ENERGY EFFICIENCY IN BIOREFINERIES—A CASE STUDY OF FISCHER-TROPSCH DIESEL PRODUCTION IN CONNECTION WITH A PULP AND PAPER MILL

TURO HAIKONEN*, MARI TUOMAALA, HENRIK HOLMBERG, PEKKA AHTILA

ABSTRACT

A problem arises in integrated production plants, where several products are produced simultaneously, when different plants are evaluated in respect to their own energy efficiency indicators. Energy efficiency is measured as the ratio of energy input to products produced. In a mill that produces pulp and paper products, heat, electricity, and liquid transportation fuels, the challenging problem is how to define a mill-specific energy efficiency indicator and how it can be compared to corresponding indicators in other mills. In this study, energy efficiency figures were calculated for a stand-alone Fischer-Tropsch (FT) plant and for a case in which the same stand-alone plant is connected to an integrated pulp and paper mill. In addition, the study also evaluated CO_2 emission efficiencies. The results clearly indicate that the introduction of the FT plant into an integrated pulp and paper mill is beneficial from the perspective of primary energy and biomass use. When considering CO_2 emissions, the benefit depends on the definition of the plant boundary and the degree of optimization of the integrated process.

INTRODUCTION

For a long time, wood-based biomass has been used mainly in the production of pulp and paper products in the forest industry. Recently, forest industry companies have become increasingly interested in producing alternative end-products such as bio-chemicals, bio-plastics, food ingredients, and bio-fuels. These new bio-based products represent a new business potential for the forest industry. The bio-based products can also replace existing fossil-fuel-based products, for example polymers. Because of the existing infrastructure, available side streams, and process flows, it seems economical to connect these new production units with an integrated pulp and paper mill. The purpose of this integration is to create efficient processes with minimum utilization of raw materials and energy as well as low CO_2 emissions. Energy efficiency improvements are seen as one of the most effective ways to reduce CO_2 emissions [1].

A need has arisen for new bio-based transportation fuels since the European Union set targets for bio-fuel use within the transportation sector. According to the EU, the share of bio-fuels should have been 5.75% by the end of 2010 and should rise to 10% by 2020 [2,3]. Biomass-based Fischer-Tropsch (henceforth FT) diesel is an attractive end-product because it has properties similar to those of conventional fossil-based diesel and therefore is easily used in modern diesel engines. Furthermore, FT production technology is well known because it has been in existence since the early 20th century.

The effects of introducing an FT plant into an integrated pulp and paper mill have been studied, e.g., in [4]. However, relatively few studies have investigated the benefits of integrating an FT plant into a pulp and paper mill, and therefore this study presents a good overview of the benefits of this type of integration. Table 1 represents the energy flows in this study. In the integrated pulp and paper mill, only energy production from the power boiler was studied. Steam production in the power boiler decreased when the FT plant was implemented. Therefore, the assumption was made that when steam from the FT

TURO HAIKONEN
School of Engineering,
Aalto University,
P.O. Box 14100,
00076 Aalto,
Finland

MARI TUOMAALA
School of Engineering,
Aalto University,
P.O. Box 14100,
00076 Aalto,
Finland

HENRIK HOLMBERG
School of Engineering,
Aalto University,
P.O. Box 14100,
00076 Aalto,
Finland

PEKKA AHTILA
School of Engineering,
Aalto University,
P.O. Box 14100,
00076 Aalto,
Finland

*Contact: Turo.Haikonen@aalto.fi

plant replaces power boiler steam production, the old power boiler (biomass input 151 MW) can be replaced with a new, smaller one (biomass input 39 MW).

