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Journal of Food Engineering 77 (2006) 792–802

JOURNAL OF
FOOD
ENGINEERING

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Energy efficiency in the slaughter and meat processing industry—opportunities for improvements in future energy markets

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Received 11 June 2005; accepted 2 August 2005
Available online 22 September 2005

Abstract

In the study presented in this paper different energy efficiency measures that can be carried out in a slaughter and meat processing (SMP) plant were evaluated both in terms of economy and CO_2 emission reduction for four different future energy market developments. It was found that it is economically interesting to invest in an increased heat exchanger network or heat pumps in the fictitious non-integrated plants studied and that between 5% and 35% of the total CO_2 emissions can be saved. The most cost effective way of reducing CO_2 emissions was found to be switching fuel from heavy fuel oil to natural gas or wood chips. For the studied plants that are already heat integrated it was shown that investing in a new heat pump can be economically interesting and can reduce CO_2 emissions.

The profitability of investing in a combined heat and power (CHP) unit for the SMP plants was also investigated and found to be smaller than extended heat recovery or new heat pumps in the studied plants. However, the payback period for CHP units installed at an ecocyclic industrial park, consisting of an SMP plant and for example a Swedish dairy, was found to be short enough to be interesting.

Keywords: Energy efficiency; Combined heat and power; Heat pumps; Heat recovery; Slaughter and meat processing

1. Introduction

The consumption of industrially processed meals, such as ready-made and semi-prepared meals, is increasing in Sweden, see Eidstedt, Svensson, and Wikberger (2004), as well as in other countries, see for example Olsson (2003). As these meals replace home-made meals, a larger part of the energy used in a meal's life cycle is found in food processing plants. In a study by Sonesson, Mattson, Nybrant, and Ohlsson (2004) the environmental impact of three similar but differently prepared meals (home-made, semi-prepared and ready-made) was quantified with Life Cycle Assessment methodology. The differences between the total emissions and the energy use for the preparation of the meals were shown to be small, and agriculture was the dominating contributor to the environmental impact. However, the industrial energy use in the life-cycle of the semi-prepared and ready-made meals represented a larger part of the total energy use than was the case for the home-made meal. In this paper, the slaughter and meat processing (SMP) industry is used as a representative for the semi-prepared foods industry.

Even if the industrial energy use is not a large part of the life cycle of a meal, increased energy efficiency in a plant is important for an SMP plant's profitability, especially as energy prices rise. Technically interesting options of making SMP plants more energy efficient have been found by Fritzson and Berntsson (2005). In the paper the possibilities of increasing heat integration, heat pumping and reducing the electricity use in an SMP plant were examined. Among other results, a potential of saving external heat demand by installing a heat pump was found. Similarly,

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0260-8774/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jfoodeng.2005.08.005

Nomenclature

α	efficiency for a CHP, $\frac{\text{total electricity production}}{\text{total heat production}}$ (%)
η_T	the isentropic efficiency of the turbine. It describes the turbine's capacity to transfer the energy content of the steam to mechanical work (%)
η_{tot}	total efficiency for a CHP, $\frac{\text{total (electricity + heat) production}}{\text{total fuel consumption}}$ (%)
IP	integrated plant
HRSG	heat recovery steam generator
NIP	non-integrated plant
PBP	payback period (years)
SMP	slaughter and meat processing

an energy investigation at a relatively large ready-made meal producer in Sweden has shown that in a plant with heat and electricity demands close to those in one of the plants studied in this paper it is profitable to install a heat pump (Gierow, 2004).

In addition to an increasing production of industrially processed food, there is also a trend in the European countries towards fewer and larger SMP plants (European Commission, 2003). As plant sizes increase, there is an increased potential for saving energy, and thereby decreasing the CO_2 emissions associated with energy use in the plants, by means of, for example, extended internal heat exchange or installation of a heat pump.

Increasing the size of a food processing plant also increases the potential for a combined heat and power (CHP) plant supplying both electricity and heat to the plant. A CHP plant can consist of a steam turbine operated together with a boiler or a gas turbine with a heat recovery steam generator (HRSG). A large gas engine can also be part of a suitable CHP plant for a food processing plant; however, this is not studied in this paper. A steam turbine can be operated with various types of boilers and fuels while a gas turbine usually uses natural gas as fuel. Steam turbines are frequent in the Swedish pulp and paper industry where there are large steam excesses well suited for a turbine. In the Swedish food industry CHP plants are almost non-existing. In other parts of Europe CHP plants are, according to Colonna and Gabrielli (2003), "rather common" in the food industry. This is due to generally larger plant sizes and historically higher electricity prices than in Sweden. In addition, some installations of trigeneration plants that use steam for cooling as well as for power production have been introduced in plants in Europe (Colonna & Gabrielli, 2003). In the US, gas turbine plants in the food industry are reported by Axford and Bailey (1992) for large cold warehouses, a fruit processing plant and a large cheese plant.

To obtain even larger energy utility systems it can be profitable to locate several different food processing plants or other industrial plants in the same area, so called ecocyclic industrial parks, so that different companies can "co-own" the utility system. Nearby residential areas can also be included as the production of district heating can represent an extra profit to the plants. Integration of the energy utility system or several plants of district heating systems can enable investments that would not be profitable for a stand-alone plant.

