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SWEDISH INDUSTRIAL AND ENERGY SUPPLY MEASURES IN A EUROPEAN SYSTEM PERSPECTIVE

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To my wonderful children
Frans and Lydia

This thesis is based on work conducted within the interdisciplinary graduate school Energy Systems. The national Energy Systems Programme aims at creating competence in solving complex energy problems by combining technical and social sciences. The research programme analyses processes for the conversion, transmission and utilisation of energy, combined together in order to fulfil specific needs.

The research groups that participate in the Energy Systems Programme are the Department of Engineering Sciences at Uppsala University, the Division of Energy Systems at Linköping Institute of Technology, the Department of Technology and Social Change at Linköping University, the Division of Heat and Power Technology at Chalmers University of Technology in Göteborg as well as the Division of Energy Processes at the Royal Institute of Technology in Stockholm.

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Abstract

A common electricity market in Europe will in all probability lead to a levelling out of the electricity price, which implies that Swedish consumers will face higher electricity prices with a European structure. This new market situation will force industry and energy suppliers to take new essential measures as actors in a deregulated European electricity market.

In this thesis it is shown how over 30 Swedish small and medium-sized industries can reduce their use of electricity by about 50%. When scaling up the result to include all Swedish industry, the measures will lead to a significant reduction in global CO_2 emissions, and a situation where Sweden will have a net export of electricity.

Changing industrial energy use towards increased use of district heating will consequently affect the local energy suppliers. As a local energy supplier invests in CHP and co-operates on heat with an industry that has altered its energy use, the system cost will be halved. Considering higher European electricity prices, the benefits will be even higher with possibilities to reduce global emission with over 350%.

In Sweden where district heating is very well established, heat driven absorption technology is especially favourable since it will lead to cost effective electricity production and increased utilization time for a CHP plant. Vapour compression chillers have been compared with heat driven absorption cooling for a local energy utility with a district cooling network and for industries in a Swedish municipality with CHP. The results show that the higher the share of absorption technology is, in comparison to compression chillers, the lower the production cost will be for producing cooling.

This thesis illustrates measures for Swedish industry and energy suppliers in a fully deregulated European electricity market that will shift the energy systems in the direction of cost-effectiveness and resource effectiveness. The thesis also shows that the benefits of the measures will increase even more when accounting with electricity prices with a higher European structures. To methodically change the use of electricity would be an economical way to increase the competitiveness of Swedish plant in relation to other European plants.

Taking advantage of these particularly Swedish conditions will contribute to the creation of lean resource systems, and as a result help the whole EU region to meet its commitment under the Kyoto Protocol. Altering industrial energy use towards less electricity and energy dependence will be a competitive alternative to new electricity production and help secure energy supply in the European Union.

Acknowledgement

I would first like to thank my supervisor, Professor Björn Karlsson, for giving me the opportunity to write this thesis and for all our inspiring and interesting discussions. His guidance and always encouraging support has been invaluable. I still believe it is a privilege to get the chance to conduct postgraduate studies and especially within the area of energy systems.

There are many to whom I want to express my gratitude. Without these persons, this work would not have been possible:

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Dr Jörgen Sjödin at the Swedish Energy Agency for constructive and helpful comments on my thesis.

My mother for giving me self-confidence, and for all our never-ending discussions regarding energy issues.

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Our dog, Biggles, for keeping me company late nights.

My dear husband, Harald, for always helping me, always believing in me and always encouraging me.

Finally, our children, Frans and Lydia, for being the light of my life, and for enduring with a mother how always "have to work".

Table of contents

1 Introduction

With a common electricity European market the electricity price in Europe will most likely level out to an equilibrium price. Sweden is characterized as an energy dimensioned system where the electricity price varies over the year, while the electricity supply system in continental Europe is characterized as power load dimensioned with changes in electricity price over the day. Since the Nordic market constitutes only a minor portion of the common European market, it is likely that the conditions on the European continent will be valid for the entire common European market and that electricity prices between Scandinavia and northern Europe will level out [SEA, 2006].

This theory implies that a new European electricity market leads to both electricity prices that vary over the day and higher prices for Swedish energy users. Since Swedish plants are characterized by higher electricity use compared to plants in the EU region, the combination of high electricity use and a high electricity price will lead to an untenable situation for Swedish industries. Given these assumptions, Swedish plants will need to focus on reducing their electricity usage and changing the relation between electricity and fuel in order to maintain their competitiveness with industries in other EU countries.

A higher electricity price will at the same time encourage energy suppliers to concentrate their production to more electricity generation. In combination with an increased demand for district heating, which will be a result of industries converting from electricity or fuel to district heating, this will make investment in combined heat and power plants (CHP) an extremely interesting option. Since the district heating grids in Sweden are among the world's most extensive [Werner, 1989], it will probably prove attractive for Swedish energy suppliers to consider further investment in these power plants, which would consequently increase electricity production in Sweden. Increased production in CHP plants is promoted in the EU directive 2004/8/EC [COM, 2004] and according to the Swedish District Heating Association electricity production from Swedish CHP can increase from today's low level of 5 TWh/year to 20 TWh/year [Swedish District Heating Association, 2004].

Due to the ban on landfill of both combustible and organic waste, there has been an increase in waste incineration in Sweden [Ministry of the Environment, 2001] and about 12% of the total heat demand in Swedish district heating networks is supplied by waste incineration [SEA, 2005e]. In energy systems with waste incineration there is often a surplus of heat during the summer. Since the demand for cooling is highest during the summer, the surplus of heat can be used for heat driven cooling in the form of absorption cooling. In energy systems with CHP, the increased demand for heat will mean a higher potential for electricity production. Converting from vapour compression cooling to absorption chillers will consequently have a positive impact on the overall energy system, as the production of cooling will lead to an increase in electricity production instead of consuming electricity. Compression cooling is also acknowledged to leak refrigerants, which has a significant effect on global warming.

Reduced use of electricity in Sweden will mean freed capacity for the energy supplier that can be sold to other European countries. Since electricity production in Sweden is mainly supplied from hydropower and nuclear power [SEA, 2001] it is mostly free from emissions of carbon dioxide. Electricity generated in Sweden but sold in another European country, could then replace electricity produced with higher external costs. When accounting for electricity with marginal production and assuming coal condensing to be the marginal source, reduced industrial electricity use and increased electricity production in Swedish CHP-system will lead to possibilities for cost-efficient measures to reduce global emissions of carbon dioxide. It would thus help the whole EU region to meet its target as regards lower emissions of carbon dioxide.

According to the Green Paper [COM, 2000] the European Union is consuming more and more energy and will not be able to free itself from its increasing energy dependence without an active energy policy. A strategy for reducing industrial energy use is therefore measures that will be competitive alternatives to new electricity production and help secure energy supply in the European Union.

Sustainable development can be defines as “development that meets the needs of the present generation without compromising the ability of future generation to meet their own needs” [World Commission on Environment and Development, 1987]. Johansson [2001] points out that more efficient use of energy is one of the technological developments that are a prerequisite for energy sustainable development. Initiatives to redirect energy use towards less use of electricity and increased use of district heating can in other word be referred to as measures that will shift the energy system towards sustainability.

The measures will naturally be more successful and have a greater impact if all actors can derive benefits from the process. This means that both energy users and energy suppliers must see these measures as profitable measures. However, although there are unquestionable strong motives for an industry to consider measures that will only result in environmental improvements, the driving force will most likely be stronger if there is also an economic initiative connected to the measures. In other words, measures that imply both economic and environmental effects will most certainly be the ones that will have the strongest driving force and the ones that will have the greatest impact. In this thesis, results from energy system analyses will show measures that will be profitable for both energy suppliers and industrial energy users as well as for the environment with possibilities to reduce global emissions of carbon dioxide.

1.1 Aim and research questions

The aim is to identify technical measures for Swedish industry and energy utilities that will be profitable in a deregulated European electricity market with higher electricity prices in Sweden.

The hypothesis is that when considering a fully deregulated European electricity market with higher electricity prices for Swedish consumers, there are technical measures that will make the combined energy systems of Swedish industries and energy suppliers significantly more resource effective.

The thesis deals with energy system analyses of Swedish small and medium-sized industry and energy utilities. The focus can be summarized in four research questions:

1 What industrial measures will redirect industrial energy use towards less electricity use and increased use of district heating in Swedish small and medium-sized industries?

2 How will the two energy supply measures energy-related co-operation and investment in CHP affect a local energy supplier, as the industry alters its energy use?

3 How will the measure conversion from compression chillers to absorption chillers affect industries and energy suppliers?

4 What will the impact be on the Swedish national power supply of changed industrial energy use towards less use of electricity and increase use of district heating?

1.2 Scope of the thesis

The industry analyses embrace small and medium-sized industries situated in the municipalities Oskarshamn, Ulricehamn, Skövde, Norrköping, and Örnsköldsvik. Larger electricity-intensive industries are only briefly touched upon in paper VII where national power supply and industrial energy use are analysed. Energy suppliers analysed include, in addition to Swedish national power supply, local energy utilities situated in Skövde and Norrköping.

The energy system analyses include technical measures; a socio-technical approach is only performed in one paper (III). All the included papers have a European perspective with the important assumption that a fully deregulated European electricity market with no restrictions on transfer capacity will probably mean that the electricity price in Europe will level out to an equilibrium price which will lead to higher prices for Swedish electricity users. The investigated environmental impacts are restricted to CO_2. The work assumes that global warming is caused by increased emissions of CO_2 and that action to reduce the greenhouse effect and redirect our energy system towards sustainability is crucial.

1.3 Disposition

The thesis consists of nine chapters. The first chapter gives an introduction to the project and a description of the research questions, the aim and the scope of the thesis. The chapter also includes a short overview of the seven papers included. In the second chapter, some topics related to a deregulated European electricity market are discussed. These are: accounting for electricity consumption, electricity price, use of electricity, and transfer capacity in a common electricity market.

The climate issue is discussed in the third chapter and in the fourth chapter the most important assumption for this thesis is stated. Related work is discussed in the fifth chapter. Methodologies used in this thesis are described in chapter six and in chapter seven, results from the included papers are presented. A concluding discussion and some suggestions for further work end the thesis in chapters eight and nine respectively

1.4 Paper overview

Paper I
Louise Trygg, Björn G Karlsson
Industrial DSM in a European electricity market - a case study of 11 industries in Sweden
Energy Policy, 33:1445-1459 Elsevier (2005)

The main purpose of the paper is to analyse how eleven small and medium-sized industries in the Swedish municipality of Oskarshamn can redirect their energy use towards less use of electricity and increased use of district heating. Each industry's energy use in the study was analysed thoroughly and the method used for analysing the companies is based on the *Tool for Analysis*, which describes a strategy for system changes of industrial load management with the purpose of adapting the use of electricity to an average European level. In addition to measurement work during the daytime, the industries were also visited at night with the purpose of studying energy use when no production was going on.

Paper II

Louise Trygg

Generalized method for analysing industrial DSM towards sustainability in a deregulated European electricity market - method verification by applying it in 22 Swedish industries

Proceeding of the 2nd International Conference on Critical Infrastructures, Ed. J-C Sabonnadiere, s10-a2, Grenoble, France, 25-27 October 2004

On the basis of the results in paper I, a generalized, less time-consuming method has been developed with the aim of analysing how Swedish industry can alter its energy use to a minimum of electricity dependence and hence move towards sustainability. The aim of paper II is to present the method and verify results by applying it in 22 Swedish industries in the municipalities of Ulricehamn and Örnsköldsvik.

Paper III

Dag Henning, Louise Trygg, Wiktoria Glad, Stig-Inge Gustafsson

Socio-technical analyses of energy supply and use in three Swedish municipalities striving toward sustainability

Proceeding of the 1st VHU Conference on Science for Sustainable Development, Ed. B Frostell, p 133–142, Västerås, Sweden, 14-16 April 2005

This paper aims at a comprehensive view of energy supply and use. The analyses include socio-technical interaction and relationships between different energy systems. Technical and social analyses of energy systems were performed in the Swedish municipalities of Solna, Ulricehamn and Örnsköldsvik. The approach presented in the paper considers a number of ecological, economic, and social elements of sustainability.

Paper IV

Dag Henning, Louise Trygg, Alemayehu Gebremedhin

Enhanced biofuel utilisation in Swedish industries, buildings and district heating

Proceeding of the World Bioenergy 2006, Conference and exhibition on Biomass for Energy, Jönköping, Sweden, 30 may – 1 June 2006, p 198-203, Swedish Bioenergy Association and Authors 2006

The objective of this paper is to make a nation-wide estimation of possibilities for biofuel use in industries, buildings and district heating systems. The aim is to investigate for what purposes and to which extent biofuel may be used in various societal sectors. The analyses are based on the energy audits made in papers I and II and on analyses made in the rural municipality of Vingåker. In the study it is assumed that all Swedish industries with similar products use energy in the same way as the studied industries. The potential for switching to biofuel and district heating has then been scaled up to national level.

Paper V

Louise Trygg, Alemayehu Gebremedhin A, Björn G Karlsson

Resource effective systems through changes in energy supply and industrial use: the Volvo - Skövde case

Applied Energy 83, 801-818, Elsevier, 2006

This paper analyses how two parameters will affect a local energy supplier in a Swedish municipality, as the largest industrial energy user in the municipality alters its energy use and converts from electricity and oil to district heating in the same way as the industries in papers I and II. The parameters studied are investment in a new combined heat and power plant and co-operation on heat supply between the energy supplier and the industrial energy user. Economic consequences and impact on emission of CO_2 are studied, when considering various electricity price structures. The analyses were made using the MODEST method at the energy utility in Skövde and the Volvo Car and Truck plant in Skövde. A sensitivity analysis was performed to investigate the effects of price on emission trading, the cost of investment, the price of biofuel and the admixture of biofuel

Paper VI

Louise Trygg, Shahnaz Amiri

Absorption cooling in a European perspective - a case study from Norrköping

Accepted for publication in Applied Energy

The aim of this paper is to analyse, in a European system perspective, the most cost-effective technology for the production of cooling by comparing vapour compression chillers with heat driven absorption chillers for a cooling network and for seven industries in the Swedish municipality of Norrköping. Impact on emissions of CO_2 and economic effects were analysed using the MODEST method as a European electricity price and natural gas are introduced into the energy system. A sensitivity analysis was performed to investigate the effects of a higher demand for cooling and different COP.

Paper VII

Reduction of electricity use in Swedish industry and its impact on national power supply and European CO_2 emissions

Dag Henning, Louise Trygg

Submitted for journal publication

This paper consists of a compilation of previously performed audits of electricity consumption and the possibilities to reduce energy use in Swedish industries, a scaling of audit results to all Swedish industry and an analysis of the impact on national electricity supply of electricity conservation. Electricity supply, use and conservation have been analysed with the MODEST method with the aim of elucidating the interplay among present and potential electricity generation, electricity consumption and more efficient electricity use. Time-dependent electricity demand and industrial measures are described for various processes and lines of business.

1.5 Co-author statement

Papers I and II were written entirely by the author of this thesis while Björn Karlsson contributed with valuable insights and discussion on Paper I. Paper III was written in collaboration with Dag Henning and Stig-Inge Gustafsson at the division of Energy Systems, Linköping University, and with Wiktoria Glad at the department of Technology and Social Change, Linköping University. The paper was outlined together and the author of this thesis wrote the section about energy audits and parts of the discussion and introduction.

Paper IV was co-authored with Dag Henning and Alemayehu Gebremedhin at the division of Energy Systems, Linköping University. The authors planned the paper and discussed the results together. The sections and analyses about biofuel use, electricity reduction, and enhanced use of biofuel/district heating in Swedish industry were written by the author of this thesis together with parts of the introduction and conclusions.

Paper V was written and modelled entirely by the author of this thesis. Professor Björn Karlsson provided constructive discussions and comments. Alemayehu Gebremedhin contributed with valuable comments on the model runs.

In Paper VI, Shahnaz Amiri, at the division of Energy Systems, Linköping University, developed a model that the author of this theses expanded to include the use and production of cooling at different electricity prices. The author of this thesis contributed with all writing and modelling while the results were discussed together.

Paper VII was planned and outlined together with Dag Henning. The author of this thesis contributed with inputs regarding energy audits and national power supply and wrote parts of the paper, especially regarding electricity use and energy audits. The results and conclusions were discussed together.

1.6 Other publications not included in the thesis

In addition to the seven papers presented above, the thesis is also based on the following publications:

Louise Trygg
Systemförändringar av Industriell Energianvändning i Oskarshamn
(System Changes in Industrial Energy Use in Oskarshamn, in Swedish) LiTH-IKP-R-1225, Institute of Technology, Dept of Mech. Eng., Linköping University, Sweden, 2002.

Henrik Bohlin, Dag Henning, Louise Trygg
Energianalys Ulricehamn
(Energy analysis of Ulricehamn, in Swedish) ER 17:2004, Swedish Energy Agency, Eskilstuna, Sweden, 2004.

Dag Henning, Robert Hrelja, Louise Trygg
Energianalys Örnsköldsvik
(Energy analysis of Örnsköldsvik, in Swedish) ER 15:2004, Swedish Energy Agency, Eskilstuna, Sweden, 2004.

Marcus Eriksson, Robert Hrelja, Susanne Lindström, Louise Trygg
Förändrade randvillkor för de kommunala energisystemen i Borås och Skövde – påverkan och effecter
(Changed boundary conditions for the municipal energy systems in Skövde and Borås – influence and effects, in Swedish), Arbetsnotat Nr 23, Programme Energy Systems, IKP, Linköping Institute of Technology, Sweden, 2003.

Shahnaz Amiri, Louise Trygg, Sven-Olof Söderberg, Bahram Moshfegh
Naturgasens möjligheter och konsekvenser i Östergötland
(Consequences and possibilities for natural gas in Östergötland - in Swedish) LiTH-IKP-R-1390, Linköping Institute of Technology, Sweden, 2005.
Report SGC 115 Swedish Gas technical Center, Malmö, Sweden, 2006.

Louise Trygg, Björn Karlsson, Alemayehu Gebremedhin
Combination of energy supply and industrial end use measures
LiTH-IKP-R-1362, Institute of Technology, Dept of Mech. Eng., University of Linköping, Sweden, 2005.

2 Deregulation of the European electricity market and its implications for industrial energy use

In 1996 the Swedish electricity market was deregulated and Swedish consumers were free to buy electricity from any electricity supplier of their choice. In 2004 the whole European electricity market was deregulated. The EU has prescribed common rules for the internal electricity market in its EU Electricity Directive [Directive, 96/92/EC] and according to the directive, all member state should have at least opened their markets by 30%. The reason for deregulating the European electricity market was to improve Europe's competitiveness and the welfare of the citizens. Electricity is the most important secondary source of energy in the European Union and the electricity industry is one of the largest sectors of the economy in Europe [COM, 200l]. The objective of the directive is to open up the electricity market through the gradual introduction of competition, thereby increasing the efficiency of the energy sector and the competitiveness of the European economy as a whole.

According to Stoft [2002] the most common argument for deregulation is the inefficiency of regulation. Deregulation is not equivalent to perfect competition, which is well known to be efficient. Truly competitive markets provide full-powered incentives to hold down the price to marginal cost and to minimize cost. Regulation can do one or the other but not both at the same time. It must always make a trade-off since the suppliers always know the market better than the regulators [Stoft, 2002].

In this chapter, four topics related to the deregulation of a European electricity market are briefly outlined and discussed; (1) different ways to account for electricity consumption in a common European market; (2) electricity prices in Sweden and other European countries; (3) electricity use in Europe; and finally (4) transmission capacity in a deregulated European electricity market.

2.1 Accounting for electricity consumption

There are many different opinions as to how to account for electricity consumption in a deregulated market. The discussion around the environmental value of the electricity used reflects widespread controversies among, for example, scientists, various interest groups, professionals, industrial organizations, public authorities and so on. To decide how to account for electricity consumption is vital when considering the environmental effects of a planned investment in an industry or when considering converting from an oil fired boiler to a heat pump. The issue is also central when a company balances the books and wants to account for the electricity used over the previous year. Sjödin and Grönkvist [2004] discuss some different ways to account for changes in greenhouse gas emissions due to changes in the use or supply of electricity. According to Sjödin and Grönkvist, a comprehensive accounting scheme would provide an accurate link between various types of energy measures and their related emissions in order to facilitate cost-effective carbon dioxide mitigation procedures.

