Environmental sustainable utilization of waste resources for energy production

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Technical University of Denmark

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DTU Environment
Department of Environmental Engineering

PhD Thesis
March 2010

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Preface

The work reported in this PhD thesis entitled "Environmentally sustainable utilization of waste resources for energy production" was carried out at the Department of Environmental Engineering at the Technical University of Denmark (DTU) from August 2006 to January 2010. The thesis was supervised by Professor Thomas Højlund Christensen and funded 1/3 by DTU and 2/3 by the Danish Council for Strategic Research.

The content of the thesis is based on six scientific journal papers prepared in collaboration with internal and external partners. The papers are in the text referred to by the name of the authors and their appendix number written with Roman numerals, e.g. Fruergaard et al. (I).

I Fruergaard, T., Ekvall, T. & Astrup, T. (2009): Energy use and recovery in waste management and implications for accounting of greenhouse gases and global warming contributions. Waste Management & Research, 27, 724-737.

II Mathiesen, B.V., Münster, M. & Fruergaard, T. (2009): Uncertainties related to the identification of the marginal energy technology in consequential life cycle assessments. Journal of Cleaner Production, 17, 1331-1338.

III Fruergaard, T., Christensen, T.H. & Astrup, T. (2009): Energy recovery from waste incineration: Assessing the importance of district heating networks. (Submitted to Waste Management).

IV Fruergaard, T. & Astrup, T. (2010): Optimal utilization of waste to energy in an LCA perspective. (Submitted to Waste Management).

V Astrup, T., Møller, J. & Fruergaard, T. (2009): Incineration and co-combustion of waste: accounting of greenhouse gases and global warming contributions. Waste Management & Research, 27, 789-799.

VI Damgaard, A., Riber, C., Fruergaard, T., Hulgaard, T. & Christensen, T.H. (2010): Life-cycle-assessment of the historical development of air pollution control and energy recovery in waste incineration. (Manuscript).

The papers are not included in this www-version but can be obtained from the library at DTU Environment. Contact info: Library, Department of Environmental Engineering, Technical University of Denmark, Miljoevej, Building 113, DK-2800 Kgs. Lyngby, Denmark or library@env.dtu.dk.

March 2010
Thilde Fruergaard

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Summary

Energy recovery from waste is a highly prioritized treatment option in Denmark, and energy from waste accounts for approximately 20 % of the annual heat production and 4 % of the electricity production. Utilization of other fuel types would be necessary if waste was not available for energy production. To evaluate the environmental impacts of energy recovery from waste, the interactions with the energy system have to be identified as the substitution of other fuels may have profound effects on the outcome. Identification of energy substitution is further related to the overall framework of the assessment, i.e. definition of the goal and scope. The main aim of this PhD thesis was to provide a systematic framework for life cycle assessment (LCA) modeling of waste-to-energy technologies.

This thesis included the following main activities:

- Establishment of a framework for accounting of greenhouse gases related to energy use and recovery within waste management. Such a framework was also established for waste incineration and co-combustion in a study assessing the importance of direct greenhouse gas emissions relative to indirect emissions.
- Assessment of the uncertainties related to identification of the marginal technology for electricity production. This included a review of developments in marginal technologies from a historical perspective, a survey focusing on how the marginal technology was identified and assessed in different studies, and an energy system modeling of the Danish energy system evaluating the consequences of increased waste incineration in a (future) short-term perspective.
- Evaluation of the importance of local conditions for quantifying the environmental consequences of waste incineration with energy recovery. Two specific district heating networks were used as basis for the assessment focusing on important design and operational properties of the other heat producing facilities in the network to which the waste incinerator was connected.

- LCA of three waste-to-energy technologies treating two different types of waste: organic household waste and solid recovered fuel (SRF). Anaerobic digestion was evaluated as treatment method for organic household waste, and co-combustion at a coal-fired power plant was evaluated as treatment method for SRF. Both waste fractions were compared with waste incineration with and without energy recovery.
- LCA of the historical development of air pollution control technologies for waste incinerators and the importance of energy substitution in this context.

Based on these activities the following goal and scope related factors were identified as critical to ensure transparency and consistency in LCA studies of waste-to-energy technologies: 1) goal definition, 2) the LCA approach, 3) the scale of the change, 4) the time perspective, 5) the technological and 6) the geographical scope, and 7) the effects of the CO_2 emission trading scheme. Also the type of effects (short-term or long-term) included in the LCA was identified as critical for the outcome. It was recommended to focus on determining the long-term effects, i.e. decisions affecting investments in production capacity. As future effects are associated with substantial uncertainties, it was recommended to test the importance of energy substitution for the LCA results by using two significantly different technologies. Wind and coal were recommended for electricity production, and biomass and coal (or another type of fossil fuel depending on the local conditions) for heat production.

Several contributions besides energy substitution were identified as significant for the results of an LCA of waste-to-energy technologies. The toxic impact categories were heavily influenced by emissions of heavy metals related to the chemical composition of the waste and the technology considered. Assumptions concerning the final disposal of digestate from anaerobic digestion were important for nutrient enrichment as well as the toxic impact categories.

Recommendations for treatment of combustible waste in Denmark depended to some extent on the focus of the assessment. However, waste incineration with energy recovery proved to be the best alternative in the majority of impact categories provided all heat could be utilized.

Dansk sammenfatning

Energiudnyttelse af affald er højt prioriteret i Danmark, og affaldsbaseret energi udgør ca. 20 % af den producerede varme og 4 % af elektriciteten. Hvis ikke affald var tilgængeligt for energiudnyttelse skulle andre brændsler anvendes i stedet. I en evaluering af de miljømæssige påvirkninger af energiudnyttelse af affald er det vigtigt at tage højde for udvekslingerne med energisystemet, da disse kan have stor betydning for resultatet. Det samme gælder for de faktorer, der definerer undersøgelsens rammer, dvs. definition af målsætning og afgrænsning. Formålet med denne phd-afhandling var at fastlægge de nødvendige rammebetingelser for livscyklusvurderinger (LCA) af affaldsbaserede energiteknologier.

Afhandlingen har omfattet de følgende aktiviteter:

- Etablering af rammebetingelser for opgørelse af drivhusgasser relateret til energiforbrug og energigenvinding i affaldshåndtering. Lignende rammebetingelser var etableret for affaldsforbrænding og medforbrænding i et studium, der kortlagde betydningen af de direkte emissioner af drivhusgasser i forhold til de indirekte.
- En undersøgelse af usikkerhederne knyttet til identificering af den marginale teknologi for produktion af elektricitet. Dette studium omfattede en gennemgang af udviklingen i marginale teknologier set i et historisk perspektiv, en undersøgelse af fremgangsmåden for at bestemme den marginale teknologi i en række studier samt en energisystemanalyse af de (fremtidige) kortsigtede konsekvenser af øget affaldsforbrænding i Danmark.
- En evaluering af betydningen af lokale forhold for en kvantificering af de miljømæssige konsekvenser af affaldsforbrænding med energiudnyttelse. Undersøgelsen var baseret på to specifikke fjernvarmenet, og fokus for undersøgelsen var betydningen af de konstruktions- og driftsmæssige parametre af de andre varmeteknologier ligeledes tilsluttet fjernvarmenettet.
- En LCA af tre affaldsbaserede teknologier til behandling af to typer affald: organisk husholdningsaffald og energirige affaldsfraktioner (RDF). Bioforgasning var evalueret som behandlingsmetode for det organiske

husholdningsaffald, og medforbrænding på et kulfyret kraftværk var undersøgt for RDF. For begge affaldstyper blev affaldsforbrænding med og uden energiudnyttelse brugt som reference.

- En LCA af den historiske udvikling af røggasrensningsteknologier for forbrændingsanlæg samt betydningen af energiudnyttelse.

