Publication III

Sari Siitonen and Henrik Holmberg. Estimating the value of energy saving in industry by different cost allocation methods. International Journal of Energy Research. Accepted for publication.

INTERNATIONAL JOURNAL OF ENERGY RESEARCH
Int. J. Energy Res. (2010)

Estimating the value of energy saving in industry by different cost allocation methods

Sari Siitonen*,† and Henrik Holmberg

School of Science and Technology, Department of Energy Technology, Aalto University, P.O. Box 14100, 00076 Aalto, Finland

SUMMARY

In complicated systems, such as a highly integrated industrial plant with its own energy production, estimating the value of energy conservation is not so straightforward. Often, heat is priced using different kinds of methods for allocating the fuel cost to heat and electricity. However, there is no consistent way to valuate the process steam in industry, and not just one useful method for allocating costs to heat and power. In this paper, the energy method, exergy method, benefit distribution method and market-based method are evaluated and compared from different decision-making perspectives. The results of this study indicate that the allocation methods may overestimate by up to 200–300% the benefits from the mill perspective compared to the benefits from the mill site perspective. So, the most suitable method may vary, depending on the selected system boundary, i.e. the decision-making perspective, the type of CHP plant and energy prices. Based on the results of this study, the exergy method fits well with the CCGT plant with a condensing unit and constant fuel input. On the other hand, the market-based method is the most correct way to estimate the value of heat when heat conservation reduces the production of CHP electricity. Copyright © 2010 John Wiley & Sons, Ltd.

KEY WORDS
energy efficiency; CO_2 emissions; CHP production; cost allocation methods; pulp and paper industry

Correspondence
*Sari Siitonen, School of Science and Technology, Department of Energy Technology, Aalto University, P.O. Box 14100, 00076 Aalto, Finland.
†E-mail: sari.siitonen@tkk.fi

Received 20 February 2010; Revised 7 September 2010; Accepted 19 September 2010

1. INTRODUCTION

Energy conservation is seen as the most economic way of reducing CO_2 emissions and dependency on fossil fuels. Combined heat and power (CHP) production is seen as an important technology to enhance energy efficiency and contribute to climate policy objectives [1]. Also, the International Energy Agency (IEA) [2] concludes that CHP, especially in conjunction with district heating and cooling, is an important element in national and regional greenhouse gas emission reduction strategies.

In the Nordic countries, CHP production is widely used in energy-intensive industry. An industrial CHP plant (or cogeneration plant) produces multiple products, i.e. electricity and heat at different pressure levels. When heat is conserved in an industrial process that is integrated into the CHP plant, energy conservation actions also influence the structure of energy supply. Depending on the power plant construction, heat conservation is realized as reduced fuel consumption (and emissions) or increased electricity production. We showed in our previous paper [3] that the definition of system boundaries affects considerably the primary energy conservation and CO_2 reduction achieved by a heat conservation investment. In addition, there are other uncertainties, such as the thermodynamic value of different energy products and energy prices.

CHP production has a high total efficiency, up to 90% or more, and thus consumes around 25% less fuel than the separate production of heat and power [4]. In order to allocate the benefit of CHP production, i.e. fuel conservation between heat and electricity, many different methods have been developed. First, different allocation methods were used to price the heat and electricity produced. Recently, the allocation of CO_2 emissions in CHP power production has also became an important issue. In both cases, the principle is the same, i.e. the fuel consumption of the CHP plant is first allocated to the heat and electricity. The fuel allocation is then multiplied by fuel costs to obtain the monetary value of each energy product. Similarly, the fuel allocation is multiplied by the appropriate carbon dioxide emission factor of the fuel to determine the emissions allocated to each product.

The cost allocation is needed when different products of a CHP plant are sold to the market. In the case of an industrial CHP plant, valuation of the process steam is needed if the CHP plant is outsourced or the industrial plant and CHP plant operate as separate profit centres.

The allocation of CO_2 emissions to electricity and heat is not needed under the European Union Emissions Trading Scheme (EU ETS), since the CO_2 emissions are monitored on the basis of realized fuel consumption at the installation level. However, to price the different products of the CHP plant, the costs of EU allowances (EUA) have to be allocated to each product.

Nowadays an increasing number of consumers are interested in the environmental impacts and carbon footprint of products. In order to calculate the specific CO_2 emissions of different industrial products, the CO_2 emissions of the electricity and heat consumed have to be determined. Therefore, in CHP production the emissions have to be allocated to electricity and heat. In addition, many energy companies report the specific emissions of their electricity production and utilize environmental arguments in marketing.

Analogically, in life cycle assessment (LCA) and environmental/carbon footprint analysis raw materials, energy consumption, CO_2 emissions and other environmental burdens have to be allocated to different products. González *et al.* [5] stated that the allocation of environmental loads in processes with several useful products (co-products) is one of the most important and frequent methodological problems to be tackled when carrying out the life cycle inventory.

There are multiple methods for allocating costs and CO_2 emissions to electricity and heat production in CHP power plants, and they are well described in the literature [6–8]. Liikanen [6] listed and compared the following methods for allocating CO_2 emissions from cogeneration systems:

1. Energy method
2. Exergy method
3. Work method
4. Alternative energy production method
5. Method based on fuel consumption ratios of heat and power
6. Benefit distribution method
7. Method based on economic value of the products (market-based method)

In addition to these methods, Rosen [7] mentions allocation by agreement. This method is widely used in industry where the steam from an industrial CHP plant is used in an industrial production plant on the same site. Rosen also lists the allocation methods of incremental fuel consumption to electrical energy production and incremental fuel consumption to thermal energy production. These are two different applications of the alternative energy production method. In addition, Xue-min Ye [9] presents the reduced exergy method, which is formulated by introducing the concepts of the available anergy and reduced exergy. The International Council of Forest and Paper Associations (ICFPA) [10] presents the simplified efficiency method for allocating emissions from CHP plants. This method is based on the use of assumed efficiency for the production of power and steam.