Electricity is one of the few products that is consumed continuously by all customers. It is consumed within a second of its production and less than a tenth of a second of power can be stored as electrical energy. No other product has a delivered cost that changes anywhere near as fast. Electricity is a product that originates from a number of different production plants with different resource costs and environmental costs. It is impossible to distinguish any unit from another and therefore also impossible to calculate the direct and accurate environmental effect of one specific used kWh of electricity. The methods for accounting electricity consumption are as argued earlier diverse; a few of them are briefly discussed and comment in this chapter. It is vital to emphasise that none of the methods of accounting electricity can be acknowledged as the absolutely correct method and in the same way none can be identified as completely wrong. What is important, though, is that assumptions made when presenting environmental effects from the use of electricity are stated and explained thoroughly.

2.1.1 Accounting according to average electricity production

Average electricity production is sometimes used when analyzing electricity consumption. One of the problems with using average production is to decide which average to use: global production, EU production, Nordic production or Swedish production? Another issue that deserves attention is which time interval to use: a year, a week, a day? If boundary limits are set, it is, though, a method that is easy to apply and easy to communicate. Using average production gives you a view of the production of electricity over the chosen time period, but it will not reflect the impact of changes in electricity use, for example increased electricity use due to conversion from an oil fired boiler to a heat pump or decreased electricity use resulting from energy efficiency measures in an industry. Average emissions do not illustrate the dynamics of the power system.

2.1.2 Accounting according to emissions trading

Emissions trading is a scheme whereby companies are allocated allowances for their emissions of greenhouse gases according to the overall environmental ambitions of their government. The companies can trade the allowances with each other. The emissions trading system has introduced an upper limit of carbon dioxide emissions and is divided into two periods; the first from 2005 to 2008 and the second from 2008 to 2012 [SEA, 2005c]. It is still uncertain what will take place after 2012. This means that even if electricity consumption is decreased this will not lead to a decrease in carbon dioxide emissions since the freed allowances can be sold and thus used to increase electricity use and carbon dioxide emissions in another part of the market. The total amount of carbon dioxide emissions can subsequently not decrease below the upper limit of the system. It is therefore often argued that the effect of emissions trading is that measures to decrease electricity use will have no impact on global carbon dioxide emissions at all.

One consequence of such arguments might be that efforts to change any energy system towards sustainability by converting from electricity to renewable sources stops. Motivation will also very probably be affected, as the environmental correlation no longer exists. Even though measures to reduce electricity consumption not will lead to any direct reduction in emissions of carbon dioxide because of the emissions trading system, the measures will demonstrate how to help the member states of the EU to lower their emissions of carbon dioxide and thus fulfil their commitments under the Kyoto protocol. If any measures to reduce electricity is proven to be economically profitable, the measures consequently illustrate possible cost-efficient ways to reduce emissions of carbon dioxide and might thus contribute to lowering the upper limit set by the emissions trading system. It will also be a competitive alternative to new production.

2.1.3 Accounting according to labelled electricity

In Sweden, the Swedish Society for Nature Conservation (SSNC) operates a system of environmental labelling of electricity delivery contracts since 1996. Labelling is available for suppliers offering electricity from renewable sources of energy such as solar power, wind power, hydropower plants built before 1996, and biofuel plants. Companies may acquire a licence to use the label by proving their ability to deliver such electricity and by agreeing to be audited [SNF, 2001].

Kåberger and Karlsson [1998] argue that long-term and regular electricity consumption may be a reason for the electricity producer to invest in more base-load production capacity. This means that whether the consuming process was established or not would not affect the use of electricity production plants as marginal production capacity. Life-time or investments in nuclear reactors, coal fired plants or other base load type plants would instead be affected, for example when an electricity intensive process industry sets up or shuts down. Using labelled electricity means that data from specific contracted electricity production plants should be used when accounting electricity consumption.

2.1.4 Accounting according to marginal production

It is the most expensive plants, and probably with the poorest efficiency, that supply the margin. Marginal cost is defined as the running cost (RC) of the most expensive generating plant that is needed to supply the immediate demand for electricity. Marginal costs consider future costs either in a short-range perspective (SRMC) or in a long-range perspective (LRMC). SRMC can be described as the sum of RC and SC, where SC is the shortage cost due to the risk of a shortage of power during periods when electricity demand is high and approaches the limits of generating capacity. If there is a need for investment in new power plants due to an increase in power demand, the investment cost must be included in the marginal cost. The criteria for an investment in a new power plant can be described as RC + SC >= LRMC. When the relation is satisfied there is a need for investment.

Using marginal production to account electricity is a way to reflect the changes in electricity consumption as the demand decreases or increases. In continental Europe, as well as in the Nordic electric power system, it is usually coal condensing power plants that have the highest variable cost and thus act as the marginal electricity source (see Figure 1). The principal of coal condensing power being on the margin of Swedish electric power system is supported in a report from the Swedish Energy Agency [SEA, 2002] where it is claimed that coal-condensing power has been the last dispatched source of power. The same report also states that in the short run (SRMC) coal-condensing power will remain the marginal source and in a longer perspective the marginal source (LRMC) in a European system will be generated in natural gas based power plants. Kågeson [2001] makes the same observation and assumes that in perhaps 20 years, natural gas combined cycle generation will take over as the marginal source of electricity.

When marginal production is used it is important to distinguish short-range changes, as for example turning on and off a lamp, from long-range changes as when converting from an electricity boiler to a biofuel boiler. Marginal production can sometimes be complex to explain for those who are going to use the method, but is nevertheless the method that best reflects increases or deceases in electricity consumption. As the electricity usage alters it will be the most expensive source of power that will be affected.

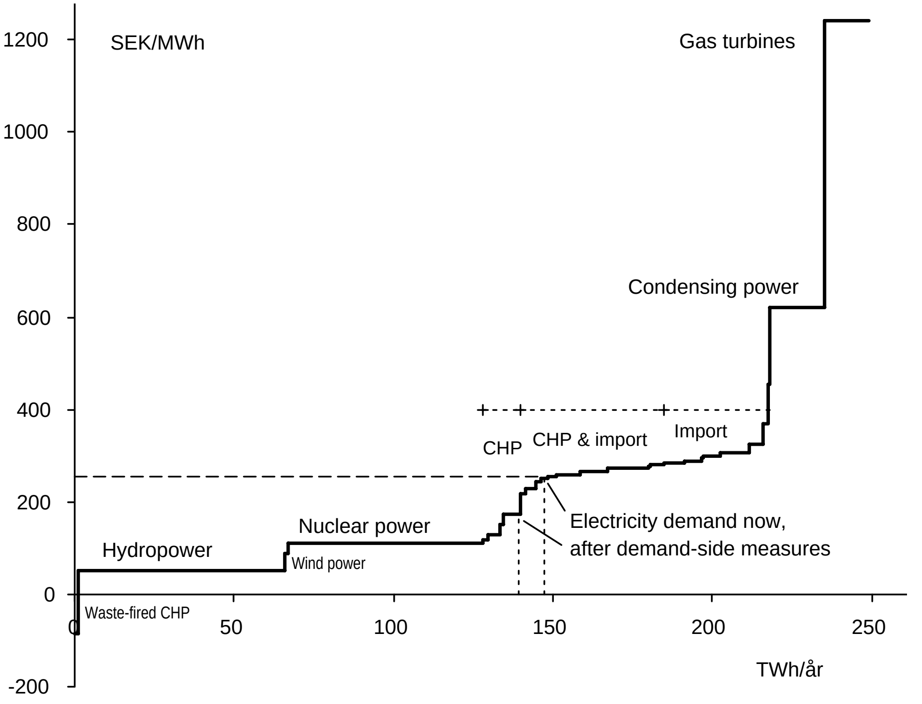

Figure 1: Principe for electricity production on a spot market, [paper VII]

Based on the argumentation above, marginal production has been used when accounting for electricity in this thesis. In the same way as for average production, system boundaries must be set. It must be determined whether marginal production is to be used for Swedish production, Nordic production, EU production or global production.

2.2 Electricity prices in a deregulated European market

The price of electricity in European countries varies, which can be explained by different national markets with sometimes modest trading between the countries. A comparison of the price paid by industries in different European countries (2 000 MWh/year, including fee for grid and taxes) shows that Sweden has one of the lower prices (Figure 2). Sweden’s historically low electricity prices can be explained by the country’s supply system, which is mainly based on hydroelectric and nuclear power plants with low operating costs. In other countries, such as Denmark and Germany, where the electricity supply system is primarily based on thermal power plants fuelled by coal with high operating costs, the electricity price is higher. Figure 3 shows the variations in average price of electricity from 1996 to 2006 in Sweden.

[Euro/100 kWh]

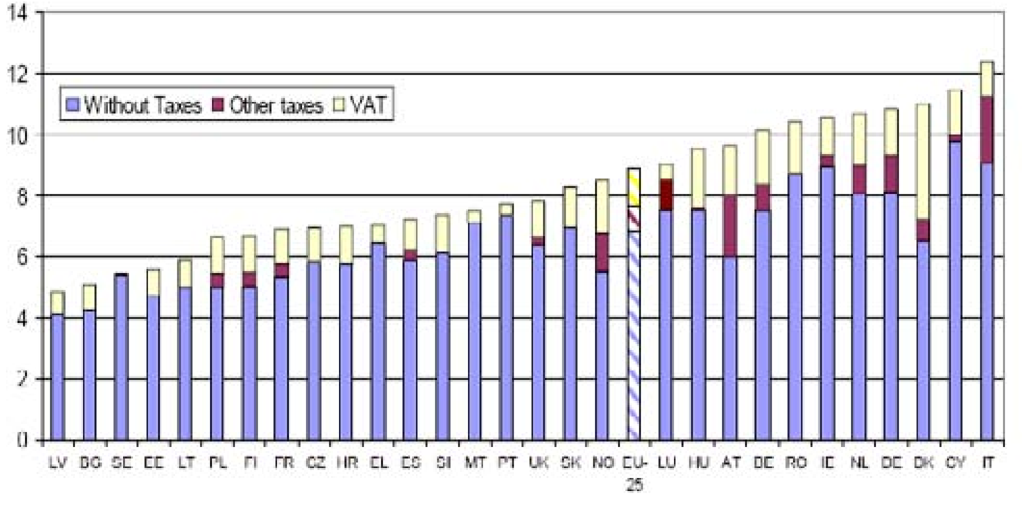

Figure 2: The price of electricity for industrial consumers on the 1st July 2005, 2 000 MWh/year. [Eurostat, 2006]

Comment to Figure 2:
EU25= weighted average for the following 25 countries: Belgium, Czech Republic, Denmark, Germany, Estonia, Greece, Spain, France, Ireland, Italy, Cyprus, Latvia, Lithuania, Luxembourg, Hungry, Malta, Netherlands, Austria, Poland, Portugal, Slovenia, Slovakia, Finland, Sweden and the United Kingdom.

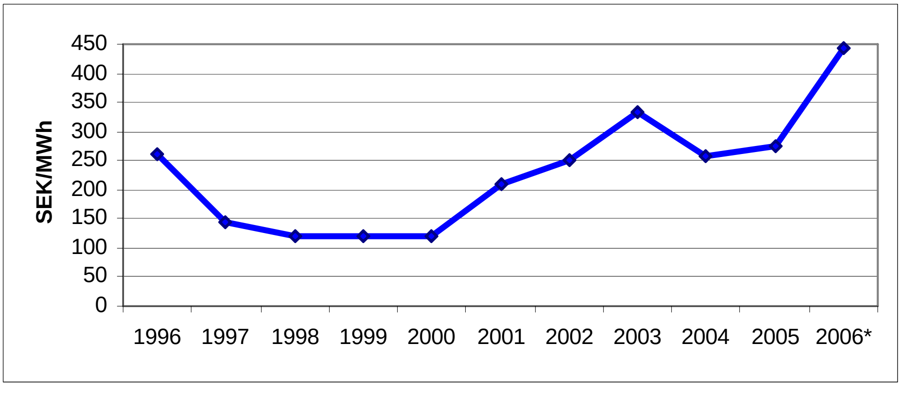

Figure 3: Average elspot price for Sweden. Source: Nordpool 2006
**) The value for 2006 includes only the months January to August.*

A well-functioning electricity market in Europe has daily variations in electricity price, corresponding to price behaviour in a power load dimensioned system. In a deregulated market with many producers and consumers, the competition should drive prices to marginal cost according to basic economical theory. The electricity price in a deregulated European electricity market should therefore in the long run level out the marginal cost of electricity generation (LRMC) in the European system.

Since the price of electricity in many of the member states of the EU is almost twice as high as in Sweden (see Figure 2) it implies the Swedish electricity producers to sell electricity to consumers in the EU at a much higher price than to Swedish consumers in a deregulated European electricity market. As a consequence, the electricity price in Sweden will rise and the electricity price on the European continent will fall in the same way as the Swedish electricity price decreased after the deregulation of the Nordic market. A fully deregulated electricity market in the EU with no restrictions on transfer capacity will therefore most likely gradually level out to a European "equilibrium" electricity price. A single European market with higher marginal costs for electricity generation will therefore lead to higher electricity prices in Sweden. Based on the arguments above, a highly probable scenario for how the electricity price may develop in Sweden when facing a deregulated European electricity market in the long term is shown in Figure 4.

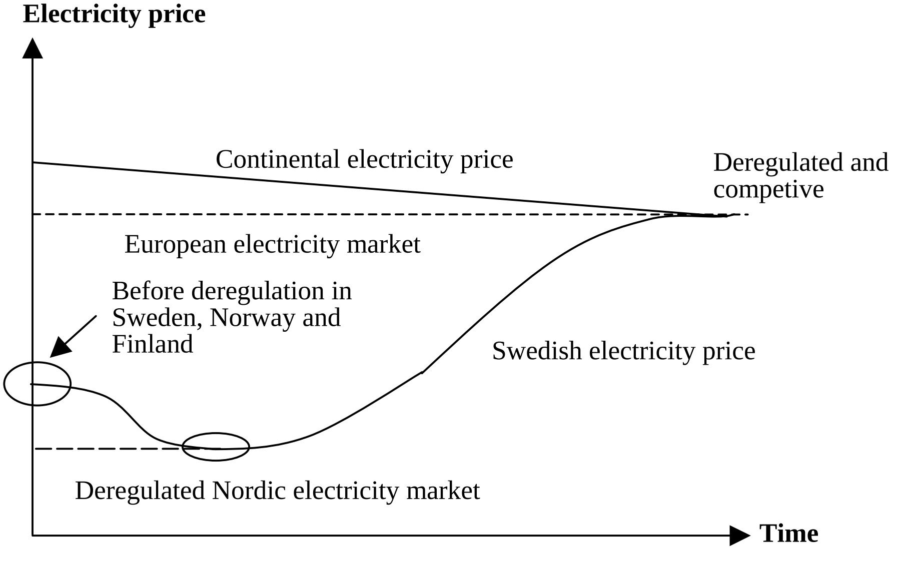

Figure 4: A probable scenario for the development of electricity prices in Sweden. Source: Dag, 2000.

Sweden is characterized as an energy dimensioned system where the electricity price varies over the year, while the electricity supply system in continental Europe is characterized as power load dimensioned with changes in electricity price over the day. Figure 5 shows how the electricity price in the German spot market is both higher than the electricity price on Nordpool and also varies over the day. The price on Nordpool, on the other hand, fluctuates very little over the day.

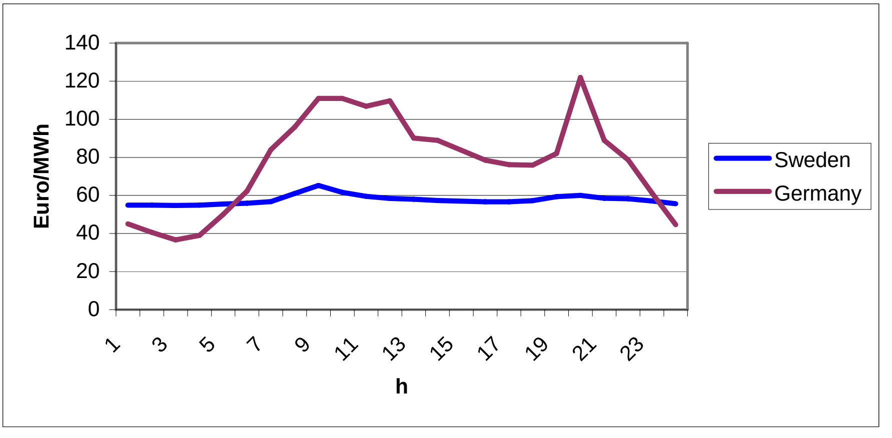

Figure 5: Electricity spotprices, Sweden and Germany, 060322.
Source: Nordpool 2006, EEX 2006.

Since the Nordic market constitutes only a minor portion of the common European market, it is likely that the conditions on the European continent will be valid for the entire common European market including Sweden. Altogether this implies that Swedish electricity consumers will have to face both higher electricity prices and prices that vary over the day instead of over the season. This means a higher daytime electricity price and a lower price at nights and weekends.

2.3 Use of electricity within Europe

In Sweden, the use of electricity per capita is the fourth highest in the world; only Norway, Iceland and Canada have a higher consumption. In industrialised European countries such as Germany and France, per-capita electricity use is less than half that of Sweden [SEA, 2005d]. Figure 6 shows the use of electricity per capita in different European countries and in Canada.

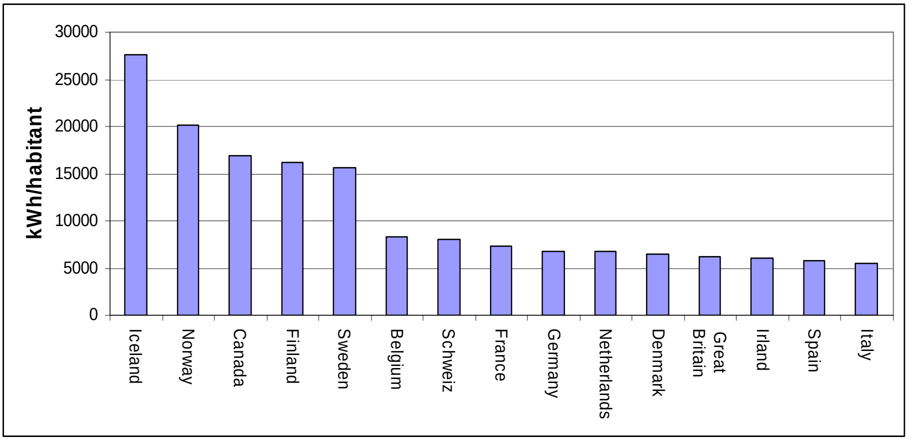

Figure 6: The use of electricity per capita in Europe, 2002
Source: SEA 2005a

Studies of industrial electricity use in Europe show the same pattern: the use of electricity is higher in Sweden than in other countries. A comparison between Volvo's factories in Sweden and Belgium shows that electricity use per produced car in Volvo's Swedish facility is twice as high as at the company's facility in Belgium. The climate difference between the two countries is not an argument for the higher use at the Swedish plant since a warmer climate is more likely to lead to a system, which is more electricity intensive [Dag, 2000].

In a benchmarking study of Electrolux factories, Nord Ågren [2002] described a correlation between low electricity price and high electricity use and the converse, high electricity price and low electricity use. One explanation for the high electricity use in Sweden can thus be the historically low electricity price compared to other countries in Europe. The analyses of the Volvo factories and the factories in the Electrolux group seem to indicate that electricity price multiplied by electricity use is constant, which means that if the price of electricity were to rise, the use of electricity would decrease. This phenomenon of rising electricity use with decreasing electricity price can be explained by the theory of price elasticity. Every product has price elasticity. If the price of a product rises, demand will decrease, partly because customers wish to make their use more effective and partly because some customers will choose another supplier. Price elasticity can be defined as

$$\text{volume} = \text{constant} * \text{price}^{\text{exponent}}$$

If the exponent is equal to minus one, the product is said to be completely price elastic. An increase in price will then give rise to a decrease in demand. This would mean that rising electricity prices in Sweden would in a long-range perspective lead to a decrease in electricity use .

