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Potential and cost-effectiveness of CO₂ reductions through energy measures in Swedish pulp and paper mills

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Abstract

Using the two criteria of potential CO₂ reduction and cost of CO₂ reduction, technical energy measures in Swedish pulp and paper mills are investigated. Principal CO₂-reducing measures analysed are: decreased specific energy utilisation, fuel switch, and CO₂ capture and sequestration. Among the investigated measures, conventional technologies for electricity conservation and improved electrical conversion efficiency in existing systems for cogeneration of heat and power are identified as the most cost-effective alternatives that also have large CO₂ reduction potentials. For commercially available technologies, the results indicate an accumulated reduction potential of up to 8 MtCO₂/y (14% of the Swedish net emissions). If emerging technologies for black liquor gasification (BLG) with pre-combustion CO₂ capture and sequestration are considered, the CO₂ reduction potential increases by up to 6 MtCO₂/y (10% of the Swedish net emissions). Commercialised BLG, CO₂ capture and reliable CO₂ sequestration technologies are identified as important potential contributors to Swedish compliance with Kyoto Protocol targets, especially in a scenario of nuclear power closure.

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1. Introduction

In the Kyoto Protocol, many nations agreed upon greenhouse gas reduction targets and are called upon to reach average emission reductions of 5% from the 1990 level by the first commitment period 2008–2012. The identification of cost-effective CO₂ reduction alternatives through comparison of the specific reduction costs of various alternatives is a fundamental part of a strategy aimed at minimising the total cost of reaching future CO₂ emission targets.

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Nomenclature

ADt	air-dry tonne pulp
BLG	black liquor gasification
BLGCC	black liquor integrated gasification with combined cycles
CC	combined cycle
CCS	CO ₂ capture and sequestration
CHP	combined heat and power production
COR	cost of CO ₂ reduction
IGCC	integrated gasification combined cycle
LHV	lower heating value
m ³ o.b.	cubic metres over bark
NGCC	natural gas-fired combined cycle
O&M	operation and maintenance
t	metric tonne
TMP	thermomechanical pulping
y	year

Subscripts

e	Electricity
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If emissions from externally produced electricity consumed by industry are allocated to industrial production, world-wide industrial production accounted for 43% of CO₂ released to the atmosphere in 1995 [1]. Moreover, the pulp and paper industry ranks as one of the most energy-intensive industrial groups in the manufacturing sector [2]. Pulp and paper industries are experienced in handling large amounts of biomass fuels and are normally located in areas with abundant biomass. If properly managed, biomass energy systems have an advantage in that energy requirements can be fulfilled while the long-term net CO₂ emissions to the atmosphere are kept very low [3]. Due to these circumstances, it is of general interest to study possibilities for CO₂ reductions in the pulp and paper industry.

Opportunities for CO₂ reductions in the pulp and paper industry is the topic of some recent publications [4–12]. A considerable potential to reduce the consumption of fossil fuels and electricity in north American mills has been identified through benchmarking the energy consumption of American pulp and paper mills against (1) Scandinavian mills and (2) theoretical model mills based on the most efficient existing technologies [4,5]. Mannisto and Mannisto [4] identify energy conservation (steam and electricity) as the most profitable option based on available technologies for reducing CO₂ emissions in the Canadian pulp and paper industry. Among predicted technology improvements assessed by Koleff [6], gasification of spent pulping liquors in Kraft pulp mills for combined heat and power production (CHP) with combined cycles (CC) ranks as the alternative with the highest potential impact on CO₂ reductions. Studies by Isaksson [7], and Möllersten and

Yan [8] show that there are several alternative technologies based on gasification of black liquor that display considerable CO₂ reduction potentials, e.g. combining CHP with production of methanol or hydrogen. Möllersten et al. [9] estimate reduction potentials and specific CO₂ reduction costs of some technical alternatives in Swedish pulp and paper mills. In this paper, we carry out a more comprehensive discussion concerning alternatives for CO₂ reductions through energy measures in Swedish pulp and paper mills, and calculate the reduction potential and cost-effectiveness of a wider set of available and emerging technologies, including CO₂ capture and sequestration (CCS) from biomass. The results are discussed in relation to Swedish Kyoto Protocol commitments.

2. The Swedish pulp and paper sector

The pulp and paper industry in Sweden produces approximately 10.5 Mt pulp and 10 Mt paper annually. The pulp production is 63% sulphate, 6% sulphite, 29% mechanical and 2% semi-chemical. The pulp and paper industry accounts for approximately 45% of industrial utilisation of fuels and electricity in Sweden. The fuel consumption in 1997 was dominated by 40 TWh biofuels (33 TWh black liquor and 7 TWh wood fuels). Industry-wide fossil fuel consumption was 7 TWh, used mainly for CHP, lime kilns, and generation of steam for paper production. 20 TWh electricity was consumed, of which around 16 TWh was purchased and 4 TWh generated with internal CHP [13,14]. In 1997, the CO₂ emissions from fossil fuel combustion were 2.4 Mt, contributing to approximately 4% of the Swedish net CO₂ emissions. Between 1990 and 1997, the CO₂ emissions per tonne paper and market pulp increased by 20%, mainly due to a higher fuel oil consumption. The increase in fuel oil consumption can be explained by a rise in production during the same period, whereby fuel oil was used as marginal fuel to satisfy the increased process steam demand [15].

3. CO₂ emissions from the pulp and paper industry

A simplified description of material and energy flows in the pulp and paper manufacturing process is shown in Fig. 1. The net (fossil) CO₂ emissions come from the following three sources:

- On-site use of fossil fuels
- Use of fossil fuels for the generation of purchased electricity
- Use of fossil fuels for the extraction, manufacturing and transportation of raw materials.

