SYSTEMS ASPECTS ON NEW ENERGY TECHNOLOGIES IN THE PULP AND PAPER INDUSTRY

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ABSTRACT

Concerns about energy security, energy prices, and the impact of energy use on the global climate have put focus on ways to reduce CO_2 emissions and oil dependency. In this paper we examine consequences of new energy technologies in the pulp and paper industry and estimate the costs for achieving certain CO_2 emissions and oil use reductions with different pulp mill technologies. Stand-alone production of electricity and transportation fuel from biomass is included to balance the systems compared, so that they produce the same CO_2 emission and oil use reductions. The technologies considered are black liquor gasification (BLG) with electricity and motor fuels production in chemical pulp mills and increased energy efficiency in mechanical pulp mills. The entire production chain from the extraction of primary resources is included in the analysis. Changes in the production chain are assumed to affect energy production on the margin. The technology alternatives are evaluated with respect to five parameters: Net CO_2 emission, oil use, primary energy use, biomass use and monetary cost. We find that BLG in chemical pulp mills is favourable compared to stand-alone production of fuels and electricity from biomass. If both CO_2 emission reductions and oil use reductions are to be achieved, it is more efficient to implement BLG with motor fuels production and stand-alone electricity production from biomass, than to implement BLG with electricity production and stand-alone production of motor fuels. Increased energy efficiency in refining of thermomechanical pulp is found to achieve CO_2 savings more efficiently than stand-alone production of electricity from biomass.

Keywords: bioenergy, black liquor gasification, climate change mitigation, energy efficiency, oil use reduction, thermomechanical pulping

INTRODUCTION

Increased awareness of the climate changes caused by anthropogenic greenhouse gas emissions has triggered a call for ways to reduce CO_2 emissions from fossil fuel use. Fluctuating oil prices and dependency on crude oil resources controlled by a limited number of states has lead to a desire to reduce the dependency of oil and oil products in many countries. An increased use of biomass for energy can contribute to a reduction of fossil CO_2 emissions and reduced oil dependency. Today, forest biomass plays an important role in many countries as a raw material for wood-based products as paper and construction material, but also for energy. Biomass is, however, a limited resource and needs to be used as efficiently as possible.

The pulp and paper industry is energy intensive and a large user of biomass. Biomass residues in pulp and paper mills make a major contribution of wood-based energy in for example Sweden and Finland (Statistics Sweden 2006; Statistics Finland 2007). Technology development and the role of the pulp and paper industry in greenhouse gas reduction has been discussed over recent years (IEA 1999; Pingoud et al. 1999; Martin et al. 2000; Nyström and Cornland 2003; STFI 2003; Wising 2003; Farahani et al. 2004; Ådahl 2004). Black liquor gasification (BLG) is a technology being developed for efficient recovery of biomass-based residues in chemical pulp mills and several studies analyse the technical, economic and climate change mitigation performance of the technology (McKeough 1994; Berglin et al. 1999; Larson et al. 2000; Berglin et al. 2003; Eriksson and Harvey 2004; Ekbom et al. 2006). For mechanical pulp mills the focus has been on electricity conservation (Cannel 1999; Kallioinen et al. 2003). Möllersten et al. (2003) and Martin et al. (2000) assess the economic efficiency of several energy system improvements in the pulp and paper industry, including electricity conservation in mechanical pulping, with respect to CO_2 emission reduction. Several of these studies take into account changes in CO_2 emissions from marginal fossil electricity production and fuel use, but few explicitly consider alternative uses of biomass for energy purposes. Different options are often evaluated with respect to cost effectiveness. Monetary costs are, however, often very uncertain in a society perspective where also external costs are considered (Gustavsson and Karlsson 2006).

Here, we evaluate and compare energy system improvements in chemical and mechanical pulp mills with respect to net CO_2 emission, oil use, biomass use, primary energy use and monetary production costs. We consider BLG and efficient mechanical pulping technologies and contrast them to stand-alone production of fuel and electricity from biomass, based on Swedish conditions.

