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Reduction of Greenhouse Gases in Integrated Pulp and Paper Mills – Possibilities for CO_2 Capture and Storage

Erik Hektor*, Thore Berntsson
Department of Energy and Environment, Heat and Power Technology,
Chalmers University of Technology, SE-412 96 Göteborg, Sweden

Earlier work has shown that capturing the CO_2 from flue gases in the recovery boiler at a market pulp mill can be a cost-effective way of reducing mill CO_2 emissions. In this paper it is investigated if the same is valid for an integrated pulp and paper mill. Five configurations are compared, supplying the extra energy needed by a biofuel boiler, an NGCC, a heat pump or by reducing the steam demand at the mill in combination with a biofuel boiler or an NGCC. The configurations with the NGCC have the lowest avoidance costs.

1. Introduction

Process industries like the pulp and paper industry use large amounts of energy to produce their products. In a climate-conscious society, the emissions of CO_2 must be reduced. One way of doing this is to capture and store the CO_2. Earlier work has shown that capturing the CO_2 from the flue gases in the recovery boiler in a market pulp mill can be a cost-effective way of reducing CO_2 emissions (compiled in Hektor et al, 2006). Here it is investigated if the same is valid for an integrated pulp and paper mill.

2. Studied systems

The calculations in this work are based on the eco-cyclic reference pulp and paper mill (KAM), which was a Swedish national research and development programme. The integrated pulp and paper mill is a fictitious integrated kraft pulp and paper mill based on the best available technology in Sweden and Finland in the late 1990s (STFI, 1999). The first eco-cyclic pulp and paper mill (KAM 1) was based upon a plant capacity of 1000 ADt (Air dried tonne, 90 % dry content) pulp per day, but in this work the mill is scaled up to a capacity of 1500 ADt per day. Key figures for the mill can be found in Table 1. A chemical absorption unit is added to the recovery boiler in order to capture the CO_2 from the flue gases. Chemical absorption is a proven way to separate CO_2 from flue gases and requires no rebuilding of the recovery boiler. The CO_2 is captured using mono-ethanolamine (MEA) as an absorbent. The absorption column has a working temperature of 60°C and the desorption column has a working temperature of 110°C. After the capture, the CO_2 is compressed in two stages with intercooling to a pressure of 80 bar. In order to regenerate the absorbent, large quantities of low-pressure (LP) steam are needed for the reboiler in the desorption unit. This steam demand can be satisfied in different ways. In this paper the following alternatives are investigated; producing more steam by making the biofuel boiler larger or introducing a natural gas combined cycle (NGCC) working as a combined heat and power unit, introducing a heat pump or by performing thermal process integration at the mill in combination with a biofuel boiler or an NGCC. The alternatives are described in more detail below.

* Corresponding author: erik.hektor@chalmers.se
Telephone: +46-(0)31-772 8536; Fax: +46-(0)31-82 19 28

2.1 Biofuel boiler

In the biofuel boiler alternative, the boiler is made larger in order to produce a sufficient amount of steam for the regeneration of the absorbent. The boiler produces high-pressure (HP) steam that is fed into the steam cycle of the mill and then expanded in the steam turbine to LP steam. The CO_2 from the biofuel boiler is also captured. The studied configurations can be viewed in Fig. 1. Key figures for the reference mill and the studied alternatives can be found in Table 1.

2.2 NGCC – CHP

In this alternative the biofuel boiler is replaced with an NGCC. The NGCC is designed so that the heat recovery steam generator (HRSG) can produce the sufficient amount of HP steam, so that there is enough LP steam for capture of the CO_2 from the recovery boiler and the NGCC.

2.3 Heat pump

The heat pump uses low temperature heat available at the mill to produce LP steam. The heat pump is an electrically driven closed cycle using three three-stage turbo compressors. The coefficient of performance (COP) value is 4.4.

2.4 Process integration

In order to satisfy the need for steam for regeneration of the absorbent, the mill is process-integrated and the boiler is resized. The thermal process integration has been performed within the eco-cyclic pulp mill programme and generates a surplus of steam. The steam surplus is 2 GJ/ADt, which corresponds to 36 MW (Alghed, 2002). This steam is not sufficient for the regeneration of the absorbent; therefore the biofuel boiler is resized to supply the rest of the steam needed. An alternative where the boiler is replaced with an NGCC unit, designed as above, is also investigated.