As SMP plants increase in size a more efficient production at the plant can be obtained, from an energy, as well as from a waste and loss of raw material, point of view. In this paper, however, only the energy efficiency aspects are addressed.

Naturally, as plants get fewer and larger the lengths of transports to and from the SMP plants increase. This has consequences for transport emissions and fossil fuel use for transports of finished products from the SMP plant to distribution centers, but also for the emissions and fossil fuel use for the animal transport to the slaughterhouse and for the animal's welfare. These issues are not further studied in this paper.

In this paper, several different fictitious SMP plants based on real production sites (see Fritzson & Vamling, 2004; Fritzson & Berntsson, 2005), are studied. The plants have different heating and cooling demands as well as production capacities, and in the study, changes are made to save external heat demand in the plants and to reduce emissions associated with energy use at the plant. The pay-back periods and the changes in CO_2 emissions are calculated and compared for these options. The changes considered are:

- increasing heat integration by an extended heat exchanger network,
- integrating one or more heat pumps,
- installing a steam turbine producing electricity to the plant from steam either from the already existing heavy fuel oil boiler or from a new boiler using other types of fuels and
- installing a gas turbine using natural gas.

2. Aim

The aim of this paper is to compare different energy efficiency measures carried out in a slaughter and meat processing plant and to evaluate these measures both in terms of economy and CO_2 emission reduction. Four different fictitious plants with different production sizes and external heating and cooling demands are compared. The comparison is made for four different future combinations of energy market parameters such as energy prices and emissions from electricity production.

Another objective is to consider the potential for implementing a steam or gas turbine into the plants assuming the future combinations of energy market parameters sets mentioned above.

3. Methodology

Three factors are important when studying different energy efficiency measures for a plant: the development of the energy market, e.g. the energy costs and policy instruments, the size of the plant and its energy demands, as well as what type of energy efficiency measures that already have been applied. To study these parameters in a systematic way, four fictitious plants based on real plants are studied. The plants have two different sizes and two degrees of heat integration and they are studied for four different future energy market parameter sets.

3.1. The studied plants

All fictitious SMP plants studied in this paper are assumed to produce the same products with the same sort of equipment but in different amounts. The plants have a rather large electricity demand and the electricity is bought from the grid. The electricity demands include electricity for compressors in refrigeration and freezing plants, air compressors and different types of conveyor equipment. Heavy fuel oil is used in a steam boiler to produce process steam and warm, hot and tap water as well as comfort heating. Some of the steam demand for heating water can be decreased by using typical heat excesses, such as heat in refrigeration plants and compressors, for heat exchange. The time of operation is set to 6300 h/year.

The non-integrated plant 1 (*NIP1*) is a plant where none of the heat integration measures mentioned above have been made, see Table 1. All of its heat demand is supplied by the boiler.

NIP2 is comparable to NIP1 but production and all demands and excesses are doubled, see Table 1.

The integrated plant 1 (*IP1*) is a plant with the same production and basic heat and electricity demands as NIP1, but a large part of the heat demands in the plant are met by heat integration and two installed heat pumps, see Table 1. The heat integration shown in Fritzson and Berntsson (2005), such as using the heat excess from compressor cooling water and heat in the refrigeration media in superheaters and condensers, are used in IP1. They can be considered reasonable energy saving measures in an SMP plant. IP1 has a higher electricity demand than NIP1 because of electricity use in its heat pumps.

IP2 is comparable to the IP1 but production and all demands and excesses are doubled. The amount of integration and heat pumping in the plant is also doubled, see Table 1.

Both NIP1 and IP1 have a size representing a relatively large existing SMP plant for Swedish conditions. The energy data, such as electricity consumption and heat demand, for these plants are taken from Fritzson and Berntsson (2005). As the trend towards larger and fewer plants develops, a reasonable size of such a plant in the future is double the size of the current plants.

3.1.1. System boundaries

The system boundary for the energy related CO_2 emissions considered in this study is set on a global level. The fuels used at the plant give CO_2 emissions when being combusted at the plant and during production and transportation of the fuel. Changes in the amount of electricity purchased from the grid are assumed to change the marginal production of electricity in the national/international grid.

3.2. Data

The energy efficiency measures considered in this paper are briefly described in this section. For more information, see for example Smith (2005) or Sinnott (1999).

Table 1
The studied plants

Case	NIP1	NIP2	IP1	IP2
SMP production [kg]	x[a]	$2x$	x	$2x$
Plant heat demand [MW]	2.9	5.9	2.9	5.9
Integration[b] [MW]	0	0	1.0	2.1
Heat excess from heat pumps [MW]	0	0	0.9	1.8
Process steam demand [MW][c]	0.9	1.8	0.9	1.8
Total steam demand [MW][d]	3.8	7.7	1.9	3.8
Fuel demand [GWh/year]	26.7	53.3	13.2	26.3
Electricity demand [GWh/year]	31	62	32.2	64.3

[a] x corresponds to slaughter of approximately 700 000 animals per year, the greatest part of which is pigs, plus processing meat into different meat products.

[b] Integration in this context means a reduction of external heat demand by increasing internal heat exchanging in a plant.

[c] The steam demand is used for process needs, i.e. excluding steam demand for heating needs that in reality do not need steam.

[d] The total steam demand for a plant is the process steam demand + the heat demand that is not covered by heat integration or heat excess from heat pumps.