In addition, large quantities of CO₂ are emitted due to the combustion of biomass fuels. However, since the growing stock in Swedish forests has increased steadily since the 1920's it is reasonable to regard the combustion of biomass fuels as CO₂-neutral. The current annual growth is around 100 Mm³o.b./y while the gross felling is around 76 Mm³o.b./year [16]. It is important to note that the energy systems of pulp and paper industries interact with the energy system outside the mills. Hence, changes in the energy utilisation within the industries may affect emissions elsewhere, for example those of fossil-fired power plants.

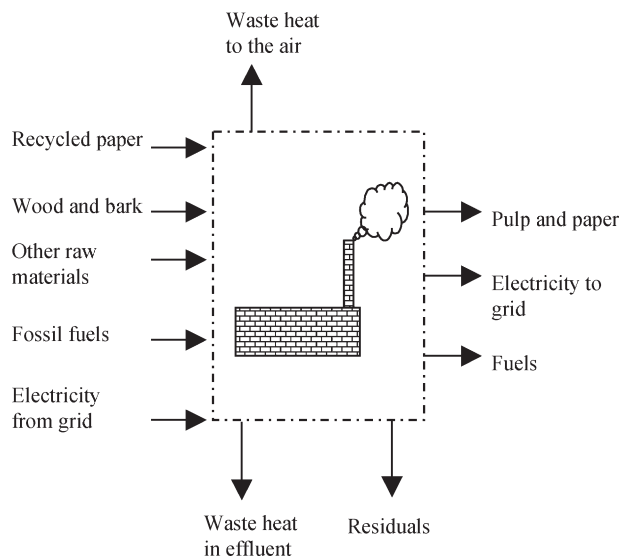


Fig. 1. Energy and material flows in the pulp and paper production process.

The level of CO₂ emissions from the pulp and paper industry can be determined by the six factors of production volume, product mix, energy mix, specific energy utilisation, implementation of CO₂ capture, and specific material consumption. Fig. 2 illustrates how these factors are in turn affected by the external factors of national environment, global market demand, and available technologies.

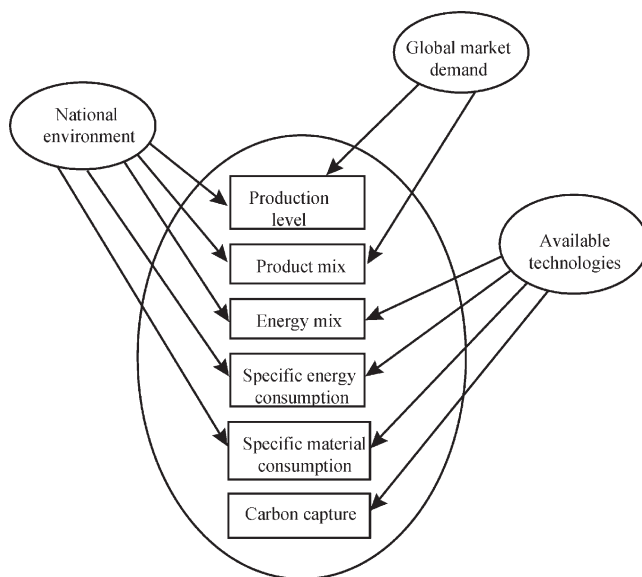


Fig. 2. Internal factors determining the level of net CO₂ emissions from the pulp and paper industry and their relation to external factors.

4. Scope of the present analysis

The present investigation is limited to CO₂ reductions that can be achieved through energy measures in Swedish pulp and paper mills. Both near-term and long-term possibilities are considered. Energy measures should be understood as measures that will have an impact on the overall energy consumption in the energy system without imposing major changes on the mills' main products. The rationale behind this limitation is that the analysed measures should be such that they could be considered by mill management whose range of available options to meet CO₂ reduction requirements is restricted by their customers' demands for specific qualities of pulp or paper. Both available and emerging technologies are included in the analysis.

4.1. Overview of analysed opportunities for CO₂ reductions

It is beyond the scope of this paper to analyse the factors of production level, product mix, and specific material consumption. Furthermore, the national environment is restricted to Swedish conditions. Measures within the scope then belong to the following three categories:

- Decreased specific energy utilisation
- Fuel switch (to less carbon-intensive fossil fuels and biomass fuels)
- CO₂ capture and sequestration.

4.1.1. Decreased specific energy utilisation and fuel switch

Improved heat exchanging, heat pumping, and introduction of new processes with lower heat demand can be used to decrease pulp and paper mills' direct fuel consumption per tonne of product. Compared to today's Swedish average, a model Kraft pulp mill using the most energy efficient available technology reduces the heat demand by approximately 30% according to a recent study [17]. The level of CO₂ reductions that can be achieved through such heat savings depends on the amount of fossil fuels that is used for steam production. Due to the low portion of fossil fuels used for steam production in Swedish pulp and paper mills, reducing steam consumption would save mainly biomass fuel. However, reductions in process heat requirements can create opportunities for increased electricity production since a larger share of the energy in steam generated with available biomass fuels can be converted to electricity. In some cases it is possible to make use of waste heat from mills, e.g. in district heating networks where other fuels can be saved.

Reduced electricity consumption can be achieved e.g. by introducing processes with lower specific electricity consumption in mechanical pulping, reducing oversizing of electric motors, replacement of older pumps, fans and electric motors with more efficient ones, the introduction of variable-speed drives, and minimising leaks in compressed air systems [18,19]. The potential CO₂ reductions are determined by the extent to which the efficiency of the electricity utilisation can be improved and by the specific CO₂ emissions from marginal electricity production.