Pulp and paper production

Pulp for paper can be produced by two principally different processes: Mechanical pulping, in which the wood fibres are separated mechanically, and chemical pulping, in which the fibres are separated mainly through chemical treatment. In mechanical pulping, about 95% of the wood becomes pulp, while chemical pulping serves to separate the cellulose fibres from lignin and other wood components and has a pulp yield of about 40–50%. The pulping technologies considered in this paper are the sulphate (kraft) process for chemical pulp and thermomechanical refining (TMP) for mechanical pulp. The lignin and hemi-cellulose separated from cellulose in chemical pulping and the spent pulping chemicals form the black liquor. Conventionally, black liquor is combusted in a recovery boiler (RB) to recover the chemicals and to generate steam and electricity in a steam turbine combined heat and power unit (CHP). Black liquor gasification (BLG) is an alternative technology where the recovery boiler is replaced with a gasifier. The gas produced can be used in combined cycle CHP unit, a concept known as black liquor gasification with combined cycle (BLGCC). Alternatively, the gas from the gasifier can be passed through a synthesis step to produce liquid fuels, a concept referred to as black liquor gasification with motor fuels production (BLGMF) (Ekbom et al. 2003).

METHODOLOGY AND ASSUMPTIONS

Production costs and energy and biomass use in pulp and paper production and upstream processes are estimated for a chemical market pulp mill, an integrated chemical pulp and paper mill and a newsprint mill integrated with a TMP mill. Calculations are performed for a reference case, where conventional but modern technology is used in the mills and for cases with BLGCC and BLGMF in the chemical pulp mills and improved energy efficiency in the TMP mill. Changes in the energy balance of the mills are assumed to affect the marginal energy supply. Currently, marginal electricity production in the Nordic system is largely coal based (STEM 2002). Demand for external electricity will thus give rise to CO₂ emissions in external power plants. A surplus of biomassbased electricity in the mill will similarly replace marginal electricity, and reduce CO₂ emissions. Forest residues are assumed to be the marginal fuel for steam generation in the pulp and paper mills. The amount of CO₂ emitted at combustion of biomass produced in a sustainable way is assumed to equal the CO₂ uptake in biomass regrowth and to give no net contribution of CO₂ to the atmosphere. The basis for the calculations is the production of one oven-dry metric tonne (1 t) of pulp and paper produced from 1 t of pulp, respectively, for the pulp and paper mills. All weight measures refer to dry-substance weight. Energy efficiencies and energy contents of fuels are based on the lower heating value (LHV). To compare the efficiency of CO₂ emission and oil use reduction between different technologies, we consider a case where stand-alone production of DME and electricity from biomass balances the CO₂ emission and oil use reduction so that they are equal for systems compared, i.e. they produce the same amount of pulp or paper product and render the same CO₂ emission and oil use benefits (Figure 1) when the whole systems are considered.



Figure 1. Comparison of a system that produces a surplus of electricity and a system that produces a surplus of transportation fuel. We require the systems to render the same total oil use reduction and CO_2 emission reduction, when the complete systems are considered. Stand-alone production of DME and/or electricity from biomass is added (parts within dashed frames) to balance the systems when needed.

Studied system

The studied system includes all processes from primary resources to final product at the factory gate including extraction, refining and transportation of raw materials and primary energy resources. Further refinement, use and recycling or disposal of the product is not included in this study.

The studied mill and technology combinations and the naming convention used are summarized in Table 1. Energy and material balances for the chemical pulp mills are based on calculations by Berglin et al (1999; 2003) and Ekbom et al. (2003). No data is available for DME production in an integrated pulp and paper mill, however, the configuration and performance of the DME process is very similar to the methanol process, and we use information in Ekbom et al. (2003) to extrapolate the performance of the DME configuration from data for the methanol configuration reported by Berglin et al. (2003). We consider DME since it is better suited for diesel

engines than methanol (Kavalov and Peteves 2005). Diesel is the main fuel used in transports related to pulp and paper production in this study and considering DME instead of methanol as renewable fuel avoids including another fuel-chain into the analyses.