3.2.1. Integration cost

The investment cost for increasing the degree of integration in the plants are approximated to 460 €/kW.[1] This is based on the assumption that heat integration measures in the plant studied in Fritzson and Berntsson (2005) have reasonable pay-back periods (3 years) for its integration investments. Normally, the investment cost per kW for integration measures is relatively small for the first exchangers and increases as more energy is saved and the temperature difference between streams in exchangers decreases. The cost used in this study is considered a reasonable average for the suggested integration measures. No additional variable cost due to the integration is included.

3.2.2. Heat pumps

The investment cost for installing a heat pump is taken from a recent report by Gierow (2004) about process integration in a ready-made meal plant, see Table 2. Investment costs for a particular heat pump and its surrounding equipment are increased or decreased from the data in Table 2 using the six-tenths rule[2] for the size of the heat pump needed for a particular plant.

The Carnot efficiency varies with the kind of heat pump used, the size of the compressor and the temperature lift. These factors are approximately the same for all heat pumps in this study. Therefore the Carnot factor is reasonable for all studied heat pumps and consequently it can be used to calculate the COP for the heat pumps.

The heat pumps all operate on heat excess from the refrigeration plants and, as shown by Fritzson and Berntsson (2005), there is at all times enough heat available for the heat pumps. Assuming that there are sufficient capacities in warm and hot water tanks already installed in the plant, only one accumulator tank is included in the cost for the heat pump.

The heat pumps installed in this study are integrated into the plant according to the process integration study made by Fritzson and Berntsson (2005). The data from that study is refined so that the operational time and the size of the heat pumps are fitted to a summer and a winter (9 months per year) case as well as during the day (06.00–18.00) and night (18.00–06.00). The largest difference between the seasons is that there is no need for comfort heating during the summer. During the night there is no production at the plant and there is also a larger need for warm water for cleaning compared to the daytime. There is no consideration taken to the variation of the product mix over the year. The size of the heat pumps considered in this paper, as well as the heat delivered by them, can be seen in Table 3.

Table 2
Basic data for the heat pump

Data	
Size of heat pump [MW]	2
COP	4.1
Carnot efficiency [%]	65
Working media	NH_3
Condensation temperature [°C]	65
Evaporator temperature [°C]	28
Investment costs	
Heat pump [k€]	378
Accumulator tank [k€]	12
Other surrounding equipment [k€]	100

Table 3
The size of [MW] and heat delivered [MWh/year] by the heat pumps considered for NIP1, NIP2 and IP2

		HP 1	HP 2
NIP1	Size[MW]	1.2	1.3
	Delivered heat [MWh/year]	5400	6800
NIP2	Size [MW]	2.4	2.7
	Delivered heat [MWh/year]	10900	13600
IP2	Size [MW]	3.3	–
	Delivered heat [MWh/year]	13700	–

3.2.3. Combined heat and power (CHP)

Two types of CHP plants are considered in this study; installation of a steam turbine or a gas turbine with a HRSG. The turbines are assumed to operate only when there is production in the plants.

The net operating cost for the CHP plants is assumed only to be affected by the electricity production and fuel use in the CHP plants. The cost for additional employees to operate the unit is considered small and is not included.

With such small heat demands as in this study, only rather simple steam or gas turbines with relatively low efficiencies are available. Larger turbines generally have higher isentropic efficiency. A higher admission pressure to a steam turbine also gives a larger isentropic efficiency. The largest steam or gas turbine possible is used for the studied plants. The size of the turbines is limited by the heat demand in the plant, compare Tables 1, 4 and 5.

The investment cost for the technology needed for CHP plants might decrease in the future as they become more common in smaller plants.

3.2.4. Steam turbine

Three alternative steam turbines are suggested to produce electricity and hot water to the plants, see Table 4. The investment cost for the steam turbines is also shown.

The steam produced in the boiler either goes through the turbine or is reduced in pressure and used as process steam. A turbine with steam extraction is technically possible, but

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[1] €1 = 9.13 SEK = 1.13 USD. This corresponds to the average exchange rate between March 2002 and March 2005 (European Central Bank, 2005).

[2] $C_2 = C_1\left(\frac{S_2}{S_1}\right)^n$, where C_2 is the capital cost of the project with capacity S_2 and C_1 the capital cost of the project with capacity S_1. n is traditionally taken as 0.6, hence the six-tenths rule. For more information see Sinnott (1999).

Table 4
Data (Gulliksson & Petersson, 2002) and investment cost for the steam turbines

Turbine	A	B	C
Admission pressure [bar]	16	16	16
Steam temperature [°C]	Saturated	Saturated	350
Generator effect [kW]	340	690	1550
α [%]	13	13	21
η_T [%]	50	50	71
Heat to condenser [kW]	2615	5308	7381
Pressure in condenser [bar(a)]	0.5	0.5	0.5
Hot water temperature [°C]	75	75	75
Investment [k€/kW$_{el}$]	1.42	0.88	0.66
Investment [k€]	485	605	1020

is not considered in this paper since this means a more complicated technical solution and therefore a larger investment cost. The hot water heated in the condenser is used for heating and the electricity is used either in the plant or sold to the grid, see Section 3.2.9.