Increasing electricity production reduces fuel consumption for marginal electricity production in the external power system, and thereby also the associated CO₂ emissions. Large specific CO₂ reductions through increased power production can be achieved if the additional fuel demand in mills is covered with biofuels or waste heat [7–9,20]. If the marginal electricity production in the

external power system originates from fossil-based condensing power, increasing fossil-based CHP using CC or gas turbine simple cycles can lead to CO₂ reductions through improving the overall efficiency of the fuel energy utilisation [4,11].

Through fuel switching, CO₂ emissions from the pulp and paper industry can be reduced by substituting fossil fuels with biofuels or with fossil fuels that have a lower carbon content (e.g. from coal to natural gas). Refined biofuels, such as pellets or liquid fuels, can also be produced with woody biomass or black liquor as feedstock [7–9,21]. The refined fuels produced can then be used to displace fossil fuels and reduce emissions in or outside pulp and paper mills.

4.1.2. CO₂ capture and sequestration (CCS)

CO₂ that would otherwise be emitted to the atmosphere can be captured and sequestered so that it does not reach the atmosphere. CCS will be most economically feasible where there are large emissions of CO₂ from one source and the annual operating time is long. In Swedish pulp and paper mills, therefore, reducing CO₂ emissions through CCS is feasible in connection with the energy recovery from black liquor [8,22]. Technologies for CO₂ capture are commercially available, but may of course be improved. Methods for CO₂ sequestration in geological formations, or in the oceans, still need to be further investigated regarding its reliability and safety of long-term sequestration. Swedish pulp mills are generally located near harbours, which is a prerequisite for economically feasible tanker transportation of liquefied CO₂ to sites for sequestration underground or in the ocean.

5. Methods

5.1. Selection of alternatives studied and data sources

The selection of alternatives is aimed to include those measures that can contribute substantially to reductions in CO₂ emissions. The selection of measures to be included in the study was based on published energy statistics for the Swedish pulp and paper industry and an initial assessment of available technical alternatives. More detailed calculations of reduction potentials and reduction costs were then carried out according to the principles described below. Data for the calculations were obtained from published energy statistics, literature and communication with industry representatives.

5.2. Calculation of CO₂ reductions

For the technical measures studied, we considered emission changes that arise on site as well as outside the boundary of the industry ('global CO₂ reductions'). The following definition of global CO₂ emission reductions was used:

$$\begin{aligned}
 (\text{Global CO}_2 \text{ emission reduction}) = & (\text{Change in emissions from the mill}) + \\
 & (\text{Change in emissions from the external power system corresponding to the change} \\
 & \text{in net power exchange between the mill and the grid}) + \qquad (1)
 \end{aligned}$$

(Change in emissions from external energy utilisation corresponding to fuel and/or heat exported from the mill)

Specific values used to calculate CO₂ emissions from energy conversion are presented in Table 1. Only primary emissions from fuel combustion were considered. This implies an underestimation of the benefits of biomass fuels compared to fossil fuels, because fossil fuels have larger secondary emissions (see footnote Table 1). This is however within the margin of error for the overall results. For marginal electricity production, two alternative emission levels have been used, based on marginal electricity supply from coal-fired power plants and natural gas-fired combined cycles (NGCC), respectively.

5.3. Calculating the cost of CO₂ reduction

The net annual cost of a CO₂ reduction alternative has been defined as:

$$\begin{aligned} \text{Net annual cost} = & \text{Fixed annual capital charge} + \text{Extra O\&M costs} \\ & - \text{Extra O\&M credits} \end{aligned} \quad (2)$$

The following definition of the cost of CO₂ reduction (COR) (US\$/t CO₂) has been used:

$$\text{COR} = \text{Net annual cost} / \text{Net annual global CO}_2 \text{ reduction} \quad (3)$$

Requirements for high financial returns often act as an economic barrier that prevents the industries themselves taking CO₂ reducing measures. From society's point of view longer pay-off times

Table 1
Energy prices, excluding tax, [23,24] and specific CO₂ emission levels

Fuel	Price (US\$/MWh)	CO ₂ emissions ^a (t CO ₂ /MWh)
Wood fuel	11	0 ^b
Wet bark	8	0 ^b
Light fuel oil	10	0.27
Heavy fuel oil	6	0.27
Petroleum gas	13	0.23
Natural gas	10	0.20
Methanol from biomass	23	0 ^b
Petrol	Not used	0.26 ^c
Electricity	20	0.85 ^d /0.34 ^e

^a Values are based on the primary emissions from fuel combustion. Emissions due to fuel extraction, transportation, and refinement are not included. In Sweden, wood-based fuels require a fossil-energy input of around 4% of their energy value before they are burned. Corresponding figure for fuel oil is 12% [25].

^b When new biomass grows, CO₂ corresponding to CO₂ released from biomass fuel combustion is absorbed.

^c For the displacement of petrol with biomass-based methanol, a methanol-fuelled engine has been assumed to be 10% more efficient than a petrol-fuelled engine [26].

^d Coal-fired power plant with 38% electrical efficiency.

^e NGCC with 60% electrical efficiency.

and lower discount rates can generally be accepted. The fixed annual capital charge has been calculated for two alternative cases. In the first case, representing an industrial valuation of capital, a depreciation time of 3 years and an interest rate of 15% have been used. In the second case, representing a societal valuation of capital, a depreciation time of 15 years and an interest rate of 6% have been used. For capital costs a scaling factor of 0.7 has been used. Using the Chemical Engineering Plant Cost Index [27], all capital costs have been adjusted to the cost level of 2000. Extra operating and maintenance (O&M) costs (Eq. (2)) are additional expenditures for personnel, maintenance and energy. Extra O&M credits are additional energy incomes and reduced expenditures for personnel, maintenance and energy. Swedish market energy prices excluding taxes used in the study are presented in Table 1.

