Recovering energy from waste in Sweden—a systems engineering study

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Abstract

The possibilities for recovering energy from waste in Sweden around the year 2010 are explored in this paper. To capture the issue from the perspectives of both the waste management and the district heating systems, separate systems engineering studies are performed for each. Four questions are explored: (1) Is recovering energy from waste economic from a waste management system perspective; (2) Is there a significant untapped energy resource in the form of waste in Sweden; (3) Is recovering energy from waste economic from a district heating system perspective; and (4) What are the global warming implications of recovering energy from waste? The results show that recovering energy from waste is part of all solutions studied, since energy recovery is necessary in order to fulfil the coming ban on landfilling of combustible and organic waste. However, the optimal quantity of energy to recover from waste differs considerably depending on the system perspective taken. From a waste management point of view, the economically optimal solution is to combine heat recovery with a high level of materials recovery. In this case, the quantity of heat recovered is close to the present Swedish level. From a district heating point of view, the potential could be 2–6 times larger. In terms of global warming implications, the preferable solution is to combine materials recovery and combined heat and power from waste. By bringing both the waste management and the district heating systems into focus, knowledge has been gained. The district heating study reveals a future market for heat recovery from waste that could be significantly larger than today. The waste management study points out that new policy instruments will be introduced in Swedish waste management that could direct waste towards increased energy recovery if the materials recovery sector does not develop strongly. These potential changes would have been more difficult to foresee had one system or the other been

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1. Introduction

Solid waste is an important energy resource in Sweden. In 1997, approximately 5.1 TWh were recovered through solid waste incineration and 0.4 TWh of landfill gas and biogas from anaerobic digestion of organic waste was recovered. The majority of the energy was used for district heating purposes (The Swedish Association of Waste Management, 1998). In total, waste supplied 7% of the fuel combusted in district heating plants and combined heat and power plants (Fig. 1; Swedish National Energy Administration, 1999). Since district heating plants currently supply about 40% of the total use of space and water heating in the residential and service sectors in Sweden, one can conclude that solid waste at present represents an important contribution to Swedish energy supply.

There are reasons to believe that the importance of solid waste as an energy resource will increase in near future. Why? Policy trends in Swedish, as well as European, waste management currently point towards reduced landfilling. For example, a new directive was adopted by the European Union in 1999 that gradually reduces the quantities of biodegradable municipal waste allowed for landfilling to 35% by the year 2016 (The Council of the European Union, 1999). Sweden has gone further, banning landfilling of combustible and organic waste from 2002 and 2005, respectively (Ministry of the Environment, 1998). Moreover, Denmark, Great Britain, and Norway have introduced taxes on landfilling, as Sweden did in 2000.

At present, landfilling is by far the most common waste treatment method in Sweden. Half of all household waste is landfilled. Three fourths of all solid waste is...
Consequently, bans on landfilling of combustible and organic waste and landfilling taxes are policy instruments that are destined to impact Swedish waste management. If waste is not to be landfilled, what is the optimal integrated approach of treating it: by combining energy recovery, biological treatment and material recovery?

If recovering energy from waste is promoted by the waste management situation, the issue needs to be analysed from a district heating perspective as well. The environmental and economic competitiveness of supplying energy from waste are important aspects in this regard. Global warming mitigation is one key environmental issue in the energy sector. A shift towards renewable or less fossil-CO₂-intensive fuels is one of the solutions discussed. About one third of Swedish district heat production is currently of fossil origin (Fig. 1), which suggests a potential for reducing fossil CO₂-emissions. Could increased use of solid waste as an energy resource offer an opportunity to reduce greenhouse-gas emissions? Furthermore, could the fact that solid waste is a fuel that can be supplied at low costs make recovering energy from waste economically advantageous?

This paper presents a systems engineering study of Swedish waste management and district heating with focus on energy recovery from waste. The study is performed as part of a larger research project in which regional case studies are also included. The national study is designed to shed light on the following questions with regard to Swedish circumstances:

1) Is recovering energy from waste economic from a waste management system perspective?
2) Is there a significant untapped energy resource in the form of waste in Sweden?
3) Is recovering energy from waste economic from a district heating system perspective?
4) What are the global warming implications of recovering energy from waste?

To capture the issue from the perspectives of both the waste management system and the district heating system, separate systems engineering studies are performed for each. The methodology is further discussed in Sections 2 and 3. The study is based on four scenarios. In all scenarios, the possibility of recovering energy from waste around the year 2010 is studied and assumptions about the development of the environment surrounding the waste management and district heating systems are made, see Section 4. The quantitative results are presented in Section 5. The discussion in Section 6 and the summary and conclusions in Section 7 address quantitative as well as methodological aspects of the analysis.

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1 Here, ‘all solid waste’ refers to household waste, industrial waste, construction and demolition waste, park and garden waste, waste from municipal wastewater, waste from industrial wastewater, waste from extraction of mineral products and energy recovery waste treated by municipal waste actors and private establishments.

2 The regional studies will be reported elsewhere.
2. Studying energy recovery from waste

2.1. Two systems in focus

Two systems are in focus when studying energy recovery from waste in Sweden: the waste management system and the district heating system (Fig. 2).

The primary objective of waste management systems is to treat waste. Recovering energy from waste has an additional function of providing valuable by-products, be they heat, power or biogas. The energy recovered can be disposed of at prices and quantities determined by the level of energy demand and availability of other competing district heating supply options.

The primary objective of district heating systems is to satisfy heat demand. Heat recovered from solid waste can, among a number of options, be used for that purpose. Heat recovered from waste is available to the district heating system at quantities and prices determined by the treatment options in the waste management system.

It is clear that the waste management and district heating system share the economic and environmental consequences of recovering energy from waste. To capture the issue of recovering energy from waste from the perspectives of both the waste management system and the district heating system, separate systems engineering studies are performed for each system in this study. In the waste management study, the analysis is carried out using the National Waste (NatWaste) model (Ljunggren, 1997) (Section 3.1). In the district heating study, the analysis is carried out using a marginal-cost ordering procedure (Section 3.2).

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Fig. 2. The waste management system and the district heating system, their system environment and common relations.

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3 NatWaste was formerly referred to as MWS (MIMES/Waste for Sweden, Ljunggren, 1997).
Energy from waste could also be recovered as power and vehicle fuel (biogas) as indicated in Fig. 2. But district heating is the application for which energy recovered from waste has the largest current and potential influence, economically and quantitatively, in Sweden. The current and potential quantities of both power and vehicle fuel recovered from waste are small compared to their total markets. Consequently, energy recovery from waste can have little influence on these markets. Therefore, the power and vehicle fuel systems are analysed as part of the systems environment in this study. Alternatives to energy recovery from waste are materials and nutrients recovery, also in Fig. 2. The materials and nutrients recovery systems are also analysed as part of the systems environment.