2.4 Transmission capacity on a deregulated European electricity market

According to the Electricity and Gas Directives [COM, 2002] cross border trading is crucial for the function of the European electricity market. Without electricity trading between the countries there will be no common European market and the intention of is the creation of one truly integrated single market, not fifteen more or less liberalized but largely national markets [COM, 2002]. According to the directive, the aim is a slow, gradual and partial opening of the member states' electricity markets. The liberalization in the EU has been a top-down process driven by the directives of the European and of the Council. The directives lay down the general conditions that should be in place to assure the creation of a single Internal Electricity Market (IEM) in Europe, but refrain from designing a concrete market. Given this freedom, most European countries have chosen to keep centralized components to a minimum and to leave market organization to the dynamics of private initiative [Meeus et al., 2005].

If the European Single Market is to be extended effectively to the electricity supply industry, then EU member states will need to make better use of transmission capacity, particularly interconnector capacity, to facilitate cross-border trade. The poor correlation of spot prices between many neighbouring countries implies that the national electricity markets are for the most part poorly integrated. This suggests that either cross-border flows are inefficiently impeded by the management of the existing interconnectors or there is insufficient interconnector capacity to allow price equalisation [Brunekreeft et al., 2005].

There has been progress in cross-border trade, which is a fundamental aspect of a single internal market. Net exports from Scandinavia to Germany were 10 TWh higher in 2005 than in 2004 [SEA, 2006]. However, the level of trade in electricity is much lower than in other sectors that have gained greatly from the internal market, such as the telecommunications sector. In the Communication concerning ‘Completing the internal energy market‘ [COM, 2001], it is concluded that a harmonised system for cross-border tarification needs to be developed in order to prevent obstacles caused by the current system of different national tarification systems. The problem may be solved by constructing new capacity and allocating the available capacity in such a way as to ensure a competitive internal market [COM, 2001].

Swedish Energy Agency has analysed how limits in the Swedish electricity transmission system is handled [SEA, 2005b]. Their report states that internal bottle-necks are often resolved by reducing cross-border transmission capacity. This can give rise to large price differences between price areas and also means that the price reflects the marginal costs less. The Swedish Energy Agency points out that an important issue is that rules to manage national limits in transmission capacity must be consistent with the aim of creating a well-functioning internal electricity market in the EU [SEA, 2005b].

In 2004, Sweden hade a net export of 2 TWh [SEA, 2005b]. Figure 7 shows the transmission connections for exports from and imports to Sweden. Table 1 shows prognosis for trading capacities for Monday of week 36 2006 for different time periods. According to the table, total exports forecast for this specific day amount to about 8 000 MW.

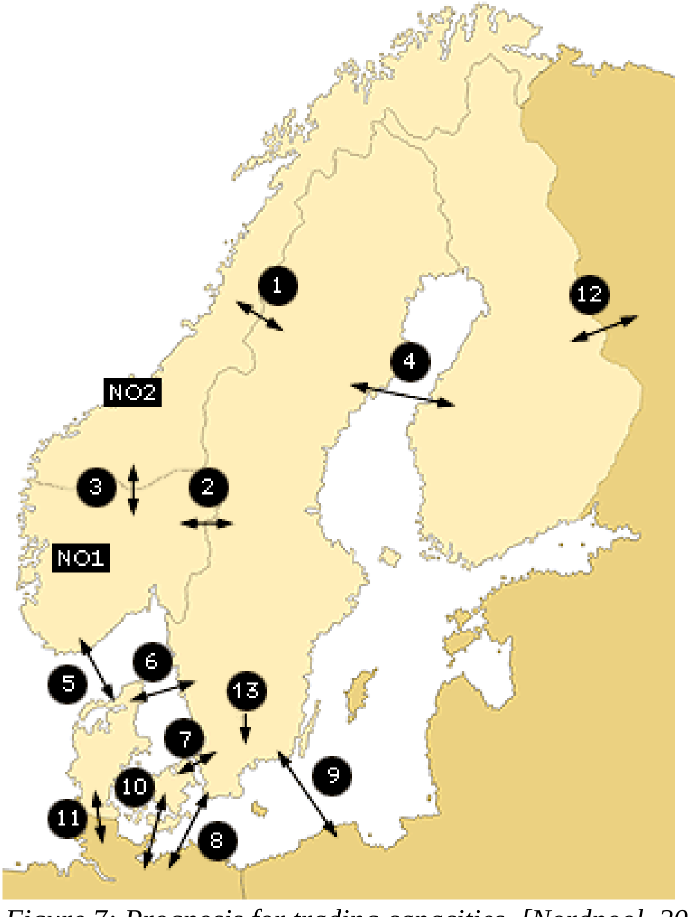

Figure 7: Prognosis for trading capacities [Nordpool, 2006]

Table 1: Capacities prognosis 2006, week 36, Monday
Source: Nordpool, 2006

	Transmission connections	**Time**	**Capacities prognosis [MW]**
1	Sweden–Middle/north Norway (NO2)	00-08	1300
2	Sweden - South Norway (NO1)	00-24	2000
4	Sweden – Finland	00-24	2000
5	Norway - Denmark West	00-24	500
6	Sweden - Denmark West	00-24	620
7	Sweden - Denmark East *	00-24	1100
8	Sweden - Germany *	00-24	600
9	Sweden - Poland *	00-24	600
13	Sweden – total exports south of cut 4 (to 7, 8, 9)	00-24	1850

*Comment on table 1: *13 represents the prognosis for total export limit south of Swedish cut 4. Thus, 7, 8 and 9 only show physical line limits which will be influenced by the sum limitation.*

As stated earlier, the intention of the Electricity and Gas Directives is the creation of one truly integrated single market. Despite this, the market cannot be considered as well-functioning; modest cross-border trading and different price areas indicate that the market is poorly integrated. However, there are indications that it is possible to increase the transfer capacity as regards the existing interconnectors and the difference in spot price between EU countries should in fact also be a strong driving force to increase cross-border trading.

3 Climate changes

The climate problem is one of the most significant environmental issues. Rising emissions of CO_2 and other pollutants intensify the greenhouse effect in our atmosphere, which makes measures to reduce mankind's influence on our global climate increasingly important. In this chapter, climate changes are briefly discussed and commented upon, primarily based on arguments put forward by IPCC, Swedish National Environmental Protection Board and SweClim (Swedish regional climate modelling programme) [Naturvårdverket and SweClim, 2003], [IPCC, 2001a], [IPCC, 2001b].

3.1 The climate is changing

Heatwaves, sustained drought, heavy rain that causes flooding will often raise questions as to whether the climate is changing. But no individual weather situation, no matter how extreme it may appear, can be used as a foundation for concluding that the climate has changed. Weather is a description of. temperature, atmospheric pressure, cloudiness etc, while climate is a summary of how the weather generally is in a specific area.

Nonetheless, there are facts that indicate that the climate is changing. The global average surface temperature per year increased by about 0.6 degrees during the 20th century. After 1975 the increase accelerated and in less than 25 years the average temperature has risen by nearly a half degree. At the same time as it has become warmer, rainfall has increased, the glaciers have receded, snow and ice cover has contracted and the sea level has begun to rise much faster than on average over several thousands of years. Globally it is very likely that the 1990s were the warmest decade, and 1998 the warmest year of the period from 1861 to 2000. Something has obviously happened to the earth's climate in recent centuries [Naturvårdverket and SweClim, 2003].

In 1998 the international climate panel IPCC (Intergovernmental Panel on Climate Change) was jointly established by the World Meteorological Organisation (WMO) and the United Nations Environmental Programme (UNEP). Its present terms of reference are to assess available information on the science, the impacts, and the economics of – and the options for mitigation and/or adapting to – climate change. IPCC also provide scientific/technical and socio-economic advice to the United Nations Framework Convention on Climate Change. The first assessment report presented by IPCC in 1990 pointed out both natural and anthropogenic processes that could have caused global warming during the 20th century. Even though it could not be proven that mankind affects the climate, it was predicted that human activity in a future could cause a rise in temperature that in time would lead to serious consequences for both society and nature.

In IPCC's second evaluation it was stated with a reasonable degree of certainty that man has begun to change the climate. It their third assessment report this statement has been strengthened even further and it is claimed that the earth's climate system has demonstrably changed on both a global and a regional scale since the pre-industrial era, and that new and stronger evidence exists that proves that most of the warming observed over the last 50 years is attributable to human activity. [IPCC, 2001a], [IPCC, 2001b] and [Naturvårdsverket and SweClim, 2003].

According to IPCC [IPCC, 2001a] the climate change issue is a part of the larger challenge of sustainable development. As a result, climate policies can be more effective when consistently embedded within a broader strategy designed to make national and regional development paths more sustainable.

3.2 Rising carbon dioxide concentrations and a warmer climate

When emissions of greenhouse gases are counted as carbon dioxide equivalents, CO_2 will appear as the most predominant greenhouse gas emitted by human activity. The concentration of CO_2 in the air is today (2000) 370 ppm and is rising by 1.5 ppm per year, which is the highest concentration in at least twenty million years [Naturvårdsverket and Sweclim, 2003], [COM, 2000].

IPCC has described a number of scenarios for future emissions of greenhouse gases which illustrate how much will have to be done if unduly drastic climate change is to be avoided. CO_2 concentrations, global average surface temperature, and sea level are projected to increase under all IPCC emissions scenarios. The medium term scenario points to a rise in the carbon dioxide concentration to 550 ppm, twice the preindustrial level, which was 270 ppm. According to the Committee on Climate, 550 ppm carbon dioxide would mean excessively great risks. The projected concentration of CO_2 in 2100 ranges from 540 ppm to 970 ppm. Figure 8 illustrates projections for CO_2 based on IPCC scenarios [Government Bill, 2001], [IPCC, 2001a].

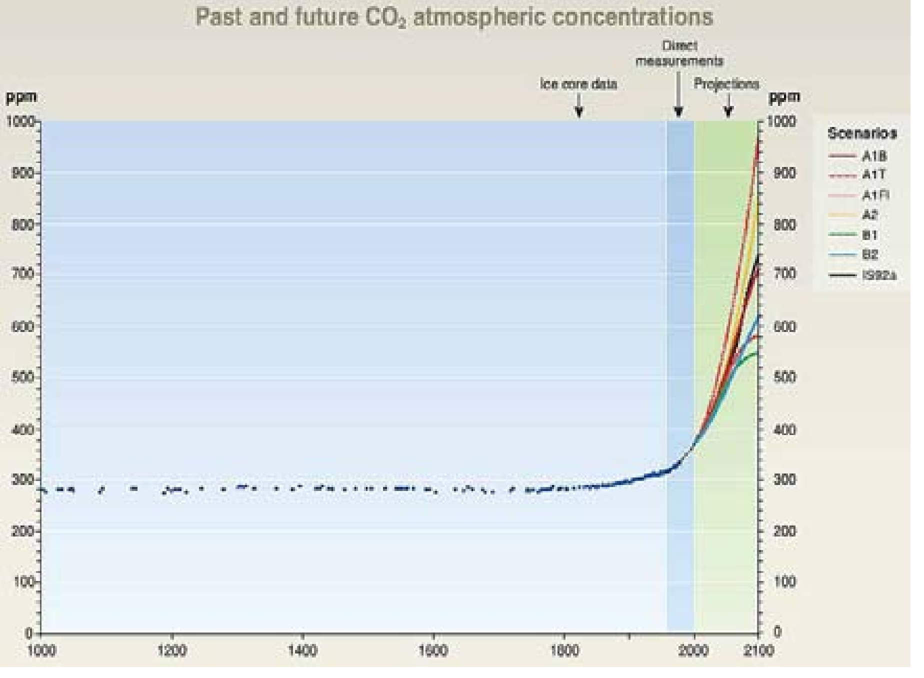

Figure 8: Atmospheric CO_2 concentration from year 1000 to year 2000. Projections of CO_2 concentrations for the period 2000 to 2100 are based on six illustrative scenarios. [1] *[IPCC, 2001a].*

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[1] *The A1 scenarios describe a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. The three A1 groups are distinguished by their technological emphases: fossil intensive (A1F1), non-fossil energy sources (A1T), or a balance across all sources (A1B). In the A2 scenario the population is continuously increasing and economic growth and technical change are slower than in other scenarios. The B1 scenario has the same global population as in A1 but with introduction of clean and resource-efficient technologies. The emphasis is on global solution and environmental sustainability but without additional climate initiatives. The B2 scenario is a world with continuously increasing population at a lower rate than A2. B2 is also oriented towards environmental sustainability but it focus on local and regional levels*

The IPCC scenarios result in projected increases in globally average surface temperature of 1.4 to 5.8 ^{o}C over the 1990 - 2100 period. This is between about two and ten times larger than the central value of the observed warming over the 20th century and the projected rate of warming is very likely to be without precedent during at least the last 10,000 years [IPCC, 2001a]. Figure 9 illustrates the projected increase in temperature according to the IPCC scenarios.

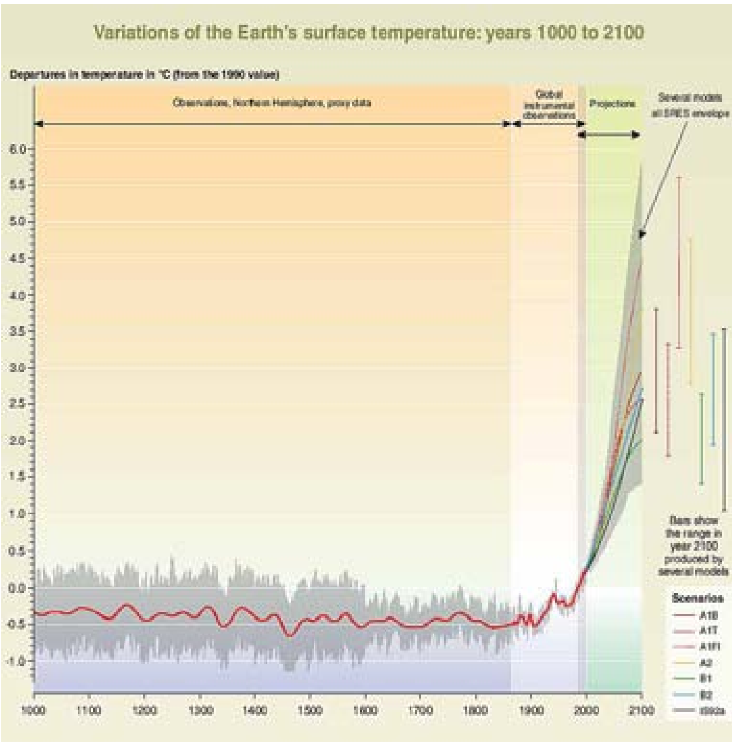

Figure 9: Variations in the earth's surface temperature: years 1000 to 2100. From years 2000 to 2100. projections of global average surface temperature are shown according to IPCC scenarios[2] [IPCC, 2001a].

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[2] *For explanation of the IPCC scenarios se figure 8.*

3.3 Commitments under the Kyoto protocol

Under the Kyoto protocol, the EU region has committed itself to reducing its emissions of six greenhouse gases by 8% between 2008 and 2012 compared to their 1990 levels. The six greenhouse gases listed in the Kyoto protocol are carbon dioxide, methane, nitrous oxide, hydrofluorocarbons [HFCs], perfluorocarbons [FCs], and sulphur hexafluoride [SF_6]. Emissions should be counted as carbon dioxide equivalents to comprise the six greenhouse gases.

In its Green Paper [COM, 2000], the EU Commission emphasizes that greenhouse gas emissions in the EU region are increasing. Sweden has signed and ratified the UN Framework Convention on Climate Changes, which was adopted in Rio de Janeiro in 1992. At the Third Conference of Parties, held in Kyoto in 1997, a protocol was adopted setting out limits on the greenhouse gas emissions of industrial countries. According to the terms of the EU burden sharing agreement, Sweden, with its relatively low per capita emissions of greenhouse gases, is entitled to increase emissions by up to 4%. The aim of the Swedish climate policy, however, is that emissions of greenhouse gases are to be at least 4% lower in 2010 than they were in 1990. [Government Bill, 2001], [COM, 2000]

The Kyoto Protocol also introduced three international mechanisms without which the Protocol is unlikely to enter into force and which are intended to facilitate the cost-effective implementation of the Protocol:

- Joint implementation, i.e. one developed country carrying out projects in another and being credited with the resultant reduction of emissions.

- Clean Development Mechanism, i.e. a developed country carrying out a joint emissions reduction project with a developing country and being credited with the emission reductions.

- Emissions trading[4] between developed countries, in such a way that a country which reduces emissions in excess of its commitment can, but need not, sell emission rights to a country which has difficulty in meeting its target.

The purpose of these mechanisms is to lower the cost of emission reduction (all three), and to provide technology transfer from affluent developed countries to poorer developed countries (joint implementation) and to developing countries (clean development). The national objective of reducing greenhouse gas emissions by at least 4 percent shall, according to the Government's proposals, be achieved without compensation for uptake in carbon sinks or with Flexible Mechanisms. By 2050, Sweden's total CO_2 emissions should be less than 4.5 tonnes per capita annually, diminishing further thereafter. Achievement of this target will depend to a decisive extent on international co-operation and initiatives in all countries [Government Bill, 2001].

3.4 Fossil-fuel burning as a cause to global warming

Carbon dioxide has a prolonged lifetime in the atmosphere, which will make the emissions to continue to rise during this century even if the emissions should begin to decline. The greater the reductions in emissions and the earlier they are introduced, the smaller and slower the projected warming and the rise in sea levels. IPCC points out that reducing emissions of greenhouse gases to stabilize their atmospheric

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[4] The effects of emissions trading are discussed in chapter 2.1.2.

concentration would delay and reduce damage caused by climate change. Stabilizing CO_2 concentrations would require substantial reductions of emissions below current levels but sea levels and ice sheets would still continue to respond to warming for many centuries. There is, though, a wide band of uncertainty in the amount of warming that would result from any stabilized concentration of greenhouse gases [IPCC, 2001a].

IPCC states that emissions of CO_2 from fossil fuel burning are virtually certain to be the dominant influence on the trend in atmospheric CO_2 concentration during the 21st century and concludes that development and transfer of environmentally sound technologies are important components of cost-effective stabilization of the greenhouse gas concentration [IPCC, 2001a].

It is obvious that there is strong evidence that global surface temperature is rising and that most of the warming observed over the last years is credited to human activity. In this thesis, technical measures for energy suppliers and industrial energy user are presented, such as for example more efficient use of electricity, co-operation and investment in CHP. Assuming that reduced electricity use and increased electricity production in Swedish CHP plants will replace coal-based condensing power plants these measures will result in possible cost-effective means to reduce global emissions of CO_2 and thus help fulfil the commitments under the Kyoto protocol.

4 Important assumptions in this thesis

On the basis of the arguments in chapter 2 and 3 regarding a deregulated European electricity market and climate issues, the following important assumptions have been made when conducting the analyses included in this thesis:

- The electricity price in a fully deregulated European electricity market will in the long run level out the marginal cost of electricity generation (LRMC) in the European system. For Swedish consumers, this implies higher electricity prices with daily variations.

- Marginal production for a Northern European electricity system is used to account for electricity consumption.

- Coal condensing is assumed to be the marginal source in the short run (SRMC). In a longer perspective (LRMC) natural gas based power plants are assumed to be the marginal source. Electrical efficiencies of a coal-condensing plant are normally between 35% and 45%. However, it should be the plants with the poorest efficiency that supply the margin. Assuming marginal power production with a 33% electrical efficiency, each megawatt-hour of electricity generated in such a coal fired condensing plant thus releases approximately one tonne of carbon dioxide [Sjödin, 2003].

- The case studies conducted assume an ideal fully deregulated European electricity market with no restrictions on transfer capacity.

- The climate issue is one of the greatest global environmental problems and most of the warming is attributed to human activity according to IPCC. Global warming is a major threat that must be taken into consideration in every strategic decision.

5 Related literature within energy efficiency

There are several EU directives that are of relevance for the work in this thesis. Some of them are outlined and referred to in the included papers, as for example the EU directive for electricity and gas in a liberalized European market [COM, 2002], the Green Paper on greenhouse gas emissions trading within the European Union [COM, 2000], Communication from the Commission to the Council and the European Parliament Completing the internal energy market [COM, 2001]. Other directives, studies and report that are not described earlier and which are considered to be of relevance to the work in this thesis, are briefly outlined and discussed in this chapter. Literature relating to the methodology used, is discussed in chapter 6 Method.

