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Systems analysis of integrating biomass gasification with pulp and paper production – Effects on economic performance, CO₂ emissions and energy use

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Abstract

This paper evaluates system aspects of biorefineries based on biomass gasification integrated with pulp and paper production. As a case the Billerud Karlsborg mill is used. Two biomass gasification concepts are considered: BIGDME (production of dimethyl ether) and BIGCC (combined cycle electricity production). The systems analysis is made with respect to economic performance, global CO₂ emissions and primary energy use. As reference cases, BIGDME and BIGCC integrated with district heating are considered. Biomass gasification is shown to be potentially profitable for the mill. The results are highly dependent on assumed energy market parameters, particularly policy support. With strong policies promoting biofuels or renewable electricity, the calculated opportunity to invest in a gasification based biorefinery exceeds investment cost estimates from the literature. When integrated with district heating the BIGDME case performs better than the BIGCC case, which shows high sensitivity to heat price and annual operating time. The BIGCC cases show potential to contribute to decreased global CO₂ emissions and energy use, which the BIGDME cases do not, mainly due to high biomass demand. As biomass is a limited resource, increased biomass use due to investments in gasification plants will lead to increased use of fossil fuels elsewhere in the system.

Keywords: Biomass gasification, Biorefinery, Energy systems analysis, Biofuels, Pulp and paper production

Nomenclature

ADt	air dry tonne
BIGCC	biomass integrated gasification combined cycle
BIGDME	biomass integrated gasification DME production
CEPCI	Chemical Engineering plant cost index
CHP	combined heat and power
CCS	carbon capture and storage
DH	district heating
DME	dimethyl ether
HP	high pressure (steam)
HRSG	heat recovery steam generator
LP	low pressure (steam)
MP	medium pressure (steam)
O&M	operation and maintenance

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1. Introduction

With increased concern for greenhouse gas emissions and energy security and ambitious targets for renewable energy, interest in bioenergy today is considerable, both in the stationary and in the transportation sector. Although renewable and with a potential to decrease CO₂ emissions, biomass is a limited resource, which makes efficient resource utilisation essential. In order to maximise CO₂ emission mitigation, it is generally more cost-efficient to use biomass for heating purposes or for combined heat and electricity generation than for the production of biofuels for transportation (hereafter referred to only as biofuels), as shown by e.g. Azar et al. [1] and Wahlund et al. [2]. However, the referenced studies also show that assumptions about the systems surrounding the biomass conversion process, for example regarding the status of carbon sequestration technology, have a significant effect on the cost efficiency of different ways of utilising biomass for CO₂ emission mitigation. If instead reduction of the dependency on fossil oil is the primary objective biomass will have a given place in the transportation system, as shown by e.g. Gustavsson et al. [3], since the renewable alternatives are fewer for transportation than for electricity and heating.

Thermo-chemical gasification of biomass offers several advantages compared to combustion, the two principal advantages being a potential for higher electrical efficiency if used for preprocessing of biomass used for electricity generation purposes, and the opportunity for downstream conversion of the gas produced to higher value products, for example transportation fuels, see e.g. McKendry [4]. The gasification-based processes have a considerable surplus of heat that, if unutilised, lowers the overall efficiency. A number of system studies of integration of large-scale biomass gasification in district heating systems show that the heat from both BIGCC (biomass integrated gasification combined cycle) and gasification-based biofuel production can be competitive in the future in district heating systems [5–7]. The referenced studies also show that CO₂ emissions could be reduced by integrating biomass gasification with district heating, but that the cost optimal type of investment is highly dependent on fuel and electricity prices as well as policy support.

Biomass gasification could also be integrated in industrial processes. In the sugarcane processing industry integration of bagasse gasification for co-production of electricity or liquid fuels has been shown to have positive economic as well as environmental effects; see e.g. Walter and Ensinas [8] and Pellegrini and de Oliveira Junior [9]. Andersson and Harvey [10, 11] have compared different options for producing hydrogen via gasification of solid biomass or black liquor, and showed that integration of hydrogen production with pulp production has several advantages, both economic and from a CO₂ reduction perspective. Consonni et al. [12] have made a comprehensive assessment of different biorefinery concepts, comprising gasification of both solid biomass and black liquor, for pulp and paper mills in the United States. They conclude that once commercialised those concepts may play a vital role in the pulp and paper industry. System studies of black liquor gasification in pulp and paper mills have also been performed by e.g. Pettersson and Harvey [13].

In this paper integration of biomass gasification with an integrated pulp and paper mill is studied, using the Billerud Karlsborg mill as a case study. In the considered mill the steam from the recovery boiler is insufficient to cover the steam demand of the mill; thus a power boiler, partly fired with purchased wood fuel, is also necessary. The mill also needs to purchase electricity, since the internal production is insufficient for the mill's demand. The mill can be considered representative for pulp and paper mills with a steam deficit. By integrating biomass gasification processes having a heat surplus, steam from the bark boiler could be replaced. The considered mill's recovery boiler is sufficient to process the black liquor volume and does not need replacement. Therefore only gasification of solid biomass is considered, and not of black liquor.