Baseret på disse aktiviteter blev følgende målsætnings- og afgrænsningsrelaterede faktorer identificeret som værende kritiske i forhold til at sikre gennemsigtighed og sammenhæng i LCA studier af affaldsbaserede energiteknologier: 1) definition af målsætning, 2) LCA-tilgangen, 3) omfanget af ændringen, 4) tidsperspektivet, 5) den teknologiske og 6) den geografiske afgrænsning og 7) effekterne af det europæiske CO_2 kvotesystem. Også typen af de inkluderede effekter (kortsigtede eller langsigtede) blev identificeret som værende kritiske. Det blev anbefalet at fokusere på de langsigtede effekter, dvs. de investeringsmæssige effekter. Da fremtidige effekter er behæftet med stor usikkerhed, blev det anbefalet at teste betydningen af energisubstitution for LCA'ens resultater ved at anvende to signifikant forskellige teknologier. Det blev anbefalet at benytte kul og vind for elektricitetsproduktion samt biomasse og kul (eller et andet fossilt brændsel afhængigt af de lokale forhold) for produktion af varme.

Udover energisubstitution blev adskillige bidrag identificeret som vigtige for resultaterne af en LCA af affaldsbaserede teknologier. Emissioner af tungmetaller relateret til affaldets kemiske sammensætning og den specifikke teknologi havde stor betydning for de toksiske påvirkningskategorier. Antagelser vedrørende behandlingen af rådneresten fra biogasprocessen var vigtige i forhold til næringssaltsbelastning og de toksiske påvirkningskategorier.

Anbefalinger for behandling af den brændbare affaldsfraktion i et dansk perspektiv afhang i nogen grad af undersøgelsens fokus. Ikke desto mindre var affaldsforbrænding med energiudnyttelse det bedste alternativ i hovedparten af påvirkningskategorier, forudsat at al varme kunne udnyttes.

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1 Introduction

The increased focus on energy resources and climate has altered the perception of waste. Waste prevention is still the main goal; nevertheless, it is now generally accepted that waste may be beneficial to the environment provided the waste is managed properly. However, determining whether or not a given waste management option is beneficial is not a straightforward task as many parameters influence the results. The waste management system is not an isolated unit but interacts with the surroundings: especially interactions with the energy system have a profound effect. As utilization of waste for energy production has high priority in the Danish waste management system, assessing these interactions and explaining their consequences are the focal points of this thesis.

1.1 Waste based energy production in Denmark

Various waste-to-energy technologies exist today, such as waste incineration, anaerobic digestion, gasification, etc. Mass burn incineration is the most common. Denmark is one of the countries in Europe where waste incineration with energy recovery percentage-wise constitutes the largest part of the waste treatment options. According to the Danish Environmental Protection Agency, 58 % of the household waste was incinerated in 2006, 33 % recycled and 9 % landfilled (DEPA, 2008). Waste incineration was also a dominant treatment method for waste from the service sector (45 % incinerated), but less significant for the industrial sector (14 % incinerated). In total, 3.5 million tonnes of waste was incinerated in 2006. A main reason for the widespread distribution of waste incineration in Denmark is a ban on landfilling of combustible waste which became effective in January, 1997 (Miljøministeriet, 1995). This ban relocated combustible waste from landfills to incineration plants, and is the reason why waste incineration rather than landfilling is used as frame of reference for new waste technologies in Denmark.

Another reason for the widespread distribution of waste incineration can be found in the design of the energy system, more specifically the widely distributed district heating networks facilitating utilization of various types of inhomogeneous fuels such as municipal solid waste (MSW) as well as surplus heat from industries. The district heating networks supply heat to around 2/3 of the Danish population. The first incineration plant in Denmark was commissioned in 1903 and was only producing heat, while some of the plants built in the following years generated steam for both heat and power production (Kleis & Dalager, 2004). For a period of 25 years the plants commissioned produced heat only, but from 1990 all new incineration plants have provided combined heat and power production (Kleis & Dalager, 2004). Today, Denmark is equipped with 30 waste incinerators with an average net energy efficiency of 85 % based on the net calorific value. 20 % is generated as electricity and 65 % as heat (DEA et al., 2005).

Energy recovered from waste accounted in 2007 for around 20 % of the Danish heat production and 4 % of the electricity production (DEA, 2008). Waste incineration accounted for approximately 98 % of the generated energy and anaerobic digestion for 2 %.

1.2 Evaluation of waste management options

Different assessment methods exist which can be used for evaluation of waste management systems. Some methods focus on environmental performance whereas others focus on economic aspects. Different methods may also be combined to provide a more comprehensive survey. Environmental impact assessment (EIA), strategic environmental assessment (SEA), life cycle assessment (LCA), risk assessments, energy system analysis (ESA) and material flow accounting (MFA) are examples of methods focusing on environmental aspects and/or resources, whereas cost benefit analysis (CBA) and life cycle costing (LCC) focus on the economic performance of waste management systems. The methods have different focus and hence different fields of applications. Finnveden et al. (2007) provided an overview of the various methods and a guideline for choosing among the different methods, suggesting LCA as appropriate for comparing environmental impacts from different waste management options.

Reviews conducted by e.g. Villanueva & Wenzel (2007) and Cleary (2009) confirmed that LCA has been a widely applied tool for assessment of waste management solutions during the past 15-20 years. In addition, several models have been developed as support tools for LCA on waste management systems. Examples are ORWARE (Dalemo et al., 1997; Björklund, 2000), WRATE (Thomas & McDougall, 2005; Gentil et al., 2005) and EASEWASTE (Kirkeby et al., 2006; Christensen et al., 2007). Overviews and comparisons of the different models are provided in Winkler & Bilitewski (2007) and Gentil et al. (2009). Finally, the use of life cycle thinking in waste management has been promoted in the European waste framework directive (Directive 2008/98/EC) stating that departing from the waste hierarchy, which is otherwise the guiding principle behind waste management in EU, may be possible when justified by life cycle thinking (European Parliament, 2008).

1.2.1 Evaluation of waste based energy production

Energy plays a significant role in waste management systems as energy is needed to operate the various treatment facilities and often more importantly because energy can be recovered from waste. To account the impacts and potential savings from waste based energy production, the energy products and their application should be addressed separately. Electricity and heat, for example, are produced, distributed and used differently which should be reflected by the identification of the substituted energy.

A critical factor with respect to evaluating waste based energy production is related to identification of the substituted energy. Identification of the substituted energy in a short-term time perspective can be done based on the current design of the energy system. To model the impacts of a decision with long-range consequences is much more problematic and associated with large uncertainties as the future is inherently uncertain. Energy system analysis (ESA) has within recent years been used as a method for determining the affected energy technologies and fuels (e.g. Ljunggren-Söderman, 2003a; Sahlin et al., 2004), but also this approach is associated with uncertainties as the results of the ESA depend on the technical specifications of the energy system, and the constraints and assumptions employed in the model.

1.3 Aim of the thesis

In order to provide an improved basis for selecting technologies for energy production from waste in Denmark, the overall aim of this thesis was to provide a systematic framework for LCA modeling of waste-to-energy technologies and recommendations for preferred technologies. With a focus on LCA of energy use and recovery within waste management, this involved the following more detailed objectives:

- Identify critical goal and scope related factors (such as time perspective, and scale of the change) with potential significant influences on the outcome of the LCA
- Evaluate and suggest how these factors should be addressed and quantified in a Danish context
- Evaluate which contributions are important for the environmental performance of waste-to-energy technologies
- Assess how the substituted energy should be identified
- Based on the items above, identify the preferred waste-to-energy technologies in a Danish perspective

The above issues were investigated from a Danish perspective with a focus on combustible waste (as received today at municipal solid waste incinerators in Denmark). The waste-to-energy processes included in the thesis were waste incineration, anaerobic digestion and co-combustion as these processes were considered most relevant from a Danish perspective. Waste incineration was given most focus; though, due to its significance in the Danish waste management system. Anaerobic digestion is applied as a treatment option for the organic household waste only in some municipalities, but the technology may become more widespread in the future e.g. for co-digesting with manure which is considered a large unused energy potential. Co-combustion of waste is not yet used in Denmark, but has been tested in a few cases. Several other waste-to-energy alternatives exist such as gasification, pyrolysis, and production of bioethanol or biodiesel (Münster, 2009). None of these processes; however, are likely to be real alternatives to waste incineration within a foreseeable future. Gasification and pyrolysis are only suitable for a limited amount of waste fractions, and technologies for production of liquid biofuels are still in an early stage of development.