In the White Paper on the Treaty establishing a Constitution for Europe it is claimed that promotion of energy efficiency is one aim to preserve and improve the environment [FCO, 2004]. Energy efficiency as a means to reduce CO_2 emissions has been discussed in several scientific analyses e.g. [Blok, 2005], [Metz et al., 2001], [Kelly, 2005], [Brownsword et al., 2005]. Energy efficiency issues have been an important phenomenon in the global balance over the past 30 years and without energy efficient improvements, the OECD nations would have used approximately 49% more energy than was actually consumed as of 1998 [Geller et al., 2006]. In 1970 to 1983 Sweden was a model country for energy-wise housing but today other countries are catching up and some countries, as for example the USA, are overtaking Sweden in energy efficiency. The increases in the price of oil between 1972 and 1985 correlate well with the improvements in energy efficiency, but the effect was limited by the low electricity prices at that time [Nässén and Holmberg, 2005].

In the EU document "Report on the Analysis of the Debate of the Green Paper on Energy Efficiency" [COM, 2005], opinions from a public consultation regarding energy efficiency are described. The report includes concrete proposals and observations from 241 contributions regarding 25 questions. The report concludes that there is strong support for energy efficiency, demonstrating a win-win potential of a determined and resolute strategy for this initiative but there is a lack of information and citizens and industry are not familiar with the technology and other policies they can use to improve energy efficiency. Projects and measures that were successful in a certain area should be widely disseminated and supported in areas with similar characteristics. CHP is widely supported as representing a huge potential if effectively connected to district heating grids. Finally, it is extensively recognised that the EU can and should do more to spread better energy efficiency practices globally.

In the publication "World Energy Assessment, Overview 2004 Update" [UNDP, 2004] a comprehensive view of energy for sustainable development issues and options are presented. It is stated that for example more efficient use of energy, increased reliance on renewable energy sources and an accelerated development of new energy technologies are options that supports a redirection of our energy system toward sustainability.

Varone and Aebischer [2001] analyse the design process of the energy efficiency policies implemented in five countries, including Sweden, from 1973 to 1996. The study identifies the potential for reducing CO_2 emissions through electricity end-use efficiency in the domestic and service sectors.

Initiatives to change consumers' behaviour towards more efficient behaviour are referred to as demand side management (DSM). In the document "DSM and IRP, experience and strategies for Europe" it is claimed that overall savings of 15-20% in electricity consumption could be accomplished in Europe if all energy saving measures with a payback time of less than 3 years were to be carried out [EU, 1998]. Didden and D´haeseleer [2003] argue that the DSM initiative can be accomplished if governments give the responsibility for implementing energy efficient measures to a proper actor, where a proper actor is an actor who does not suffer a financial loss due to the implementation. When considering all actors being affected by an energy efficiency measure Didden and D´haeseleer claims that the consumer will appear on the winners' side, due to the fact that energy savings will pay back the initial investment while the suppliers of primary energy will be noticed on the losers' side. The definition of a winner is in this case an actor who will benefit from the measure

Industrial energy audits with the aim of reducing energy cost through energy efficiency have been studied by for example Thollander et al. [2005] and Karlsson [2002]. Many studies indicate that energy efficiency measures are not always implemented even though they are cost-efficient. Johansson and Goldemberg [2002] points out that barriers to energy efficiency improvements include for example transaction costs, high initial and perceived cost of new technologies, and lack of information. The authors state that pricing and metering the energy right is one important way to overcome the barriers, but it is not sufficient. Energy-efficiency standards and labelling, low-interest loans to cover investments in energy improvements tradable certificates for energy efficiency improvements are some of the approaches that have been effective in various contexts according to Johansson and Goldemberg.

Qualitative studies by Sandberg [2004] investigate the demand for decision support, and the barriers to and incentives for energy-related co-operation. The results indicate that even though companies state that it is important to have a more comprehensive view of energy efficiency in investment decisions and adequate information about the conditions, few resources are allocated to these issues, for example to monitor energy use. Sandberg points out that example of barriers to energy efficiency are lack of capital and personnel resources dedicated to energy, the use of capital for competing investment priorities and that capital is subject to high hurdle rates for energy efficiency improvements. According to Sandberg there are several reasons why a company should consider environmental issues, as doing so may reduce cost and risk, achieve goodwill, and be a sales argument. A study of energy intensive Swedish foundry industry shows that the largest barrier to energy efficiency is limited access to capital, risk of production disruptions, and lack of budget funding. The largest drivers found were long term strategy, people with real ambition, and an environmental company profile [Rhodin et al., 2006].

In her thesis, Andersson [1997] presents a system analysis for cooperation in local markets including distributors and customers. One case study included in the thesis shows that end-use measures will reduce the system cost (excluding investment cost) of an industry by 50%. The end-use measures imply reduced power demand during peak load periods in the local market, and increased power demand during non-peak load periods.

All the above-presented studies have provided important and relevant input to this work. However, no research with a system perspective has been found that analyses measures for energy suppliers and industrial users in a fully deregulated electricity market when a substantial increase in electricity price is assumed. Furthermore, no work has been found that considers this in combination with the basic assumption that global warming is a major threat that must be taken into consideration in every strategic decision.

6 Metod

Most of the analyses included in this thesis were conducted as case studies with a system approach for the analysed energy systems. Ingelstam [2002], Churchman [1968] and Wallén [1996] have discussed system analyses and system thinking in various literatures. The first chapter is primarily based on their arguments concerning system analyses, followed by discussions regarding case studies that are primarily based on Merriam [1988] and Yin [2003].

6.1 System analyses

Churchman [1968] begins his book “The System Approach” by listing a number of problems that in principle could be solved by modern technology but remain unsolved. The problems listed include feeding, sheltering and clothing every inhabitant of the world, instituting social sanctions that will prevent the outbreak of i war and providing adequate medical care for every inhabitant of the world. If man has the capability to solve all these problems, why doesn’t he do so, Churchman asks. Looking at the problems it is obvious that the problems are interconnected and overlapping. The solution of one clearly has a great deal to do with the solution of another. The answer to the question is that we are not organized to do so. Applying a system approach to the problems is instead recommended. System analyses are above all a way of thinking about these total systems and their components, an approach, not a number of methods, and it is only one approach to the way in which humans should respond to reality; but it is a "grand" approach according to Churchman [1968].

The definition of a system and its boundaries are central issues as regards system analyses. Churchman [1968] outlines five basic considerations that must be kept in mind when thinking about the meaning of a system:

- The total system's objectives, and more specifically, the performance measures
- The system's environment: the fixed constraints
- The resources of the system
- The components of the system, their activities, goals and measures of performance
- The management of the system

Of these issues the second aspect; "the system's environment" is perhaps the one that needs most attention since it is tightly connected to the systems boundaries. This is further discussed in this chapter together with the definition of a system.

6.1.1 System definition

One broad definition of a system is that it is a group of objects that interact [Wallén, 1996]. This implies a system as a totality with different qualities than what can be found in the objects. According to Wallén, system thinking starts with a need to follow, understand, and plan for development and changes in complex connections where a number of factors interact with each other. The reason for letting the system consist of a certain number of components and connections is that they constitute a totality. In the same way, Ingelstam [2002] points out that a system consists of two sorts of parameters: some sort of components and the connection between them. According to Churchman [1986] a system is made up of sets of components that work together for the overall objective of the whole.

This work has been carried out within the interdisciplinary graduate school “Energy systems”. The research program definition of an energy system is that it consists of technical artefacts and processes as well as actors, organizations and institutions, which are linked together in the conversion, transmission, management and utilization of energy. According to the definition of the program, the view of energy as a socio-technical system implies that also knowledge, practices and values need to be taken into account to understand the on-going operations and processes of change in such systems.

However, this thesis does not deal with the behaviour and norms of different actors; only one paper (III) embraces a socio-technical analyze of the energy system including the actors’ roles and values. The definition of an energy system used in this work is therefore in line with Churchman’s meaning of a system, i.e. *sets of components that work together for the overall objective of the whole.*

6.1.2 System boundaries

In many applications, the criteria of what’s inside the system is what an actor controls while parts he does not control belong to the environment. Ingelstam [2002] claims that identifying the interactions between the components of the system and the connection between them is an important issue for system analyses as is the elucidation of the system itself. It is easy to argue that everything is connected. System analysis does not deny that there is a connection between practically everything, but it stipulates that the intellectual method to handle the questions must be to distinguish a system and a subsystem and to draw a borderline between this and the environment. It is often natural to look upon a system as compounded of several subsystems. The larger system will be the environment to the subsystems. The subsystems can then be divided into subsystems that will result in a hieratic of systems logically related to each other like Russian dolls [Ingelstam, 2002].

Wallén [1996] points out that the fist assignment for a system analysis is to find suitable delimitation: what is inside and what is outside the system. Some of the main points in system theoretical analyses are, in addition to system delimitation, the construction of a system and studies of, for example, energy flows inside the system and between the system and the surrounding, interactions between the different parts of the system and how the system changes over time [Wallén, 1996]. The environment is something that is outside the system's control and also something that determines in part how the system performs. Churchman [1968] gives one example on how to look upon the environment. If the system is operating in a very cold climate so that its equipment must be designed to withstand various kinds of severe temperature change, then the temperature changes are in the environment, because these indicate the given possibilities of the system's performance and yet the system can do nothing about the temperature changes. This means that if we can answer *No* to the question: "Can I do anything about it" and answer *Yes* to the question "Does it matter relative to my objectives?" then "its" is the environment, according to Churchman [1968].

In all the papers included in this thesis, the system boundaries are defined as a European energy system. The reason for choosing Europe as system boundary is mainly due to the fact that we in Europe have common commitments under the Kyoto protocol and that the EU has prescribed common rules for the internal electricity market in its Electricity Directive of 1996 [Directive 96/92/EC]. In papers I, II, III and IV the analyzed systems are Swedish industries and in papers V, VI and VII the analyzed energy systems are a totality that consists of both Swedish industries and Swedish energy supplier. The objective is to find a cost efficient optimal energy system considering different prerequisites. In all the papers, the system's environmental consists of institutional regulations, such as taxes, fees, fuel prices, emissions trading, and electricity certificates since these are conditions that we can not do anything about but that nonetheless have a bearing on the objective.

6.2 Case study research

This thesis embraces several case studies where energy systems with different boundary conditions are analyzed. An essential issue with case studies is weather the specific result from an individual study can be regarded as generalized. This is briefly discussed in this chapter together with the theory about case study research.

A case study is an empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident. According to Yin [2003], a case study, like other research strategies, is a way of investigating an empirical topic by following a set of pre-specified procedures. Merriam [1998] declares that a case study does not claim any particular methods for data collection or data analysis, unlike experimental, survey or historical research. Any and all methods can be used. Determining when to use a case study as opposed to some other researcher design depends on what the investigator wants to know [Merriam, 1998]. Yin [2003] states that a case study has a specific advantage in situations when a "how" or "why" question is being asked about a contemporary set of events over which the investigator has little or no control. A case study might be selected for its very uniqueness for what it can reveal about a phenomenon, knowledge that we would not otherwise have access to [Merriam, 1998].

For the case study strategy different types of designs can be used: single-case holistic designs, single-case embedded designs, multiple-case holistic designs, and multiple-case embedded designs. An embedded case study is characterized by involving more than one unit of analysis and occurs when a subunit or subunits in a case study are also analyzed. In contrast, if the case study examines the global nature of, for example, a program, a holistic design is used. If the same study contains more than a single case the study has a multiple-case design. According to Yin [2003] multiple-case studies have increased in frequency in recent years and are often considered more compelling and robust. At the same time, the unusual or rare cases, the critical cases, are all likely to be single-case studies and not multiple cases. A multiple-case study can, though, sometimes require resources and times that are beyond the means of a researcher investigator [Yin, 2003].

In this thesis both embedded single-case and multiple-case studies are included. In papers I to IV embedded multiple-case design are conducted. Altogether 34 industries are analyzed as multiple cases. The energy use in every single industry is divided into unit processes that are subsequently analyzed as embedded units. The type of sample can be described as "maximum variation" since the industries are selected to show variation in energy use, electricity use and branch. Paper V, on the other hand, has a single-case embedded design. The Volvo plant and the local energy utility are analyzed as a single case while the industry has analyzed embedded subunits. In paper VI the industries are analyzed as embedded multiple-cases and the energy utility as a single case. In Paper VII the industries are also analyses as embedded multiple-cases, and the energy suppliers as multiple-cases.

6.2.1 Generalizing from case studies

Yin [2003] points out that a common concern about case studies is that they provide little basis for scientific generalization or external validity. Case study can simply present individual case studies or also use the cases to make broader generalizations. When considering cases, the mode of generalization is analytic generalization in which a previously developed theory is used as a template with which to compare the empirical results of the case study. If two or more cases are shown to support the same theory, replication may be claimed. Yin [2003] argues that the appropriately developed theory is the level at which the generalization of the case study will occur. The generalization, though, is not automatic. A theory must be tested through replication of the findings in other areas where the theory has specified that the same result should occur. Once such replication has been made, the result might be accepted for a much larger number of similar areas, even though further replications have not been made [Yin, 2003].

Merriam [1998] points out that another way of viewing external validity is to think in terms of the reader or user of the study. This means leaving the extent to which a study's findings apply to other situation up to the people in those situations.

In paper II, a theory is developed regarding changes in industrial use that originate from previous studies. The theory is tested on industries that according to the theory should show the same result and, as can be concluded from paper II, the findings support the theory. The results from the studies are also supported by the industries that participated in the study[5].

[5] Se also chapter 7.5 and 7.6.

6.3 Modelling energy system

The advantage of using models is to be able to answer questions about the system without conducting any experiments that can be impossible, too expensive, or ethical doubtful to perform. Another advantage is to model the effects of changes when there are several factors to consider and all the factors alone are clear but the totality is not. It is, though, important to remember that any model is only an approximation of the real system. Practically all technical analyses and construction work is dependent on models. Models' usefulness depends on how well the model describes the "real" system. It is important to define a model's area of validity and to verify the model [Ingelstam, 2002], [Wallén , 1996].

A number of models have been developed for analyzing energy systems for example MODEST [Henning, 1999], MARKAL e.g. [Unger and Ekvall, 2003], EFOM e.g. [Holttinen and Tuhkanen, 2004], MESSAGE e.g. [Messner and Schrattenholzer, 2000] and TIMES e.g. [Remme et al., 2001]. A review of different types of energy models has been performed by Jebaraj and Iniyan [2006].

According to Wallén [1996], a model should fulfil these requirements: systematic, efficiency, validation, model conditions and generalization. A model for analyzing energy systems must also be able to represent, for example [Henning, 1999]:

- Many energy forms
- Investment costs and fixed and variable operation costs
- Demand-side measures
- Flexible, seasonal, monthly, weekly and diurnal time division
- Optimal operation
- Marginal costs

In this thesis, the MODEST model has been used. The reason for choosing MODEST was above all due the possibility to model flexible time division. The MODEST model (short for Model for Optimisation of Dynamic Energy System with Time-dependent components and boundary conditions) was developed to deal with the above-mentioned fundamental criteria as well as other criteria, see [Henning, 1999]. The MODEST model is briefly described in chapter 6.4. When analyzing industrial energy use in the included papers, a method is used that is based on a strategic checklist called *Tool for Analysis* [Karlsson 2001]. The method describes a strategy for system changes of industrial load management with the purpose of adapting the use of electricity to an absolute minimum and is further described in chapter 6.5.

6.4 MODEST

The MODEST model is used for minimising the cost of existing and potential new plants [Henning, 1999] and [Gebremedhin, 2003]. It is a model framework developed for simulation of municipal and national energy systems and is based on linear programming. The aim of the optimisations is to minimise the total cost of supplying the demand for heat and steam by finding the best types and sizes of new investments and the best operation of existing and potential plants. The total system cost is calculated as the present value of all capital costs of new installations, operation and maintenance costs, fuel costs, taxes and fees. The system is optimised over a period of years. In the case studies included in this thesis, the time period is ten years and the capital costs are based on a discount rate of 6%. Each year in the optimisation model is divided into seasons, which are then divided into daily periods. In papers V and VII the model is divided into a total of 28 different periods during one year, and in paper VI a total of 88 periods is used.

The method assumes an ideal situation where for example the demand for district heating and electricity is known and the capacity of the plants is available. MODEST is not primarily a model for operational optimisation, even if such an optimisation can be made in an approximate manner. MODEST has no other objective than total cost minimisation such as minimisation of emissions or the use of certain energy forms at cost maximum.

The MODEST model has its limitations as for example:

- Hourly and daily operations are not the aim of the model, although every hour of the year could be reflected. Even faster or continuous fluctuations can, however, not be treated at all.
- Binary variable and mixed-integer linear programming included in the model. This means that start-up costs cannot be represented and minimum operation capacity consequently must be modelled manually.
- Investment costs are stated per output unit (SEK/MW). This is important to point out since smaller installations are characterized by higher cost per capacity than larger installations. In paper VI, this means that the modelled absorption chillers are divided into different groups in order to be able to consider variations in investment cost for absorption chillers of different sizes.

Further limitations within the MODEST model are described in Henning [1999].

6.5 Generalized method for analysing industrial DSM

To analyse how and in what processes the industries can redirect their energy use towards a minimum of electricity use, the industries' existing energy use is divided into unit processes, which is a way of splitting industrial energy demand into smaller parts. The reason for the division into unit processes is to obtain a well-defined structure and thereby facilitate a comparative analysis of the energy use in different industries. The unit processes are the smallest components an industry is built upon and consist of a number of production processes and support processes. The production processes produce products while the support processes support production [Söderström, 1996], [Nord-Ågren, 2002]. Space heating and lighting are examples of support processes, while drying and shaping are examples of production processes. To create an energy balance for the energy flow of the industry a document is drawn up with data about the industry's energy use divided into support processes and production processes (Figure 10).

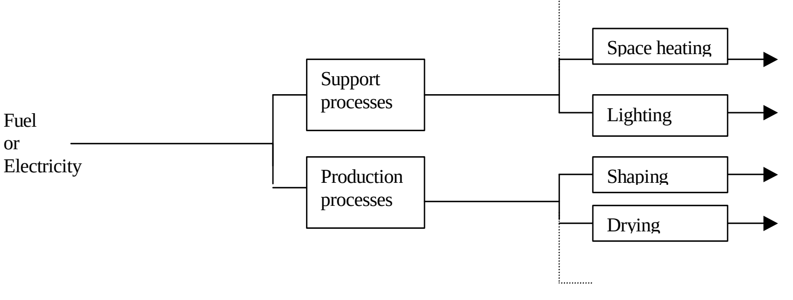


Figure 10: Example of energy flows divided into support and production processes

To study how Swedish industries can reduce their use of electricity, 11 plants in the Swedish municipality of Oskarshamn were analysed (paper I). Each industry's energy use in the study was analysed thoroughly. In addition to measurement work during the daytime, the industries were also visited at night with the purpose of studying the energy use when no production was going on.

The method used for analysing the industries in paper I was based on the *Tool for Analysis* [Karlsson, 2001], which describes a strategy for system changes of industrial energy use to a minimum of energy and electricity use. The analysis tool is based on a top-down approach and is focused upon finding system changes in the use of energy, and not the traditional way of making existing energy utilization slightly more efficient.

On the basis of the results in paper I, a generalized, less time-consuming method has been developed for analysing the potential for industrial electricity reduction (paper II). To verify the method's validity it was applied in 22 industries in the municipalities of Ulricehamn and Örnsköldsvik (paper II). This generalized method, based on every industry's specific prerequisites for electricity reduction, has led to a computer-based method called Ensam [Franzén, 2005] that is used for example by consultants, industries, and energy suppliers to analyze how they can change their energy use in the direction of less energy and electricity dependence.

The generalized method is based on analysing a number of areas which are presented in the following chapters.