TABLE 1 *Energy flows in the reference case [4].*

	Fischer-Tropsch (FT)	Integrated pulp and paper mill	FT + integrated pulp and paper mill
Purchased biomass, MW	260	151	299
Produced electricity, MW	26	31	27
Consumed electricity, MW	27	31	58
Purchased electricity, MW	1	---	31
Biomass for purchased elect., MW	2.6	---	79
Produced heat, MW	---	100	100
Produced FT liquids, MW	156	---	156

Table 1 demonstrates the reduction achieved in the biomass utilization rate. Before integration, the total biomass utilization was 414 MW (260+151+2.6), and after, it fell to 378 MW (299+79). One drawback of integration is the increase in electricity consumption. The efficiency of purchased electricity production was assumed to be 39%.

In this study, the FT plant is introduced into an integrated pulp and paper mill (IPPM). This connection is highly favourable if the excess heat from the FT process can be used in the IPPM [5]. Integration also makes it possible to use the existing infrastructure of the mill site, thus lowering the investment cost for roads, biomass pre-treatment, connections to the external power grid, and so forth. The primary focus of this study is to calculate the energy and CO_2 emissions efficiency of an FT plant and then to investigate how these figures change when the FT plant is integrated into an integrated pulp and paper mill. The FT process has been modelled in Excel, and the chemical composition of syngas has been calculated using the HSC-Chemistry program. Energy and CO_2 balances have been calculated using these software programs.

METHODOLOGY

Description of the Fischer-Tropsch process

In the FT plant studied, waxes are produced from biomass, and it is assumed that these waxes will be refined to liquid transportation fuels somewhere else. First, biomass is pre-treated (cleaned and crushed) and then dried to a moisture content of 15 wt%. The moisture content of the biomass entering the gasifier should be 10–15 wt% for efficient operation of the gasifier [6]. In this study, biomass drying is accomplished with secondary heat (hot water and condensates) and with low-pressure steam. The proportions of drying media can be varied, but for these calculations, 50% for each was chosen.

The gasifier is modelled using the HSC-Chemistry program, which calculates the equilibrium composition of the synthesis gas (= syngas) by minimizing Gibbs' free energy. Carbon conversion is assumed to be 100%. After the gasifier, light gaseous hydrocarbons (e.g., methane, ethane, and propane) will be reformed to carbon monoxide (CO) and hydrogen (H_2). Tars are assumed to be catalytically destroyed in the gasifier. After the reformer, the syngas is cooled before entering the shift reactor. Cooling is accomplished by first generating high-pressure (HP) and then medium-pressure (MP) steam. In the shift reactor, steam is used to adjust the H_2/CO ratio of the syngas to a value suitable for the FT reactor (a practical value with a Co catalyst = 2.15 [7]). At this point, syngas contains some impurities, such as hydrogen sulphide (H_2S), carbonyl sulphide (COS), and hydrogen cyanide (HCN). Therefore, the catalysts used in the shift reactor must tolerate sulphur compounds. Particles will be removed in the filter upstream of the shift reactor. The shift reactor is also modelled using the HSC-Chemistry program. After the shift reactor, syngas is again cooled by generating MP and LP steam before entering the scrubber.

Before the FT reactor, the syngas pressure is raised to 4.0 MPa, and the syngas is fed to the regenerative absorber. Impurities are assumed to be removed to an acceptable level in the scrubber and in the regenerative absorber followed by guard beds. A slurry-bed FT reactor and a low-

TABLE 2 *Initial values.*

	Gasifier + Reformer	Shift reactor	FT reactor
Pressure [MPa]	1.5	1.3	4.0
Temperature, exit [°C]	850	437	240
Dry biomass flow	10 kg/s		
Biomass moisture	15% after dryer		
Dryer heat demand	3.7 MJ/kgH_2O		
Production of O_2	390 kWh/t		
Steam to gasification and shift	0.4 kg/kg dry matter		
LP steam to regenerative absorber	6 MW		
LP steam production	0.5 MPa, 160°C, 6 MW		
MP steam production	2.2 MPa, 320°C, 36 MW		
HP steam production	9.0 MPa, 510°C, 16 MW		
Annual operation	7884 h		

temperature (240°C) conversion process are assumed. In the FT reactor, long- and short-chain hydrocarbons are formed from H_2 and CO. Hydrocarbons consisting of five or more carbon atoms are regarded as the desired end-product (so-called FT waxes), and short-chain hydrocarbons are regarded as off-gas. Reactions in the FT reactor are highly exothermic, and the temperature increase in the reactor is controlled by generating MP steam. Part of this steam can be used in the process, and the rest can be superheated and sent to the turbine for electricity generation. The initial values used in this study are presented in Table 2 and a flow-sheet of the FT process in Fig. 1.