Fuel substitution was modeled by crediting the waste management system with the avoided energy production in the energy system. The underlying assumption behind this approach was that energy produced from waste offsets energy produced from other fuels, which would otherwise have been used to fulfill the energy demand. The benefits were ascribed the waste management system, as energy recovered from waste is a consequence of the specific treatment waste is subject to in the system.

1.4 Content of thesis

The structure of the thesis is as follows:

- Chapter 2: Describes LCA methodology in general and the specific LCA methodology applied in the thesis. Included impact categories and units are described.
- Chapter 3: Evaluates and discusses factors related to the goal and scope definition to provide a basis for LCA of waste-to-energy technologies. The chapter elaborates on some of the topics in Fruergaard et al. (I), Mathiesen et al. (II) and Damgaard et al. (VI).
- Chapter 4: Identifies which contributions are significant in LCAs of waste-to-energy technologies. Evaluates different approaches for identification of the substituted energy, and provides examples and results from two case studies. This chapter elaborates on the findings in Fruergaard et al. (I), Fruergaard et al. (III), Fruergaard & Astrup (IV) and Astrup et al. (V).
- Chapter 5: Based on Chapter 3 and 4 this chapter discusses issues regarded as most problematic to address and account in LCA.
- Chapter 6: Concludes on the outcome of the thesis.
- Chapter 7: Discusses topics which could be further investigated based on this thesis.

2 Method

2.1 LCA within waste management

This PhD thesis is based on the principles of LCA. Full LCAs were conducted in Fruergaard & Astrup (IV) and Damgaard et al. (VI). The remaining four papers employed life cycle thinking, focused on a single LCA impact category or discussed the method. LCA was chosen as method in this thesis as it is a standardized method (ISO, 2006a; 2006b) and commonly used for environmental evaluations of waste management systems. LCA aims at including and quantifying all direct and indirect emissions and resource consumptions throughout the life cycle of the considered product or system, thereby providing a holistic perspective for the evaluation.

LCA was originally developed as an environmental assessment method for products, usually referred to as "cradle-to-grave" assessments. Extraction of raw materials for production of the product is the "cradle" of the assessment, and disposal of the product the "grave". This is different from the life cycle of waste management systems, where the "cradle" is disposal of a product, i.e. when a product enters the waste management system as waste. This is also referred to as the "zero burden" approach, as all upstream emissions associated with generating the waste are omitted from the LCA (e.g. Clift et al., 2000). The "grave" is when waste leaves the system, either as emissions (from e.g. landfills) or as energy or secondary materials, potentially substituting production of energy and virgin materials in the interlinked systems.

LCAs consist of four phases which according to the ISO 14040 standards are the following: Goal and scope definition, inventory analysis, impact assessment and interpretation (ISO, 2006a). The first phase includes specification of the aim of the LCA and definition of system boundaries and the functional unit (the unit which qualitatively and quantitatively describes the service provided by the system). As calculations in the later phases of the LCA are based on the functional unit and this unit further is the basis for comparison with other alternatives and scenarios, it is an important parameter. Often, the functional unit is defined based on the considered waste type and waste treatment option. Other critical aspects within the first phase of the LCA are related to defining the framework of the assessment with regard to the temporal, technological and geographical scopes, the LCA approach applied, etc. These definitions serve as foundation for the subsequent phases and should accordingly be thoroughly addressed. In the second phase, all relevant direct and indirect emissions associated with upstream and downstream activities are collected and presented based on the functional unit, followed by the third phase where the emissions are characterized and aggregated in accordance with the included impact categories. In the fourth and last phase, the results of the impact assessment are interpreted based on the goal and scope of the assessment and the inventory analysis.

2.2 Applied LCA methodology

The environmental impacts were assessed and evaluated by EDIP97, a midpoint LCA methodology developed by Wenzel et al. (1997). The calculations were performed by use of the LCA based model, EASEWASTE (Kirkeby et al., 2006). The results were normalized using the latest version of the normalization references for EDIP97 (Stranddorf et al., 2005). The impact categories included were: Global Warming (GW), Acidification (AC), Nutrient Enrichment (NE), Photochemical Ozone Formation (POF), Human Toxicity via air (HTa), via water (HTw) and via soil (HTs), and Ecotoxicity in Water (chronic) (ETw) and in soil (ETs). The first four impact categories are commonly referred to as energy related impacts, or non-toxic impacts, whereas the remaining categories are referred to as toxic impacts. Where general consensus exists with regard to assessing the energy related impacts, the opposite is the case for the toxic impact categories. Lack of inventory data and lack of consensus concerning the characterization method used have resulted in these impacts being considered less robust than the energy related impacts (Finnveden et al., 2009). Consequently, the two impact groups are often kept separate when LCA results are presented to emphasize that the two groups are perceived differently. Another possibility is to simply omit the toxic impact categories from the LCA; however, this may provide misleading results. An example could be a comparison of two waste incinerators with different levels of flue gas cleaning, where the incinerator with the most efficient cleaning system usually consumes more resources and energy compared with the incinerator with more simple equipments installed. An opposite situation is seen for emissions of toxic substances where the emission level in the latter case would be larger than in the first case. By only including energy related impacts, the outcome of the LCA would favour the incinerator with an inefficient cleaning system thereby not crediting the efficient incinerator for reducing the air emissions.

The results from the impact assessments were in this thesis shown either as characterized impact potentials (in kg CO_2-eq.) or normalized impact potentials (in milli-person equivalents (mPE)). 1 mPE represents one thousandth of the annual impact from an average person in a given area, i.e. 100 mPE corresponds to 10 % of the annual impact from an average person.

3 Important goal and scope related factors

The goal and scope definition forms the foundation of any LCA and is therefore critical for the results. Several factors related to the goal and scope definition need to be clarified, though. Either because these factors are often not addressed in LCAs or clear descriptions regarding how the factors have been addressed are omitted. As these factors can be considered critical with regard to evaluation of waste-to-energy technologies and in LCAs in general, the purpose of this chapter is to clarify and elaborate on these factors and provide recommendations for how they should be addressed. The chapter expands on the findings in Fruergaard et al. (I), Mathiesen et al. (II) and Damgaard et al. (VI).

3.1 Goal definition

The goal of an LCA should state the intended application, the reason for performing the study, the intended audience and whether the results are intended for use in comparative assertions disclosed to the public (ISO, 2006a). If the latter is the case, a critical review of the LCA should be conducted. The first two items are often given most focus and they must also be considered as the most critical with respect to clarifying the purpose of the LCA. As the remaining phases of the LCA depend on the defined purpose, the purpose should be clearly described. If the aim of the study is to compare recycling of paper with incineration, it should be clarified whether the intention is to support the decisions of a specific municipality or to support national decision makers. The process for substitution of virgin paper is the same in both cases, but the substituted heat from waste incineration depends on the location of the waste incinerator (e.g. Fruergaard et al. (III)). At a municipal level data representing a specific district heating network should be applied, but this is not feasible at a national level. Here data illustrating the “average” affected heat should be applied, e.g. a weighted average of heat substitution from the approximately 30 waste incinerators in Denmark. The conclusions may not be the same in the two cases.

3.2 The LCA approach

Two overall LCA approaches exist: attributional and consequential. Where focus of the attributional LCA is on quantifying the environmental loads of a product or system by describing all environmentally relevant physical flows to and from the object in focus, the aim of the consequential LCA is to assess the consequences of a decision by including only the potentially affected physical flows (Weidema et al., 1999). Average data are used for the attributional approach whereas marginal data, data representing the technologies actually affected by the change, are used for the consequential approach. Often; however, lack of marginal data makes it impossible to perform a 100 % consequential LCA and average data are often used to some extent.

Another factor differentiating the two approaches is the method used for distribution of environmental burdens in the cases of open-loop recycling or multi-output or multi-input processes: allocation or system expansion. Open-loop recycling is conversion of a recycled material into another product different from the original, e.g. recycling of polyethylene terephthalate (PET) bottles into polyester for production of fleece sweaters. An example of a multi-output process is waste incineration, where the products/services provided are waste treatment and energy production. Another example is combined heat and power production. Production of biogas from anaerobic digestion of organic household waste and manure, and management of residual waste (consisting of numerous waste fractions) are examples of multi-input processes. All types of processes are frequent in LCA of waste management systems, which renders consensus important with regard to which method to apply. This is not fully the case today as also discussed by Finnveden et al. (2009). Nevertheless, usually allocation (partitioning of environmental burdens between the products) is associated with the attributional approach, whereas system expansion (expanding the system to include substitution of other products) is associated with the consequential approach. This division is based on the arguments that attributional LCAs do not include unit processes outside the life cycle investigated, as opposed to consequential LCAs which include all affected unit processes independent on these being inside or outside the life cycle (e.g. Russell et al., 2005).