1.1. Objective

The aim of the study is to analyse the system effects of integrating gasification of solid biomass with an integrated pulp and paper mill, thus creating a biorefinery, and to identify key parameters with large impact on the opportunity to invest in biomass gasification. Two different biorefinery concepts are considered:

- BIGDME: Biomass gasification followed by synthesis of DME (dimethyl ether) for use as a transportation fuel

- BIGCC: Electricity production in a biomass integrated gasification combined cycle

The systems analysis is made with respect to economic performance in order to determine the opportunity for the mill to invest in biomass gasification, as well as with respect to global fossil CO₂ emissions and primary energy use. As a reference for the biorefinery cases, BIGDME and BIGCC integrated with a district heating network are considered.

2. Methodology and input data

For each of the two gasification concepts (BIGDME and BIGCC) two cases are considered: one biorefinery case, where the gasification process is integrated with the pulp and paper mill, and one stand-alone case, where the pulp and paper mill and the gasification plant operate separately in different geographic locations. It is assumed that the stand-alone BIGDME and BIGCC plants are integrated with a district heating network, to which heat can be sold for 5000 hours annually. Fig. 1 shows the four cases schematically with more detailed descriptions given in the sections following.

In the systems analysis the opportunity to invest in biomass gasification is calculated for the mill as well as for the stand-alone cases. For each of the cases the effect on global CO₂ emissions and on primary energy use for implementation of biomass gasification is also evaluated. To assess economic performance for different possible future energy market conditions, various energy market scenarios are used. The scenarios contain fuel and electricity prices, policy support levels, and CO₂ emission and primary energy use factors.

Figure 1: Schematic overview of the studied BIGDME and BIGCC cases.

2.1. Studied system

In this section the data used and the assumptions made in the integration calculations are described. Data from publicly available studies on a BIGDME plant [14, 15] and a BIGCC plant [16] is used as a basis for the calculations. For the mill actual operation data for the years 2008-2009 has been used. The

energy and mass balances of the biorefinery processes are calculated using a static Excel spreadsheet model, at steady state operation. Exchange rates for 2008 have been used (9.61 SEK/EUR, 6.58 SEK/USD). Investment costs have been adjusted using the Chemical Engineering Plant Cost Index (CEPCI) [17].

2.1.1. Pulp and paper mill

The integrated pulp and paper mill used as a case study, Billerud Karlsborg, is situated outside Kalix in northern Sweden. At the mill bleached kraft pulp and sack and kraft paper is produced. The maximum annual production capacity amounts to approximately 320,000 ADt (air dry tonnes) pulp and 165,000 t paper. The mill incorporates batch digesters but has for this study been approximated as continuous. High pressure (HP) steam is produced in the recovery boiler and in a power boiler, fired mainly with falling bark and purchased wood fuel. A small amount of oil (around 2%) is used in the boilers. As fuel for the lime kiln internally produced tar oil is used. Electricity is produced in a backpressure turbine installed in 2006, with intermediate extraction of steam at two levels. The maximum power output of the turbine is 44 MW, but with the current production and demand of steam it usually delivers around 30 MW. Excess low pressure (LP) steam can be vented. The in-house electricity production covers approximately 70% of the mill's electricity demand. Key data for the mill is given in Table 1, with the resulting overall energy balances shown in Table 2.

To be able to make economic comparisons it is assumed that the mill needs to invest in a new bark boiler to a cost of 24 MEUR [5] in the stand-alone case.

Table 1: Key data for the Billerud Karlsborg mill as used in this study.

Kraft pulp production	ADt/d	890
Paper production	t/d	460
Steam production ^a , recovery boiler/bark boiler	t/h	234/47
Steam use, MP/LP ^b	t/h	88/165
Electricity, total consumption/purchased	MW	45/14
Biomass to bark boiler, total consumption/purchased	MW	46/10
Oil to recovery boiler/bark boiler	MW	2.0/3.7
Tar oil to lime kiln	MW	21

^aHigh pressure steam (HP), 60 bar.

^bMedium pressure steam (MP), 10 bar/low pressure steam (LP), 4 bar.

Table 2: Overall energy balances and key data. For the biorefinery cases the energy balances include both the mill and the gasification plant. Data from [5, 14–16].

		Mill	BIGDME		BIGCC	
		Stand-alone	Bioref.	Stand-alone	Bioref.	Stand-alone
<i>Overall energy balances</i>						
Total biomass use ^a	MW	46	200	200	54	54
Purchased biomass	MW	10	164	200	19	54
Electricity production	MW	31 ^b	30 ^b	11	49 ^b	26
Electricity consumption	MW	45	69	21	49	4.1
Oil use	MW	5.7	2.0	–	2.0	–
Tar oil use in lime kiln	MW	21	12	–	21	–
Tar oil sale	MW	–	9.1	–	–	–
DME production	MW	–	130	130	–	–
District heating production	MW	–	–	30	–	22
<i>Key data</i>						
Operating time	h/y	8000	8000	8000 ^c	8000	5000
Total O&M costs	MEUR/y	1.6	16	16	3.5	3.1

^aInternal falling bark and purchased wood fuel. Pulp feedstock or black liquor not included.

^bIncluding electricity from steam produced in recovery boiler.

^cHeat delivery to district heating network for 5000 h/y.

