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A System Perspective on District Heating and Waste Incineration

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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.

PROGRAM
ENERGISYSTEM
Forskning och forskarskola

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

Energy recovery by waste incineration has a double function as waste treatment method and supplier of electricity and/or heat, thereby linking the systems of energy and waste management. Both systems are undergoing great changes, mainly due to new regulations. Important regulations within waste management in Sweden are a ban on landfill of combustible waste and organic waste, and a tax on landfill of waste. New waste incineration facilities are being built in order to increase capacity to meet these demands.

The aim of this thesis is to investigate impacts on Swedish district heating systems of increased use of waste as a fuel in economic and environmental terms, the latter mainly by assessing emissions of carbon dioxide. Of importance is the influence of various policy instruments. To highlight the connection between the energy and waste management systems and how these influence each other is another goal, as well as the function of district heating systems as user of various waste heat supplies. An important assumption for this thesis is a deregulated European electricity market, where the marginal power production in the short term is coal condensing power and in the long term natural gas based power, that affects the conditions for combined heat and power in district heating systems. The method used is case studies of three Swedish municipalities that utilise waste in their district heating systems. In two papers, the scope is broadened from the energy utility perspective by comparing the energy efficiency of energy recovery and material recovery of various fractions, and the effect of including external costs for CO_2 as well as SO_2, NO_x and particles. The ambition is that the results can be part of the decision making process for energy utilities and for policy makers in the energy sector and waste management.

It is economically advantageous to use waste as a fuel in the energy sector and regulations in the waste management sector and high taxes on fossil fuels contribute to profitability. Waste incineration plants are base suppliers of heat because they derive revenue from receiving the waste. Economic conditions for waste incineration are altered with the introduction of a tax on incinerated municipal waste. A conflict may arise between combined heat and power production in district heating systems and waste incineration, since the latter can remove the heat sink for other combined heat and power plants with higher efficiencies. Combined heat and power is the main measure to decrease carbon dioxide emissions in district heating systems on the assumption that locally produced

electricity replaces electricity in coal condensing plants. It can be difficult to design policy instruments for waste incineration due to some conflicting goals for waste management and energy systems. Comparing the energy efficiency of material recovery and energy recovery is a way to assess the resource efficiency of waste treatment methods. From that perspective, if there is a district heating system which can utilise the heat, biodegradable waste and cardboard should be energy recovered and plastics and paper material recovered. To put costs on environmental effects, so called external costs, is a way to take these effects into regard in traditional economic calculations, but the method has drawbacks, e.g. the limited range of environmental effects included and uncertainties in the monetary valuation of environmental effects.

Acknowledgements

My time as a PhD student has been rewarding. The work atmosphere at the division of Energy Systems at Linköping University and the graduate school Energy Systems has been creative and stimulating and I thank everyone involved for contributing to this. I want to thank my supervisor Professor Björn Karlsson for visionary discussions, support and enthusiasm that have always left me encouraged. Thanks to my co-supervisor Associate Professor Dag Henning, especially for help with MODEST and comments on my papers that have definitely improved them. My other co-supervisor, Associate Professor Mats Bladh, I want to thank for giving me new angles on my work. I am grateful to Professor Emeritus Lars Ingelstam who was my opponent at the final seminar, which improved this thesis. Professor Per Alvfors commented on the first draft of my thesis and for that I am grateful. Thanks to all my co-authors for making the work much more enjoyable. A special acknowledgement to my colleagues Louise Trygg and Fredrik Karlsson for all discussions that never failed to enrich me with newfound energy!

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Thank you, my mother Inga-Lill and father Jan for your support, emotional as well as practical, such as minding my kids. You are really part of this thesis! Thanks also to my brother Anders for your support and curiosity in what I am doing. My thoughts go to my grandfather Karl-Verner and grandmother Maja. Grandfather's favourite saying was: "knowledge is not a heavy burden to carry". I suppose I was influenced after all. Grandmother was very proud of me when I started my PhD studies.

Thanks to friends for lifting my spirit!

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Table of contents

1 Introduction

1.1 Background

Energy recovery through waste incineration[1] connects two vital systems in modern society: the waste management system and the energy system. In Sweden, with an extensive district heating system that supplies 47% of the total heating demand of buildings and premises, heat supply from waste incineration accounts for a substantial share of the total district heating supply of about 12% (Swedish Energy Agency, 2005a). Furthermore, both these systems are the focus of attention mainly due to increasing environmental concerns, and changes are taking place in both systems. The waste management and district heating sectors are influenced by the country's membership of the European Union. Of importance here are the common legislation and policies in these sectors. Important regulations regarding waste management in Sweden include a ban on landfill of combustible waste, and from 2005 a ban also on organic waste (Ministry of the Environment, 2001), and a tax on landfill of waste of at present 46.5 €[2]/ton waste (Ministry of Finance, 2005). Many municipalities have difficulties in complying with the new set of rules and therefore invest in waste incineration capacity to treat waste by an acceptable method and produce district heating and electricity. This has a significant impact on district heating systems since waste incineration plants function as the base heat supplier due to the revenue they receive for treating the waste. In the municipalities that have waste incineration, it is often a substantial part of the total heat supply.

The deregulation of the electricity market in the EU (European Union, 2003a) and the ensuing cross-border trade are also important. The trade in electricity has an impact on how to value electricity since the marginal power producer in the European electricity system is assumed to be coal condensing power in the short term and natural gas based power in the long term (Swedish Energy Agency, 2002). The price of electricity is also assumed to be higher in the future than has traditionally been the case in Sweden (Trygg and Karlsson). Utilisation of district heating systems for

[1] Digestion also has this function, since it is a treatment method for easily biodegradable waste, where the residual products are a fertilizer and a gas which can be used for electricity and heat production or for transportation after cleaning, but this paper will address only waste incineration.

[2] 1 € is equivalent to 9.36 SEK (May 2006).

combined heat and power production becomes more interesting, both in economic terms and for environmental reasons. A directive is in place within the EU that aims to promote increased utilisation of cogeneration based on useful heat demand (European Union, 2004a). It is seen as an efficient way to utilise resources and one measure towards fulfilling the obligations in the Kyoto protocol.

Environmental concerns as regards energy supply and waste management include e.g. increased global warming, acidification, eutrophication and health impacts on the public, and the more general issue of how to use resources. Increased global warming due to anthropogenic emissions of greenhouse gases is one of the major environmental threats on which the scientific society is mainly in agreement. Carbon dioxide accounts for the largest share of the greenhouse gases. The major sources are the burning of fossil fuel for heat and electricity production and vehicle fuel. It does not matter where emissions take place and the effects are global. The risks involved are e.g. increased drought and flooding, decreased harvest, threat to biological diversity and increased spreading of diseases. This is the reason why emissions of carbon dioxide are the main environmental concern of this thesis. Another environmental consideration is the efficient use of resources, both in energy systems and in waste management. Different alternatives for increasing efficiency in resource usage, under the assumptions used, are a basic consideration in this thesis.

Figure 1 shows how waste management and the energy system are connected and surrounding systems that are influential. This figure does not cover every aspect of waste incineration and all factors shown in the figure have not been analysed but demarcations have been made, as described in section 1.2 below.

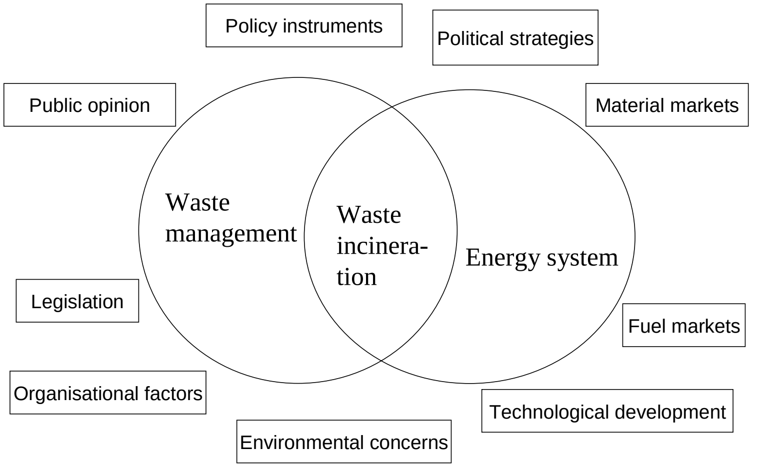

Figure 1. Waste incineration links the energy system and the waste management system. A number of factors influence both systems.

1.2 Aim and scope

The aim of this thesis is to highlight the impacts of increasing waste incineration on Swedish district heating systems by answering the following research questions:

How are the district heating systems affected by increased use of waste as a fuel for heat supply, in economic and environmental terms?

How energy efficient is energy recovery of municipal waste compared to material recovery, provided there is a district heating system able to utilise the heat?

Can there be competition for space between various forms of waste heat in district heating systems?

How do various policy instruments affect energy systems and waste management systems?

Is the inclusion of environmental effects by using data on external costs a suitable method to assess the environmental impacts of a district heating system that utilises waste as a fuel for heat and electricity purposes?

To show the connection between the energy and waste management systems and how these influence each other is a major goal. The connection with Europe through strategic goals, legislation, and trade in electricity is vital to this thesis. The thesis aims to point out resource effective solutions under the assumptions made. The ambition is that the results can be part of the decision making process at energy utilities active in waste management, and for policy makers in energy and waste management systems.

The scope is not a thorough environmental assessment since the environmental impacts surveyed are limited to carbon dioxide emissions in Papers 1-4. Paper 5 tries to broaden the view by calculating energy efficiency and in Paper 6 other emissions to air are included. The aim of the study is not to show how to maximise profit in the utilities analysed, but how to use the resources of the system to fulfil a given demand in the most cost-efficient way under the assumptions made. How the utilities are organised, how decision making is done in the companies and how the networks between people in the organisations affect measures taken are not considered. The study assumes a fixed heat demand. Public opinion has not been analysed. Technological development has been surveyed to a certain degree, in the case of gasification of waste. The fuel market is included in terms of fuel prices. Political strategies come in via policy instruments and legislation which are also taken into account. Material markets are included in the study of energy efficiency comparison of energy recovery and material recovery.

1.3 Paper overview

This thesis is based on the following papers:

Paper 1
Kristina Holmgren and Michael Bartlett
Waste incineration in Swedish municipal energy systems – modelling the effects of various waste quantities in the city of Linköping.
In: Afghan NH, Bogdan Z, Duic N. Editors. Sustainable development of energy, water and environment systems. Proceedings of the Conference, 2-7 June 2002, Dubrovnik, Croatia; 2004

This paper analyses the impact of using waste as a fuel in the existing district heating system of Linköping, in terms of economic impact for the energy utility and carbon dioxide emissions. The waste incineration plant is the base supplier in the district heating system. In that plant, electricity can be produced when integrated with an oil-fired gas turbine. Other plants include a combined heat and power plant utilising biomass/plastics, rubber/coal/biomass and oil/animal fat, a combined heat and power plant consisting of two oil-fuelled diesel engines, hot water boilers utilising oil and electricity. The conditions varied in the study are the amount of available waste (three levels) and electricity price (two levels), making six scenarios. In scenarios with less available waste, biomass fuel is used in the waste incineration plant instead.

Paper 2
Kristina Holmgren and Alemayehu Gebremedhin
Modelling a district heating system: introduction of waste incineration, policy instruments and co-operation with an industry
Energy Policy 32 (2004) 1807-1817

This paper studies the district heating system of Skövde, which was planning to invest in a waste incineration plant and also to extend the network to include a large industrial consumer. The economic effects on the district heating system of these measures are studied as well as environmental effects in terms of carbon dioxide emissions. The consequences of two different policy instruments, green electricity certificates and a waste incineration tax, are also assessed.

Paper 3
Kristina Holmgren
Role of a district heating network as a user of waste heat supply from various sources – the case of Göteborg.
Applied Energy 83 (2006) 1351-1367

This study analyses a Swedish municipal utility, Göteborg Energi, which uses different waste heat in their district heating system; from industries, waste incineration and combined heat and power. The base load of heat supply is waste heat from oil refineries and from a waste-fired cogeneration plant. Other heat sources are a natural gas fired cogeneration plant, heat pumps and hot water boilers utilising pellets, natural gas, and oil. The utility is currently investing in a natural gas fired cogeneration plant where the profitability of the plant is dependent on electricity prices and policy instruments, but also on the utilisation of the heat in the district heating system and annual operating time. The situation is complicated by the connection to other systems, e.g. the waste management system and the industries providing waste heat. In the study, the “competition” between the energy carriers in the municipal district heating system is analysed. The resulting economic and environmental consequences, in terms of carbon dioxide emissions, of different amounts of heat delivered by industries and from waste incineration, and of increasing electricity production at the waste incineration plant, are shown. The phasing out of heat pumps due to their age or increasing electricity prices is also analysed. An important assumption in this study is the realisation of an integrated European electricity market, which will mean higher electricity prices than are traditional in Sweden.

Paper 4
Dag Henning, Maria Danestig, Kristina Holmgren and Alemayehu Gebremedhin
Modelling the impact of policy instruments on district heating operations – experiences from Sweden
In: Lectures, 10th International Symposium on District Heating and Cooling, Hanover, Germany, 3-5 September 2006, AGFW-VDEW, Frankfurt a M, Germany; 2006

This paper shows the impact of policy instruments in municipal district heating systems. Examples used are the Swedish municipalities of Stockholm, Göteborg, Linköping, Skövde, and Örnsköldsvik. Energy taxation, electricity certificates, carbon dioxide emission allowance trading, and a tax on incinerated waste are explained. The function of a district heating network as a heat-sink resource is elaborated on. The role of MODEST as a tool to analyse the impacts of policy instrument is also highlighted.

Paper 5
Kristina Holmgren and Dag Henning
Comparison between material and energy recovery of municipal waste from an energy perspective. A study of two Swedish municipalities. Resources, Conservation and Recycling 43 (2004) 51-73

This paper compares material recovery and energy recovery by waste incineration from the perspective of energy efficiency. Material recovery saves virgin material and energy, since production processes that use recovered material are in general less energy intensive than processes that use virgin material, whereas energy recovery saves other fuels that differ between energy systems. The study analyses two Swedish municipalities: Skövde, which is planning to build a waste incineration plant and Linköping, which is planning to extend their existing waste incineration facility. Optimisation of the municipalities is performed in order to show the amount of waste incinerated and the fuels that are replaced by the waste and electricity production. Energy savings resulting from material recycling waste are also calculated.

Paper 6
Kristina Holmgren and Shahnaz Amiri
Internalising external costs of electricity and heat production in a municipal energy system
Submitted for journal publication

This paper aims to compare a socio-economic perspective and a business economic perspective on a district heating system (Linköping) using waste as a fuel. In the socio-economic case, external costs using data from the EU's ExternE project are added to private costs. In those cases, costs for policy instruments, e.g. taxation and emission allowance trading, are not included, since taxation can be seen as a means to internalise external costs. Assessment is made of whether putting monetary values on external effects is a suitable method to analyse the environmental effects of a district heating system that utilises waste as a fuel.

Paper 7
Kristina Holmgren
Energy recovery from waste incineration: linking the technical systems of energy and waste management
Invited paper in Conservation and Recycling of Resources: New Research, ed. Christian V. Loeffe, Nova Publishers; 2006

This paper aims to emphasise the fact that waste incineration has two purposes: as a waste treatment method and as a supplier of electricity and/or heat. The difficulties caused by this dual function when designing policy instruments (green electricity certificates and tax on incinerated waste) are analysed and conflicting goals in the systems are shown. How to deal with the dual function in models for assessing waste incineration/management with the aim of helping decision makers is discussed. The paper shows the connection between Sweden and the rest of the European Union through common legislation and trade, e.g. in electricity and waste, and how this affects waste incineration in Sweden. The situation in European countries as regards amounts of district heating, cogeneration, and waste treatment methods is also shown.

1.3.1 Co-author statement

In Paper 1, the author of this thesis did the model runs and wrote the paper. Michael Bartlett contributed with discussions of the project and commented on the paper.

In Paper 2, Alemayehu Gebremedhin and the author of this thesis planned the project together, did model runs and wrote sections of the paper; the author was responsible for the parts concerning waste incineration and policy instruments and Alemayehu Gebremedhin for the part concerning the connection of the industry to the district heating network.

In Paper 4, the author of this thesis wrote the parts on landfill tax and tax on incinerated waste, the major part of the section on electricity certificates, the first half of the section on emission allowances, and some parts of district heating as demand source.

In Paper 5, the author of this thesis planned the project, did the model runs for Skövde and wrote the paper. Dag Henning did the model runs for Linköping, discussed the project, and provided comments on the paper.

In Paper 6, the author of this thesis planned the project, collected data, and wrote the major part of the paper. Shahnaz Amiri did the model runs, discussed the project, wrote the part on Linköping's district heating system, and commented on the other parts of the paper.

1.3.2 Other publications not included in the thesis

Michael Bartlett and Kristina Holmgren
Waste incineration in Swedish municipal energy systems. 2001. An investigation of the system consequences of waste quantities in Linköping and the conditions for conventional and evaporative hybrid cycle operation. Arbetsnotat 19. Programme Energy Systems. Linköping Institute of Technology, Linköping, Sweden

Michael Bartlett, Karin Wikman, Kristina Holmgren and Mats Westermark
Effective Waste Utilisation in Hybrid Cycles for CHP Applications – A Cycle and Systems Study.
Proceedings ECOS 2002, Berlin, Germany, July 3-5, 2002.