Table	1. Abbreviations	used for t	he studied	mills and	technologies.
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	Chemical market pulp	Integrated chemical pulp	Integrated
Technology	mill (CM)	and paper mill (CI)	TMP/Newsprint mill
Conventional technology (Reference)	CM-RB	CI-RB	TMNews
BLG with electricity production	CM-BLGCC	CI-BLGCC	N/A
BLG with DME production	CM-BLGMF	CI-BLGMF	N/A
Efficient TMP refining	N/A	N/A	TMNewsEff

No detailed model studies are available for the TMP/newsprint mill. We base the wood and energy consumption of the reference mill on information from university and industry representatives (personal communication: Inger Eriksson, SCA Forest Products, Per Engström, Holmen paper, Martin Åberg, ÅF-Process AB, Hans Höglund, Mid Sweden University). Newsprint is assumed to be manufactured from 100% TMP. The total energy balances of the mill is calculated from the heat and electricity demand of the processes, assuming that combustion of internal bark residues is used to co-generate steam and electricity, and that 50% of the electric energy use can be recovered as low-pressure steam. Several measures have been suggested for improved energy efficiency in TMP refining for printing papers (Falk et al. 1989; Ferritsius et al. 1989; Sundholm 1993; Höglund et al. 1995; Sabourin 1999; Kallioinen et al. 2003; Norgren et al. 2004). Based on this literature and personal communication (Hans Höglund, Mid Sweden University) we estimate that the refining energy requirements could be lowered with 20%, compared to the most efficient technology in use today.

Table 2. Wood and energy consumption per tonne of pulp assumed for the pulp and paper mills. A negative value means that energy is exported from the mill.

	pulpwood	Sawmill	Additional	Electricity	Liquid
Mill		chips	fuel ^a		fuels
	kg	kg	GJ	GJ	GJ
CM-RB	1870	713	-1.5	-2.2	-
CM-BLGCC	1870	713	-1.5	-4.5	-
CM-BLGMF	1870	713	4.4	3.0	-14
CI-RB	1870	713	-0.1	1.4	-
CI-BLGCC	1870	713	4.5	-2.3	-
CI-BLGMF	1870	713	13	4.3	-14
TMNews	1290	-	-2.1	11	-
TMNewsEff	1290	-	-0.62	8.6	-

a) 1.5 GJ of tall oil from the chemical market pulp mills and 0.1 GJ from the integrated chemical pulp mills is exported. Bark and wood residues is exported from the TMP/newsprint mill. In efficient TMP refining less steam can be recovered and more bark is needed for steam generation.

Motor fuel and electricity input in roundwood production is assumed to correspond to 1.1% and 0.02% of the wood energy content, respectively (Berg and Lindholm 2003). The life-cycle energy use for timber production reported in (Athanassiadis 2000) is in the same range as our assumptions. Energy input for the recovery of forest residues is about 3.3% of the output energy content (Börjesson 1996). The LHV of fresh biomass is taken to be 15.3 MJ per kg dry substance.

Marginal electricity is assumed to be produced in modern coal-fired steam turbine plants with a conversion efficiency of 47% (Bärring et al. 2003). Diesel is taken to be the marginal transportation fuel. Biomass-based electricity is assumed to be generated with a conversion efficiency of 47% in biomass gasification plants with combined cycle (BIGCC) (Gustavsson and Karlsson 2002) and DME with 63% efficiency in a biomass gasification process (Elam 2002). The DME process requires 0.11 GJ of electricity per GJ DME produced.

Distances and energy intensities for transportation are summarized in Table 3. We assume that all transport is done by road, since the share of rail and ship in transport of wood and other supplies to pulp mills is comparatively small (Larsson and Lidén 1997). Larsson and Lidén (1997) report average road transportation distances for roundwood ranging from 80 to 120 km and for woodchips ranging from 76 to 150 km in a case study of four Swedish mills in 1995. The average road transportation distance of roundwood in Sweden was 78 km in 1995 and had increased to 93 km in 2004 (Loman 2004). Pulp mills generally have above-average transportation distances, since they have larger uptake areas than sawmills. We assume transportation distances of 120 km for both roundwood and sawmill woodchips. Harvest residues for energy use is assumed to be transported by truck for 85 km, which was the average distance for woodchips and wood waste in 2004 (Loman 2004). Chemicals are assumed to be transported with truck for somewhat longer distances than biomass.