2.1.2. BIGDME

For the BIGDME case, a plant process integrated with a district heating network is considered. The process is assumed identical to that described within the Biokombi Rya project [14, 15]. In the process wood chips are dried and gasified in a pressurised, oxygen-blown fluidised bed gasifier, followed by a high-temperature filter, catalytic tar reforming, water gas shift and synthesis to DME via methanol. Excess heat from the BIGDME plant is used for production of HP steam (for use in a steam turbine), MP and LP steam and for district heating production. HP steam is produced in the cooler after the reformer and superheated in an external superheater that is fired with off-gas from the DME synthesis. The steam is expanded in a condensing steam turbine, with intermediate extraction of MP and LP steam. The electricity produced is not sufficient to cover the plant’s demand, therefore electricity also needs to be purchased from the grid. Heat for district heating originates from a number of places in the process, mainly from gas and compressor cooling and from the fuel dryer.

In the integration calculations in the biorefinery case the BIGDME plant is dimensioned to deliver the same amount of steam to the mill as the bark boiler does in the stand-alone mill. The BIGDME steam system is completely integrated with the mill’s steam system with one common steam turbine, and steam data is adapted to the mill’s steam system. It is assumed that the falling bark originally used in the bark boiler can be used in the BIGDME process, with purchased forest residues as additional fuel. The suitability of bark as a gasification fuel has been demonstrated for example in the Värnamo demonstration plant [18]. Excess off-gas from the DME synthesis replaces tar oil in the lime kiln. Excess tar oil can be sold. Low grade heat in the approximate interval 90-150°C is assumed to be used in the mill’s secondary heat system for make-up water and condensate preheating, and for production of LP steam via very low pressure steam compression. Fig. 2 shows an overview of the BIGDME biorefinery.

The stand-alone case is assumed to have the same feedstock input as in the biorefinery case, with heat being delivered to a district heating network and surplus off-gas being used to produce additional heat for district heating. It is assumed that the annual operating time is 8000 hours [14, 15], but that the district heating supplier is only interested in purchasing surplus heat from the BIGDME plant for a limited part of the year, since heat from the BIGDME plant competes with other production in the district heating network. For this reason heat can only be sold for 5000 hours annually, which corresponds to a realistic annual operating time for a CHP plant [19].

Table 2 presents the resulting overall energy balances and key data.

2.1.3. BIGCC

The BIGCC considered is based on directly heated, atmospheric air-blown gasification with cold-gas clean-up, using data for a BIGCC CHP plant from Harvey [16]. In the process the clean syngas is fired in a gas turbine, after which the gas turbine exhaust is cooled in a heat recovery steam generator (HRSG) to produce steam for the steam turbine. Most of the heat for district heating (>90%) is produced in the steam cycle condenser, with the rest of the heat produced by syngas and compressor cooling. The fuel—wood chips—is dried in a flue gas dryer.

As in the BIGDME case, in the biorefinery case the BIGCC plant is dimensioned to deliver the same amount of steam to the mill as the bark boiler, with one common steam turbine. Steam data is adapted to the mill’s steam system. The heat from the syngas and compressor cooling is assumed to be used in the mill’s secondary heat system. Falling bark and purchased forest residues are used as fuel.

In the stand-alone case the same BIGCC plant size (feedstock input) as in the biorefinery case is considered. It is assumed that the BIGCC plant has an annual operating time of 5000 hours, as given by Harvey [16]. Contrary to Harvey, who assumes that the BIGCC plant operates under part-load conditions for part of the year, full load for the whole operating time is assumed here.

Fig. 3 shows an overview of the BIGCC biorefinery. The resulting energy balances and key data are presented in Table 2.

2.2. Economic evaluation

For each of the studied cases the annual energy system cost is calculated. The system cost includes costs for biomass, electricity and operation and maintenance, as well as revenues for sold DME (including revenue

Figure 2: Overview of the studied BIGDME biorefinery. Grey boxes and flows indicate new processes compared to the stand-alone mill. Hatched boxes indicate processes included in the stand-alone mill but not in the biorefinery. Excess low grade heat has not been included in the figure but is described in the text.

from biofuel policy support instruments), tar oil, district heating and electricity. All electricity produced in the plants is credited with policy support promoting renewable electricity. The capital cost for a new bark boiler is also included in the stand-alone mills' system cost, and discounted using the annuity method with a capital recovery factor of 0.1 (representing, for example, an interest rate of 6% and an economic lifetime of 15 years). In the stand-alone cases separate system costs are calculated for the mill and for the stand-alone gasification plants. The annual system cost C_{system} (MEUR) is calculated as:

$$C_{system} = C_{biomass} + C_{el} + C_{oil} + C_{O\&M} - (R_{el} + R_{DME} + R_{DH} + R_{taroil}) \quad (1)$$

where $C_{biomass}$, C_{el} , C_{oil} and $C_{O\&M}$ are the annual costs for biomass, electricity, oil (in the mill) and operation and maintenance, and R_{el} , R_{DME} , R_{DH} and R_{taroil} are the annual revenues for sold electricity including renewable electricity policy support, DME and tar oil (in the BIGDME case), and district heating, respectively (MEUR/y).

The biomass gasification investments are not included in the system costs. Instead the potential annual investment opportunity IO (MEUR/y) is calculated based on the annual system costs. For each of the biorefinery cases the opportunity for the pulp and paper mill to invest in gasification is given by the difference in system cost between the stand-alone mill and the biorefinery, according to:

$$IO = C_{mill} - C_{biorefinery} \quad (2)$$

where C_{mill} denotes the annual energy system cost for the pulp and paper mill in the stand-alone case, and $C_{biorefinery}$ denotes the annual energy system cost for the integrated gasification plant/pulp and paper mill in the biorefinery cases. In the stand-alone cases the annual opportunity to invest in the biomass gasification plants is given directly by the gasification plants' annual system cost, as calculated by Eq. 1.