Dag Henning, Shahnaz Amiri and Kristina Holmgren
Modelling and optimisation of electricity, steam and district heating production for a local Swedish utility
European Journal of Operational Research 175 (2006) 1224-1247

Kristina Holmgren
Waste incineration in Swedish district heating systems.
In: Waste Management and the Environment III, editors: V. Popov, A.G. Kungolos, C.A. Brebbia and H.Itoh, WIT Press; 2006
Presented at the Third International Conference on Waste Management and the Environment, June 21-23 2006, Malta

2. Sustainable development and environmental issues

Increasing environmental awareness has led to the introduction of the concept of sustainable development, meaning "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development, 1987). Two areas of great importance in sustainable development are the waste management system and the energy system due to the substantial impacts on the environment from both systems. Environmental concerns have changed from mainly local environmental problems and controlling pollutants by regulating emissions from various activities, to issues on how to use resources and regional and global concerns. This demands a system perspective on the activities giving rise to environmental impacts.

This section consists of several parts that describe various methods with the common purpose of contributing to steering towards a more sustainable development. They correlate to this thesis in various ways, e.g. methodology or study object. Environmental economics is discussed with the purpose of showing where the ideas behind some policy instruments, mainly taxation and emission allowance trading, originate. Policy instruments play a large part in this thesis, making this aspect interesting. Efforts have been made to put monetary values on environmental effects and some studies that use this to evaluate waste incineration are surveyed. This method is used in Paper 6. Life cycle assessment is a large research area with many studies made on the subject of waste management. The aim of life cycle assessment is to show the environmental impacts of a product or service from the cradle to the grave. Life cycle assessment has a system perspective, making it instructive to compare with this thesis. Finally, some studies that use the same approach as in Paper 5, energy efficiency, are described, as well as studies in the research area of industrial ecology. Within industrial ecology, some studies have focused on the main issues in this thesis, waste as a fuel and combined heat and power, making it interesting to survey how another research discipline deals with these subjects.

2.1 Environmental economics

Environmental economics deals with inclusion of the environment in traditional economics. Bladh (2001) makes an overview of four lines in environmental economics, where two are background to some policy instruments important in this thesis: interventional line and ownership line.

Interventional line

The main concept is externalities, i.e. the negative effects that arise from some activity, which are not included in the cost for the activity, but which affect some third party. If the cost of such effects is not taken into account, suboptimal consumption of the commodity or service will occur. This line was principally propounded by Pigou in 1920, and as examples he points out that the smoke from a factory raises the cost for laundry for the people living in the proximity, or that sparks from the railway can cause fires in surrounding woods. This can be written as:

Socio-economic costs = private costs + external costs

That the market can not incorporate the external costs, Pigou views as a failing that the Government should rectify by taxing the activity that gives rise to the external cost and that the polluter should pay. Pigou's examples mainly concern effects on neighbours, even if he also expresses concerns as to how natural resources are used. In 1968, Dahmén published a report in the spirit of Pigou, but he extended external effects from neighbours to the environment. The environment, e.g. clean air and clean water, can be seen as a "common", meaning that the use of a "common" by one person does not reduce another person's ability to use the resource. However, it is seen that the environment is threatened, and it is therefore necessary to also put a value on these "commons". Dahmén claims that the consumption of commodities should be lowered to the benefit of the environment if the value of the improvement of the environment is higher than the loss of commodity consumption. Dahmén favours fees instead of taxes on the environment, since he wants no fiscal effect.

The main disadvantage of this line is the difficulty of how to put a value on external effects. However, Pigou lays the foundation for environmental taxes and fees, mainly by claiming that over-consumption will occur if a product/service is not priced so as to include all costs and that the Government should intervene to rectify this. That the polluter should pay is a guiding principle of environmental taxes. Pigou is also a starting point for all efforts to estimate external costs for various activities, elaborated on in Section 2.3.

Ownership line
This line was introduced by Coase in 1960 and criticises Pigou's desire to internalise external cost by means of taxes. Coase instead wants to internalise external effects by taking the problem back to the parties involved. By negotiation of "allowances" to use various resources, the problems of effects between neighbours could be solved. Coase does not state who should pay since the result is the same in the end. This presupposes equal partners and obvious effects and involved parties. The Government should not interfere, the involved parties should deal with the issue since they have the greatest knowledge of the situation, which means lower costs. The most important objections to Coase are that environmental problems affect many people, transaction costs could be high, and coming generations can not participate at the negotiation table. Still, trade in carbon dioxide emission allowances, for example, has a bearing on these lines of thought, e.g. that the involved parties have the greatest knowledge about how to tackle the problem and thus ease the Government's work load. The biggest differences between Coase's theory and today's carbon dioxide emission allowance trading programme are that the Government regulates the emissions by putting a cap on them and that the transactions are between the causes instead of between the cause and the affected parties.

2.2 Policy instruments as a method to internalise environmental effects

Policy instruments, including taxation, fees, and trading systems are means of internalising external costs, as described in the previous section. In Sweden, there are a number of policy instruments, that aim to steer towards a more sustainable energy system.

Fossil fuels for heating purposes are subject to energy tax, carbon dioxide tax and sulphur tax. Fossil fuels used to generate electricity are only taxed with sulphur tax, but the consumer pays an electricity tax (electricity for industrial purposes has a very low tax compared to that paid by households and the service sector). The carbon dioxide tax is 97.2 €/ton emitted carbon dioxide. Fossil fuels producing heat for industrial purposes have deducted levels as well as cogeneration; for the latter the change was introduced in 2004. Besides oil and coal, the sulphur tax also applies to peat. A nitrogen oxide levy equals 4.3 €/kg emitted NO_x from conversion units with a minimum output of 25 GWh /year, regardless of fuel. The levy is redistributive; most of the revenues are refunded in proportion to the individual producer's energy yield. Energy taxation is further explained in e.g. Paper 3.

A tax on incinerated municipal waste was introduced on July 1st 2006 (Ministry of Finance, 2006). Waste should be incorporated in the existing energy taxation system by taxing the fossil content of the waste, e.g. plastic packaging. The fossil content is set according to a template. Table 1 shows the levels of taxation on incinerated municipal waste and how they apply to different energy conversion units. It can be seen that the level varies greatly between hot water plants and combined heat and power (CHP) plants. This is a strong incentive for increased electricity production in waste incineration plants.

Table 1. Levels of taxation on incinerated municipal waste (Ministry of Finance, 2006).

	Energy tax (€/ton waste)	Carbon dioxide tax (€/ton waste)	Total (€/ton waste)
Fossil content 100%	16	360	371
Fossil content: 12.6% of total weight (assumed value for municipal waste)			
Hot water boiler	2	45	47
Condensing power plant	0	0	0
CHP plant, electrical efficiency 5%	0	37	37
CHP plant, electrical efficiency 15%	0	9.5	9.5

Important regulations governing waste management in Sweden; a ban on landfill of combustible waste and from 2005 also of organic waste, and a tax on landfill of waste of at present 46.5 €/ton waste, also effects the energy system.

In Sweden, green electricity certificates were introduced in 2003 (Ministry of the Sustainable Development, 2003a). Plant owners receive certificates when producing electricity in approved conversion units, primarily plants fuelled with biomass, peat, biogas or sorted demolition wood waste, as well as solar cells, wind power, and new or small hydropower plants. Municipal waste is not included in the system. Consumers need a quota of certificates in relation to their electricity consumption, creating a demand for certificates, thus giving them an economic value. The aim is to increase annual renewable electricity production by 10 TWh from 2003 to 2010, when the system ends. The system is further described in Papers 2 and 7. A decision was taken by

Parliament in June 2006 to prolong the green electricity certificate system until 2030.

Increasing concern about global warming has led to the implementation of the Kyoto protocol. The Kyoto protocol aims to curb greenhouse gas emissions through flexible mechanisms, among them tradable emission allowances. Trading in emission allowances is scheduled to begin in 2008. Emission allowance trading began in the EU in 2005 (European Union, 2003b). Every member country has decided its own quantity of allowances and their allocation. The national allocation plans have then been approved by the EU; these should be in line with the agreements in the Kyoto protocol, where the EU has committed itself to decrease emissions of greenhouse gases by 8% from 1990 levels by 2008-2012. The allocations are made by “grandfathering”, meaning distribution in proportion to historical emissions. The only greenhouse gas that will be traded in 2005-2007 is carbon dioxide. Sectors that are included are the following:

- Energy (oil refineries and coke oven plants, combustion plants larger than 20 MW, and plants connected to district heating systems with a total capacity exceeding 20 MW). Plants for treatment of hazardous and municipal waste are not included.
- Production and processing of ferrous metals.
- Mineral industry (production of cement clinker, glass, and ceramic products).
- Pulp, paper and cardboard industry.

The Government has incorporated this into Swedish legislation (Ministry of Sustainable Development, 2004a). In Sweden, about 700 plants with around 30% of total emissions of carbon dioxide are included in the trading system, in accordance with the guidelines in the EU directive. Allocations will be made based on average emissions during 1998-2001. For new entrants, allowances are allocated according to a norm, in this case the average emissions from existing plants (Swedish Environmental Research Institute, 2004). The system of allocating allowances by “grandfathering” may give old plants with high emissions an advantage over newer, more efficient plants. Parliament has laid down guidelines for the trading system’s next period (Ministry of Sustainable Development, 2006) and on August 31, the national allocation plan was delivered to the European Commission. Again, the guiding principle is to decrease emissions of greenhouse gases within the EU by 8% compared to 1990 levels by 2008-2012.

2.3 Studies using external costs as a method to analyse environmental impacts

Many activities, such as energy conversion and consumption and waste management give rise to negative environmental effects and if the costs are not taken into account, suboptimal consumption of various commodities will occur, as described in Section 2.1. Several attempts have been made to put a value on these costs in order to incorporate them into other costs using various methods such as loss of production, protection costs, avoidance costs, restoration costs, compensation costs, travel costs, hedonic methods, and contingent valuation. This thesis will not describe these methods but the reader is referred instead to Carlsson (2002) for an overview.

Studies which compare energy recovery from waste incineration with landfill by using external costs are Dijkgraaf and Vollebergh (2004) and Miranda and Hale (1997), and a comparison of various electricity production methods is made by Roth and Ambs (2004). Eshet et al (2006) make a review of studies that have been made that use external costs to compare landfill and incineration of waste, showing that different methods are used when putting a value on environmental impacts and that costs vary significantly. The costs should at best provide an order of magnitude. The studies reviewed lean towards incineration being more expensive than landfilling from a social point of view. However, this is dependent on the benefits of avoided burdens, for example of recovery of electricity and heat, and how these are included in the studies. Carlsson (2002) studies how the inclusion of external costs will affect the energy systems in three regions, an industrial energy system, and the district heating system of Linköping. The results show more use of biomass fuel, and when the assumption is that locally produced electricity replaces electricity produced with coal condensing power, more electricity production when external costs are taken into consideration.

2.4 Studies using life cycle assessment

Life cycle assessment (LCA) is a widely used method of evaluating environmental impacts of products and services (Rydh et al, 2002). It studies impacts over the whole life cycle, from raw material acquisition to production and use and final disposal. How to perform an LCA is stated in ISO standards. The methodology has four basic steps:

1. Goal and scope definition
2. Inventory analysis, where data is compiled

3. Life cycle assessment involving classification of data to different environmental impacts[3], characterisation, where data is analysed as to what extent they contribute to different impacts, and also valuing or weighting. However, valuing is questioned since it is seen as subjective.
4. Interpretation of results.

A great many studies have been made of the environmental impacts of waste management using life cycle assessment, of which some will be presented in this section. Of importance when analysing waste management is that for a fair comparison, all processes must have the same functions. Waste treatment options provide different output of e.g. materials and energy. The recommendation is to widen the system boundaries to include the effects of avoided production of, for example, heat, electricity, materials, and fuels, instead of trying to allocate the environmental burdens. The connection between the systems and how to handle it is very important in this field.

ORWARE is a tool based on life cycle assessment methodology and used for the environmental analysis of waste management systems, as described in, for example, Eriksson et al (2002). It was developed in cooperation between four research institutes[4] in Sweden. ORWARE has been used for a number of studies, e.g. Sonesson et al (2000) and Eriksson et al (2005). Sonesson et al compare incineration, digestion. and composting of solid waste and sludge in a Swedish municipality and one of their conclusions is that fuel used for district heating production is an important factor when the waste is digested or composted instead of incinerated to produce heat. If biomass fuel is assumed, incineration has the greatest negative impact on global warming, and when coal is assumed, composting has the greatest negative impact on global warming. In both cases, digestion is the best alternative, but the drawback with digestion is that it is more expensive than incineration and composting. Eriksson et al use ORWARE to compare waste treatment options: incineration with energy recovery, material recycling, biological treatment, and landfilling with energy recovery in three Swedish

[3] Such as greenhouse gases, eutrophication, acidification.
[4] The Royal Institute of Technology, the Swedish Environmental Research Institute, the Swedish Institute of Agricultural and Environmental Engineering and the Swedish University for Agricultural Sciences.

municipalities. Their conclusion is that landfilling should be avoided, and a combination of the other methods may be the most suitable mean to achieve this.

Finnveden et al (2005) summarise the results from a study comparing waste treatment methods by using life cycle assessment: incineration, landfilling, anaerobic digestion, composting and recycling. The study analyses Swedish municipal waste and aims to help policy and strategic decision makers in waste management and to test the waste hierarchy of the European Union. The connection between the energy and waste management systems and the need to consider both systems when making policy decisions are emphasised. The main focus is on energy use and climate change but other environmental impacts are included, such as eutrophication, acidification, photo-oxidant formation and toxological effects. The waste hierarchy, that puts recycling before incineration is valid as a rule of thumb. However, the study shows that assumptions on, for example, compensatory fuels for district heating and electricity, are important as well as the time-scale for landfills and what happens with biomass saved when for example material recycling paper and cardboard. Finnveden and Ekvall (1998) make an overview of several studies that compare incineration and recycling of paper. The studies show that less energy is used in material recycling, but the main feature of the paper is the discussion of the importance of various assumptions as regards compensatory fuels/energy sources for heat and electricity production for example.

Björklund and Finnveden (2005) make a survey of 10 publications using life cycle assessment for waste management options. Recycling is compared to incineration and/or landfilling, and total energy use and global warming potential were evaluated. Key factors effecting environmental performance are identified: type of recycled material, type of material avoided, energy sources avoided, and time frame for impacts from landfills.

Eriksson et al (2006) make a life cycle assessment of fuels for district heating, waste, biomass, and natural gas, with two options for energy conversion: combined heat and power or heat only production. They use two alternatives for alternative waste management, landfill or material recovery, and two alternatives for marginal power production, fossil lean or intensive. The marginal power production is derived from energy system modelling of what this will be in the Nordic power system in the future. These alternatives are varied in a number of combinations. The study shows the importance of assumptions made; for example, waste incineration is the best option when replacing landfill, but never the best when replacing material recovery. Natural gas fired cogeneration is an environmentally interesting solution with intense fossil content in marginal power production. More robust results are that combined heat and power has environmental advantages compared to heat only production, especially when marginal power is based on intense fossil content. Biomass fuel in combined heat and power production seems the best option in most cases, but since other uses of biomass fuel are not assessed, it can not be concluded that this is the most environmentally preferable option for biomass use.

Other life cycle assessments with regard to waste incineration include an analysis of the benefits of introducing flue gas treatment in a plant in Spain (Sonneman et al, 2003). One main aim of the study is to discuss uncertainties in LCA results. A waste incineration plant in Italy was studied (Morselli et al, 2005), which applies LCA methodology and an environmental monitoring system to assess the environmental consequences of the plant.

2.5 Energy efficiency and industrial ecology

Another way to analyse environmental effects is to calculate the energy use of various activities. Even if other environmental impacts are not included, energy usage is often an indicator of other environmental effects as well. This starting point can be seen in for example Dornburg et al (2006), who have designed a model for evaluating waste treatment methods by maximal primary energy savings or minimal cost per unit of primary energy saving. The model is used for a case study of treatment of biomass residues and other solid waste in the Netherlands (Dornburg and Faiij, 2006), which analyses a number of scenarios and shows substantial savings in primary energy with a combination of recycling methods, energy conversion plants, and production of transport fuels. Savings from treatment methods vary between scenarios, but production of transportation fuels makes only a modest contribution. Of importance is for example (biomass) integrated gasification technology. Morris (1996) uses the same approach as in Paper 5 to investigate municipal waste in the U.S. The study found that for 24 out of 25 solid waste materials, recycling saves more energy than is generated by incineration. The main difference in comparison with Paper 5 is the absence of a district heating system to utilise the heat; instead, only electricity is generated.

Industrial ecology is a concept which looks at natural ecosystems as an analogy: the ecosystem recycles the essential nutrients and its input is energy from the sun. An industrial ecosystem is “an industrial park which captures and recycles all physical materials internally, consuming only energy from outside the system and producing only non-material services for sale to consumers” (Ayres and Ayres, 1996). This is an idealised picture, but the main endeavour of industrial ecology is to increase efficiency in material and energy usage by for example integrating actors. At the industrial level, a group of companies should be organised so that waste from one company can constitute the raw material feedstock for another, thus increasing efficiency and reducing the need for primary materials. Verhoef et al (2006) discuss whether the concept of industrial ecology is suitable when waste management systems are designed. The systems should be organised in order to match recovered material with demands from production processes, to secure the possibility to use secondary materials. Recycling of materials and cascading of energy are important in industrial ecology. Energy cascading means that energy is used in various quality, temperature and pressure levels. Korhonen (2002) wants to see combined heat and power production as an anchor tenant of a local industrial ecosystem. An anchor tenant is defined as a key actor in a region around which the recycling network of actors can be merged. The energy cascading that takes place in a combined heat and power plant is electricity production, steam for industrial purposes, heat for district heating systems, and the last level, for example heating for fish farms or horticulture. Waste can be used for combined heat and power production and replace fossil fuels. The plant functions as a decomposer according to ecosystem analogy (Korhonen, 2001).

3. Main infrastructural systems related to this study

In this section, the main infrastructural systems studied in this thesis will be described: waste management, district heating, and the electricity market.