Different allocation methods have been applied in many studies. Among others, Gochenour [8] has compared different methods for allocating variable costs in the cases of coal-fired and natural-gas-fired CHP plants. VTT [11] has analyzed the impact of the allocation method on the efficiency of electricity generation in CHP.

Regardless of the high number of allocation methods, there is no consensus on which method should be used; rather, different methods are used in different countries and for different purposes. In Finland, Statistics Finland uses both the energy method and the benefit distribution method for the purpose of compiling statistics [12]. Gochenour [8] recommends using the alternative heat supply method and the benefit distribution method for the cost allocation in Eastern European countries in transition so as to ensure the competitiveness of district heat production compared to the other heating alternatives. Rosen [7] feels that the exergy-based method is the most meaningful and accurate of the allocation methods. On the other hand, the market-based method might seem attractive from the business management perspective.

The aim of this paper is to estimate the value of heat conservation in an industrial CHP plant by using different methods for allocating fuel and CO_2 emission costs. In this paper, the energy method, exergy method, benefit distribution method and market-based method are evaluated and compared from different decision-making perspectives.

2. METHODOLOGIES

In this study different allocation methods are applied to two different industrial CHP power plants, one using natural gas and the other solid fuels for energy production. Those CHP processes were analyzed with Solvo$^{®}$, which is a commercial software application for modelling and simulating the heat balances of a power plant in steady-state conditions.

2.1. Different decision-making perspectives

Figure 1 presents the system boundaries considered in this study. The pulp and paper mill in Figure 1 is

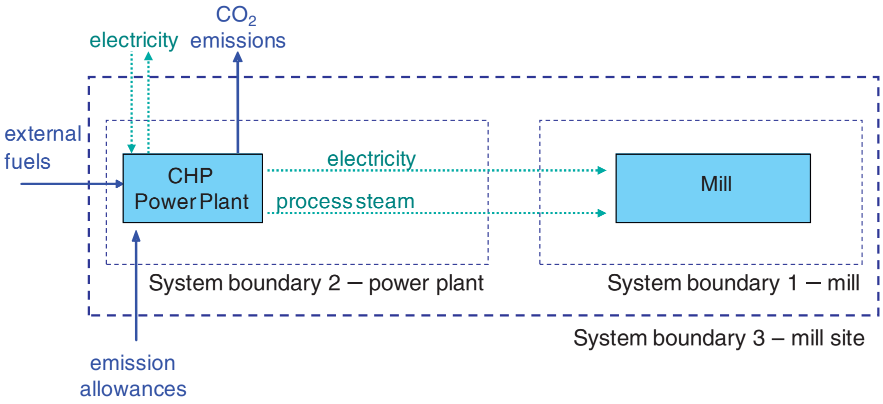

Figure 1. System boundaries of a pulp and paper mill.

integrated with a CHP power plant at the mill site. For simplicity, it is assumed that the CHP power plant is capable of producing all the process steam and electricity required by the mill. In addition, the CHP plant is connected to the electricity market, so it can either sell or purchase additional electricity.

There are three different perspectives to analyze the effects of a heat conservation investment: from the mill perspective (1), less process steam is purchased from the CHP power plant; from the power plant perspective (2), less process steam is fed to the mill, which might affect the demand for external fuels, emission allowances and/or electricity sales/procurement; and from the mill site perspective (3), reduced steam consumption might affect the demand for external fuels, emission allowances and/or electricity sales/procurement. In this study, the costs of emission allowances are included in the fuel prices.

The major difference between the perspectives is that the process steam has to be valuated in perspectives 1 and 2, whereas in perspective 3 the process steam does not cross the system boundary and thus its price is irrelevant. In perspective 3, the energy prices can be used as such, but in perspectives 1 and 2 the fuel costs have to be allocated to each energy product using some kind of allocation method.

Depending on the perspective, the profitability of heat conservation may vary. In this study, the changes in costs/revenues for each perspective are calculated using the following equations:

Perspective 1: *Mill*

$$\text{Changes in steam procurement costs} = (E_{\text{heat},2} - E_{\text{heat},1})P_{\text{heat}} \qquad (1)$$

Perspective 2: *Power plant*

$$\begin{aligned}\text{Changes in revenues} =& (E_{\text{el},2} - E_{\text{el},1})P_{\text{el}} \\ &+ (E_{\text{heat},2} - E_{\text{heat},1})P_{\text{heat}} \\ &- (E_{\text{fuel},2} - E_{\text{fuel},1})P_{\text{fuel}} \qquad (2)\end{aligned}$$

Perspective 3: *Mill site perspective*

$$\text{Changes in energy procurement costs} = (E_{\text{el},2} - E_{\text{el},1})P_{\text{el}} - (E_{\text{fuel},2} - E_{\text{fuel},1})P_{\text{fuel}} \qquad (3)$$

where E_{heat} is the annual heat production/use, E_{el} the annual electricity sales/procurement of the CHP plant, P_{heat} the price of heat, P_{el} the market price of electricity and P_{fuel} the market price of the fuel. Subscript 1 refers to the situation before the heat conservation investment and subscript 2 after the investment.

Equations (1) and (3) give a negative value if heat conservation is profitable. Equation (2) gives a positive value if heat conservation is profitable from the perspective of the CHP plant.

2.2. Description of CHP processes

In this study the implications of heat conservation are analyzed in two different CHP power plant cases. The natural-gas-based CHP technology analyzed in this study is based on the combined cycle gas turbine (CCGT) process, while the solid-fuel-based CHP technology is based on the Rankine cycle. The simplified process charts of the two CHP power plants are presented in Figure 2.

In a CCGT plant, natural gas is combusted with compressed air in the combustion chamber of the gas turbine. The flue gas from the combustion chamber expands through the gas turbine. The mechanical rotation energy is converted into electricity in the generator. The hot exhaust gases from the gas turbine are fed to the heat recovery steam generator (HRSG), where high-pressure feed water is heated, vaporized and superheated in the heat exchangers of the HRSG. Superheated live steam is fed to the steam turbine, where it expands through the turbine and produces 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 industrial plant. The steam releases its heat to the process by condensing and most of the condensate is

DOI: 10.1002/er

pumped back to the feed water tank of the power plant and thence into the HRSG. The process includes a steam turbine condensing unit, which can be used to produce additional electricity for the electricity market.