	Distance ¹	Energy intensity ²	Cost ² (excl. fuel)
	km	MJ/tonne-km	€/tonne-km
Pulpwood	120	1.1	0.066
Saw-mill chips	120	0.96	0.058
Harvest residues	85	1.3	0.090
Chemicals	500	1.1	0.080

Sources: 1) see text, 2) (Löfroth et al. 2005) and own calculations

Economic analysis

Production costs are calculated from estimated investment and operation and maintenance costs for pulp and paper mills and external energy conversion plants (Table 4). Upstream production costs for fuels, chemicals and raw materials are assumed to be included in their price. Investment costs are annualised using a 6% real discount rate and assuming a lifetime of 25 years for pulp mill and energy plant investments. Costs and prices are without taxes and converted to euros in the year 2006 value. All costs and benefits are allocated to the pulp product.

We estimate investment, operation and maintenance costs for the BLG mills from calculations by Berglin et al (2003) Ekbom et al. (2003) and STFI (2003). No cost data for the integrated pulp and paper mill was available and as an approximation we add the investment and operation costs for a paper machine estimated by Hekkert and Worrell (1998) to the costs for the market pulp mill.

Our data for the newsprint mill is not based on a model mill study, and no cost data is available. As a rough approximation we assume the costs for the reference integrated TMP/newsprint mill to be the sum of the costs estimated by Hekkert and Worrell for a TMP mill and for a newsprint paper machine. Martin et al (2000) estimated the investment cost for energy savings measures in TMP refining to 50–227 US\$ per t annual capacity (54–250 €/t). Möllersten et al (2003) give investment costs of 87–193 US\$ per MWh annually saved (26–58 €/GJ) for various energy conservation measures in TMP refining. At 20% energy savings this represents about 47–100 € per t capacity. We assume an additional investment cost of 100 € per t capacity, in line with the upper limit given by Möllersten but below the higher cost estimate given by Martin et al. Prices used for biomass are given in Table 5. The diesel price is assumed to be 8.4 €/GJ based on a crude oil price of 40 US\$/barrel (32 €/barrel) and a diesel-to-crude oil ratio of 1.3, following projections by JRC (2006).

Table 4. Investment and operation and maintenance (U&M) cost	ost for energy plants an	a puip and p	aper milis
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Energy supply	Investment	O&M
	€/kW _{output}	€/kWh _{output}
BIGCC (η=47%) ¹	1226	2.47
Coal ST $(\eta = 47\%)^2$	1260	1.05
DME (η=63%) ³	2030	2.80
Pulp/paper mills ⁴	€/(t pulp/year)	€/t pulp
CM-RB	1320	88
CM-BLGCC	1440	92
CM-BLGMF	1450	91
CI-RB	2900	175
CI-BLGCC	3020	180
CI-BLGMF	3020	180
TMNews	1780	100
TMNewEff	1880	100

Sources: 1) (Gustavsson and Karlsson 2002), 2) (Bärring et al. 2003), 3) (Elam 2002), 4) See text.

Table 5.	Average	biomass	prices	2000-2005	with	and	without	(in	brackets)	estimated	energy	and	transportatio	'n
costs.														

Assortment		Cost incl. and (excl.)			
		energy and transport ^a			
Pulpwood ¹	€/m³sub	34 (25)			
	€/GJ	4.8 (3.5)			
Saw-mill chips ¹	€/m³sub	33 (26)			
-	€/GJ	4.7 (4.0)			
Forest fuel ²	€/GJ	3.9 (2.5)			

 a) Prices are assumed to include upstream energy and transportation costs. To avoid double-counting, we estimate the energy and transport costs and deduct these from the prices. The prices with transportation costs deducted are given in parentheses.
Sources: 1) (Swedish forest agency 2007) and own calculations, 2) (STEM 2006)

RESULTS

Figure 2, Figure 3 and Figure 4 show the additional biomass (biomass cost), additional primary energy (primary energy cost) and monetary resources (monetary cost) used, in comparison to the reference case, to achieve the

same total CO_2 emission and oil use reduction in the system, when different configurations of the same mill are compared. In the chemical market pulp mill and integrated pulp and paper mill, both BLG configurations are more favourable than stand-alone production only, and BLGMF is more favourable than BLGCC, with respect to biomass, primary energy and monetary costs. About 5–10 GJ more of biomass and 110 \in per tonne pulp is needed to achieve the same CO_2 and oil use reductions if BLG is not implemented at all, compared to if BLGMF is implemented. The difference in total primary energy use shows the same trend. For the TMP/newsprint mill, CO_2 emission and oil use reductions are achieved more efficiently through increased energy efficiency than through stand-alone production of biomass-based electricity. The costs are not directly comparable between the different types of mills (chemical market pulp, integrated chemical, TMP/Newsprint) since the reductions achieved are not equal for the different mill types.



