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The influence of operational flexibility on the exploitation of CO_2 reduction potential in industrial energy production

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ABSTRACT

Energy conservation is a key measure for reducing CO_2 emissions. However, realising the emission reduction potential of an energy conservation investment depends on many factors, such as energy prices. The EU emissions trading scheme has made the investment analysis more complicated and increased the economic value of operational flexibility under fluctuating carbon prices. The different operational options in industrial energy production complicate the estimation of CO_2 reduction potential in the investment phase. Increasing operational flexibility enables optimisation in the economic dimension, which may lead to less than optimum CO_2 reduction. In our case study, which analysed the effects of an energy conservation investment made in the pulp and paper industry, the deviation from the expected emission reduction was around 30% over the period from 2000 to 2007. However, it seems that with high carbon prices, increasing operational flexibility has no significant effect on the carbon emissions. In policy-making, the freedom of action that is made possible by increasing operational flexibility should be taken into account when evaluating the contribution of an individual energy efficiency investment towards meeting the national targets for energy efficiency improvement and CO_2 emission reduction.

1. Introduction

The European Union has set targets for (1) reducing its CO_2 emissions by at least 20%, (2) increasing the proportion of renewable energies in its energy mix to 20% and (3) reducing its energy consumption by 20% by 2020. In the Action Plan for Energy Efficiency (EC, 2006) the target for reducing energy consumption is specified as a 20% saving in annual consumption of primary energy by 2020 compared with the energy consumption forecasts for 2020.

The Finnish Ministry of Employment and the Economy (2008) has created the Long-Term Climate and Energy Strategy, which aims to fulfil the EU's requirements to reduce greenhouse gas emissions, increase the use of renewable energy sources and reduce energy consumption. According to the effort sharing decision (EC, 2009a), Finland has to reduce its greenhouse emissions from non-trading sectors by 16% by 2020 compared with 2005 levels. Based on the new EU directive on renewable energy (EC, 2009b), Finland's national overall target for the share of energy from renewable sources in gross final consumption of energy in 2020 is 38%. The target for reducing energy consumption is −20%, the same as in the Action Plan for Energy Efficiency (EC, 2006).

Although the improvement of energy efficiency is regarded as the fastest and cheapest way of reducing CO_2 emissions (IEA, 2007a), defining the emission reduction potential of an energy efficiency improvement is often complicated.

At the national or international level the energy conservation and CO_2 reduction potentials are typically evaluated on the basis of scenario studies. For example, the International Energy Agency (IEA) is using this methodology in the World Energy Outlook reports (IEA, 2007a). Also the Intergovernmental Panel on Climate Change (IPCC) has developed emission scenarios for analysing the costs and benefits of different approaches to mitigating climate change (IPCC, 2007). Energy efficiency plays a key role in CO_2 emission reduction across both IEA and IPCC scenarios. In scenario studies numerous assumptions have to be made about economic development, technology penetration, fuel prices, etc. In addition, typically only a few policy scenarios are compared to one baseline or reference scenario, and therefore the uncertainties of different variables are difficult to take into account.

At the plant level the profitability of investments, including energy efficiency improvement, is typically evaluated by investment analysis (also called feasibility analysis). This methodology is used by Gabbrielli et al. (2006), among others, to identify the energy saving opportunities in the tissue industry. The economic indices used most often in investment analysis are the payback

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period (PBP), the net present value (NPV) and the internal rate of return (IRR). In addition to profitability, also the CO_2 reduction potential of an energy efficiency investment is often estimated before making an investment decision. In investment analyses the effects of uncertainties are typically studied by using sensitivity analyses, which helps one understand the effects of combined variations in the values of the input parameters. Svensson et al. (2009) developed a more advanced methodology for evaluating energy efficiency investments that considers the uncertainties of future energy prices and policies. In that methodology the probability distributions of the expected values of uncertain parameters, such as future energy prices, can be taken into account by using a stochastic programming model. However, no results on the application of the methodology have yet been published.

The energy conservation and CO_2 reduction potential can be defined in different ways and the realisation of potentials are affected by various issues. Tuomaala (2007) divided the potentials for process integration, which is a central energy conservation measure in the process industry, into theoretical, technical and economic potentials. Theoretical potential represents the maximum improvement opportunities available. Technical and economic potentials consider technological restrictions and economic constraints, respectively. In addition, Tuomaala (2007) stated that the potential for improvement is greatest in the process design phase. In the operational phase, when the structure of the process and its connections to the external environment have already been determined, the efficiency can be improved mainly through adopting better operational practices. Retrofitting an existing facility of an existing system can provide bigger improvements, but often it is a more expensive alternative.