From the annual investment opportunity the total investment opportunity (MEUR) is calculated using a capital recovery factor r of 0.1.

2.3. Evaluation of CO₂ emissions and energy use

Global fossil CO₂ emissions are evaluated in an expanded system, as described by e.g. Andersson and Harvey [11] and Wetterlund et al. [20]. It is assumed that the net flows of energy and material entering or

Figure 3: Overview of the studied BIGCC biorefinery. Grey boxes and flows indicate new processes compared to the stand-alone mill. Hatched boxes indicate processes included in the stand-alone mill but not in the biorefinery. Excess low grade heat has not been included in the figure but is described in the text.

leaving the plant affect the surrounding system. Electricity produced or consumed in the studied systems causes a change in the surrounding electricity system by decreasing or increasing the need for externally produced electricity. Similarly, it is assumed that district heating delivered from the gasification plants in the stand-alone cases replaces alternative district heating production and that DME replaces diesel in heavy trucks. The supply of biomass is regarded as limited, thus additional demand for biomass at the biorefinery plant site will lead to increased use of fossil fuels elsewhere in the expanded system, as discussed in reference [20]. The marginal CO_2 effects of increased biomass use are taken into account by assuming an alternative biomass usage. The alternative where biomass is not subject to competition, and thus the use can be viewed as CO_2 neutral, is also considered in order to illustrate the marginal effect of biomass usage.

Correspondingly, when evaluating the primary energy use of the system, local as well as global fuel use are considered. For example, the electricity produced or consumed in the studied system affects the surrounding electricity system. Thus the change in global fuel use due to an altered electricity balance is influenced by the efficiency of the electricity production of the surrounding system.

The global CO_2 emissions CO_2 ($\text{kt}_{\text{CO}_2}/\text{y}$) and primary energy use Energy (GWh/year) of a studied system are calculated according to:

$$\text{CO}_2 = c_{\text{bio}}n_{\text{bio}}^{\text{used}} + c_{\text{oil}}(n_{\text{oil}}^{\text{used}} - n_{\text{taroil}}^{\text{exp}}) + c_{\text{el}}(n_{\text{el}}^{\text{used}} - n_{\text{el}}^{\text{prod}}) - c_{\text{DME}}n_{\text{DME}} - c_{\text{DH}}n_{\text{DH}} \quad (3)$$

$$\text{Energy} = e_{\text{bio}}n_{\text{bio}}^{\text{used}} + e_{\text{oil}}(n_{\text{oil}}^{\text{used}} - n_{\text{taroil}}^{\text{exp}}) + e_{\text{el}}(n_{\text{el}}^{\text{used}} - n_{\text{el}}^{\text{prod}}) - e_{\text{DME}}n_{\text{DME}} - e_{\text{DH}}n_{\text{DH}} \quad (4)$$

where $n_{\text{bio}}^{\text{used}}$, $n_{\text{oil}}^{\text{used}}$ and $n_{\text{el}}^{\text{used}}$ are the annual amounts of biomass, oil and electricity used, $n_{\text{el}}^{\text{prod}}$, n_{DME} and n_{DH} the amounts of electricity, DME and district heating produced and $n_{\text{taroil}}^{\text{exp}}$ the amount of tar oil exported (GWh/y). c denote the CO_2 emission factors ($\text{kt}_{\text{CO}_2}/\text{GWh}$) and e (GWh/GWh) the energy use factors of the various energy carriers, as indicated by the subscripts.

The effect of the implementation of large-scale biomass gasification on global CO_2 emissions, ΔCO_2 ($\text{kt}_{\text{CO}_2}/\text{y}$), and on primary energy use, ΔEnergy (GWh/y), is evaluated for both the biorefinery and the stand-alone cases. For the stand-alone cases the CO_2 and energy effects are given directly by Eq. 3 and Eq. 4. For the biorefinery cases the effects are evaluated compared to on the one hand the stand-alone mill, and on the other hand the complete stand-alone case with both mill and stand-alone gasification plant

included. The integration effects when using only the mill as reference are calculated according to:

$$\Delta CO_2 = CO_2^{biorefinery} - CO_2^{mill} \quad (5)$$

$$\Delta Energy = Energy^{biorefinery} - Energy^{mill} \quad (6)$$

The effects with both mill and stand-alone gasification plant used as reference are correspondingly calculated as:

$$\Delta CO_2 = CO_2^{biorefinery} - (CO_2^{mill} + CO_2^{BIG-standalone}) \quad (7)$$

$$\Delta Energy = Energy^{biorefinery} - (Energy^{mill} + Energy^{BIG-standalone}) \quad (8)$$

The CO_2 emissions and energy use of each system, as indicated by the superscripts, are calculated according to Eq. 3 and Eq. 4.

2.4. Energy market scenarios

Four energy market scenarios with interdependent parameters for around 2030 are used for the evaluation of the performance of the studied systems under different possible future energy market conditions. The scenarios have been developed by Axelsson et al. [21, 22] and are based on assumptions about future fossil fuel prices and policy instrument levels, with two different fossil fuel price levels and two different levels of CO_2 charge. Fossil fuel price predictions from the European Energy and Transport Trends to 2030 [23] (baseline and soaring prices, respectively) are applied.