In the solid-fuel-based boiler, domestic solid fuels such as peat and biomass are combusted in the boiler to produce live steam for the steam turbine. The steam cycle is like that presented above for the CCGT plant, except that there is no steam turbine condensing unit.

Heat conservation at the pulp and paper mill affects the operation of the two power plants in different ways. In the case of the CCGT power plant, reduced demand for process steam enables additional electricity production in the condensing unit. In the solid-fuel-based power plant, reduced steam consumption in the mill reduces CHP electricity production and fuel consumption. In reality, the reduction of CHP electricity production is site specific but we assume here that the reduction can be defined according to the power-to-heat ratio of the industrial CHP plant. It is assumed that heat conservation reduces marginal fuel (peat) consumption, which also reduces the CO_2 emissions from the mill site and the demand for emission allowances. Table I shows the qualitative effects of heat conservation in both power plant cases from the three different perspectives.

2.3. Efficiency and power-to-heat ratio

The European Commission has developed detailed guidelines for the calculation of the electricity produced by cogeneration [13]. The guidelines emphasize that it is necessary to identify the electricity and heat that are not produced in the cogeneration mode. Therefore, heat-only-boilers, which in many cases are part of the on-site technical installations, are to be excluded. Then, the total efficiency of CHP production is calculated according to Equation (4):

$$\eta = \frac{\text{Energy output}}{\text{Fuel input}} \tag{4}$$

If the total efficiency is higher than 80% in the CCGT plant and in plants based on steam-condensing extraction turbines or higher than 75% in the other types of CHP plants, all the measured electrical energy output and all the measured useful heat output can be taken into account when determining the total efficiency of the CHP plant. If the total efficiency is lower than the reference values mentioned above, the power unit can be split into two virtual parts, the CHP part and the non-CHP part. For the CHP part, the actual power-to-heat ratio can be defined according to Equation (5) [13]:

$$\text{Power} - \text{to} - \text{heat ratio} = \frac{\text{Electricity produced}}{\text{Heat produced}} \tag{5}$$

Then, the actual power-to-heat ratio can be used to calculate the CHP electricity production during the reporting period and the consequent primary energy savings.

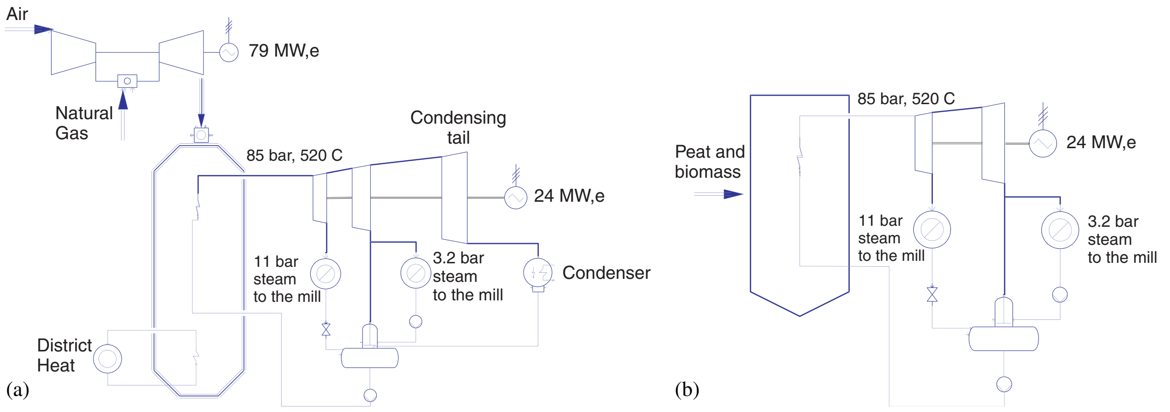

Figure 2. Industrial CHP plants considered in this study: (a) CCGT and (b) solid-fuel-based CHP plant.

Table I. The effects of heat conservation in two different power plant cases from three different perspectives.

	Perspective 1: Mill	Perspective 2: Power plant	Perspective 3: Mill site
CCGT plant	Reduced demand for process steam at a pressure level 3.2 bar	Reduced steam sales Increased electricity production	Increased electricity sales
Solid-fuel-based CHP	Reduced demand for process steam at a pressure level 3.2 bar	Reduced steam sales Reduced peat purchase Reduced purchase of EUAs Increased electricity purchase	Reduced peat purchase Reduced purchase of EUAs Increased electricity purchase

The power-to-heat ratio depends on the power plant construction. Typical power-to-heat ratios for the industrial CCGT and solid-fuel-based power plants are 0.9...1.0 and 0.2...0.3, respectively.

Usually, the heat demand of the industrial plant is covered as a whole by its own heat production. The CHP production process endeavours to utilize this heat load in the best possible way and thus at least some part of the mill's electricity demand can be covered. However, the electricity demand of an industrial plant is seldom in balance with electricity production supplied by the CHP plant. Therefore, in addition to being integrated into the industrial plant, the CHP plant might be integrated into the electricity market. Moreover, industrial plants might sell district heat to the local community.

2.4. Descriptions of selected allocation methods

In this paper, the energy method, exergy method, benefit distribution method and market-based method have been selected for evaluation. These four methods are briefly described below.

2.4.1. Energy method. The energy method is the simplest of the allocation methods. It divides the fuel consumption based on the amounts of energy products. Therefore, fuel consumption is allocated to electricity and heat according to the efficiency of the CHP plant. In the energy method, fuel consumption is allocated to electricity (F_{el}) and heat (F_{th}) according to the following equations [7]:

$$F_{\mathrm{el}} = \frac{E_{\mathrm{el}}}{E_{\mathrm{el}} + E_{\mathrm{th}}} * F \tag{6}$$

$$F_{\mathrm{th}} = \frac{E_{\mathrm{th}}}{E_{\mathrm{el}} + E_{\mathrm{th}}} * F \tag{7}$$

where E_{el} is electricity production, E_{th} heat production and F the realized fuel consumption in the CHP plant.

