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Implications of process energy efficiency improvements for primary energy consumption and CO_2 emissions at the national level

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ABSTRACT

The improvement of energy efficiency is seen as one of the most promising measures for reducing global CO_2 emissions. However, the emission reduction potential may seem different from the industrial plant and policy-maker's perspectives. This paper evaluates the influences of process heat conservation on CHP electricity production, primary energy consumption and CO_2 emissions from both the mill site and national perspectives. The results indicate that heat conservation in an industrial process may lead to varying results in primary energy consumption and CO_2 emissions, depending on the form of marginal heat production used at the mill site. In the CHP process, reduction of the heat load lowers electricity production, and this reduction may have to be compensated for at the national level. Therefore, the energy conservation potential in industry has to be evaluated by taking into account the connections to the outside society, which means that a wider system boundary than a mill site has to be used. This study demonstrates by theoretical analysis and case mill studies the magnitude of the effects of system boundary definition when evaluating the contribution of an individual energy efficiency investment towards fulfilling the commitment to reduce CO_2 emissions at the national level.

1. Introduction

The improvement of energy efficiency is seen as one of the most promising measures for reducing global CO_2 emissions. The European Union has set an indicative objective to reduce its primary energy consumption by 20% by 2020 compared to projected 2020 energy consumption in order to reduce emissions and dependence on imported fossil fuels [1]. It is estimated that in Finland the primary energy consumption should be reduced by 14% from the 2005 level in order to attain this target (reduction of 53 TWh [2]).

An IEA country report [3] shows that Finland is known for its energy efficiency, especially for the high share of combined heat and power (CHP) production and good results achieved by voluntary energy conservation agreements between the Finnish authorities and industrial companies. By the end of 2006, under the voluntary energy conservation agreement for industry, the annual conservation of heat/fuel and electricity were 5.2 TWh/y and 1 TWh/y, respectively [4]. So, it seems easier to find options for conserving heat than electricity in Finnish industry. This is the case also in the pulp and paper industry, which is responsible for about a half of industrial energy consumption in Finland.

Typically, Finnish pulp and paper mills are highly integrated. Whereas modern stand-alone pulp mills are nowadays more than self-sufficient in energy, integrated pulp and paper mills need external energy sources to meet their energy requirements. Usually, the heat demand of a mill is covered by on-site heat production, but often at least part of its electricity requirement has to be purchased from the grid. In Finland, on-site energy production is mainly based on energy-efficient industrial CHP production, and therefore energy conservation actions might influence the demand for grid-based electricity, too.

Depending on the design of the power plant, heat conservation can lead to either reduced or increased electricity output from an industrial CHP plant. In the case of a back-pressure plant, reduced heat output leads to reduced electricity output, which enables fuel conservation at the mill site but at the same time increases the demand for grid-based electricity. On the other hand, if there is a condensing unit in the steam turbine, heat conservation enables increased electricity output from the industrial CHP plant, and therefore less grid-based electricity is needed, i.e. from a wider perspective the effects seem similar to electricity conservation at the mill. In some cases, the pulp and paper mills supply district heat to nearby communities, and so it might be possible to increase sales of district heat as a consequence of reduced heat consumption at the mill. When a heat conservation action at the mill affects the supply of electricity and/or district heat between the mill site

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Nomenclature

CCGT	combined cycle gas turbine	HRSG	heat recovery steam generator
CHP	combined heat and power	LCA	life cycle assessment
CO_2	carbon dioxide	PEC	primary energy consumption
EU ETS	European Emissions Trading Scheme	α	power-to-heat ratio
HFO	heavy fuel oil	η	efficiency
HOB	heat-only-boiler		

and the outside society, primary energy consumption and CO_2 emissions change outside the mill site, too.

Scientific studies have considered the energy efficiency and CO_2 emissions of the pulp and paper industry. Many of them have come from countries with significant pulp and paper production, such as the USA, Sweden and Finland. In the Nordic countries, CHP production is widely used in the pulp and paper industry, but in the USA it is increasing being seen as an important technology to improve energy efficiency and reduce CO_2 emissions. Therefore, the studies made in the USA have focused on the potential of CHP, whereas the Nordic studies have concentrated on improved process integration of industrial plants and existing CHP plants.

Martin et al. [5] identified almost 50 commercially available technologies and measures to reduce energy consumption and CO_2 emissions in the US pulp and paper industry. In this study, the carbon dioxide emissions and the emission reduction potential of different measures were calculated by using average CO_2 emission factors defined for different sub-processes. Khrushch et al. [6] defined the CO_2 emission reduction potential in the US chemicals and pulp and paper industries by applying CHP technologies. In this study, the emission reduction was evaluated based on the assumption that CHP electricity production replaces electricity purchased from the grid. So, significant emission reduction potential at negative cost was found.

In Sweden, Ecocyclic pulp milling, including energy efficiency and the greenhouse effect, was studied in the KAM Programme in 1996–1999 [7]. In this study it was found that the more efficient use of wood-based fuels enables the replacement of fossil fuels and thus the avoidance of CO_2 emissions. In addition, it was found that the net amount of avoided CO_2 emissions varies according to the marginal production of electricity. Axelsson [8] found that the opportunities for energy and cost savings and emission reductions in industry are heavily dependent on the existing design of the process and the energy system, the electricity-to-fuel price ratio, and the emissions of purchased electricity production.