2.2. Other methods proposed

Several methods have been applied in other systems engineering studies to address the issue of recovering energy from waste. The most common method is to focus on one system and to regard the other systems as part of the system environment. Scenario analysis is often used to explore potential changes in the system environment. With one system in focus, there is a risk of a static analysis since the interplay between the system and the environment is easily neglected. This also holds for potential interplay between factors in the system environment. The risk may be intensified by the fact that studying waste management and energy systems traditionally involves two different disciplines, which makes the bringing together of competence more difficult. Examples of studies with focus on the waste management system are (Björklund et al., 1998; Barlaz et al., 1995; Ljunggren, 2000). Energy systems studies are e.g. Johnsson et al. (1992). The issue of energy recovery from waste has been part of the analysis in all of these studies, even if it was not always among the main questions.

A second way of studying energy recovery from waste is by integrating the waste management and energy systems, either by hard- or soft-linking. This method reduces the risk of neglecting interplay and potential changes. The hard-linking method integrates the waste management system and the energy system in one systems engineering model (Gielen, 1998; Lehtilä and Tuhkanen, 1999; Cosmi et al., 2000). One advantage of hard-linking is that no manual exchange of information is required. On the negative side, however, are reduced transparency of the model and its results, and the necessity of making trade-offs between detail and scope. Furthermore, methodological difficulties can arise if integrated systems are driven by different objectives, such as maximising productivity versus maximising energy efficiency (Nystrom, 2001). Also, the labour required to build an integrated model should not be neglected. The soft-linking method is being used and developed in the

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4 The current Nordic market for power is 380 TWh. The current Swedish market for vehicle fuels is 90 TWh of which 0.1 TWh is natural gas, LPG and biogas.

5 In Gielen (1998), Lehtilä and Tuhkanen (1999), other interacting systems such as the agriculture, forest and manufacturing industry sectors are included as well.
regional study in this research project. In the regional study, two systems engineering models, one for each system, are used iteratively with manual exchange of information between the models for the actual model calculations, an approach which requires extensive work in establishing how and what information to exchange and interpreting results.

The method proposed in this study, one separate systems engineering study used for each system, increases the possibilities of analysing potential changes in both systems and interplay, compared to focusing on one system. It is less suitable than an integrated approach for analysing interplay. However, it is a step towards understanding the links between the waste management and the district heating system, and can be informative for pointing out the aspects of the issue where an integrated analysis could be required.

3. The systems engineering approaches applied

3.1. The waste management study

The analysis of the potential role of energy recovery in the waste management system is carried out using the NatWaste model (Ljunggren, 2000, 1997). The NatWaste model is a systems engineering model for strategic planning of national solid waste management systems. In the model, the Swedish national waste management system is represented by ten coupled generalised municipal waste management systems. Integrating the generalised systems into a national model allows analysis on a national level while accounting for differences at the municipal level.

The NatWaste model is suitable for finding synergistic waste management solutions and for analysing the potential effect of different objectives and policy instruments. Cost minimisation and emissions accounting are integrated, offering the possibility to perform economic as well as environmental analyses. The NatWaste model is a one-period linear programming model, i.e. the model analyses the waste management system for a single time period, describes the system in linear equations and optimises the system for a defined objective function. The objective applied in this study is minimisation of the total annualised cost for the national waste management system. The costs represent private sector costs (certain taxes and fees are included when stated in the assumptions). The environmental aspects of the waste management system are addressed by (1) quantifying emissions to air and residual content of harmful substances in the waste and (2) introducing environmental constraints and fees, such as emission restrictions, material and energy recovery goals and waste taxes. Model run outputs include: the economically optimal waste management solution, described in terms of total annualised costs; the

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6 Emissions to water could also be quantified (if required data is available). However, NatWaste has not yet been used in a study in which emissions to water have been in focus.
quantity of waste and material treated in the various processes and energy turnover; and the resulting emissions from the processes.

3.2. The district heating study

The focus of the analysis of the economic competitiveness from an energy perspective of recovering energy from waste in Sweden is on the district heating system, as explained in Section 2.

The cost-effectiveness of importing heat recovered from waste to the existing Swedish district heating system is examined by performing a marginal-cost ordering procedure. 7,8 The marginal heat production costs of all types of production options currently available in the district heating system are calculated.9 Then the production options are dispatched under the district heating load curve according to lowest marginal costs, while considering available installed capacity. Heat recovered from waste is imported to the district heating system if its sales price is lower than the marginal costs for the other production options. The marginal heat production costs include fuel costs, power costs (for options that consume power), power revenues (for options with combined heat and power production), energy taxes, emission fees and taxes, and operation and maintenance costs. The load curve is approximated to one annual period.

There are currently about 300 district heating networks in Sweden. In reality, if heat recovered from waste were to supplant other production options, the options replaced would differ depending on the configuration of the local district heating system. However, when calculating the marginal costs of the production options, it was found that the production units are clustered in groups of marginal costs (Fig. 3a). This fact makes it possible to represent Swedish district heating with one single national district heating system, to which the marginal-cost ordering procedure can be applied. The marginal-cost ordering applied to one national system does not examine the consequences of importing heat recovered from waste to the local district heating systems, but provides an overall picture that is deemed sufficient for the purposes of this study.

3.3. The environmental analysis

The global warming implications of recovering energy from waste are assessed in the environmental analysis. The Global Warming Potential (GWP, 100 years) (Houghton et al., 1996) resulting from emissions of three greenhouse gases is assessed: fossil CO$_2$, methane and nitrous oxide.

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7 In the analysis, heat is imported to the district heating system from the waste management system, where the actual energy recovery, its costs and its emissions take place.
8 The procedure is derived from the Martes model (Josefsson et al., 1996).
9 Investing in new options is not analysed.
The results from the waste management and district heating studies are brought together in the environmental analysis. The total GWPs for different combinations of the waste management and district heating systems are calculated. Since the waste management system turned out to be the limiting factor in recovering heat from waste (Section 5), the combinations are based on each of the optimal solutions in the waste management study. The district heating system is assumed to import the quantities of heat supplied by the waste management system, while reducing its own production so that the total heat production is constant. The analysis also includes the effect of varying quantities of power exports from (or imports to) the waste management and district heating systems on the GWP. The power produced internally is assumed to replace power production outside of the two systems, i.e. the total demand for power is assumed constant. The effect on GWP of exporting biogas produced in the waste management system to the transportation sector for using

Fig. 3. (a) Marginal heat production costs (SEK/MWh heat) for the district heating production options analysed (in the Base, Bio and Recov scenarios); (b) GWP (kg CO₂-equivalents/MWh heat) for the district heating production options analysed (in the Base, Bio and Recov scenarios).
instead of diesel is also accounted for. Thus, the total GWP calculated for each of the combinations comprises the effects of emissions from waste management, district heating, power production, and vehicle fuel production and combustion (Fig. 2).