The cost of electricity production, capital costs included, is assumed to be the total generation cost for a new base load power plant. The technology with the lowest production cost constitutes the base load build margin and determines the electricity price in each scenario. In scenarios with low CO_2 charge (scenarios 1 and 3) the lowest cost technology is coal power, while the lowest cost technology in scenarios with high CO_2 cost (scenarios 2 and 4) is coal power with CCS. New renewable electricity production is assumed to be entitled to policy support.

High-volume users' willingness to pay for biomass determine the wood fuel price. In the scenarios used here coal power plants co-firing biomass have the highest willingness to pay for biomass, which makes coal (including CO_2 charge) price setting for wood fuel. Tar oil can be used to substitute oil and is priced as heavy fuel oil.

The DME price is set so the end user will have the same cost per unit of fuel energy for DME as for diesel. Energy taxes and VAT are assumed to be the same for DME as for diesel, but diesel is subject to the CO_2 emission charge. However, DME is more expensive to distribute from plant gate to filling station than diesel, which is also accounted for. As has been mentioned previously, gasification-based biofuels need economic policy support to be competitive. The scenarios used in this study are thus supplemented by a biofuel policy instrument providing an extra source of revenue for the biofuel producer. The policy support is set to give a stand-alone large-scale biofuel production plant (DME from gasified biomass) the same willingness to pay for biomass as a coal power plant.

District heating networks are of a very local character, which gives assumptions about general price setting production a high degree of uncertainty. Axelsson and Harvey [22] give two district heating price levels. The lower level is based on the assumption that the heat price is set by heat produced in a coal CHP plant, and the higher level on the assumption that the price is determined by gas-fired heat-only boilers. In this study a weighted average consisting of 75% of the lower price and 25% of the higher price is used, to reflect a situation where heat from gasification plants competes with base or intermediate load in the district heating system.

The resulting energy market scenarios contain different marginal technologies for electricity production, biomass use, district heating production and transportation, which lead to different corresponding marginal CO_2 emissions and energy use factors. The scenarios are presented in Table 3.

Table 3: Modelled energy market scenarios.

<i>Scenario</i>		<i>1</i>	<i>2</i>	<i>3</i>	<i>4</i>
Fossil fuel price level ^a		Low	Low	High	High
CO ₂ charge		Low	High	Low	High
<i>Prices and policy instruments</i>					
Wood fuel	EUR/MWh	31	57	34	60
Electricity	EUR/MWh	68	90	74	98
Heavy fuel oil (incl. CO ₂ charge)	EUR/MWh	45	67	67	89
Tar oil (selling price)	EUR/MWh	34	34	57	57
DME (selling price)	EUR/MWh	57	77	88	109
District heating	EUR/MWh	19	49	27	56
CO ₂ charge	EUR/t _{CO2}	35	109	35	109
Renewable electricity policy support ^b	EUR/MWh	26	26	26	26
Biofuel policy support	EUR/MWh	46	67	20	41
<i>CO₂ effect (kt_{CO2}/GWh)</i>					
Electricity ^c		0.679	0.129	0.679	0.129
Biomass with/without marginal effects ^d		0.227/0	0.244/0	0.227/0	0.244/0
Oil/tar oil ^e		0.295	0.295	0.295	0.295
District heating ^f		0.242	0.468	0.242	0.468
DME ^g		0.273	0.273	0.273	0.273
<i>Energy use factors (GWh/GWh)^h</i>					
Electricity ^c		2.49	3.03	2.49	3.03
Oil/tar oil ^e		1.03	1.03	1.03	1.03
Biomass		1.04	1.04	1.04	1.04
District heating ^f		0.750	0.528	0.750	0.528
DME ^g		1.10	1.10	1.10	1.10

^a Oil prices: low 37 EUR/MWh, high 63 EUR/MWh; natural gas prices: low 34 EUR/MWh, high 53 EUR/MWh; coal prices: low 11 EUR/MWh, high 14 EUR/MWh [22, 23].

^b Average value for Europe [22].

^c Marginal electricity production: Scenario 1 and 3 coal power ($\eta_{el} = 0.45$), Scenario 2 and 4 coal power with carbon capture and storage (CCS) ($\eta_{el} = 0.37$).

^d Marginal biomass use: co-firing with coal (50%), DME production (50%). The alternative where biomass use is considered CO₂ neutral is also included.

^e Tar oil is assumed to replace heavy fuel oil.

^f Alternative heat production: 75% coal CHP ($\eta_{el} = 0.31$, $\eta_{tot} = 0.88$), 25% gas heat-only boiler ($\eta_{heat} = 0.85$).

^g DME is assumed to replace diesel as transportation fuel.

^h Including total feedstock energy with given efficiencies, and distribution energy [3, 22, 24].

2.5. Sensitivity analysis

The energy market scenarios constitute a packaged sensitivity analysis with respect to energy related costs. Additional sensitivity analysis of the investment opportunity is conducted with respect to a number of other parameters that were identified as having potentially large influence on the investment opportunity.

The annual capital cost naturally has large impact on the profitability of capital-intensive investments. Here the capital recovery factor is increased from 0.1 to 0.2, which represents a less long-term view on the investment.

A base assumption in this study is that the mill faces a necessary investment in a new bark boiler, with the option to instead invest in gasification. The alternative where the mill does not need to replace the existing bark boiler is included in the sensitivity analysis.