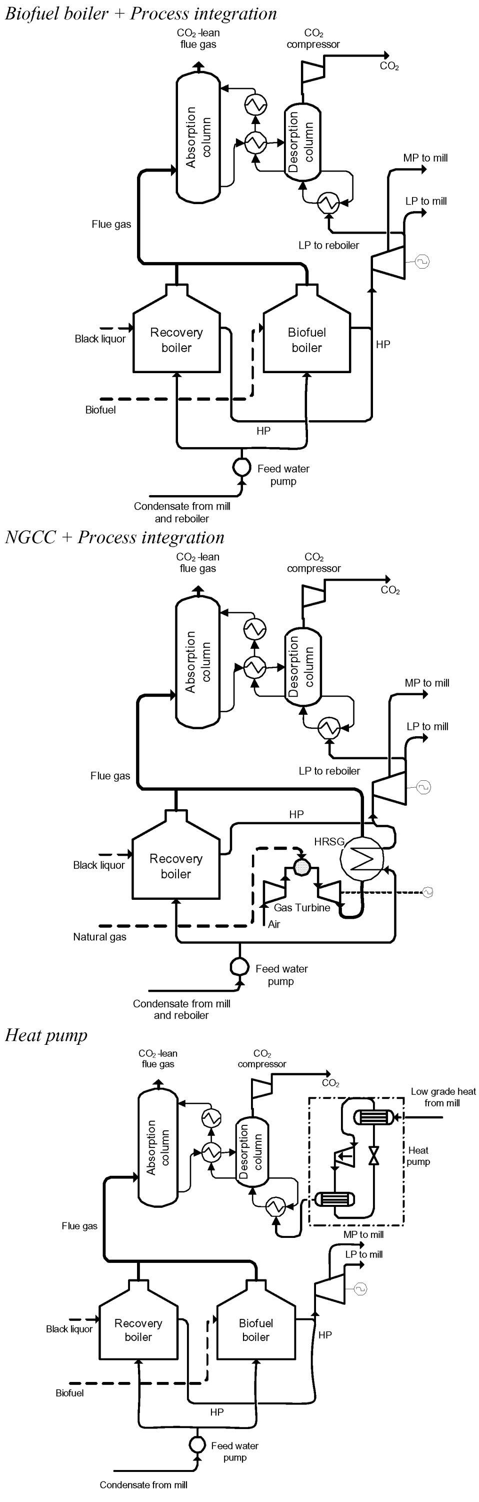

Figure 1: Simplified chart of the CHP systems.

Table 1. Key specifications for the reference mill and the studied alternatives.

	Ref. mill	Biofuel boiler	NGCC CHP	Heat pump	PI + Biofuel	PI + NGCC
Black liquor [MW]	338	338	338	338	338	338
External fuel [MW]	80	289	260	80	222	123
CO_2 formed [kg/s]	37	58	44	37	51	37
CO_2 recovery [%]	-	90	90	90	90	90
CO_2 capture rate [kg/s]	-	52	40	34	46	33
MP steam to mill [tonne/h]	176	176	176	176	176	176
LP steam to mill [tonne/h]	200	200	200	200	148	148
Heat consumption for CO_2 separation [MW]	-	150	115	-	132	95
Power consumption for heat pump [MW]	-	-	-	22	-	-
Power consumption for CO_2 compression [MW]	-	24	18	16	21	15
Steam turbine output [MW]	58	96	91	58	83	77
Gas turbine output [MW]	-	-	84	-	-	28
Mill electricity consumption [MW]	74	74	74	74	74	74
Electricity surplus [MW]	-16	-2	83	-53	-12	31

3. Methodology

The main methodology used in this paper is to combine knowledge from several different areas in order to achieve new system knowledge. These areas are process integration possibilities at pulp mills, design of absorption units and systems for transportation and storage of CO_2. In this way the most promising system solutions can be identified. They can then be studied in more detail in future work. The approach for each area is described below.

The original design of the absorption system is taken from Möllersten et al. (2004) and was simulated in the ASPEN PLUS process simulator. The absorption system is then redesigned, with regard to size, energy economy and performance, in order to be suitable in the different alternatives investigated within the scope of this work.