The GWP of the waste management system is calculated in the NatWaste model (Section 3.1). The GWP of the district heating system is based on the average full fuel cycle GWP of Swedish district heating systems.\(^{10}\) As shown in Fig. 3b, the GWP per unit of heat produced differs considerably within each marginal-cost cluster of production options. Consequently, the effect on emissions of replacing existing heat production with heat from the waste management system varies significantly depending on the configuration of the local district heating system. Assuming that heat from the waste management system replaces average heat production in existing district heating systems is considered to provide a reasonable approximation in the national study. An alternative would have been to analyse emissions from the heat production replaced at the margin on a national level. However, this would at least require analyses of a significant number of different types of district heating systems (if not every local district heating system). The results of such an analysis would differ between the different types of district heating systems. It would also differ depending on the quantity of heat production to be replaced at the margin. It is beyond the scope of this study to perform such an extensive analysis of Swedish district heating, and there are currently no other studies available on the matter. However, in this study, the use of scenario analysis captures some of the uncertainties related to district heating. In the scenario analysis (Section 4.2), different assumptions regarding the marginal power production have been analysed. These assumptions also affect the average GWP of the district heating system, since some district heating options consume or produce power (Sections 4.2 and 5.4).

The GWP of the replaced power production is based on the full fuel cycle GWP of marginal Nordic power production. The choice of marginal production, and not average, is deemed appropriate since the potential power exports from (or imports to) the waste management and district heating systems are small in comparison with total power production and are not likely to affect the production mix (Section 2.1). The choice of Nordic rather than Swedish power is justified by the fact that power trade is so extensive that the Nordic power market can be regarded as one common market.

The approach for biogas varies depending on the scenario assumptions (Section 4.2). When biogas is used for combined heat and power production, it is assumed to replace marginal power and average heat production, as described above. When biogas is exported to the transportation sector for using as vehicle fuel for lorries, it is assumed to replace the full fuel cycle GWP of using diesel fuelled lorries.

\(^{10}\) Full fuel cycle indicates that emissions from both pre-combustion (fuel production and distribution) and combustion are included.
4. Structure of the study

4.1. Analytical approach

As stated in Section 1, the study is designed to answer four questions:

1) Is recovering energy from waste economic from a waste management system perspective?
2) Is there a significant untapped energy resource in the form of waste in Sweden?
3) Is recovering energy from waste economic from a district heating system perspective?
4) What are the global warming implications of recovering energy from waste?

The two first questions are analysed in the waste management study using the NatWaste model. The third question is analysed in the district heating study using the marginal-cost ordering procedure. The results from both studies are brought together to answer the last question.

Four main scenarios are created to illustrate how the four questions are affected by different assumptions regarding the future situation in the waste management and district heating systems. The assumptions regard the situation in the year 2010, e.g. CO₂-targets, the ban on landfilling, the landfilling tax, energy related taxes and values of products such as energy, material and compost. The main scenarios, which are common for the waste management and district heating studies, are presented in Section 4.2.

In the waste management study, each main scenario is divided into four sub-scenarios. The sub-scenarios differ with respect to the waste treatment options available. These are presented in Section 4.3. The purpose of the sub-scenarios is to study several waste management solutions and not restrict the study to one optimal solution per main scenario. Thus, the sub-scenarios function as sensitivity analyses within each main scenario.

In the district heating study, the economically optimal solution is calculated for each of the four main scenarios. No sub-scenarios are included. The heat production options studied are presented in Section 4.4.

4.2. Main scenarios

The four main scenarios evaluated are the Base scenario, the High Carbon scenario, the Bio scenario and the Recov scenario. In all four main scenarios, the total quantity of waste generated and its composition are held constant, as is the total demand for heat (Table 1). The figures correspond to the actual situation in 1997. Neither waste generation nor heat demand are expected to change significantly up to the scenario year 2010 (Swedish Environmental Protection Agency, 1999; Unger et al., 2000).

The total Swedish demand for power and vehicle fuel is also held constant in all scenarios. The demand for power and vehicle fuel are not described in terms of total
quantity, but as marginal changes depending on (1) imports and exports of power from the waste management and district heating systems and (2) exports of vehicle fuel from the waste management system (Fig. 2).

4.2.1. The Base scenario

In the Base scenario, a ban on landfilling of combustible and organic waste is in force (Ministry of the Environment, 1998). The recovery goals for products included in the Ordinances on Producer’s responsibility are met (Ministry of the Environment, 1994, 1997), and the combustible products are recovered through a combination of material and energy recovery (Table 2). Furthermore, the tax of 250 SEK per tonne of waste landfilled, introduced in 2000, is still valid (Ministry of Finance, 1999). The recovered biogas is converted to heat and power.

Fuel prices and energy related taxes and fees are assumed to be unchanged compared to today. However, the marginal power price is higher at 235 SEK/MWh. The increased power price is a result of the assumption that the Kyoto protocol has been ratified and that Sweden’s CO2-target has been reached through a joint Nordic commitment. Furthermore, power is traded between Sweden, Norway, Denmark and Finland in a common market. According to Unger et al. (2000), this situation would lead to a shift of marginal power production and would increase the price of power at the margin. Today, Danish coal-fired power plants are commonly regarded as the primary source of power at the margin. With the Kyoto protocol in force, coal-fired power plants power would not be cost effective and would be replaced by

<table>
<thead>
<tr>
<th>Amount of waste generated (kt/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Household waste</td>
</tr>
<tr>
<td>Construction and demolition waste</td>
</tr>
<tr>
<td>Industrial waste (non-industry-specific)</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Composition of waste generated (% of total amount of all three waste types)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper</td>
</tr>
<tr>
<td>Cardboard</td>
</tr>
<tr>
<td>Glass</td>
</tr>
<tr>
<td>Biodegradables</td>
</tr>
<tr>
<td>Plastics</td>
</tr>
<tr>
<td>Metal</td>
</tr>
<tr>
<td>Wood</td>
</tr>
<tr>
<td>Other combustibles</td>
</tr>
<tr>
<td>Other non-combustibles</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>District heating demand (TWh/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

Table 1

Waste generated and district heating demand in all scenarios

11 1 SEK (Swedish Krona) = 0.12 USD = 0.11 Euro (May 2000).
power produced with natural-gas-fired combined cycle gas turbines (Unger et al., 2000).12

4.2.2. The High Carbon scenario

The High Carbon scenario differs from the Base scenario in the conditions for power production. In this scenario, it is assumed that the Kyoto protocol targets will not be met. Coal-fired power plants would be used for power production at the margin, at a price of 170 SEK/MWh (Unger et al., 2000).