6.5.1 Lighting

The installed electric power for lighting can often be reduced and still maintain the same amount of light. A future guideline value for installed capacity for lighting will probably be 3 – 5 W/m^2 [STEM, 2005f]. Reducing installed capacity and electricity use for the process lighting, can be achieved by installing high-frequency illuminators and introducing section control and systems for detecting human presence. The relative reduction of installed capacity for the process can be expressed as

$$\delta_P = (P_l - \psi * A) / P_l \qquad (1)$$

where P_l is the installed capacity for lighting, A stands for the area and ψ represents the guideline value for installed capacity for lighting. If lighting is only needed during the industry's working hours, the relative reduced electricity use [δ_L] for the process can in the same way be expressed as

$$\delta_L = (P_l * \eta * T_p - \psi * A * T_a) / P_l * \eta * T_p \qquad (2)$$

where η is the assumed coefficient of utilization for the process, T_p the operating time and T_a the industry's working hours.

6.5.2 Ventilation

There are regulations for the lowest limit for ventilation in offices, houses, schools and other meeting places. For industries, no lowest limit is stipulated. Instead, the requirement is that the concentration of deleterious substances in the air must be less than the marginal value ratified by the Swedish Labour Market Board.

The reason for ventilating an industry is often to remove heat, instead of reducing the amount of deleterious substances in the air. In such cases, the ventilation system is being used as a cooling system. If the ventilation system is dimensioned to reduce heat during the summer, and the dimension of the system is the same the whole year, the result will be an increased demand for heating during the winter period.

A precise, time-consuming foundation is needed to describe in detail how an industry can reduce its ventilation. However, an easy way is to begin by restricting the ventilation system' operating times to the industry's working hours; this will give an indication of the potential for reducing the electricity use for the process. The relative reduction in electricity use by the ventilation process δ_V can then be described as

$$\delta_V = Pv * \eta * (T_p - T_a) / Pv * \eta * T_p \qquad (3)$$

where Pv is the installed capacity for the process.

When an industry is ventilated, warm indoor air is replaced with cold air from the outside. If the ventilation is reduced, the result will be less need for space heating. Reducing the ventilation as described in *(3)* will therefore decrease energy use for space heating.

6.5.3 Compressed air

Compressed air is used extensively in many industries. The efficiency is barely 5 – 10% in compressed air systems, while it is as high as 90% for electrically powered tools. Leakages are also very common in compressed air systems, which means that the compressor set will need to work more than it should to maintain pressure.

If compressed air is used to power hand tools, it is easy to switch to electrically powered alternatives. If compressed air is integrated in the mechanical equipment, it may be considered difficult and expensive to switch to other alternatives. Regarding the low efficiency in compressed air sets, it ought then to be a long-term goal to phase out the use of compressed air and set other requirements for the machinery and equipment when it is time for investment or rebuilding. Sometimes there is no alternative to using compressed air; if so, it is instead important to focus on leak detection.

The reduced electricity use when compressed air tools are exchanged for electric tools can be described as

$$C_\varphi = Cv * \eta * T_p * \alpha \qquad (4)$$

where α is the difference in efficiency between electrically driven tools and compressed air and *Cv* is the installed capacity for the process.

6.5.4 Reduced use of electricity when no production is taking place

If an industry is visited at night or during a weekend, when there is no production, one will most likely find ventilation systems operating, electric motors running, fans turning, lights on, etc. Hourly power demand values for twenty-four hours can be requested from the electricity supplier. By studying the variations in power demand during a day and a night when there is no ongoing production, the amount of electricity used during those periods can be calculated. Figure 11 is an example of how these power demand values varied for one industry on a Sunday in August and one day during the Christmas holiday. The industry, from which the values are collected, had no production activity during those days.

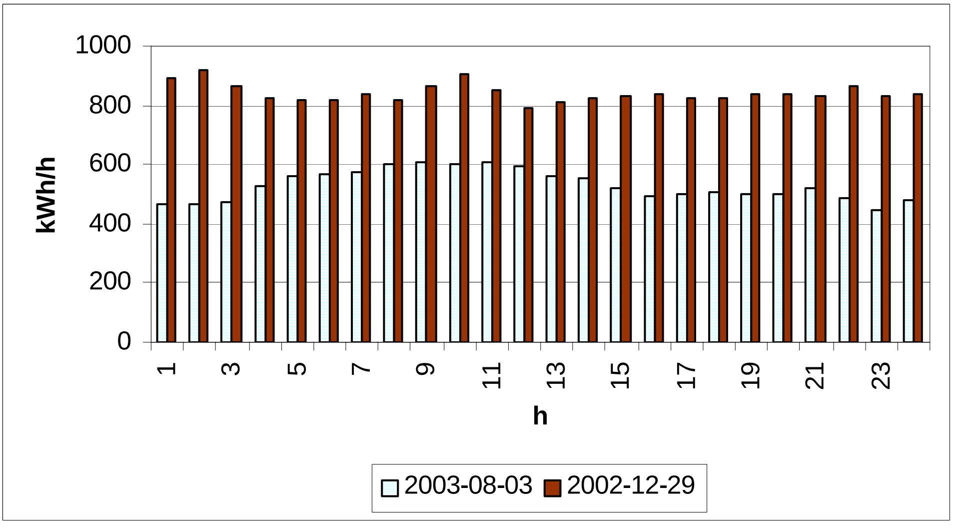


Figure 11: Hourly power demand from an industry in Örnsköldsvik [paper II]

Sometimes the mechanical equipment needs to be turned on at night and during holidays. This fact must be considered when analysing what energy use can be reduced.

6.5.5 Conversion of non-electricity specific processes

Energy-carrier switching from electricity to biofuel can be done for many reasons. Heating, melting, and drying are examples of processes that are non-electricity specific. If any of these processes, or part of a process, is driven by electricity, district heating can be used instead if available and where its temperature is sufficient for the processes. In the mentioned studies, the possibilities to convert from electricity to other energy carriers, in electricity-driven processes that not were electricity-specific, were analysed.

6.5.6 Use of surplus heat and simultaneously heating and cooling

Industrial machines often emit substantial amounts of heat. Space heating in industries is thus sometimes unnecessary and in combination with emitted heat from the machines, will give rise to a greater need for space cooling. Waste heat from the industrial processes can be used to reduce, for example, the energy used for space heating and hot water.

Instead of lowering the temperature if the indoor climate is perceived as too warm, the solution is very often to supply more cooling. This results in a simultaneous need for both heating and cooling, which in turn leads to an overall increase in energy use.

6.5.7 Investment opportunity

Investment opportunity, defined as reduced variable energy, for the industrial measures has been calculated instead of direct investment cost in the industrial analyses included in this thesis. The reason for this is argued as follows.

Considering that industry on the European continent has in several studies proven to use more electricity than Swedish industry (chapter 2.3), minimizing electricity use in Swedish industry can thereby be considered as adapting them to a European level. As argued earlier, it is assumed that the electricity price in Europe will level out to a European equilibrium (chapter 2.2). This will imply that measures to reduce electricity use in Swedish industry to a European level can thus be regarded as profitable since they have obviously already been implemented on the European continent, where electricity use is lower.

When analysing the economic consequences of the industrial measures it is clear that the investment costs vary. Connection to a local district heating grid is based on negotiation with the local district heating supplier. Phasing out the use of compressed air for example is a long-term goal depending on the need for investment in the specific industry and not an economically viable measure in the short term. Reducing electricity use when there is no production is a change that does not involve any cost at all. The variation in subscription time for the different industries is also wide. Reduction in variable cost due to the industrial measures has been calculated both with an electricity price than reflects today’s price and a higher European electricity price. This is in other words equal to the investment opportunity to realize the industrial measures.

6.6 Validation

The validation of a model is an important issue when modelling energy system since the validation will give guidelines on how well the model describes reality. Comparing the model with the real system’s behaviour can validate a model. It is, though, important to remember that models and simulations can never replace observations and experiments [Glad and Ljung, 1991]

The MODEST model has been tested and applied to electricity and district heating supply for approximately 50 local utilities, biomass use in three regions and Swedish power supply [Sjödin and Henning, 2004], [Gebremedhin and Zinko, 2003]. For the studies in this thesis, the results of the optimisations have been thoroughly checked by analysing input as well as output data and have also been communicated to local energy utilities.

Sjödin and Henning [2003] calculated the marginal cost of heat supply for a Swedish district heating utility. Three different methods where used in the study; a manual spreadsheet method, the MODEST model, and a least-cost dispatch simulation model. The calculated marginal costs obtained by the three methods turned out to be similar. This means that the results from MODEST were the same as from the manual spreadsheet method, which can therefore be seen as validation of the MODEST model.

MODEST has also been compared with ordinary manual calculation [Byman, 1999]. The result showed that the output from MODEST was equal with a traditional study carried out by an experienced energy consultant, but MODEST proved to be a much faster method. The comparison also showed that MODEST presents the most optimal solution within restricted boundaries. It is important to emphasize that the results from MODEST are naturally dependent on knowing how to analyze and interpret the outputs.

An analysis of the outcome of the application in industries in paper II showed a potential for electricity reduction and economic benefits in the same range as the study of the 11 industries in Oskarshamn [paper I] that the method arose out of. The method could thus be a valid tool for analysing how Swedish industries can alter their energy use towards less electricity dependence. The results from the analyzed industries have been communicated to all the industries and are accepted and supported by the management of the individual industries.

7 Results from case studies

The case studies aim to identify technical measures for Swedish industries and energy utilities that will be profitable in a deregulated European electricity market with higher European electricity prices by answering this thesis research questions (see chapter 1.1). Table 2 shows in what paper the different research questions are analysed and in what chapter in this thesis they are presented. The chapter starts by discussing the electricity prices used in the different case studies and concludes with how the results from the analyses were communicated to the industries and energy suppliers, and how and if the measures have been implemented.

Table 2: Research questions analysed in included papers

Research questions	Paper	Chapter
1. What industrial measures will redirect industrial energy use towards less electricity use and increased use of district heating in Swedish small and medium-sized industries?	I, II, III, IV, V	7.2
2. How will the two energy supply measures energy-related co-operation and investment in CHP affect a local energy supplier, as the industry alters its energy use?	V	7.3
3. How will the measure conversion from compression chillers to absorption chillers affect industries and energy suppliers?	VI	7.3
4. What will the impact be on the Swedish national power supply of changed industrial energy use towards less use of electricity and increase use of district heating?	VII	7.4

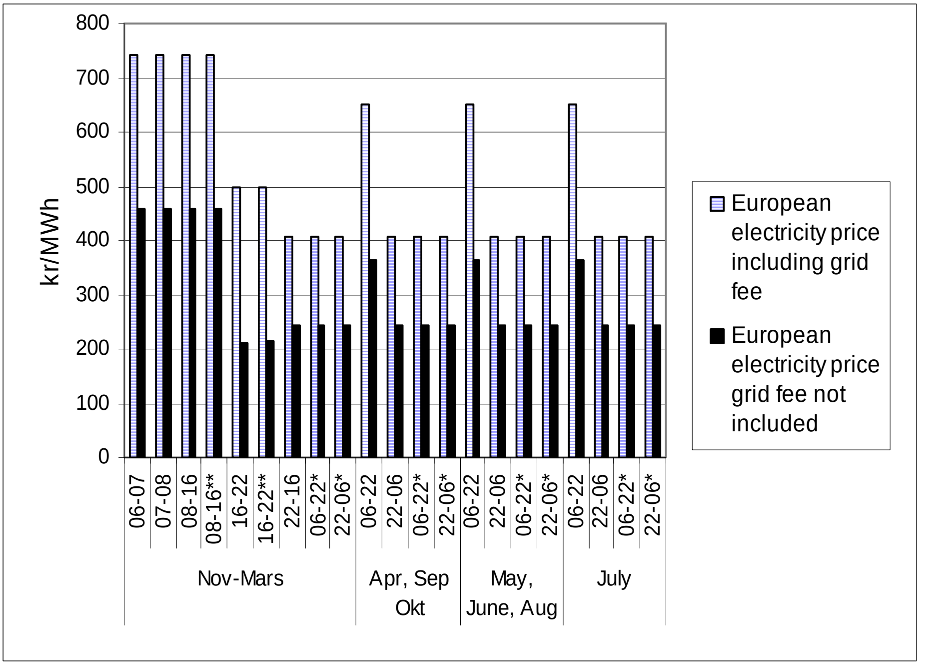
7.1 Modelled electricity prices

As argued in chapter 2.2 Swedish electricity consumers will most likely face both higher electricity prices and prices that vary over the day instead of over the season. This means a higher daytime electricity price and a lower price at nights and weekends. In this work, the effects of the studied measures are analysed by modelling different electricity price structures: one that is referred to as the price today, and one that represents a possible future higher European level.

The cost of electricity used as the price today is based on historical data from Nordpool and is specified in the different papers. The electricity prices modelled to represent a higher European price are primarily based on a study at Linköping University and financed by Eon [Melkersson and Söderberg, 2004]. The study analyses how a European electricity market will affect the price of electricity in Sweden]. Within the study, a model was developed for calculating the marginal costs for electricity production including grid fees.

The model has been used in all the papers included in the thesis except paper I since that paper was written before the model was available. The papers were conducted in different years and the model was updated with new input for the different papers. The electricity price referred to as European prices therefore sometimes varies between the different case studies and is specified in each paper.

Figure 12 shows the variations in electricity price when modelling European prices in papers VI and VII.



*) Saturdays, Sundays and weekends

Figure 12: Modelled European electricity prices in paper V.

7.2 Industrial measures

Eleven industries in Oskarshamn, ten industries in Ulricehamn, twelve industries in Örnsköldsvik and the Volvo Car and truck plant in Skövde have been analysed according to generalized method for analysing industrial DSM presented in chapter 6.5. Örnsköldsvik is a municipality in the north of Sweden while Ulricehamn, Oskarshamn, and Skövde are municipalities situated in the south and southwest of Sweden. The results from the analysed industries are presented in paper I, II, III, IV, V and relate to the first research question. Tables 3 – 6 present the energy use and the electricity use for the industries studied in Oskarshamn, Ulricehamn, Örnsköldsvik and Skövde.

Table 3: Analysed industries in Oskarshamn

Industries in Oskarshamn	**Type**	**Energy [MWh/year]**	**Electricity [MWh/year]**
ABB Figeholm Bruk	Engineering	30 700	11 700
ABB Fårbo	Engineering	2 100	1 500
Bohmans Fanér	Wood, paper	16 700	3 700
Elajo Mekanik	Engineering	2 400	1 000
Liljeholmen Stearinfabrik	Process	9 100	3 100
OKG Rest, Storage	Power plant	4 500	4 500
OP Kuvert	Wood, paper	5 100	4 000
SAFT	Process	34 100	17 100
Samhall Brahe	Engineering	1 700	1 000
SCANIA, approx.	Engineering	70 000	40 000

Table 4: Analysed industries in Örnsköldsvik

Industries in Örnsköldsvik	**Type**	**Energy use [MWh/year]**	**Electricity [MWh/year]**
Alvis Hägglunds	Engineering	26 000	16 000
Avesta Polarit	Steel	7 400	5 000
Glasfiberprodukter	Plastics	500	500
Hägges Finbageri	Bakery	3 400	2 200
Hägglunds Drives	Engineering	17 300	12 400
Industri I [7]	---	3 900	1 900
LPAB	Construction	700	300
Polarbröd	Bakery	10 400	3 500
Profillack	Engineering	2 000	1 400
Sanmina	Electronic	3 900	2 300
Strandberg Industri	Engineering	4 600	1 900
ÖMV	Engineering	3 100	3 000

[6] Industri I represents a medium-sized industry in the municipality of Örnsköldsvik that does not want its name published.

Table 5: Analysed industries in Ulricehamn

Industries in Ulricehamn	Type	Energy use [MWh/year]	Electricity [MWh/year]
AP&T	Engineering	1 800	1 200
Bogesunds Väveri	Textile	1 800	500
Ekro Möbeldetaljer	Furniture	400	300
Emballator	Packing	6 800	6 300
Helge Nyberg	Engineering	900	900
IRO	Engineering	6 800	6 500
Per Schürer	Plastic	1 400	1 400
Svensk Brikett Energi	Wood/Energy supplier		14 000
Ulricehamns Betong	Construction	1 000	600
Zinken Weland	Engineering	3 000	2 900

Table 6: Analysed industries in Skövde

Industry in Skövde	Type	Energy use [MWh/year]	Electricity [MWh/year]
Volvo Car	Engineering	109 900	81 000

The analyses of the 22 industries in Ulricehamn and Örnsköldsvik were part of a study assigned by Swedish Energy Agency in the project "Sustainability municipality" (Uthållig kommun). The industries participating were selected from a larger group of industries that applied to participate. Selection for participating was based on the following two criteria:

- the industries were to represent different intensities of electricity, energy use and branch.
- management had to show interest and involvement in energy efficiency issues.

To analyse the industries energy use the energy flow was divided into support processes and production processes as described in chapter 6.5.

Figure 13 shows an example of how the energy flow can be divided into support processes and production processes.

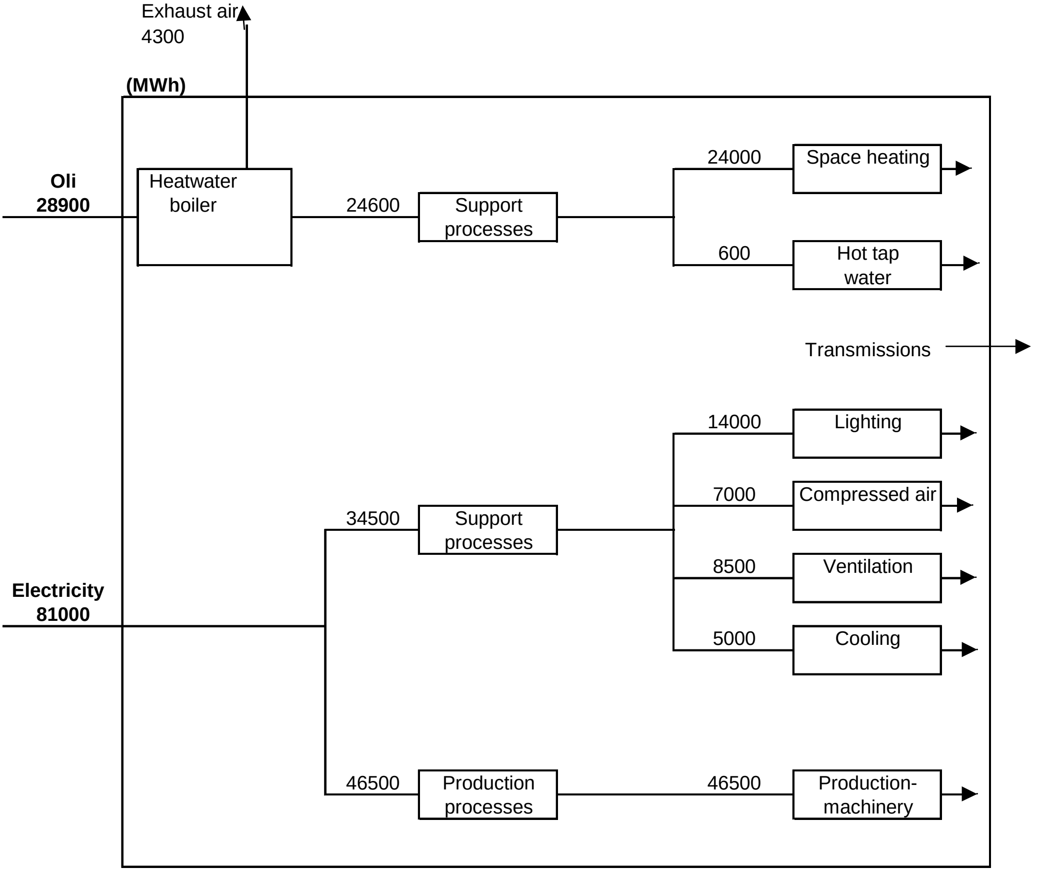


Figure 13: Annual energy flows in the Volvo Car plant before adjustments [paper V]

7.2.1 Reduced electricity use for the processes lighting, ventilation, and compressed air

The possibilities to reduce electricity use for the processes lighting, ventilation, and compressed air were analysed for the industries in Oskarshamn, Ulricehamn, Örnsköldsvik and Skövde according to the method presented in chapter 6.5.1-6.5.3. Figures 14-16 show the reduced electricity use for the three processes in the four municipalities. Table 7 shows average electricity reduction for the three processes.