3.1 Waste management

The waste management goals for the EU are expressed in the Sixth Environmental Action Programme from the European Commission (2001) which states, for example, that the amount of waste should decrease by 20% between 2000 and 2010 and by 50% over the years up to 2050. To achieve this, the existing correlation between economic growth and waste production must be broken. The waste hierarchy, which is the core of the EU's waste policy, is described and states that first comes waste prevention, then recovery (reuse, material and energy recovery where material recovery, including biological treatment is preferred to energy recovery), and finally disposal, where landfill and waste incineration without energy recovery are included. Swedish waste policy is based upon this hierarchy. The strategy for Swedish waste management can be found in (Swedish Environmental Protection Agency, 2005). The responsibility for collecting waste is divided among three parties. The municipalities collect municipal waste, which is waste from households and waste which is similar in content. The producers collect waste which is covered by the law of producers' responsibility[5] and for other types of waste, the responsible party is the one that causes the waste.

The EU member states are obliged to incorporate EU directives into national legislation. The main directive concerning waste management is the Framework Directive (European Union, 1975) which classifies waste. The Directive on Landfill (European Union, 1999) and the Directive on the Incineration of Waste (European Union, 2000) aim at harmonising standards in waste treatment methods in the European Union. The

[5] The law of producers' responsibility prescribes the recovery levels for some waste fractions, e.g. packaging, used cars, and car tyres, newspapers, and electric and electronic devices. The legislation is further explained in Paper 5.

Directive on Packaging Waste, states recovery levels for packaging materials (European Union, 2004b). These directives are further explained in Paper 7. As stated, the amount of waste should decrease in the European Union, but up until now, little has been achieved. For example, Sweden has been successful in moving waste “up the ladder” in the waste hierarchy by decreasing amounts of waste for landfill by using other treatment methods, but the total amount of waste is still increasing and the first priority in the waste hierarchy, prevention, has not received much attention. The directives stated above are mainly concerned with setting emission levels, recovery levels, and technical standards. However, the European Union aims at taking a broader view in their thematic approach to material flows and product design (European Commission, 2005).

In Sweden, the total amount of waste in 2002 was around 90 million tons, of which the mining industry accounts for 54 million and manufacturing industry 19 million tons (Swedish Environmental Protection Agency, 2004). Treatment methods for industrial waste are shown in Figure 2. Mining waste is mostly landfilled at sites the mining companies themselves run.

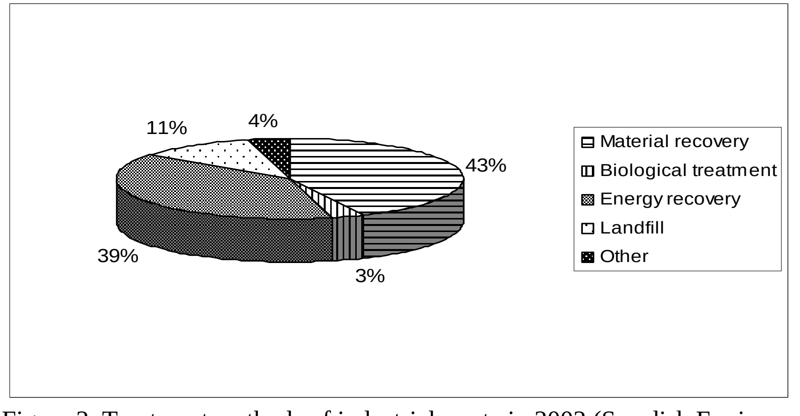

Figure 2. Treatment methods of industrial waste in 2002 (Swedish Environmental Protection Agency, 2004).

Sewage sludge accounts for 1 million tons per year. Demolition waste is estimated at around 5-10 million tons per year, and other industrial waste, apart from manufacturing industry, accounts for around 2 million tons, but these figures are uncertain (Swedish Environmental Protection Agency, 2005). Municipal waste was around 4.2 million tons in 2004 (Swedish Association of Waste Management, 2005a) and treatment methods can be seen in Figure 3.

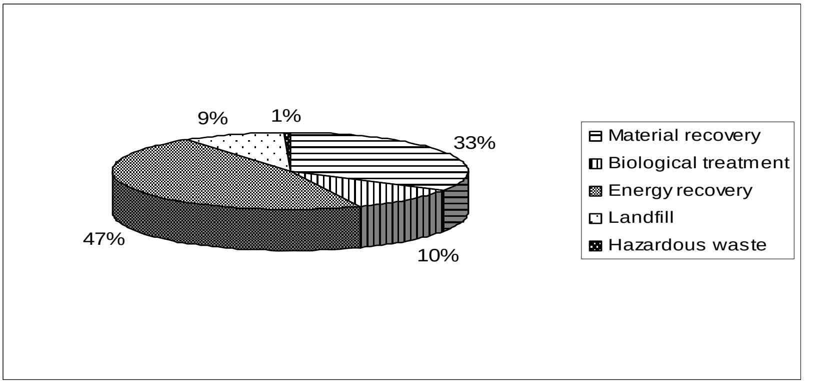

Figure 3. Treatment methods of municipal waste in 2004, total 4.2 million tons (Swedish Association of Waste Management, 2005a).

The amount of landfill has decreased substantially in recent years, for both industrial and municipal waste. Waste incineration, biological treatment, and material recovery have increased. In 2004, there were 29 waste incineration facilities in Sweden, both hot water boilers (14) and combined heat and power plants (15) producing about 8.6 TWh heat and 0.74 TWh electricity (Swedish Association of Waste Management, 2005a) by using 1.95 million tons of municipal waste and 1.2 million tons of other waste, mainly from the manufacturing industry. Capacity for waste incineration is forecast to increase from 2.8 to 4.9 Mton between 2002 and 2008, if all planned projects are carried out (Swedish Association of Waste Management, 2004), resulting in a total of 40 waste incineration plants. Despite these investments there will still be a lack of treatment capacity. Quantities of waste are also increasing, between 1985 and the present by some 2-3 % per year. If this trend is not broken, additional waste treatment capacity will also be needed after 2008.

Waste management systems have been analysed using a variety of models as described by Morrissey and Browne (2004) who differentiate between cost-benefit models, life cycle assessment models (described in section 2.4), and models based on multi-criteria analysis. The article criticises all models for not being sustainable since no model includes both environmental, economic, and social aspects. A model developed and applied to Swedish conditions is MIMES/WASTE which uses a system approach to find the most cost-efficient waste management solution with acceptable environmental performance (Sundberg et al, 1994). The article presents the model as well as the results from a pilot study of the waste management system in Göteborg. The model NatWaste is built on MIMES/WASTE, but is tailored for national applications (Ljunggren Söderman, 2000). It was developed for Swedish conditions though it could be used for other countries. It uses cost minimisation and emissions accounting and aims to analyse, for example, the effects of policy instruments and uncertainties at the national level and support decision-making.

The biological treatment methods, i.e. composting and digestion, and material recovery, are described in Paper 5, waste incineration in Papers 1,2, and 5 and Holmgren (2006), and landfill in Bartlett and Holmgren (2001).

3.1.1 Waste as an energy source

Incineration of waste is the main measure to utilise the energy content in waste, but there are others. Gasification, where waste is partially incinerated with limited access to oxygen results in mainly gas and some tar. Pyrolysis, where waste is heated with no access to oxygen results in mainly gas and solid char. Biodegradable waste can be digested, resulting in biogas that can be utilised for heat and/or electricity production or as vehicle fuel.

Olofsson et al (2003) compare three different waste-to-energy technologies in the Swedish district heating systems, incineration, pyrolysis, and gasification, and conclude that incineration is the most cost-efficient solution and gasification the least. Murphy and McKeogh (2004) analyse energy production from municipal waste in Ireland by incineration, gasification or digestion of the biodegradable part, thereby producing biogas. The biogas is used either for combined heat and power production or vehicle fuel. Gasification enables a lower gate fee than incineration, although gasification has not yet been proven on a commercial scale. The results are sensitive to assumptions as regards access to a heat market. Biodegradable waste for biogas production for vehicle fuel enables the lowest gate fee and for combined heat and power production the second lowest. However, since it is only biodegradable waste that can produce biogas and the scenarios utilising gasification and incineration instead use a fraction of non-biodegradable and non-recyclable waste, the gate fees can not be directly compared. Possibilities to reduce carbon dioxide emissions are shown and the main measure is to decrease methane emissions from landfills. Assefa et al (2005) make a technology assessment of gasification with either catalytic or flame combustion, incineration with energy recovery and landfill with energy recovery. The potential for global warming, acidification, eutrophication, consumption of primary energy carriers and welfare cost are also assessed. Gasification with catalytic combustion in a combined cycle appears to be the most environmentally competitive alternative. The catalytic combustion decreases the NO_x emissions considerably. How to deal with residues from gasification and estimation of investment cost for gasification since it is not a mature technology are uncertain parameters. Compensatory electricity is assumed to be natural gas fired power plants and for district heating biomass; this can also affect the results. Anticipated higher electricity prices in the future will make gasification more economically competitive due to higher electrical efficiency in gasification plants than in incineration plants.

The high standards of flue gas cleaning in waste incineration plants has mainly moved the problems with emissions to air to pollution in the ashes, as stated by Sabbas et al (2003). Sabbas et al. make an overview of treatment methods of municipal solid waste incineration residues. Approximately 20-25% of the waste mass remains as residues, where bottom ash is the main part (Sabbas et al, 2003; Swedish Association of Waste Management, 2005b). Hazardous substances end up in the fly ash[6], which is around 4% of the total weight of the waste and classified as hazardous waste and has to be treated in order to prevent leakage. The fly ash consists for example of heavy metals and various organic substances (Reijndeers, 2005). Due to the high chloride content, very few landfills are permitted to receive fly ash from waste incineration. Today, fly ash from plants in Sweden is mainly exported to Norway and used to fill in an old mine. The question of suitable places in Sweden for this is being looked into[7].The EU's Directive on Incineration of Waste (European Union, 2000) demands that the ashes should be reused to the greatest possible extent. What happens with the bottom ash is as follows: metals are separated, then unburnt material is separated in order to be incinerated again. Slag can be used to replace all-in gravel and crushed rock in for example road construction and buildings[7]. Another field of application is to cover old landfills. There is a great need for this today with many landfills being closed in anticipation of stricter demands in the European Landfill Directive (European Union, 1999), but the need will diminish. In other countries, the slag is used to a large extent in road construction (Swedish Association of Waste Management, 2005b) and tests have been carried out to investigate whether this could be implemented in Sweden.

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[6] Fly ash is the residue from the flue gas cleaning.

[7] Personal communication with Mikael Johnsson, Swedish Association of Waste Management.

To what extent bottom ashes are recycled today in Sweden differs widely between plants.

Ashes from waste incineration can be compared to ashes from biomass combustion, which amounts to at most around 5%, often 1-2%[8]. Efforts are being made to recycle ashes from biomass combustion back to the forest. Why this procedure still is not in place is mainly a matter of costs. Biomass fly ash is not considered hazardous waste but can be used for cement construction, for example. Ash from coal combustion amounts to around 8%, and can be used among other things for road construction. This is widely done in Europe with its large amount of coal combustion.

One disadvantage of waste incineration is the low electrical efficiency compared to plants using other fuels. This is mainly due to the impurity of the fuel. The temperature of the steam in the boiler can not exceed 400ºC without entailing high maintenance costs due to corrosion, as stated for example by Korobitsyn et al (1999) and Caputo et al (2004). In Sweden, out of 29 existing waste incineration plants, 14 are heat only production and 15 combined heat and power (Swedish Association of Waste Management, 2005a). Apart from the difficulties in using waste for electricity production, historically low electricity prices also have influence in this respect. However, the waste incineration tax introduced in July 2006 with different levels for hot water boilers and combined heat and power plants should modify this, since the taxation will differ substantially for hot water boilers and combined heat and power plants, as described in Section 2.2. The planned waste incineration plants in Sweden all have electricity production[9].

An overview of the historical development of waste incineration in Sweden can be found in Hrelja (2006) and Paper 7.

3.2 District heating

District heating is a network consisting of pipes that transport heat, using hot water or steam as energy carrier, from one or several central heat producers for use as space heating, hot tap water and/or industrial process

[8] Personal communication with Claes Ribbing, Svenska Energiaskor AB
[9] Personal communication with Anders Hedenstedt, Swedish Association of Waste Management

purposes. District heating is characterised by high initial capital cost when building the system, but also by the ability to use fuels and heat sources which otherwise would be of limited use, such as combined heat and power production, heat from waste incineration, industrial waste heat, geothermal heat and difficult fuels (Andersson and Werner, 2005). Other advantages include economy of scale and a better environment when individual heat sources are replaced with efficient boilers with controlled combustion and emission limits. Furthermore, it is a flexible system which can change fuels and supplies rather quickly in order to adapt to changing fuel prices and policy instruments for example.

District heating accounts for 47% of the total heat supply of buildings and premises in Sweden (Swedish Energy Agency, 2005), and there are district heating grids in 232 of Sweden's 290 municipalities. The municipalities began to be interested in district heating in the late 1940s; the first district heating grid in Sweden was in operation in Karlstad in 1948. In the beginning, district heating systems were a means of producing electricity through combined heat and power, since hydropower was foreseen as insufficient to meet future electricity demand. During the 1950s and 1960s, the district heating systems expanded and several combined heat and power plants were built in the early 1960s. The effect was also increased interest in waste incineration in the 1970s (Swedish Association of Waste Management, 2005b) as one measure to decrease dependency on oil and solve the problems of waste management. As plans for nuclear power emerged, the major Swedish electricity producer Vattenfall saw the municipal combined heat and power plants as a threat to the expansion of nuclear power and discouraged further investment (Werner, 1989). Instead of being a supplier of electricity, the district heating grids became users of electricity by utilising electric boilers and heat pumps for heat production, due to the abundance of cheap electricity in Sweden with both hydro and nuclear power. Today, electricity production in Swedish district heating systems is still low. The development of electricity production and consumption by electric boilers and heat pumps in Swedish district heating systems between 1970 and 2003 can be seen in Figure 4. The resulting net electricity can also be seen. Sjödin (2002a) makes a more thorough survey of the development of the Swedish district heating systems.

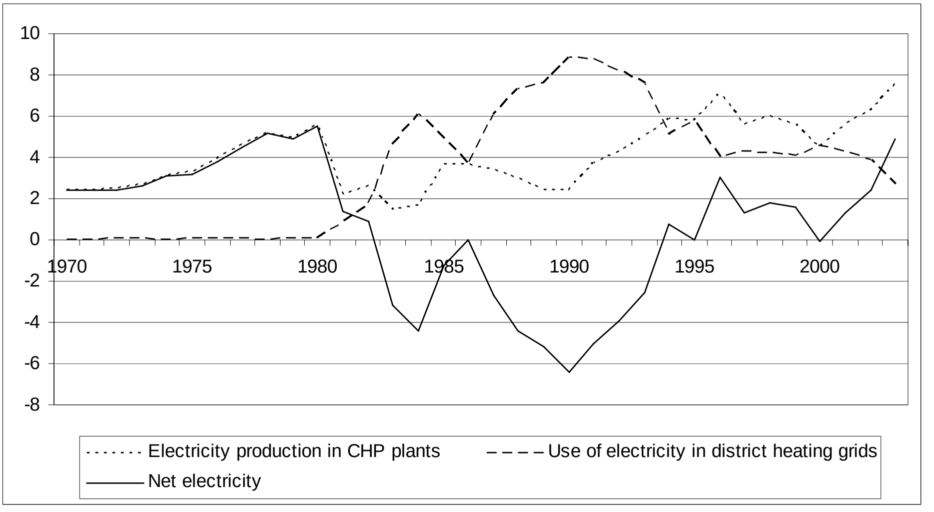

Figure 4. Net electricity in Swedish district heating networks between 1970 and 2003 (Swedish Energy Agency, 2004, an earlier version shown in Sjödin, 2002a).

The owner structure of the district heating systems is today dominated by municipal utilities but private actors are also influential owners. The private actors include the major energy companies in Sweden: Vattenfall, Eon and Fortum (Andersson and Werner, 2005). Some are still managed by municipal administration, which was the organisational form under which the networks were developed. During the 1970s, most of the municipal administrations were reorganised into municipal utilities that were partly sold to private actors during the 1990s.

Energy taxation in Sweden has had a significant effect on what fuels are used in the district heating systems since heat from fossil fuels has been heavily taxed. There has been a major shift from an almost total dependency on oil up until 1980 to a diversified supply where renewables represent a substantial proportion. This can be seen in Figure 5. Energy tax on oil was introduced in 1980, the main aim being to replace oil with other fuels and electricity in the wake of the oil crises in the 1970s. Other fossil fuels were also burdened around that time and the level increased gradually. Carbon dioxide tax, which has a more environmental profile since it is linked to the carbon content of the fuel, was introduced in 1991. Bohlin (1998) makes an ex post analysis of the effects of the carbon dioxide tax between 1990 and 1995 and shows a substantial increase in biofuel in the district heating sector, mainly replacing coal, due to the tax. Hillring (2000) points out the carbon dioxide tax as the main incentive for increased utilisation of biomass in district heating systems, even if there are others, such as the investment support for biofuelled combined heat and power existing prior to the green electricity certificates.