The incongruence related to the choice of LCA approach, the data types used and the method applied for distribution of environmental loads is caused by the fact that when LCA was introduced no distinction was made between the two approaches. Originally, LCA was developed simply as a tool for performing comprehensive environmental assessments of products, but the need for a harmonization of the method resulted in the 1990'ies in development of a number of guidelines and recommendations, e.g. a "Code of Practice" developed by SETAC in 1993 (Consoli et al., 1993). The importance of including market aspects in LCAs was proposed the same year by Weidema (1993), and later a distinction was made between LCAs aiming at describing the consequences of a change rather than LCAs aiming at describing all environmentally relevant physical flows to and from the object in focus (Baumann, 1998). The terminology used today (consequential versus attributional) was formally adopted at a workshop in 2001 (Curran et al., 2005), but different terminologies have been used throughout the years and are sometimes still used. The consequential approach may also be referred to as prospective and comparative, and the attributional approach as retrospective, descriptive or of the accountancy type (e.g. Weidema, 1998; Ekvall et al., 2005). Today, LCA is a standardized method; however, the ISO standards refrain from providing recommendations on methodological choices, thereby leaving the choice of LCA approach to the LCA practitioner.

The LCAs performed in this thesis were based on the consequential approach as this approach was regarded as most suitable for the purpose of the majority of LCAs: to evaluate the possible consequences of a decision. System expansion and marginal data have been used where possible; however, it was not possible to entirely avoid allocation: in case of energy substitution from waste incineration the environmental loads of the conventional CHP plant identified as affected were partitioned between heat and electricity by means of allocation. Overall, the approach may be defined as "pragmatic consequential", and the topics addressed in the subsequent chapters of the thesis were based on this approach.

3.3 Scale of the change

Evaluating the consequences of a change is linked to identification of the marginal technology. The marginal technology has been defined as the technology actually affected by a *small* change in demand (e.g. Weidema et al., 1999), and this definition originates from economics where the marginal cost is the cost of producing one more unit of a good. From a mathematical perspective the change is infinitesimal. Using the term marginal therefore implies that the change is insignificant with respect to the affected system. In LCAs of waste management systems where a decision may involve hundred thousands tonnes of waste, it is relevant to ask whether the induced changes can be defined as marginal.

The answer to this question depends on which systems are affected by the change. The volume of the waste management system is small compared with the surrounding systems, such as the electricity grid and the market for materials. Also a district heating network is small in comparison with the electricity grid. A decision which have a significant effect of the waste management system, may therefore only have very limited effect on the market for materials. Skovgaard et al. (2007) suggested that marginal data are used for modeling of recycling processes and most processes outside the waste management system, such as the electricity system, whereas average data or data representing a significant effect are used for most of the waste management system. The recommendations for the waste management system naturally depend on the expected effects of the decision, but most waste management policies will have significant effects within the waste management system (Skovgaard et al., 2007). Decisions influencing district heating networks will also often be significant as heat recovered from waste contributes significantly to the district heating production in Denmark, and in some networks constitutes the majority of the heat production.

The abovementioned aspects emphasize the importance of 1) specifying the processes and systems possibly affected by the considered decision and 2) defining how much waste is affected by the decision. The latter should be a part of the functional unit definition, as this is a prerequisite for evaluating the scale of effects on the waste management system and, if affected, the district heating network system. Regardless of the scale in question, the results of the LCA may still be reported per tonne of waste to ensure comparability with other studies.

Finally, this illustrates that the recommendation of employing “marginal” data in consequential LCAs is only true for small changes; however, treatment of hundred thousand tonnes of waste can still be defined as a small change if traded on large market which is the case for e.g. steel. In many cases; though, the consequences of decisions in waste management will be significant, indicating that instead of using the term “marginal”, terms such as “affected” or “influenced” would be more appropriate. This is in line with Weidema (2003) who suggested avoiding the term “marginal” and instead using the term “the technology actually affected”. In general, the recommendation for LCA practitioners is to pay attention to the underlying assumptions with regard to the terminology (such as the scale of a change) and to specify how the terminology has been used in the specific LCA. In this thesis, the term “marginal” is used when referring to effects on electricity production, whereas “affected” is used for effects on the waste management system and the district heating network.

3.4 Time perspective

Several time perspectives should be considered in LCAs of waste management systems.

3.4.1 Global warming characterization

One time horizon is related to global warming, where the impacts can be assessed over 20 years, 100 years or 500 years. The characterization factor of the various gasses contributing to global warming depends on how the gas concentration decays over time in the atmosphere. A common procedure is to use a time horizon of 100 years.

3.4.2 Emissions from landfilled waste

Another time horizon concerns evaluation of landfilled waste where only a small amount of the materials is released within a foreseeable future. The majority of materials is stored in the landfills and emissions from landfills can continue for thousands of years. Different approaches exist for modeling the impacts of landfilled waste: from using a time horizon of 100 years or shorter, thereby accounting for only a minor fraction of the emissions, to an infinite time horizon including all emissions. Another approach is to include a new impact category referred to as "Stored toxicity" (Hauschild et al., 2008) which accounts for the toxicity of the materials remaining in the landfill after the defined time period of 100 years. The outcome of the LCA with respect to toxicity depends heavily on the time aspects applied rendering a clear description of the approach important.

3.4.3 System lifespan

A third time horizon which should be considered is the lifespan of the system or the treatment technology in focus, e.g. introduction of a new collection scheme for recyclables or construction of a new incineration plant. The lifespan includes the planning phase, the construction/implementation phase, the use phase and the decommission phase. Ideally, the environmental impacts of all phases except the planning phase are included and accounted for in the LCA, often however, only the use phase is included due to lack of data on the remaining phases. The impacts of the omitted phases are either assumed insignificant compared with the impacts from the use phase, or in case the LCA compares two systems with similar construction and decommission phases the impacts are often assumed to be of similar size thereby counterbalancing each other in the LCA. The lifespan of a new collection scheme for recyclables may not be longer than 3-5 years, if the following is assumed: planning + implementation: 1 year, trial period: 2-4 years. Depending on the result of the trial period the collection scheme may either continue or be terminated. The lifespan of a waste incinerator is significantly longer, approximately 25-30 years based on the following assumptions: planning: 2 years, construction: 2 years, use: 20-25 years, decommission: 1 year.

Often, the functional unit is defined as treatment of 1 tonne of waste without considering the lifespan of the system. The expected lifespan; however, significantly influences technology data, efficiencies, energy substitution, etc.

3.5 Technological scope

The technological scope is highly related to the time horizon and the geographical scope as technology data should reflect the time period as well as the location of the assessment. During the past years waste-to-energy technologies have been subject to a significant improvement with respect to emission control and energy recovery efficiencies. Damgaard et al. (VI) assessed the development in direct emissions from waste incinerators by modeling eight scenarios with increasingly effective flue gas cleaning: from no flue gas cleaning to very advanced air pollution control technology. Time wise, a period of 40 years was reflected, from the early 1970'ies until today. The study showed a major decrease in impacts from waste incineration, especially with respect to the toxic impact categories which were all reduced by several orders of magnitude. Also the development in energy recovery efficiencies was evaluated in Damgaard et al. (VI) emphasizing the significance of recovering both electricity and heat.

The study illustrated the importance of taking technology development into consideration when modeling scenarios with longer time horizons. Finally, it stresses the importance of collecting up-to-date technology data and not blindly use old data, which is often the situation when using LCA databases.

3.6 Geographical scope

The geographical scope is significant as the technological level and the combination of technologies may differ from country to country. Where some countries are still dependent on old, inefficient technology other countries utilize new, efficient equipment with a minimum of environmental impacts. Also the effects of energy substitution are highly related to the geographical scope, as the composition of energy systems with respect to technologies and fuels vary between countries. Fruergaard et al. (I) reviewed several studies focusing on the CO_2 emission factors employed for electricity production. The results are seen in Figure 1.