Previous studies have shown that economic policy support is of importance for the profitability of large-scale biomass gasification (see e.g. [5, 7, 25, 26]). This is accounted for here by varying the levels of support for renewable energy (biofuels and electricity).

For the stand-alone cases an important assumption is that the gasification plants have the possibility to sell excess heat to a district heating network. As shown by e.g. Jönsson and Algehed [27] pricing of excess heat is difficult, with large energy price dependent variations of the district heating suppliers' willingness to pay for the heat. For this reason additional sensitivity analysis with respect to the district heating price is conducted. Furthermore, studies have also identified that a key parameter is the number of hours annually that heat delivery to the district heating network is possible; see e.g. [16]. In this study it is assumed that

the annual heat delivery time for both the stand-alone BIGDME and the stand-alone BIGCC amounts to 5000 hours, while the total annual operating time for the BIGDME plant is 8000 hours. To analyse the effect of annual heat delivery time additional sensitivity analysis is performed where it is assumed that the stand-alone gasification plants can operate and sell all surplus heat for 8000 hours annually.

To summarise, the following parameters are included in the sensitivity analysis:

- Capital recovery factor increased from 0.1 to 0.2
- No need for mill to invest in new bark boiler
- No renewable electricity policy support
- Biofuel policy support -50%
- No biofuel policy support
- District heating price +50%
- District heating price -50%
- Operating/heat delivery time for stand-alone gasification plants increased to 8000 hours/year

3. Results

3.1. Investment opportunity

Fig. 4 shows the resulting annual investment opportunity for the two BIGDME cases and the two BIGCC cases, over the four energy market scenarios used.

The results show that the economic performance of the BIGCC is significantly better in the biorefinery case than in the stand-alone case, for all scenarios. This can be explained mainly by integration effects and to some extent also by longer annual operating time in the biorefinery case. As can be seen in Table 2 the increased electricity production in relation to the increased biomass input is significantly higher in the biorefinery case than in the stand-alone case. This advantage for the biorefinery can be noticed also for the BIGDME, although to a much lesser extent.

Fuel and electricity prices obviously affect the results. In Scenario 2 and 4 the electricity prices are considerably higher than in Scenario 1 and 3, hence the higher investment opportunity in Scenario 2 and 4 for the BIGCC biorefinery with its high electricity output per unit of biomass input. For the stand-alone BIGCC the electricity output per input of biomass is significantly lower than for the biorefinery, which causes a lower investment opportunity in Scenario 2 and 4 than in Scenario 1 and 3.

Scenario 2 and 4 are also characterised by a lower ratio between the DME and biomass prices than Scenario 1 and 3. This is compensated, however, by higher policy support in Scenario 2 and 4, which gives higher investment opportunity for the BIGDME in those scenarios than in Scenario 1 and 3.

3.1.1. Sensitivity analysis

Fig. 5 and 6 show the results of the sensitivity analysis for the four energy market scenarios, with the calculated investment opportunities presented as total investment opportunity, using a base capital recovery factor of 0.1. The figures also show ranges of investment cost estimations found in the literature (adjusted using the CEPCI) for plants of the corresponding sizes. All the studied cases except the stand-alone BIGCC show significant investment opportunity (base cases), compared to the estimates found in previous publications. As the figures show, this is however strongly related to a number of factors.

When changing the capital recovery factor to 0.2, the investment opportunity decreases substantially, which is an indication that the profitability is sensitive to uncertainties concerning capital costs. It was assumed that the bark boiler needs to be replaced, which is shown not to be a prerequisite, as both the BIGDME and the BIGCC biorefineries still show considerable investment opportunity also when removing this condition.

Figure 4: Annual investment opportunity for (a) the BIGDME cases and (b) the BIGCC cases.

Assumptions regarding economic policy support are of major importance. From Fig. 6 it can be seen that when removing the policy support for renewable electricity, the stand-alone BIGCC even shows a negative investment opportunity, while the BIGCC biorefinery still shows profitability. In the BIGDME biorefinery the electricity production is practically equal to the production in the stand-alone mill why the removal of the renewable electricity support does not have any effect. The stand-alone BIGDME plant has a relatively low electricity production and is thus only moderately affected by an electricity support removal. The influence of the biofuel policy support is however significant, for the biorefinery as well as for the stand-alone plant. When completely removing the biofuel support (light grey squares in Fig. 5) the investment opportunity drops considerably; two scenarios (Scenario 1 and 2) even showing negative investment opportunity. However, in one scenario (Scenario 3), the investment opportunity actually reaches the reported investment cost range with no policy support. This is due to the high oil price and relatively low biomass price in this scenario, which creates an incentive for biofuel production even without policy support.

The sensitivity analysis also confirms the discussed strong dependency on local district heating conditions for the stand-alone plants, in particular for the BIGCC plant with its high heat output. An increase of the heat price by 50%, which roughly corresponds to the heat production cost from a new biomass-fired CHP plant based on a conventional steam cycle, is however still not enough to increase the investment opportunity of the stand-alone BIGCC into the range of estimated investment costs. Similarly, an increased annual operating time (8000 instead of 5000 hours) would not be enough to make the BIGCC profitable. The stand-alone BIGDME has a low heat output, which makes it relatively insensitive to changes in district heating market conditions.