4.2.3. The Bio scenario

In the Bio scenario, biological treatment of waste is favoured. The specific costs of composting and anaerobic digestion are assumed to be halved compared to the Base scenario, through technological development and accumulated experience on these relatively new technologies. Furthermore, the sales prices for compost and anaerobic digestion residues are higher, based on the assumption that their value as nutrients for the agricultural sector increases. In the transportation sector, the demand for biogas as a replacement for diesel grows. Biogas is sold to the transportation sector as a vehicle fuel, which increases its sales price significantly compared to the other scenarios in which it is used for combined heat and power production (Table 3).

12 Despite the fact that the study focuses on recovering energy from waste in the form of heat, power issues are important. The power price is important for the economic competitiveness of several heat producing technologies, such as combined heat and power plants, electric boilers and heat pumps. Emissions from power produced at the margin are important for the environmental analysis.

Table 2
Minimum levels of recovery in the scenarios

<table>
<thead>
<tr>
<th>Type of material</th>
<th>Base, High Carbon and Bio</th>
<th>Recov⁴</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Minimum levels of combined material and energy recovery (%)</td>
<td>Minimum levels of material recovery (%)</td>
</tr>
<tr>
<td>Waste paper</td>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td>Paper and cardboard packaging</td>
<td>40</td>
<td>70</td>
</tr>
<tr>
<td>Corrugated board packaging</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td>Plastic packaging</td>
<td>30</td>
<td>70</td>
</tr>
<tr>
<td>Packaging of glass, aluminium and metal</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>Wood packaging</td>
<td>15</td>
<td>70</td>
</tr>
<tr>
<td>Gypsum, Concrete</td>
<td>0</td>
<td>50</td>
</tr>
</tbody>
</table>

⁴ In the Recov scenario, recovery levels are based on the whole waste fraction of paper, cardboard, corrugated board, glass, plastic, aluminium, metal and wood and not only on the packaging in the respective fractions.
4.2.4. The Recov scenario

This scenario reflects the consequences of increasing materials recovery from waste. As opposed to the Base scenario, it is assumed that energy recovery is not allowed for meeting the recovery goals for products included in the Ordinances on Producer’s responsibility. Also, the recovery goals for the Producer’s responsibility products are extended to include the whole material fractions and not only the packaging in the respective fractions (Table 2). The sales prices are also extended and applied to the whole material fraction. Furthermore, a minimum level of recovery of gypsum and concrete from construction and demolition waste is required.

Further details on scenario data are available in Ljunggren Söderman and Olofsson (2000).

4.3. Options and sub-scenarios analysed in the waste management study

A number of waste treatment options are analysed with the NatWaste model in the waste management study. For each combination of main and sub-scenario, the economically optimal solution is calculated (in total 16 solutions). The waste treatment options analysed are: waste incineration with heat recovery; waste incineration with combined heat and power recovery; central composting; anaerobic digestion with biogas recovery; landfilling; large-scale separation of household waste; large-scale separation of industrial and construction and demolition waste; materials recovery; source separation; and local and regional transport. The waste treatment options and their systemic relations are illustrated in the Appendix.

In the sub-scenarios, certain waste treatment options are excluded from the solution.13 In the DH sub-scenario, investments in new incineration are restricted to heat recovery. New combined heat and power recovery is excluded. The CHP sub-

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13 This is achieved by introducing constraints in the NatWaste model.
scenario is identical with the DH sub-scenario, except that investments in new incineration are restricted to combined heat and power recovery. In the C&DH sub-scenario, investing in large-scale central separation of household waste followed by composting of organic fractions, incineration of combustible fractions and landfilling of residual fractions is compulsory. Investments in new incineration are restricted to heat recovery. The AD&DH sub-scenario is identical with C&DH except that anaerobic digestion of the organic fractions with biogas recovery is compulsory instead of composting.

Note that the amount of source separation is fixed within each main scenario. Furthermore, in all main scenarios, industrial waste and construction and demolition waste is centrally separated, followed by recovery of materials, incineration of combustible fractions and landfilling of residual fractions. These two constraints are consequences of the main scenario assumptions on source separation and the ban on landfilling.

4.4. Options analysed in the district heating study

A number of options for heat production are analysed in the district heating study using the marginal-cost ordering procedure. One economically optimal heat production configuration is calculated for each of the four scenarios.

The options analysed are: heat production from oil, wood chips, coal, natural gas and peat; combined heat and power production from oil, wood chips, coal, natural gas and peat; electric boilers; heat pumps; waste heat; and importing heat from the waste management system. The production options and their systemic relations are illustrated in the Appendix.

5. Results

5.1. The economics of recovering energy from waste from a waste management perspective

The first question put forward in this study is ‘Is energy recovery from waste economic from a waste management perspective?’. To answer the question, the economically optimal solutions within the waste management study are presented.\textsuperscript{14} In addition, the importance of the ban on landfilling for the results is explored.

5.1.1. The economically optimal solutions in the waste management study

In the waste management study, 16 optimal solutions are calculated, one for each combination of main and sub-scenario. For the main scenarios Base, High Carbon and Bio, each sub-scenario results in the same optimal solution, irrespective of main scenario. The Recov scenario also results in the same optimal solutions, but the

\textsuperscript{14} Henceforth, ‘optimal’ is used synonymously with ‘economically optimal’.
quantities differ from the other scenarios as a result of the higher minimum level of source separation. The main features of the optimal solutions are shown in Table 4.

In the optimal solution in the DH sub-scenario, all household waste remaining after source separation is incinerated. Industrial and construction and demolition waste are centrally separated, followed by recovery of materials, incineration of combustible fractions and landfilling of residual fractions. The energy is recovered as heat. The optimal solution in sub-scenario CHP is the same as the DH optimum with the exception that energy is recovered as combined heat and power. The optimal solution in sub-scenario C&DH differs from the one in DH in that all household waste is centrally separated followed by composting of organic fractions, incineration of combustible fractions and landfilling of residual fractions. In sub-scenario AD&DH, the optimal solution is the same as that of the C&DH sub-scenario, except that composting is exchanged for anaerobic digestion. Heat is recovered from incineration. Biogas is used to produce heat and power, except in the Bio scenario, in which biogas is sold as a vehicle fuel.

Although the optimal solutions are the same for each sub-scenario, irrespective of main scenario, total costs vary since cost-related assumptions, such as investment costs and sales prices, differ between the main scenarios. Fig. 4 shows the difference in total annual costs for the optimal solutions. All costs are compared to the optimal solution in sub-scenario DH in the Base scenario.