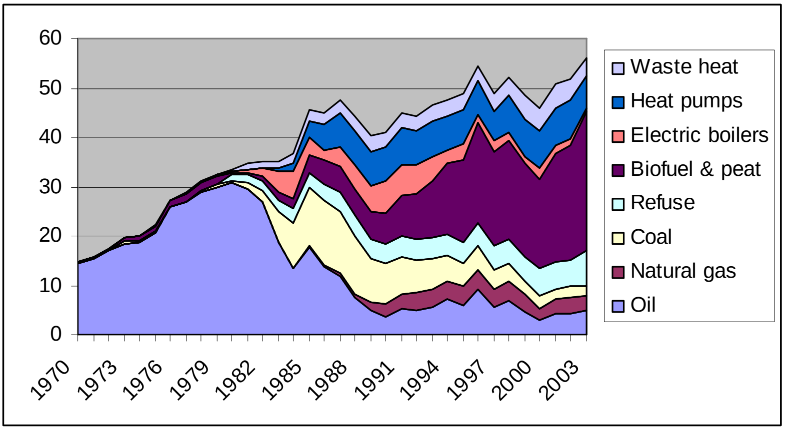

Figure 5. Development of heat supply to the district heating networks between 1970 and 2003 (Swedish Energy Agency, 2004).

There are several question marks concerning the energy taxation in the future. One is how the carbon dioxide tax should interact with other policy instruments, in particular tradable emission allowances. Another is whether energy taxation needs to be changed to comply with EU rules on governmental aid. In Sweden, business is divided into sectors, with differentiated energy tax levels, for which Sweden has been granted temporary exemption. A governmental investigation has analysed this and suggests a new energy taxation system that only differentiates between households and business (Ministry of Finance, 2003). This would bring energy taxation into line with EU rules. It would lower carbon dioxide taxes in the district heating sector since the government would be very reluctant to increase taxes on industry exposed to competition. It would go hand in hand with the guiding principle that in the trading sector, trading should be the main policy instrument. Since the carbon dioxide tax has been successful in transforming the fuel supply in the district heating sector, it is unclear what will happen.

Up until 1996, district heating activities were governed by the Local Authority Act of demands for self cost for example, meaning that the costs for the product should be the foundation for the price, and equality, meaning that all consumers should have the same price if the cost is the same. When the electricity market was deregulated (further described in Section 3.3), it was said that district heating should be operated ”in a business-like fashion”; prices were set free. Westin and Lagergren (2002) describe this transition and argue that consequences for district heating were overlooked when the electricity sector in Sweden was deregulated. A governmental investigation of district heating (Ministry of Sustainable Development, 2003b; 2004b; 2005) aims to study the district heating market in order to protect the consumers against eventual unreasonable pricing. According to the Government, the distribution of hot water is a natural monopoly. There is a risk of cross-subsidisation when utilities also have activities in the electricity market, which is exposed to competition. The Government wants an expansion of district heating and for this to happen, customers must have confidence in the district heating market. Other issues investigated include how to implement the EU Directive on promotion of cogeneration (European Union, 2004) and third party access, i.e. open up the district heating grids for competition. Activities within electricity and district heating have to be in separate utilities, this was implemented in 2005. Other proposals are that a model for calculation of reasonable pricing should be designed, an appointed District Heating Committee should mediate in disputes and as Supervising Authority, the Swedish Energy Agency is suggested. The investigation does not recommend third party access, but energy utilities' obligation to negotiate with industries who want to supply waste heat, and to let the District Heating Committee decide if the involved parties can not reach a decision. There is also a proposal for a new District Heating Law which will not, as now, be incorporated in the Electricity Law (Ministry of Sustainable Development, 1997).

3.2.1 Studies on the role of waste incineration in district heating systems

Sahlin et al (2004) analyse the impact of increased waste incineration in the Swedish district heating systems. The methods used are a questionnaire sent to the largest district heating utilities to find out which fuels are affected by expanded waste incineration and modelling with an annual merit-order duration curve model of the 163 largest district heating systems. Results are that the fuel primarily replaced by an expansion of waste incineration is biomass, that waste incineration enables an expansion of the district heating grid due to the low operational cost of waste as a fuel, and that increasing waste incineration is affecting combined heat and power production. Waste incineration plants function as base suppliers of heat due to the negative operational costs for receiving the waste, and can therefore remove the heat sink in the district heating system, making other, more efficient, combined heat and power plants operate less.

Olofsson (2001) links the energy system and the waste management system in case studies of two Swedish municipalities, Jönköping and Göteborg, in order to reach cost-efficient solutions with respect to both systems, emphasising the importance of considering both systems when choosing waste treatment methods. The model MIMES/WASTE[10] is used to model the waste management system. MARTES, which is a simulating model using least-cost dispatching order, is used to model the energy system. In Jönköping, MARTES was run to yield a demand for waste as a fuel, and that demand was used as input to MIMES/WASTE. Results were evaluated in cooperation with representatives of both waste management and energy systems. The most suitable investment is a waste incineration plant and was not an optimal choice when the systems were analysed individually. In Göteborg, the working order was reversed. Additional waste incineration capacity was evaluated together with investment in a natural gas fired combined heat and power plant and both options seem economically beneficial. The neutral arena, where the operators of the waste management and energy systems met was beneficial to the exchange of knowledge.

Ljunggren Söderman (2003) looks into the potential of recovering energy from waste in Sweden, aggregating Swedish district heating systems into one system using a marginal-cost ordering procedure model. The waste management system is modelled using a linear programming model which minimises the total annualised cost[11]. Research questions are if recovering energy from waste is economically viable from the waste management perspective and from the district heating perspective, if waste is a significant untapped energy resource in Sweden, and global warming implications of recovering energy from waste. From the waste management perspective, energy recovery is part of the optimal solution and should be maximised but combined with a high level of material recycling. The competitiveness of energy recovery in the district heating sector is analysed by calculating at what selling price it is profitable to sell heat. The modelling of the waste management system shows that at that price, less heat is available than the district heating market can incorporate. This implies that waste types not included in the study could be used if available at that price. The main factors affecting global warming are the quantity of heat and power recovered in the waste

[10] The model is mentioned in Section 3.1.
[11] NatWaste is mentioned in Section 3.1.

management system, the plastics content of the incinerated waste, and the marginal power producer assumed, either coal condensing power or natural gas based power. The study gives a relevant overview of these questions, but due to the aggregated level of describing the systems, average carbon dioxide from the district heating sector is used. This can vary substantially between systems.

A review study that aims to find critical factors for the environmental assessment of energy recovery by waste incineration in comparison with landfill, material recovery, and biological treatment are conducted by Olofsson et al (2005). Important general factors are the time perspective, technology development, local conditions, alternative electricity and heat generation, renewable energy supply in Europe, and waste transportation by passenger car. For incineration, emission levels, efficiency in energy recovery, the time perspective, and the fate of landfill residues are also relevant.

Palm (2004) makes an analysis of the policy processes in two municipal energy systems between 1977 and 2001, whereas one is Linköping. Institutional factors can connect the waste management system and the district heating system. One reason for the introduction of waste incineration in Linköping was that the same municipal utility operated both the waste management system and the district heating system and saw that with waste incineration they could solve two problems at the same time: both an acceptable waste treatment method and heat production for the district heating system.

3.2.2 District heating and combined heat and power

Combined heat and power production is seen as an efficient way to save primary energy and is recognised as one measure to decrease carbon dioxide emissions in the European Union, as well as other emissions. Additional advantages are avoiding network losses and greater power grid reliability by means of power generation near load centres. Of importance is that cogeneration can contribute to security of supply through its ability to use indigenous fuels. A directive is in place that aims to create a framework for promoting high efficiency cogeneration based on useful heat demand (European Union, 2004a). In order to be defined as high efficient cogeneration, the savings in primary fuel have to be at least 10%. A governmental investigation has been carried out on how to implement this in Swedish legislation (Ministry of Sustainable Development, 2005). However, electricity production in the Swedish district heating networks is low, as described in Section 3.2.

The efficiency of combined heat and power instead of separate production has been assessed in several studies. Werner (2001), for example, analyses possibilities for district heating systems and combined heat and power to reduce carbon dioxide emissions in the European Union. Werner claims that in the short term, as long as coal-fired power plants with high carbon emissions are the marginal electricity producers, district heating and combined heat and power production could make a significant contribution towards fulfilling the commitments of the Kyoto protocol. This advantage will be weaker in the long term, when natural gas fired combined cycle power plants are the marginal producer of electricity. Lund et al (2005) analyse how Lithuania will solve their need for additional electricity supply when the Ignalina nuclear plant is closed down, and show fuel savings if combined heat and power in the district heating systems are implemented in small cities. Mortensson and Overgaard (1992) give an overview of the development of district heating and combined heat and power production in Denmark and claim large energy savings due to an increased share in the Danish district heating systems utilised for combined heat and power production.

Rydén et al (1993) investigate the potential for combined heat and power production in five Swedish communities as well as competition between combined heat and power production and waste heat, and conclude that there is a significant untapped potential for combined heat and power production in Swedish district heating systems and that detailed bottom-up studies are needed in order to understand how to utilise this potential. Knutsson and Werner (2003) study the potential for electricity production in district heating systems if the natural gas grid was extended in Sweden[12]. They find that the annual potential for further natural gas based electricity production is 26 TWh[13]. Knutsson et al (2006) analyse the impact of green electricity certificates and carbon dioxide trading on investments in combined heat and power production in Swedish district heating systems, showing a large potential of increased combined heat and power production and hence considerable savings of carbon dioxide emissions. The Swedish District Heating Association (2005) predicts

[12] At the moment, the natural gas grid covers only the south-west part of the country, but there are plans to extend it.
[13] It is important to be aware of one assumption in the study; electricity prices are at a level that makes only waste heat and heat from waste incineration cheaper than heat from CHP production. Heat pumps are more expensive than heat from CHP.

increased electricity production by combined heat and power from 5.7 TWh in 2002 to 12.5 TWh in 2010 in Sweden. Driving factors are the green electricity certificate system increasing profitability in biomass fuelled cogeneration and recently changed energy taxation meaning more beneficial conditions for fossil fuel cogeneration[14].

3.3 Electricity market

Electricity production in Sweden is mainly based on hydropower and nuclear power, accounting for about 90%, with roughly half each. The rest is fossil and biomass cogeneration plants and some wind power. In 2004, total production was 148.2 TWh (Swedish Energy Agency, 2005a). In 1996, the Swedish electricity market was deregulated and conditions are stated in the Law of Electricity (Ministry of Sustainable Development, 1997). The reason given was to achieve lower electricity prices through competition among actors since consumers would be able to choose freely among producers. Distribution of electricity is seen as a natural monopoly and that meant that distribution and production of electricity had to be separated into disparate companies to avoid cross-subsidisation between monopoly activities and activities exposed to competition. Svenska Kraftnät was established to operate the national high power transmission grid. The Swedish Energy Agency supervises the prices and conditions the distribution companies offer their customers. In 1996, the Norwegian-Swedish electricity market Nordpool was in operation (it had been a Norwegian marketplace since their deregulation in 1991). Finland joined Nordpool in 1998 and Denmark in 2000. About 40% of the total trade in electricity in the Nordic countries goes through Nordpool (Swedish Energy Agency, 2005b).

The core of the European Union is free movement of goods, capital, services and people. The introduction of a common internal electricity market is in line with this. The objective of the directive (European Union, 2003a) on a common internal electricity market is to open up the electricity market by subjecting it to competition in order to increase efficiency in the energy sector. Industrial consumers can choose their supplier from July 1st 2004 and all consumers from July 1st 2007. The European Commission publishes a yearly report about the implementation of the internal market (European Commission, 2004)

[14] As explained in Section 2.2.

which states that the result of the implementation has so far been unsatisfactory. One reason is barriers to cross-border trade, e.g. market structures, and the need for further investments in infrastructure. However, the report states that these problems must be solved. The impact of this directive in Sweden is that electricity prices will increase due to harmonisation with the electricity prices in continental Europe, which are higher than has traditionally been the case in Sweden. This is further described in Trygg and Karlsson (2005) for example.

3.3.1 Marginal power

The question of how to value the environmental performance of electricity is the subject of much debate and opinions vary. The first issue is whether marginal data or average data should be used. Other questions are what system boundary to draw and what time frame to consider. Calculating average data is done by evaluating the environmental impacts of all electricity production units in for example a country or region depending on the chosen system boundary. Swedish or European electricity mixes have been used. The cost of producing an additional unit according to traditional economics is called the marginal cost. The producer of this additional unit is called a marginal producer. This also means that when the electricity demand decreases, this is the unit that switches off first. When estimating what the marginal power producer is, system boundaries are important; for example, Nordic marginal power or European marginal power has been used. In both average and marginal data, a time frame is essential, since both the mix of electricity production and the marginal power can be expected to change. The common internal electricity market in the European Union means cross-border trade and this affects what system boundaries to chose.

In the research area of life cycle assessment, several publications deal with this. Average data has often been used in an accounting perspective, e.g. account for the total environmental impact of activities within a municipal or an industry. However, when analysing the impacts of changes, marginal data should be used. Tillman (2000), for example, differentiates between a retrospective or accounting perspective and a prospective perspective when performing life cycle assessments, the latter meaning that the impacts of alternative actions are investigated. The author claims that the debate on methodological issues within LCA stems from the failure to recognise these two perspectives. Another division is between foreground and background systems, the former being all processes in which measures may be taken as a result of the study (“core system”) and the latter all processes being affected by measures in the foreground system (“enlarged system”). A waste water study is given as an example, where alternative treatment methods are assessed and average data is used in the foreground system and marginal data in the background system. Ekvall (1999) investigates methodological issues within LCA and analyses the question of whether to use an average mix of Swedish electricity production or marginal production. The study leans towards using marginal data since the effect on the total electricity production in the geographical area is small. Weidema et al. (1999) argue for using marginal technology in life cycle assessments, and describe a 5 step procedure for identifying marginal technology, using electricity as a case. Kåberger and Karlsson (1998) discuss how to value electricity in life-cycle analysis in a deregulated electricity market. How large can a change be and still count as only affecting the marginal producer? Can a large change in demand instead affect base load production of electricity? The authors state that the use of a mix of Swedish electricity production for life cycle assessment valuation erodes with increased cross-boarder trade of electricity. What they argue for is contractual valuation, meaning that when consumers buy electricity they can specify the production unit and therefore their electricity consumption should be valued according to that.

Sjödin and Grönkvist (2004) analyse different methods for emissions accounting for the use and supply of electricity, comparing average, marginal, and labelled. Their aim is to find an accounting scheme for energy measures and their emissions of carbon dioxide. They also point out the impact of price elasticity, meaning that when electricity is added to the system, prices go down and demand therefore increases. They argue that the most suitable method to capture the dynamics of the electricity market is through marginal power and at present this means coal condensing power. A report from the Swedish Energy Agency (2002) states that the marginal power producer in the European Union is at present coal condensing power plants and in the future it is predicted to be natural gas fired power plants. A mix of marginal producers was used in a study of life cycle assessment of fuels for district heating supply (Eriksson et al, 2006), described in Section 2.4. The mix was the result of energy modelling of perturbations in the Nordic electricity market.

The debate on what data to use is important, since the environmental performance of electricity varies greatly according to different assumptions. In this thesis, the assumption is made that marginal data best captures the dynamics of the electricity market. The underlying assumption is of a functional deregulated European electricity market where trade barriers are removed. This is not yet the case since several

European countries are still not deregulated and additional infrastructure is needed but implies that this will be the case in the future. The changes analysed in this thesis; mainly consumption and production of electricity in district heating systems, can be deemed small in comparison to the whole system which is a prerequisite of marginal data. The short-term marginal power producer is assumed to be coal condensing power and long term marginal power is probable natural gas based power. The time frame for the change is hard to estimate, so in this thesis both coal condensing (Papers 1, 2, and 6) and natural gas based power (Papers 3 and 6) have been used and assumption is made that locally produced power can replace marginal power. Varying the marginal power producer highlights the impact of these assumptions.

3.3.2 Impact of carbon dioxide emission allowance trading

Carbon dioxide emission allowance trading means a cap on carbon dioxide emissions in the sectors included in the trading system. This has implications for the assumption that locally produced power replaces power produced by the marginal production unit in the European power system. In the trading system, the replacement of coal condensing electricity means that carbon dioxide emissions saved in those plants would instead take place elsewhere in the trading system. Replacement of electricity implies instead that the price of emission allowances decreases since it liberates emission allowances for sale.

The argument for showing potential savings in emissions of carbon dioxide is nevertheless that it is still interesting to see the possible contribution of various measures. The trading system is a policy instrument in effect at the moment and how the future will be is not certain. The cap on emissions needs to be tightened in the future and by highlighting efficient measures to decrease emissions, political agreements on tightening of the cap might be easier to achieve.

In a report from the International Energy Agency (2002), system boundary issues are discussed in relation to emission allowances. These arise in several contexts, e.g. whether or not the sector where a saving take place is included in the trading scheme and whether an entity taking measures resulting in reductions has ownership or control of where the reductions take place. This applies to reductions in demand in the power grid, whether it be electricity produced in combined heat and power plants, a demand side measure, or electricity production from renewables. The utility enabling the reduction do not receive the credit. The electricity price has increased due to the trading system since the marginal power production in the European power system is carbon intensive. A higher electricity price naturally means increased incentives to for example save electricity or invest in combined heat and power production. The question is whether this is enough.

4. Method

4.1 System analysis and system boundaries

The main aim of this section is to present how the concept of system analysis is used in this thesis. The terms “system analysis” and “system” are today applied in a variety of meanings, making it important to clarify their meanings as they are used in this thesis.

Ingelstam (2002) makes an overview of system analysis; how it has evolved, how it has been used and how it is being used. Ingelstam gives some definitions of what characterises a system; there are components and connections between these and they form some kind of entity. The system must be discernible in relation to its surroundings; a system boundary must exist. Only in exceptional cases is the system closed. The rest of the world that does not belong to the system but still has influence on the system is called its surroundings. The connection to the surroundings and the influences on the system is an essential part of system analysis.

The system approach, as described by Churchman (1968), gives guidance as to how to use the concept. Churchman can be seen as an offspring to operational research. Operational research began during the Second World War, mainly for military purposes. It was characterised by borrowing thoughts and methods from different fields for military problems in tactics, organisation and behaviour. Many prominent researchers from different fields were involved. It was target-oriented and of importance was that the problem guided the methods used in an unconventional way.

