Pathways to a sustainable European pulp and paper industry: Trade-offs between different technologies and system solutions for kraft pulp mills

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Earlier studies have shown that for chemical pulp mills there are many technologies and system solutions which can increase energy efficiency and thus reduce the process energy demand and consequently also the global emissions of CO_2. Which technology pathway (combination of technologies and system solutions) holds the greatest potential for future profits and reduction of global CO_2 emissions depends both on mill-specific conditions and on the surrounding energy system through e.g. policy instruments and energy market prices.

In this paper the trade-off, in terms of system revenue and global CO_2 emission consequences, between different technology pathways for utilization of excess heat at chemical kraft pulp mills is investigated for a case depicting a typical Scandinavian mill of today. The trade-off is analysed for four future energy market scenarios having different levels of CO_2 charge. The technology pathways included in this study are (1) increased electricity production in new condensing turbines, (2) production of district heating, (3) increased sales of biomass in the form of bark and/or lignin, and (4) carbon capture and storage (CCS). Lignin extraction and CCS are considered as new and emerging pathways and the other pathways are considered to be well-tried.

The results show that well-tried pathways such as increased electricity production in new turbines, selling bark and district heating production are economically robust, i.e. they are profitable for all of the studied energy market scenarios. The new and emerging technology pathways such as carbon capture and storage and lignin extraction hold a larger potential for reduction of global CO_2 emissions, but their economic profitability is more dependent on the development of the energy market. All in all, it can be concluded that to realize the larger potential of reduction of global CO_2 emissions a high carbon cost alone may not be sufficient. Other economic stimulations are required, e.g. technology-specific subsidies.

1. Introduction

Research has shown that for the chemical pulp and paper industry there are many technologies and system solutions (henceforth called technology pathways), both well-tried and new, which with economic profitability can increase energy efficiency and thus reduce the process energy demand and consequently also the global emissions[1] of CO_2 (Algehed, 2002, Axelsson, et al., 2006, IEA, 2004, Kilponen, et al., 2001, Mollersten, et al., 2003, Olsson, et al., 2006, Wising, 2003). Previous studies have investigated the trade-off between increased electricity production and diverse other technology pathways for utilization of kraft pulp mill excess heat one at a time: e.g. lignin removal (Olsson, et al., 2006), carbon capture and storage (CCS) (Hektor, 2006) and production of district heating (Jönsson, et al., 2008). Yet how the simultaneous trade-off between all of these pathways is affected by different future energy market scenarios and levels of CO_2 charge has not previously been studied.

2. Objective

The aim of this paper is to examine the trade-off, in terms of system revenue and global CO_2 emission consequences, between different technology pathways for utilization of excess heat at kraft pulp mills, under different future energy market scenarios.
For this purpose the following questions are addressed:

- How does the choice of pathway affect the mill's overall energy balance and thus the global CO_2 emissions?
- How is the trade-off between the studied pathways and thus the emissions of CO_2 affected by the development of the energy market and the level of CO_2 charge? Are any of the pathways robust to the uncertainty of the future energy market?

3. Methodology

The work presented in this paper follows a methodology previously developed and described by one of the authors (Jönsson, et al., 2008). For this work a model of a kraft pulp mill was constructed and optimized, using the energy systems modelling tool reMIND which is based on mixed-integer linear programming. With the reMIND tool, the constructed model is optimized with the objective of minimizing the total annual system cost of the studied energy system (the mill), assuming a surrounding system (the energy market, including policy instruments). The objective function can schematically be described as;

min $Z = rI_{tot} + B_{tot} - C_{tot}$ (1)

where *r = Capital recovery factor (0.2)*

I_{tot} = Total investment cost (energy efficiency measures and technology pathways)

B_{tot} = Benefit of sold energy products including policy instruments (electricity, district heating, bark, captured CO_2 etc.)