3.2.5. Gas turbine

The gas turbine unit considered in this paper is a natural gas driven gas turbine with a HRSG that produces steam by using the heat in the exhaust gases from the turbine. It is assumed that the HRSG can be supplementary fired with natural gas to be able to meet all the heat demand at the plant. This way, there is no need for an additional boiler to produce steam. The exhaust gas from the turbine is cooled down to 130 °C in the HRSG.

In Gas Turbine World (2000) the investment cost of many different gas turbine models is given for a free on board (FOB) case. According to Strömberg, Franck, and Berntsson (1993), the installed cost of a gas turbine plant was about a factor 2.5 times the budget price for the considered gas turbine. This factor includes steam equipment such as a HRSG, electrical equipment, architecture and engineering services and installation costs and is used in this study. The increase of the price for gas turbines from 2001 to 2005 is considered to be within the margin of error. For each plant, the payback period (PBP) for several different gas turbine models is calculated and the model with the shortest PBP is chosen, see Table 5.

Table 5
Gas turbine data (Gas Turbine World, 2000)

Turbine model	Saturn 20	UGT-2500	501-KB5S	ST18A
Electricity base load [kW]	1210	2850	3950	1960
Exhaust temperature [°C]	504	511	530	532
Exhaust flow [kg/s]	6.5	14.9	18.4	8.0
η_{tot} [%]	81.5	88.2	88.8	84.6
Investment cost [k€]	1489	3066	3529	2647

Table 6
Investment cost [k€] and efficiency [%] for boilers in this study

Fuel	Effect [MW$_{fuel}$]			Boiler efficiency
	5	10	15	
Oil	N/A	N/A	N/A	90
Natural gas	100[a]	160[a]	210[a]	95
Pellets	1280[b]	1780[b]	7890[c]	85
Wood chips	1580[b]	2760[b]	5720[c]	85

N/A = not applicable.

[a] Svensson (2005).

[b] Fire tube boiler (Larsson, 2005).

[c] Water tube boilers (Larsson, 2005).

3.2.6. Boilers

The steam turbines described above can be powered by steam from an existing (oil-fired) boiler or by a new boiler using natural gas or a biofuel of some kind. Approximate investment costs for a new boiler, presented in Table 6, include extra equipment for fuel handling when needed. Some boilers can switch to a new fuel only by changing the burner. This possibility is not considered in this study. Access to natural gas for the plants is assumed. The boilers are designed so that a steam turbine in a CHP plant as well as the steam demand in the plant can be covered.

Since the production at the plant is only 6300 h/year, the boiler is not operated continuously. Therefore it is important that the boiler can be easily started and stopped. Usually the stops in these plants are long enough, i.e. weekends, to be acceptable for all boiler types in this study.

3.2.7. Energy prices

The energy costs in this study are taken from a paper by Ådahl and Harvey (2004). In this paper four possible energy market parameter sets reflecting different climate policies are proposed. These sets are presented as "building blocks" of plausible combinations of energy market parameters that can be valid at different periods of time in the future. In this paper the timing of the blocks is not considered, see Section 5. The four parameter sets represent the Nordic energy market and are defined below:

Block I corresponds to the Swedish energy market in the near future. This block uses energy prices from 2003 to a large extent.

Block II corresponds to a "business as usual" evolution of society, i.e. focus on high economic growth with corresponding high energy usage. The indicative time period for this set of parameters is 2010–2030.

Block III corresponds to a "moderate change" evolution of society, i.e. a balance between economic growth, reduced energy usage, and reduction of CO_2 emissions. The indicative time period for this set of energy market parameters is 2010–2050. The timing, however, is dependent on climate target ambitions.

Block IV corresponds to a "sustainable" evolution of society, i.e. CO_2 emissions are reduced to levels estimated to be sustainable. Conditions for this case are likely to occur in the more distant future.

For more information about the conditions and prices used to calculate the energy prices see Ådahl and Harvey (2004).

3.2.8. Fuel

The fuels considered in this study are heavy fuel oil, natural gas, wood fuels, e.g. wood chips, and refined biofuels, e.g. pellets. The fuel prices used in this paper are presented in Table 7.

Fossil fuels emit CO_2 when refined, transported and combusted. There are no net CO_2 emissions from combustion of biofuel since the amount of CO_2 emitted when burning biofuel is the same as the CO_2 absorbed by the biofuel when growing. However, there are CO_2 emissions during production and distribution of the biofuel, see Table 8.

Table 7
Prices used in the study (Ådahl & Harvey, 2004)

	I	II	III	IV
CO_2				
CO_2 value in heating sector [€/t]	20.3	5.5	27.4	54.8
Fossil fuels				
Price of heavy fuel oil including CO_2 cost [€/MWh_{fuel}]	22.0	18.0	24.0	33.6
Price of natural gas including CO_2 cost [€/MWh_{fuel}]	17.3	14.2	18.7	26.0
Biofuels				
Price of wood fuels [€/MWh_{fuel}]	13.7	14.1	17.6	24.3
Price of refined biofuels, e.g. pellets [€/MWh_{fuel}]	21.4	21.8	25.3	32.0

Original prices and costs have been converted: 9.13 SEK = €1 (European Central Bank, 2005).

3.2.9. Electricity

The electricity price used is a sum of several different costs. Included in the electricity price are grid transmission costs, the cost of electricity production and policy instruments for decreasing CO_2 emissions and other greenhouse gases. Possible policy instruments can include taxes, regulations and tradable permits. The grid transmission costs are assumed constant, in other words, all of the electricity certificates are included in the variable price.