Laukkanen [9] studied process integration in the pulp and paper industry, including the influences of steam saving on CHP production. He found that steam saving is not always profitable if the conserved heat cannot be somehow utilised, e.g. for the production of district heat or additional electricity from a condensing unit in the steam turbine. Therefore, the energy utility system and the production plant should be optimised together. According to Axelsson and Berntsson [10] heat conservation can, depending on energy prices, be realised as fuel savings or increased electricity production by investing in a new steam turbine. In a market pulp mill, fuel savings would require additional investments in the extraction of lignin from black liquor.

In some pulp and paper industry related studies made before the introduction of EU's Emissions Trading Scheme (EU ETS), both the mill site emissions and emissions from the production of purchased and exported energy were included in the analyses [7,8,11–13]. However, the operators of industrial plants are nowadays more interested in their own emissions than external emissions because under the EU ETS, introduced in 2005, the emission allowances have been allocated and CO_2 emissions are monitored at the installation level. From the industrial plant perspective, CHP production at the mill site increases fuel consumption and CO_2 emissions compared to separate production of heat. Therefore, the owner of the CHP plant needs additional emission allowances, which increases the costs. Since cost-effective production and profit maximisation are usually the main goals of industrial operation, the attractiveness of CHP production has to be ensured by proper energy policy and supporting mechanisms. Therefore, many EU countries have supported CHP within their national allocation plans due to its favourability from the wider perspective. For example, double benchmarking and CHP bonuses have been applied in order to promote CHP [14]. In Finland's allocation plan, separate CHP sectors for industry and communities were established, and more free allowances were given to those sectors than to the condensing power production sector.

A wider perspective can be considered by widening the system boundary. The importance of clearly defining the system boundary has been noted in some industry related energy efficiency studies, such as Larsson et al. [15] and Tanaka [16]. In addition, wider system boundaries have been used when the integration of industrial energy production into the district heating system of outside society has been studied in Sweden [17,18]. These studies have focused on evaluating the increase in energy efficiency and the reduction in CO_2 emissions in integrated systems.

The effects of different system boundary definitions on CO_2 emissions have also been studied in sectors other than manufacturing. One example is Rolfsman [19], who studied energy measures in buildings in Norrköping, Sweden. He found that heat conservation by means of new types of windows or increasing the insulation of buildings connected to the district heating network may increase CO_2 emissions. If heat is produced with CHP, electricity production declines with reduced heat load. If the lost electricity is replaced with the form of marginal production in the Nordic electricity market, i.e. coal condensing power, CO_2 emissions will rise. In the real estate sector, the wider system boundary has already been taken into account in legislation and standardisation. The standard EN 15603 [20] describes the methodology for calculating the integrated energy performance of buildings in accordance with the Energy Performance of Buildings Directive [21] and presents informative values for primary energy factors and CO_2 production coefficients.

The purpose of this paper is to compare the effects of process heat conservation in the Finnish pulp and paper industry at the mill site and national levels. The idea is to test whether it is possible that heat conservation at the mill site leads to increased CO_2 emissions, i.e. whether the effect found by Rolfsman [19] is possible also in the case of industrial CHP production.

2. Materials and methods

In this study the effects of process heat conservation on industrial CHP electricity production, primary energy consumption (PEC) and CO_2 emissions were studied with different process constructions. The effects were studied at both the mill site and national level since the energy system of the mill is typically integrated into the society. Different definitions used for the system boundary are presented in Section 2.1. Section 2.2 describes the methodology for evaluating changes in primary energy consumption and CO_2 emissions at the national level.

This study combines theoretical analysis with case mill studies: (1) in the theoretical analyses, simplified power plant processes were simulated with Solvo®, and (2) in the case mill studies, real energy conservation data from five Finnish pulp and paper mills were analysed. The methodologies used in the theoretical analysis and case mill studies are presented in greater detail in Sections 2.3 and 2.4, respectively.

2.1. System boundaries

Fig. 1 presents the system boundaries considered in this study. The mill in Fig. 1 can be either a market pulp mill producing only pulp or an integrated pulp and paper mill (an integrate) producing both pulp and paper. In addition, the mill site includes the energy production plants at the site. Energy production is typically based on CHP production, but heat-only-boilers (HOBs) can be used to provide additional peak-load capacity. The mill provides biofuels such as bark and black liquor to the energy production plant. The mill site interacts with the society through its raw material, fuel and energy streams, so decisions made on a mill site level also have effects on a national level.

Typically, market pulp mills are self-sufficient in energy. Some mills can even sell biofuel (bark), surplus electricity or district heat outside the mill site. On the other hand, the energy production plant of an integrated mill has to buy additional electricity from the market and to some extent also external fuels such as natural gas, heavy fuel oil, coal or peat. The demand for external fuels depends on the process and products of the pulp and paper mill. Emissions from the mill site also have implications at the national level or, for example in the case of CO_2, even globally.

2.2. Evaluation of changes in primary energy consumption and CO_2 emissions at the national level

The evaluation of changes in CO_2 emissions at the national level is based on the following methodology presented by Möllersten et al. [11] for defining the global CO_2 emission reduction:

Global CO_2 emission reduction
= Change in emissions from the mill
+ Change in emissions from the external power system corresponding to the change in net power exchange between the mill and the grid + Change in emissions from external energy utilisation corresponding to fuel and /or heat exported from the mill.

In this paper a simplified formulation for change in the national CO_2 emissions ($CO_{2\ National}$) is used:

$$CO_{2\ National} = CO_{2\ Mill} + CO_{2\ Grid} + CO_{2\ Heat} \quad (1)$$

where $CO_{2\ Mill}$ is the change in CO_2 emissions from the mill site, $CO_{2\ Grid}$ is the change in CO_2 emissions from grid-based electricity production and $CO_{2\ Heat}$ is the change in CO_2 emissions due to heat/fuel export from the mill.