In the Base scenario, investing in new combined heat and power recovery (sub-scenario CHP) instead of heat recovery alone (sub-scenario DH) results in a total cost increase of 180 MSEK/year, because the value of the power recovered does not compensate for the higher investment costs. The solutions in which incineration with heat recovery is combined with composting or anaerobic digestion (sub-scenarios C&DH and AD&DH) increase the costs by 560 and 840 MSEK/year, respectively. This owes to low sales prices for compost and digestion residues and high costs for separating the organic waste from other waste fractions and for landfilling the separation residues. Furthermore, the investment costs of anaerobic digestion are high.

In the High Carbon scenario, where the price of power at the margin is lower, the total costs for sub-scenarios CHP and AD&DH increase, while the costs of the other optimal solutions are unchanged compared to the Base scenario.

In the Bio scenario, where the values for compost, digestion residues and biogas are higher and the costs for biological treatment are lower, the total costs for sub-scenarios C&DH and, in particular, AD&DH are essentially reduced. The costs for sub-scenario AD&DH is close to those for sub-scenario DH, mainly because of the low treatment costs and high value of biogas, while C&DH, in spite of the reduction, is the most expensive sub-scenario in Bio.

In the Recov scenario, all optimal solutions reduce costs significantly compared to the Base scenario. All sub-scenarios, except AD&DH, even result in decreased costs compared to DH in Base. In Recov, the sales prices of the Producer’s responsibility products are extended and applied to the whole fraction of the respective materials (Table 2). This assumption could be considered as an overestimation of their value. But when substituting the sales prices in Recov for the ones in Base, total costs in
Table 4
Main features of the economically optimal waste management solutions (kt/year)

<table>
<thead>
<tr>
<th>Sub-scenario</th>
<th>Incineration (w. heat recovery)</th>
<th>Incineration (w. comb. heat &amp; power recovery)</th>
<th>Composting</th>
<th>Anaerobic digestion</th>
<th>Landfilling</th>
<th>Source separation</th>
<th>Central separation</th>
<th>Material recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>DH</td>
<td>3098</td>
<td>n.a.</td>
<td>0</td>
<td>n.a.</td>
<td>2167</td>
<td>1597</td>
<td>2246</td>
<td>1712</td>
</tr>
<tr>
<td>CHP</td>
<td>1883</td>
<td>1215</td>
<td>0</td>
<td>n.a.</td>
<td>2167</td>
<td>1597</td>
<td>2246</td>
<td>1712</td>
</tr>
<tr>
<td>C&amp;DH</td>
<td>1574</td>
<td>n.a.</td>
<td>1275</td>
<td>n.a.</td>
<td>1932</td>
<td>1597</td>
<td>4575</td>
<td>1712</td>
</tr>
<tr>
<td>AD&amp;DH</td>
<td>1574</td>
<td>n.a.</td>
<td>n.a.</td>
<td>1275</td>
<td>1932</td>
<td>1597</td>
<td>4575</td>
<td>1712</td>
</tr>
</tbody>
</table>

Recov (kt/year)

| DH                 | 2486                           | n.a.                                          | 0           | n.a.                | 1818        | 2480              | 1713               | 2527              |
| CHP                | 1883                           | 603                                           | 0           | n.a.                | 1818        | 2480              | 1713               | 2527              |
| C&DH               | 1036                           | n.a.                                          | 1275        | n.a.                | 1586        | 2480              | 3711               | 2527              |
| AD&DH              | 1036                           | n.a.                                          | n.a.        | 1275                | 1586        | 2480              | 3711               | 2527              |

NB, The quantities of recovered energy are presented in Section 5.2.
Recovery are still reduced compared to Base. For example, with these low sales prices, sub-scenario DH in main scenario Recovery reduces the costs by 400 MSEK/year compared to sub-scenario DH in Base. This result indicates that the economic advantages of material recovery depend not only on revenues from selling the materials, but also on the fact that costs are avoided when less actual waste is treated in the system.

One can conclude that, from the waste management point of view, recovering energy from waste is part of all optimal solutions. However, the cheapest optimal solution is not to maximize the quantity of energy recovered, but to combine energy recovery with a high level of material recovery as in sub-scenario DH in the Recovery scenario. This is mainly explained by the relatively high specific values for recovered materials and heat. Investing in new heat recovery (sub-scenario DH) is less expensive than combined heat and power recovery (sub-scenario CHP) as long as the value of power does not exceed 350 SEK/MWh. Investing in composting or anaerobic digestion (sub-scenarios C&DH and AD&DH) is more expensive in all of the main scenarios, except for in the Bio scenario, where the low treatment costs and high value of biogas substantially reduces the costs of anaerobic digestion. Note that the difference in costs does not exceed 13% of the total turnover for Swedish waste.
management for any optimal solution (The Swedish Association of Waste Management, 1997).

5.1.2. The importance of the ban on landfilling

The ban on landfilling of combustible and organic waste is to a large extent decisive for the outcome of the results in the waste management study. Fig. 5 shows the optimal recovery of heat when the sales price of the heat is varied in sub-scenario DH in the Base scenario. With the landfill ban in place, all waste available for energy recovery is used at heat sales prices over 50 SEK/MWh. Below 50 SEK/MWh, some household waste is diverted from incineration to composting.

Without the ban on landfilling, also in the figure, energy recovery is more sensitive to the sales price for heat. At the price of 140 SEK/MWh, recovery is considerably lower, since only incineration of household waste is optimal.15 Below 70 SEK/MWh, all non-source-separated industrial and construction and demolition waste is landfilled and the sales price must reach 350 SEK/MWh before all is incinerated.

It is clear that as long as the ban on landfilling is in force, there are no viable alternatives to incinerating certain fractions of industrial and construction and demolition waste. In addition, incinerating all non-source-separated household waste is economically favourable. An exception is if one would have to pay to

15 140 SEK/MWh is the assumed average sales price in all of the main scenarios.
dispose of the heat, which would make composting or anaerobic digestion of parts of the household waste preferable.

5.2. Quantity of energy recoverable from waste

The results in Section 5.1 show that recovering energy from waste is part of all waste management solutions studied. The quantity of recovered energy does, however, vary depending on main and sub-scenario, which answers the second question of this study: ‘Is there a significant untapped energy resource in the form of waste in Sweden?’

Based on the waste types included in the study (Section 4.2), the recovered energy ranges from 7.1 to 8.5 TWh of heat, from 0 to 1.0 TWh of power and 0 to 1.1 TWh of biogas, as shown in Fig. 6. With higher waste separation efficiency, recovered energy from incineration could increase by approximately 1 TWh.

Fig. 6 also shows that recovered heat is reduced to 5.6 TWh in the Recover scenario, where the quantity of material recovery increases. However, in no case, energy recovery from waste decreases compared to the current situation. In 1998, 5.8 TWh of heat and 0.4 TWh of power were recovered.