Green certificates are traded in the time period described in Blocks I and III. The certificates provide an extra income for biofuel based electricity production. Therefore, when electricity production is based on biofuel it is advantageous to sell the electricity to the grid. In Blocks II and IV it is more profitable to use the electricity in the plant than to sell it to the grid since a large part of the electricity cost, such as the grid transmission cost, thereby is avoided.

In this paper it is assumed that the marginal power production technology gives the CO_2 emissions associated with electricity generation, see Table 9.

3.2.10. Payback period

The payback period (PBP) of a project is the time to recover the cost of an investment. The PBP can be expressed as:

$$\mathrm{PBP} = \frac{\text{Cost of project}}{(\text{Reduction of operational cost due to project})}$$

Table 8
CO_2 emissions for the studied fuels [g CO_2/MJ_{fuel}]

	Heavy fuel oil	Natural gas	Pellets	Wood chips
Production and distribution [g CO_2/MJ_{fuel}]	5.9[a]	2.6[b]	1.2[c]	3[d]
Combustion [g CO_2/MJ_{fuel}]	76.6[e]	57.1[e]	0	0
Total CO_2 emissions [g CO_2/MJ_{fuel}]	82.5	59.7	1.2	3

[a–d] Data from summaries in Uppenberg et al. (2001). This data has been collected from the literature cited below.

[a] Sydkraft (2000).

[b] Gunnarsson and Skarphagen (1999).

[c] Edholm (2000).

[d] Vattenfall (1996).

[e] Ådahl and Harvey (2004).

Table 9
Electricity prices and emission for electricity used in the study, Ådahl and Harvey (2004) and Marbe et al. (2003)

	I	II	III	IV
Electricity				
CO_2 value in electricity sector [€/t]	5.5	5.5	27.4	54.8
Price of marginal electricity (fossil fuel) [€/MWh_{el}]	38.8	38.4	50.3	67.8
Net income from sales of renewable electricity to grid [€/MWh_{el}]	53.6	33.0	53.9	62.3
Marginal [baseline] electricity CO_2 emissions including 7% grid losses [kg/MWh_{el}]	834[a]	778[b]	374[c]	97[d]

Original prices and costs have been converted: 9.13 SEK = €1 (European Central Bank, 2005).

[a] Operating margin. Coal fired steam turbine plants (η_{el} 42%).

[b] Build margin. Advanced coal power plants (η_{el} 45%).

[c] Build margin. Natural gas combined cycles, NGCC (η_{el} 58%).

[d] Build margin. Coal power plants with CO_2 separation and storage (η_{el} 36%).

All other things being equal, the better investment is the one with the shorter payback period. There are two main drawbacks with the payback period method: it ignores the time value of money and any benefits that occur after the payback period. However, since investments in industry often require a fast return on capital, this method is commonly used. For investments with a long time horizon the PBP method is less useful. In this paper all payback periods shorter than 3 years are considered realistic. A PBP of between 3 and 4 years are interesting to study further, since the data used in this paper is general.

4. Results

4.1. Non-integrated plants

The results for the largest non-integrated plant, NIP2, are shown in Fig. 1.

4.1.1. Energy efficiency by heat integration—heat exchanging

One way of decreasing the external energy demand in the non-integrated plants is by heat integration. Heat integration in this study means heat recovery by installation of heat exchangers for heat exchanging between heat excesses and demands. The PBP for increasing the degree of integration in the non-integrated plants in this paper to the same level as the integrated plants is realistic or interesting in all blocks.

4.1.2. Energy efficiency by heat integration—heat pumps

Another way of decreasing the amount of external energy needed in the non-integrated plants is to install one or more heat pumps. The reduction in operational cost is greater with a heat pump than for increased heat exchanging and so is the investment cost. The PBP for installing two heat pumps in a non-integrated plant is around the same as increased heat exchange. In the smaller plant (NIP1) the extended heat exchange is somewhat more profitable while in the larger (NIP2) the heat pumps have a somewhat shorter PBP.

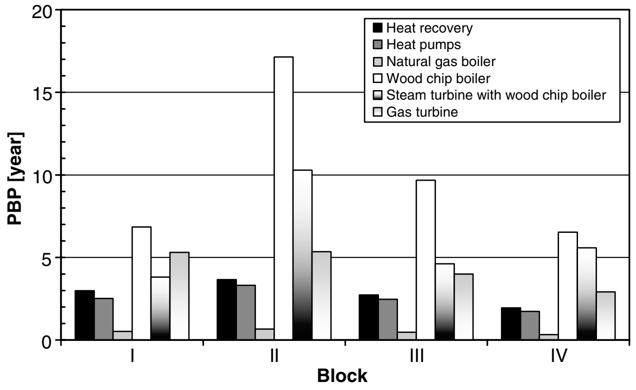

Fig. 1. Payback period for energy efficiency options for NIP2. The ratios between the payback periods for these options in NIP1 are similar to the NIP2.

4.1.3. Changed fuel to boiler

For both non-integrated plants studied it has been found that the PBP for replacing the old heavy fuel oil boiler by a new natural gas fired boiler is rather short, see Fig. 1. The price of natural gas is lower than the price of oil in all blocks and the investment cost for a natural gas boiler is fairly low.