If a CHP plant can operate in condensing mode, the fuel consumption of condensing power has to be subtracted before utilizing the allocation method [6].

The price of the process steam is calculated as follows:

$$P_{\mathrm{th}} = F_{\mathrm{th}} * P_{\mathrm{fuel}} \tag{8}$$

2.4.2. Exergy method. Exergy is defined as the 'useful' energy, or the ability to do or receive work [14]. It can also be viewed as a measure of the quality of energy. Exergy is always destroyed in all processes because processes are irreversible, generating entropy. When emitted to the environment, exergy represents a potential to cause changes in the environment, i.e. environmental impacts [15]. The exergy method is based on the general principles of exergy analysis presented in the literature [14–18] and widely applied to thermodynamic evaluation of thermal power plants [19–21].

In the exergy method, fuel consumption is allocated to electricity and heat as follows [7]:

$$F_{\mathrm{el}} = \frac{\mathrm{Ex}_{\mathrm{el}}}{\mathrm{Ex}_{\mathrm{el}} + \mathrm{Ex}_{\mathrm{th}}} * F \tag{9}$$

$$F_{\mathrm{th}} = \frac{\mathrm{Ex}_{\mathrm{th}}}{\mathrm{Ex}_{\mathrm{el}} + \mathrm{Ex}_{\mathrm{th}}} * F \tag{10}$$

where $\mathrm{Ex}_{\mathrm{el}}$ and $\mathrm{Ex}_{\mathrm{th}}$ denote electrical exergy and thermal exergy, respectively.

Since the thermodynamic value of electricity is equal to 1, electrical exergy is equivalent to electrical energy. The thermal exergy can be calculated using the classic exergy equation, as follows:

$$\mathrm{Ex} = \dot{m}[(h_1 - h_2) - T_0(s_1 - s_2)] \tag{11}$$

where $\dot{m}$ is the mass flow of process steam in this case, h_1 is the specific enthalpy of the flow at the inlet, h_2 is the specific enthalpy of the flow at the outlet, T_0 is the environmental temperature, s_1 is the specific entropy of the flow at the inlet and s_2 is the specific entropy of the flow at the outlet.

Contrary to the allocation method based on energy content of products, the exergy method accounts for the thermodynamic value of energy.

The price of the process steam is calculated according to Equation (8) in a similar way as in the energy method.

2.4.3. Benefit distribution method. By using the benefit distribution method the benefits of CHP production are divided between both electricity and heat. The allocation is based on shared fuel savings between electrical and thermal energy.

The benefit distribution method was developed in Finland in the early 1990s for the cost allocation of CHP production [6,22]. In this method, the fuels used in CHP production are allocated to electricity and heat in proportion to the fuel consumption for the alternative energy supply forms. The alternatives used are condensing power production and heat production in a heat-only boiler. The fuel consumption of the alternative forms of energy supply, F'_{el} for electrical energy and F'_{th} for thermal energy, can be calculated according to the equations below [6]:

$$F'_{\mathrm{el}} = \frac{E_{\mathrm{el}}}{\eta_{\mathrm{el}}} \tag{12}$$

$$F'_{\mathrm{th}} = \frac{E_{\mathrm{th}}}{\eta_{\mathrm{th}}} \tag{13}$$

where E_{el} is electricity production in the CHP plant, η_{el} the efficiency of the alternative form of electricity production (condensing power), E_{th} heat production in the CHP plant and η_{th} the efficiency of the alternative form of heat production (heat-only boiler). The constant efficiencies of 39 and 90% are used for the alternative forms of electricity and heat production, respectively. The efficiencies correspond to the average existing energy production structure in Finland.

The realized fuel consumption in the CHP plant, F, is divided according to the ratio of the fuel consumption of the alternative energy supply forms, as follows [6]:

$$F_{\mathrm{el}} = \frac{F'_{\mathrm{el}}}{F'_{\mathrm{el}} + F'_{\mathrm{th}}} * F \tag{14}$$

$$F_{\mathrm{th}} = \frac{F'_{\mathrm{th}}}{F'_{\mathrm{el}} + F'_{\mathrm{th}}} * F \tag{15}$$

Separate production of condensing power or heat and their fuel consumption are subtracted before utilizing the allocation method [6].

The price of the process steam is calculated in a similar way as in the energy method and exergy method.

2.4.4. Market-based method. In Finland, both fuel and electricity prices are determined in open energy markets. By using the market-based method the heat price can be determined on the basis of those two prices. That method is used in the Finnish forest industry. The formulas used here are modified based on the description by Kilponen *et al.* [23] of the pricing of conserved steam.

The power-to-heat ratio is defined as follows:

$$\alpha_{\mathrm{steam}} = \frac{W_{\mathrm{el}}}{Q_{\mathrm{process}}} \tag{16}$$

where W_{el} is the power production and Q_{process} is the heat demand of the process.

There are usually two pressure levels for the process steam (extraction steam and backpressure steam) in an industrial CHP plant, and the power-to-heat ratio can be separately defined for both steam pressure levels. In this case, W_{el} in Equation (16) represents the electricity available from the turbine when steam expands from the pressure of live steam to the pressure of process steam. In the CCGT plant, the power production of the gas turbine must also be allocated to the power-to-heat ratios of the process steams. For example, for backpressure steam the power-to-heat ratio can be calculated as follows:

$$\alpha_{\mathrm{bp,\ steam}} = \frac{\frac{\dot{m}_{\mathrm{bp}}}{\dot{m}_{\mathrm{ls}}} W_{\mathrm{gt}} + \eta_{\mathrm{st}}\eta_{\mathrm{g}}\dot{m}_{\mathrm{bp}}(h_{\mathrm{ls}} - h_{\mathrm{bp}})}{\dot{m}_{\mathrm{process}}(h_{1,\mathrm{process}} - h_{2,\mathrm{process}})} \tag{17}$$