Analogically, the change in national primary energy consumption ($PEC_{National}$) can be calculated as follows:

$$PEC_{National} = PEC_{Mill} + PEC_{Grid} + PEC_{Heat} \quad (2)$$

where PEC_{Mill} is the change in primary energy consumption at the mill site, PEC_{Grid} is the change in primary energy consumption of grid-based electricity production and PEC_{Heat} is the change in primary energy consumption due to heat/fuel export from the mill.

The changes in CO_2 emissions and PEC from the mill site were calculated based on the mill's marginal heat production. Changes in electricity consumption and production at the mill site affect the purchase of electricity between the mill site and the grid. The way in which the purchased electricity is assumed to be produced affects the emissions considerably [12,17]. Sometimes the average

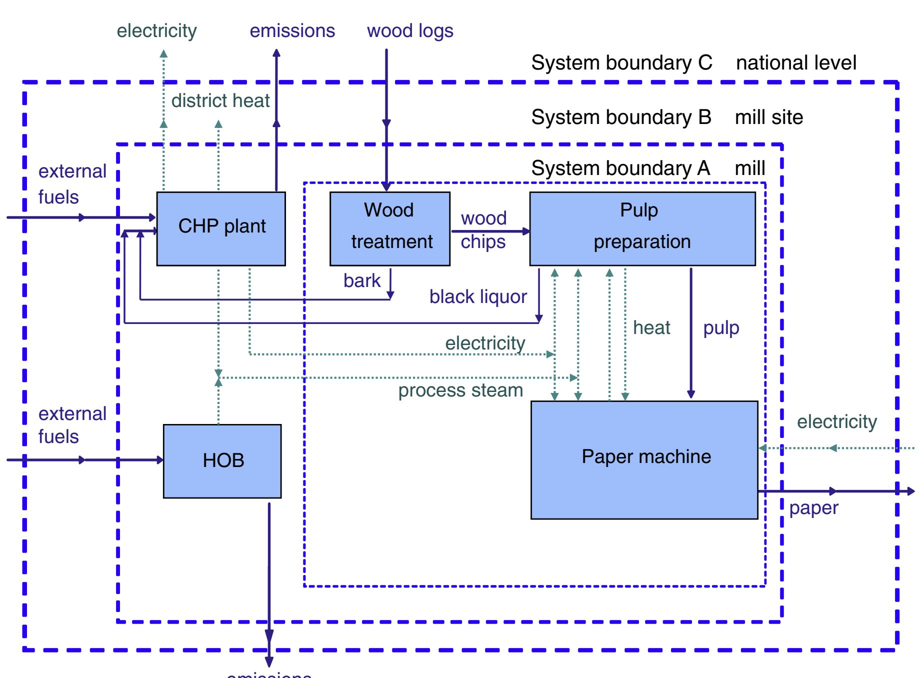

Fig. 1. System boundaries of a pulp and paper mill.

grid electricity production is used, which is typically the case in life cycle assessment (LCA) [17]. Also, Motiva's instructions for calculating the CO_2 emissions of an individual energy consumer in Finland suggest the use of the average emission factor for grid-based electricity production if the real emission factor for purchased electricity is not obtained from the electricity supplier [22]. However in economics, rational decisions are based on weighting up marginal costs and benefits [23]. There is a common view that the marginal approach should be used for change-oriented studies, since the marginal data represent the effects of a small change in the output of products or services [17,24]. Therefore, in this study the changes in purchased electricity were assumed to influence the amount of the marginal electricity production in the electricity market. This approach is also supported by the fact that electricity pricing in the Nordic electricity markets is based on the production costs of a marginal unit. The same approach has been used in many previous studies [7,11,18]. Coal-based condensing power is marginal in the Nordic electricity market most of the time, and therefore it is used as a form of marginal electricity production in this study. For longer time perspectives, natural-gas-based CCGT is expected to be the form of marginal power production [18] and therefore the sensitivity of the results with respect to the emission factor for purchased electricity is included in Sections 3.1 and 3.2.

If heat conservation increases the production of district heat or biofuel export from the mill site, it is assumed to replace separate district heat production based on heavy fuel oil. In reality, 74% of district heat production in Finland was based on CHP production in 2008. Natural gas, coal, peat and wood represent together 92% of the fuels used to produce district heat and CHP, whereas the share of oil is only 4.6% [25]. However, in addition to CHP plants, energy companies usually have oil-based or natural-gas-based heat-only-boilers as peak and reserve capacity. Although exported biofuel is combusted in solid fuel boilers, the fuel replaced at the annual level is a marginal fuel of the energy company in question. The marginal fuel differs case by case, and may be natural gas, peat or heavy fuel oil. HFO-based separate production is selected here because it is a potential option throughout Finland. If natural-gas-based production was selected instead, the reduction in CO_2 emissions would be lower. However, the case would be opposite if peat was selected. The sensitivity of the results with respect to the emission factor for replaced district heat is dealt with in Section 3.1.

Table 1 shows the efficiencies of the different production forms and emission factors used in this study. The efficiencies presented here represent typical values for modern energy production plants in industry. Official emission factors for fuels in Finland [26] were used. In this study, neither electricity transmission losses nor life cycle effects were taken into account when the CO_2 emission factor for grid-based electricity was defined.

2.3. Theoretical analysis

In the theoretical analysis the effects of process steam conservation on four different forms of marginal heat production at the mill site were studied. For each form of heat production, there are different operational options to realise the benefits of process steam conservation. Table 2 summarises the modelled forms of marginal heat production with different operational options.