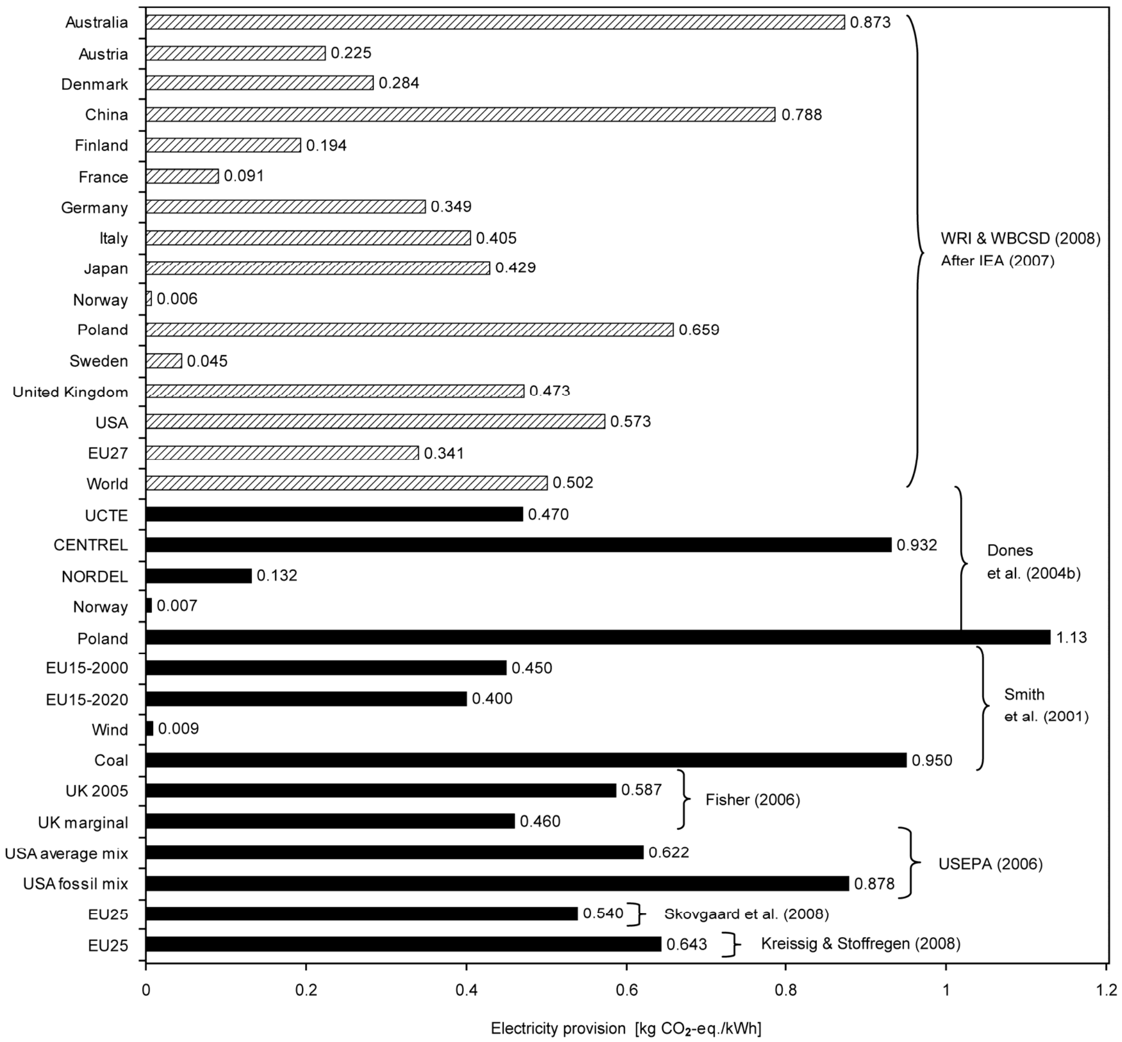

Figure 1. Greenhouse gas emissions for electricity production. The filled bars include emissions from fuel combustion as well as upstream emissions. The striped bars only include emissions from fuel combustion (Fruergaard et al., I).

Most data in Figure 1 represent electricity mixes, whereas a few represents a single fuel type. The data showed variations up to 160 times illustrating the impacts of energy substitution to be highly country specific if average data are used in the modeling. As emphasized previously the consequences of energy substitution should be modeled by data representing the actual change, but the study of Fruergaard et al. (I) showed that also these data may vary significantly dependent on the technological level. Despite its importance for the results it may be a difficult task to define where effects of a decision will happen. Recycled materials are traded on a global market and electricity is transmitted across national borders. Also the time perspective is critical as markets develop over time. These issues should; nevertheless, be considered as they may significantly impact the results.

3.7 CO_2 emission trading scheme (ETS)

Another important aspect with respect to evaluating the consequences of energy substitution is the effect of the European CO_2 emission trading scheme (ETS) which came into force in 2005 (European Parliament, 2003). The trading scheme involves around 10000 companies within the energy and industrial sectors annually being responsible for approximately 40 % of the EU's greenhouse gas emissions. The scheme establishes an upper limit (often referred to as a "cap") to the CO_2 emissions within the EU from the sectors included in the trading system, as only a certain level of emission permits are available each year. As an increase in energy production (and accordingly CO_2 emissions) in one area must be met by similar decreases in another area the effects of a change in energy production is being discussed. Finnveden (2008) for example discussed whether the marginal electricity production in the future may be regarded as CO_2-free as any action under the cap is counterbalanced by another action. This may be true in a short-term perspective, as CO_2 emissions within the current trading period (2008-2012) are fixed. After this period, a new trading period for 2013-2020 will be established, where the cap needs to be lowered for EU to obtain its goal of reducing its CO_2 emissions by 20 % before 2020 (compared with the 1990 level). In a long-term perspective, measures affecting energy production will thus have an effect on CO_2 emissions, as the EU countries need to reduce their energy consumption, increase their share of renewable energy and introduce cleaner energy technologies. It is therefore reasonable to assume that introduction of new waste based energy technologies in a long-term perspective can contribute to fulfilling these targets.

For a country to fulfill its obligations with respect to reducing its CO_2 emissions it is allowed to buy a restricted amounts of credits in countries outside EU by investing in ventures which reduce CO_2 emissions in these countries (e.g Clean Development Mechanism (CDM) and Joint Implementation (JI)). In principal, this means that the marginal technology for electricity production in a long-term perspective could be constituted by a CDM project. However, whether the marginal energy technology or a CDM project should be used depend on actual fuel prices, CO_2 quota prices, etc.

In general, in a short-term perspective the marginal electricity production may be regarded as essentially CO_2-free, whereas this is not the case in a long-term perspective. Measures affecting energy use and production will have an effect in a long-term perspective; however, this may potentially be investments in a CDM project.

3.8 The type of effects included

The goal and scope related factors discussed in the previous chapters relate to the considered system and the assessment approach. At a next level the type of effects (short-term or long-term) included need to be addressed. This chapter accounts for the essential aspects of defining these effects.

3.8.1 Short-term or long-term effects

The type of effects to include in an LCA is often regarded as directly linked to the time horizon of the study. Nevertheless, despite the terms “short-term” and “long-term” effects, these expressions are only indirectly linked to the lifespan of the investigated system. Instead the terms refer to the type of effects to include in a consequential LCA (Weidema et al., 1999). A distinction originating from economics is made between decisions which only affect the existing production capacity (the short-term effects) and decisions which are expected to involve changes in production capacity (the long-term effects) (Weidema et al., 1999). In a short-term perspective the production capacity is considered fixed, implying that the short-term technology is an existing technology capable of responding to changes in demand by adjusting its output. Condensing coal power is often referred to as the marginal short-term technology for electricity in the Scandinavian countries due to the fact that a surplus of coal capacity exists in the Danish grid as reserve capacity to meet electricity demand in periods with low production from wind turbines. In a long-term perspective the production capacity is considered flexible, implying that the marginal long-term technology is a new facility built or an old plant decommissioned (Weidema et al., 1999). The marginal long-term technology in Scandinavia may therefore be construction of new wind turbines or decommissioning of old coal-fired power plants depending on the trend in demand.