Figure 2. Biomass (biomass cost), primary energy (primary energy cost) and monetary resources (monetary cost) needed to achieve the same total CO_2 emission and oil use reduction in the system, when different configurations of the chemical market pulp mill are compared. Costs are given per tonne pulp.



Figure 3. Biomass (biomass cost), primary energy (primary energy cost) and monetary resources (monetary cost) needed to achieve the same total CO_2 emission and oil use reduction in the system, when different configurations of the integrated chemical pulp and paper mill are compared. Costs are given per tonne pulp.



Figure 4. Biomass (biomass cost), primary energy (primary energy cost) and monetary resources (monetary cost) needed to achieve the same CO_2 and oil use reductions with stand-alone production as achieved with increased energy efficiency, for the TMP/newsprint mill.

DISCUSSION

Biomass-based energy provides an important potential for reducing CO₂ emissions and oil use, and biomass waste streams in pulp and paper mills constitute a considerable biomass resource. There are, however, a variety of technological options for using biomass and these options vary considerably in cost and in the extent to which they address CO₂ emissions and oil use. We show that if both CO₂ emission reductions and oil use reductions are to be achieved, it is more efficient to implement BLGMF with DME production and stand-alone electricity production from biomass, than to implement BLGCC and stand-alone production of DME. It can be noted that if reduced CO₂ emissions is considered a much more important objective than oil use reductions, then BLGCC is to prefer. We also consider increased energy efficiency in TMP refining and find that CO₂ savings are cheaper to achieve through efficiency measures than through stand-alone production of electricity from biomass. The advantageous results for BLG compared to gasification of alternative biomass sources in stand-alone plants can be explained by several factors including, but not limited to (Ekbom et al. 2006): (i) simplified logistics as the biomass is handled within the ordinary operation of the pulp and paper mill; (ii) the process is easily pressurised as the feedstock is liquefied, which enhances production efficiency; (iii) gasification capital cost is shared between the recovery of inorganic chemicals, steam production and syngas production. The reasons for the favourable results from BLGMF compared to BLGCC need further investigation. Further development of this work could also include quantification of uncertainty ranges and improved data for mechanical pulp mills.

Uncertainties

Data in this study have been collected from multiple sources, which probably used different methodologies, e.g. with respect to system boundaries and allocation, which gives rise to uncertainties. In particular, exclusion of small streams gives truncation errors and may lead to underestimation of e.g. energy use (Mongelli et al. 2005). While detailed cost estimates were available for the chemical market pulp mill, cost estimates of pre-commercial technologies still carry large uncertainties, initially about ±30%, which are further increased by conversion and scaling. Less detailed data have been available for the TMP/newsprint mill and cost uncertainties can be assumed to be at least as large as for the chemical pulp mills. Price relations between biomass and fossil fuels, as well as between different biomass assortments influence the results.

CONCLUSIONS

If both CO_2 emission reductions and oil use reductions are to be achieved, it is more efficient to implement BLGMF with DME production and stand-alone electricity production from biomass, than to implement BLGCC and standalone production of DME. Increased energy efficiency in TMP refining achieves CO_2 savings less costly than stand-alone production of electricity from biomass.

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NOMENCLATURE

BIGCC	biomass integrated gasification power plant with combined cycle
BLG	black liquor gasification
BLGCC	black liquor gasification with combined cycle
BLGMF	black liquor gasification with motor fuels production
CHP	combined heat and power production
CI	integrated chemical pulp and paper mill
CM	chemical market pulp mill
DME	di-methyl-ether
LHV	lower heating value
O&M	operation and maintenance
RB	conventional recovery boiler
ST	steam turbine
t	metric ton
TMNews	integrated newsprint/TMP mill
TMNewsEff	integrated newsprint/TMP mill with energy efficient refining
TMP	thermomechanical pulp
RB ST t TMNews TMNewsEff TMP	conventional recovery boiler steam turbine metric ton integrated newsprint/TMP mill integrated newsprint/TMP mill with energy efficient refining thermomechanical pulp

Greek Letters

η conversion efficiency

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