Despite the existence of significant potential for cost-effective investment in energy efficiency, market barriers and market failures prevent its exploitation (IEA, 2007b; Brown, 2001). Brown (2001) named this difference between the cost-efficient investments in energy efficiency and the actual level of investment as the "efficiency gap". The IEA (IEA, 2007b) lists the following market barriers: low priority of energy issues, lack of access to capital, and the incomplete market for energy efficiency. Market failures occur when markets do not operate efficiently. Examples of market failures are split incentives, i.e. different goals or incentives of participants in an economic exchange, and insufficient and inaccurate information. The realisation of emission reduction potential might also seem different, depending on the selected system boundary. In our previous paper (Siitonen et al., 2009) it was shown that a heat conservation investment in a single industrial process has different implications for primary energy consumption and CO_2 emissions at the mill site and national levels.

Recently, climate policy has become a major source of uncertainty in energy investments (Laurikka, 2004). At the beginning of 2005 the European Union Emissions Trading Scheme, EU ETS (EC, 2003), gave a monetary value for CO_2 emissions. Therefore, the price of an EU allowance (EUA) became an additional variable that has to be taken into account in the investment analysis. Under the EU ETS the credits provided by the project-based mechanisms, i.e. clean development mechanism (CDM) and joint implementation (JI), can be utilised. The prices of certified emission reductions (CER) from CDM projects and emission reduction units (ERUs) from JI projects are typically lower than EUAs. The operator of a plant under the EU ETS has three different options to meet its emission reduction target: to (1) reduce CO_2 emissions at the site, (2) purchase EUAs, or (3) purchase CERs/ERUs. At the site, emissions can be cut by reducing the production rate, adopting improved operating practices, or making an investment that reduces CO_2 emissions. Laurikka (2004) stated that the value of flexibility in energy investments grows as the uncertainty caused by climate policy increases. Based on Ashby's Law of Requisite Variety (Ashby, 1958), strategic flexibility increases the company's capability to generate the variety of responses required to maintain stability in a dynamic environment (Sanchez, 1995). When Ignatenko et al. (2008) studied the recycling system flexibility, they found that restrictions in the flexibility of the recycled material processing options may lead to a large negative impact on overall recycling performance. So, the increased flexibility seems to enable improved sustainability.

The purpose of this paper is to study how operational flexibility and changes in energy prices affect the realisation of the energy conservation and CO_2 reduction potential of an energy efficiency investment. In this study an individual energy efficiency investment made in a Finnish pulp and paper mill is used as a case study. The investment saves process steam, which depending on the case, can be realised either as fuel (peat or bark) savings or as export of additional power generation to the grid. The effects of flexibility are analysed by monitoring the cost savings, energy conservation and CO_2 reduction of an investment after the uncertainties have disappeared, i.e. the realised energy prices are known. The effects were studied at both the mill site and national level, since the energy system of the mill is typically integrated into society. This study is based on process modelling made by Solvo® software and economic analysis. Solvo® is a commercial software application developed by Fortum for modelling and simulating the heat balances of a power plant in steady state conditions.

2. Materials and methods

In the case study, the hypothetical energy conservation investment in the pulp and paper mill located in Finland is supposed to be made in early 2000. The investment reduces process steam consumption in the paper mill (2 MW or 1300 MWh/month). The investment cost is assumed to be EUR 400,000 and the simple payback period 3.5 years. Since CHP production is widely used in energy-intensive industry in the Nordic countries, electricity and steam used by the mill are assumed to be produced by the mill's own CHP power plant using domestic solid fuel.

2.1. System boundaries used in this study

Fig. 1 presents the system boundaries considered in this study. The mill site (system boundary A) includes the pulp and paper mill as well as the on-site energy production plant. 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 society through its raw material, fuel and energy streams, so decisions made at the mill site level also have implications at the national level (system boundary B). In addition to biofuels provided by the mill, some external fuels, such as peat and heavy fuel oil, might be needed. Usually, the heat demand of the industrial plant is covered on the whole by its energy production plant, but the electricity demand of an industrial plant is seldom in balance with its own electricity production. For simplicity, however, it is assumed here that the CHP power plant is capable of producing all the process steam and electricity required by the mill. In addition, the energy production plant is integrated into the electricity market, which enables selling and purchasing of additional electricity, depending on the internal demand/supply balance of electricity.