It is not a trivial task to decide which type of effects to include in an LCA as most decisions have both short-term and long-term effects. Another issue complicating the decision is related to the fact that the time perspective of the assessment also affects the decision. This complexity is illustrated in Table 1.

Table 1. Type of effects to include in consequential LCA.

	Current	Future
Short-term	decision made today, which only affects the existing production capacity	decision made in the future, which only affects the existing production capacity
Long-term	decision made today, which involves changes in production capacity	decision made in the future, which involves changes in production capacity

Most LCAs are performed to support decisions made today, which means that it is most relevant to focus on the left side of the diagram. Thus, when referring to a short-term or long-term effect in this thesis, it refers to decisions made today.

The type of effect to include depends to some extent on the scale of the change and the lifespan of the decision. However, the following discussion suggests that the lifespan of the decision is of minor importance. The examples from section 3.4.3 are used for clarification, as they represent systems with a short and a long lifespan, respectively. The scale of change is addressed in the following.

Introducing a new collection scheme for recyclables in a municipality would presumably imply more collection (and hence an increased demand for transport fuels, e.g. diesel). The benefit would be more recyclables collected and hence more virgin materials substituted (disregarding any market constraints, etc.). The scale of change must be regarded small (the changes occur in the fuel supply system and at the market for virgin materials) and the lifespan short (3-5 years). This suggests that the extra demand for diesel and the reduced demand for virgin materials possibly can be met by adjustments within the existing capacity, implying that a short-term marginal technology is affected. Nevertheless, even though the lifespan is too short for new investments in production capacity (or decommissions), introduction of a new collection scheme would likely also have consequences on future investments. The market would not “know” that the increased/reduced demand may only be temporary and would still have to adjust its production capacity. If the collection scheme after the trial period is made permanent the decision would affect investments provided the scale of change is large enough, i.e. the effects referred to as the long-term marginal effects. It could also be argued that even if the scheme would only run in a short time period the most correct way of evaluating the consequences of its introduction would be to consider the possible effects of increased recycling within a longer time period than 3-5 years. This discussion suggests that even in cases where the lifespan is short, the actual consequences will most likely be far-reaching, and the effects best modeled with data representing long-term marginal effects.

In the case of construction of a new incineration plant with a total lifespan of 25-30 years it seems more evident that this will at some point affect investments in the energy system. In the first years of the incinerator’s use phase, the existing production capacity needs to adjust (i.e. leading to short-term marginal effects), but hereafter investments are affected. The introduction of new incineration capacity will have a significant effect on the district heating network and a minor effect on the electricity system. To evaluate the effects on the district heating network the location of the waste incinerator should be taken into consideration as local conditions are critical for the environmental performance. This is elaborated in Fruergaard et al. (III) and further discussed in Chapter 4.4. The effects on the electricity system are best modeled with data representing long-term marginal effects.

As aforementioned is any decision expected to cause both short-term and long-term effects. The main impacts; however, are the effects on investment decisions (e.g. to decommission an old coal-fired power plant) as well as avoided utilization of the decommissioned plant (e.g. avoided combustion of coal). Ideally, both types of effects should be included in an LCA; however, in most cases the short-term effects are negligible compared with the long-term effects. This is due to long-term effects being more permanent, as the short-term effects will only last until the next capacity change (Weidema, 2003). For simplicity, it is therefore recommended to focus on identifying the long-term effects.

3.8.2 Identifying the long-term effects

The technologies considered as the possible long-term technology (marginal or affected) may be constrained, which means that their production capacity cannot be expanded. This may be due to natural constraints, political constraints, or market constraints for co-products (Weidema et al., 1999). An example is constraints on hydropower in some countries where it is not allowed to expand the areas used for hydropower generation. Another example is emission limits and quotas which may constrain the use of highly polluting technologies. Use of biomass for energy production is also expected to be constrained in the future due to insufficient availability of land for both energy crops and crops for food and fodder. However, the International Energy Agency estimates that energy production from biomass could be four to five times doubled without risking the world's future food supply (IEA Bioenergy, 2007). This suggests that biomass will not be constrained the next many years; however, this may depend on regional conditions. Wind is often mentioned as constrained as its production cannot be adjusted to the demand; however, this is only true for the short-term effects. As constraints may change over time, due to e.g. changes in political objectives, it may lead to false conclusions to exclude a technology due to current constraints. Consequently, it is recommended to regard all technologies as options, or at least thoroughly investigate the conditions before excluding a given technology.

Also the trend in demand is important; however, as this will affect whether a decision will impact the planning of new technology or phasing out of old technology. To use the market for electricity as an example: if the overall demand for electricity is increasing (or decreasing at a slower rate than the average replacement rate of old technology) new production capacity must be installed to meet the demand (Weidema, 2003). This will usually be the most preferred option, such as modern, competitive technology. If the overall demand for electricity is decreasing (at a faster rate than the average replacement rate) production capacity will be decommissioned. This will usually be the least preferred option at the market, e.g. an old polluting technology.

The consequences of a decision either induce a decrease or an increase in demand. Increased energy recovery from waste reduces the demand for conventional fuels and vice versa. Identifying the long-term marginal effects of a decision should be related to the general trend of the marked. This is illustrated in Table 2.

Table 2. Scheme for identification of the long-term marginal technology.

		Consequence of decision in waste system	
		Increased demand	Decreased demand
Trend in market demand	Increasing	Investments in new plants initiated	Investments in new plants not initiated/postponed
	Decreasing	Avoided decommissioning of old plants/Prolonging the life of (old) existing plants	Decommissioning of old plants

Table 2 suggests the trend in demand rather than the consequence of a decision to be decisive for identification of the long-term marginal technology. If the market for electricity is increasing, a reduced demand for electricity will have the effect that investments in new plant capacity is postponed, whereas an increased demand result in investments being initiated. In both cases, the data used in the modeling should represent energy production at the most preferred technology. If the market for electricity is decreasing, on the other hand, a reduced demand results in decommissioning of old plants, whereas an increased demand most likely result in the life of old plants being prolonged. Again, data used for modeling the consequences should be alike and illustrating energy production at the least preferred plants.

Projections can be used for defining the trend in demand; however, the trend in demand is affected by various factors such as economy, political objectives, etc, and may accordingly be difficult to define. The trend in demand may also be considered constant, suggesting that the consequence of a decision may be to prolong the life of an old plant as opposed to investing in a new. Consequently, the long-term marginal technology may shift back and forth between various technologies.

It should be emphasized that the discussions above only apply to changes which can be considered small compared to the overall market, e.g. electricity. Introducing a new incineration plant (or implementing a decision of a similar size) will have a significant effect on a district heating network and the effects should be evaluated case-by-case. This recommendation is in line with Weidema (2003) who distinguished between small and large effects.

Identifying the future affected plants is associated with large uncertainties as the future is inherently uncertain. This was discussed in Mathiesen et al. (II) where an assessment of the historical development of the Danish energy system was performed through reviews of several publications. The publications were a mix of official energy plans, energy plans from NGOs and statistical data showing what actually happened. Discrepancies between what would have been identified as the long-term marginal technology for electricity by using the plans and which technology was actually introduced/phased out were found in several cases. Various causes were identified for the discrepancies: technological development being disregarded, wrong price prediction of e.g. fuels and CO_2 quotas, and a shift in objectives in the time period considered. As a variety of technologies could potentially by identified as the long-term marginal technology Mathiesen et al. (II) recommended to use several significantly different technologies in the LCA to test the importance of electricity. If energy was critical for the results it was suggested to perform energy system analysis of different future scenarios. However, for most LCA practitioners it is too time consuming to perform an energy system analysis in addition to the LCA, and it should also be acknowledged that the outcome of an energy system analysis heavily depends on the constraints and assumptions applied in the model. On the other hand, energy system analysis can be useful as a tool for showing the possible consequences of different actions, and can as such be used more generally for identifying possible important interactions in the energy system. In Chapter 5.1 results from an energy system analysis is used to show how the long-term marginal electricity production could be identified.