The forms of marginal production modelled here cover the marginal fuels typically used in the Finnish pulp and paper industry. Both peat and biomass are often fired together in one solid fuel boiler, and oil-based HOBs are used as peak and reserve capacity. However, in this study the energy production processes have been simplified so as to avoid speculation about seasonal variation in the forms of marginal production and the marginal fuels used in

Table 1
Efficiencies and emission factors used.

Energy source	η_{Mill} (%)	η_{Grid} (%)	η_{Heat} (%)	$CO_{2\ Mill}$ (t/MWh_{Fuel})	$CO_{2\ Grid}$ (t/$MWh_{Electricity}$)	$CO_{2\ Heat}$ (t/$MWh_{District\ Heat}$)
Heavy fuel oil (HFO-based HOB)	93			0.284		
Natural gas (CCGT,CHP)	90			0.198		
Peat (CHP)	88			0.381		
Biomass (CHP)	85			0.000		
Coal (CHP)	88			0.341		
Electricity, coal condensing		40			0.851	
District heat, biomass-based HOB			88			0.000
District heat, HFO-based (HOB)			93			0.305

Table 2
Modelled forms of marginal heat production with different operational options.

Forms of marginal heat production at the mill site	Operational option
1. Heavy fuel oil-based heat only boiler (HOB)	(a) Reduction of heavy fuel oil consumption at the mill site
2. Combined Cycle Gas Turbine (CCGT) plant	(a) Increase in district heat production at the mill site (b) Reduction of natural gas consumption at the mill site (auxiliary burner in the HRSG) (c) Increased electricity production from a condensing unit in the steam turbine
3. Peat-fired CHP plant	(a) Increase in district heat production at the mill site (b) Reduction of peat consumption at the mill site (c) Increased electricity production from a condensing unit in the steam turbine
4. Biomass-fired CHP plant	(a) Increase in district heat production at the mill site (b) Reduction of biomass consumption at the mill site (exported biomass is assumed to replace heavy fuel oil in district heat production outside the mill site) (c) Increased electricity production from a condensing unit in the steam turbine

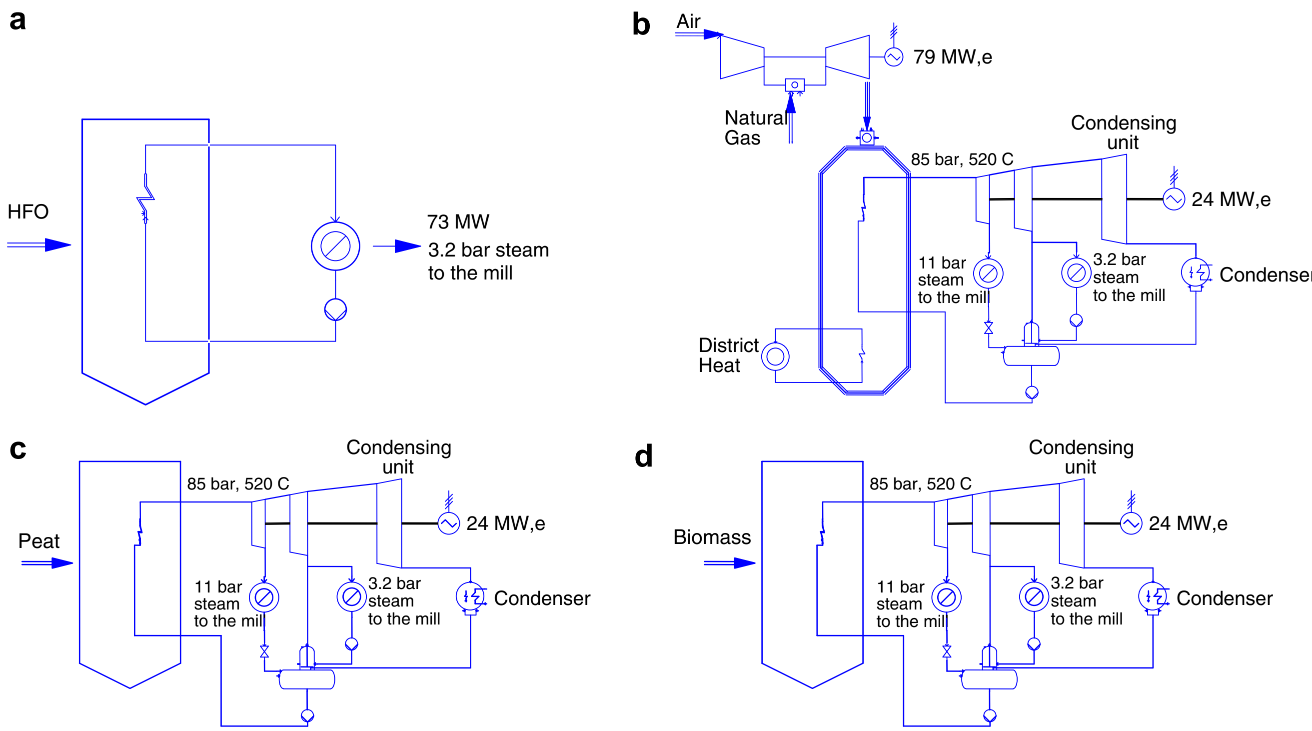

Fig. 2. Four alternative forms of marginal heat production at the mill site: (1) Heavy-fuel–oil-based HOB (2) CCGT (3) Peat-fired CHP plant (4) Biomass-fired CHP plant.

multi-fuel boilers. Actually, for example the results obtained here for the peat-fired CHP could be utilised in the case of a multi-fuel boiler with peat as the marginal fuel. The simplified process charts for the different forms of marginal heat production at the mill site are presented in Fig. 2.