6. The studied alternatives

In this section, we present the assumptions that have been made in calculating the reduction potentials and COR for the studied alternatives. Table 2 presents the estimated full technical potential of the respective alternatives in the Swedish pulp and paper sector based on the present production volumes. The data that have been used to calculate the COR are also presented in Table 2. The data in Table 2 are commented upon in Appendix A.

7. Results

Using cost-supply curves, Figs. 3 and 4 illustrate mean values of the calculated potential CO₂ reduction and COR for the analysed alternatives. Fig. 3 shows the results for commercially available technologies, and Fig. 4 shows results for emerging technologies based on black liquor gasification (BLG). In Fig. 3, alternative B is not included because it has a significantly higher cost than alternative K and the two alternatives could not be implemented together in the same mill. The results differ considerably depending on the origin of marginal electricity. In the case with marginal electricity from coal-fired power plants, the accumulated reduction potential of the commercially available technologies analysed is around 8 MtCO₂/y. The largest contributions are from electricity conservation (C&D) and increased electricity production through improved utilisation of the present process steam demand for CHP (E&F). For an industrial valuation of capital, around 1.2 MtCO₂/y can be saved at negative cost, while 5 MtCO₂/y can be saved at negative cost if a societal valuation of capital is applied. The order of the alternatives from lowest-cost to highest-cost (illustrated by the curves) depends on the assumed capital valuation. This is explained by variations between the alternatives regarding the relative importance of fixed (capital) and variable (O&M) costs.

In the case with marginal electricity from NGCC, the results are less in favour of alternatives that reduce electricity consumption or increase electricity production. The accumulated reduction potential of the analysed commercially available technologies is 3.3 MtCO₂/y. The largest contributions are from electricity conservation (C&D), increased electricity production through improved utilisation of the present process steam demand for CHP (E&F), and fuel substitution

Table 2
Assumed technical and economic performance for studied alternatives

Alternative	Annual potential in Sweden	Extra capital cost	Extra O&M costs	Extra O&M credits
(A) Reduced process steam requirements: Utilisation of surplus steam for additional power production in Kraft pulp mills	0.4 TWh _e	0.3 MUS\$/MW _e [28]	0	Additional electrical output
(B) Increased heat integration: Utilisation of surplus steam for additional power production in Kraft pulp mills	0.2 TWh _e	15 USD/MWh _{process heat saved} [12] 0.3 MUS\$/MW _e [28]	0	Additional electrical output
(C) Electricity conservation: TMP	0.7 TWh _e saved	87–193 US\$/annually saved MWh _e [12,18,29]	0	Saved electricity
(D) Electricity conservation: Pumps, fans, mixers, and other motor systems	3.7 TWh _e saved	35–200 US\$/annually saved MWh _e [12,18,23,29–31]	0	Saved electricity
(E) Increased utilisation of installed steam turbine capacity	0.7–1.0 TWh _e	0–0.2 MUS\$/MW _e ^a [32]	1.1 MW _{biofuel} /MW _e	Additional electrical output
(F) Adjusting steam turbine capacity to present process steam demand	1.3–1.7 TWh _e	0.3–0.5 MUS\$/MW _e ^b [32]	1.1 MW _{biofuel} /MW _e	Additional electrical output
(G) Wood powder-fired superheater after Tomlinson boiler	0.6 TWh _e	0.4 MUS\$/MW _e [33]	Non-energy O&M: 0.04 MUS\$/y ^c , 1.4 MW _{wood powder} /MW _e [33]	Additional electrical output
(H) BLGCC	4.0–5.0 TWh _e	0.05–0.1 MUS\$/MW _{black liquor} ^d [17,34,35]	Non-energy O&M: 5 MUS\$/y ^e [34,35], 0.2 MW _{wood fuel} /MW _{black liquor}	Additional electrical output
(I) BLGCC with pre-combustion CCS ^f	3.0–4.0 TWh _e , 4.5 Mt captured CO ₂	0.13–0.19 MUS\$/MW _{black liquor} ^d [34–36]	Non-energy O&M: 15–19 MUS\$/y ^g [22], 0.2 MW _{wood fuel} /MW _{black liquor}	Additional electrical output
(J) Black liquor gasification with pre-combustion CCS, methanol production and CC ^f	–3.3 TWh _e , 8.7 TWh _{methanol} , 4.5 Mt captured CO ₂	0.15–0.20 MUS\$/MW _{black liquor} ^d [34–36]	Non-energy O&M: 15–19 MUS\$/y ^g [8], 0.2 MW _{wood fuel} /MW _{black liquor} , decreased electrical output	Produced methanol
(K) Electricity production from waste heat	0.3–0.4 TWh _e	1.5–1.7 MUS\$/MW _e [7]	0.15 MUS\$/y ^h [7]	Additional electrical output

Table 2 (continued)

Alternative	Annual potential in Sweden	Extra capital cost	Extra O&M costs	Extra O&M credits
(L) Conversion of lime kilns to biofuels	1.0–1.2 TWh fuel oil substituted	0.5–0.6 MU\$ _{oil} /MW _{oil} substituted [37]	Non-energy O&M: 0.4 MU\$ _{oil} /y [38], 1.3–1.4 MW _{wet biofuel} /MW _{oil} (LHV) [38,39], 0.04 MW _e /MW _{oil} substituted [38]	Saved fuel oil
(M) Substituting fuel oil for biofuels in steam production	1.0 TWh fuel oil substituted	0.2 MU\$ _{thermal} /MW _{thermal}	1.2 MW _{wet biofuel} /MW _{oil} (LHV) [40]	Saved fuel oil

^a Lower value: No additional boiler capacity necessary. Higher value: Additional boiler capacity needed to meet process steam demand.