For the NGCC, the design has been chosen using data from Gas Turbine World Handbook (2005) and with an iterative approach selecting the NGCC that best fits the application. The heat pump is designed using the software IEA Annex XXI (IEA, 1997). The purpose of this software is to suggest suitable working fluids and compressors for a given application. The potential for steam savings at the mill has been identified by using Pinch Technology, which is a valuable tool when estimating the potential for energy savings in a heat-demanding industry. The calculations have been performed within the eco-cyclic pulp mill programme (Algehed, 2002).

The data regarding transportation are taken from Svensson et al. (2004) and are based on technological, economic and logistic data from both CO_2 transportation and the liquefied petroleum gas industry. The final storage is a crucial issue. Elforsk (2004) has performed a study to find suitable alternatives in Sweden and these data have been used.

For the evaluation, energy market scenarios are used. The scenarios are created by Axelsson et al (2007) and are based on an energy market model. Four different scenarios for 2020 are used. Two levels of fossil fuel prices and CO_2 emissions charge were combined into four sets of input data for the scenarios, see Table 2. The scenarios are used here as an indication of how different futures affect the economic performance of the technology in each case, i.e. as a packaged sensitivity analysis.

Table 2. Energy market scenarios

	Scenario 1	2	3	4
Fuel prices [EUR/MWh$_{fuel}$]				
- Natural gas	26	29	34	37
Biofuel prices [EUR/MWh$_{fuel}$]				
- Pellets	25	34	27	49
- Chips	17	23	18	33
- Biproduct	14	20	15	21
Electric power price [EUR/MWh$_{el}$]				
- Price	54	59	57	62
- Power cert.	16	5	16	5
CO_2 emissions[a] [kg/MWh$_{fuel / el}$]				
- Biofuel	329	329	329	159
- Electricity	426	136	723	136
CO_2 price [EUR/tonne]				
- Price	27	43	27	43

[a] From marginal use, see Axelsson et al

4. Economic Evaluation

In order to evaluate the performance of the suggested systems for capturing the CO_2, the cost of each avoided tonne of CO_2 is calculated:

$$c_{avoid} = \frac{C_{annual}}{m_{annual}} \quad \text{[EUR/tonne CO}_2\text{]} \quad (1)$$

where

m_{annual} Annually avoided CO_2 [tonne]

$$C_{annual} = \Delta C_{inv} + \Delta C_{O\&M} + \Delta E \cdot p_e + \Delta E_{prod.} \cdot p_P + \Delta F \cdot p_F + C_{tr} \quad \text{[EUR]} \quad (2)$$

where

ΔC_{inv} Incremental investment cost, annualised using the annuity method [EUR]
$\Delta C_{O\&M}$ Annual change in operation and maintenance cost, 4 % of invest. cost [EUR]
ΔE Annual change in net electricity output [MWh]
p_e Electricity price [EUR/MWh]
ΔE_{prod} Annual change in electricity production from renewable sources [MWh]
p_P Power certificates [EUR/MWh]
ΔF Annual change in fuel use [MWh]
p_F Fuel price [EUR/MWh]
C_{tr} Annual cost for transportation and storage of the CO_2 [EUR]

The avoided CO_2 amounts are the produced CO_2 emissions for the same services (paper, electricity) when there is no capture minus the emitted CO_2 with the capture.

The energy market parameters are taken from the scenarios described above and the values are presented in Table 2. The investment costs are taken from the sources presented in the methodology chapter and are presented in Table 4. They correspond to the incremental investment cost compared to the reference mill. The mill is regarded as new or a mill in need of improvement. All costs connected to the CO_2 capture are included even the changes made to the mill. When there is a change in equipment, it is the difference between a new unit designed as needed and a new unit of the original design that is used. A scale factor of 0.7 is used when needed. The general economic assumptions can be found in Table 3.

Table 3. Economic assumptions

Annuity factor	0.1[a]	Operating time [h/year]	8000
Exchange rate [SEK/EUR]	9.13[b]	Transportation cost [EUR/tonne]	4.1[c]
Exchange rate [USD/EUR]	1.2[b]	Storage cost [EUR/tonne]	3.3[d]

[a] Annuity factor used for the pulp and paper industry when evaluating strategic investments.
[b] Average exchange rate during 2006
[c] Transportation cost taken from Svensson et al. (2004)
[d] Estimated storage cost for on-shore aquifer in Skåne in the south of Sweden (Elforsk, 2004).