All produced off-gas can be directly combusted to produce HP steam, or part of the gas can be recycled to the reformer, where hydrocarbons will be cracked to H_2 and CO, thus increasing the conversion to FT waxes. In addition to the conversion efficiency η, the product deviation of the FT reactor is dependent on the so-called chain-growth probability factor α. The larger the value of α, the longer are the hydrocarbons produced. Both η and α are influenced by several factors, among them temperature, pressure, the catalyst used, and catalyst activity, but these factors are not addressed in this study [7].

CALCULATION OF CASES

a) Stand-alone Fischer-Tropsch plant

In the stand-alone case, the amount of FT wax produced is maximized by recycling most of the off-gas, but not all off-gas can be recycled. Inert gases (e.g., CO_2) can accumulate in the process, and consequently the specific energy consumption in pumping and compression increases. Excess off-gas, HP steam, and MP steam generated in the process are used for electricity production in the CHP plant.

b) Integrated FT wax production

The FT production unit can be integrated into an integrated pulp and paper mill, and in this case, processes can be connected so that the steam produced in the FT plant can be used in the pulp and paper mill. This reduces the need for steam production in the CHP plant. As a result, additional options are available in the new situation:

1. Steam production in the biomass boiler can be reduced and the excess biomass used in the FT plant to replace purchased biomass. Off-gas is burned in the CHP plant.
2. Same as option 1, except that off-gas is burned in the lime kiln to reduce the use of fuel oil.
3. Excess steam is sent to the condensing turbine to produce electricity.