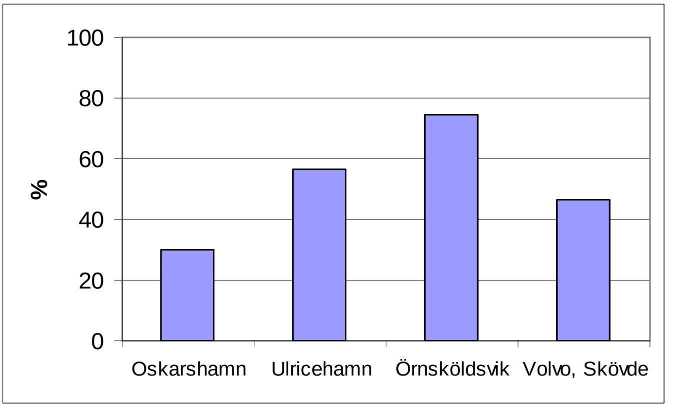


Figure 14: Reduced electricity use for the process lighting

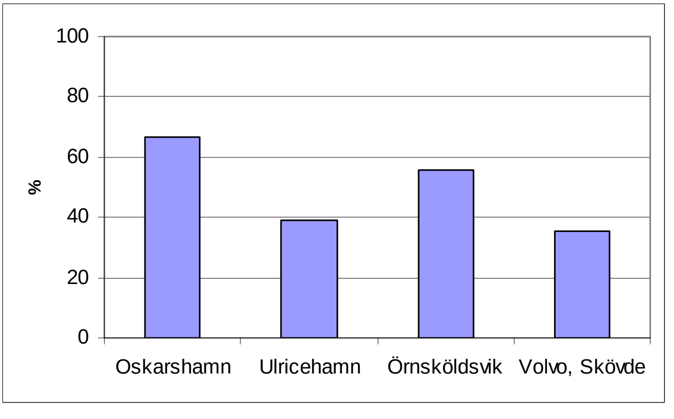


Figure 15: Reduced electricity use for the process ventilation

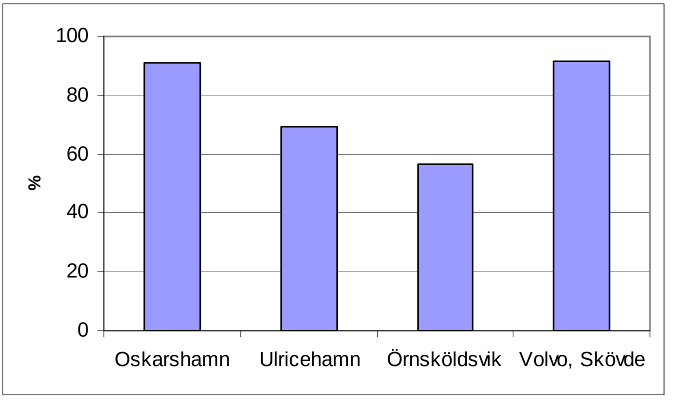


Figure 16: Reduced electricity use for the process compressed air

Table 7: Average reduction of electricity as a share of the total electricity use for the industries in Oskarshamn, Ulricehamn, Örnsköldsvik, and Volvo, Skövde

Process	**Average reduction of electricity as a share of the total electricity use for the process**
Lighting	48%
Ventilation	51%
Compressed air	81%

7.2.2 Reduced electricity use when production is ongoing

The average value of electricity use when no production was active for all the analysed industries is 30-40% of the total electricity use. Figure 17 presents the electricity use when there was no production ongoing in relation to the total amount of electricity used by the industries in Oskarshamn.

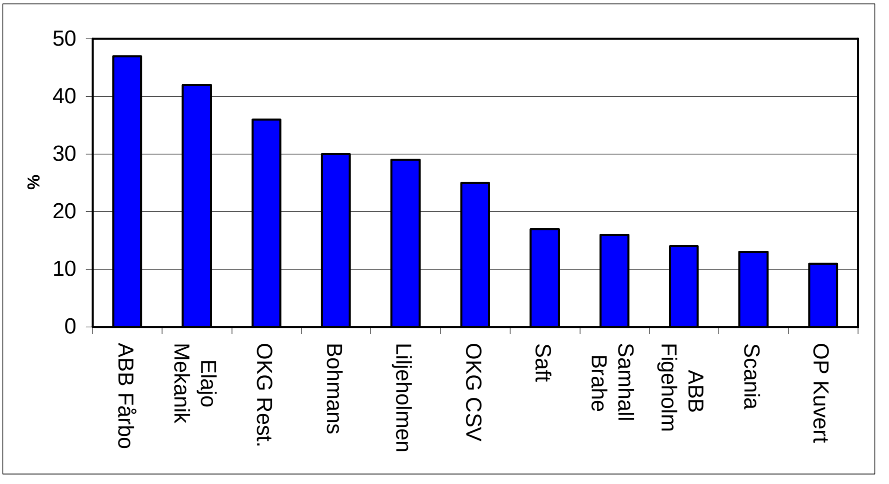


Figure 17: Electricity use when there was no production ongoing in relation to the total amount of electricity used in the industries in Oskarshamn [Trygg, 2002]

7.2.3 Conversion of non-electricity specific processes and increased use of district heating/biofuel

The possibilities to convert non-electricity specific processes to district heating or bio fuel were analysed for the industries. The results showed that converting, for example, hot tap water, heating of goods and space heating leads to increased use of district heating by about 8 500 MWh a year and increased use of biofuel by over 4 600 MWh a year for the 22 industries in Örnsköldsvik and Ulricehamn. The industries in Oskarshamn can similarly increase their annual use of district heating from 1 800 MWh to 59 000 MWh by converting processes, such as heating, drying, hot tap water and cooling, from electricity to district heating. Five of the 22 industries in Ulricehamn and Örnsköldsvik could use waste heat from the industrial processes to reduce the energy used for space heating and/or hot water.

At the Volvo plant in Skövde, hot tap water and space heating can be converted from oil to district heating and cooling can in the same way be converted from compression chillers to absorption chillers supplied by district heating. This increases the use of district heating by 77 000 MWh per year.

If all district heating is produced with biofuel, this altered energy use in the analysed industries in the four municipalities means an increased use of biofuel with around 150 GWh per year.

The analysis of increased use of district heating for industrial use was scaled up to a national level (paper IV), assuming that all Swedish industries with similar products were able to switch from electricity to district heating and biofuel in the same way as the studied industries in papers I and II. The lines of business included are: food, machinery, electronics, vehicles etc., paper production (partially) and paper, metal, wood and telecom products. They consume one-third of the electricity in Swedish industry and 15% of the national electricity use.

Technically possible increased use of district heating and biofuels that replace electricity in the studied industries at a national level are shown in Table 8.

Table 8: Possible increased use of district heating and biofuel in several industrial lines of business [GWh/year]

	District heating	**Biofuel**
Support processes		
Space heating, hot tap water	480	280
Steam	30	510
Manufacturing processes		
Heating	200	540
Drying	40	240
Melting		30
Shaping	330	
Cooling	120	
Total	**1 200**	**1 600**

The analyses show that in this group of industry, 2.8 annual TWh of biofuel and district heating can replace electricity, especially for heating of premises and goods and steam production.

7.2.4 Total reduction in electricity and energy use

The total potential reduction in electricity and energy use for the industries in Oskarshamn, Ulricehamn, Örnsköldsvik, and Skövde due to the measures presented earlier, are presented in Tables 9 - 12.

Table 9: Reduced electricity and energy use at the industries in Oskarshamn

Industries in Oskarshamn	Reduced electricity use [%]	Reduced energy use [%]
OKG Restaurang	90	40
OKG CSV	88	84
Samhall Brahe	86	59
Bohmans	75	23
Elajo Mekanik	65	81
ABB Fårbo	62	66
Liljeholmen	51	38
Saft	50	47
ABB Figeholm	47	30
OP Kuvert	40	43
Scania, närmevärden	40	40
Average	**48**	**40**

Table 10: Reduced electricity and energy use at the industries in Örnsköldsvik

Industries in Örnsköldsvik	Reduced electricity use [%]	Reduced energy use [%]
Glasfiberprodukter	78	30
ÖMV	87	7
Strandberg Industri	61	21
Hägges Finbageri	21	13
Alvis Hägglunds	55	34
Avesta Polarit	70	45
Industri I	73	24
Sanmina	58	45
LPAB	57	24
Profillack	39	22
Polarbröd	39	22
Hägglunds Drives	57	34
Average	**58**	**31**

Table 11: Reduced electricity and energy use at the industries in Ulricehamn

Industries in Ulricehamn	**Reduced electricity use [%]**	**Reduced energy use [%]**
Helge Nyberg	49	44
IRO	80	64
Per Schürer	14	14
Zinken Weland	89	10
Bogesunds Väveri	52	12
AP&T	62	41
Ulricehamns Betong	81	39
Emballator	62	34
Svensk Brikett Energi	24	-
Ekro Möbeldetaljer	50	39
Average	**50**	**38**

Table 12: Reduced electricity and energy use at the Volvo Car plant in Skövde

Industry in Skövde	**Reduced electricity use [%]**	**Reduced energy use [%]**
Volvo Car	44	17

7.2.5 Reduction in support and production processes

The results of the study showed in what processes the highest electricity reduction could be achieved and what measures were required. The results of the industrial studies show that the potential for electricity reduction is higher for support processes than for manufacturing processes. Figure 18 shows the electricity reduction as a share of electricity use before and after adjustments to support processes and to production processes for the industries in Oskarshamn (paper I).

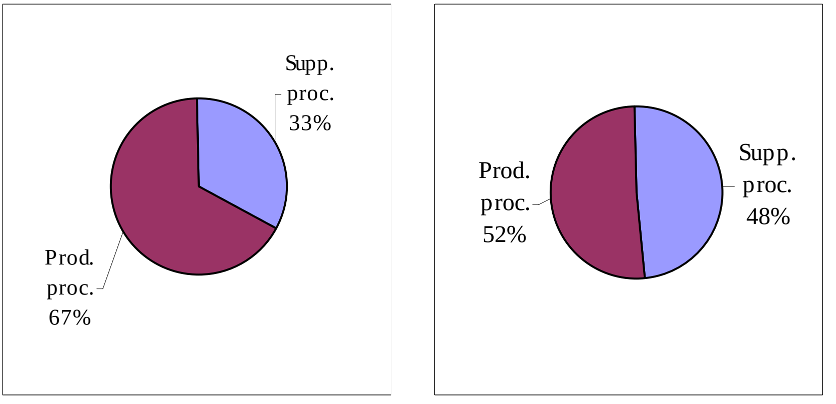


Figure 18: Electricity reduction as a share of electricity use before and after adjustments to support processes and to production processes for the industries in Oskarshamn

7.2.6 Investment opportunity and CO_2-emissions

As stated earlier investment opportunity, defined as reduced variable energy, for the industrial measures has been calculated instead of direct investment cost (see chapter 6.5.7). What is important to emphasize is that the majority of the industrial measures to reduce electricity use to a minimum are measures that have no investment cost at all. The results from the analyses show for example that reducing electricity use when there is no production activity corresponds to about 30-40% of the specific industries' total electricity use (see chapter 7.2.2).

Tables 13–15 shows the investment opportunity when considering different electricity prices[9]. The lower price represents the actual electricity price at the time the analyses were conducted. The case study of the industry in Oskarshamn was conducted earlier than the study of the

[9] Fee for connection to the district heating grind is not included

industries in Ulricehamn and Örnsköldsvik. Electricity prices in the different studies are therefore not the same (see also chapter 7.1).

Table 13: Investment opportunity for the 11 industries in Oskarshamn

Industries in Oskarshamn	**Investment opportunity**
Reference electricity price 390 SEK/MWh	40 MSEK/year
European electricity price 910 SEK/MWh	62 MSEK/year

Table 14: Investment opportunity for the 10 industries in Ulricehamn

Industries in Ulricehamn	**Investment opportunity**
Reference electricity price 450 SEK/MWh	6 MSEK/year
European electricity price 800 SEK/MWh	11 MSEK/year

Table 15: Investment opportunity for the 12 industries in Örnsköldsvik

Industries in Örnsköldsvik	**Investment opportunity**
Reference electricity price 450 SEK/MWh	13 MSEK/year
European electricity price 800 SEK/MWh	24 MSEK/year

The investment opportunity is in other words the amount the industries can spend on investments to realise the suggested changes. The higher the electricity price the higher the investment opportunity will be which most likely will lead to a gradual implementation of the measures (se also chapter 7.6). Investment opportunity for the individual industries in Oskarshamn, Ulricehamn, and Örnsköldsvik is presented in Figures 19-21.

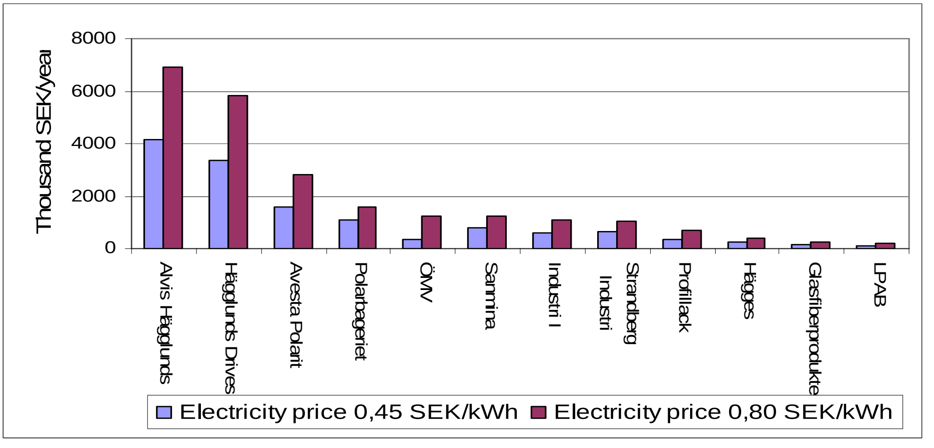


Figure 19: Investment opportunity for the industries in Örnsköldsvik
Source: Henning et al., 2004

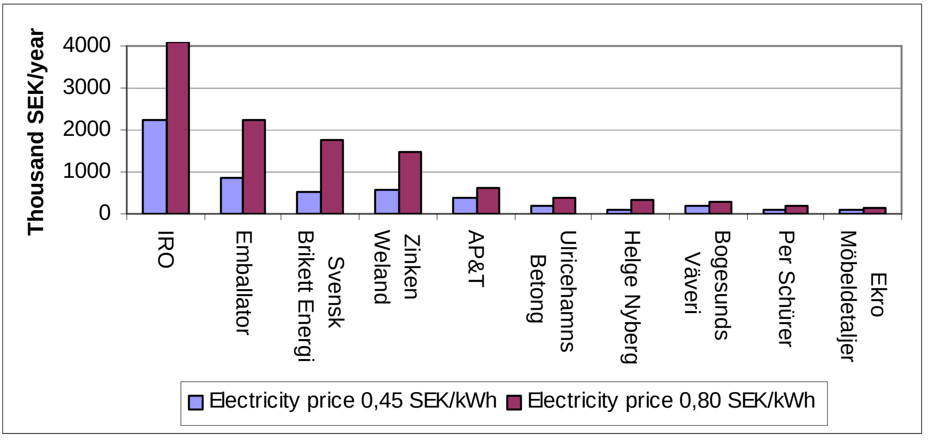


Figure 20: Investment opportunity for the industries in Ulricehamn
Source: Bohlin et al., 2004

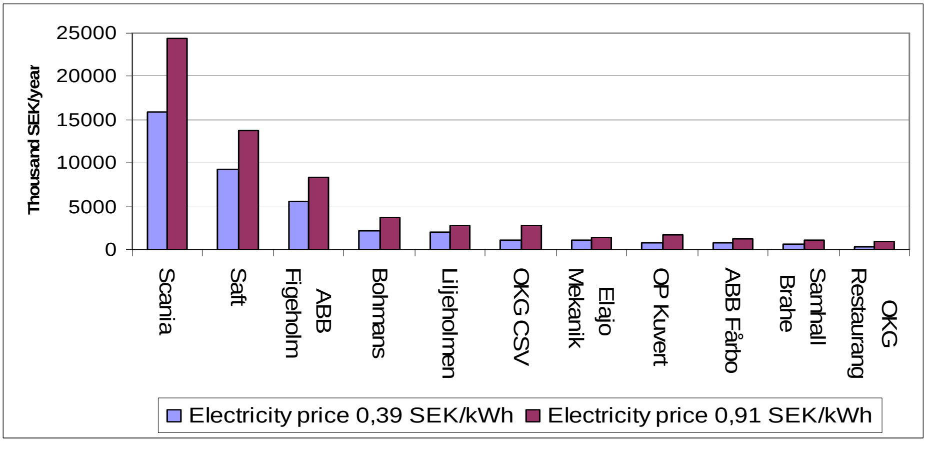


Figure 21: Investment opportunity for the industries in Oskarshamn
Source: Paper I

When accounting for electricity with marginal electricity and assuming coal condensing as the marginal electricity source in a longer perspective (LRMC), the altered energy use at the industries in Oskarshamn, Ulricehamn, Örnsköldsvik and the Volvo plant in Skövde will lead to a possible cost-effective reduction in global CO_2 emissions of about 159 000 tonnes per year.

Investment opportunity and possibilities to reduce global CO_2 emissions for every specific industrial measure in each of the industries in Oskarshamn, Ulricehamn, and Örnsköldsvik are presented in the following publications:

- Trygg L (2002) 'Systemförändringar av Industriell Energianvändning i Oskarshamn' (System Changes in Industrial Energy Use in Oskarshamn, in Swedish), LiTH-IKP-R-1225, Institute of Technology, Dept of Mech. Eng., Linköping University, Sweden

- Bohlin H, Henning D, Trygg L. 2004. 'Energianalys Ulricehamn'(Energy analysis of Ulricehamn, in Swedish), ER 17:2004, Swedish Energy Agency, Eskilstuna, Sweden.

- Henning D, Hrelja R, Trygg L. 2004. 'Energianalys Örnsköldsvik' (Energy analysis of Örnsköldsvik, in Swedish), ER 15:2004, Swedish Energy Agency, Eskilstuna, Sweden

7.3 Energy supplier measures and industrial measures

In this chapter both energy supplier measures and industrial measures are presented. The measures are energy-related co-operation, investment in CHP, and conversion from vapour chillers to absorption chillers, which consequently relates to the second and third research questions.

Conversion from vapour chillers to absorption chillers are measures for both energy suppliers and for industries. The measures are analysed for seven industries and for a district cooling network owned by the local energy utility in Norrköping.

Investment in CHP is a strict energy supplier measure analysed for the local energy supplier in Skövde. Energy-related co-operation on heat was studied between the Volvo plant and the local energy supplier in Skövde. The impact of both co-operation and investment in CHP is examined assuming that the Volvo plant has altered its energy use towards less electricity dependence and increased use of district heating. The Volvo plant is the largest industry and employer in Skövde and has two factories in the municipality: Volvo Car and Volvo Truck. Volvo Car has a heat demand of 25 GWh a year and Volvo Truck a heat demand of 55 GWh. 20 GWh of heat a year is supplied using waste heat from production [Trygg et al., 2005].

When the Volvo Car and Truck plant alters its energy use and converts the processes hot tap water and space heating to district heating and converts from compression chillers to absorption chillers supplied by district heating, the demand for district heating will be around 77 GWh a year for the Volvo plant (cf. chapter 7.2.3). This will lead to changed load duration curves for the local energy utility (Figure 22) and thus increased potential for the local energy utility to generate electricity in a CHP-system.

