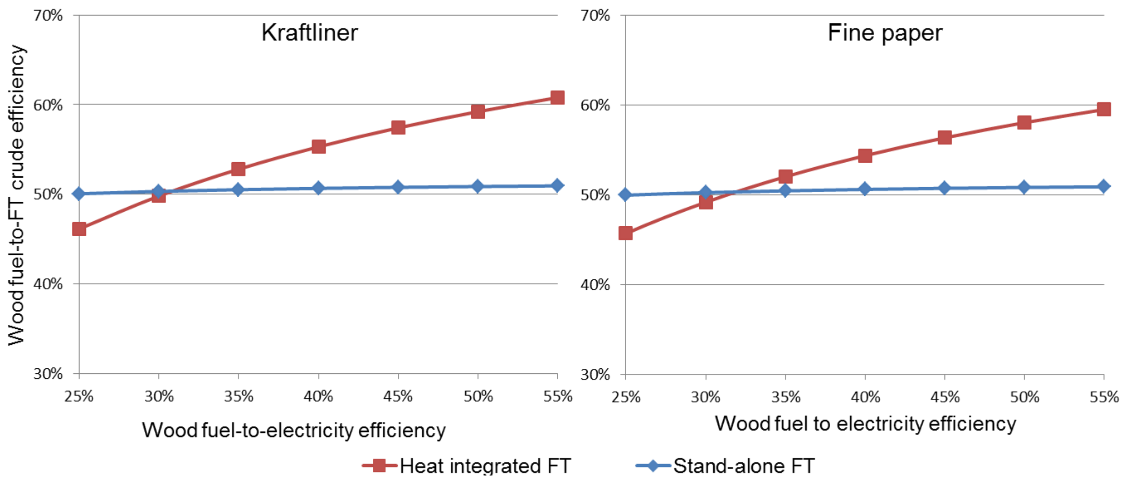


*Figure 2: Wood fuel-to-FT crude efficiency. Electricity is valued as wood fuel, using varying wood fuel-to-electricity efficiencies*

The FT stand-alone plant is almost self-sufficient in terms of electricity and therefore the wood fuel-to-FT crude efficiency is approximately constant at 50 %, regardless of the wood fuel-to-electricity efficiency. At a wood fuel-to-electricity efficiency above approximately 30 %, heat integration with a pulp and paper mill achieves higher wood fuel-to-FT crude efficiency than the stand-alone production of FT crude. Indicative efficiency values for electricity generation from wood fuel range from 36 % for advanced steam cycle power plants to 48 % for an integrated gasification combined cycle. Reduction of GHG emissions associated with the production of FT crude and further replacement of fossil feedstock in an oil refinery are presented in Figure 3 for the heat integrated and stand-alone FT crude production.

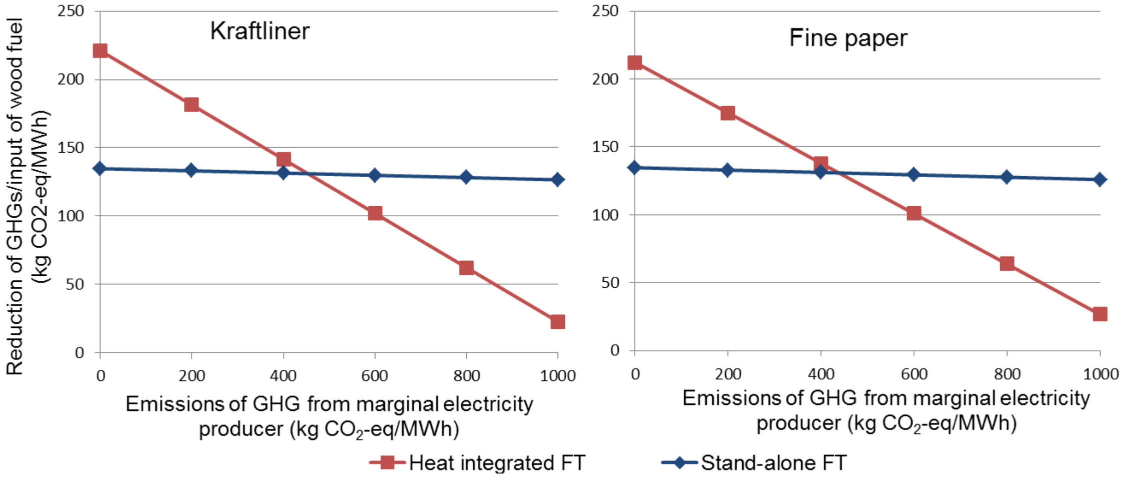


*Figure 3: Reduction of GHG emissions for stand-alone and co-located FT crude production*

State-of-the-art natural gas combined cycle (NGCC) power plants typically emit approximately 400 kg $CO_2$-eq/$MWh_{el}$). If marginal grid emissions are higher than this value (as is the case for e.g. coal power plants which is currently the marginal power generation technology in many European grid systems), stand-alone FT crude production is shown to have a larger potential to reduce GHG emissions than co-located production. However, FT crude production from biomass is assumed not to be implemented in commercial scale in the near-term, and it is thus more relevant to assume relatively low emissions associated with grid power generation (i.e. lower or equal to emissions from NGCC power plants). Under such conditions, the predicted decrease in GHG emissions connected with future electricity generation is more beneficial for heat integrated than for stand-alone production of FT crude.