Churchman lists five basic considerations as regards how to view a system:

“1. The total system’s objectives and, more specifically, the performance measures of the whole system
2. The system’s environment; the fixed constraints
3. The resources of the system
4. The components of the system
5. The management of the system”

Churchman states that system analysis is a method to avoid sub-optimisation, but one always has to keep in mind that the system is in its turn embedded in a larger system. The system is influenced by its surroundings but can not influence them. Churchman states that the problem should define what tool to use. Churchman summarises his view on system analysis by stating, for example:

"1. The systems approach begins when first you see the world through the eyes of another.
2. The systems approach goes on to discovering that every world view is terribly restricted.
3. There are no experts in the systems approach."

4.1.1 Implications for this thesis

System analysis is used as a "thought model" when approaching the study object. How the concept of system analysis is used in this thesis differs somewhat in the various papers. The first perspective is the energy utility perspective in Papers 1-4 and part of Paper 5. The system consists of the municipal district heating system with the objective of fulfilling a given heat demand with available resources at the lowest possible cost. The management of the system is the management of the energy utility operating the district heating system. The resources of the system are the various conversion units available for heat and power production. Factors belonging to the surroundings but influencing the system include the fuel market and the electricity market by setting prices, and legislation and policy instruments, that also affect the system via price signals.

In Papers 5 and 6, it is more complicated since these studies have the objective of analysing what is most suitable for society as a whole. In Paper 5, an energy efficiency method is used, and in Paper 6, external costs are added to the private costs. Who is the management in these cases? In this kind of study, which aims to draw a picture of the benefits to society as a whole, Churchman (1968) also states that it is often difficult to point to who the management is. Even if it is delicate to identify the management of the systems, the aim is to offer guidance to decision makers on a national level and increase general knowledge.

4.2 Models

A model is a reproduction of reality (Gustafsson et al, 1982), where the essential properties of the system should be included. Arguments for building a model are that real-world experiments are costly and risky or if you want to study a planned system. Other arguments are that when building a model and making analyses with that model, much is learnt about the system which is being studied. It can also have educational value for others; you can discuss around a model. One risk with using models is that you must always be aware of the limitations in the model. You must also be aware of what purposes the model can be used for. When discussing results from the model, it is important to point out that reality can differ from the results obtained from using it. Churchman (1968) states that models are a way in which "human thought processes can be amplified."

Mathematical models of energy systems are powerful tools for finding suitable ways to use available resources. Complex connections in the system can be found and impacts by the surroundings can be analysed. Wene and Rydén (1988) discuss the issue of what role a mathematical model can have in municipal energy planning processes. They claim that the greatest advantage is not the optimised results but the learning process a model can mean for an organisation. Eriksson et al (2003) discuss how model-based system analysis can be improved to make it more common to use in waste management decision making. Two case studies are carried out in the same municipality using two different models[15], a follow-up study is made by interviewing representatives for the energy utility and the municipal organisation responsible for waste management. One of the essential results of using models and systems analysis is building competence in the organisations. As for decision making, the officials in the organisations interpreted the results and presented them in a form suitable for where the decisions were taken (the board of the energy utility and politicians) Other aspects of modelling were to be specific in scenario building, divide between internal (impacts that the organisations decide, e.g. investments in treatment capacity) and external (factors the organisation can not decide, e.g. electricity price and policy instruments), the importance of sensitivity analyses of compensatory systems, since these are often crucial for the results and the level of detail. Groscurth and Schweiker (1995) point out that models may support decision making by enhancing understanding of energy systems. When decision makers base their decisions on model results, it is vital that they thoroughly understand the assumptions made and agree with them. There are qualitative parameters, e.g. security and safety, that can not easily be incorporated into mathematical energy models.

A number of energy models have been built for various purposes. Jebaraj and Iniyan (2006) give a broad survey of such models. Henning (1999)

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[15] ORWARE, described in Section 2.4 and MIMES/WASTE in Section 3.1

makes a survey of the ones that are most related to the one used in this thesis, MODEST, such as MARKAL, MESSAGE, and EFOM and compares the differences and similarities between them. After consulting this survey, MODEST is deemed appropriate to use for the purpose of this study.

4.2.1 MODEST model framework

An optimisation model known as MODEST (Model for Optimisation of Dynamic Energy Systems with Time-dependent components and boundary conditions) is used to optimise the district heating system in this thesis. The model is thoroughly described in (Henning, 1998; 1999). It is a linear programming model that minimises the cost of supplying the heat demanded during the analysed period. Several alternatives with regard to energy supply and conservation may be included in an analysis. The model has a flexible time division, which can reflect demand peaks and diurnal, weekly and seasonal variations in energy demand and other parameters. The main purpose of the MODEST modelling program is to find suitable investments in the studied energy systems but the program can also be used to optimise operations at existing plants. A Windows interface has been developed and is used in this thesis (Gebremedhin, 2003).

MODEST is made up of nodes connected by flows of energy. The nodes are divided into starting, conversion, storage, demand and waste nodes. In the nodes, various properties and constraints are set. Starting nodes have only outflow, conversion both outflow and inflow, demand and waste nodes only inflow. Examples of parameters that describe the energy system include the costs of fuel, electricity and taxes, capital costs of investments, efficiencies and capacities of plants, and limitations in fuel supply. Emissions of carbon dioxide, NO_x and SO_2 are also parameters that can be set. A cap on emissions can be set as a constraint. The cap has not been used in this thesis, but emissions of carbon dioxide have been calculated in Papers 1-3. An objective function is formulated by MODEST which is solved by the optimisation tool CPLEX.

The model can choose whether energy conservation measures should be implemented instead of supplying energy. This has not been analysed in this thesis but a fixed heat demand varying in time has been used.

All costs are discounted to their present day value. In this thesis, the studied time period is ten years, and this means that if investments are included and their economic lifetime is longer, a residual value exists which is deducted from the system cost. Other time periods can also be chosen. The model can also include several time periods, where the model can make investments between the time periods.

The MODEST model does not calculate a utility's maximum profit. The calculations show minimised costs for satisfying a demand. There can therefore be other ways to use the available resources when making investment decisions; these are for the utility to decide. Desired profit, for example for an investment, is an input to the model, in terms of the discount rate used. Hence, the chosen value for the discount rate has a large impact. In this thesis, the value is 6%.

Figure 6 shows an example of the principle of a model built in MODEST.

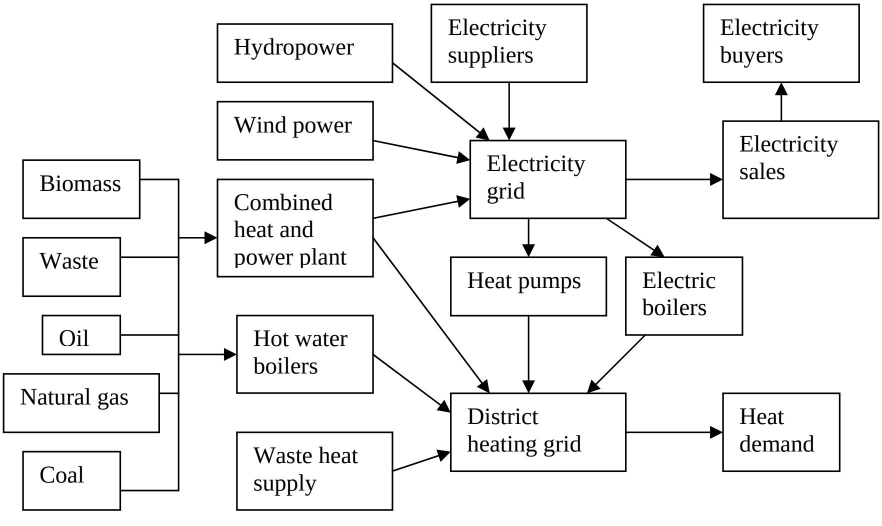

Figure 6. An example of the principle of a model built in MODEST

One limitation in MODEST is the absence of mixed integer linear programming. No fixed costs, e.g. start-up costs, can be attached to the plants. Neither can investment costs be fixed; they are calculated in SEK/kW, which means that after the modelling, the results must be checked. If the plant chosen by the model is considerably smaller than the one planned, investment costs must be changed and additional modelling performed. No minimum level can be set at which the plants can operate. This must be checked manually and if necessary changes must be made and additional model runs carried out.

Simplifications are always made in models and in the Papers the simplifications made to the models for the various municipalities are described.

4.2.2 Input data and uncertainties

The input data to the modelling of the energy system consists, for example, of plant characteristics, fuel costs, operation and maintenance, electricity prices, energy taxation, and investment costs. The characteristics of the plants in the energy system were obtained from the utilities operating the district heating systems. The central characteristics are built into the MODEST framework to replicate the energy system.

Costs for fuels are collected from the utilities and sometimes from other sources, as described in the Papers. In the Linköping and Skövde studies, electricity prices are based on data from Nordpool, the Nordic electricity market. In the Göteborg study, a model was used to calculate the electricity price based on the assumption that natural gas based power was the long-term marginal power producer, at least for high loads. This is described in the Papers.

To compare the energy efficiency of material and energy recovery, data on energy usage in production processes from virgin and recovered material was obtained from literature and through contact with industries, all described in Paper 5.

The costs of external effects were obtained from the EU’s ExternE project. Emission levels from plants in the district heating system was obtained from the utility’s environmental report, the environmental permission for the new waste incineration plants, and from literature, as described in Paper 6.

There are uncertainties in this data. For example, assumptions of electricity and fuel prices and policy instruments. The time frame in this study is ten years and during that time changes can occur that are difficult to predict. Groscurth and Schweiker (1995) state that energy prices are different from, for example, conversion data such as efficiencies, since the prices reflect current preferences which are uncertain and can change, especially during the long life-times that are usually used in energy system modelling.

Sundberg (2001) analyses which parameters are most influential when investing in combined heat and power production and concludes that these are fuel price, taxation, operation and maintenance costs, electricity price, investment cost, and overall efficiency. The ratio between electricity price and fuel price is analysed, and when investment is profitable. Combined heat and power plants is a long-term investment, and important factors can change drastically during the life-time of the investment. A thorough sensitivity analysis of various parameters is therefore essential when investment decisions are being made.

The aim of this thesis is not to make this kind of thorough analysis of whether various combined heat and power plants are profitable, but it is important to keep in mind the uncertainty in such assumption as fuel and electricity prices. Fuel prices have proved difficult to predict as can be seen from the increases as regards fossil fuels in recent years. Kjärstad and Johnsson (2006) discuss the development of the European gas market and what influences the price of natural gas. The phasing out of nuclear power, the carbon dioxide emission allowance trading system, and too slow an increase in the supply of renewables are pushing Europe towards a substantial increase in natural gas usage, especially in the power sector, making Europe more dependent on energy imports and more vulnerable as regards security of supply. Another factor influencing the development of natural gas usage is the future for storing carbon dioxide in subsurface reservoirs. The price of natural gas has been linked to the oil price and even if the gas-gas competition increases in the future, the oil linkage will still be strong. The oil price is dependent on the demand/supply balance, geopolitical tensions, the weather affecting production, and also a fear that “peak oil” is approaching (Kjärstad and Johnsson, 2006). What can make natural gas prices competitive is that there are many suppliers and in the short term, Europe may be over-supplied. An upward pressure is the growing proportion of liquid natural gas (LNG), which is more expensive to produce.

Taxation and other policy instruments can change rapidly due to political decisions, which can prove a challenge for energy utilities when making investment decisions. The cost level for some policy instruments is set by the market, e.g. green electricity certificates and carbon dioxide emission allowances, and the future picture is thus uncertain.

4.2.3 Validation

MODEST has been applied to electricity and district heating supply for approximately 50 local utilities, see for example (Sjödin, 2002b; Sundberg and Henning, 2002). The model of the district heating system in Linköping built in MODEST has been used in several studies of various issues, thoroughly described in Henning et al (2006). The Linköping model is used in Papers 1, 5, and 6.

A type of validation has been made by Byman (1999) who has compared results from MODEST with a traditional consultant investigation showing similar results. Another validation is made by Sjödin and Henning (2004) who calculate the marginal cost of district heating of a municipal utility by using three separate methods: MODEST, a least-cost dispatching model; MARTES; and manual calculation. All show similar results.

Since this thesis is not about model development, no validation of the model is provided here; the reader is instead referred to the papers and literature mentioned above. The results of the case studies have been shown to representatives of the utilities and discussed to varying extents, which constitutes a validation against reality with the people most familiar with the actual operation of the district heating system's resources.

4.3 Case study research

4.3.1 Cases studied

This thesis is based on three case studies; the district heating systems in three Swedish municipalities: Skövde, Linköping, and Göteborg. They vary in size but have in common that they all use waste incineration to supply substantial amounts of heat for the district heating system. Linköping is investigated in Papers 1, 5, and 6, Skövde in Paper 2, and Göteborg in Paper 3. In Papers 4 and 7, experience from all three cases is used. The municipalities' district heating systems are described in detail in the papers; a brief description follows below.

Skövde is the smallest district heating system with a heat demand of 280 GWh/year, including the demand of the largest industrial consumer, Volvo. At the time the study was made, Volvo was not connected to the grid, but one aspect of the analysis was whether such a connection would be an advantage. Apart from the waste incineration plant that was planned, there are a wood-chip fired plant with a capacity of 50 MW, oil fuelled boilers, some waste heat from a cement factory, and electric boilers. Only the planned waste incineration plant is equipped for electricity production.

Linköping is studied in Papers 1, 5, and 6 and some changes have taken place over the period between the studies. In Paper 1, heat demand is 1 340 GWh/year, and plants include the waste incineration plant where electricity can be produced when integrated with an oil-fired gas turbine, the central combined heat and power plant utilising biomass, plastic, coal, rubber, oil and animal fat, and the two oil-fuelled diesel engines for electricity and heat/steam production. Peak loads are covered by means of oil boilers and electric boilers. In Papers 5 and 6, the district heating system has been connected to nearby population centres, Mjölby and Ljungsbro, which has increased heat demand to 1 640 GWh/year. Two biomass fuelled boilers are added to the system, as well as extended capacity for waste incineration producing electricity and heat.

Göteborg is the largest system, with a heat demand of 4 600 GWh/year. A large part of the demand is covered by waste heat from oil refineries and waste incineration, which the energy utility buys from the industries and the company operating the waste incineration plant. The energy utility operates a natural gas fired combined heat and power plant, heat pumps, hot water boilers fuelled with oil, natural gas, biomass (wood chip and pellets), and bio-oil. An additional natural gas fired combined heat and power plant are taken into operation in autumn 2006.

4.3.2 Theory on case studies

Since cases are used in this thesis, case study research will be defined and the thoughts behind it used in this thesis will be accounted for. The theory is mainly based on Yin (1994), but to some extent also on Merriam (1988). Yin defines case studies as “when a ’how‘ or ’why‘ question is being asked about a contemporary set of events over which the investigator has little or no control”. Case studies can use various methods, and they can be of both quantitative and qualitative characteristics. Case studies seek more to bring forward theories instead of trying hypotheses, which is more common in experimental research. A case study ”investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context is not clearly specified”. This can be compared with system analysis, which emphasises the need to set a system boundary. But one of the main aims of system analysis is to analyse the impact of the surrounding system on the system itself, and both theories stress the importance of context or embedded systems. As can be seen in Section 1.2, the aim of this thesis is mainly to answer “how” questions.

Another idea from Yin that is worth considering is how case studies can be generalised. A common complaint is that case studies can not be generalised and the results only applies to the specific case. Yin uses the term “external validity” when discussing how to generalise case studies. The key is to not try to make a statistical generalisation since that will fail, but to rely on analytical generalisation, in analogy to how the experimental results are generalised to theory. Yin also states that the theory that leads to a case study in the first place will help identify other cases where the results are generalisable. What thoughts can be drawn out of this that helps this thesis? The results from the case studies can not be generalised as such, since they depend on the specific characteristics of that particular district heating system. What can be generalised to some extent is what can be learnt from the case studies, what might be expected from the next case study and what research questions that could be interesting to study in the next case.

4.3.3 Descriptive or normative case study

Another issue to keep in mind is what kind of study is being attempted. Merriam (1988) defines case studies to be descriptive, analytical or normative. A descriptive study aims at making an account and gathering information without any aspirations to build theories or hypotheses. Analytical case studies include descriptions but are also used to highlight, support or questions theories. A normative case study includes descriptions and explanations but also valuations. Merriam states that most case studies are a combination of descriptive and analytical or descriptive and normative.

Yin (1994) uses the definitions descriptive case studies, exploratory case studies, and explanatory case studies. The goal of an exploratory study is to develop hypotheses and propositions for further inquiry. An explanatory study seeks to build explanations of various events.

Korhonen (2006) writes about normative and prescriptive research, which is defined as how the world ought to be and what we should do, and descriptive and analytical research which asks questions as to how the world is, how things are. The concept of sustainable development is ethically loaded. Industrial ecology strives to be a means of moving towards a more sustainable society, and as such includes several normative values. These are recycling, diversity and cooperation, for example. Korhonen wants to break down normative values into descriptive indicators and to look into every specific case to find out what is the most suitable solution for that case. Noteworthy is that Korhonen does not differentiate between descriptive and analytical research.

This thesis has both a descriptive and a normative approach. The descriptive approach include accounts for the energy system, waste management, and various policy instruments. A model is a normative tool which describes what should be done under the assumptions made. The model shows an optimal way to use existing resources and possible investments according to the input data. The thesis includes an analytical phase that aims to explain various relationships and connections.

5. Results from case studies

This section will summarise the results from the case studies. The summary will follow the perspective taken in the studies: energy utility perspective, energy efficiency perspective, and external cost perspective. There is also a section on the double function of waste incineration and Sweden’s linkages to the EU through legislation and trade.