where W_{gt} is the power produced by the gas turbine, η_{st} the mechanical efficiency of the steam turbine, η_{g} the efficiency of the steam turbine's generator, h_{ls} the enthalpy of the high-pressure live steam, h_{bp} the enthalpy of the backpressure steam, $h_{1,\mathrm{process}}$ the enthalpy of the steam used in the process and $h_{2,\mathrm{process}}$ the enthalpy of the condensate coming back from the process. Mass flow $\dot{m}_{\mathrm{ls}}$ is the production of high-pressure live steam, $\dot{m}_{\mathrm{bp}}$ the steam mass flow taken out of the turbine at the pressure of backpressure and $\dot{m}_{\mathrm{process}}$ the steam mass flow used as process steam. The mass flow $\dot{m}_{\mathrm{bp}}$ includes the mass flow used to heat feed water in the feed water tank and therefore differs from the mass flow $\dot{m}_{\mathrm{process}}$.

In the solid-fuel-based CHP, the term W_{gt} is zero. As Equation (17) reveals, the power-to-heat ratios can be calculated separately for the process steam at different pressure levels.

If one energy unit of process heat is produced, the power-to-heat ratio defines the amount of power produced. The fuel consumption F can be defined as follows:

$$F = \frac{1 + \frac{\alpha_{\mathrm{steam}}}{\eta_{\mathrm{t}}\eta_{\mathrm{g}}}}{\eta_{\mathrm{process}}} \tag{18}$$

where η_{t} is the mechanical efficiency of the turbine and η_{process} the process efficiency of the CHP plant. The process efficiency in Equation (18) is calculated using the following definition:

$$\eta_{\mathrm{process}} = \frac{\frac{W_{\mathrm{gt}}}{\eta_{\mathrm{gt}}\eta_{\mathrm{g}}} + \frac{W_{\mathrm{st}}}{\eta_{\mathrm{st}}\eta_{\mathrm{g}}} + Q_{\mathrm{process}}}{F} \tag{19}$$

where η_{gt} is the mechanical efficiency of the gas turbine, W_{st} the power produced by a steam turbine and η_{st} the mechanical efficiency of the steam turbine. For the solid-fuel-based CHP, the term W_{gt} is zero, and the process efficiency is equal to the boiler efficiency with a good accuracy.

By multiplying Equation (18) by the fuel price we obtain the operational costs of the CHP plant when one energy unit of heat is produced. The CHP plant also produces electricity and by selling the electricity at the market price the price of heat produced becomes:

$$P_{\mathrm{th}} = \frac{\left(1 + \frac{\alpha_{\mathrm{steam}}}{\eta_{\mathrm{st}}\eta_{\mathrm{g}}}\right) P_{\mathrm{fuel}}}{\eta_{\mathrm{process}}} - \alpha P_{\mathrm{el}} \tag{20}$$

where P_{fuel} is the market price of fuel and P_{el} the market price of electricity.

In an industrial CHP plant, no explicit price for process steam exists and therefore the method based on economic value of the products has been adjusted to a method based on the market prices of electricity and fuel. The method described above has been used to some extent in the Finnish pulp and paper industry.

3. RESULTS AND DISCUSSION

3.1. Base cases

In the theoretical analysis the effects of process steam conservation on two different CHP plant cases, a CCGT plant and a solid-fuel-based plant, were studied. The effects of process steam conservation were studied by reducing the low-pressure (3.2 bar) steam consumption by 2 MW. Calculation of the annual changes was based on an estimated peak load hours of 8000 h a^{-1}.

In the base case, the total efficiencies of the CCGT and solid-fuel-based power plants are 90 and 88%, respectively.

Table II shows the energy prices used in this study. The fuel prices presented here include the EUA cost of $10\,\text{euro}\,t^{-1}$ CO_2. Therefore, the emission factors used for natural gas and peat [24] are also presented in the table. The energy prices have varied a lot in the Nordic energy market lately. So, the prices used in this study represent typical prices over recent years.

Table II. Emission factors and energy prices used in this study.

	CCGT plant (natural gas)	Solid-fuel-based CHP (peat)
Emission factor ($t\,MWh_{fuel}^{-1}$)	0.198	0.381
EUA cost included in the fuel price ($euro\,MWh_{fuel}^{-1}$)	1.98	3.81
Fuel price including EUA cost ($euro\,MWh_{fuel}^{-1}$)	25	13
Electricity price ($euro\,MWh_{el}^{-1}$)	40	

Since the fuel prices presented here include the EUA cost, the costs of CO_2 emissions are automatically allocated to electricity and heat when the different allocation methods are used.

The implications of heat conservation investment are dependent on the perspective. In the mill where energy production is integrated into industrial production, the mill site perspective (perspective 3) gives the whole picture and no cost allocation is needed. However, when the mill and power plant are different product centres, different allocation methods give different results. Table III collects the changes due to

Table III. The effects of heat conservation in the base case: electricity price of $40\,\text{euro}\,MWh^{-1}$, natural gas price of $25\,\text{euro}\,MWh^{-1}$ and peat price of $13\,\text{euro}\,MWh^{-1}$ (fuel prices include EUA price of $10\,\text{euro}\,t^{-1}$).