Note that no attempt was made to estimate the total potential for recovering energy from waste in Sweden in this study. Studies focusing on estimating the total potential include additional waste types such as industry-specific industrial waste and waste from municipal wastewater (Swedish Environmental Protection Agency,
1999; Swedish Bioenergy Association, 1998; Profu, 1999). The results of these vary considerably (7, 15 and 40 TWh, respectively), due to such factors as different waste types included, uncertain statistics, and different assumptions regarding what waste is available for energy production (which, in turn, is a consequence of assumptions regarding the extent of material recovery, biological waste treatment and waste minimizing activities). Therefore, it is difficult to estimate the additional energy resource in waste types not included in this study.

5.3. Competitiveness of energy recovered from waste

Recovering energy from waste is part of all waste management solutions studied. But is recovering energy from waste economically competitive with other forms of heat production? If so, what are the economically competitive quantities? The third question of this study is explored in the district heating study.

Fig. 7 shows how the economically optimal import of recovered heat from waste to the district heating system varies with the price of the heat. The total demand for heat is 41 TWh. Existing industrial and municipal waste heat cover 4 TWh at no cost, which leaves 37 TWh to be covered by other production options.

The results of the Base, Bio and Recov scenarios are the same, since they do not differ with regard to energy-related assumptions. At heat prices below 50 SEK/MWh, import to the district heating system of heat recovered from waste reaches the maximum of 37 TWh, since no production options are cheaper. At prices over 50 SEK/MWh, other options become less expensive, and less recovered heat is imported as the price increases. At heat prices between 50 and 100 SEK/MWh, bio-fuelled combined heat and power plants are more competitive. Between 100 and 200 SEK/MWh, heat pumps, bio-fuelled heat plants and fossil-fuelled combined heat and

![Fig. 7. Optimal import of recovered heat from waste to the district heating system (TWh/year) as function of the price of heat (SEK/MWh).](image-url)
power plants are more competitive. Between 200 and 300 SEK/MWh, the options are fossil-fuelled heat plants. Over 350 SEK/MWh, all other options are more competitive.

In the High Carbon scenario, the lower power price changes the marginal heat production costs of the options that consume or produce power. The costs of electric boilers and heat pumps are reduced, whereas they are increased for combined heat and power plants. However, the competitiveness of importing heat recovered from waste is nearly unchanged compared to the Base, Bio and Recov scenarios (Fig. 7).

The results in Fig. 7 must be interpreted with care. Waste incineration is typically a base load technology with long operational time, an even fuel supply and production over the year. Therefore, it is unlikely that heat recovered from waste would replace typical peak load technologies such as electric boilers and fossil-fuelled heat plants. However, in the analysis, heat recovered from waste was modelled as a completely flexible import to the district heating system. A first correction to account for the consequences of this simplification would be to reduce the import by the amount of peak load, i.e. around 5 TWh, over the entire span of the price of heat.

Three conclusions can be drawn from Fig. 7. First, importing heat recovered from waste to the district heating system is economically competitive compared to many other heat production options. In particular, at heat prices between 0 and 150 SEK/MWh there is a large market. Second, the results in the waste management study indicate that, even at low heat prices, recovering heat from waste is optimal in the waste management system (Fig. 5). Thus, heat recovered from waste is available to the district heating system in the price range where it has a large market. Third, in this price range, the market is larger than the supply of heat recovered from waste presented in Section 5.2. This implies that other waste types not included in this study could be used for recovering heat if it can be made available in the same price range.

5.4. The global warming implications of energy from waste

What are the global warming implications of recovering energy from waste? A comparison of GWPs answers the last question of this study with regard to potential climate effects of fossil carbon dioxide, methane and nitrous oxide. The total GWPs for different combinations of waste management and district heating systems were calculated, which is explained in Section 3.3. Then, each total GWP was compared to that of the combination of waste management and district heating representing sub-scenario DH in the Base scenario.

Fig. 8 shows the difference in total GWP compared to that of sub-scenario DH in the Base scenario. The individual contributions of waste management, district heating, power, and use of vehicle fuel are also shown.

In the Base scenario, sub-scenario CHP results in the lowest total GWP, while DH and AD&DH result in nearly the same higher total GWP, and C&DH results in the highest total GWP. The difference in GWP of the waste management system between the sub-scenarios is small. But since the quantity of heat and power recovered in the waste management system differs, the production in the district
heating and power systems required for keeping the total production constant differs. This, in turn, affects the GWP for the district heating and power systems. CHP results in an especially low total GWP compared to DH, because the power
produced in the waste management system makes it possible to reduce natural-gas-based production in the power system. In terms of GWP, the benefit of producing less fossil-based power outweighs the disadvantage of increased production in the district heating system. In C&DH, the higher total GWP is explained by the fact that no power and less heat are recovered in the waste management system. In AD&DH, waste incineration recovers heat, and biogas is used for combined heat and power recovery. The total quantity of heat recovered in the waste management system is smaller than in DH, but thanks to the benefit of biogas based power, the total GWP of AD&DH is nearly equal to that of DH.

In the High Carbon scenario, the total GWP for sub-scenarios CHP and AD&DH are improved compared to DH and C&DH. This is because the power produced in the waste management system replaces power based on coal in High Carbon, whereas it replaces power based on natural gas in Base (with lower GWP per unit of power produced). Note that since some district heating options consume or produce power, the GWP of the district heating system is also affected by the marginal power production. This explains, e.g. why the total GWP for C&DH is higher in the High Carbon than in the Base scenario.

The Bio scenario differs from Base only in sub-scenario AD&DH. In Bio, the biogas produced is used as a vehicle fuel instead of diesel, whereas it was used for combined heat and power production in Base. This results in slightly lower total GWP for AD&DH in Bio than in Base.

With increased material recovery in the Recov scenario, the share of plastics in the waste incinerated is reduced. This results in a substantial reduction in the GWP of the waste management system, in spite of increased local transport of recovered material. The GWP of the district heating system increases since production is increased in order to keep total heat production constant. However, because the reduction in the waste management system is larger than the increase in the district heating system, all sub-scenarios result in lower total GWP in Recov than in Base. Note that this also holds for sub-scenarios CHP and AD&DH, which benefit less from reduced production in the power system in Recov than in Base.

Since incineration of plastics was found to have such a large impact on the GWP, an alternative set of GWPs was calculated for the Alt Recov scenario, equal to the Recov scenario except for that production in the power system is based on coal (as in High Carbon). The Alt Recov scenario shows that the difference in total GWP for all sub-scenarios except CHP are reduced compared to High Carbon, but to a smaller extent than in Recov.