5.1 Energy utility perspective

Papers 1-4 have the energy utility perspective, as does part of Paper 5. The municipalities studied are: Skövde (Paper 2), Linköping (Papers 1 and 5) and Göteborg (Paper 3). Paper 4 deals with the knowledge gained of the impacts of policy instruments in several municipalities, including the three mentioned. Some comments from Paper 7 are also included.

The system studied is the district heating system of a municipal utility and the managers of the system are the managers of the energy utility. The resources of the system are the various conversion plants that supply heat to the district heating network and also electricity when it is profitable. The surrounding system affects the studied system in terms of, for example, electricity and fuel prices. Legislation and policy instruments belong to the surrounding system even if this is not totally correct; an energy utility can have an impact on decisions on policy instruments through lobbying. An individual energy utility’s possibility to influence decision on policy instruments, however, is considered to be small.

The studied impacts are

- system costs, which constitute the cost of supplying heat for, in these cases, a ten-year period where both operating costs and investment costs for new plants are included
- environmental impacts in terms of carbon dioxide
- fuels and conversion units used to provide heat
- electricity produced and by which fuels.

Scenarios illustrate both measures the utility can decide upon, e.g. the amount of waste used as a fuel, investment in waste incineration, inclusion of a big industrial consumer in the district heating grid, introduction of a natural gas fired combined heat and power plant; and circumstances the utility can not decide upon, such as electricity prices and various policy instruments. Some sensitivity analyses are carried out on issues the energy utility can not decide upon such as taxation and electricity prices. The scenarios are chosen to reflect the research questions stated in Section 1.2.

5.1.1 Effects on system costs

Due to the revenue collected for receiving waste at the waste incineration facility, waste has a negative operational cost making it profitable to use as a fuel in the district heating systems. This is shown for the case where waste is used as a fuel in an existing plant (Papers 1 and 3), when a new waste incineration plant is constructed (Paper 2), and when more capacity is added (Paper 5). The waste incineration plants are used as base load in the systems. Waste incineration plants are costly investments, due to high costs for among other things flue gas cleaning, compared to plants using other fuels, but a negative operational cost compensates for this. Waste management legislation banning landfill of combustible and organic waste and the tax on landfill in combination with favourable taxation of waste used as a fuel in the energy system contribute to profitability. The tax on incinerated municipal waste introduced July 1st 2006, as described in Section 2.2, will have an effect on the profitability of using waste as a fuel. This is further elaborated on in Section 5.1.5.

The electricity price assumed is a factor that influences system costs. Since electricity sales generate an income to the system, a high electricity price means additional electricity generation, at a higher price, generating more income. This means decreasing system costs, as shown in Paper 1. This paper describes scenarios with both low and high electricity prices. With a high electricity price, the gas turbine in the waste incineration plant operates, but the electric boilers in the system do not.

Another issue effecting the system cost is shown in Paper 2; connection to the district heating grid of a large industrial consumer, Volvo. This connection is profitable and lowers the system cost of the district heating system, due to substantial savings in the usage of oil. The reduction in system cost is also larger when Volvo is connected, since more waste is used as a fuel. In general, peak loads are mainly supplied by oil boilers and in order to keep system costs down, the operational time for these plants must be kept down.

Waste heat from industries is shown in Paper 3 to have a beneficial impact on system costs in Göteborg’s district heating system. In one of the scenarios studied, the amount of waste heat was reduced, and that meant higher system costs since more expensive conversion units had to operate more. The decrease in waste heat enabled the combined heat and power plants to operate more, but in this case, the additional income from increased electricity sales could not compensate for the loss of an economically beneficial energy carrier. This was the same for a scenario with assumed gasification of waste; less heat from waste involves more expensive conversion units to operate which the increased electricity sales could not cover. A scenario where heat pumps were removed also meant higher system costs due to longer operational times for more expensive units.

5.1.2 Waste replacing other fuels

Waste incineration plants are the base load suppliers of heat in the district heating networks where there is such a plant, due to the revenue received for accepting the waste. When waste incineration is introduced in a district heating system, other plants are affected. What fuel the waste replaces differs between district heating systems due to different configurations. In Linköping, in Paper 1, when waste amounts decrease, the main replacement is biomass. This is due to the assumption that biomass is the only fuel that can replace waste in the existing waste incineration plant because it has a similar moisture content and calorific value. Another alternative is the boiler in the central power plant which utilises a biomass/plastic mix. In Paper 5, that analyses the extended waste incineration capacity in Linköping, the fuel affected most is oil, but all plants are affected except for two biomass fuelled hot water boilers. Hot water plants fuelled with oil function as peak load supply and with the new plant it was possible to reduce this oil supply substantially.

In Skövde, presented in Paper 2, where investment in a new waste incineration plant is introduced, the main replacement is biomass, since that was the previous base supplier of heat in the system, but also oil and electricity used in electric boilers. In Göteborg, presented in Paper 3, one scenario with additional heat from waste incineration and one with less heat from waste incineration are analysed, the latter due to the introduction of a waste gasification plant. Such a plant would mean more electricity from waste and hence less heat to the district heating grid since only the same amount of waste is available. In both these scenarios, all other production units are affected, but the greatest impact is on the heat pumps in the system.

The results show that in order to state the replacement fuel for waste, studies need to be made in the specific district heating system, since every system has its unique combination of various conversion plants and heat supplies.

5.1.3 Waste and combined heat and power

Combined heat and power production is seen as an effective way to use resources and a large untapped potential for increased combined heat and power production exists in Swedish district heating systems. Increased waste incineration can impact the possibilities for combined heat and power production in district heating networks, since it can "occupy space" for more efficient combined heat and power plants. This is shown in Linköping, where increased waste incineration affects the operating time for the other combined heat and power plants in the district heating system. In Skövde, the existing production plants have no electricity production, so this does not happen in that particular district heating system. In Göteborg, there seems to be space in the district heating system for all waste heats since the new plant mainly replaces hot water boilers. However, in the scenario with much less heat from waste incineration due to an assumed gasification plant, the electricity production in the natural gas fired combined heat and power plant can increase.

A conflict can arise between the need to treat waste in an environmentally acceptable manner, and to utilise the energy content in the waste as efficiently as possible, and the goal of increasing combined heat and power production in district heating systems. This is further elaborated on in Paper 7.

5.1.4 Carbon dioxide emissions

In Papers 1-3, carbon dioxide emissions are calculated, both emissions resulting from the local plants, and global emissions, meaning that the local carbon dioxide emissions are credited with the saved carbon dioxide emissions since locally produced electricity can replace power produced with the marginal production method in the European power system. In Papers 1 and 2, it is assumed that the marginal power producer is coal condensing plants and in Paper 3 natural gas fired power plants. The theory behind this is presented in Section 3.3.1. Production units using electricity, meaning electric hot water boilers and heat pumps are burdened with these carbon dioxide emissions. Fossil fuels are burdened with their resulting emissions of carbon dioxide, whereas biomass fuel is assumed to have zero net emissions, due to carbon dioxide capture in growing biomass. This can be debated since biomass can be regarded as a limited resource and savings in biomass may therefore mean savings in fossil fuel elsewhere in the energy sector. In Paper 7, some studies are surveyed that attempt to estimate the potential biomass supply, giving an indication that biomass utilisation could increase substantially, but a vast expansion could lead to other environmental and social problems. Waste has fossil content, e.g. plastic packaging, and that is included. Waste heat from industries is assumed to have zero carbon dioxide emissions, even though this could be discussed since it presupposes that everything has been done to optimise the energy usage within the industry.

The result is that local carbon dioxide emissions that arise from introducing, increasing or decreasing heat from waste incineration differ according to what fuel the waste replaces, which varies in the different cases due to the disparate configurations of the systems. In Linköping, the local emissions decrease slightly when waste incineration decreases, since waste is largely, but not fully, replaced by biomass. In Skövde, carbon dioxide emissions increase when waste incineration is introduced since waste largely replaces biomass but also oil and electric boilers. Volvo’s connection to the district heating grids saves large amounts of emissions since oil can be replaced. Waste heat is important in Göteborg to keep carbon dioxide emissions down, since otherwise heat production in fossil fuelled hot water boilers needs to increase. More waste incineration decreases local carbon dioxide emissions since it replaces heat pumps and fossil fuel hot water boilers.

The main measure in all cases to decrease global carbon dioxide emissions is to increase electricity production in the district heating systems since it can replace marginal power in the European power system. Which marginal power producer is assumed is an important factor; results will be different depending on whether the marginal producer is natural gas based power or coal condensing power. Combined heat and power production is much more beneficial when it is coal condensing power instead of natural gas which is replaced. The benefit of combined heat and power production will not be of the same magnitude as at present in the long run as electricity production will be more carbon lean. In line with this goes that heat supply from conversion units using electricity, is detrimental; in Göteborg, the removal of heat pumps as heat supply reduces carbon dioxide emissions even though fossil fuelled hot water boilers operate more, and in Linköping, carbon dioxide emissions decrease when the electricity price is too high to operate the electric boilers.

5.1.5 Impact of policy instruments

The impacts of policy instruments on district heating, electricity production and waste management are profound and the impacts of various policy instruments have therefore been assessed. In Paper 2, the impacts of a tax on incinerated waste at two levels are analysed as well as if electricity produced by waste were to receive green electricity certificates. In Paper 3, the costs for carbon dioxide emission allowance trading are included in the modelling of the system, and a sensitivity analysis is carried out of abolishment of carbon dioxide taxes in the trading sector. In the Papers, energy and carbon dioxide taxes are included, as is the landfill tax at least partly, since it can be assumed to be incorporated in the revenue the waste incineration plants receive for treating the waste. Paper 4 is a survey of studies made in several municipalities of the impact of various policy instruments.

In Paper 7, the conflict between waste management goals and energy system goals when designing policy instruments is shown. When designing the tax on incinerated waste, the energy system perspective was the predominant factor, the main objective being to harmonise taxes on incinerated waste with taxes on other fuels and greater incentives for cogeneration. The incentive for increasing material recovery and biological treatment was mainly set aside, except in the case of plastic waste. In the design of the electricity certificate system, the waste management goals, e.g. more biological treatment, prohibit waste incineration plants from receiving certificates even if this would increase the incentive for cogeneration, consistent with the goals for the energy system.

In Paper 2, the impact on the investment in a waste incineration plant in the municipality of Skövde of two policy instruments are assessed; green electricity certificates and a tax on incinerated waste. When a waste incineration tax level of 11 €/ton is introduced, the investment in waste incineration is still profitable, but not at the level of 42.5 €/ton. These levels were chosen since they were proposed in an earlier governmental investigation. They are in the proximity of the levels introduced for a combined heat and power plant and hot water boilers respectively. Naturally, this is on the assumption that the utility can not raise their gate fee. However, at the higher tax level, there is an incentive to start looking at other solutions. The study shows that with the electricity prices assumed, it is necessary to receive green electricity certificates for municipal waste in order for the investment in electricity production to be economically feasible.

In Paper 3, it seems that the new natural gas fired combined heat and power plant is a beneficial investment even though there are costs for carbon dioxide emission allowance trading. This is partly due to assuming higher electricity prices, that reflect a deregulated European electricity market and the costs for emissions trading, which raise electricity prices still further. Of importance for the municipal utility's decision to invest in a new natural gas fired combined heat and power plant was the change in taxation on fossil combined heat and power plants, with a reduction from full carbon dioxide tax applied to fuels for heat production in cogeneration plants to the industrial tax level of 21%. When carbon dioxide taxes were removed in the sensitivity analysis, it was clear that heat supply from hot water plants fuelled with natural gas and oil increased substantially. This presupposes that the price ranges of fossil fuels and their possible substitutes continue to be the same.

5.1.6 A district heating network as a heat sink resource

District heating systems have an important advantage: they utilise heat that would otherwise be of limited use, hence raising the efficiency of resource usage. This is done by means of various alternatives, e.g. combined heat and power production, utilisation of waste heat from industries, and waste incineration. Paper 3 is an example of a system which uses all the above-mentioned energy sources, i.e. heat from industries, waste incineration, and combined heat and power, in its district heating system. The base load of heat supply is waste heat from oil refineries in the vicinity of the city, and heat from a waste-fired combined heat and power plant that treats waste from Göteborg municipality and neighbouring municipalities. The utility is currently investing in a natural gas fired combined heat and power plant, in addition to an already existing one, where the profitability of the plant is dependent on electricity prices and policy instruments, but also on the utilisation of the heat in the district heating system and annual operating time. In Paper 3, the "competition" between the energy carriers in the municipal district heating system is analysed. The conclusion is that there is space in the system for all these different waste heat sources. However, this can differ between systems.

5.1.7 Additional comments on the studies with an energy utility perspective

The studies presented in this section were conducted over a period of several years. The energy and waste management systems exist in a changing environment, and assumptions made in the studies might therefore be different if they were carried out today. This highlights the difficulties involved in making predictions, for example as regards prices in the fuel market. Electricity prices have risen substantially since the studies in Papers 1 and 2 were made. In Paper 1, for example, scenarios with an electricity price based on data from Nordpool for the year 2000 was used, as well as a doubling of the prices after ten years. Today, the latter electricity prices seem more realistic. In Paper 2, there is a scenario where the effects of municipal waste receiving green certificates were analysed and the conclusion was that certificates were needed for electricity production at the waste incineration plant. However, today's electricity price would make it profitable to produce electricity even without certificates. This possible development was mentioned in the Paper. It can also be mentioned that the assumed cost for green electricity certificates was also too low, 120 SEK/MWh compared to the average price between August 2nd 2005 and August 2nd 2006 of 199.47[16] SEK/MWh. Both green electricity certificates and emissions trading are policy instruments where future prices are unknown and can be hard to predict. The price of emission allowances has been volatile but the market is still not mature. The waste incineration plant that was eventually built in Skövde is a combined heat and power plant. The municipality has also connected Volvo to the district heating grid. At the moment, the utility is considering investing in biomass fuelled combined heat and power to increase electricity production in the district heating grid.

In Paper 3, the largest difference which can impact the results is the increase in natural gas prices that has taken place in recent years. This has naturally had an impact on the investment in the natural gas combined heat and power plant. However, since the electricity price was calculated on the assumption that natural gas based power is the marginal producer, at least at high load, and hence sets the electricity price, the higher natural gas prices would also increase the electricity price. That means that the investment might still be profitable due to higher electricity price. The sensitivity analysis show that the hot water boilers fuelled with natural gas would operate substantially more if carbon dioxide tax were removed at the expense of, for example, the pellet boilers. Recent developments with a substantial increase in fossil fuel price should mean changed results, however depending on development of biomass fuels. In autumn 2006, the new natural gas fired combined heat and power plant is in trial

[16] The price can be found at the homepage of Swedish Energy Agency: www.stem.se (accessed August 2006).

operation and will according to schedule be handed over to Göteborg Energi in December 2006.

The introduction of the tax on incinerated waste will affect the profitability of the plants in the three municipalities studied. However, since all the plants are cogeneration plants, the tax level is not very high. Their profitability is also dependent on the possibility to raise waste fees for consumers to let them shoulder the increasing costs due to this tax.

5.2 Energy efficiency perspective

In order to extend the study from the perspective of the energy utility to a wider range, material recovery and energy recovery through waste incineration are compared from the perspective of energy efficiency in Paper 5. The starting point for this is that even though other environmental impacts are not included, primary energy use is often an indicator of other environmental impacts as well. The aim is to show the implications for two existing district heating under present conditions.

Material recovery saves virgin material and energy, since production processes that use recovered material in general are less energy intensive than processes that use virgin material, whereas energy recovery saves other fuels that differ from energy system to energy system.

The study analyses two Swedish municipalities: Skövde, which is planning to build a waste incineration plant, and Linköping, which is planning to extend their existing waste incineration facility. Optimisation of the municipalities by using the MODEST model is performed in order to show the amount of waste incinerated, what fuels are replaced by the waste, and the resulting electricity production in the district heating systems. Energy savings resulting from material recycling various fractions are calculated. For biodegradable waste, the assumption is made that it is treated by anaerobic digestion. Composting is not considered since no biogas is produced which can be utilised for heat and/or electricity production or as vehicle fuel.

The fractions of glass and metal do not make any heat contribution when incinerated, but save varying amounts of energy when material recycled, metals substantially more than glass. One main incentive to sort out glass is that it occupies space in the incineration facilities and only ends up as slag in the ashes. Concerning the combustible fractions, the study shows that even if there is a district heating system able to utilise the heat, paper and plastics should be material recycled, whereas cardboard and biodegradable waste is more suited for energy recovery through waste incineration. An essential assumption is that biomass fuel is a limited resource. This implies that when biomass is saved, it is used for example in another district heating system and eventually it saves oil. Furthermore, in the calculations, electricity was multiplied by 2.5, based on the assumption that electricity is produced in a condensing plant with an electrical efficiency of 0.4. This makes it extra important with combined heat and power production in district heating systems and also to consider how electricity intensive the various material production processes are. The difference in results for paper and cardboard are largely a result of the assumption that paper is produced by and replaces mechanical pulp, a electricity intensive production process, and cardboard is produced by chemical pulp, which is not so electricity intensive. Plastic waste is beneficial to recover, but there have been problems with the recovery system; a large amount of reject. These results imply that efforts should be made to develop this technical system. In order to do so, greater efforts are needed earlier in the process, already in the design and construction phase.

Concerning system analysis and this perspective, it is complicated compared to the energy utility perspective. The system modelled is still the district heating systems, influenced by fuel prices and policy instruments such as energy taxation, but the waste management system is also included with the energy use of material recovery and biological treatment of waste. The aim is to show a resource effective system that is beneficial for society as a whole. Management of the system is hard to point out, but the aim is to support policy makers on a national level.