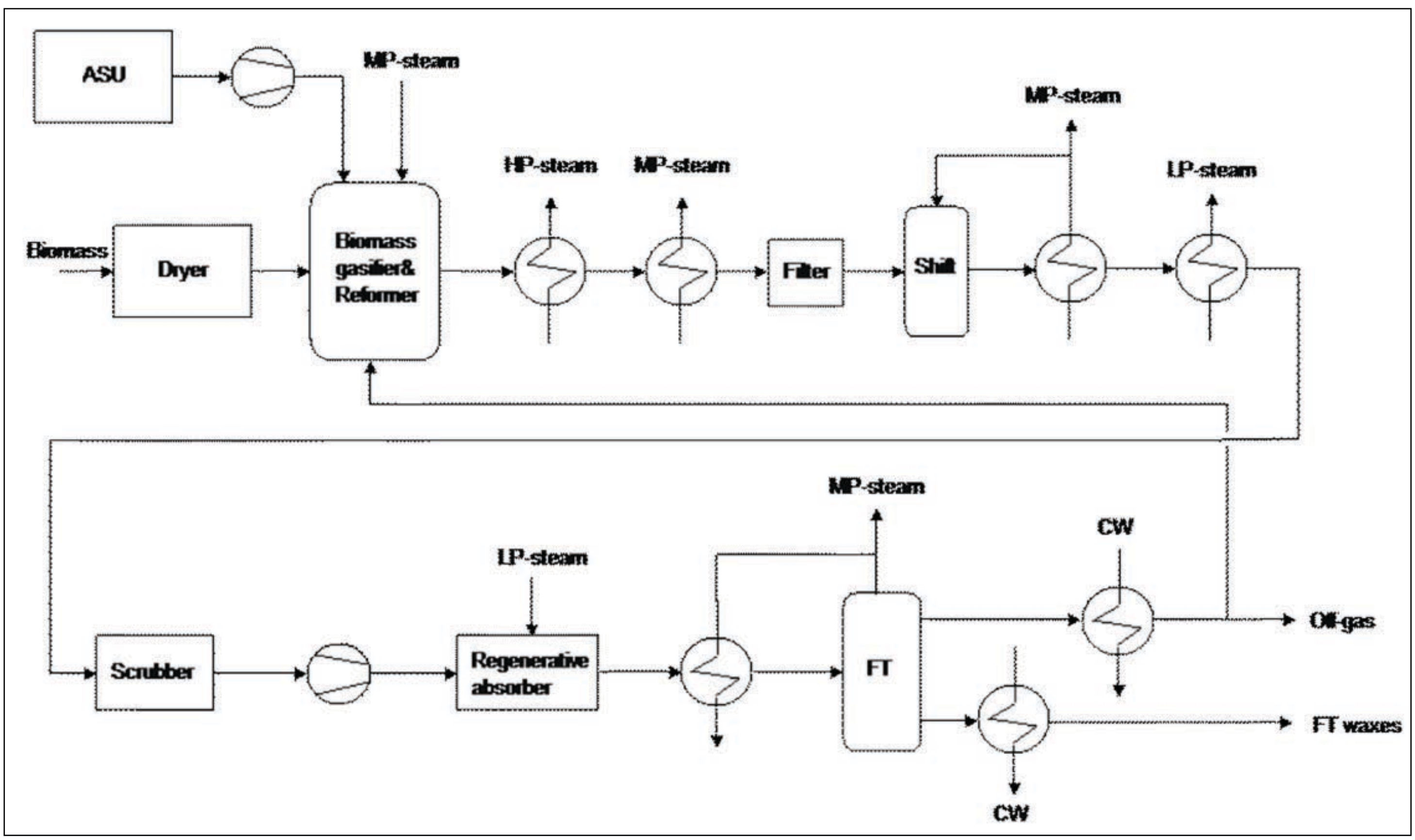

Fig. 1 - Flow-sheet of the Fischer-Tropsch process.

Typical heat and electricity consumption figures for integrated pulp and paper mills were used in this study. It is assumed that the mill's other processes remain unchanged. A recovery boiler supplies part of the heat and electricity needed at the mill site. Heat supplied from the CHP power plant is 82 MW and remains unchanged. The purchased electricity is assumed to be produced from coal (assumed η = 40%). The selected study boundaries are shown in Fig. 2.

RESULTS AND DISCUSSION

Table 3 presents the calculated results, which only indicate the changes in the flows crossing the boundaries shown in Fig. 2. The changes in the flows include the CO_2 emissions and the amounts of purchased biomass, electricity, and fuel oil. The base case represents the stand-alone options for the FT plant and the integrated pulp and paper mill. As a result of the integration, the FT process generates most of the heat required at the mill site. This reduces the biomass input to the CHP boiler. The drawback is the reduction in electricity production in the CHP plant. The CO_2 figures presented in Table 3 include emissions from both coal and fuel oil combustion.

TABLE 3 *Calculated energy flow changes.*

	Purchased biomass [MW]	Purchased electricity [MW]	Coal for purchased elect. [MW]	Fuel oil [MW]	FT waxes [MW]	CO_2 [t/a]
Stand-alone FT	167	0.2	0.5	0	100	1340
Stand-alone IPPM	33	12	30	26	0	138000
Option 1	130	18	45	26	100	178000
Option 2	140	18	45	16	100	156000
Option 3	200	-7	-17.5	26	100	10100

In Option 1, the off-gas and heat produced in the FT plant can be used to replace biomass in the CHP plant. In this process option, the use of biomass can be decreased by 70 MW. The decrease in the electricity production of the CHP plant increases the need for electricity from the external power grid. This then increases the coal-based CO_2 emissions. This process configuration has the highest CO_2 emissions and the lowest biomass utilization rate.