C_{tot} = Running costs (e.g. electricity for heat pump, chemicals for lignin extraction)

For the energy system studied in this paper, the annual system cost is always negative, meaning that the system is profitable. Due to this fact, the annual system cost is hereafter denoted the annual system revenue.

4. The studied system and input data

The studied energy system consists of a kraft pulp mill with the possibility to invest in energy efficiency measures (reducing the process steam demand) and/or new

[1] In this paper the term 'global emissions' refers to both on-site and off-site emissions.

technology pathways (new turbines, export of district heating or bark, lignin extraction and CCS). The studied energy system is connected to a surrounding energy market in which imported and exported energy carriers are priced and the associated CO_2 emissions are calculated.

4.1 Data for the mill and the studied technology pathways

The kraft pulp mill model is based on data from the national Swedish research programme "Future Resource Adapted Pulp Mill" (FRAM) and represents an average Scandinavian kraft pulp mill (FRAM, 2005). Technical and economic data for the different studied pathways are based on previous research (Hektor, 2006, Jönsson, et al., 2008, Olsson, et al., 2006). The mill can invest in a variety of energy efficiency investments decreasing the mill's steam demand and increasing the amount of excess heat (hot water and steam) (Axelsson, et al., 2006). The excess heat itself does not generate any positive cash flow but can be utilised in different ways, the studied technology pathways, to increase the mill's revenue. An overview of data for the mill is presented in Table 1. In Table 2 the studied technology pathways are presented.

Table 1. Overview of mill data

Production kraft pulp, design	[ADt/d]	1000
Process thermal energy use*	[GJ/ADt	14.3
Electricity use/production	[kWh/ADt]	791/593
Electricity surplus (+) or deficit (-)	[kWh/ADt]	-198
Biomass surplus (bark sold)	[t DS/Adt]	0.19
Direct reduction of steam	[t/h]	10.4 HP-MP, 31.2 HP-LP
Steam surplus	[MW]	8.2

*Excluding steam consumption in back pressure turbine.

Table 2. Description of technology pathways studied

Pathway	New larger turbines (BP, Cond)	Bark (sold)	District heating	Lignin extraction	CCS
Type Costs & technical data rom	Well-tried (Olsson, et al., 2006)	Well-tried (FRAM, 2005)	Well-tried (Jönsson, et al., 2008)	New (Olsson, et al., 2006)	New (Hektor, 2006)
Description	Investment in new back pressure and condensing turbines for increased electricity production. Utilises excess steam and previously throttled steam.	Selling all or parts of the falling bark instead of burning it in the bark boiler.	Using excess heat for production of district heating. The excess heat is used either directly or by a heat pump, depending on quality of heat.	Extracting lignin from the black liquor. Due to the lignin extraction, less steam is produced in the recovery boiler, decreasing the electricity production.	Using the excess LP steam for the heat demand needed to regenerate the absorption medium, MEA, when capturing CO_2 from the recovery boiler flue gases.

4.2 Energy market scenarios

In order to evaluate the future trade-off between the different pathways studied, four energy market scenarios, which reflect different possible future energy market prices, are used; see Table 3. The scenarios reflect futures with high or low fossil fuel prices coupled with high or low CO_2 charge. In the scenarios, different marginal production technologies, with associated CO_2 emissions, are assumed for electricity production, alternative use of biomass and production of district heating – and thus the scenarios can be viewed as cornerstones for the future development of the energy market (Axelsson, et al., 2007). Using these scenarios also works as a sensitivity analysis with respect to varying energy market prices.