5.3 External cost perspective

This study is presented in Paper 6 and is another attempt to widen the perspective from energy utility to society. This is done by putting monetary values on external effects, as outlined in Section 2.1. Linköping’s district heating system is used as an example. The main aim is to investigate whether using external costs is a suitable way to assess the environmental performance of a district heating system with special emphasis on waste incineration.

The scenarios compared are a business economic case where taxes and other policy instruments are included and socio-economic cases where external costs are included instead of taxes. Taxes is a means of internalising external costs, so these have to be excluded when adding external costs otherwise double accounting for environmental impacts can occur. Data used is from EU's ExternE project. In this way, how data for external costs correlates to taxation can be studied. Environmental effects included in the data are emissions to air of CO_2, SO_2, NO_x and particles. Electricity production in the district heating system is credited with avoided marginal power production in the European electricity system. Electricity used in electric boilers is burdened with the same external costs. The socio-economic cases differ due to assumptions as to which source is the marginal power producer, coal condensing power or natural gas based power. Then assumptions, as to what discount rate to use when assessing costs for emissions of carbon dioxide are varied, 1% or 3%, giving different values for carbon dioxide, according to the ExternE project. Waste incineration is credited with the avoided burden of landfill, but only emissions of methane and carbon dioxide are included.

The result is that waste as a fuel is used to full extent in all scenarios. The main difference is that in the socio-economic cases with natural gas based power as marginal producer, more waste is used for heat only production. Lacking an incentive to steer towards cogeneration applied in the business economic case, in the cases with natural gas as marginal power producer, the additional crediting of electricity does not compensate for the loss of a policy instrument that strongly steers towards cogeneration at waste incineration plants. When coal condensing power is assumed to be the marginal power producer, the compensation is enough and more electricity is produced than in the business economy case. In those scenarios, even the diesel fuelled power plant produces some electricity. In the business economic case, it can be seen that the policy instruments in place at present, green electricity certificates, deductions in carbon dioxide tax for fossil fuel based cogeneration, and the introduction of a tax on incinerated municipal waste with significantly different levels for hot water boilers and combined heat and power plants, are strong incentives for cogeneration, also in comparison with adding external costs and crediting locally produced electricity for avoided costs for marginal power production.

When it comes to whether using data on external costs from the ExternE project constitute a beneficial method to analyse the environmental performance of a district heating system with waste incineration as a base supplier, there are advantages and disadvantages. One advantage of using external costs of environmental impacts is that data can be incorporated directly into the optimising modelling of the system, or in other economic calculations. The data obtained from ExternE is site-specific, which is an advantage compared to most life cycle assessment studies, for example.

The human health impacts are explored quite thoroughly. Damage costs are used, which can be deemed the most realistic way to put value on the cost, in comparison to other methods such as hedonic pricing, experimental judgment, avoidance costs, and using taxation as a method for valuing.

The main disadvantages could be listed as follows:
-Uncertainty in data: Both in methodological issues, such as willingness to pay, data collection for dose-response functions, and emissions from conversion units.
- Limited number of environmental effects included. Environmental impact of ashes, for example, is not included in the ExternE data. Today, when advanced flue gas cleaning has moved a lot of the emissions from the air to mainly end up in the fly ashes, the lack of inclusion of ashes is a drawback.
- How to treat inter-generational environmental impacts is difficult. Carbon dioxide, for example, has a global impact which is extended in time. The ExternE project also highlights the fact that the uncertainties are considerably larger for emissions of carbon dioxide than the regional emissions of NO_x and SO_2. How to discount the cost for intergenerational impacts are debated and in the ExternE project, different discount rates are presented. Two discount rates for the cost of carbon dioxide are used in Paper 6, 1% and 3%, and this means that the environmental cost for emitting carbon dioxide varies considerably as a result of that assumption.
- How to treat avoidance burdens for other waste treatment methods is not clear. In this study, data from another study using data for emissions from landfill of carbon dioxide and methane is deducted from the cost of waste incineration. This is not really satisfactory, but in the absence of other data, this was used.

As in the energy efficiency perspective, it is a complicated matter to point out, for example, the management of the system, compared to the energy utility perspective. The system modelled is still the district heating system, influenced by fuel prices and policy instruments such as energy taxation, but external costs are included in some scenarios to reflect costs to society. The aim is to show a resource effective system that is beneficial for society as a whole. Management of the system is hard to point out, but the aim is to support policy makers on a national level.

5.4 The double function of waste incineration and links within the EU

One aim of this thesis is to highlight the double function of waste incineration as a supplier of heat and/or electricity and a waste treatment method. In Paper 7, this is stressed by considering some models used to support decision-making and when designing policy instruments. The difficulty when designing policy instruments for waste incineration is elaborated on in Section 5.1.5.

Various models are often used as decision support tools in decision making processes, e.g. when municipalities make investment decisions. When designing and using these models, the dilemma of the two functions needs to be faced and the ways in which some models handle this is described in Paper 7. The importance of being aware of the double function of waste incineration and the impacts of different assumptions, for example as regards a compensatory system in life cycle assessments, are discussed. Various models deal with the double function in different ways, and have their own strengths and weaknesses. A model's construction and the results from it should be seen as way of gaining knowledge of the system and as a support in decision-making. When decisions are to be made, there are other aspects that can be of importance that have not been included in the model.

Policy instruments in Sweden are highly dependent on legislation in the European Union. The policy instruments discussed in this paper are no exception. Therefore, the second issue in focus in this paper is the connection via common legislation between countries in the EU. The consequences of this are discussed, with a special emphasis on its impact on waste incineration in Sweden. Furthermore, the countries in the EU are connected via trade, and of special importance for waste incineration in Sweden is naturally the trade in waste, but also in electricity. The market share of district heating as well as the total heat supply from district heating is included and compared to the waste management systems in the European Union, to search for similarities and differences.

Sweden has extensive district heating networks and therefore better possibilities to efficiently recover the energy content in the waste than countries with a less developed infrastructure of this type. There is a correlation between extensive district heating networks and substantial incineration as a waste treatment method in Sweden, and the connection is both historical and organisational. This correlation can not be unambiguously shown to exist in any other EU country. In this context, Sweden differs from other Western European countries, since relatively little electricity is produced in the district heating networks. In other countries in Western Europe with extensive district heating, cogeneration has been more important and a driving force for district heating. Many countries in Eastern Europe have extensive district heating but untapped potential for increased supply from various sources of waste heat: cogeneration, waste incineration, and waste heat from industries. There are possibilities to make these systems much more efficient from both an economic and an environmental perspective.

Waste incineration can decrease the potential for producing combined heat and power in the district heating networks and this can be seen as a conflict between the need to treat waste in an acceptable way and the goal of more combined heat and power production in the energy system as described in Section 5.1.3. There is a conflict in the European Union between the internal market and waste management policy, e.g. that waste should be treated close to its origin. A shortcoming in the directives is that they do not clearly define what an energy efficient waste incineration plant is and hence not when a waste incineration plant should be defined as recovery versus destruction.

6. Discussion, conclusions and further work

6.1 Discussion

Many Swedish municipalities have chosen to make substantial investments in waste incineration, and this is an ongoing process. Waste incineration as treatment method will be a major part of the Swedish waste management system for years to come. It is an important supplier of cheap heat in the district heating grids. One risk with the massive infrastructural development of waste incineration in Swedish municipalities is lock-in and dependency in a system which might hamper other efforts, for example waste reduction. The significant investment costs for waste incineration plants in comparison to plants using other fuels mean that profitability of a plant is dependent on an abundant supply of waste which yields high revenue when received. Those responsible for collecting and treating municipal waste, the municipalities, are often owners of energy utilities that invest in waste incineration, which can stifle interest in other treatment methods and waste reduction. The risk of lock-in and "stiffness" in industrial systems are discussed within industrial ecology, e.g. O'Rourke et al (1996). Increased interdependency among industries might impede process innovation. One example can be less effort in waste minimisation when the waste from an industry is used as raw material to another.

The main environmental problem existing today concerning waste incineration is the residues from incineration, the ashes. The ashes constitute a substantial proportion of the total weight of the original waste, some 20-25%, which is more than for other fuels. The flue gas cleaning residues are hazardous. Usage areas are available for the large bulk of bottom ash and efforts are ongoing in this field as well as for ashes from other types of fuel combustion. This development must continue in order to increase the sustainability of using waste as a fuel. For the fly ash, it is difficult to find a suitable treatment method, and is at the moment used for filling up old mines and this should be kept in mind when considering the sustainability of waste incineration.

It would make sense to start dividing waste streams according to materials instead of e.g packaging waste, for example, with their own legislation on treatment methods. Looking at materials in the waste stream to sort out how to treat the different material fractions in the most suitable way from an environmental and economic viewpoint would be beneficial. This is in line with a more holistic approach to waste management that looks into the whole chain and works with design and construction in order to minimise waste. Within the EU, the need for this kind of approach is receiving increasing attention. It seems that most agree that landfill is to be avoided, otherwise various methods should complement each other and the most suitable choice can be site-specific and dependent on material fractions.

A model is a powerful tool to try different scenarios and learn about the system under study. However, it is vital to keep in mind the limitations of the model and what assumptions lie behind the results. The systems of energy and waste management are both changing rapidly; the latest developments in the fuel market and electricity markets, for example, are examples of the difficulties involved in predicting future price levels. Policy instruments are also a factor that greatly influences the systems; they are the results of political decisions which might be delicate to predict. Other examples are the levels of the policy instruments, e.g. the price for carbon dioxide emission allowances which has tended to vary. The question of at which level these will be in the future, what sectors will be included, or if the system will even exist are difficult to estimate. A model can then be a tool for assessing the impact of these changes. The most profound value of using a model is the knowledge and understanding of the system which is gained. This can be used for decision-support, but in the end the decision maker must make the decision and needs to value other aspects as well.

What is the contribution of this thesis in comparison to other studies? The point of departure is to show resource effective solutions under the assumptions made. The main contribution is the examples of three real municipalities to show how waste incineration affects the system in terms of for example system costs, fuel used for heat production, and the amount of electricity production. It increases knowledge about the uniqueness of different district heating systems and the predicament in stating in general terms what fuels are affected when waste incineration is introduced. This complements similar studies on the national level. The difference compared to studies that use life cycle assessment is the procedure to seek the most efficient way to use resources while those studies mainly compare the environmental impact of chosen scenarios. District heating is often assumed to be for example biomass and then varied in sensitivity analyses. The contribution of this study is to give examples of actual replacement fuels. A diversion from most other energy system studies is the clear focus on waste incineration. The methodological approach with an optimising model is also a departure from some studies. In studies using an energy efficiency perspective or external costs as an assessment method, a difference is how the recovery of heat is handled; most studies presuppose electricity only production and that the heat is wasted.

6.2 Conclusions

Waste incineration has a negative operational cost due to the fact that revenues are received for treating the waste. Waste incineration plants are base load suppliers of heat in district heating grids and introduction of waste incineration therefore entails new conditions for other plants which can make them operate less. Waste as a fuel is economically profitable for the energy utilities operating the district heating grids. Waste management legislation banning landfill of combustible and organic waste and the taxes on landfill make waste even more competitive as a fuel. Heat can be sold to district heating customers, making incineration of waste competitive compared to other waste treatment methods. An additional effect is the favourable taxation of waste as a fuel and high taxes on fossil fuels. However, a tax on incinerated waste has recently been introduced which will alter the economic conditions for waste incineration.

The Swedish infrastructure with its extended district heating systems has great potential for several purposes: untapped potential for increasing resource effective combined heat and power production, taking care of waste heat from industries that would otherwise be wasted, and treating waste in an acceptable way and recovering a large part of its energy content. However, the purposes might conflict with each other. Waste incineration can make combined heat and power production in district heating networks less viable and this can be seen as a conflict between the need to treat waste in an acceptable way and the goal of more combined heat and power production in the energy system. Combined heat and power production is the main measure to decrease carbon dioxide emissions from district heating systems on the assumption that locally produced electricity replaces electricity produced in coal condensing power plants. The results are dependent on what power production is assumed to be marginal; the environmental benefit is much less when it is natural gas power instead of coal power. How the future looks and when a shift will take place is hard to say, but it is vital to be aware of the impact of the assumptions made.

Policy instruments have a significant impact on the development of both energy and waste management systems, e.g. green electricity certificates, carbon dioxide taxes, emission allowance trading, landfill taxes, and taxes on incinerated waste. Aspects affected are for example fuels used in the district heating systems and incentives for combined heat and power production. It can be a complicated matter to design policy instruments for waste incineration since the goals for waste management and the energy system conflict in some areas.

It is important to sort municipal waste in order to treat the different fractions of the waste according to the most preferable method for that fraction, and a variety of treatment methods are needed to avoid landfill. When choosing a waste treatment method, the connection to the technical energy system is important; whether it is possible to utilise the heat from the waste incineration and what other energy carriers are used. The structure of the energy system affects the consequences of choices made in the waste management system. The importance of a district heating system to utilise the heat is shown in the comparison of energy efficiency of material and energy recovery. Plastics and paper are more energy efficient to material recover whereas cardboard and biodegradable waste are more appropriate for energy recovery. The level of cogeneration in the district heating system and how electricity intensive production processes are important for the result, since electricity is multiplied with a factor 2.5. This is the main difference between paper and cardboard. An essential assumption is that biomass fuel is a limited resource. That implies that when biomass is saved, it is used in another district heating system, for example, and eventually it saves oil.

The concept of external costs is one way to include environmental impact in economic calculations. The data from the ExternE project is site-specific in contrast to the data often used in life cycle assessments for example. There are many uncertainties, both methodological and ethical. One example of an ethical uncertainty is the discussion as to which discounting rate to use. The higher the rate, the higher burden laid on coming generations. The ExternE project include a limited number of impacts, and especially important concerning waste incineration is that the environmental impact of ashes is not included. How to value an avoided burden in other treatment methods is a question that can affect results. An advantage of using external costs and of the efforts made by the ExternE group is the knowledge gained of environmental impacts and of the system under study.

The situation in Sweden differs from other European countries with extended district heating systems in combination with the historically low interest in Sweden for combined heat and power production due to the abundance of cheap hydropower and nuclear power. Other Western

European countries with a high amount of district heating also have a lot of combined heat and power. In Sweden, the connection has not been strong, and that can be a reason why waste incineration has been such a suitable solution for municipal authorities; two functions and problems solved in one plant. Some Eastern European countries also have a significant number of district heating systems but their waste management systems are not particularly developed and rely heavily on landfill. This might change with increasing demands for waste treatment, e.g. decreased landfill, from the European Union. These district heating systems have the potential for more cogeneration and utilisation of heat from waste incineration and waste heat from industries.

6.3 Suggested further work

It is interesting to follow the development of the connection between the systems of district heating and waste management, e.g. the impact of various policy instruments. Of special importance here is the introduction on July 1st 2006 of the tax on incinerated municipal waste: will this impact the development of waste incineration? The design of the tax implies that the main influence should be increased cogeneration in waste incineration plants. The total amount of incinerated waste is less likely to be affected.

It would be informative to put costs on the calculations of the energy efficiency of the waste treatment methods shown in Paper 5 in order to obtain costs per unit saved energy. It could further point in directions where the greatest effort in material recycling should be made.

In the waste management sector, it is essential to “move up the ladder” in the waste hierarchy. The main step to take in the years ahead is to find ways of reducing the amount of waste and breaking the correlation between economic growth and waste growth. How can we reduce waste in order to move towards sustainability? What means are there to break the connection between economic growth and waste growth? How can we develop design and production processes in order to decrease waste amounts? What kind of policy instruments would be necessary to stimulate this progress?

Concerning district heating systems, the development of electricity and fuel prices, principally natural gas, is interesting to study as is the progress of the common European electricity market. More sensitivity analyses of the impact of various electricity and fuel prices on district heating systems would be valuable. There are uncertainties as regards the development of taxation and other policy instruments, such as the emission trading programme. Further studies of the impact of policy instruments would be instructive. Combined heat and power has been shown to be efficient and is it necessary to support it in additional ways, apart from the green electricity certificates and the changes in fossil fuel taxation for combined heat and power? Concerning district heating, does it need further encouragement for extension?

The people who are part of these systems have not been very visible in this thesis. However, the aim of the thesis is to support the decision makers and policy makers and to increase knowledge about the district heating and waste management systems and their interaction. It would be interesting to study how decision makers and policy makers work and what their aspirations are. Incorporating the public would also be valuable. Public acceptance is necessary to achieving a functional waste management system. How do the public view the increase in waste incineration? How do the public think we could reduce the amounts of waste? Concerning district heating, it would be interesting to study the public’s opinion of and confidence in district heating.

7 References

Andersson S and Werner S. 2005. Fjärrvärme i Sverige 2003. En analys av råvarukostnader, ägande, jämställdhet, priser och lönsamhet i svenska fjärrvärmeföretag. (District heating in Sweden. An assessment of raw material costs, ownership, equality and profitability in Swedish district heating companies, in Swedish.) www.fvb.se (February 2006).