The theoretical analysis is based on process modelling made by Solvo®, which is a commercial software application developed by Fortum for modelling and simulating the heat balances of a power plant in steady state conditions. The software can be used for modelling turbine and boiler plants, CHP plants as well as pulp and paper and gasification processes.

First, the demand for low-pressure process steam (3.2 bar) was set to 73 MW and the energy production of different operational options was modelled. Then, the effects of process steam conservation were studied by assuming that the consumption of low-pressure steam can be reduced by 2 MW (2.7%). The annual changes were calculated on the basis of an estimated peak load duration of 8000 h per year, which is a typical operation time in the Finnish pulp and paper industry.

A typical isentropic efficiency of 85% was used for the steam turbine. In the operational options 2.c, 3.c and 4.c the condenser pressure was set to 0.1 bar, which is equivalent to a moisture content of 12% after the turbine's condensing unit.

2.4. Case mill studies

The energy production systems in real-world pulp and paper mills are more complicated than the theoretical examples shown in Fig. 2. For example, multi-fuel boilers can act as marginal heat producers and the form of marginal heat production can be different in winter and summer. In this study five Finnish pulp and paper mills with different forms of marginal heat production were used as case mills (Table 3). These case mills are well representative of the various forms of energy production in Finnish industry. Another criterion for the selection of these case mills was the availability of high-quality energy analysis reports, including detailed information on energy conservation potential. The mills are designated with the letters A through E. Mill E is a market pulp mill and the other four are integrated pulp and paper mills.

The energy analysis reports of the mills' power plants were used as background information for the case mill studies. In the energy analysis reports the results of energy audits made under the

Table 3
Case mills and their forms of marginal heat production, marginal fuels and possibilities to control heat production.

Mill	Market pulp mill/integrate	Form of marginal heat production	Marginal fuels	Possibilities to control heat production
A	Integrate	CCGT (CHP)	Natural gas	Auxiliary burner in the HRSG Auxiliary condenser District heat sales
B	Integrate	Solid fuel boiler (CHP)	Peat 50%, HFO 50%	Auxiliary condenser District heat sales
C	Integrate	Solid fuel boiler (CHP)	Biomass 70%, Coal 30%	Auxiliary condenser Steam accumulator District heat sales
D	Integrate	Solid fuel boiler (CHP) Natural gas boiler (HOB)	Biomass (increase of fuel consumption) Natural gas (fuel conservation)	Auxiliary condenser
E	Market pulp mill	Solid fuel boiler (CHP)	Biomass	Condensing unit in the steam turbine

voluntary energy conservation agreement scheme for industry had been collected. The energy analysis reports included lists of feasible investments in energy conservation. The investment costs, pay-back periods, amount of saved electricity and fuels, increased electricity production as well as CO_2 emission reduction were presented in the reports.

In the case mill studies the mill site effects of feasible energy conservation measures on electricity and fuel consumption, on-site electricity production and CO_2 emissions were collected from the energy analysis reports. Then the primary energy consumption and CO_2 emissions at the national level were calculated using the principles presented in Section 2.2.

3. Results and discussion

3.1. Theoretical analysis

The modelling results of the effects of process steam conservation on the four selected forms of marginal heat production at the mill site with different operational options are presented in Table 4.

In the case of the heavy-fuel–oil-based HOB (1.a) the effects of process steam conservation of 2 MW or 16,000 MWh/y on PEC and CO_2 emissions are equal at the mill site and national level.

In 2.a, 3.a and 4.a, district heat can be produced at the mill site instead of process steam, so the PEC and CO_2 emissions at the mill site remain unchanged. Increased district heat export from the mill site is assumed to replace heavy-fuel–oil-based district heat production, which reduces the PEC and CO_2 emissions at the national level.

In 2.b and 3.b, the PEC and CO_2 emissions decrease at both the mill site and national levels. The heat conservation also reduces the CHP electricity production, and the reduced electricity production has to be made up by purchases from the grid. Therefore, the national-level effects are not as strong as those seen at the mill site. In 2.b, where natural gas consumption can be reduced by running the auxiliary burner in the heat recovery steam generator (HRSG) at lower load, the national-level effect is insignificant.

In 4.b, the conservation of process steam saves biofuel, which can be exported from the mill site. The exported biofuel is considered to replace heavy fuel oil in district heat production. Due to the lower efficiency of biomass-based district heat production compared with heavy-fuel–oil-based production, the PEC of district heat production increases. Since biomass is a carbon–neutral fuel, CO_2 emissions cannot be reduced at the mill site, but emissions of district heat production decrease. Overall, the PEC and CO_2 emissions can be reduced at the national level.

If the processes are modified by adding a condensing unit to the CHP process (2.c, 3.c and 4.c) additional electricity can be produced because the steam expands to the lower pressure in the steam turbine. It seems that adding a condensing unit reduces both PEC and CO_2 emissions at the national level.

The comparison shows that from the national perspective the production of district heat at the mill site is the best option to realise the benefits of heat conservation. The reduction of peat consumption (3.b) seems to be favourable from both the mill and the national perspective. In 2.c, 3.c and 4.c the benefits at the national level are smaller than those achieved by increasing district heat production at the mill site because of the low efficiency of electricity production in the condensing mode. In the biomass-based CHP production, adding a condensing unit leads to higher national-level emission reductions than biomass export from the mill site (4.b).

The sensitivity analyses with regard to the emission factors for purchased electricity and replaced district heat production are presented in Fig. 3.