Emissions from the mill site also have effects on a national level or, for example in the case of CO_2, even globally. EU ETS has enabled

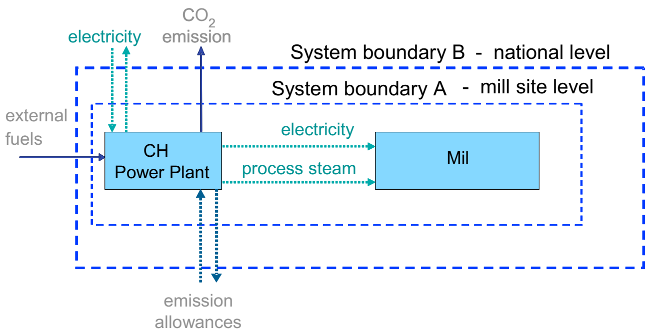

Fig. 1. System boundaries of a pulp and paper mill.

the purchase and sale of emission allowances since the beginning of 2005.

2.2. Energy production at the mill site

The energy production at the mill site is assumed to be based on solid-fuel-based CHP technology. In this study two slightly different CHP power plant cases are included: power plant 1 and power plant 2. The simplified process charts of a CHP power plant are presented in Fig. 2a and b.

In both power plant cases peat and biomass (bark from the mill) are burnt in a modern fluidised bed boiler producing high-pressure steam for a turbine. Superheated live steam is fed to the steam turbine, where it expands through the turbine to a lower pressure. The mechanical rotation energy of the turbine shaft is converted into electricity in the generator. Extraction steam, at a pressure of 11 bar, and backpressure steam, at a pressure of 3.2 bar, from the turbine are fed to the pulp and paper mill. The steam releases its heat to the process by condensing and most of the condensate is pumped back to the feed water tank of the power plant and thence back to the heat exchangers of the boiler.

The only difference between the two power plant cases is that in the power plant 2 there is a steam turbine condensing unit, which can produce additional electricity. The condenser pressure was set to 0.1 bar, which is equivalent to a moisture content of 12% after the turbine's condensing unit.

2.3. Process modelling and potential for energy conservation and CO_2 reduction

The effects of a steam conservation investment on fuel consumption, energy production and CO_2 emissions in different operational options are modelled by Solvo® software. The software can be used to model turbine and boiler plants, CHP plants as well as pulp and paper and gasification processes.

In early 2000, the feasibility of the investment and the CO_2 reduction potential were evaluated based on the assumption that heat conservation reduces the consumption of marginal fuel, i.e. peat, at the mill site. However, there is also another way to realise the process steam conservation, i.e. to reduce bark consumption at

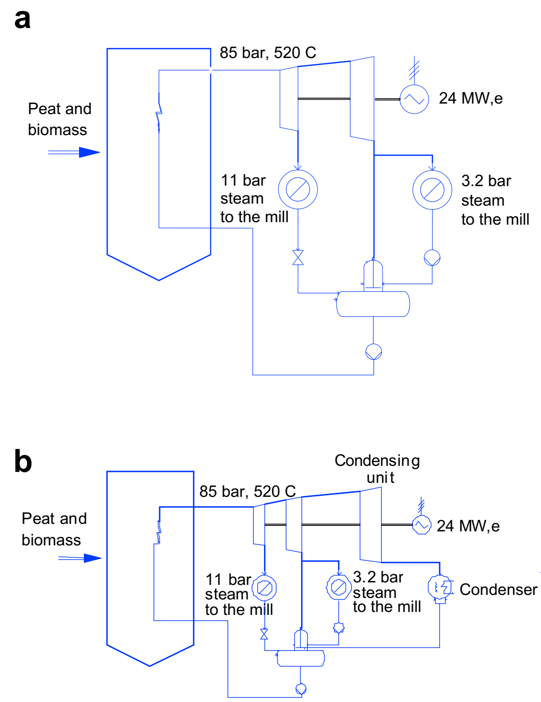

Fig. 2. Industrial CHP plants considered in this study. a) Power plant case 1, b) Power plant case 2.

the mill site and sell it to the market. In addition, in power plant case 2 with the steam turbine condensing unit there is an option to sell electricity to the market. These alternatives give the operator of a power plant an opportunity to make strategic decisions according to the market situation. That opportunity is referred to as '*operational flexibility*' in this paper.