On the other hand, the PBP for investing in a new pellet boiler is too long to be interesting in any of the blocks. The pellet and oil prices are fairly equal and the investment cost for a pellet boiler is quite large. This means that much larger CO_2 emission fees on fossil fuels than suggested in the energy market "Blocks" used in this study are needed if pellet is to be an interesting fuel for the studied industry. If a less refined fuel, e.g. wood chips, can be used in the burner, the fuel cost is reduced and the PBP is shorter than for the pellet boiler. However, the investment cost for the wood chip boiler is still too high to be an interesting option.

4.1.4. Combined heat and power generation

In a plant with external heat demand it is also interesting to study integration of a CHP unit for the plant instead of investing in heat pumps or heat integration in the plant. It can be assumed that the existing oil boiler has enough capacity to produce steam for a steam turbine without making changes in the boiler.

For the smaller non-integrated plant, there is not a reasonable PBP for investing in a steam turbine (turbine A, see Table 4) for any of the studied fuels or a gas turbine with a HRSG (Saturn 20, see Table 5). For NIP2, all turbines are more advantageous than the same units of a smaller size in NIP1. The only steam turbine option (turbine B, see Table 4) with a short enough PBP to be interesting is investing in a steam turbine with a wood chip boiler in Block I. The PBP for a gas turbine in NIP2 (UGT-2500, see Table 5) is short enough to be interesting in Block IV.

As a conclusion, it is more profitable to install heat pumps or increase the heat recovery in the plant than to install turbines for both non-integrated plants. However, it is even more profitable to change fuels to natural gas, i.e. invest in a new natural gas boiler, for both plants, see Fig. 1.

4.1.5. Ecocyclic industrial food processing park

If another food processing plant is built close to an SMP plant in an ecocyclic industrial park there might be a potential to integrate the energy utility systems of these plants and to increase the economic potential for a CHP plant. A dairy using approximately 100 000 t of raw milk per year can benefit from being geographically close to an SMP plant. In such a dairy producing milk and cheese, warm water is used for process needs, cleaning and comfort heating. The two plants together represent a total heat demand large enough to buy a larger steam or gas turbine with a

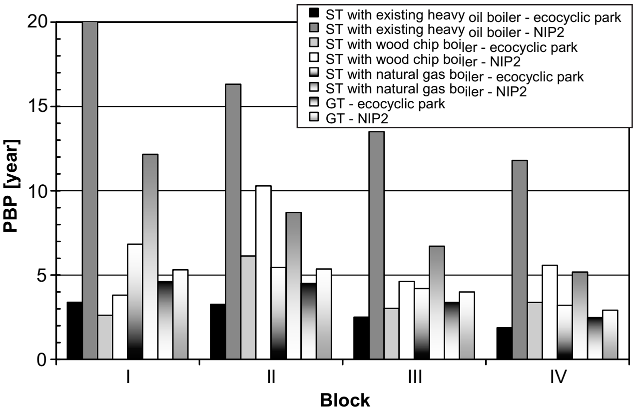

Fig. 2. Payback period for installing turbines in an ecocyclic industry park compared to a stand-alone plant (NIP2) (ST = steam turbine, GT = gas turbine).

better efficiency and a lower investment cost per kWh electricity than a smaller turbine.

Another type of plant that also needs warm water for process needs, cleaning and comfort heating is a ready-made meal plant. A couple of ready-made meal plants in Sweden have heat demands that, together with an SMP plant, would fit well into the heat excess from a CHP unit.

If another food processing plant with a heat demand large enough to use condenser heat from a steam turbine of type C (see Table 4) is integrated with NIP2, the PBP for the CHP unit is short compared to a stand-alone NIP2. For example, the PBP for installing a steam turbine with a heavy oil boiler is very long for a stand-alone NIP2 while it is realistic in some blocks for an ecocyclic industrial park. The PBP for steam turbines with natural gas or wood chips is also short enough to be realistic for some blocks. Installing a gas turbine (501-KB5S see Table 5) is a somewhat more profitable way of using natural gas for heat and power generation, see Fig. 2. Using biofuel for cogeneration is most advantageous in Blocks I and III where electricity made from biofuels is credited with green certificates.

4.2. Integrated plants

In the smaller integrated plant, IP1, the external heat demand is not large enough to make CHP an interesting option. Additionally, increasing the heat integration in the plant is considered too expensive. Installation of a third heat pump has been shown to be a technically interesting option, see Fritzson and Berntsson (2005). Using the economic data in this paper it can be shown that the PBP for this installation is short enough to be interesting in Blocks I and III, and realistic in Block IV, see Fig. 3.

In the larger integrated plant, IP2, installation of a steam turbine is technically possible, but not economically interesting. However, a gas turbine (ST18A, see Table 5) can be economically interesting in Block IV. As in the smaller integrated plant, increased heat exchanging is considered too expensive; however, installation of a heat pump is more interesting. The PBP from a heat pump installation is realistic in Blocks I, III and IV and interesting in Block II, see Fig. 3.