The results show a strong dependency on assumed energy market conditions, which can be seen in the figures as a considerable distribution within a given set of results. The largest variation over scenarios can be found for the BIGDME cases when the biofuel policy support is reduced or removed, which implies that the necessary support is highly dependent on other energy market conditions.

3.2. CO₂ emissions and energy use

The results of the evaluation of the CO₂ effect, ΔCO_2 , and the primary energy use effect, $\Delta Energy$, when taking into account marginal CO₂ effects from biomass use are shown in Fig. 7. Negative values correspond to a decrease in global CO₂ emissions or energy use.

The figure shows that implementation of large scale biomass gasification does not necessarily entail a reduction of global CO₂ emissions. In fact, none of the BIGDME cases show any reduction potential at

Figure 5: Results from the sensitivity analysis for the two BIGDME cases. The markers show the calculated total investment opportunity for the four scenarios using a base capital recovery factor of 0.10. The grey areas indicate ranges of investment cost estimations found in the literature for correspondingly sized plants [5, 28–30].

all. For the case comparing the BIGDME biorefinery to the stand-alone mill, as well as for the stand-alone BIGDME, the main reason for this is the large amount of biomass needed for the BIGDME plants. Since biomass is a limited resource, all increased biomass use is penalised with the CO₂ emissions of the assumed alternative biomass usage. The CO₂ emissions avoided from diesel replaced by produced DME and from alternative heat production (in the stand-alone case) are not enough to offset the indirect emissions from the large biomass use. For the case comparing the BIGDME biorefinery to the complete stand-alone case, the CO₂ emissions related to biomass use are lower for the biorefinery, since the biorefinery uses less biomass than the combination of stand-alone mill and stand-alone BIGDME. Here the main reason for the slightly increased CO₂ emissions is that in the stand-alone case heat from the BIGDME plant replaces fossil district heating, while in the biorefinery case no heat is delivered to the district heating network. The biorefinery also has a higher electricity deficit than the combination of stand-alone mill and BIGDME plant which also affects the CO₂ emissions adversely. Since the BIGDME cases lead to increased electricity demand, the CO₂ emissions are lowest in the scenarios with low emitting marginal electricity production (Scenario 2 and 4, coal power with CCS).

The BIGCC cases in general show some potential for decreased global CO₂ emissions, particularly in the scenarios with high emitting marginal electricity production (Scenario 1 and 3, coal power), due to the high electrical efficiency of the combined cycle. In Scenario 2 and 4 with low emitting marginal electricity, the CO₂ reduction potential is however low.

Fig. 7 also shows that the implementation of BIGCC would lead to a decrease in primary energy use, again due to the high electricity production. Highest energy use reduction is found when comparing the BIGCC biorefinery to the stand-alone mill, as a relatively modest increase in biomass input to the mill leads to a large increase in internal electricity production. Implementation of BIGDME, both operating stand-alone and in a biorefinery when compared to the stand-alone mill, would instead lead to a significant increase in energy use. Again, this is a result of the increased demand of biomass and electricity. As shown by the figure, this is more pronounced in Scenario 2 and 4 where the marginal electricity is produced with a lower electrical efficiency (due to the CO₂ capture) than in Scenario 1 and 3. However, if comparing the biorefinery to the complete stand-alone case, the lower total biomass demand leads to a decrease in primary energy use.

As discussed in Section 2.3 the alternative where the use of biomass is regarded as CO₂ neutral has also been considered. This is shown in Fig. 8. When comparing Fig. 8 to Fig. 7 it is evident that when the

Figure 6: Results from the sensitivity analysis for the two BIGCC cases. The markers show the calculated total investment opportunity for the four scenarios using a base capital recovery factor of 0.10. The grey areas indicate ranges of investment cost estimations found in the literature for correspondingly sized plants [5, 16, 31–33].

effect of alternative use of biomass is excluded from the analysis the CO_2 reduction potential is considerable. In particular the BIGDME applications benefit from the removed CO_2 penalty of biomass use, since the BIGDME plants use very large amounts of biomass compared to the BIGCC plants. When comparing the biorefineries to the complete stand-alone cases the CO_2 emissions increase when biomass is considered CO_2 neutral (compare the black markers in Fig. 7 and in Fig. 8). The reason is that when marginal effects of biomass use are not taken into account, there is no CO_2 advantage of efficient biomass utilisation. However, since the systems compared here have very different input-output balances the results shown in Fig. 8 are a bit misleading. If the CO_2 emission effect would instead be shown per unit of biomass input, as discussed in eg. [20], the BIGDME cases would for example lose some of their apparent advantage. Those results thus emphasise the importance of considering marginal biomass use effects.

4. Discussion

The economic results show a high dependency on several parameters, in particular regarding policy support and other energy market conditions. Biofuel policy support introduces the highest uncertainty, with the largest dispersion over scenarios. The biofuel support level was set such that large-scale biofuel producers would have the same willingness to pay for biomass as coal power plants, which led to very high support levels in some scenarios. For example, in Scenario 2 the support level in the base case is 67 EUR/MWh. This could be compared to the current Swedish exemption from energy tax for biofuels, which amounts to approximately 30 EUR/MWh. If the support is removed or reduced, the BIGDME, both in the biorefinery and stand-alone, still show some prospect of profitability, but with a strong dependency on oil prices.