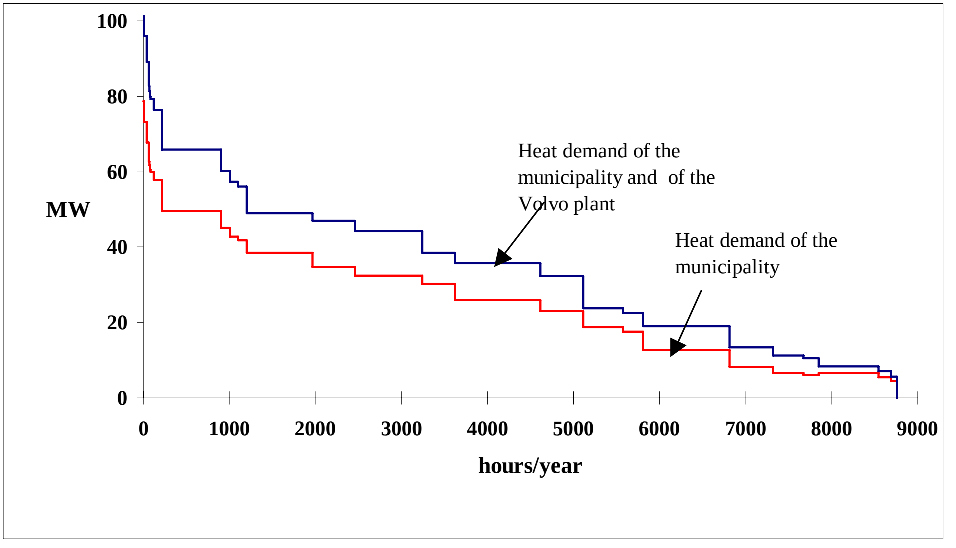


Figure 22: Load duration curves for district heating before and after the Volvo plant converts hot tap water, space heating and cooling to district heating.

7.3.1 Energy related co-operation

The Volvo plant in Skövde earlier had a local district heating grid of its own supplied by two oil-fired boilers and a one-way pipe connected the municipality's district heating grid with the Volvo plant. This means that the pipe transferred heat from the plant to the district heating grid but it was not possible to supply the plant with heat produced at the district heating utility. When the Volvo plant alters its energy use as described above, the demand for district heating will increase. In the process of altering its energy use, the company became interested in co-operating with the local energy company on heat supply. This would mean that the two boilers situated at the plant would become part of the municipality's district heating production; it would also mean investment in a two-way pipeline for a full connection between Volvo's local heat system and the municipality's district heating grid (paper V).

Modelling this co-operation with the MODEST[10] optimisation model results in a system cost including investment cost of a new pipeline between the Volvo plant and the energy utility. The system cost represents the cost of meeting the demand for district heating for the municipality and the Volvo plant, including income from sold generated electricity. The price Volvo pays for heat in the case study is assumed to be equal to the cost of producing heat.

The effects of co-operation on heat supply between the energy utility and the Volvo plant were analysed with two different electricity price structures: one that is referred to as the price today, and one that represents a possible future higher European level. The cost of electricity used as the price today is based on historical data from Nordpool [2002] and varies from 0.30 SEK/kWh[11] down to 0.15 SEK/kWh. To that figure is added an electricity grid cost of 0.62 SEK/kWh for the Volvo plant and 0.97 SEK/kWh for the municipality [SEA, 2003]. A future European electricity price including grid fees, averages 0.74 SEK/kWh[12] during daytime working hours and 0.41 SEK/kWh the rest of the time, is used in the study.

The results from the study show that the cost of producing heat and cool will decline from 0.17 SEK/kWh to 0.14 SEK/kWh due to the co-operation. When considering a European electricity price, the co-operation will lead to a reduction in production cost from 0.18 SEK/kWh to 0.15 SEK/kWh. This means that co-operation on heat supply between the Volvo plant and the Skövde energy utility reduces the production cost

[10] Se chapter 6.4 for a description of MODEST and for the definition of system cost
[11] 1 EUR = 9,22 SEK (October 2004).
[12] Based on Melkersson and Söderberg 2004, see also chapter 7.1

by 15% when the electricity price is at a Swedish level and by 19% with the higher European electricity prices. The consequences of co-operation and increased demand for district heating will evidently lead to further reductions in production cost when considering a CHP-system and increased electricity production. The effect of such measures is presented in the following chapter.

7.3.2 Energy related co-operation and investment in CHP

The consequences of investment in a biofuel CHP together with the described co-operation on heat supply described above were analysed for the energy system in Skövde (Paper V). The local energy utility in Skövde is wholly owned by the municipality and has a district heating system with a total heat demand of 220 GWh annually. Energy supply units used by the utility include a biofuel-fired heating plant with stack gas condensing, which normally runs as base load production. Electricity-driven boilers and heating oil boilers also produce heat for the district heating grid [cf. Holmgren and Gebremedhin, 2004].

By investing in a combined heat and power plant the prerequisites for absorption refrigeration machines improve since they can be supplied by district heating, and will therefore increase the potential for electricity generation. In the analyses it has therefore been assumed that investing in a combined heat and power plant will open up the possibility to introduce absorption refrigeration machines, which are assumed to be low-temperature machines. Investment in a future grid for district cooling or in a cooling tower is not included in the study. The income from selling electricity produced in the new CHP plant is assumed to be equal to the price of buying electricity in a common electricity market. The price Volvo pays for heat in the case study is assumed to be equal to the cost of producing heat.

In the same way as presented in chapter 7.3.1, the measure is analysed both with an electricity price referred to as the price today and a higher European electricity price with variations over the day. The electricity prices used are the same as those presented in chapter 7.3.1.

Eight scenarios have been modelled with the aim to describe potential future cases under given circumstances. Different boundary conditions can be simulated and their impact on the energy system in its entirety will be evaluated. The scenarios are chosen to reflect the impact on both the local energy supplier and the Volvo plant. The first scenario describes the energy system without co-operation, investment in CHP and altered energy use at the Volvo plant (Table 16).

Table 16: Description of the scenarios

No	**Title**
1	Reference
2	Altered industrial energy use, co-operation
3	Altered industrial energy, co-operation, inv. in new CHP
4	Altered industrial energy use co-operation, opt. of new CHP
5	Existing energy system, Euro.el. prices
6	Altered industrial energy use, co-op., Euro. el. prices
7	Altered industrial energy use, co-op., inv. in new CHP, Euro el. prices
8	Altered industrial energy use, co-op., Euro. el. prices, opt. of new CHP

Modelling the scenarios with the MODEST[14] optimisation model results in a system cost representing the cost of meeting the demand for district heating for the municipality and the Volvo plant, including income from sold generated electricity. As described earlier, the system cost includes the present value of all the capital costs of new installations, operation and maintenance costs, fuel costs, taxes, and fees for a period of ten years. This means that the investment cost of a new pipeline between the Volvo plant and the local energy utility is included, and that the investment costs of a new combined heat and power plant and absorption chillers are also included in the system cost

The results from the case study showed that with a restricted capacity of 19 MW for the CHP plant, the production cost [SEK/kWh] decreases by 46% when the two measures co-operation and investment in a combined

[14] Se chapter 6.4 for a description of MODEST and for the definition of system cost

heat and power plant are taken, and the energy prices are at a Swedish level. With identical restrictions on the CHP plant capacity and higher European electricity prices, the same measures lead to a decrease in production cost of 56%.

With an optimized size of the CHP plant[15], co-operation and investment in a combined heat and power plant will lead to a decrease in production cost of 49% when the energy prices are at a Swedish level and 64% if the electricity prices adapt to a European structure. Figure 23 shows the system cost for the analysed scenarios.

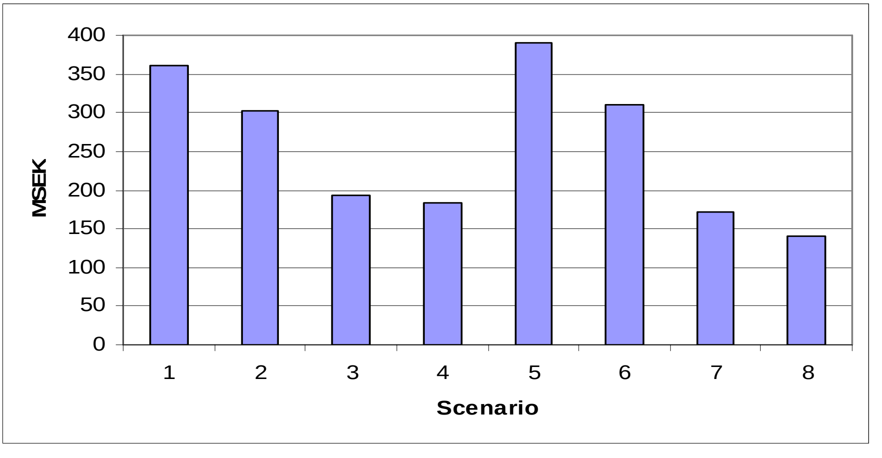


Figure 23:. Total system cost for a period of ten years for the analysed scenarios.

The analyses show that the measures co-operation on heat and investment in CHP are profitable when the energy prices are at a Swedish level and even more profitable when calculating with higher European prices.

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[15] The optimized size of the CHP plant will be 39 MW when electricity prices are at a Swedish level and 49 MW with European prices.

The electricity generated in the new CHP plant will affect global emissions of carbon dioxide when assuming coal-fired condensing power plants to be the marginal source in a European power system[16]. This means that electricity produced in the new combined heat and power plant in Skövde can lead to cost-effective reduction in emissions of carbon dioxide in another European country, which explains why global emissions of carbon dioxide will be negative in some scenarios in Table 17.

Table 17: Local and global emissions of CO_2 due to the energy supply measures co-operation and investing in a CHP

Scenario	Electricity production [GWh/year]	Local emissions of CO_2 [ktonnes/year]	Possible impact on global emissions of CO_2 [ktonnes/year]
1	-	23	23
2	-	8	-22
3	9	17	-30
4	35	26	-46
5	-	23	23
6	-	8	-22
7	23	16	-45
8	48	29	-57

**) Due to district heating and electricity production.*

In scenario 7, where electricity prices are at a European level and the Volvo plant has altered its energy use, the two measures co-operation and investing in a CHP plant will lead to possibilities to reduce total global emissions of carbon dioxide amounting to 68,000 tonnes annually, equal to -298%, compared to the existing system. In scenario 8, the global emissions of carbon dioxide can be reduced by 80,000 tonnes annually, equal to -350%, as the prices adjust to a European level.

[16] See chapter 2.1

To analyse the impact on the system cost due to changes in different areas' sensitivity analyses were made with regard to the following four areas:

- Price of emissions trading
- Cost for investment
- Price of bio fuel
- Admixture of biofuel

The sensitivity analyses show that if there is a shortage of waste in the future and an admixture of 50% biofuel is necessary, the effects of such measures will have the highest influence on the system cost of the analysed parameters. A 25% higher biofuel price and a 25 % higher emission trading price will have less impact on the different scenarios' system costs, as Figure 24 shows

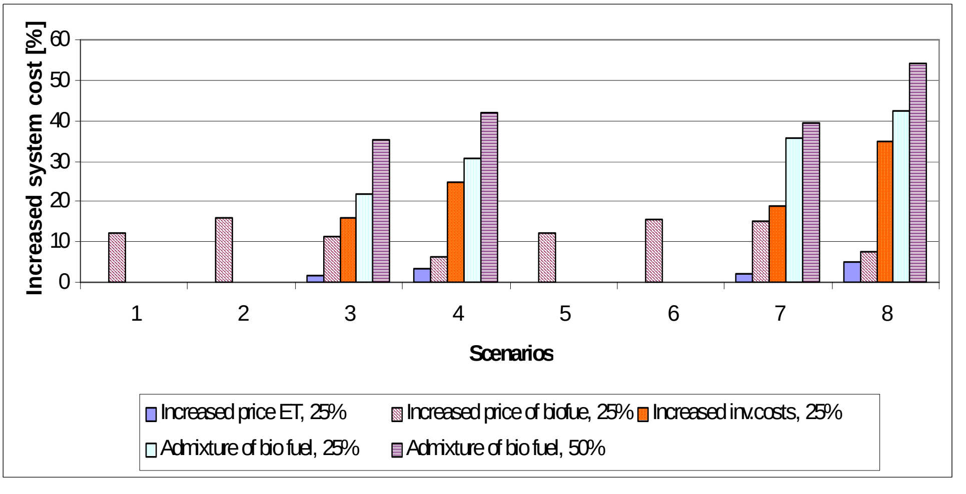

Figure 24: Sensitivity analysis, increased system cost (%).

7.3.3 Investment in absorption chillers

The effects of introducing absorption chillers have been studied for the municipality of Norrköping (paper VI). Norrköping is a town in the southeast of Sweden with about 120,000 inhabitants. Eon, which is one of the largest energy suppliers in Sweden, owns the local energy utility in the municipality. The energy plant in Norrköping produces electricity, district heating, district cooling, and steam. About 1,050 GWh district heating, 170 GWh steam, 320 GWh electricity and 6 GWh district cooling are produced every year. Energy supply units used by the utility today include a waste fired CHP plant, bio-fuel, rubber, oil, and compression chillers. There is also an oil-fired boiler that produces heat for the district heating network [Amiri et al., 2005].

The conversion of an oil-fired steam boiler to natural gas and investment in a new natural gas fired CHP are currently under discussion. These discussions are based on the planned expansion of the existing pipeline system for natural gas in Sweden that includes a pipeline through the municipality of Norrköping.

Since Norrköping's energy system includes a waste fired CHP plant there is a surplus of heat during the summer, which could be used for heat driven absorption cooling. The case study analyses the most cost-effective technology for the production of cooling by comparing vapour compression chillers with heat driven absorption cooling to supply the district cooling grid and seven industries in the municipality with cooling. It is not economically realistic to supply the seven industries with district cooling from the district cooling grid since their geographical location is very widespread and not close to the cooling grid. The case study therefore analyses the consequences of locally placed absorption machines to supply the industries with cooling. If the industries had instead been situated nearer the cooling grid, supplying the industries from the grid would most probably have been a more economical solution.

The seven analysed industries are presented in Table 18. The industries have been divided into three groups according to installed capacity. The reason for this division is to be able to separate different levels of investment cost when considering new absorption machines. The total demand for cooling for both the seven industries in the table and for the district cooling grid totals 34 GWh per year.

Table 18: Industrial demand for cooling

Group	Industry	Cooling capacity convertible to absorption cooling [kW]
A	Freudenberg Household Products	4 050
A	Rostiprimpac	1 350
B	Vitamex	300
B	Miljösäck	270
B	Stenqvist Emballage	250
C	National Starch & Chemical	100
C	Suominen Packaging	50

The described energy system in Norrköping and the cooling demand for the seven industries have been modelled MODEST[18]. Table 19 shows the four analysed scenarios.

Table 19: Model scenarios

No	Title
1	Existing energy system
2	Introducing abs. cooling
3	Introducing abs. cooling and European elect. prices
4	Introducing abs. cooling, European elect. prices, and natural gas

[18] See chapter 6.4

In both scenarios 1 and 2, the cost of electricity is based on figures obtained from Nordpool [2004] and varies from 432 SEK/MWh down to 173 SEK/MWh. When calculating a future European electricity price according to the model presented in chapter 7.1, the price of electricity including grid fees will average 1,033 SEK/MWh during daytime working hours and 464 SEK/MWh the rest of the time.

The analyses show that producing cooling with absorption cooling gives the most cost effective result in scenario 4 for both the district cooling network and the 3 groups of industries. In scenarios 2 and 3, the cooling is produced with a combination of absorption chillers and vapour compression chillers. For district cooling, absorption cooling is the principal source in all three scenarios. The low percentage of absorption cooling for industry group C is explained by the high investment cost per megawatt for small absorption cooling machines. Table 20 shows the system-optimal percentage production of cooling produced by means of absorption technology for district cooling and the industry groups.

Table 20: System-optimal percentage of absorption cooling of total cooling produced.

Absorption cooling (%)	**District cooling**	**Industry group A**	**Industry group B**	**Industry group C**	**Total**
1	0	0	0	0	0
2	81%	0	0	0	12%
3	99%	77%	62%	0	77%
4	100%	100%	100%	100%	100%

The results show that when natural gas is introduced in addition to higher electricity prices, the most cost-effective solution to produce cooling is by absorption technology exclusively. When the cooling is produced only by absorption technology, the production cost of cooling will be –95

SEK/MWh, a reduction of 170%, due to revenues from electricity production.

Converting to absorption chillers will also mean possibilities to reduce global emissions of CO_2 When assuming coal-fired condensing power plants to be the marginal source in a fully deregulated European power system, and considering the effects of emissions trading (see also chapter 2.1), the electricity generated will imply possible cost-efficient measures to lower global emissions of carbon dioxide (Table 21). The higher production of electricity in scenario 4 is principally explained by the introduction of natural gas.

Table 21: Production of electricity and emissions of CO_2.

Scenario	Production of electricity GWh/year]	Local emissions of CO_2 [ktonnes/year]	Possible impact on global emissions of CO_2 [ktonnes/year]
1	335	111	-224
2	336	110	-223
3	347	74	-272
4	779	405	-394

Due to its relatively low efficiency, absorption cooling is dependent on heat with low production costs to be an economically viable option. Where European electricity prices and natural gas are introduced and cooling is produced solely by means of absorption chillers, the marginal cost for heat are even negative and averages about –70 SEK/MWh. The demand for cooling is highest during summer and at the same time the shadow prices for heat are at the lowest level, which subsequently favours absorption cooling (Figure 25).

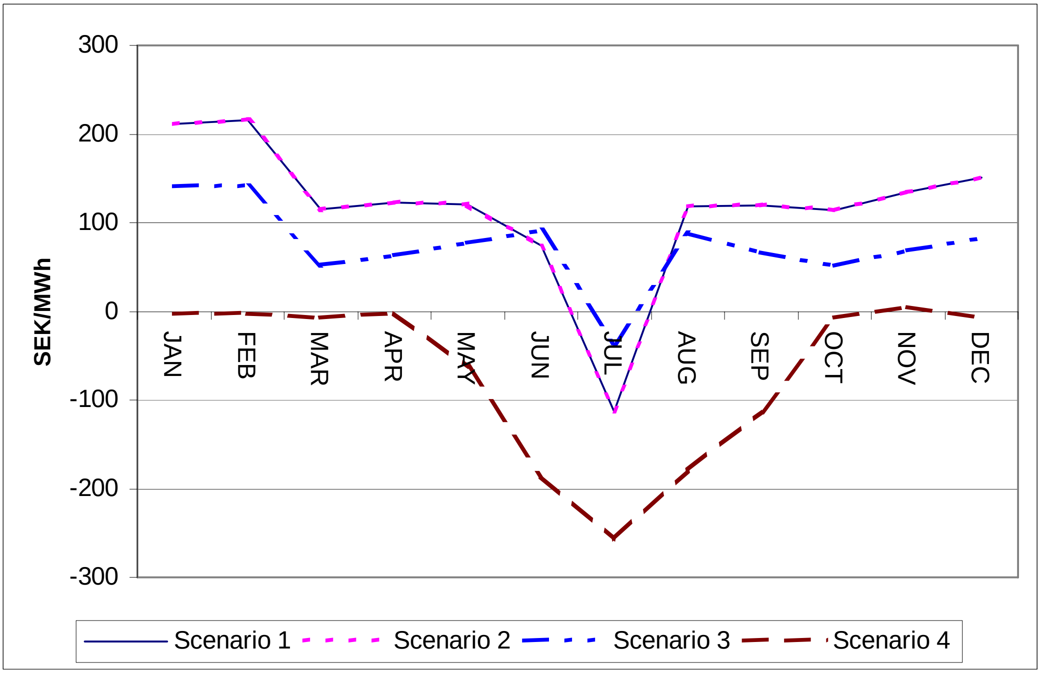

Figure 25: Shadow prices for heat. Shadow prices for scenarios 1 and 2 are identical.

A sensitivity analysis was performed to investigate how the COP for absorption chillers affects the total system cost. The result shows that when the COP for the absorption chillers changes from 0.7 to 0.5, this will only increase the system cost by between 1% and 2% for scenarios 2 and 3, and in fact decrease the system cost in scenario 4 by 2% when European electricity prices and natural gas are introduced (Figure 26). This phenomenon is explained by the high electricity production in relation to heat (the α-value) in the natural gas combined cycle power plant in combination with higher European electricity prices and the fuel costs used in this study.