In this analysis, the reduction of peat consumption is referred to as the 'base case'. In addition, the effects of operational flexibility on the cost savings and the reduction of CO_2 emissions were analysed. In the case of 'flexibility 1' it is assumed that power plant 1 can sell bark to the market as an alternative to peat conservation. In 'flexibility 2', in addition to the operational options to reduce peat or bark consumption, there is also an option to produce additional electricity using the steam turbine condensing unit of power plant 2. Table 1 lists the effects of heat conservation in the base case and flexibility cases for two different power plants.

Reduced peat consumption means that less peat needs to be purchased, which also reduces the CO_2 emissions from the mill site. From the beginning of 2005, it has been possible to sell emission allowances equal to the reduced CO_2 emissions. If biomass consumption is reduced, it is assumed that bark can be sold outside the mill site, where it is supposed that it will replace heavy fuel oil in district heat production. Then CO_2 emissions are reduced outside the mill due to carbon-neutral district heat production. If one of the options to reduce peat consumption or sell biomass to the market is

Table 1
The effects of heat conservation in different cases.

	Base case	Flexibility 1	Flexibility 2
Power plant case 1	- Reduced peat purchase - Increased electricity purchase - Sales of EUAs	- Increased biomass sales - Increased electricity purchase	–
Power plant case 2	- Reduced peat purchase - Increased electricity purchase - Sales of EUAs	- Increased biomass sales - Increased electricity purchase	– Increased electricity sales

Table 2
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$_{District\ Heat}$]
Peat (CHP)	88%			0.381		
Biomass (CHP)	88%			0.000		
Electricity, coal condensing		40%			0.851	
District heat, biomass-based HOB			88%			0.000
District heat, HFO-based (HOB)			93%			0.305

selected, the decline in CHP electricity production has to be made up with electricity purchased from the market. However, in the case of additional electricity production using the steam turbine condensing unit of power plant 2, electricity can be sold to the market. The changes in purchased electricity affect the CO_2 emissions of grid-based electricity, too.

For each operational option the energy conservation and CO_2 reduction potentials at the mill site and national levels are calculated. The changes in CO_2 emissions at the national level are calculated according to the principle presented in our previous paper (Siitonen et al., 2009) using the following equation first presented by Möllersten et al. (2003):

$$CO_{2\ National} = CO_{2\ Mill} + CO_{2\ Grid} + CO_{2\ Heat} \tag{1}$$

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 fuel (i.e. biomass) export from the mill.

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

$$PEC_{National} = PEC_{Mill} + PEC_{Grid} + PEC_{Heat} \tag{2}$$

where PEC_{Mil} 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.

In this study the changes in national primary energy consumption and national CO_2 emissions are used for comparing the realisation of the energy conservation and CO_2 reduction potentials of different flexibility cases.

Table 2 shows the efficiencies 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 (Statistics Finland, 2006) were used. In this study the emissions from grid-based electricity production were evaluated based on the marginal production form of electricity in the Nordic electricity market, because there is a common view that the marginal approach should be used for change-oriented studies (Wolf and Karlsson, 2008; Ekvall et al., 2005). Mathiesen et al. (2009) states that the marginal approach is also used in consequential life cycle assessment (LCA) because the markets affected are often included in the analysis. The marginal approach has been used by Möllersten et al. (2003) and Karlsson et al. (2009), among others. In this study coal-based condensing power is used as a form of marginal electricity production because it has been marginal in the Nordic electricity market most of the time in recent years.

2.4. Economic analysis

Since business is based on profit maximisation, management is assumed to select the most profitable operational option at any given time. We assume efficiently operating markets, which means that management has perfect information on energy markets and prices, there are no barriers to enter or exit the markets, and all the transactions are costless. In addition, we assume there is no switching cost between different fuels and operation of the condensing unit.

The profit maximisation target can be simplified to the maximisation of cost savings (CS) at the mill site due to the energy conservation investment according to the following function:

$$\text{MaxCS} = -\Big(\Delta Q_{peat} \times p_{peat} + \Delta \text{EUA} \times p_{EUA} + \Delta Q_{biomass} \times p_{biomass} + \Delta E_{purchased} \times p_{electricity}\Big) \tag{3}$$

where ΔQ_{peat} is the change in peat purchased, p_{peat} is the price of peat, ΔEUA is the change in emission allowances needed due to reduced peat consumption, p_{EUA} is the price of emission allowances, $\Delta Q_{biomass}$ is the change in biomass consumption, $p_{biomass}$ is the price of biomass, $\Delta E_{purchased}$ is the change in purchased electricity and $p_{electrcity}$ is the price of electricity.