Table 3. Description of the four energy market scenarios used

Scenario	**1**	**2**	**3**	**4**
Fossil fuel price/CO_2 charge	Low/Low	Low/High	High/Low	High/High
Prices and policy instruments				
Electricity [€/MWh]	54	59	57	62
District heating* [€/MWh]	14	21	31	30
Bark [€/MWh]	14	20	15	21
Lignin [€/MWh]	17	23	18	25
CO_2 charge [€/ton CO2]	26	42	26	42
Electricity certificate price# [€/MWh]	16	5	16	5
CO2 effect [kg/MWh]				
Electricity	374	136	723	136
(marginal production of electricity)	(NGCC)	(CP w CCS)	(CP)	(CP w CCS)
Biomass	329	329	122	159
(alternative use of biomass)	(CP)	(CP)	(DME)	(DME)
District heating	278	373	-143	140
(alternative heat supply technology)	(bio CHP)	(bio CHP)	(bio CHP)	(bio CHP)

* Based on new biomass CHP as the competing heat supplier and an investment in 18 km of piping (for a maximum of 40 MW and 4000 h).
# A Swedish policy instrument giving the mills extra revenue for their 'green' electricity sold.

5. Results

The key results are presented in Figure 1. In the figure the changes in system revenue and global CO_2 emissions are displayed for the optimal solution as well as for the different technology pathways. The optimal solution, for all scenarios but the first, is a combination of different pathways, as presented on the left side of the figure. Baseline for the comparison (0%) is the existing energy balance of the mill without making any investments, "business as usual" (BAU). Since the energy market prices and the CO_2 emissions effect vary between the different scenarios, so do the system revenue and global emissions for both the baseline, BAU and the different studied pathways.

As can be seen in the figure, the pattern in trade-off between the different pathways is similar for the scenarios having the same level of CO_2 charge. For the two scenarios with low CO_2 charge, Scenarios 1 and 3, the well-tried pathways are substantially more profitable than the new emerging pathways, CCS being directly unprofitable for both scenarios and lignin extraction directly unprofitable in Scenario 1. For the two scenarios with high CO_2 charge, Scenarios 2 and 4, all of the pathways are profitable compared to doing nothing, BAU. The variation in reduction of global CO_2 emissions between the different pathways is large in all scenarios, CCS giving the largest reduction for all studied scenarios. Consequently, for Scenarios 2 and 4 the marginal cost is low for further, and large, reduction of CO_2 emissions (compared to the optimal solution).

6. Concluding discussion

As can be seen from the results, the new and emerging technology pathways, combined with energy efficiency, hold much larger potential for reduction of global emissions of CO_2 than the well-tried pathways. However, studying the trade-off between these different pathways for different CO_2 prices and corresponding developments in the energy market, it can be concluded that from an economic point of view the well-tried pathways are much more robust and thus likely to be preferred by the industry.

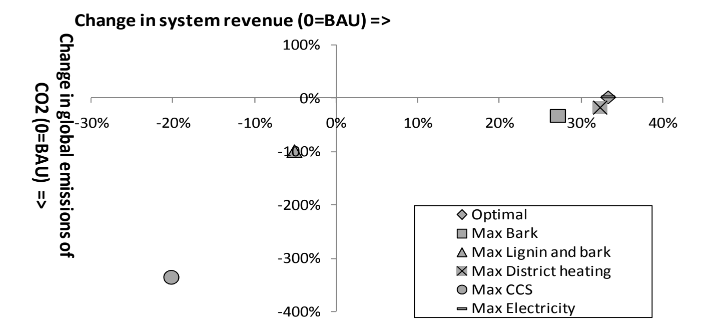
Consequently, it can be concluded that applying a high cost of CO_2 alone, as in Scenarios 2 and 4, may not be enough to reach the full potential of CO_2 emissions reduction, since this also profits the well-tried pathways. To reach the full potential, the new and emerging technology pathways may also need some direct support, e.g.

technology-specific subsidies. Yet due to the low marginal cost of further reduction of CO_2 emissions in Scenarios 2 and 4, these economic supports do not need to be large if the energy market and policy instruments resemble these scenarios.