Several of the economic advantages of the biorefineries over the stand-alone plants can be attributed to integration effects. It should be noted that neither the integrated nor the stand-alone processes have been optimised for this study. Here data for an existing pulp and paper mill was used in combination with conceptual studies of BIGDME and BIGCC processes for the biomass gasification plants data. The level of detail in the studies used varies, and a number of assumptions on process performance have been made. One main uncertainty is that the studied mill incorporates batch digesters that have out of necessity for the static model employed in this study been approximated as continuous. The gasification studies are also

Figure 7: Effect on global CO₂ emissions (x-axis) and on primary energy use (y-axis) when considering marginal CO₂ effects of biomass use. The biorefinery is compared to both the stand-alone mill (unfilled markers), and the complete stand-alone case including mill and stand-alone gasification plant (black markers). Figures in brackets refer to scenarios.

relatively old, therefore reported costs have been adjusted accordingly. This study could be extended and improved by incorporating more recent process data and by performing more thorough process integration calculations.

District heating systems are highly site specific concerning, for example, heat load and production mix, which affects both heat production costs and annual operating time of the plants in the system. As the results show, the possibility of delivering heat is of decisive importance for the economic performance of the stand-alone gasification plants. In this study it was assumed that the BIGCC plant is built by the district heating supplier, and thus dimensioned to fit the heat load. It was also assumed that it is unlikely that a BIGDME plant would be erected by a district heating supplier directly, thus the surplus heat from the BIGDME is likely to be competing with other heat production. However, the results show that there are incentives to search for possible further heat demands when investing in this kind of plant, and that the size of the potential heat load and the shape of the load duration curve are important factors to consider. Since the BIGDME has a smaller heat surplus for a given primary product output and feedstock input than the BIGCC, it could be easier to find networks that can accept the entire amount of heat. The alternative heat production was here assumed to be a mix between existing coal CHP and gas heat. If the stand-alone gasification plants would instead be assumed to compete with, for example, new biomass-fuelled CHP, both the heat price and the CO₂ emissions and primary energy use associated with district heating would be affected.

Regarding CO₂ emissions, the results generally show little or no potential of the studied technologies to contribute to reduced global CO₂ emissions. This is an effect of the system expansion method used for evaluating CO₂ emissions, primarily because alternative biomass use is included in the analysis. When the use of biomass is considered CO₂ neutral, as is done in many similar studies, the emission reduction potential is consequently considerably higher. However, since biomass is a limited resource it is not possible to solve

Figure 8: Effect on global CO₂ emissions (x-axis) and on primary energy use (y-axis) when biomass is considered CO₂ neutral. The biorefinery is compared to both the stand-alone mill (unfilled markers), and the complete stand-alone case including mill and stand-alone gasification plant (black markers). Figures in brackets refer to scenarios.

the entire CO₂ emission problem by fuel substitution. To be able to give credit for efficient energy use the marginal effects of limited resources need to be taken into account. This has been discussed in detail by Wetterlund et al. [20].

5. Conclusions

The results from this study show that integration of biomass gasification with integrated pulp and paper production could be economically feasible, but that the economic performance is highly dependent on a number of parameters. Unsurprisingly the assumed energy market parameters have a large influence. Particularly significant is the dependency on economic policy support, especially policies promoting biofuels. The biorefinery cases show a considerably better economic performance than the stand-alone cases, even when the heat price or the annual operating time are increased for the stand-alone cases, which is due to a higher rate of conversion from purchased biomass into high value products (DME or electricity) in the integrated biorefinery cases.

Regarding the possibility to reduce global CO₂ emissions and energy use, the results are very much dependent on assumptions regarding the surrounding system, in particular regarding alternative biomass use and electricity production.

For the BIGDME biorefinery the investment opportunity using a capital recovery factor of 0.1, which represents a rather strategic investment approach, is estimated to be an unexpectedly high 460-560 MEUR. This can be compared to investment cost estimations found in the literature for a plant of the same size of 230-420 MEUR [5, 28–30]. As has been discussed the sizable investment opportunity can largely be attributed to the high policy support assumed here. With a 50% reduction of the support level the investment opportunity drops to 180-380 MEUR, which is still within or close to the previously estimated range. The BIGDME

also shows promise in stand-alone operation, with a calculated investment opportunity of 420-470 MEUR (110-320 MEUR with a 50% decrease of policy support) and relatively low dependency on district heating system specific parameters. The BIGDME cases show little or no potential to reduce primary energy use and no potential to reduce global CO₂ emissions, unless biomass is regarded as completely CO₂ neutral. This is due to a very high increased biomass demand in combination with increased electricity usage and, compared to in particular coal power based electricity production, the relatively low emissions and low primary energy use of the replaced fossil energy carrier (diesel).

The BIGCC biorefinery shows a calculated investment opportunity of 90-120 MEUR, using a capital recovery factor of 0.1, with figures from the literature estimating the costs to between 38-67 MEUR [5, 16, 31–33]. The stand-alone case is more uncertain and shows a larger dependency than the BIGDME on district heating system specific assumptions, with a calculated investment opportunity ranging from 1-19 MEUR in the base case. The BIGCC cases show a consistent potential to reduce the primary energy use, due to the substantial decrease in demand for marginal electricity. If the marginal electricity production is high emitting (coal power), this also leads to a decrease in global CO₂ emissions.

Finally, it can be concluded that if the aim is to implement biomass gasification in pulp and paper production as a means to meet both economic and environmental objectives, biomass gasification for electricity production could provide a more robust solution than gasification for biofuel production.

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