Fig. 3 shows the price development of peat, biomass, electricity and EUA between 2000 and 2007. The peat price has been stable but the price of biomass has risen due to higher demand and improved competitiveness under emissions trading. The EUA price rose to EUR 30/t CO_2 by April 2006. However, after the verified emissions for the year 2005 were published, the EUA price started to decline because of the higher allocation compared to actual emissions. In the beginning of 2007 it was clear that there would be a surplus of emission allowances on the market during the period 2005–2007 and so the EUA price dropped close to zero. The electricity price in the Nordic area has changed considerably in recent years. During the winter 2002–2003 the electricity price increased due to the low level of hydropower reservoirs and cold weather. From 2005, the EUA price has affected the electricity price because of the carbon pass-through effect. Although most of the allowances have been received for free, they have an opportunity cost, i.e. the

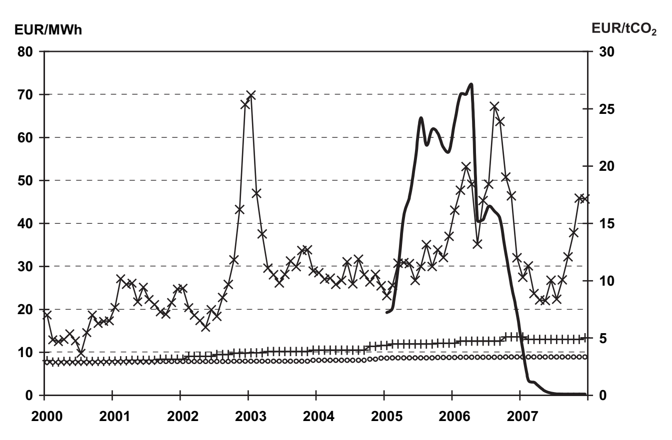

Fig. 3. Average monthly prices of energy and emission allowances (EUA) in Finland in 2000–2007 (Kosunen, 2008; Nordpool, 2008).

Table 3
The effects of process steam conservation at the mill site and national level.

Option	Change in energy production [MWh/month]			Change in primary energy consumption [MWh/month]				Change in CO_2 emissions [t/month]			
	Process steam	Electricity	District heat	PEC_{Mill}	PEC_{Grid}	PEC_{Heat}	$PEC_{National}$	$CO_{2\ Mill}$	$CO_{2\ Grid}$	$CO_{2\ Heat}$	$CO_{2\ National}$
Base case	−1300	−423	0	−1986	1058	0	−928	−757	360	0	−397
Flexibility 1	−1300	−423	0	−1986	1058	67	−861	0	360	−534	−174
Flexibility 2	−1300	272	0	0	−679	0	−679	0	−231	0	−231

actors under the emissions trading scheme have an option to sell EUAs to the market at the market price. Therefore, in line with economic theory, the opportunity costs of the allowances are passed on to the price of electricity. According to Honkatukia et al. (2006) on average about 75–95% of a change in the EUA price has been passed on to the price of electricity in Finland. Based on the model calculations made by the VTT (Kara et al., 2008), in the Nordic area the carbon pass-through effect raises the average annual electricity price by EUR 0.74/MWh for every EUR 1/t CO_2 in the EUA price.

3. Results and discussions

The modelling results of the effects of process steam conservation at the mill site are presented in Table 3. In addition, the table shows the changes in primary energy consumption and CO_2 emissions both at the mill site and national levels. Based on these results the variables in Eq. (3) can obtain the sets of values presented in Table 4. The cost savings for each month were calculated using these sets of values and the monthly prices for fuels, electricity and emission allowances presented in Fig. 3.

Fig. 4 shows the cost savings of the different operational options. Producing additional electricity has been the most feasible option during periods of high electricity prices (see Fig. 3). In 2007, the sale of biomass was feasible because of collapsed EUA and electricity prices. Overall, after introducing the EU ETS at the beginning of 2005, the variation of cost saving in the different operational options has been larger than in the previous years.

Fig. 5a shows that the base case produced less cost savings than expected in 2000. The simple payback period calculated prior to the investment was 3.5 years. However, the realised payback period in the base case was 4.7 years, i.e. 34% longer than expected. In the flexibility cases 1 and 2 the simple payback periods were 4.2 years and 3.3 years, respectively. Actually, in the case of flexibility 2, the costs savings were higher than expected over the whole period except in 2001. This example shows that the flexibility of the energy production process improves the profitability of energy conservation investment, as the theory predicts.