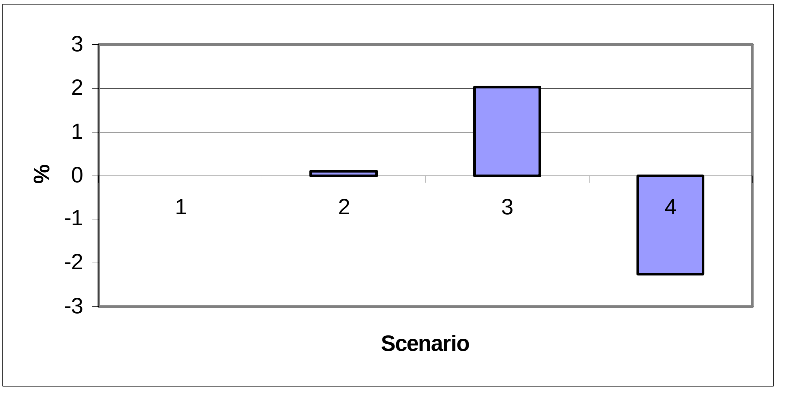

Figure 26: Percentage change in system cost when the COP for absorption chillers is changed from 0.7 to 0.5 (positive values mean increased cost and negative values reduced cost).

It is important to emphasise that the price of natural gas used in this study is from January 2005[19] and must be considered relatively low considering the recent price trend for natural gas, cf [Neij et al., 2006]. It would therefore be most interesting to analyse the effect of a higher price for natural gas.

7.4 Impact on national power supply

In paper VII a scaling of audit results to whole lines of Swedish business and an analysis of the impact on electricity supply of demand-side measures are performed. The work is based on the simplification that electricity use and conservation possibilities are assumed to be the same in the whole lines of business as in the audited industries. It is also assumed that the current level of industrial activity will be maintained [cf. Henning, 2005]. The analyses relate to research question number four.

[19] Se paper VI

The study consists of a compilation of previously performed audits of electricity consumption and the possibilities to reduce energy use in small and medium-sized Swedish industries [paper I], [paper II], [Bohlin et al., 2004], [Henning et al., 2004], [Franzén 2005]. Energy-intensive industry is not analysed in the above-mentioned studies, these industries have therefore been briefly analysed in the paper.

Electricity supply and use have been analysed with the MODEST model (see chapter 6.4) to elucidate the interplay between present and potential electricity generation, electricity consumption and more efficient electricity use. Time-dependent industrial measures are described for various processes and lines of business.

The result presentation consists of scenarios with standard conditions and high energy costs, without and with demand-side measures in small and medium-sized industry, and in all industry. The standard conditions reflect the current situation but do not include policy instruments (taxes, electricity certificates, emission allowances). The cases with higher energy-carrier costs include higher European electricity prices and high fuel prices and policy instruments (2005 taxes and 50% higher emission-allowance and green-certificate prices than in 2005). In these cases, renewable electricity benefits from a revenue from certificate sales whereas consumers (except heavy industry) must pay a certificate cost.

When introducing industrial measures in small and medium-sized industry with standard conditions concerning energy costs etc. the result shows that there is a net export of 2.5 TWh of electricity per year. The industrial measures reduce the annual cost for satisfying electricity demand by 2 MSEK, which is the investment opportunity for the measures and reflects their value in a societal perspective.
When comparing scenarios with and without demand-side measures in small- and medium sized industry and in all industry respectively, it

shows that without industrial measures, there is a net electricity import but in the other cases exports of power exceed imports (Figure 27).

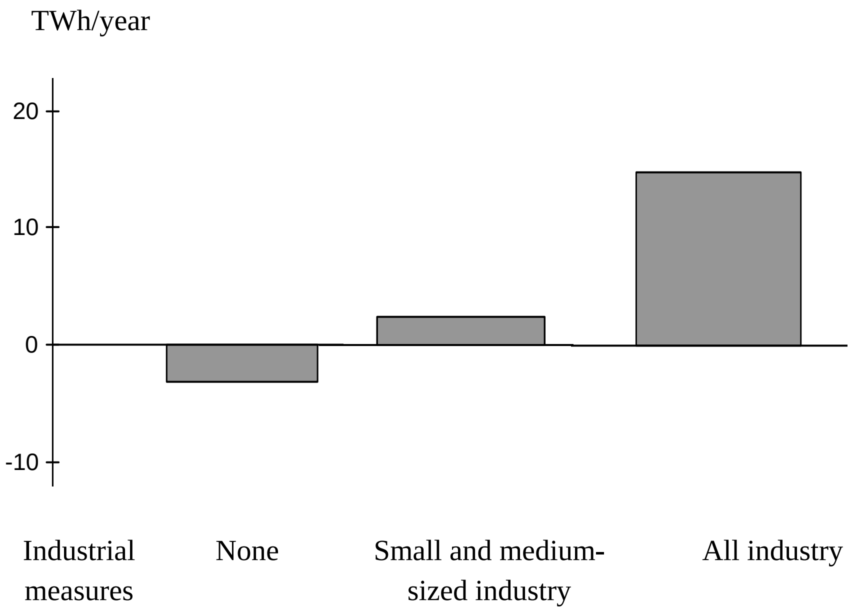

Figure 27: Net electricity exports with standard conditions

In the scenarios with high-energy carrier costs and no industrial measures or just measures in small and medium-sized industry, transmission capacity abroad does not limit foreign electricity trade. When industrial measures are applied in all industries, net exports are much larger (Figure 28) but they are limited by the transmission capacities at times. If the transmission capacity abroad were twice as high as today, electricity exports would be slightly larger but the lines would also be used to import electricity during peak days and net electricity exports are unchanged.

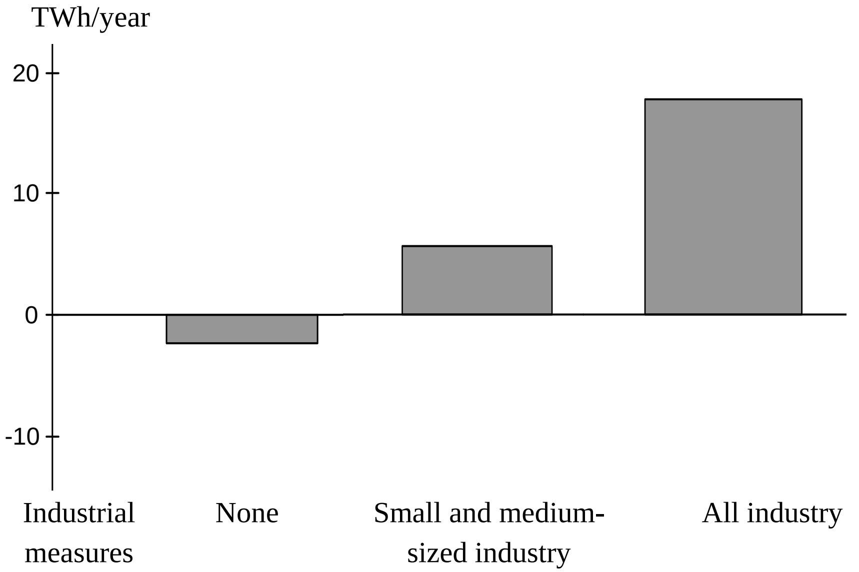

Figure 28: Net electricity export with high energy-carrier costs.

As can be concluded from Table 22 demand-side measures reduce costs more with high energy costs than with standard conditions because both the fuel and import costs avoided and the increased export revenues are higher.

Table 22: Reduction in energy supply cost due to electricity conservation

Demand-side measures in	**Small and medium-sized industry [%]**	**All industry [%]**
Standard conditions	8	23
High energy-carrier costs	22	58

Table 23 shows the net CO_2 emissions in the various cases, i.e. emissions that are domestic and due to imported coal-condensing electricity with the deduction of exported power that displaces coal. Without industrial measures, there is more fossil CHP production with high energy costs but net electricity imports are smaller, which lowers net emissions.

Table 23: Net CO_2 emissions

Demand-side measures	**None** [Mton/year]	**Small and medium-sized industry** [Mton/year]	**All industry** [Mton/year]
Standard conditions	6.6	0.8	-10
High energy-carrier costs	6.1	-0.9	-12

In the cases with industrial measures, there is a net electricity export which can contribute to a reduction in European CO_2 emissions. The domestic emissions are primarily due to coal, peat, gas and waste used in CHP plants and, with demand-side measures, gas-fired boilers replacing electricity. Without demand-side measures or with high energy costs, there is also oil-fired cogeneration, primarily in heavy industry, which is economically preferable to imported electricity. With industrial measures, the higher net electricity export with high energy costs reduces net emissions more than the increase in oil-fired cogeneration increases emissions, i.e. efficient CHP production displaces condensing power.

Figure 29 shows the global CO_2 emissions resulting from satisfying the Swedish electricity demand through power supply or switching to fossil fuels and due to producing electricity in Sweden for export at high energy-carrier costs and industrial measures in all kinds of industries. In the figure, there are emissions from combustion of fossil fuels in Sweden and the generation of imported electricity in coal-fired condensing power plants but also the emissions that are avoided at coal-condensing plants through the export of Swedish electricity. To the right in the Figure 29, it is shown that the net emissions are negative if these three components are totalled. This amount can be a contribution to the reduction of global CO_2 emissions within the European Union.

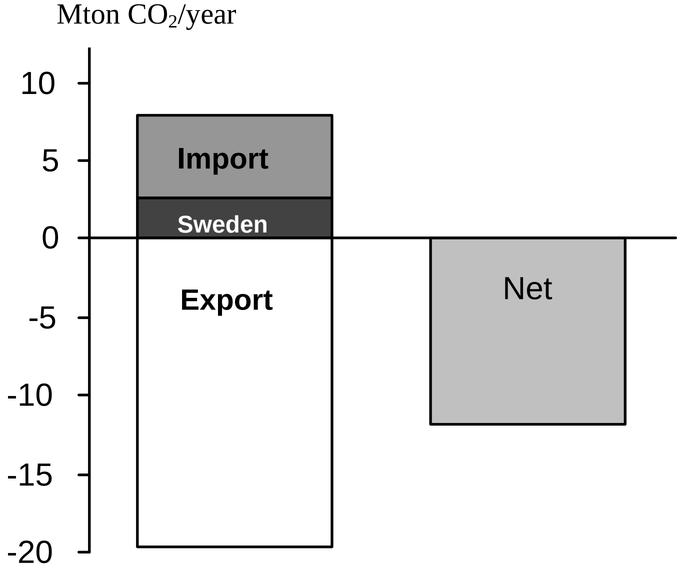

Figure 29: CO_2 emissions in Sweden and due to electricity imports, emission reduction due to the export of electricity, and resulting net emissions with high energy-carrier costs and industrial measures in all industries.

The investment costs for the electricity conservation measures are not considered in this study but range from almost zero (e.g. for a timer) to substantial amounts. To make an unbiased economic optimisation from a social viewpoint, energy efficiency and energy carrier switching measures and their investment and operation costs should be considered for all societal sectors. In such an integrated resource planning (IRP) approach, e.g. [D'Sa, 2005], all supply and demand side options to meet energy demand should be compared to each other on a level playing field, where all costs accruing to society, including external environmental impact, are considered.

The electricity demand in small and medium-sized industry can be reduced from 20 to 13 TWh per year when applying the industrial measures according to the method presented in chapter 6.5. One TWh of electricity annually can be replaced by district heating in the industries. The district heating would partially be used for manufacturing processes that are relatively evenly used throughout the year. That is therefore a favourable heat sink for CHP production and model calculations show that the district heating should primarily be produced in CHP plants that also generate 300 GWh of electricity a year.

When applying the industrial measures in all Swedish industry, they can reduce the operating costs related to satisfying demand that is currently covered by electricity by some 20% at the present time, but by almost 60% at estimated future higher costs for fuels, European electricity, prices and emission allowances, which reflects the benefit of adapting electricity use to harmonised electricity prices. The situation with higher energy-carrier costs and industrial measures implemented in all industry will lead to a net export of electricity in Sweden and that global CO_2 emissions can be 17 Mton lower than today.

7.5 How the results have been communicated

The industrial measures demonstrate how to reach a situation where industrial electricity and energy use is at an absolute minimum and is therefore to be seen as an optimal situation. The results must consequently be understood as indicators of processes or parts of processes where electricity use is high and can be reduced. On the basis of the presented measures some processes that can be altered at once can be prioritized and measures with a long-term goal can be included in a long-term action list.

As a suggestion, industry can begin with measures that do not involve any cost at all, for example reduction of electricity when there no production is active and proceed with other measures step-by-step. As argued earlier, the measures will have a successively implantation profitability will increase as the electricity price rises.

The results from the presented industrial and energy supply measures have been communicated to representatives of industries and local and other authorities around Sweden on about 40 different occasions arranged for example by the County Administrative Board in Östergötland and Södermanland, the National Environment Protection Board, Lantmännen, Sandvik, the Energy Agency in Dalarna, Eon, Skövde Energy utility, the Swedish District Heating Association, Miljökontoret in Östergötland, political parties, STF Ingenjörsutbildning AB, ABB, Swedish Energy Agency.

7.6 Implementation of the measures

A prerequisite for changes in an energy system is competence [Kaijser and Summerton, 1983]. Since technology is always embedded in a social context, together forming a socio-technical system, skills in social issues are as important as technical knowledge. A socio-technical analysis of buildings in Solna (paper III) showed that the competence with regard to buildings could mainly be characterised as technical skills embodied in real estate managers, engineers and technicians. In the Solna study [Gebremedhin et al., 2004] only one organisation was found that had sufficient competence to work continuously with high-aiming technical energy objectives. As an organisation introduces environmental management, it is necessary to consider the human beings interacting with the technical system as well. Environmental management implies that staff are educated in environmental issues and how to implement appropriate measures that decrease energy demand. In some organisations, however, education did not enhance environmental concern to a measurable extent [Gebremedhin et al., 2004].

Rhodin and Thollander [2006] have analysed barriers to the implementation of the industrial measures analysed in the industries in Oskarshamn (paper I). From the study it was concluded that the major barriers were above all cost/risk of production disruption / hassle / inconvenience, lack of time or other priorities, and the cost of obtaining information on the energy use of purchased equipment. Long-term strategic energy policies, increasing energy prices and the existence of people with real ambitions within the organization were found to be driving forces for the implementation of energy efficiency measures. All the respondents in the study claimed that production-related issues have higher priority than energy-related issues. Three of the respondents clearly stated that the energy audits that had been carried out (paper I) had been a prerequisite in subsequent initiatives regarding energy efficiency [Rhodin and Thollander, 2006].

The results from the case study regarding Volvo and Skövde (paper V) have resulted in most of the efforts within the project being implemented. The Volvo Car plant in Skövde is endeavouring to reduce its electricity use, Skövde energy utility have invested in a new CHP plant for waste incineration and a new pipe-line is under construction between the Volvo plant and the energy utility.

All suggested measures from the industrial energy audits in papers I and II are supported by the analyzed industries as regards technical plausibility. All the industries in the studies have had a very positive attitude both to the studies and to the results.

Most of the industries in Örnsköldsvik and Ulricehamn (paper II) states that they are now involved with energy efficiency issues with the aim of reducing their use of electricity and energy in for example the processes lighting, ventilation, and space heating [Nyman 2005], [Skoglund 2005]. One of analysed industries, Hägglunds Drives, has stated that they are aiming at reducing their use of electricity with 50% [Regeringskansliet, 2006].

8 Concluding discussion

According to the Green Paper [COM, 2000] the European Union is consuming more and more energy and will not be able to free itself from its increasing energy dependence without an active energy policy. The aim of the Green Paper is to initiate a debate on the security of energy supply. One of the strategies debated in the Green Paper is therefore which policies would permit the European Union to fulfil its obligations within the Kyoto Protocol and what measures could be taken in order to fully exploit potential energy savings which would help to reduce CO_2 emissions. The Swedish Climate Strategy claims that the climate problem is one of the greatest global environmental issues of today [Government Bill, 2001] why every long-term decision must take these questions into consideration. Altering industrial energy use towards less electricity and energy dependence will be a competitive alternative to new electricity production; it will help secure energy supply in the European Union and it will lead to cost-effective reduction in global CO_2 emissions.

Analyses of over 30 small and medium-sized Swedish industries have shown how it is possible to reduce electricity use by 50%, leading to possibilities to reduce global emissions of CO_2 when coal condensing is assumed to be the marginal source that changes as electricity use changes. When the industrial measures with aim of reducing electricity use and increasing the use of district heating, are introduced in all Swedish industry, they will lead to a situation where Sweden will have a net export of electricity and a reduction of global CO_2 emissions with 18 Mton per year.

The effects on a local energy supplier due to altered industrial energy use has been analysed. As the Volvo plant in Skövde decreases its electricity use by 44 % and converts to district heating, the increased demand for district heating makes investment in a new planned CHP and cooperation between the Volvo plant and the local energy utility, production cost to fall by about 50% at the current electricity price. With a European electricity price and investment in an optimised CHP, the production cost falls by over 60%. Global emissions of the greenhouse gas carbon dioxide can be reduced by 350% a year if the two energy supply measures are taken and the electricity prices are at a European level.

The use of absorption chillers is limited in Sweden but conditions are in fact most favourable. A rising demand for cooling and increasing electricity prices in combination with a surplus of heat during the summer in a CHP system makes heat driven cooling interesting in Sweden. The most cost-effective technology for cooling was determined by comparing vapour compression chillers with heat driven absorption cooling for a local energy utility with a district cooling network and for seven industries in a Swedish municipality with CHP. The results show that with higher European electricity prices, and when natural gas is introduced, absorption cooling is the most cost effective solution for both industries and energy suppliers. This will result in a resource effective energy system with a possibility to reduce global emissions of CO_2 by 80%, a 300% lower system cost, and a 170% reduction in the cost of producing cooling. The results also show that, with these prerequisites, a decrease in COP of the absorption chillers will not have a negative impact on the cost effectiveness due to increased electricity production.

The results of this thesis show how a system perspective on energy use and electricity production gives major economic and environmental benefits. Energy measures such as energy efficiency, conversion from electricity to district heating, co-operation on heat between industry and energy supplier, investment in CHP, and conversion to absorption chillers are important for industry and energy suppliers to take now at current Swedish electricity prices as they will reduce system cost and lead to possibilities to lower global emissions of CO_2. The measures will be of even greater importance when calculating with higher electricity prices with a European structure and will therefore be essential for Swedish energy suppliers and industry to take as actors in a deregulated European electricity market. The measures will lead to both economical advantages as well as possible reduction of global CO_2 emissions and with higher European electricity prices the benefits will increase further. These measures will in other words make the combined energy systems for Swedish industries and energy suppliers significantly more resource effective, in accordance to the hypothesis of this thesis.

A higher electricity price in Sweden will make it necessary for Swedish industry to adapt their electricity use to a European level by converting from electricity to district heating. The combination of higher electricity price and increased demand for district heating will make it most interesting for Swedish energy suppliers to consider further investment in CHP plants, which consequently would increase electricity production in Sweden. Electricity produced in Sweden but sold in another European country will replace marginal coal-based power production and as consequence lower the total environmental cost in Europe. These are outstanding favourable conditions especially for Sweden where, for example district heating is well established, the potential for electricity reduction is huge and electricity is generated with very low environmental costs. Taking advantage of these particularly Swedish conditions would most certainly contribute to the creation of lean resource systems, and make free electricity trade the most cost-effective solution of the commitments under the Kyoto Protocol. If a general free electricity trade market were to be introduced, where all producers concentrate on producing the best product and use their comparative advantages based on their individual prerequisites, the global environment would be the outstanding winner.

9 Further work

It would be interesting to complete the work in this thesis with further studies within the following areas:

- Additional analyses of the effect of different price structures and levels on various energy carriers.

- Further analyses of how electricity-intensive industry can alter its energy use towards less use of electricity and increased use of district heating.

- Analyses of further expansion of district cooling and cooling with absorption chillers in Swedish municipalities.

- Effects due to pricing district heating based on shadow prices.

- Comparative energy analyses of the use of district heating and energy efficient within the EU together with marginal costs for district heating.

- Analyses of how Swedish district heating systems in symbiosis with Swedish industry can contribute to a more cost-effective part of the global climate problem.

- Analyses of how energy strategies and policies can encourage and stimulate energy efficiency improvements.

- Socio-technical analyses to study barriers and driving forces, for both Swedish industry and energy suppliers, to implement measures suggested in this thesis.

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