^b Lower value: Steam turbine only. Higher value: Steam turbine and new boiler capacity needed to meet process steam requirements.

^c Based on a 5.9 MW_{wood powder} unit.

^d Based on predicted costs for commercially mature technology.

^e Based on a 338 MW_{black liquor} unit (LHV).

^f CO₂ penalties due to energy used for CO₂ compression, transportation 700 km to the injection site, and injection into deep storage were considered.

^g Based on a 338 MW_{black liquor} unit (LHV), including compression, transportation and injection of CO₂ (26–37 US\$/t CO₂).

^h Based on a 2–2.6 MW_e unit.

ⁱ Based on gasifier unit replacing a 11 MW oil burner.

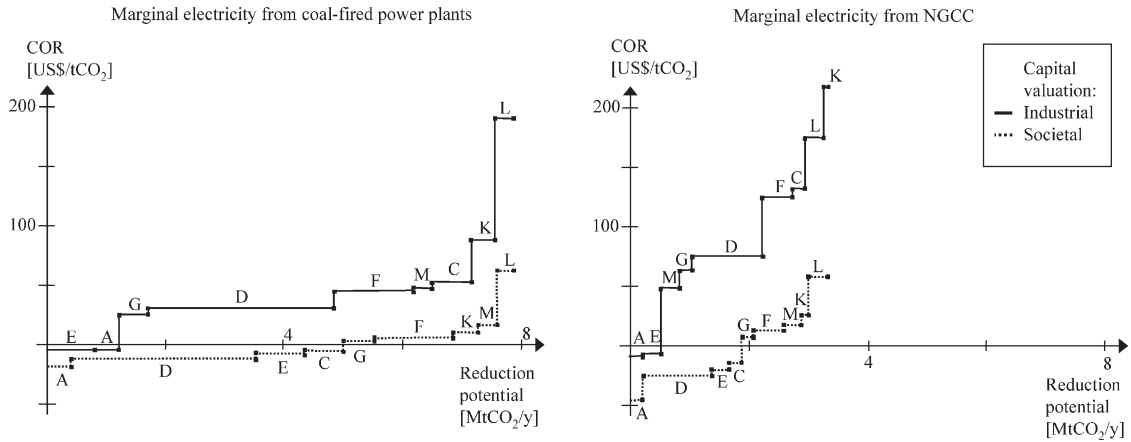


Fig. 3. COR and potential CO₂ reduction of investigated commercial technologies for alternative marginal electricity generation technologies and economic prerequisites.

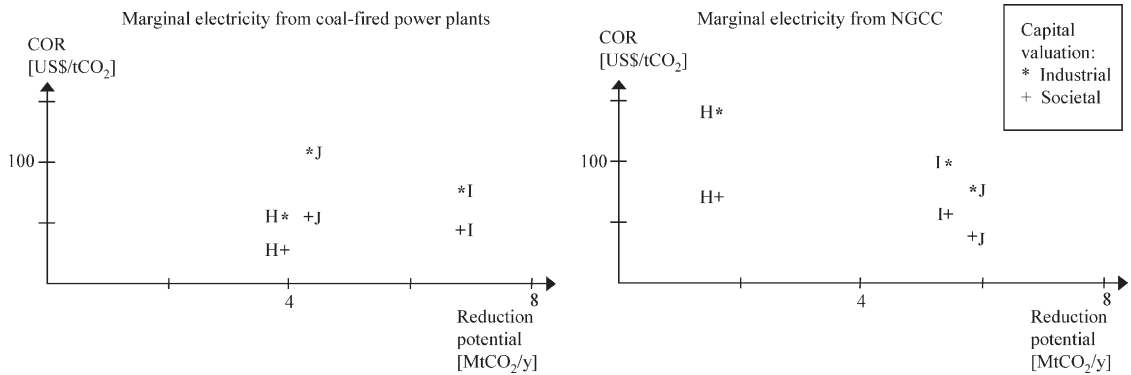


Fig. 4. COR and potential CO₂ reduction of investigated emerging technologies for alternative marginal electricity generation technologies and economic prerequisites. New Tomlinson recovery boiler with a modern steam cycle has been used as a reference.

(L&M). For an industrial valuation of capital, around 0.5 MtCO₂/y can be saved at negative cost, while 1.9 MtCO₂/y can be saved at negative cost if a societal valuation of capital is applied.

The reduction potential and COR of emerging BLG-based technologies is shown in Fig. 4, using a modern Tomlinson recovery boiler with a modern steam cycle with 15% electrical efficiency as a reference. Note that in this case, cost estimates are based on predicted values for commercially mature technologies. The figure shows that the CO₂ reduction potential increases drastically if introduction of BLG is considered (Fig. 4). The reduction potentials of the BLG-based alternatives H, I or J in Fig. 4 can be added to alternatives E and F in Fig. 3, whereby the sum represents the reduction potential of the BLG-based technologies relative to the present situation in Sweden. Thus, pressurised black liquor integrated gasification with combined cycles (BLGCC) represent a reduction potential around 6 MtCO₂/y assuming marginal electricity from coal-fired power plants, or 2.4 MtCO₂/y assuming marginal electricity from NGCC. Further reductions of around

3.8 Mt CO₂/y could be achieved through combining BLG with CCS (pre-combustion CO₂ capture). Note that BLG cannot be combined with alternative G in Fig. 3 and would, furthermore, have an impact on the reduction potential of alternatives A, K, and L.

COR has been calculated using market energy prices excluding taxes, and can be interpreted as a CO₂ charge (or subsidy) which would allow alternatives to break even economically. It is important to note that no additional cost has been included for creating the infrastructure necessary to substitute petrol with methanol in the assessment of alternative J.