Fig. 3a shows that the alternative ways of saving fuel at the mill site (2.b, 3.b and 4.b) are very sensitive to changes in the emission factor for purchased electricity. If in the future the marginal production were CCGT with an emission factor of 0.34 t CO_2/MWh instead of coal condensing power, the emission reductions of these options would be greater than at present. In the same way, the saving of peat (3.b) and export of biomass from the mill site (4.b) would be better options than increasing the production of district heat at the mill site. On the other hand, with a lower emission factor for purchased electricity, the benefits of additional electricity production from a condensing unit in the steam turbine (2.c, 3.c and 4.c) are less.

Clearly, it makes a big difference whether the emission factor for average or marginal production is used. In 2008, the average emission factor in Finland was 0.168 t CO_2/MWh [27], i.e. about 20% of the emission factor for marginal production used here. With the average factor, the reduction of natural gas consumption (2.b) and export of the biomass from the mill site (4.b) are better options from the national perspective than the additional electricity production from a condensing unit in the steam turbine (2.c and 4.c). With the emission factor for marginal production (0.851 t CO_2/MWh), the situation is opposite. The options with increasing district heat production (2.a, 3.a and 4.a) and decreasing consumption of heavy fuel oil (1.a) are not sensitive to changes in the emission factor for purchased electricity since in these options there are no changes in the amount of purchased electricity.

The options delivering district heat outside the mill site (2.a, 3.a, 4.a and 2.b) are sensitive to changes in the emission factor for replaced district heat production (Fig. 3b). Especially in the case where biomass is exported from the mill site (4.b) and used to replace district heat production, the emission factor for replaced district heat production is a crucial question. If the replaced district heat production is based on natural gas with an emission factor of 0.212 CO_2/MWh or some carbon–neutral fuel, the replacement does not lead

Table 4
The effects of process steam conservation at the mill site and national level.

Alternative	Change in energy production (MWh/y)			Change in primary energy consumption (MWh/y)				Change in CO_2 emissions (t/y)			
	Process steam	Electricity	District heat	PEC_{Mill}	PEC_{Grid}	PEC_{Heat}	$PEC_{National}$	$CO_{2\ Mill}$	$CO_{2\ Grid}$	$CO_{2\ Heat}$	$CO_{2\ National}$
1.a	−16,000	0	0	−18,702	0	0	−18,702	−5311	0	0	−5311
2.a	−16,000	0	16,000	0	0	−17,204	−17,204	0	0	−4886	−4886
2.b	−16,000	−6432	3608	−23,567	16,080	−3880	−11,367	−4666	5474	−1102	−294
2.c	−16,000	3031	0	0	−7577	0	−7577	0	−2579	0	−2579
3.a	−16,000	0	16,000	0	0	−17,204	−17,204	0	0	−4886	−4886
3.b	−16,000	−5206	0	−24,439	13,016	0	−11,423	−9311	4431	0	−4881
3.c.	−16,000	3342	0	0	−8354	0	−8354	0	−2844	0	−2844
4.a	−16,000	0	16,000	0	0	−17,204	−17,204	0	0	−4886	−4886
4.b	−16,000	−4805	0	−24,687	12,012	1327	−11,348	0	4089	−6634	−2545
4.c	−16,000	3454	0	0	−8634	0	−8634	0	−2939	0	−2939

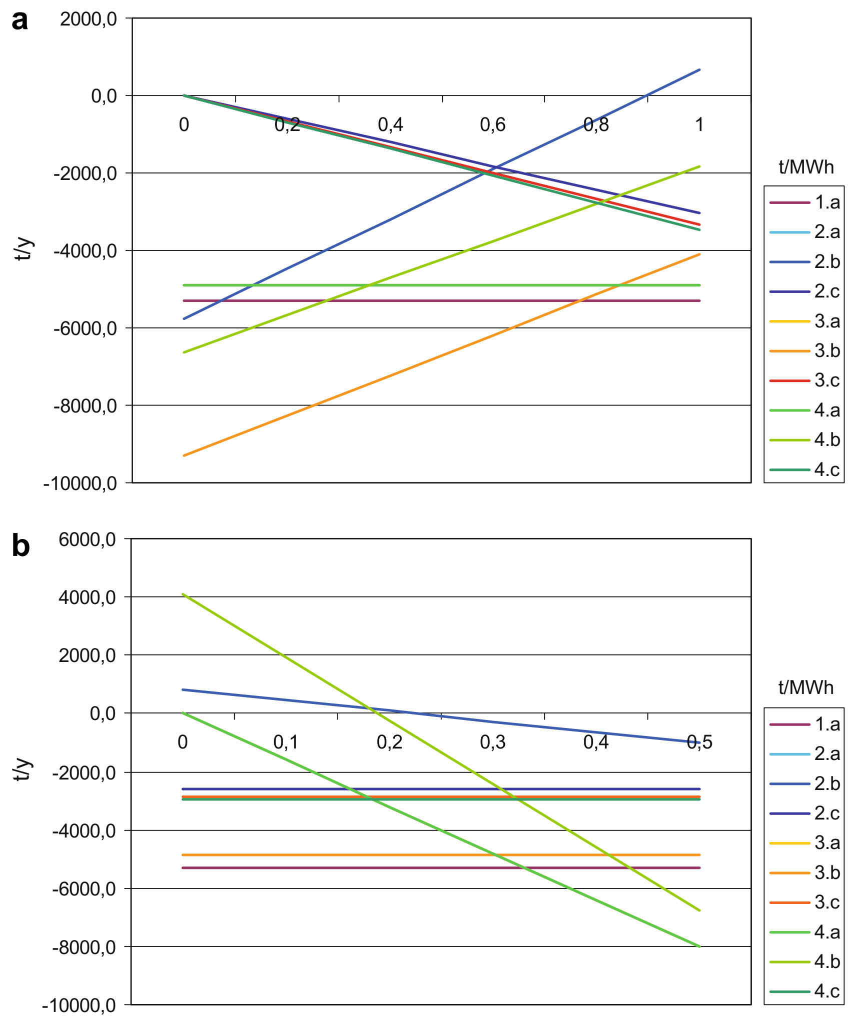

Fig. 3. Sensitivity of national CO_2 emissions with regard to: (1) the emission factor for purchased electricity (2) the emission factor for replaced district heat production.

to a reduction in CO_2 emissions at the national level. The other options are not sensitive to the emission factor for replaced district heat because there is no district heat delivery in those options.