Assefa G, Eriksson O and Frostell B. 2005. Technology assessment of thermal treatment technologies using ORWARE. Energy Conversion and Management 46:797-819

Ayres R and Ayres L.W. 1996. Industrial ecology. Towards Closing the Material Cycle. Edward Elgar Publishing Limited

Bartlett M and Holmgren K. 2001. Waste incineration in Swedish municipal energy systems. An investigation of the system consequences of waste quantities in Linköping and the conditions for conventional and evaporative hybrid cycle operation. Arbetsnotat 19. Programme Energy Systems. Linköping Institute of Technology, Linköping, Sweden

Björklund A and Finnveden G. 2005. Recycling revisited – life cycle comparisons of global warming impact and total energy use of waste management strategies. Resources, Conservation and Recycling 44:309-317

Bladh M. 2001. Fyra linjer inom miljöekonomin (Four lines within environmental economics, in Swedish) Arbetsnotat 20. Programme Energy Systems. Linköping Institute of Technology, Linköping, Sweden

Bohlin F. 1998. The Swedish carbon dioxide tax: effects in biofuel use and carbon dioxide emissions. Biomass and Bioenergy 15: 283-291

Byman K. 1999. Systemanalytisk energimodell som beslutsverktyg. Borlänge och andra kommuner i Dalarna. (A system analysis energy modelling tool as decision support. Borlänge and other municipalities in Dalarna, in Swedish.) LiU-TEK-LIC-1999:42. Linköping Institute of Technology, Linköping, Sweden

Caputo A.C, Palumbo M and Scacchia F. 2004. Perspectives of RDF use in decentralized areas: comparing power and co-generation solutions. Applied Thermal Engineering 24:2171-2187

Carlsson A. 2002. Considering External Costs – Their Influence on Technical Measures in Energy Systems. Dissertation No 766, Linköping Institute of Technology, Linköping, Sweden

Churchman C.W. 1968. The systems approach. Dell publishing, New York

Dijkgraaf E and Volleberg R.J.H. 2004. Burn or bury? A social cost comparison of final waste disposal methods. Ecological Economics 50:233-247

Dornburg V, Faiij A.P.C and Meuleman B. 2006. Optimising waste treatment systems. Part A: Methodology and technological data for optimising energy production and economic performance. Resources, Conservation and Recycling, in press

Dornburg V and Faiij A.P.C. 2006. Optimising waste treatment methods. Part B: Analyses and scenarios for The Netherlands. Resources, Conservation and Recycling 48:227-248

Ekvall T. 1999. Key methodological issues for life cycle inventory analysis of paper recycling. Journal of Cleaner Production 7:281-294

Eriksson O, Frostell B, Björklund A, Assefa G. Sundqvist J-O, Granath J, Carlsson M, Baky A and Thyselius L. 2002. ORWARE – a simulation tool for waste management. Resources, Conservation and Recycling 36:287-307

Eriksson O, Olofsson M and Ekvall T. 2003. How model-bases systems analysis can be improved for waste management planning. Waste Management and Research 21:488-500

Eriksson O, Carlsson Reich M, Frostell B, Björklund A, Assefa G, Sundqvist J-O, Granath J, Baky A and Thyselius L. 2005. Municipal solid waste management from a systems perspective. Journal of Cleaner Production 13:241-252

Eriksson O, Finnveden G, Ekvall T and Björklund A. 2006. Life cycle assessment of fuels for district heating: A comparison of waste incineration, biomass- and natural gas combustion. Energy Policy, in press

Eshet T, Ayalon O and Shechter M. 2006. Valuation of externalities of selected waste management alternatives: A comparative review and analysis. Resources, Conservation and Recycling 46:335-364

European Commission. 2001. Environment 2010: Our Future, Our Choices – The Sixth Environmental Action Programme. (COM (2001) 31 final. Brussels, Belgium

European Commission. 2004. Report from the Commission – Annual Report on the Implementation of the Gas and Electricity Internal Market. COM/2004/0863 final, Brussels, Belgium

European Commission. 2005. Taking sustainable use of resources forward: A Thematic Strategy on the prevention and recycling of waste. Brussels, Belgium

European Union. 1975. Council Directive on waste. Brussels, Belgium

European Union. 1999. Council Directive 1999/31/EC on the landfill of waste. Brussels, Belgium

European Union. 2000. Council Directive 2000/76/EC on the incineration of waste. Brussels, Belgium

European Union. 2003a. Council Directive 2003/54/EC concerning common rules for the internal market in electricity. Brussels, Belgium

European Union. 2003b. Council Directive 2003/87/EC of 13 October 2003 establishing a scheme for greenhouse gas emission allowance trading within the Community. Brussels, Belgium

European Union. 2004a. Directive 2004/8/EC on the promotion of cogeneration based on a useful heat demand in the internal energy market. Brussels, Belgium

European Union. 2004b. Directive 2004/8/EC on packaging and packaging waste. Brussels, Belgium

Finnveden G and Ekvall T. 1998. Life-cycle assessment as a decision-support tool - the case of recycling versus incineration of paper. Resources, Conservation and Recycling 24:235-256

Finnveden G, Johansson J, Lind P and Moberg Å. 2005. Life cycle assessment of energy from solid waste – part 1: general methodology and results. Journal of Cleaner Production 13:213-229

Gebremedhin A.2003. A regional and industrial co-operation in district heating systems. Dissertation No. 849. Linköpings Institute of Technology, Linköping, Sweden

Groscurth H-M and Schweiker A. 1995. Contribution of computer models to solving the energy problem. Energy Sources 17:161-177

Gustafsson L, Lanshammar H and Sandblad B. 1982. System och model - En introduction till systemanalysen. (System and model - An introduction to system analysis, in Swedish) Studentlitteratur, Lund, Sweden.

Henning D. 1998. Cost minimisation for a local utility through CHP, heat storage and load management. International Journal of Energy Research 22:691-713

Henning D. 1999. Optimisation of local and national energy systems: development and use of the MODEST model. Dissertation No. 559. Linköping Institute of Technology, Linköping, Sweden

Henning D, Amiri S and Holmgren K. 2006. Modelling and optimization of electricity, steam and district heating production for a local Swedish utility. European Journal of Operational Research 175:1224-1247

Hillring B. 2000. The impact of legislation and policy instruments in the utilization of wood fuels. Ecological Engineering 16:S17-S23

Holmgren K. 2006. Waste incineration in Swedish district heating systems. In Waste Management and the Environment III. Editor: Popov V, Kungolos A.G, Brebbia C.A and Itoh H. WIT Press

Hrelja R. 2006. I hettan från ångpannan – vetenskap och politik i konflikter om tekniska anläggningar (In the heat of the steam boiler – science and politics in conflicts about technical plants, in Swedish). Linköping Studies in Arts and Science 371. Linköpings universitet, Linköping, Sweden

IEA International Energy Agency. 2002. Promotion and Recognition of DHC and CHP Benefits in Greenhouse Gas Policy and Trading Programs. Project Report 2002:S9

Ingelstam L. 2002. System – att tänka över samhälle och teknik (Systems – to think of society and technology, in Swedish), Swedish Energy Agency, Eskilstuna, Sweden

Jebaraj S and Iniyan S. 2006. A review of energy models. Renewable and Sustainable Energy Reviews. 10: 281-311

Kjärstad J and Johnsson F. 2006. Prospects of the European gas market. Energy Policy, in press

Knutsson D, Werner S. 2003. Potential for natural gas based CHP generation in Swedish district heating systems. Article in a National Aggregation of Locally Described District Heating Systems.

Knutsson D, Werner S and Ahlgren E O. 2006. Combined heat and power in the Swedish district heating sector – impact of green certificates and CO_2 trading on new investments. Energy Policy, in press

Korhonen J. 2001. Co-production of heat and power: an anchor tenant of a regional industrial ecosystem. Journal of Cleaner Production 9: 509-517

Korhonen J. 2002. A material and energy flow model for co-production of heat and power. Journal of Cleaner Production 10:537-544

Korhonen J. 2006. Environmental planning vs. system analysis: Four prescriptive principles versus four descriptive indicators. Journal of Environmental Management, in press

Korobitsyn M.A, Jellema P. and Hirs G.G. 1999. Possibilities for gas turbine and waste incinerator integration. Energy 24:783-793

Kåberger T and Karlsson R. 1998. Electricity from a competitive market in life-cycle analysis. Journal of Cleaner Production 6:103-109

Ljunggren Söderman M. 2000. A Systems Engineering Approach to National Waste Management. Dissertation No. 1665. Department of Energy Conversion, Chalmers University of Technology, Göteborg, Sweden

Ljunggren Söderman M. 2003. Recovering energy from waste in Sweden – a systems engineering study. Resources, Conservation and Recycling 38:89-121

Lund H, Sipusinskas G and Martinaitis V. 2005. Implementation strategy for small CHP plants in a competitive market: the case of Lithuania. Applied Energy 82:214-227

Merriam S. 1988. Case study research in Education. Jossey-Bass Inc. Publishers, San Fransisco, USA

Ministry of the Environment. 2001. Förordning (2001:512) om deponering av avfall (Ordinance (2001:512) on landfill of waste, in Swedish). Stockholm, Sweden

Ministry of Finance. 2003. Svåra skatter: betänkande från Skattenedsättningskommittén. (Difficult taxes, in Swedish). SOU 2003:38. Stockholm, Sweden

Ministry of Finance. 2005. Lag (2005:962) om ändring i lagen (1999:673) om skatt på avfall (Law (2005:962) on changes in the law (1999:673) governing waste tax, in Swedish). Stockholm, Sweden

Ministry of Finance. 2006. Regeringens proposition 2005/06:125 Beskattning av visst hushållsavfall som förbränns (Proposition 2005/06:125 Taxation on incinerated municipal waste, in Swedish) Stockholm, Sweden

Ministry of Sustainable Development. 1997. Ellag (1997:857) (Electricity Law (1997:857), in Swedish), Stockholm, Sweden

Ministry of Sustainable Development. 2003a. Lag (2003:113) om elcertifikat (Law (2003:113) on electricity certificates, in Swedish) Stockholm, Sweden

Ministry of Sustainable Development. 2003b. Tryggare fjärrvärmekunder (Safer district heating customers, in Swedish). SOU 2003:115, Stockholm, Sweden

Ministry of Sustainable Development. 2004a. Lag (2004:1199) om handel med utsläppsrätter (Law (2004:1199) on emission allowance trade, in Swedish, Stockholm, Sweden

Ministry of Sustainable Development. 2004b. Skäligt pris på fjärrvärme (Reasonable pricing on district heating, in Swedish). SOU 2004:136. Stockholm, Sweden

Ministry of Sustainable Development. 2005. Fjärrvärme och kraftvärme i framtiden (District heating and combined heat and power in the future, in Swedish). SOU 2005:33. Stockholm, Sweden

Ministry of Sustainable Development. 2006. Utvecklad utsläppshandel för minskad klimatpåverkan (Developed emission allowance trading for decreased effect on climate, in Swedish) Prop. 2005/06:184. Stockholm, Sweden

Miranda L.M and Hale B. 1997. Waste not, want not: the private and social costs of waste-to-energy production. Energy Policy 25:587-600

Morris J. 1996. Recycling versus incineration: an energy conservation analysis. Journal of Hazardous Materials 47:277-293

Morrissey A.J and Browne J. 2004. Waste management models and their application to sustainable waste management. Waste Management 24:297-308

Morselli L, Bartoli M, Bertacchini M, Brighetti A, Luzi J, Passarini F and Masoni P. 2005. Tools for evaluation of impact associated with MSW incineration: LCA and integrated environmental monitoring system. Waste Management 25:191-196

Mortensson H.C and Overgaard B. 1992. CHP development in Denmark. Role and results. Energy Policy 20:1198-1206

Murphy J.D. and McKeogh E. 2004. Technical, economic and environmental analysis of energy production from municipal solid waste. Renewable Energy 29:1043-1057

Olofsson M. 2001. Linking the Analysis of Waste Management Systems and Energy Systems. ISRN CTH-EST-R-01/5-SE. Department of Energy Conversion, Chalmers University of Technology, Göteborg, Sweden

Olofsson M, Sahlin J and Unger T. 2003. Will New Waste-to-energy Technologies Enter the Swedish Waste Management Market? A&WMA 96th Annual Conference and Exhibition, June 22-26, 2003, San Diego, California, USA

Olofsson M, Sundberg J and Sahlin J. 2005. Evaluating waste incineration as treatment and energy recovery method from an environmental point of view. Proceedings of the 13th Annual North American Waste to Energy Conference, pp 175-192

O'Rourke D, Connelly L and Koshland C.P. 1996. Industrial ecology: a critical review. International Journal of Environment and Pollution Vol. 6, Nos. 2/3, 89-112

Palm, J. 2004. Makten över energin – policy processer i två kommuner 1977-2001. (Influence over energy – the process of policy in two municipalities 1977- 2001, in Swedish). Linköping Studies in Arts and Science 289. Linköpings Universitet, Linköping, Sweden

Reijnders, L. 2005. Disposal, uses and treatments of combustion ashes: a review. Resources, Conservation and Recycling 43:313-336

Roth I.F and Ambs L.L. 2004. Incorporating externalities into a full cost approach to electric power generation life-cycle costing. Energy 29:2125-2144

Ryden B, Johnsson J, Wene C-O. 1993. CHP production in integrated energy systems. Examples from five Swedish communities. Energy Policy 21:176-190

Rydh CJ, Lindahl M and Tingström J. 2002. Livscykelanalys – en metod för miljöbedömning av varor och tjänster. (Life cycle assessment – a method for environmental assessment of goods and services, in Swedish), Studentlitteratur, Lund, Sweden

Sabbas T, Polettini A, Pomi R, Astrup T, Hjelmar O, Mostbauer P, Cappai G, Magel G, Salhofer S, Speise C, Heuss-Assbichler S, Klein R and Lechner P. 2003. Management of municipal solid waste residues. Waste Management 23:61-88

Sahlin J, Knutsson D and Ekvall T. 2004. Effects of planned expansion of waste incineration in the Swedish district heating systems. Resources, Conservation and Recycling 41:279-292

Sjödin J. 2002a. Swedish District Heating Systems and a Harmonised European Energy Market – Means to Reduce Global Carbon Emissions. Dissertation No. 795. Linköping Institute of Technology, Linköping, Sweden

Sjödin J. 2002b. Modelling the impact of energy taxation. International Journal of Energy Research 26:475-494

Sjödin J and Henning D. 2004. Calculating the marginal costs of a district heating utility. Applied Energy 78:1-18

Sjödin J and Grönkvist S. 2004. Emission accounting for use and supply of electricity in the Nordic market. Energy Policy 32:1555-1564

Sonesson U, Björklund A, Carlsson M and Dalemo M. 2000. Environmental and economic analysis of management systems for biodegradable waste. Resources, Conservation and Recycling 28:29-53

Sonneman G.W, Schuhmacher M and Castells F. 2003. Uncertainty assessment by a Monte Carlo simulation in a life cycle inventory of electricity produced by a waste incinerator. Journal of Cleaner Production 11:279-292

Sundberg G. 2001.Determining parameters for combined heat and power plants – on the use of district heating for power production in a liberalised market. Dissertation No 691. Linköping Institute of Technology, Linköping, Sweden

Sundberg G and Henning D. 2002. Investments in combined heat and power plants: influence of fuel price on cost minimised operation. Energy Conversion and Management 43:639-650

Sundberg J, Gipperth P and Wene C.O. 1994. A systems approach to municipal solid waste management: a pilot study of Göteborg. Waste Management and Research 12:73-91

Swedish Association of Waste Management. 2004. Avfallsförbränning. Utbyggnadsplaner, behov och brist. (Waste incineration. Expansion plans, capacity need and lack thereof, in Swedish) RVF-report 04:02. Malmö, Sweden

Swedish Association of Waste Management. 2005a. Svensk Avfallshantering 2005 (Swedish Waste Management 2005. Sweden

Swedish Association of Waste Management. 2005b. Avfall blir värme och el. En rapport om avfallsförbränning. (Waste turns into heat and electricity. A report on waste incineration, in Swedish). RVF-report 05:02. Malmö, Sweden

Swedish District Heating Association. 2005. Kraftvärme och dess kopplingar till elcertifikatsystemet. (Combined heat and power and the connection to the electricity certificate system, in Swedish), Sweden

Swedish Energy Agency. 2002. Marginal elproduktion och CO2-utsläpp i Sverige. (Marginal electricity production and CO2-emissions in Sweden. ER 14:2002. Eskilstuna, Sweden

Swedish Energy Agency. 2004. Energy in Sweden 2004. Facts and Figures. Eskilstuna, Sweden

Swedish Energy Agency. 2005a. Energy in Sweden 2005. Eskilstuna, Sweden

Swedish Energy Agency. 2005b. Energimarknad 2005 (Energy markets, in Swedish), Eskilstuna, Sweden

Swedish Environmental Research Institute. 2004. Tilldelning av utsläppsrätter inom energisektorn baserat på riktmärken (Allocation of emission allowances in the energy sector based on benchmarking, in Swedish) Stockholm, Sweden

Swedish Environmental Protection Agency. 2004. Industrins avfall 2002 (Industrial waste 2002, in Swedish) Report 5371. Stockholm, Sweden

Swedish Environmental Protection Agency. 2005. Strategi för hållbar avfallshantering. (Strategy for sustainable waste management, in Swedish), Stockholm, Sweden

Tillman A-M. 2000. Significance of decision-making for LCA methodology. Environmental Impact Assessment Review 20:113-123

Trygg L and Karlsson B.G. 2005. Industrial DSM in a deregulated European electricity market – a case study of 11 plants in Sweden. Energy Policy 33:1445-1459

Weidema B.P, Frees N and Nielsen A.M. 1999. Marginal production technologies for life cycle inventories. International Journal of life cycle assessment. 4:1:48-56

Wene C-O and Rydén B. 1988. A comprehensive energy model in the municipal energy planning process. European Journal of Operational Research 33:212-222

Verhoef E.V, Houwelingen van J.A, Dijkema G.P.J and Reuter M.A. 2006. Industrial ecology and waste infrastructure development: A roadmap for the Dutch waste management system. Technological Forecasting and Social Change 73:302-315

Werner S. 1989. Fjärrvärmens utveckling och utbredning (The development and expansion of district heating, in Swedish), Swedish District Heating Association, Sweden

Werner S. 2001. Rewarding energy efficiency: the perspective of emissions trading. Euroheat and Power 30:14-21

Westin P. and Lagergren F. 2002. Re-regulating district heating in Sweden. Energy Policy 30:583-596

World Commission on Environment and Development. 1987. Our common future. United Nations Environment Programme, Nairobi, Kenya.

Yin R.K. 1994. Case study research. Design and Methods. Sage Publications, USA