7.1. Sensitivity analysis

The COR and potential reduction illustrated in Figs. 3 and 4 are mean values based on the assumed data presented in Table 2. The uncertainties in the assumed data (Table 2) lead to a range in the results, from a lowest to a highest calculated value for the respective alternatives. Fig. 5 shows the full range of COR calculated for each individual energy measure assessed. The COR are shown for four different combinations of marginal electricity source and capital valuation.

Energy prices have a great influence on the COR. Therefore, we have chosen to investigate the influence of the electricity price. In Fig. 5, the COR values are shown for the electricity prices 20 and 50 US\$/MWh. The sensitivity analysis shows improved economic feasibility of most analysed measures when the electricity price increases.

The particularly large variation in values for electricity conservation is explained by the fact that these alternatives cover several different technologies that have been grouped together. Furthermore, the data used for these alternatives are from a large number of reported cases and the cost of implementing the technologies varies widely from facility to facility, size of the project etc. One may notice relatively small variations in COR with electricity prices when coal-fired power plants are the source for marginal electricity. In contrast, when NGCC is the marginal electricity source, there are large variations in some of the measures. This is due to the definition of COR (net annual cost/net annual global CO₂ reduction). The net annual cost is not affected by the source of marginal electricity, while the net CO₂ reduction is affected. Thus, when the

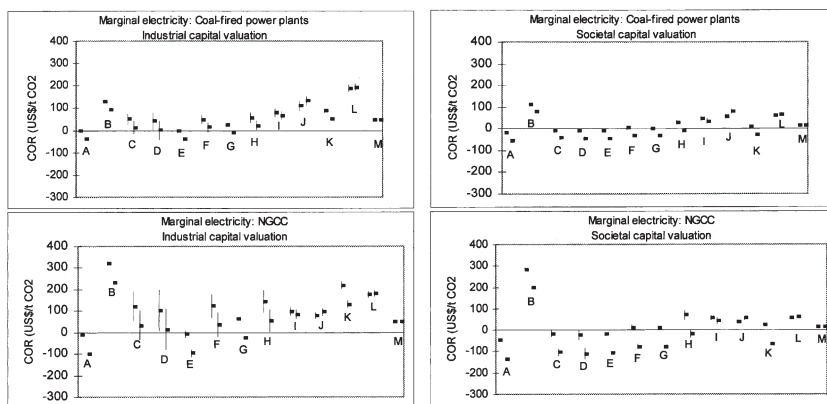


Fig. 5. COR for the electricity prices 20 and 50 US\$/MWh, respectively. For each alternative, the full range of the calculated COR is shown given the assumed performances from Table 2.

calculated range of net annual cost for one given alternative is divided by a smaller net CO₂ reduction (NGCC case), the range of COR becomes larger for this case compared to a case where it is divided by a larger net CO₂ reduction (coal-based power case).

8. Potential contribution to Swedish Kyoto Protocol compliance

According to the Kyoto Protocol Sweden also has obligations to restrict CO₂ emissions. (Under the EU umbrella goal for the Kyoto Protocol, Swedish CO₂ emissions can grow by 4% for the first commitment period.) This paper has shown that there are technical alternatives displaying considerable CO₂ reduction potentials in the pulp and paper industry. Introduction of BLGCC could reduce the net CO₂ emissions by around 9% if marginal electricity from coal-fired power plants were displaced (based on the Swedish net emissions in 1998). Combining BLGCC with pre-combustion CO₂ capture increases this potential to around 15% of the Swedish net CO₂ emissions. If, on the other hand, marginal electricity from NGCC were displaced, the corresponding figures would be 4% and 10%, respectively.

It should be pointed out that under some scenarios even the realisation of the large CO₂ reduction potentials estimated in this paper would not suffice for Swedish compliance with its CO₂ commitments. Today, Swedish nuclear power stations produce approximately 70 TWh_e/y. A political decision has been made to close down nuclear power stations in Sweden. It is realistic to assume that nuclear power closure will lead to a higher electricity price, which may result in strengthened efforts to increase electricity conservation and, furthermore, in new introduction of electricity production based on renewables such as biomass and wind power. However, an increase in fossil-based electricity will probably be required. A scenario of slow nuclear power closure reported by the Swedish Energy Commission [29] suggests 35–40 TWh_e/y from new NGCC in Sweden by 2020. Relative to the 1990 CO₂ emission levels, the total increase in Swedish emissions amounts to 45% under this scenario. The measures analysed in this paper could only partly compensate for such an increase.

The estimated COR of the analysed measures should be compared to the cost of reducing CO₂ emissions in other sectors. One important observation in light of a possible introduction of NGCC power production in Sweden is that Möllersten et al. [22] estimated that pre-combustion CO₂ capture with BLG can be achieved at lower additional cost (around US\$23/tCO₂) compared scrubbing CO₂ from NGCC flue gases (32–57 US\$/tCO₂ [41–43]). The transportation sector is a significant source of CO₂ emissions in Sweden. Swedish net CO₂ emissions could be reduced through the introduction of biomass-based transportation fuels. However, regarding methanol produced from woody biomass, for example, the COR would be higher than for all the alternatives analysed in this paper [9,44]. Bejgrowicz et al. [45] estimated the COR for small-scale hydropower, biomass-based CHP in connection to district heating networks, and wind power. Using depreciation times of 25–40 years and an interest rate of 4%, COR from 25 to 35 US\$/tCO₂ were estimated. A straightforward comparison of these costs to the results of the present study is not possible due differences in the economic methods applied and a lack of information concerning input data.