3.2. Case mill studies

Table 5 summarises the effects of feasible energy conservation measures collected from the energy analysis reports. According to the analyses, the average pay-back time for the feasible energy conservation investments ranges from 0.8 to 3.4 years, depending on the mill. The absolute figures are not comparable because the production structures and capacities of the mills differ from each other. However, the summary shown in Table 5 can be used to analyse what kind of effects energy conservation has on fuel consumption, electricity consumption and production, and CO_2 emissions at different mill sites with different forms of marginal energy production.

The energy analysis report of mill D was prepared in 2003, i.e. before the introduction of the EU ETS. It shows the CO_2 emission reduction at the national level, while other reports from the years 2005–2006 show the change in emissions from the mill site that is relevant under the conditions of emissions trading.

The results from mills A and B confirm that it is easier to find heat (or fuel) saving potential than electricity saving potential. Realising the potential reduces internal electricity production and more electricity has to be purchased from the grid.

In mills D and E, increased electricity production is feasible because it is based on the additional use of biofuels (forest residue or

Table 5
Summary of the effects of feasible energy saving measures found in the energy analyses.

Mill	Change in electricity and fuel consumption (MWh/y)						Change in electricity production (MWh/y)	Change in CO_2 emissions (t/y)
	Electricity	Biofuel	Natural Gas	Coal	Peat	HFO		
A	−2403		−57,191				−4459	11,324
B	−1788				−20,691	−108,617	−14,911	−38,208
C	−12,998	28,974		12,417		−6366	62,731	2455
D[a]	−547	5416	−26,974				18,766	−18,967
E	−1468	25,066				−16,967	40,660	−4734

[a] Includes change in the grid-based emissions.

Table 6
Summary of the changes in primary energy consumption and CO_2 emissions.

Mill	Change in primary energy consumption (MWh/y)				Change in CO_2 emissions (t/y)			
	PEC_{Mill}	PEC_{Grid}	PEC_{Heat}	$PEC_{National}$	$CO_{2\ Mill}$	$CO_{2\ Grid}$	$CO_{2\ Heat}$	$CO_{2\ National}$
A	−57,191	5140	0	−52,051	−11,324	1750	0	−9574
B	−129,308	32,808	0	−96,501	−38,730	11,168	0	−27,563
C[a]	35,025	−189,323	0	−154,298	2426	−64,445	0	−62,019
D	−21,558	−48,283	0	−69,841	−5341	−16,435	0	−21,776
E[a]	8099	−105,320	0	−97,221	−4819	−35,851	0	−40,670

[a] Additional biofuel (forest residue) is assumed to be available and therefore it does not need to be replaced with other fuels in heat production.

purchased bark). At mill site C, in addition to biofuels, coal is used to increase electricity production, and therefore CO_2 emissions at the mill site increase.

To make the results comparable and to examine CO_2 emissions at the national level, the CO_2 emissions were recalculated using Eq. (1) and the efficiencies and emission factors for grid-based electricity and district heat presented in Table 1.

Table 6 shows a summary of the changes in PEC and CO_2 emissions at both the mill site and national level. In this table PEC_{Mill} is equal to the sum of the fuel consumptions presented in Table 5. The PEC for grid-based electricity is calculated by using an efficiency of 40% for grid-based electricity and taking into account the changes in both electricity consumption and production.

For mill D the change in the national CO_2 emissions and for the other mills the changes in CO_2 emissions from the mill site are comparable (but not necessarily exactly the same due to differences in the emissions factors used in the different analyses) to the changes in the CO_2 emissions presented in Table 5.

At the national level PEC and CO_2 emissions decrease in all of the case mills. However, in mills A and B, the emissions of grid-based electricity production increase due to decreased CHP electricity production at the mill site. In the other mills, the reductions in emissions from grid-based electricity production are considerable higher than those from the mill site because of increased biomass-based electricity production at the site.

The sensitivity analyses with regard to the emission factor for purchased electricity are presented in Fig. 4.

The emission reductions at the national level are very sensitive to the emission factor for purchased electricity (Fig. 4). In mills A and B, where electricity production is decreasing, the emission reductions decrease with the increasing emission factor for purchased electricity. In mills C, D and E the situation is opposite due to increased electricity production. The bigger the change in PEC_{Grid} presented in Table 6, the more sensitive the emission reductions are with regard to the emission factor for purchased electricity.

3.3. Synthesis of the theoretical analysis and case mill studies

Both the theoretical analysis and the case mill studies show that mill site analyses can either overestimate or underestimate the potential for primary energy conservation and CO_2 emission reduction from the national perspective. If heat conservation increases the production of electricity or district heat at the site, the effects are positive from the national perspective. Conversely, if electricity production is reduced and more electricity has to be purchased from the market, the mill site effects seem to be more positive than those at the national level.

These results show that where energy production is integrated into industrial production and energy conservation investments affect CHP production at the mill site, the choice of system boundary is a crucial question.