One can conclude that there are three factors that are most decisive for the total GWP:

- The quantity of heat and power recovered in the waste management system,
- The content of plastics of the waste incinerated, and
- The emissions of the fossil fuel used for marginal production in the power system (which also affects the emissions from the district heating system).
Fossil CO₂-emissions from combustion dominate the GWPs of both the district heating and the power systems, while the contributions from methane and nitrous oxides are negligible. The exception is when power production is coal-based, where pre-combustion methane contributes about 20% of the GWP of the power system. Fossil CO₂-emissions from local transport of waste and recovered material are of less importance, as are nitrous oxide emissions from composting. Methane emissions from landfilling are a major contribution to the GWP of the waste management system (between 30 to 50%), but the quantities differ little between the scenarios.

As long as the production at the margin in the power system is based on fossil fuels, sub-scenario CHP with combined heat and power production in the waste management system is the best alternative in terms of the GWP. However, the total GWP differs significantly depending on the scenario. If natural gas is used to produce power at the margin, the best way of reducing the GWP is to increase the material recovery of plastics, thereby decreasing the plastics content of the waste incinerated (as in the Recov scenario). This results in a lower total GWP than when more energy is recovered in the waste management system (as in the Base scenario). Note that with the composition of the waste incinerated in both the Base and Recov scenarios, the GWP per unit of heat produced is higher in the waste management system than in the district heating system. This implies that if material recovery were to increase even more than it does in the Recov scenario, and the district heating system kept its large share of non-fossil fuels, it would be possible to reduce the total GWP even more.

The results are different if coal is used to produce power at the margin. Power recovery in the waste management system is highly valuable for reducing the GWP. The lowest total GWP is obtained when producing as much combined heat and power in the waste management system as possible (CHP in High Carbon) and not when recovering more plastics and less energy in the waste management system (CHP in Alt. Recov). For the other sub-scenarios, however, the total GWP differs little between the High Carbon and Alt. Recov scenarios.

In terms of the GWP, both anaerobic digestion and incineration with energy recovery are better ways of treating the organic waste than composting. The choice of anaerobic digestion or incineration with heat recovery is of little importance for the total GWP, unless biogas is used for combined heat and power production and replaces coal-based power production (as in the High Carbon scenario). Furthermore, using biogas for combined heat and power production is nearly equivalent to using biogas as a vehicle fuel instead of diesel, unless production in the power system is based on coal.

It is worth noting that the ban on landfilling of organic waste can reduce the total GWP of Sweden. Without the ban on landfilling in force, sub-scenarios DH and CHP include more methane-generating landfilling and less energy recovery from waste in all main scenarios. The strong contribution of methane to the GWP results in a considerably higher total GWP than that of all sub-scenarios with the ban in force.
6. Discussion

6.1. The economics of recovering energy from waste from a waste management perspective

From the waste management perspective, the most economic option of those studied is that which combines increased material recovery and incineration with heat recovery (sub-scenario DH in the Recov scenario). This is mainly because recovered materials and heat are highly valued, but also because less actual waste is treated in the waste management system.

It must be emphasised that the prices for recovered materials are uncertain. For example, the recovery of packaging materials is financed within the Ordinances of the Producer’s responsibility and not on a free market. Whether or not it is possible to maintain the same prices when recovered quantities increase is uncertain. The prices for products and materials not recovered previously are also uncertain. Furthermore, in this study, material recovery is mainly based on source separation and drop-off centres. This means that the actual separation is performed outside the system studied and, consequently, that the costs for separating at the household or company level are not included. Furthermore, the evaluation of the results is restricted to the recovery of a group of materials and not individual materials. No evaluation of the practicability of increasing material recovery to levels studied in the Recov scenario has been performed.

In conjunction with the landfilling tax, the possibility of introducing a tax on waste incineration is being discussed in Sweden (Swedish News Agency, 1999). The tax on waste incineration would favour material recovery and biological treatment of waste. This could reduce the economic potential for recovering energy from waste in Sweden.

Combined heat and power recovery from waste is not cost-effective compared to heat recovery only from a waste management point of view. The higher investments needed for combined heat and power recovery do not pay off given the anticipated power prices on the Nordic power market. However, it is possible that power prices will have approached the break-even level of 350 SEK/MWh by the year 2050 (Unger et al., 2000).

During the 1990s, the Swedish government has promoted biological treatment of waste, with investment allowances for biological treatment. This study shows that composting and anaerobic digestion need subsidies alternatively strong reductions in specific treatment costs to be cost-competitive options. Also, selling recovered biogas as a vehicle fuel can increase the cost-competitiveness of anaerobic digestion.

6.2. The competitiveness of energy recovered from waste

From the district heating supply point of view, heat recovered from waste has a large market potential if it can be imported to the district heating system in the price range of 0–150 SEK/MWh. In this price range, it can compete with bio-fuelled
combined heat and power plants, heat pumps, bio-fuelled heat plants and fossil-fuelled combined heat and power plants.

It is assumed that energy related taxes are unchanged compared to today in the study. However, if the Nordic CO$_2$-target would be reached through changes in taxation, and not through a commitment as assumed in the Base, Bio and Recov scenarios, the competitiveness of recovering energy from waste would be altered in these scenarios. Higher taxes on fossil fuels (such as the tax on fossil CO$_2$) would increase the costs for some of the district heating options with which heat recovery from waste competes, and, consequently, increase the competitiveness of heat recovery from waste. On the other hand, other changes in taxation of fuels, not specifically aiming at reducing fossil CO$_2$-emissions, are being debated in Sweden. These changes, which regard, e.g. lower taxes on combined heat and power production, would have the opposite effect, reducing the competitiveness of heat recovery from waste.

The study is based on the current district heating production mix. This means that the CO$_2$-target in the Base, Bio and Recov scenarios has been allocated to the power system only. However, if it was allocated to the district heating system also, the use of oil and coal would probably be reduced compared to today. The consequences for the economic competitiveness of heat recovered from waste are however impossible to estimate without a more detailed district heating study.

6.3. Energy recovery potential from waste

The analysis shows that there is a significant potential to increase energy recovery from waste in Sweden. Compared to the current situation, the size of the potential for the waste types included in this study could be sufficient to nearly double the amount of energy recovered from waste on a national scale. The district heating system can be expected to absorb more than the potential identified. But this requires that additional waste fractions are made available at costs close to the ones for the waste fractions analysed. Additional waste fractions could include e.g. other industrial waste, sludge from wastewater treatment and park and garden waste.

Importing waste from outside of Sweden could be a way of increasing the quantities available for energy recovery. The facts that landfilling is being phased out in Europe and that the extensive demand for district heating leads to better economics for recovering energy from waste in Sweden than in many European countries, speak for importing waste to Sweden as a possibility. In fact, combustible waste fractions are already being imported on a small scale (The Swedish Association of Waste Management, 1999). However, the economic and environmental aspects of adopting this solution on a large scale as well as its alternatives need to be examined closely.