Figure 4 presents the production cost of FT crude, consisting of three main parts: cost of capital (including operation and maintenance cost), cost of wood fuel and cost of net electricity use. For each case, both the production cost for heat integrated production and for stand-alone production, with the same amount of FT crude produced, are presented.

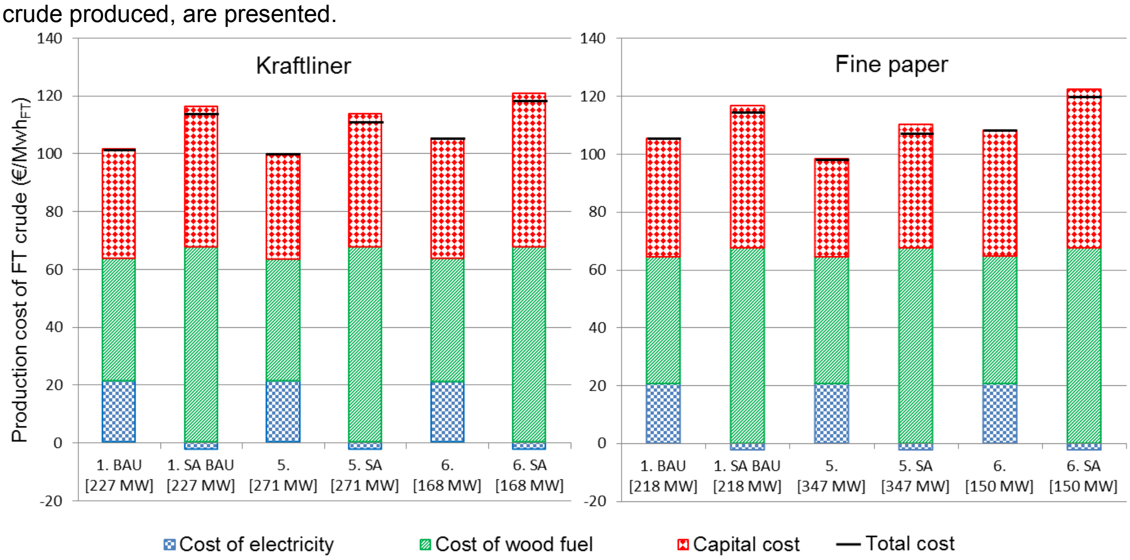


*Figure 4: Specific production cost of FT crude (wood fuel 35 €/MWh; electricity 70 €/MWh).*

For kraftliner, the production cost of FT crude is in the interval 100 – 106 €/$MWh_{FT}$ for heat integrated production and 111 – 118 €/$MWh_{FT}$ for stand-alone production. Similar differences in heat integrated and stand-alone production can be found for the fine paper mill; 98–108 €/$MWh_{FT}$ and 108–120 €/$MWh_{FT}$. This corresponds to a reduction of the production cost of FT crude by about 10 %, assuming the prices given in Figure 4, if the production is heat integrated with these types of kraft pulp and paper mills.

## 5. Conclusions

This study has quantified the opportunity for heat integrated FT crude production, co-located with a typical Scandinavian kraft pulp and paper mill producing 417,000 ADt/y of kraftliner. The influence of possible future developments at the mill, i.e. implementation of steam saving measures and lignin extraction, has also been investigated.
The following conclusions can be drawn for heat integrated FT crude production at a kraftliner mill:

- At a typical mill which adopts no changes, there exists a potential for heat integrated FT crude production at sizes above 200 MW of wood fuel input.
- The opportunities for heat integrated production of FT crude at reasonable sizes could be eliminated if the mill implements steam saving measures of more than 20 %.
- However, if lignin extraction (0.15–0.27 t/ADt assumed) is implemented simultaneously there exists a potential for heat integrated FT crude production, resulting in plants of 170–270 MW wood fuel input.

Comparison of heat integrated production of FT crude in a pulp and paper mill producing kraftliner with a mill producing fine paper shows similar values for the performance indicators used in this study (wood fuel-to-FT crude efficiency, GHG emissions balances and production costs for FT crude). However the larger specific heat demand at the kraftliner mill would provide a higher stability in demand for excess heat and consequently a larger incentive for the mill to invest in alternative heat sources, compared to the fine paper mill. Heat integrated FT crude production was also compared with stand-alone FT crude production with a steam cycle for condensing power generation. Heat integrated production achieves higher wood fuel-to-FT crude efficiencies, lower production costs and a larger potential to contribute to GHG emission mitigation (up to 220 kg $CO_2$-eq/MWh of wood fuel input), assuming a future generation of electricity emitting equal to or less than an NGCC power plant.

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