	CCGT				Solid-fuel-based CHP			
	Energy method	Exergy method	Benefit distribution method	Market-based method	Energy method	Exergy method	Benefit distribution method	Market-based method
Perspective 1: Mill								
Steam conservation ($MWh\,a^{-1}$)	16 000	16 000	16 000	16 000	16 000	16 000	16 000	16 000
Price of 3.2 bar steam ($euro\,MWh^{-1}$)	27.8	14.4	16.9	21.0	14.9	10.2	11.4	7.3
Changes in steam procurement costs ($euro\,a^{-1}$)	−395 679	−170 791	−251 843	−352 574	−237 744	−162 663	−183 180	−116 502
Perspective 2: Power plant								
Changes in steam sales ($MWh\,a^{-1}$)	−16 000	−16 000	−16 000	−16 000	−16 000	−16 000	−16 000	−16 000
Changes in fuel consumption ($MWh\,a^{-1}$)	0	0	0	0	23 848	23 848	23 848	23 848
Changes in EUAs ($t\,a^{-1}$)	0	0	0	0	−9 086	−9 086	−9 086	−9 086
Increase in electricity sales (−)/purchase (+) ($MWh\,a^{-1}$)	−3 031	−3 031	−3 031	−3 031	4862	4862	4862	4862
Changes in revenues ($euro\,a^{-1}$)	−324 037	−115 639	−149 844	−135 890	−122 189	−47 107	−67 625	−946
Perspective 3: Mill site								
Changes in fuel consumption ($MWh\,a^{-1}$)	0				−23 848			
Changes in EUAs ($t\,a^{-1}$)	0				−9086			
Changes in electricity sales (−)/purchase (+) ($MWh\,a^{-1}$)	−3031				4862			
Changes in energy procurement costs ($euro\,a^{-1}$)	−121 231				−115 556			

heat conservation from the different perspectives for two power plant cases.

From the mill perspective the heat conservation is profitable regardless of the selected method. Since the allocation methods typically overestimate the benefits from the mill perspective—in some cases up to 200–300% compared to the benefits from the mill site perspective—the power plant loses its revenues at the same time. The only exception is the market-based method in the case of solid-fuel-based CHP production, which gives the same results from the mill and mill site perspectives. In the case of the CCGT plant, the exergy method seems to be the best method, although it, too, overestimates by around 40% the benefits from the mill perspective compared to the mill site perspective.

3.2. Sensitivity analyses

Sensitivity analyses were made by varying the fuel and electricity prices. The electricity price was varied from 20 to 60 euro MWh^{-1}, the natural gas price from 15 to 35 euro MWh^{-1} and the peat price from 10 to 22 euro MWh^{-1}. The fuel prices here include the costs of emission trading and the highest fuel prices of 35 and 22 euro MWh^{-1} are expected to occur in the situation where the EUA price is 30 euro t^{-1} CO_2. In the Nordic electricity market, coal-based condensing power is marginal most of the time and there is no dependence between electricity price and the prices of natural gas and peat. Therefore, in principle, there can be situations where the electricity price is high and fuel prices are low, and vice versa. However, since the EUA price strongly affects the electricity price in the Nordic electricity market because of the carbon pass-through effect, the combination of low electricity price and high fuel prices is not so common, but might happen in the circumstances of an excellent hydrological year.

Figure 3 shows the results of the sensitivity analyses. The mill perspective (1) of different allocation methods has been compared with the mill site perspective (3). If the curves are above the x-axis the method overestimates the benefits from the mill perspective compared with the mill site perspective. On the other hand, the

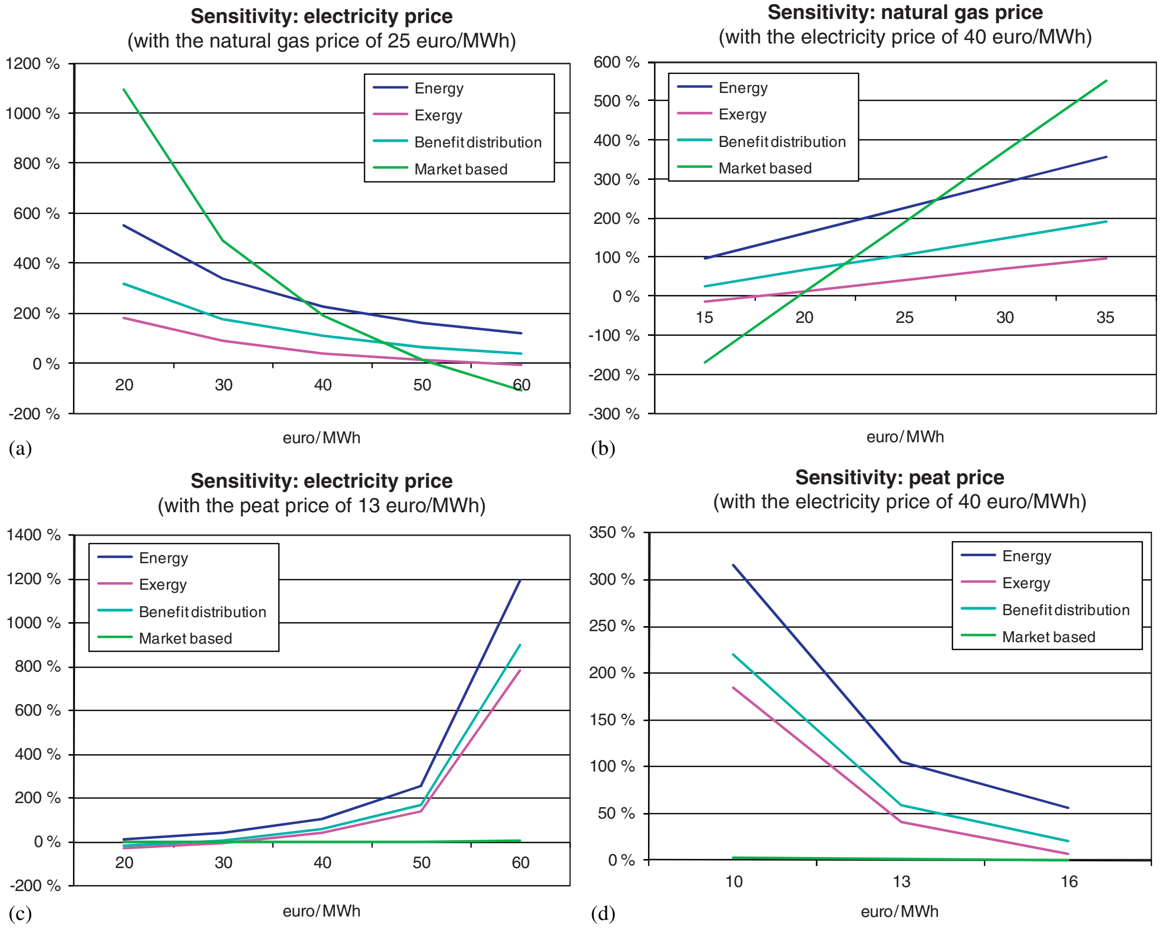

Figure 3. Sensitivity analyses: (a) CCGT, natural gas price of 25 euro MWh^{-1}; (b) CCGT, electricity price of 40 euro MWh^{-1}; (c) solid-fuel-based CHP, peat price of 13 euro MWh^{-1}; and (d) solid-fuel-based CHP, electricity price of 40 euro MWh^{-1}.

curves below *x*-axis show that the benefits are greater from the mill site perspective than from the mill perspective.