9. Discussion

The potential CO₂ reduction suggested in this paper is actually larger than the total net CO₂ emissions of the Swedish pulp and paper sector reported by Byman and Sjödin [15]. This is explained by (1) the inclusion of CCS from biofuels in our analysis and (2) differences in the way CO₂ emissions from generation of purchased electricity are calculated. Byman and Sjödin [15] have used the average CO₂ emissions from the Swedish power system (0.02 t CO₂/MWh) to calculate the CO₂ emissions caused by the pulp and paper sector's electricity consumption. This demonstrates the impact of system boundary selection.

The approach that we have used in this paper in accounting for the specific CO₂ emissions from marginal power generation deserves to be commented upon. Electricity is traded between Sweden and other Scandinavian countries and also between Scandinavia and the European continent. Coal-fired condensing power plants supply the highest-cost electricity to the Scandinavian power system the entire year, mainly from Denmark and the European continent [45]. In principle, on a functioning electricity market, it is the electric output from these power plants with the highest operating cost that should be affected by increased or decreased electricity demands. However, due to limitations in transmission capacity between different regions there may be certain constraints to the approach that we have used. It is subject to debate whether today's transmission capacity only allows a portion of the marginal electricity from coal-fired power plants to be eliminated through increased electricity conservation or alternative power generation in Sweden.

If Swedish electricity consumption were to rise above the level that could be supplied with electricity import, new production capacity would be required. It is reasonable to assume, that on a commercial basis marginal electricity would then be produced by NGCC. Increased electricity conservation or alternative electricity production would then displace some of the demand for additional NGCC capacity. There is a trend today towards increased transmission capacity between Sweden and Denmark and the continent. As the capacity to transmit electricity across these borders increases, the potential to displace marginal electricity from coal-fired power plants should increase. Moreover, NGCC can be expected to gradually displace electricity production from coal-based power plants in northern Europe. NGCC may also increase in Sweden due to a planned closure of nuclear power stations. Hence, with increased transmission capacity, the need for larger amounts of coal-based marginal electricity could be eliminated through electricity conservation or increased alternative electricity production in Sweden. In the long term, it is likely that the impact will switch to elimination of marginal electricity from NGCC.

Additional biofuel is required for several of the analysed alternatives. At the most around 8 TWh additional biofuel would be required annually if alternatives requiring additional biofuels were combined and introduced to their full potential. Predictions of the potential to increase sustainable wood fuel extraction in Sweden lie in the range 13–90 TWh/y [46]. This study is based on the present conditions in Sweden, with a potential to increase the sustainable extraction of wood fuels. In a situation with a biofuel shortage, however, biofuel savings could also be credited with a potential CO₂ reduction, as biofuels saved would then be made available for further substitution of fossil fuels [47].

It is also important to note that, while reducing heat consumption in pulp mills in the Nordic countries would save mainly biofuels, larger net CO₂ reductions could be achieved through steam

savings in other countries. For example, the specific fossil fuel consumption of north American pulp and paper mills is substantially higher than Nordic [4,5]. It is also noteworthy that electricity prices have been comparatively low in Sweden for a rather long time, which has provided poor incentives for reductions of electricity consumption. Thus, compared with other technology alternatives, the feasibility of electricity conservation may be unusually favourable in Swedish pulp and paper mills.

This paper investigates ways to reduce the CO₂ emissions through energy measures in Swedish pulp and paper mills while maintaining production volume and product mix. The level of CO₂ emissions from the Swedish pulp and paper sector will depend not only on the extent of CO₂-reducing energy measures taken, but also on the influence of changes in product mix and volume. Virtanen and Nilsson [48] and Weaver et al. [49] analysed the environmental impact of increased paper recycling in the European pulp and paper sector. The results show that increased recycling raises the net fossil fuel demand and thus the emissions of CO₂. Therefore, a balanced mixture of recycling and energy recovery is recommended as a suitable solution since recycling minimises the use of certain resources and emissions, while the use of waste paper for energy recovery minimises the consumption of fossil fuels. Increased production is predicted for the Swedish pulp and paper industry. As a consequence of increased production, biomass-based CHP would increase, but so also would the industrial need for electricity and possibly fossil fuels. The impact of increased industry-wide production on the net CO₂ emissions will therefore be determined by the extent to which additional production is dependent on imported electricity and fossil fuels. This in turn is determined by technological change and the development of the product mix. If the demand increases for products with higher value-added it is likely that the overall specific electricity demand will grow.

10. Conclusions

Although the Swedish pulp and paper industry has successfully reduced its use of fossil fuels there is still a large potential to reduce CO₂ emissions through various technical measures. Among the measures investigated in this paper, increased electricity conservation and increased electricity production in existing combined heat and power systems combine large potential reductions with relatively low CO₂ reduction cost. However, not yet commercially available technology such as black liquor gasification and CO₂ capture and sequestration can raise the potential for CO₂ reductions in the pulp and paper industry substantially. The measures that have been analysed could contribute significantly to Swedish Kyoto Protocol compliance. The paper shows that the role of CO₂ capture and sequestration becomes increasingly important as the specific CO₂ emissions from marginal electricity generation decrease.

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Appendix A

(A) *Reduced process steam requirements*: A Swedish research programme has defined a reference market pulp mill [17], based on the best technology in use in the late 1990s. In the reference mill, the required process steam is reduced from the 1994 Swedish average of 15 GJ/ADt (air-dry tonne pulp) to 11 GJ/ADt. Around one-third of the reduction comprises medium-pressure steam, and two-thirds low-pressure steam. We assumed that replacement of older equipment or production lines spontaneously realises half this potential in Swedish pulp mills thus providing surplus steam that can be used for additional electricity production. The only capital cost considered was the investments required for steam turbines (8 MW_e range units) and condensers.