Based on abovementioned findings it is recommended to test the robustness of the LCA by applying two significantly different long-term marginal technologies for electricity production. Possible technologies are discussed in Chapter 5 where also specific recommendations for heat are provided.

4 LCA of waste-to-energy technologies

This chapter outlines examples of energy flows to and from the waste management system, and accounts for significant contributions in LCAs of waste-to-energy technologies in a systems perspective. Energy substitution, for example, contributes significantly to impacts on global warming, whereas other contributions are significant for the toxic impact categories. In continuation of the findings in Chapter 3, different approaches with respect to identifying the substituted energy are accounted for. Finally, the chapter gives concrete examples of 1) identification of the substituted energy in two different district heating networks and 2) LCA of waste-to-energy technologies. This chapter elaborates on findings in Fruergaard et al. (I), Fruergaard et al. (III), Fruergaard & Astrup (IV) and Astrup et al. (V).

4.1 Energy flows

The waste management system and the energy system are closely interlinked, and the interactions between the two systems need to be addressed carefully to evaluate the effects of energy recovery from waste in a consistent and transparent manner. The waste management system needs energy to operate the different treatment processes, but the waste-to-energy technologies also generate different outputs intended for use in different parts of the energy system. The inputs and outputs are illustrated in Figure 2. Examples of energy products from the system are electricity, heat and fuels such as biogas, landfill gas, solid recovered fuel (SRF) and various biofuels. The fuels may have several applications and can be utilized for production of heat and electricity as well as utilized in the transportation sector as fuels for vehicles. The characteristics of the various outputs and calorific values of the fuels are described in more details in Fruergaard et al. (I).

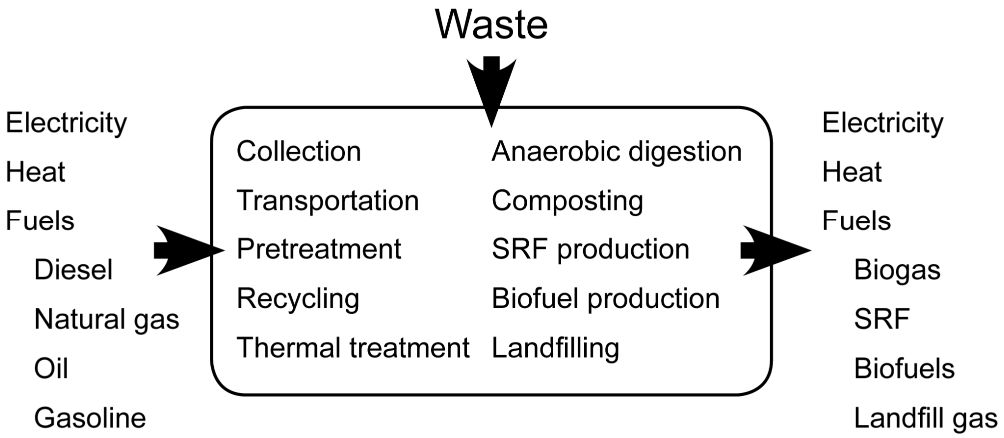

Figure 2. Examples of energy flows to and from the waste management system (Fruergaard et al., I).

4.2 Important contributions

To account for all environmental impacts related to the use of a given waste-to-energy technology all direct as well as indirect contributions should be included in the assessment. Direct contributions are directly linked to the activities within the waste management system, whereas indirect contributions occur outside the system. The indirect contributions can be divided into two categories: upstream activities such as production of materials and energy used inside the system, and downstream activities encompassing substitution of materials and energy recovered within the system and management of residues generated in the system. These issues are further elaborated on with regard to greenhouse gases in Fruergaard et al. (I) and Astrup et al. (V).

The significance of a contribution with respect to the outcome of an LCA depends on the impact categories included and the framework of the assessment. If global warming is the only impact category included the impacts of leaching from e.g. bottom ashes become insignificant for the results. Global warming is though a highly relevant impact category with respect to evaluation of energy aspects, but as emphasized by Merrild (2009) a relatively poor indicator for the overall environmental performance of a waste management system. In the following sections, the significance of various contributions with respect to evaluating the environmental performance of waste incineration, co-combustion and anaerobic digestion is addressed. A distinction was made between contributions to global warming and contributions to other impact categories.

4.2.1 Contributions to global warming

The indirect downstream contributions with respect to global warming have in many studies (e.g. Ljunggren-Söderman, 2003b; Finnveden et al., 2005) been identified as the downstream contributions caused by energy recovery, i.e. avoided greenhouse gas emissions due to energy substitution. The savings from energy substitution off-set in most cases the load from direct and indirect upstream contributions, resulting in net savings of global warming. The magnitude of savings depends; however, on the type of energy products generated (only electricity, only heat or a combination of both), on the fuel types substituted, energy recovery efficiencies and the fossil carbon content of the waste. For anaerobic digestion of organic waste the fossil carbon content is approaching zero and emissions of CO_2 are thus irrelevant for the results. Instead, fugitive emissions of methane from the anaerobic digestion plant and from combustion of the biogas become important for the outcome. Also the final destination of biogas is significant, i.e. whether utilized for heat and power production or utilized in the transportation sector (Fruergaard & Astrup, IV).

Astrup et al. (V) tested the importance of the aforementioned contributions for waste incineration of mixed household waste and co-combustion of solid recovered fuels (SRF), a high calorific waste, in a coal-fired power plant. Energy recovery efficiencies illustrating low respectively high performance based on Danish conditions were employed in the assessment. Also two different types of CO_2 emission factors for electricity production were employed: a low value representing an energy system with a high share of renewable energy and a high value representing a system predominantly based on coal. Waste incineration resulted in net global warming savings, also in the case of low energy recovery efficiencies combined with a low CO_2 emission factor for electricity. The savings were then predominantly caused by heat substitution. Co-combustion, on the contrary, resulted in net global warming loads in the case of low energy recovery combined with a low CO_2 emission factor. This was caused by the high fossil carbon content of SRF, being twice as high as the fossil carbon content of the mixed waste input for waste incineration. Also the much lower heat recovery efficiencies at the co-combustion plant influenced the results. However, in cases with a high degree of energy recovery combined with employment of a high CO_2 emission factor, co-combustion could potentially save up to twice as many CO_2-eq./tonne of wet waste (ww) incinerated compared with incineration: a net saving of approximately 1500 kg CO_2-eq./tonne SRF (ww) due to co-combustion versus 800 kg CO_2-eq./tonne mixed waste (ww) due to incineration. This confirms the significance of identifying the design of the interacting energy system with respect to technologies and fuels.

Astrup et al. (V) also found that the indirect upstream emissions were primarily related to electricity consumption at the plants, and that presorting of the waste for SRF production constituted around 50-80 % of the upstream emissions for co-combustion.

4.2.2 Contributions to other impact categories

The other impact categories included in this PhD thesis are Acidification (AC), Nutrient Enrichment (NE), Photochemical Ozone Formation (POF), Human Toxicity via air (HTa), via water (HTw) and via soil (HTs), and Ecotoxicity in Water (chronic) (ETw) and in soil (ETs). How much these various impact categories are influenced depends on the waste fraction treated (and hence the chemical composition of the waste), the waste-to-energy technology and the assumptions made with regards to treatment of the residues.

Fruergaard & Astrup (IV) included two types of waste fractions (SRF and organic household waste) and three different waste-to-energy alternatives (waste incineration, co-combustion in a coal-fired power plant and anaerobic digestion) in an LCA encompassing the abovementioned impact categories. Waste incineration with or without energy recovery was used as reference technology for both waste fractions, whereas co-combustion was employed for SRF only and anaerobic digestion employed for the organic household waste.

Treatment of SRF affected especially HTw and HTs (and GW). Energy substitution caused net GW savings for waste incineration as well as co-combustion, whereas only waste incineration yielded net savings with respect to HTw and HTs. Co-combustion caused a net load in these two impact categories, mainly due to less efficient flue gas cleaning at the co-combustion facility compared with the waste incinerator. The impacts were mainly caused by emissions of Hg. Different impact categories were affected when organic household waste was considered, and as it was the case for SRF it was crucial for the results whether the organic waste was treated by incineration or anaerobic digestion. Both waste incineration and anaerobic digestion affected GW, but especially NE, ETw and HTw were influenced by the choices made with respect to management of digestate from the anaerobic digestion process. The digestate was assumed utilized as fertilizer at Danish farmland which both created savings (in ETw) due to substitution of inorganic fertilizer but also loads (NE and HTw). The NE loads were a consequence of an increased run-off of nitrate to surface water, whereas heavy metals in the digestate caused the HTw loads.