In the CCGT plant, heat conservation does not reduce fuel input and all revenues come from the increased electricity sales to the market. From the mill site perspective, this means that revenues from heat conservation depend only on the market price of electricity and not on the fuel price. As the calculation results in Figure 3(a, b) show, all allocation methods give a different value for the heat conservation investment from the mill perspective and mill site perspective. With an increasing electricity price and decreasing fuel price the difference between the mill and the mill site perspectives is lower. In the market-based method the difference becomes negative, which means that this method underestimates the benefits from the mill perspective with high electricity prices and low natural gas prices.

In the case of a solid-fuel-based power plant, heat conservation in the mill reduces electricity production, which has to be compensated by purchased electricity from the market: the higher the market price of electricity, the more money will be lost by the power plant. In some cases, the market-based allocation method may give a negative price for heat, which means that heat conservation is not profitable.

The market-based method allocates the costs correctly—the profitability of a heat conservation investment seems similar from the mill and mill site perspectives. When other allocation methods are used, the heat price is only based on the fuel price. On the basis of the results (Figure 3(c, d)) energy conservation seems more profitable from the mill than the mill site perspective—the electricity price does not affect the cost allocation and the higher the market price of electricity, the higher the electricity purchase costs from the power plant perspective.

Figure 4 compares different methods with different combinations of electricity and fuel prices. The figure shows both the mill perspective compared with mill site perspective (1/3) and the power plant perspective compared with the mill site perspective (2/3).

When the heat conservation investment from the mill site perspective is compared with the mill and CHP plant perspectives, the exergy method is, in the case of the CCGT plant, the best way to valuate the heat. The other methods give better results only when the natural gas price is low at the same time as the electricity price is high.

The results are different in the case of the solid-fuel-based power plant, where the market-based method is the best method. The market-based method is not the best method for the CCGT because its mode of operation is not dependent on the process heat demand, i.e. the condensing unit produces additional electricity. In the cases where the exergy method allocates costs to electricity production in excess of the market price of electricity, it gives the best results from the power plant perspective also in the case of the solid-fuel-based CHP; therefore, heat conservation would be profitable from the power plant perspective because it is cheaper to buy electricity from the market than to produce it in the power plant.

The case study examples reveal that the most suitable valuation method for heat depends on the power plant type. If the CHP plant has only a back-pressure turbine without a condensing unit, the market-based method must be recommended, because it gives the same result for the heat conservation investment from the perspective of the mill and mill site. If the CHP plant is equipped with a condensing unit, the choice of method for the valuation of heat is not so obvious. In the case studies the exergy method is the best method in most cases, but it is noteworthy that the value of the heat conservation investment is not the same from the mill and mill site perspectives.

4. CONCLUSIONS

There is no consistent way to estimate the value of heat conservation in industry, and not just one useful

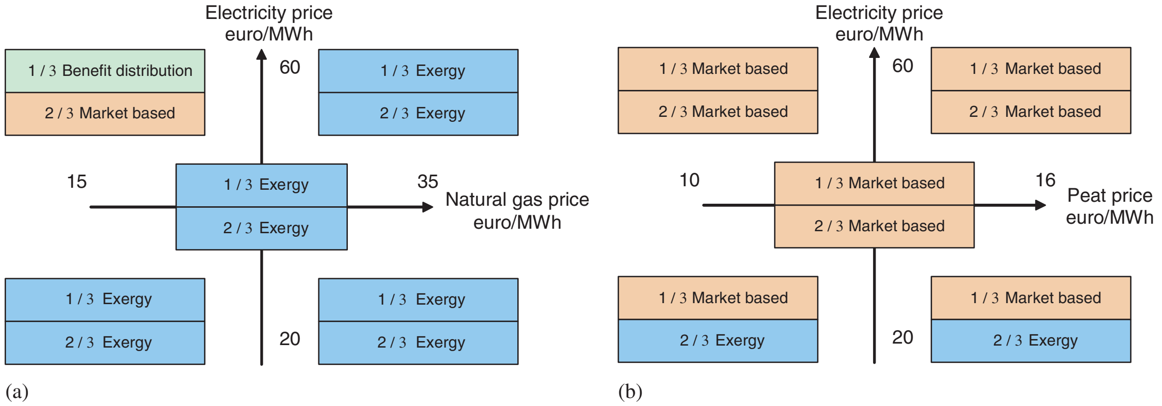

Figure 4. The best methods from the mill (1/3) and power plant (2/3) perspectives with different combinations of electricity and fuel prices: (a) CCGT plant and (b) solid-fuel-based CHP plant.

method for allocating costs to heat and power. Instead, the most suitable method may vary, depending on (1) the system boundary selected, i.e. the decision-making perspective, (2) the type of CHP plant and (3) energy prices. Based on the results of this study, the exergy method fits well with the CCGT plant with a condensing unit and constant fuel input. On the other hand, it is reasonable to conclude that the market-based method is the most correct way to valuate the heat price when heat conservation reduces the production of CHP electricity. Both the energy method and the benefit distribution method typically used in Finnish industry overestimate the profitability of heat conservation investments from the mill perspective.