In Fig. 5b and c the realised reduction in primary energy consumption and CO_2 emissions at the national level are shown. These results indicate that operational flexibility weakens the realisation of the potential for conserving energy and reducing CO_2 emissions at the national level compared with that expected in the investment phase. During the period 2000–2007, 29% of the expected primary energy savings was not realised in flexibility 2. The realisation of CO_2 emission was even weaker. In both flexibility cases only around 70% of the expected CO_2 reduction potential was realised.

Table 4
The sets of values that variables in Eq. (3) can obtain.

Option	ΔQ_{peat}	ΔEUA	$\Delta Q_{biomass}$	$\Delta E_{purchased}$
Base case	−1986	−757	0	−423
Flexibility 1	0	0	−1986	−423
Flexibility 2	0	0	0	272

As Fig. 5a shows, the introduction of EU emissions trading has increased the economic value of flexibility, just as Laurikka (2004) stated. However, the increased flexibility has no effect on CO_2 reduction when the price level of EUA is high. For example in 2005, when the EUA price rose to EUR 30/t CO_2, both energy conservation and CO_2 reduction potentials were fully realised. However, after EUA prices dropped below EUR 10/tCO_2 at the end of 2006, the effect of increased flexibility on the realisation of energy conservation and CO_2 reduction potentials was similar to the years before the launch of EU ETS. This indicates that the EUA price is an important variable affecting the realisation of CO_2 reduction potential, at least in this case, where there are big differences in the mill-site CO_2 emissions of different operational options.

Fig. 6 shows the realised reduction in annual CO_2 emissions as a function of the annual cost savings. The Fig. shows clearly that flexibility cases rarely exploited the maximum CO_2 reduction potential. However, especially in flexibility 2, more cost savings than expected were often achieved, which is a natural consequence of the optimisation being made in the economic dimension.

It should be noted that when there is operational flexibility in the system, the economic optimisation is likely to result in less than the maximum CO_2 reduction. If the potential for reducing CO_2 emissions had been evaluated based on the options other than the reduction of peat consumption, the realisation of potential would have corresponded better to the expected potential at the time of investment. Therefore, in the case of operational flexibility, more attention has to be paid to estimating the realistic energy conservation and CO_2 reduction potential in the investment phase.

Although EUA has basically the same price all over Europe, the energy prices and carbon pass-through effect vary from country to

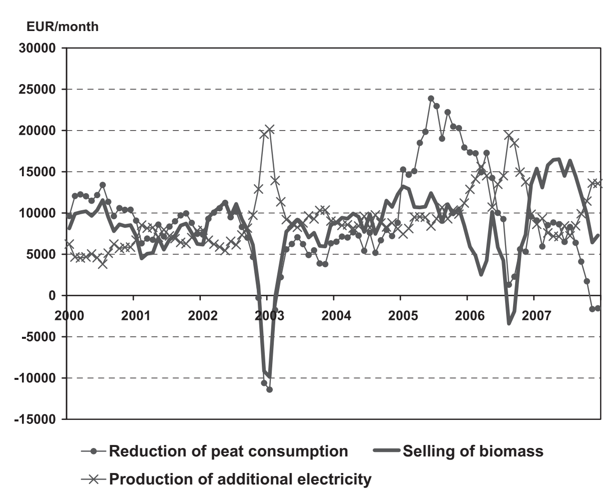

Fig. 4. Cost savings of different operational options.