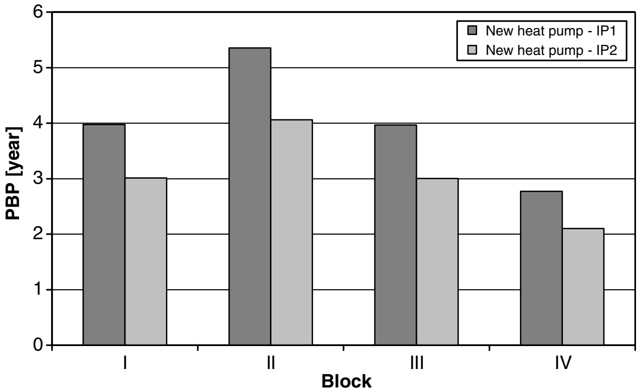

Fig. 3. PBP for installing a new heat pump in IP1 and IP2.

As for the non-integrated plants, the PBP is short for investing in a new boiler using natural gas in both of the integrated plants, see above.

4.3. CO_2 emissions

Total CO_2 emissions for the cases that are found somewhat profitable for one or more blocks in NIP2 and IP2 above are presented below. The base case for the calculation is the original fuel demand satisfied with heavy fuel oil. In the calculation of total CO_2 emissions only the emissions associated with the use of electricity and fuels at the plant are included. The products from the plants also cause CO_2 emissions from transports and packaging. The total global CO_2 emissions can be reduced by sending slaughter waste from the plant to a waste treatment plant that produce heat and/or power replacing fossil fuels. All these emissions do not change for a particular studied plant due to the changes in energy efficiency measures suggested in this paper and are therefore not included in the study. To get a perspective of the CO_2 reductions shown below it can be mentioned that the total CO_2 emissions in Sweden were approximately 70 Mt/year in 2003 (SEPA, 2004).

4.3.1. Heat recovery and heat pumps

As shown in Fig. 4, installing heat pumps in the non-integrated plants gives a greater reduction in CO_2 emissions from the plant than increasing the heat recovery. This is true since installing heat pumps saves almost twice as much fuel than increasing the heat recovery.

Installing a third heat pump in the integrated plants also gives a reduction in CO_2 emission, see Table 10.

4.3.2. Changed fuel in boiler

As can be shown in Fig. 4, there is a reduction in CO_2 emissions when switching fuels in the steam boiler in the plant. This is true for all studied plants. The reduction

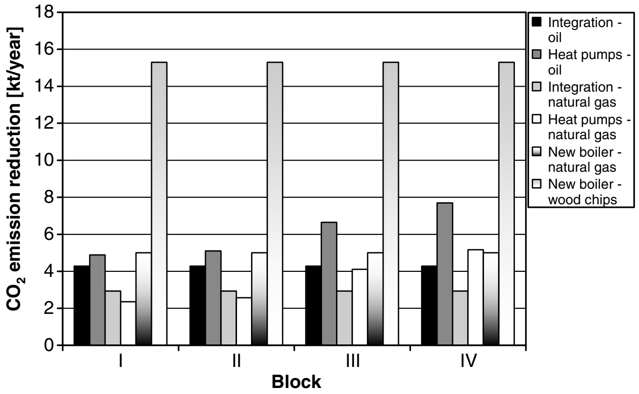

Fig. 4. Reduction in CO_2 emissions [kt/year] for some of the options considered for NIP2. For an increased heat exchanger network and installation of heat pumps the reduction is related to either a fuel oil boiler or a natural gas boiler. For the installation of new boilers the reduction is related to a fuel oil boiler.

Table 10
CO_2 emissions [kt/year] for installation of an additional heat pump in IP2

Fuel to boiler		I	II	III	IV
Oil	Base case [kt/year]	61.5	57.9	31.9	14.1
	With heat pump [kt/year]	59.3	55.6	28.6	10.2
	Emission reduction	2.2	2.3	3.3	4.0

when switching to natural gas is comparable to installing heat pumps and greater than the reduction when increasing heat recovery in the plant. As expected, switching to a biofuel in the boiler gives the greatest CO_2 emission reduction.

4.3.3. CHP units

The most profitable CHP unit solution studied in this paper consists of a steam turbine or a gas turbine in an ecocyclic industrial park. This can either reduce or increase the CO_2 emissions depending on what block is studied. For example, when a natural gas boiler is used, a steam turbine increases the total CO_2 emissions in Block IV since the marginal electricity is produced with less CO_2 emissions than the installed natural gas steam turbine. When a wood chip boiler is used there is always a reduction of emissions when installing a steam turbine. However, this reduction is rather small in Block IV, as the emissions from the marginal electricity production are rather small, see Fig. 5.

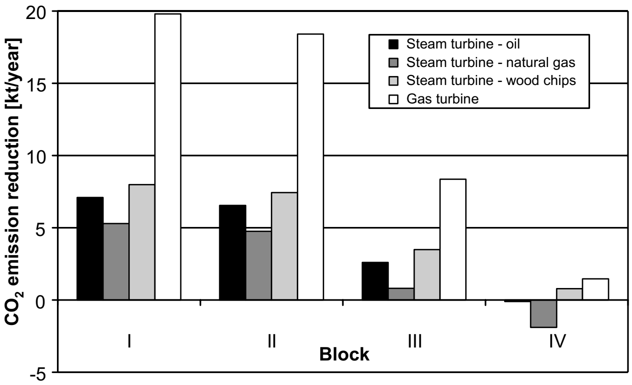

Fig. 5. Reduction in CO_2 emissions [kt/year] for investing in different turbines in the ecocyclic industrial park.