Other factors speak for a smaller energy recovery potential from waste than that shown in this study. The potential depends to a large extent on material recovery, as illustrated by the Recov scenario. If material recovery increases radically, the potential is only slightly larger than today. The potential also depends on the
quantities of waste generated and whether or not waste minimising activities are successfully realised on a large scale.

6.4. Global warming implications

The global warming implications of three greenhouse gases have been assessed: fossil CO$_2$, methane and nitrous oxide. Other emissions or environmental aspects that could be of importance are beyond the scope of this study. Emissions, e.g., of nitrogen oxides, sulphur oxides and heavy metals could also be of interest. Furthermore, the environmental effects, e.g., of processing of recovered materials into new products and nutrient recirculation and the offset burdens from such activities have not been evaluated. However, in a subsequent study it was found that the environmental effects of these activities did not affect the overall conclusions from the analysis (Ljunggren Söderman, 2000).

The fact that the emissions from district heating are based on the current production mix has consequences for the global warming implications (as well as for the competitiveness of heat recovery from waste, see Section 6.2). If the CO$_2$-target affected the production mix in the district heating system, the use of oil and coal would probably be reduced compared to today. In terms of GWP, the value of heat recovery from waste would then decrease compared to the results in the Base, High Carbon, Bio and Reco scenarios.

GWP of the district heating system is based on the average GWP of Swedish district heating systems. This means that, locally, the benefit of recovering heat from waste would be larger in some district heating networks than shown in this study, while it would be smaller in others. However, since some district heating options consume or produce power, the average GWP of the district heating system is affected by the assumptions regarding the marginal power production. Consequently, the different scenarios capture some of these local variations.

Material recovery is analysed as recovery of a combination of materials. No analysis of individual materials is performed. Therefore, it is not possible to draw full conclusions as to what materials to recover as material and what materials to recover as energy. However, the results indicate that, in terms of the GWP, material recovery of plastics is preferable to energy recovery.

6.5. Methodological aspects

This study illustrates that recovering energy from waste is economically optimal in both the waste management and district heating systems in Sweden. However, the joint optimal solution was not calculated because of the presumed large difference between the size of the market and the supply potential analysed. Total optimisation combining the two sectors is further explored in the regional study mentioned in Section 1. A future research task would be to investigate the availability, costs and environmental aspects of other waste types suitable for energy recovery and to compare that with the market in the district heating system on a national level. The
lack of reliable statistics on waste quantities and compositions would be the largest obstacle to performing such a task.

A few aspects of the district heating study must be kept in mind when considering the results. One is that the study neglects the operational characteristics of heat production, which is discussed in Section 5.3. Another aspect is that the district heating system is simplified as one single system. This has particularly important consequences for the global warming implications because of the varying configurations of local district heating systems, as explained in Section 3.2. A third aspect to consider is the fact that the study is based on the current district heating production mix. This involves assumptions about the CO2-target allocation, which has consequences for the competitiveness of heat recovered from waste and the global warming implications, as explained in Section 6.2 and Section 6.4. It is of course possible that the mix will have changed by the year 2010, as a result of other driving forces than CO2-targets. One example is the possibility of investing in new cheaper production options, which is not evaluated in the district heating study.

In the waste management study, the Swedish waste management system is described as ten generalised municipal systems. This approach provides more information than the single system approach in the district heating study, but does not encompass all of the local variations.

It should be stressed that both the waste management and district heating studies are based on the assumption that all actors within the respective systems co-ordinate and co-optimise their activities. There are of course numerous hindrances for realising such a situation. Nevertheless, the study is valuable in that it illustrates the value of such co-operation.

7. Summary and conclusions

As long as the waste quantities generated are not significantly reduced compared to today, waste can be a resource for replacing virgin fuels and materials. The possibilities for recovering energy from waste in Sweden are explored in this paper. Recovering energy from waste involves at least two systems: the waste management system and the district heating system. In this study, both systems have been explored by using separate systems engineering models.

It is found that recovering energy from waste is part of all optimal solutions. This is because recovering energy from waste is necessary in order to fulfil the ban on landfilling. As a consequence, the ban has a major impact on all of the results in this study.

However, the optimal quantity of energy to recover from waste differs considerably depending on the system perspective taken. From a waste management point of view, the economically optimal solution is to combine heat recovery with a high level of materials recovery. In this case, the quantity of heat recovered is 5.6 TWh, which is close to the present level. The waste management study does not include all existing waste types, but the effect of this on the results is unclear, since estimates of the size of the total Swedish potential vary considerably.
The potential to recover heat from waste is considerably larger from the district heating point of view. As long as heat recovered from waste can be imported to the district heating system to a price of below 150 SEK/MWh, the potential is in the range of 10–30 TWh. One could argue that such a sales price is quite plausible, since there are no viable alternatives to energy recovery of certain waste fractions because of the ban on landfilling.

The analysis of the global warming implications of recovering energy from waste shows that the preferable solution is to combine materials recovery and combined heat and power from waste. If the power recovered in the waste management system replaces natural-gas-based power, a high level of materials recovery is preferable, as in the Recov scenario. But if the power replaced is coal-based, a lower level of materials recovery combined with a higher level of energy recovery is better, as in the High Carbon scenario. Thus, the results depend not only on whether the power replaced is produced from a fossil or a non-fossil fuel, but also on what on fossil fuel is replaced.

The approach of using two separate existing systems engineering models, as was done in this study, is less suitable for analysing interplay than a fully integrated approach. However, such an approach would have required extensive modelling work for adapting existing models to Swedish conditions. In light of this, it has been advantageous to use the approach herein. Furthermore, to increase the understanding of the issue of recovering energy from waste, it would probably be more informative if the district heating study was extended to include the power system, than to perform a fully integrated study of waste management and district heating. Including the power system in the analysis would give a better understanding of the potential development of the district heating system, which would, e.g. make it possible to study the competitiveness of combined heat and power recovery from waste from an energy perspective.

By bringing both the waste management and the district heating systems into focus, knowledge has been gained. The district heating study reveals a future market for heat recovery from waste that could be significantly larger than today. The waste management study points out that new policy instruments will be introduced in Swedish waste management that could direct waste towards increased energy recovery if the materials recovery sector does not develop strongly. These potential changes would have been more difficult to foresee had one system or the other been restricted to consideration as part of the system environment.

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Division were helpful. The Swedish National Energy Administration financed the study.

Appendix

Figure A1. Graphic representation of the NatWaste model. Reference Energy and Material System (REMS) for one of the ten coupled generalised municipal waste management systems.
Figure A2. Graphic representation of the marginal-cost ordering procedure. Reference Energy System (RES) for the district heating system (HP, heat production; CHP, combined heat and power production).

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