(B) *Increased heat integration*: A potential to reduce process thermal energy requirements by 1–2 GJ/ADt through increased heat integration in pulp mills has been reported [17]. We considered additional electricity production in Swedish pulp mills, utilising 1 GJ/ADt surplus low-pressure steam supplied through increased heat integration. In this case additional capital cost for thermal energy reductions, additional condensing steam turbine capacity (8 MW_e range units), and condensers was considered.

(C–D) *Electricity conservation*: Electricity is consumed in Swedish pulp and paper mills as follows: 33% for thermo-mechanical pulping (TMP), 55% for pumps, fans, and mixers, 7% for other motor systems, 2% for electric boilers, and 3% for lighting [18]. Based on Sandberg [19], we have considered the following potentials for demand reductions through electricity conservation: TMP: 10%; pumps, fans, mixers, and other motor systems: 30%. In reality, increased electricity efficiency is mostly achieved when older equipment or production lines are replaced. According to Sandberg [19] around 1/3 to 1/2 of the estimated potential for electricity conservation would be realised spontaneously within a 15-year period, whereby no additional cost for the reductions would apply. In this study we have considered the realisation of the entire estimated potential. Costs applied are based on literature data from a large number of previous conservation projects.

(E–F) *Improved electrical efficiency in steam power systems*: The average electrical efficiency of CHP systems in the Swedish pulp and paper sector is around 9% (based on LHV) [14]. Today, existing steam turbines are operated at a low capacity factor due to low electricity prices. Moreover, as production capacities of mills have increased steam turbines have increasingly been bypassed to enable the sufficient supply of steam to the processes. The electrical efficiency that can be achieved is inhibited by material constraints that put restrictions on steam data. We have assumed that 14–15% electrical efficiency (LHV) can be achieved through increasing the time that existing steam turbines are operated, fitting CHP systems (back-pressure turbines and/or boilers) that are dimensioned for the mills' present process steam demand, and replacing old steam turbines with modern turbines that generate more power for the same steam flow.

(G) *Wood-fired superheater after Tomlinson boilers*: Due to corrosive flue gas components in Tomlinson recovery boilers, the pressure and temperature of the steam have to be restricted. This limits the electrical efficiency. Improving pressure and superheating temperature levels is very

costly and difficult in existing units. Improvements are possible when new units are considered or major modernisation is undertaken. However, the electrical output from existing Tomlinson boilers can be increased through externally superheating the steam. Based on Nygaard [33], the increased electrical output due to external superheating from 480°C to 510°C has been calculated compared to a base case. The base case performance is representative of a new Tomlinson boiler with a modern steam cycle.

(H) *Black liquor integrated gasification with combined cycle (BLGCC)*: Emerging technologies for BLGCC have a potential to drastically increase the power-to-heat ratio in CHP compared to conventional steam cycles used with Tomlinson recovery boilers. Based on Berglin et al. [50], we have assumed a 27–30% electrical efficiency and a total efficiency of 72% (LHV). The replacement of Tomlinson boilers with BLGCC is most likely to take place when existing Tomlinson boilers reach the end of their useful life. In those cases new Tomlinson boilers would be required unless BLGCC is introduced. Therefore, we have used a new Tomlinson boiler with a modern steam cycle with 15% electrical efficiency and 80% total efficiency as reference in calculating the CO₂ reduction potential. The capital cost and O&M costs and credits are the difference between BLGCC and a new Tomlinson boiler. Additional biofuel boiler capacity that is required to maintain the heat production when the power-to-heat ratio increases has been included in the capital and O&M costs.

(I) *BLGCC with pre-combustion CCS*: BLGCC can be equipped with removal of CO₂ from the synthesis gas before the gas is used for CHP in a CC. Based on Möllersten et al. [22], we have used data for 90% removal of CO₂ from the synthesis gas downstream the gasifier but upstream the CC and subsequent deep underground storage. An electrical efficiency of 24–27% (LHV) has been assumed. The ‘CO₂ penalty’ due to additional energy demand for CO₂ compression and transportation corresponds to 6–14% of captured CO₂ (depending on the source of marginal electricity production). The 700-km transportation distance from the mill to the injection site that has been used is the average distance from Swedish pulp mills to possible Swedish coastal sites for deep underground storage. The calculation of the COR has been done according to the same principles as for alternative H.

(J) *BLG with pre-combustion CCS, methanol production and CC*: Same as alternative E, but with a methanol reactor after the CO₂ removal. Unreacted gas from the methanol island is used for CHP in a CC. Assumed methanol, electrical, and total efficiencies are 24–27%, 7–9% and 80% (LHV), respectively [8]. The calculation of the COR has been done according to the same principles as for alternative H.

(K) *Electricity production from waste heat*: Isaksson [7] reports a potential to use waste heat from recovery boilers and lime kilns in chemical pulp mills as the energy source for electricity production with low-temperature power cycles (Kalina or Organic rankine cycles). Based on Isaksson [7] an electrical efficiency of 16–17% (LHV) has been assumed.

(L) *Conversion of lime kilns to biofuels*: Three Swedish lime kilns were successfully converted to biofuels (gasified or as wood powder) in the mid-1980s due to high oil prices, but most of the lime kilns have not been converted. Based on Lyytinen [51] it has been assumed that substitution of 75–85% of the fuel oil in oil-fired lime kilns is realistic.

(M) *Substituting fuel oil for biofuels in steam production*: The main use for fuel oil is in steam boilers, which amounts to around 4 TWh/y. It would not be feasible to substitute the portion of fuel oil which is used as back-up fuel, supporting fuel, and for peak-load operation. Based on [40], it has been assumed that 25%, or 1 TWh, of this fuel oil can be substituted for biomass.

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