In Option 2, the off-gas is burned in the lime kiln, reducing the use of fuel oil by 10 MW. This means an annual decrease of 22,000 t in CO_2 emissions.

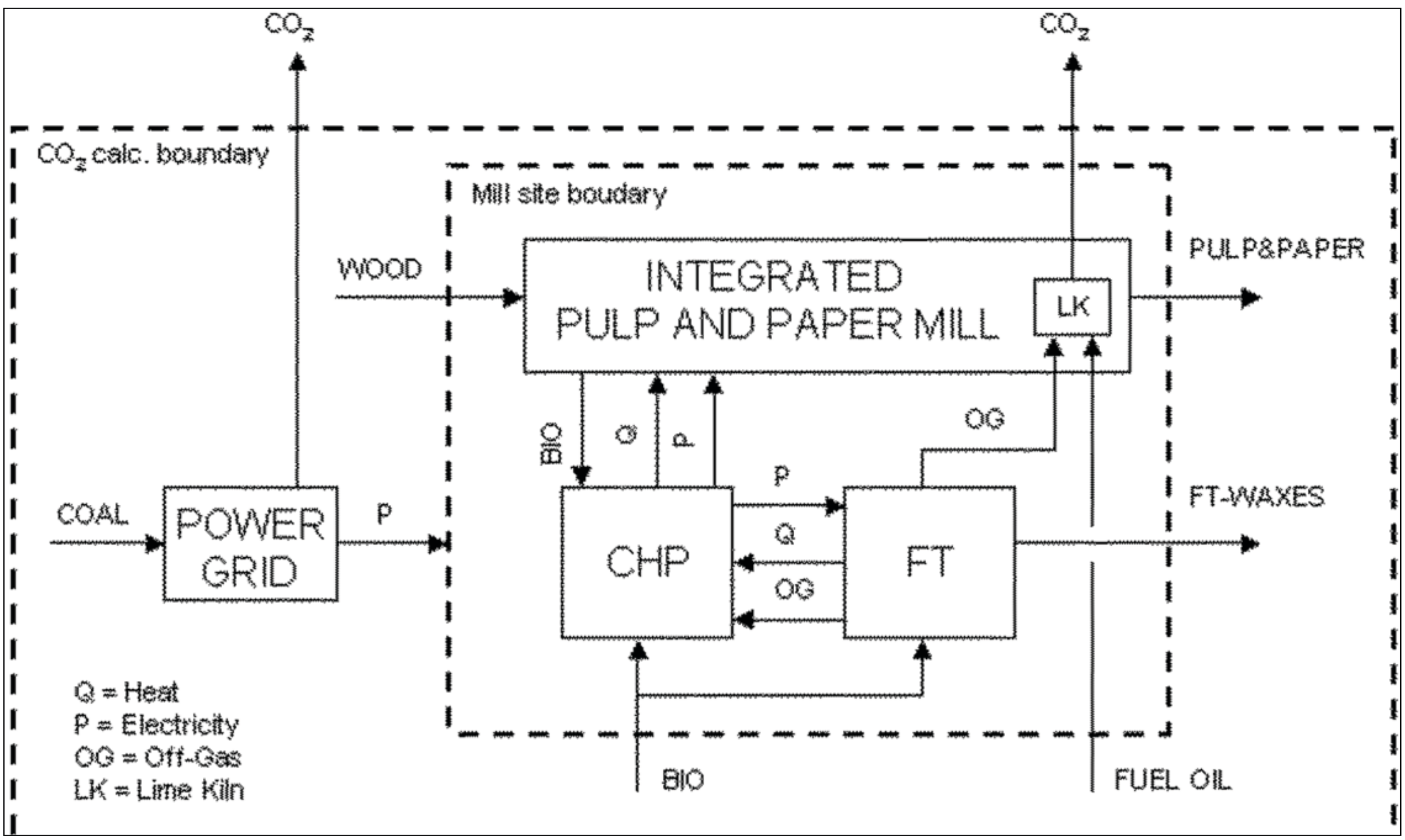

Fig. 2 - Mill-site boundary and CO_2 calculation boundary.