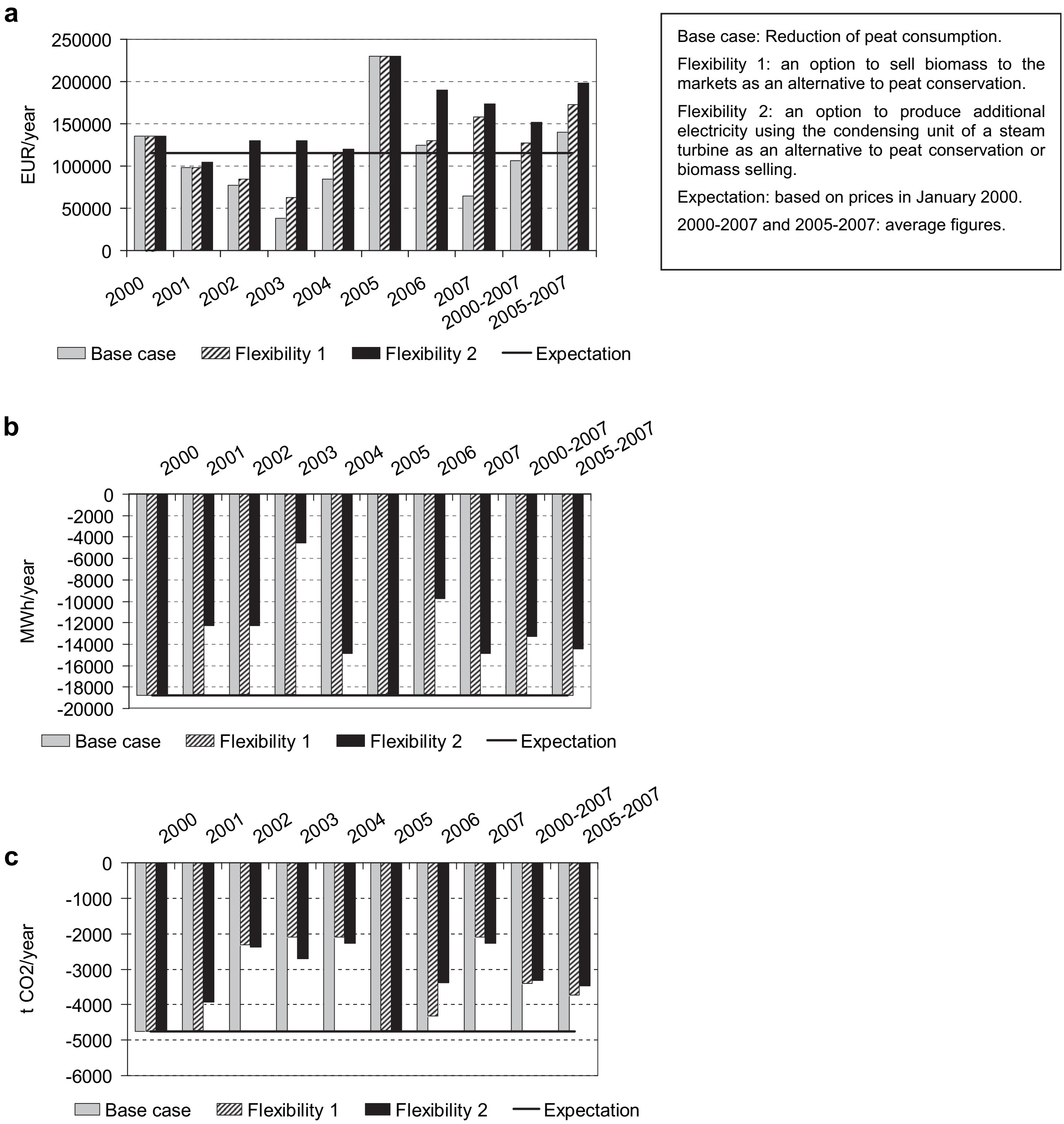

Fig. 5. (a) Cost savings, (b) energy conservation and (c) reduction of CO_2 emissions in different operational options compared with the expectations in the investment phase.

country. For example, in the UK the importance of the price ratio of coal and natural gas has risen since the launch of EU ETS, but in Spain, where the electricity market is more regulated, the effects of emissions trading are smaller. Sijm et al. (2006) concluded that the carbon pass-through rates vary for Germany and The Netherlands between 60% and 100% of CO_2 costs, depending on the carbon intensity of the marginal production unit and various other market- or technology-specific factors. Due to those differences the effects of emissions trading on operational flexibility may differ from one market area to another.

In this study, efficiently operating markets were assumed. However, this is not necessarily the case in reality. Electricity can be sold and purchased at an hourly level in the electricity market, but fuel markets are not so efficient. For example, the intermittent selling of bark is not so easy because fuel sales are typically based on long-term agreements. Therefore, especially the results for the years 2004 and 2007 should be considered as a theoretical study.

This paper presents the results from one case study where expectations of cost savings, energy conservation and reduction of CO_2 emissions were based on the energy price level in January 2000. If another base level of energy prices had been selected in the investment phase, the expectations would have been different. However, the relative benefits of operational flexibility compared to the base case in each year are dependent only on the actual price level in that year.