Table 4. Incremental investment costs compared to reference mill.

	Biofuel boiler	NGCC CHP	Heat pump	PI + biofuel	PI + NGCC
CO_2 absorber [MEUR]	85	70	63	78	62
CO_2 compressor [MEUR]	10	8	7	9	7
Biofuel boiler [MEUR]	39	-27	-	28	-27
NGCC [MEUR]	-	25	-	-	18
Steam turbine [MEUR]	4	4	-	3	2
Heat pump [MEUR]	-	-	6	-	-
Process integration of mill [MEUR]	-	-	-	10	10
Total [MEUR]	138	81	76	128	72

5. Results

The calculated avoidance costs for the investigated alternatives are presented in Table 5. The corresponding results for a market pulp mill from previous studies are also included for comparison. The displayed results are valid for a transportation distance of 500 km.

From the results one can see that the NGCC unit has the lowest avoidance cost, especially in combination with process integration. The NGCC unit uses natural gas with a lower carbon density compared to biofuel and therefore the amount of extra fuel needed is lower compared to the alternative with the biofuel boiler. At the same time the NGCC produces more electricity that generates revenue for the mill. A favourable level of the investment cost compared to the biofuel boiler also favours the NGCC. Even if there is no credit for the original boiler the avoidance cost only increases with 3 EUR/tonne, which still makes it competitive in most scenarios. The high avoidance cost in Scenario 3 is due to the lost production of electricity from renewable sources and the high price on power certificates. In comparison to the market pulp mill, the unit for the integrated mill has a lower specific cost and a cost reduction since biofuel is replaced. Another advantage with the NGCC configurations is that biofuel is liberated and can be used elsewhere in society, where CO_2 capture not is possible, and there replace fossil fuels. Thereby the societal CO_2 emissions are reduced further, as shown in Hektor et al (2005). The benefit from this for the mill is included in the fuel prices in the scenarios.

From the results one can also see that for the biofuel boiler alternatives with and without process integration, the cost is much higher for the integrated pulp and paper mill compared to the market pulp mill. This is due to the fact that a larger part of the captured CO_2 comes from the extra fuel needed for the regeneration of the absorbent.

In an existing mill the avoidance cost increases for the alternatives with a biofuel boiler since there is a need for a second boiler, which is more expansive than the incremental cost for a larger unit. The NGCC alternatives require smaller units and the effect on the avoidance cost is dependent on the fuel price ratio between biofuel and natural gas.

Table 5. Avoidance cost [EUR/tonne] in market pulp mill (M) and integrated pulp+paper mill (I).

	Biofuel boiler		NGCC-CHP		Heat pump		PI + biofuel		PI + NGCC	CO_2 price
Scenario	M[a]	I	M[a]	I	M[a]	I	M[a]	I	I	(ref.)
1	39	39	36	24	33	35	29	38	22	27
2	44	52	39	21	35	37	32	46	20	43
3	40	39	44	36	34	36	29	39	28	27
4	51	66	48	30	36	38	34	56	22	43

[a] The data is taken from Hektor et al (2006), but have been recalculated with new scenarios.

The heat pump alternatives do not have the lowest avoidance cost, but has the advantage of having a very stable avoidance cost throughout all the scenarios. This is due to the fact that the electricity price has a smaller variation between the different scenarios compared to the natural gas and biofuel price.

The avoidance cost calculated here can be compared to other studies using post-combustion with MEA. Möllersten et al. (2003) obtains a value of 29 EUR/tonne for CO_2 capture in pulp mills, which is in the same order of magnitude as in this study. The same is valid for CO_2 capture from power plants. Davison (2007) has calculated the cost to between 23 and 37 EUR/tonne. However, it should be noted that in both articles different energy market parameters, compared to this study, are used.

Conclusions

Main conclusions from the study:

- The alternative with an NGCC is the most competitive alternative for integrated pulp and paper mills, especially if it is combined with a thermal process integration of the mill.
- Biofuel boiler and process integration are not so good for integrated pulp and paper mills as for market pulp mills.

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