4.3.4. Conclusions CO_2

Looking at only the reduction in CO_2 emissions for the options studied in this paper the best case for a stand-alone plant is a new biofuel boiler; however, this is not reasonable from an economic point of view.

In Table 11, the investment per CO_2 reduction for different options studied in this paper is presented. Changing fuel from heavy fuel oil to natural gas give the smallest investment per CO_2 reduction. Also changing fuel to wood chips gives a rather small investment cost per kt CO_2 per year.

Installing heat pumps in the plants generally reduce the total amount of CO_2 emissions per year more than increasing the heat exchanger network in the plant. When considering investment per kt CO_2 emission heat pumps are also generally the least costly. Investment in a gas turbine gives a reasonable cost per reduced CO_2 in the first two blocks but is very high in Blocks III and IV where the CO_2 emissions from the electricity in the grid is low.

Table 11
Investment/CO_2 reduction [€/(t/year)] for the CO_2 reducing options discussed for NIP2

CO_2 reducing option		I	II	III	IV
Increased heat exchanger network	Investment [k€]	946	946	946	946
	Investment/CO_2 reduction	*221*	*221*	*221*	*221*
Heat pumps	Investment [k€]	1133	1133	1133	1133
	Investment/CO_2 reduction	*232*	*222*	*171*	*147*
Natural gas in boiler	Investment [k€]	159	159	159	159
	Investment/CO_2 reduction	*32*	*32*	*32*	*32*
Wood chips in boiler	Investment [k€]	2760	2760	2760	2760
	Investment/CO_2 reduction	*180*	*180*	*180*	*180*
Gas turbine	Investment [k€]	3066	3066	3066	3066
	Investment/CO_2 reduction	*207*	*223*	*470*	*1987*

The base case for the CO_2 reduction is a heavy fuel boiler.

The electricity production causes the largest part of the CO_2 emissions from the plant. Therefore, it is possible to reduce CO_2 emissions by saving electricity in the plant. In Fritzson and Berntsson (2005), a potential of saving 10% of the electricity use in the refrigeration plants has been identified. This potential can be realized by decreasing the temperature difference between refrigeration media and the needed temperatures in the refrigeration and freezing rooms.

5. Discussion

5.1. Optimal mix between IP and NIP

In this paper rather simplified cases are studied. Only one energy efficiency measure is studied at a time. Since the price for heat integration usually increases rather rapidly with decreasing temperature difference and with increased amount of energy saved, the optimal economic solution is probably a trade-off between these cases. For example, in a non-integrated plant, the optimal solution probably includes only the least expensive heat recovery measures as well as installing a heat pump. In this study, data needed for this optimization is lacking, but such a calculation is appropriate when looking at what energy efficiency measures should be made at a specific plant.

5.1.1. Using slaughter waste as a fuel

In Sweden there are currently several SMP plants that use a new procedure to dispose of their slaughter waste (Widell, 2005). In this procedure the organic waste is ground and pumped to a storage tank at the plant. Trucks then transport the slurry to e.g. a large CHP plant where it is incinerated together with peat in a fluidized bed boiler to produce heat and electricity. This type of procedure reduces the cost for disposal for the plant compared to the conventional method, but it renders recycling of phosphorous and nitrogen back to agriculture impossible. Incinerating the waste at a large CHP plant offers advantages such as a good efficiency and a moderate investment cost. Using the waste as a fuel in a boiler in an SMP plant has a lower efficiency and a less favorable economy.

5.2. Using energy market parameter sets to evaluate energy efficiency projects

When comparing different energy efficiency projects it is important not only to assume current energy market prices but also to study how the profitability of the projects changes if the prices are changed. Many of the energy market parameters, such as fuel prices, the price of electricity and possible CO_2 emission charges, are not independent from each other and many are strongly correlated. By using four energy market parameter sets ("blocks") the projects in this paper can be evaluated for different sets of energy prices and it can be concluded that different energy efficiency projects are favored in different blocks. Different combinations of blocks and their periods of validity can be made to represent scenarios of energy market development paths or energy market scenarios. However, such scenarios are not essential in this paper, since the evaluation of the energy efficiency projects is a rating between alternatives under different possible future conditions.

6. Conclusion

In this paper different energy efficiency measures carried out in four different fictitious slaughter and meat processing plants are evaluated for four different future combinations of energy market parameters. It was found that it is economically interesting to invest in an increased heat exchanger network or heat pumps in the studied non-integrated plants. Additionally, reductions of between 5% and 35% of the total CO_2 emissions in a large non-integrated plant can be made by these measures. The most cost effective reduction of CO_2 emissions is achieved by switching fuel from heavy fuel oil to natural gas.

For the already integrated plants, investing in a new heat pump was found to be economically interesting under conditions corresponding to some of the future energy market parameter sets.

The profitability of investing in a CHP plant was found to be small compared to other energy efficiency or CO_2 emission reducing options in the paper. In the integrated plants, the payback period for a CHP plant was long. The payback period for a steam or gas turbine installed at an ecocyclic industrial park was found to be short enough to be interesting.

Acknowledgments

The authors gratefully acknowledge the financial support of the Swedish Energy Agency and the knowledgeable help from Per-Åke Franck, CIT Industriell Energianalys, Katarina Lorentzon, SIK the Swedish Institute for Food and Biotechnology and Berit Mattsson, Västra Götalandsregionen.

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