However, the total CO_2 emissions are larger than in the stand-alone case. This results from the increased electricity needed from the power grid. From the mill's perspective, by replacing fuel oil with FT off-gas, savings can be achieved not only in CO_2 cost, but also in purchased fuel oil. The heat produced in the FT process reduces purchased biomass by 60 MW, meaning that all the marginal fuel (biomass) to the CHP boiler can be replaced. The biomass reduction is 10 MW lower than in Option 1 because the steam production from off-gas is made up with biomass.

In Option 3, the biomass input to the mill is kept constant, and excess steam is used to produce electricity. The negative value in Table 3 shows that this electricity (in this option, 7 MW) can be sold to the power grid. This option also produces the lowest amount of CO_2. Electricity production can even be increased if the mill's energy production is based on the gas turbine and the heat recovery steam generator, but this option was not investigated in this study.

These results show that, from the perspective of primary energy utilization, it is beneficial to integrate the FT process into an integrated pulp and paper mill. The improvement in the utilization of total primary energy is evident, even when the increase in purchased electricity is taken into account. The lowest utilization of total primary energy is 209 MW in Option 3, and the highest is 257 MW in the stand-alone case.

When the FT plant is operating within an integrated pulp and paper mill, maximum production of FT waxes is not necessarily the most reasonable option. Determining the most economical process option for an integrated plant is a multi-criteria optimization process and is strongly dependent on the current market value of the end products, raw materials, and utilities. For instance, if the CO_2 price is high, it might be beneficial from the mill's perspective to replace fossil fuels with off-gas, thus decreasing the off-gas recycling ratio in the FT plant. However, electricity production may be preferred in other situations.

This study also revealed that when various perspectives are considered, creating efficient processes becomes problematic. Another purpose of this study was to comprehend how unit processes relate to biorefineries and how these interactions influence energy efficiency.

CONCLUSIONS

The purpose of the study was to investigate how energy and CO_2 flows are influenced when an FT process is connected to an integrated pulp and paper mill. According to this study, it is beneficial to integrate the FT process into an integrated pulp and paper mill from the perspective of primary energy utilization. The benefit of integration comes from the possibility of using heat and off-gas produced in the FT process in the CHP plant to replace purchased biomass. After integration, the amount of purchased biomass can be significantly reduced. This reduction in biomass utilization increases purchased electricity requirements, which increases the CO_2 emissions from the power grid. If purchased biomass is kept constant, the mill's electricity demand can be covered by the mill's own production, and the excess electricity can be sold. This approach reduces the CO_2 emissions from the power grid.

REFERENCES

1. Siitonen, S. and Holmberg, H., "Estimating the Value of Energy Savings in Industry by Different Cost Allocation Methods", International Journal of Energy Research, 36:324-334 (2012).
2. http://ec.europa.eu/energy/res/legislation/doc (accessed 10.12.2010).
3. http://eurlex.europa.eu (accessed 10.12.2010).
4. McKeough, P. and Kurkela, E., "Process Evaluations and Design Studies in the UCG Project, 2004–2007", VTT Research Notes 2434, Espoo, Finland (2008).
5. Saviharju, K. and McKeough, P., "Integrated Forest Biorefinery Concepts", PulpPaper, Helsinki, Finland (2007).
6. Tijmensen, J.A., Faaij, A.P.C., Hamelinck, C.N., and van Hardevelt, M.R.M., "Exploration of the Possibilities for Production of Fischer-Tropsch Liquids and Power via Biomass Gasification", Biomass and Bioenergy, 23:129-152 (2002).
7. Dry, M., "The Fischer-Tropsch Process: 1900–2000", Catalysis Today, 71:227-241 (2002).