In the cases where the power plant is not outsourced, the allocation problem can be avoided by using the wider system boundary of the mill site. However, if decision-making is not possible at the mill site level and the costs have to be allocated to heat and electricity, the differences between the allocation methods should be understood and the most suitable method for each case should be selected on the basis of an analytical review of different allocation methods.

NOMENCLATURE

CCGT = combined cycle gas turbine
CHP = combined heat and power
E = energy production (J)
EUA = EU allowance
EU ETS = European Union Emissions Trading Scheme
Ex = exergy (W)
F = fuel consumption (J)
HRSG = heat recovery steam generator
h = specific enthalpy ($\mathrm{J\,kg^{-1}}$)
ICFPA = International Council of Forest and Paper Associations
IEA = International Energy Agency
LCA = life cycle assessment
$\dot{m}$ = mass flow ($\mathrm{kg\,s^{-1}}$)
P = price (euro $\mathrm{MWh^{-1}}$)
p = price of energy product (euro $\mathrm{MWh^{-1}}$)
T = temperature (K)
s = specific entropy ($\mathrm{J\,kg^{-1}\,K^{-1}}$)
W = power output (W)

Greek letters

α = power-to-heat ratio
η = efficiency (%)

Subscripts

0 = environment
1 = inlet/starting situation
2 = outlet/end situation
bp = backpressure
c = condenser pressure
el = electrical energy
g = generator
gt = gas turbine
ls = live steam
max = maximum
st = steam turbine
th = thermal energy

ACKNOWLEDGEMENTS

This study has been financed by the Finnish Funding Agency for Technology and Innovation (Tekes) under the ClimBus programme. The colleague of the authors, Mari Tuomaala, is greatly acknowledged for her many valuable comments.

REFERENCES

1. EC. Europe can save more energy by combined heat and power generation. Communication from the Commission to the European Parliament and the Council, Brussels, 13.11.2008, COM (2008) 771 final. 9p. Available from: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2008:0771:FIN:EN:PDF. Accessed on February 12, 2009.
2. IEA. Combined heat and power—evaluating the benefits of greater global investment. OECD/IEA: Paris, 2008; 39. Available from: http://www.iea.org/Textbase/Papers/2008/CHP_report.pdf. Accessed on February 12, 2009.
3. Siitonen S, Tuomaala M, Suominen M, Ahtila P. Implications of process energy efficiency improvements for primary energy consumption and CO_2 emissions at the national level. *Applied Energy* 2010; **87**:2928–2937.
4. IEA. *Energy Technology Perspectives 2008—Scenarios and Strategies to 2050*. OECD/IEA: Paris, 2008.
5. González A, Sala JM, Flores I, López LM. Application of thermoeconomics to the allocation of environmental loads in the life cycle assessment of cogeneration plants. *Energy* 2003; **28**:557–574.
6. Liikanen J. Allocation of emissions in combined heat and power production. Ministry of Trade and Industry, *Studies and Reports 19/1999*, Helsinki, 76 (in Finnish).
7. Rosen MA. Allocating carbon dioxide emissions from cogeneration systems: descriptions of selected output-based methods. *Journal of Cleaner Production* 2008; **16**:171–177.
8. Gochenour C. *Regulation of Heat and Electricity Produced in Combined-Heat-and-Power Plants*. The World Bank: Washington, 2003.

9. Xue-min Ye. Reduced exergy method for heat-electricity cost allocation in combined heat and power plants. *Entropy* 2003; **5**:432–443.
10. ICFPA. Calculation tools for estimating greenhouse gas emissions from pulp and paper mills. Version 1.0. A project of the Climate Change Working Group. 2002.
11. VTT. *Energy Use*. Visions and Technology Opportunities in Finland: Helsinki, 2007.
12. Statistics Finland. Energy Statistics—Yearbook, Helsinki, 2008.
13. EC. Commission decision of 19 November 2008 establishing detailed guidelines for the implementation and application of Annex II to Directive 2004/8/EC of the European Parliament and of the Council. 2008/952/EC. 7p. Available from: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri = OJ:L:2008:338:0055:0061:EN:PDF. Accessed on March 18, 2009.
14. Bejan A. Fundamentals of exergy analysis, entropy generation minimization, and the generation of flow architecture. *International Journal of Energy Research* 2002; **26**:545–565.
15. Rosen MA, Dincer I. On exergy and environmental impact. *International Journal of Energy Research* 1997; **21**:643–654.
16. Bejan A. *Entropy Generation Minimization. The Method of Thermodynamic Optimization of Finite-Size Systems and Finite-Time Processes*. CRC Press: Boca Raton, New York, London, Tokyo, 1996.
17. Szargut J. *Exergy Method*: *Technological and Ecological Applications*. WIT Press: U.K., U.S.A., 2005.
18. Rosen MA. Second law analysis: approaches and implications. *International Journal of Energy Research* 1999; **23**:415–429.
19. Ferdelji N, Galović A, Guzović Z. Exergy analysis of co-generation plant. *Thermal Science* 2008; **12**(4):75–88.
20. Wølneberg PW, Ertesvåg IS. Alternatives for power supply to natural-gas export compressors combined with heat production evaluated with respect to exergy utilization and CO_2 emissions. *Energy Conversion and Management* 2008; **49**: 3531–3540.
21. Siitonen S, Rauhamäki J. The role of natural gas in energy efficiency improvement. Presented at *World Gas Conference*, Buenos Aires, 5–9 October 2009; 11.
22. Siitonen S, Ahtila P. Possibilities of reducing CO_2 emissions in the Finnish forest industry. *Finnish Forest Industries Federation 1/2002*, Helsinki, 2002; 93+2.
23. Kilponen L, Ahtila P, Parpala J, Pihko M. Improvement of pulp mill energy efficiency in an integrated pulp and paper mill—a case study. *Research Report A5*, HUT/EVO, Otaniemi, 2000.
24. Statistics Finland. Fuel classification. 2006. Available from: http://www.stat.fi/tup/khkinv/khkaasut_polttoaineluokitus.xls. Accessed on February 26, 2009.