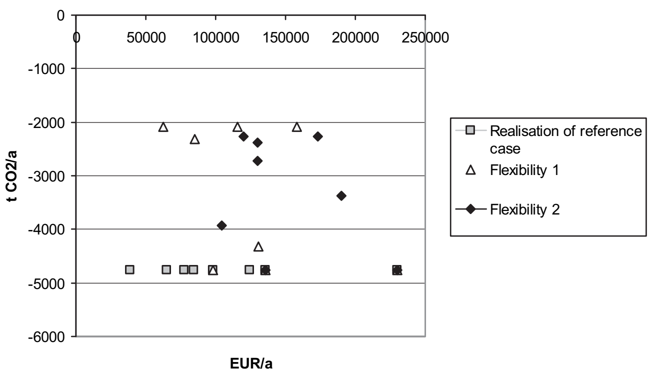

Fig. 6. The realised reduction in annual CO_2 emissions as a function of the annual cost savings.

From the investment profitability point of view, the selected energy prices play a significant role. For example, if the profitability of a heat conservation investment had been evaluated based on the energy price level of February 2001, the simple payback time would have been 5.3 years in the base case. In the case of operational flexibility 2 the payback time would have been 3.5 years. So, in the base case the payback time is much more dependent on the selected energy prices than in the case of flexibility 2, which shows that increased operational flexibility reduces the uncertainties of an investment.

4. Summary and conclusions

Energy conservation is considered to be a promising way of reducing CO_2 emissions. However, evaluating the CO_2 reduction potential of an energy conservation investment is not so straightforward. It has been shown in earlier studies that technological restrictions and economic constraints weaken the opportunities to reach the theoretical energy conservation potential. In addition, there is an "efficiency gap", i.e. market barriers and market failures prevent the exploitation of cost-effective energy efficiency investments. The launch of EU ETS has complicated the analysis of an energy conservation investment because the EUA price and its effects on energy prices have to be taken into account.

The aim of this paper was to study what kind of effects operational flexibility and changes in energy prices have on the realisation of the energy conservation and CO_2 reduction potential of an energy efficiency investment. In this study, the effects of flexibility were analysed by monitoring the cost savings, energy conservation and CO_2 reduction of a hypothetical energy conservation investment made in the pulp and paper industry. The study was based on process modelling and an economic optimisation of energy purchase and sales.

Our study shows that increased operational flexibility increases the cost savings of energy conservation investment but weakens the realisation of energy conservation and CO_2 reduction potential. In our case study, the expected CO_2 reduction potential was reached only in 2005, when the high EUA prices improved the competitiveness of the base case, i.e. reduction of peat consumption (with a high CO_2 emission factor).

The following conclusions can be drawn from the results of this study: (1) a more complicated investment environment and strong fluctuation of the EUA price increases the economic value of operational flexibility, as stated before by Laurikka (2004); (2) in the case of high operational flexibility in the system the operator of an industrial power plant has greater ability to optimise in a number of different ways and consequently it is more difficult to estimate the CO_2 reduction; (3) increased operational flexibility may lead to less than optimum CO_2 reduction when the optimisation is made in the economic dimension – in our case study only around 70% of the expected CO_2 reduction potential was realised in the flexibility cases; (4) high EUA prices give an incentive to reduce CO_2 emissions at the mill site and to achieve the CO_2 reduction potential identified in the investment phase. So, if the EUA prices are high, as they were in 2005, the operational flexibility seems not to bring additional value compared to the base case; and (5) however, if the CO_2 reduction potential had been evaluated more realistically in the investment phase, taking future uncertainties into account, improved flexibility would probably have been favourable in the CO_2 dimension, too.

Uncertainties in the energy markets, such as fluctuating energy prices, increasing dependence on imported fuels and changing climate policy, increase the interest of industrial actors in investing in the operational flexibility of energy production. From the policy-making point of view it is important to understand that increasing operational flexibility has the potential to enable improved sustainability but that the flexibility can also be used to maximise short-term profitability. Such maximisation may result in less than optimum CO_2 reduction.

Acknowledgement

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Nomenclature

CDM	clean development mechanism
CER	certified emission reduction
CHP	combined heat and power
CO_2	carbon dioxide
CS	cost savings
E	electricity
ERU	emission reduction unit
EUA	EU allowance
EU ETS	European Union Emissions Trading Scheme
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRR	internal rate of return
JI	joint implementation
LCA	life cycle assessment
NPV	net present value
p	price
Q	heat/fuel energy
PBP	payback period
PEC	primary energy consumption

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