The national CO_2 emissions are very sensitive to the emission factor for purchased electricity. However, regardless of the factor selected, heat conservation seems to have positive effects at the national level if fuels can be saved or more electricity or district heat can be produced at the mill site. So, the findings of Rolfsman [19] that there is a possibility that heat conservation and reduced CHP electricity production might lead to increased CO_2 emissions could not be confirmed in the case of industrial CHP production in the pulp and paper industry. This can be explained by the lower power-to-heat ratios (α) of industrial power plants: the weighted average of α is 0.47 in the study of Rolfsman [19], when the power-to-heat ratios of the solid-fuel-based power plants in this

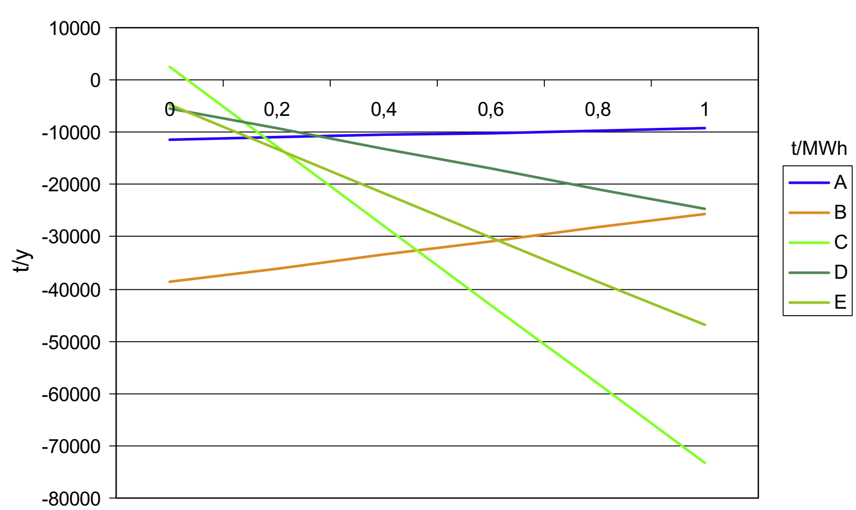

Fig. 4. Sensitivity of national CO_2 emissions with regard to the emission factor for purchased electricity.

study are around 0.30. When process heat is conserved in industry, less CHP electricity production is lost than in the case of a municipal CHP plant, and so the influence on CO_2 emissions at the national level is smaller, too. Although the CCGT plant has a high power-to-heat ratio up to 1, the CO_2 emissions are reduced at the national level also in this case. This is due to the fact that the reduction in CHP electricity production is not directly comparable to the power-to-heat ratio of the CCGT plant in the operational option 2.b. Auxiliary burners in the HRSG enable the full-load run of the gas turbine with different heat loads, so the reduced heat load affects only the electricity production of the steam turbine. However, it must be said that in this case the national-level effects are only slightly positive.

3.4. Discussion

The emission factor for grid-based electricity has a big influence on the evaluated emission reduction potential. As discussed in Section 2.2, the emission factor for marginal production should be used instead of the average emission factor. The relevancy of the results depends on the form of marginal production used in the electricity market in question. In the Nordic electricity market, coal-based condensing power with a high emission factor is the marginal production most of the time. In an electricity market with a lower emission factor for marginal production, the difference between the effects at the mill site and national level is smaller. In the future, CCGT is expected to be the marginal production in the Nordic electricity market, which will narrow the difference in Nordic countries. Therefore, marginal production should be regularly monitored and any changes taken into account in the analysis.

The scope of this study is limited to impacts at the national level. However, the Nordic energy system is integrated, so there might be some transboundary effects, too. For example, coal-based condensing power, which is often marginal in the Nordic electricity market, is produced both in Denmark and Finland. So, in some cases the reduction in electricity production at the mill site may lead to increased electricity production and CO_2 emissions in Denmark. Therefore, the national-level effects in Finland might seem more positive, but globally the effects would be the same as the national-level effects presented here. A detailed analysis at the Nordic level would require more accurate data on the marginal plant and its location.

The estimated peak load duration of 8000 h per year is relatively high since in many cases partial load running and seasonal variation weaken the benefits of heat conservation measures. However, this does not affect the comparability of the results at the mill site and national level.

This paper does not include an economic analysis of heat conservation. Instead, it has been assumed that in the theoretical analyses heat saving is always feasible, and fuels, electricity and district heat can be sold profitably to the market and more electricity can be purchased if needed. The next step is to examine both the monetary and thermodynamic value of energy conservation in industry.

4. Conclusions

The paper highlights that a heat conservation investment in a single industrial process may have different implications for primary energy consumption and CO_2 emissions at the mill site and national levels. Especially if the emission factor for purchased electricity is high, there might be big differences in emission reductions from the mill and national perspectives. Therefore, a wider system boundary than the mill site has to be used in energy analyses.

From the Finnish perspective the results mean that the potential for energy conservation and CO_2 emission reduction in Finnish industry cannot be estimated by summing up the energy conservation measures reported in the energy analysis reports under the voluntary energy conservation agreement for industry.

It should be ensured by proper regulation and supporting systems that mill site decision-making leads to the optimal results from the national perspective, too. So far, the Finnish industrial CHP producers have received more emission allowances than the condensing power production sector. Also, industry has had lower energy taxation than the other sectors. The changes in EU ETS after 2012 together with the planned increase in energy taxation of industry from the beginning of 2011 might weaken the attractiveness of industrial CHP production and lead to increased electricity purchasing. Therefore, co-operation with the government and industrial sector is essential for understanding the contribution of energy conservation measures towards meeting the energy efficiency target and CO_2 emission reduction commitment at the national level.

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