Scenario 1
Optimal solution (BAU)

System revenue
25 (18) M€/yr
Global CO_2 emissions
-164 (-167) ktonnes/yr

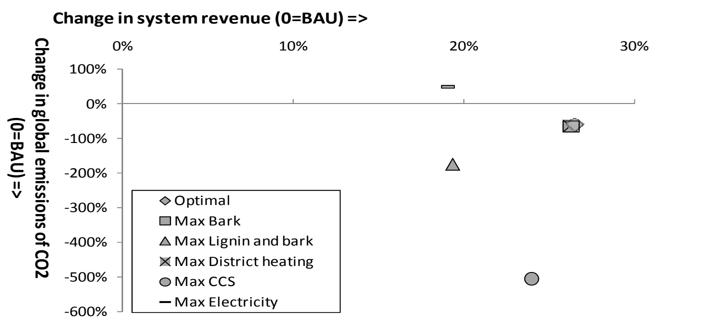
Electricity
438 (211) MWh/yr
Biomass
0 (268) MWh/yr
District heating
0 (0) MWh/yr
CCS
0 (0) ktonnes/yr



Scenario 2
Optimal solution

System revenue
24 (19) M€/yr
Global CO_2 emissions
-192 (-117) ktonnes/yr

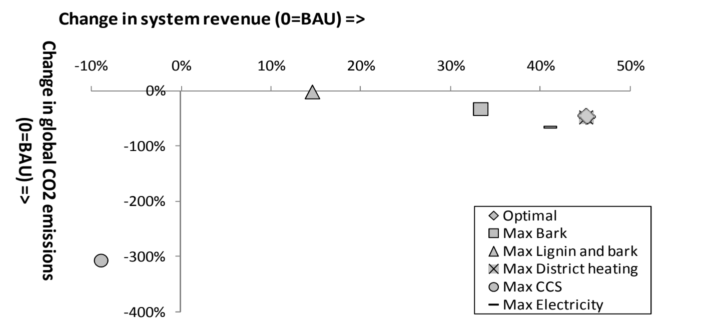
Electricity
323 (211) MWh/yr
Biomass
268 (268) MWh/yr
District heating
160 (0) MWh/yr
CCS
0 (0) ktonnes/yr



Scenario 3
Optimal solution

System revenue
28 (20) M€/yr
Global CO_2 emissions
-274 (-185) ktonnes/yr

Electricity
420 (211) MWh/yr
Biomass
0 (268) MWh/yr
District heating
160 (0) MWh/yr
CCS
0 (0) ktonnes/yr



Scenario 4
Optimal solution

System revenue
26 (20) M€/yr
Global CO_2 emissions
-100 (-71) ktonnes/yr

Electricity
353 (211) MWh/yr
Biomass
188 (268) MWh/yr
District heating
160 (0) MWh/yr
CCS
0 (0) ktonnes/yr

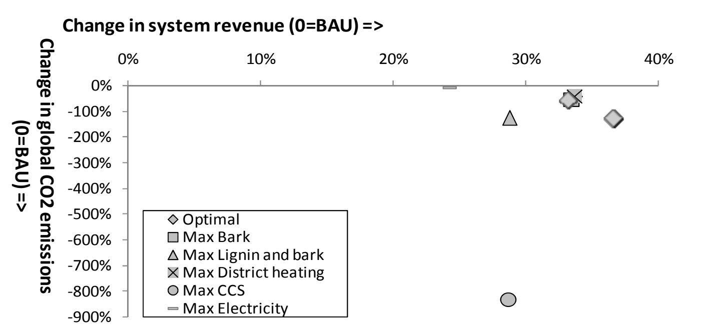


Figure 1. Summary of key results

This study and its results are based on an average Scandinavian kraft pulp (model) mill. However, the wide variety of processes, age structure of equipment, proximity to infrastructure etc. between different real mills implies that the analysis also needs to be done at a more disaggregated level in order to more thoroughly understand and analyse the potential for energy efficiency and reduction of CO_2 emissions within the whole European pulp and paper industry. In this study the trade-off is studied for four different energy market scenarios with two levels of CO_2 charge. To thoroughly analyse the impact of policy instruments such as CO_2 charge on the trade-off between different technology pathways, more scenarios and policy levels should be investigated.

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