To sum up, especially direct and indirect downstream emissions were found to be significant for the results. For treatment of SRF, especially cleaning of the flue gases was a critical factor, whereas the results for treatment of organic household waste were highly affected by the assumptions made with regard to handling of the digestate.

4.3 Approaches for modeling of energy recovery

As described in the previous chapters the substituted energy has large impacts on the results, which emphasizes the importance of identifying the real consequences of energy production from waste. Several studies have been performed during the past decades focusing on energy recovery from waste, and these studies were examined to evaluate how they addressed the goal and scope related factors elaborated on in Chapter 3. Focus was on the choice of LCA approach and the type of effects included as these issues usually are the most difficult to address properly. A range of studies focusing more specifically on heat substitution were also evaluated.

4.3.1 Approaches in literature: energy recovery in LCA

A vast range of LCA studies have been performed during the past years, and several of these studies focused on or included energy recovery from waste. Numerous studies focused on waste incineration as an individual technology

(Liamsanguan & Gheewala, 2007; Riber et al., 2008; Morselli et al., 2008; Luoranen et al., 2009; Moora & Lahtvee, 2009), or as part of a national waste system, in some cases also discussing other options such as recycling and landfilling (e.g. Ljunggren-Söderman, 2003b; Eriksson et al., 2005; Finnveden et al., 2005; Björklund & Finnveden, 2007; Eriksson et al., 2007). Some studies have evaluated anaerobic digestion (e.g. Börjesson & Berglund, 2006; 2007), and a few studies have compared several technologies with a dedicated focus on energy production (e.g. Consonni et al., 2005a;b; Azapagic, 2007).

The majority of studies did not explain which LCA approach was applied, but average data were applied in most of them. System expansion in terms of subtracting avoided energy production due to energy recovery was performed in all studies, but only around half of the studies argued for their choice of substituted energy. One study did not even mention which type of fuels was assumed substituted. Approximately one third of the studies focused on evaluating the long-term effects, whereas the remaining studies evaluated the short-term effects. Less than half of the studies performed a sensitivity analysis of the consequences of substituting another type of fuel than the original. In the studies performing a sensitivity analysis it was found that the choice of fuel used in the LCA had large impact on the results, e.g. by changing the ranking of scenarios.

Summing up, the majority of studies would benefit from a sensitivity analysis of the substituted fuel type to evaluate the robustness of the results. The same is true with respect to outlining the scope of the LCA which is a prerequisite for understanding and evaluating the results in the right context. The findings clearly indicate the necessity of providing a systematic framework for evaluating of waste-to-energy technologies, and in general to enhance the credibility of several of the studies.

4.3.2 Approaches in literature: heat substitution

In the studies above focus was especially on the waste management system or on single waste technologies and the fuels identified as substituted were based on literature or general assumptions. A range of studies (not necessarily LCAs) have evaluated the interactions between the waste management system and the energy system more thoroughly, either by use of energy system analysis or by combining different models. In the majority of studies, the aim has been to evaluate the consequences of heat recovery from waste incineration when utilized for district heating purposes. Olofsson (2001) linked a waste management model with a model for a district heating system on a case study of two municipalities. Ljunggren-Söderman (2003a) calculated the marginal heat production costs of available production alternatives, and subsequently applied the identified fuels in different scenarios for the studied waste management system. Sahlin et al. (2004), Holmgren & Gebremedhin (2004) and Knutsson et al. (2006) evaluated MSW incineration from an energy systems perspective using economic optimization models simulating the district heating network system. The studies were conducted as either local or national surveys. An example of a local survey was found in Holmgren & Gebremedhin (2004) focusing on a single municipality. Ljunggren-Söderman (2003a) on the other hand applied a national approach and modelled the consequences of MSW incineration based on the average Swedish district heating network. Sahlin et al. (2004) and Knutsson et al. (2006) also applied a national approach, but based on a model aggregating numerous local district heating networks into one large system, representing 99 % of the Swedish district heating production.

The studies above were performed with different aims and perspectives, and all of them focused on Swedish conditions. It was therefore not possibly to use the results as input to LCAs of heat substitution in a Danish perspective. First of all because several of the studies focused on costs which must be expected to differ from Danish conditions, where a large share of the heat is based on fossil fuels as opposed to Sweden where biomass covers a significant share. Secondly, because the Danish energy system contrary to the Swedish system is heavily based on combined heat and power production. Thirdly, because the design of district heating networks differs significantly rendering local conditions important when quantifying the environmental consequences of energy recovery. As a consequence a case study was performed aiming at evaluating the importance of local conditions for waste incineration with energy recovery in a Danish perspective. The study focused on important design and operational properties of the other heat producing facilities in the network to which the waste incinerator was attached.

4.4 Case study: district heating networks

In Denmark, a substantial share of the electricity and heat production is co-generated (see Table 3).

Table 3. Danish electricity and heat production in 2007 (after DEA, 2008).

	Electricity		Heat	
	PJ	%	PJ	%
Central CHP plants • separate electricity production at central plants	89.5 • 54.1	64 -	54.5 -	45 -
Decentralized CHP plants	17.0	12	26.8	22
Heat-only boilers	-	-	17.7	15
Private CHP producers	8.4	6	16.2	13
Private heat-only boilers	-	-	6.4	5
Wind turbines	25.8	18	-	-
Total	140.7	100	121.6	100

In 2007, around 50 % of the electricity produced at CHP plants were produced in combination with heat, corresponding to around 40 % of the total electricity production. Around 80 % of the total heat production was generated in combination with electricity (DEA, 2008). Consequently, in LCAs involving energy substitution in Denmark this co-production should be accounted for.

The Danish district heating network system in one of Europe’s most expanded consisting of more than 400 self-contained networks of various size and design. This necessitates a local approach in cases where heat substitution is crucial for the results, e.g. when identifying a proper location for a new waste incinerator, or evaluating whether permissions should be given with regard to increasing the capacity of existing waste incinerators. Fruergaard et al. (III) investigated the consequences of waste based heat substitution in two specific Danish district heating networks by accounting for the energy-associated interactions between the plants connected to these networks. The study focused on energy and CO_2

and 10 GJ of fuel (corresponding to approximately 1 tonne of waste) was used as basis for the calculations. A short-term time perspective was applied as the aim was to provide an understanding of the mechanisms in the district heating network rather than to predict the long-term effects.

The two networks (referred to as Case 1 and Case 2) were supplied with heat from various facilities, but each network was dominated by two plants: a waste incinerator and a large CHP plant. The CHP plant in Case 1 was a large condensing cogeneration plant mainly fuelled by coal, whereas the plant in Case 2 was a back-pressure plant mainly fuelled by wood chips, natural gas and oil. The relationship between heat (ΔQ) and electricity production (ΔP) at these two plants was characterized by the following equations:

$$\Delta P = - C_v * \Delta Q \qquad \text{(Case 1: Equation 1)}$$

$$\Delta P = C_m * \Delta Q \qquad \text{(Case 2: Equation 2)}$$

C_v = “the power-loss ratio”, usually around 0.15-0.20 for Danish plants
C_m = “the power-to-heat ratio”, ranges between 0.4 to 1 or more dependent on the technology.

The equations were used to calculate the consequences of extra waste based heat supplied to the district heating system. The technical design of the CHP plant in Case 1 allowed for a flexible production of heat and electricity, and equation 1 was used to calculate how much extra electricity the plant could produce when the demand for heat was reduced. The technical design of the CHP plant in Case 2, on the other hand, imposed a fixed ratio between heat and electricity, as these types of plants can only generate electricity when a demand for heat exists. Equation 2 was used to calculate the reduced electricity production. Figure 3 illustrates how the effects of increased waste incineration in terms of heat and electricity substitution were modeled with Case 2 as example.

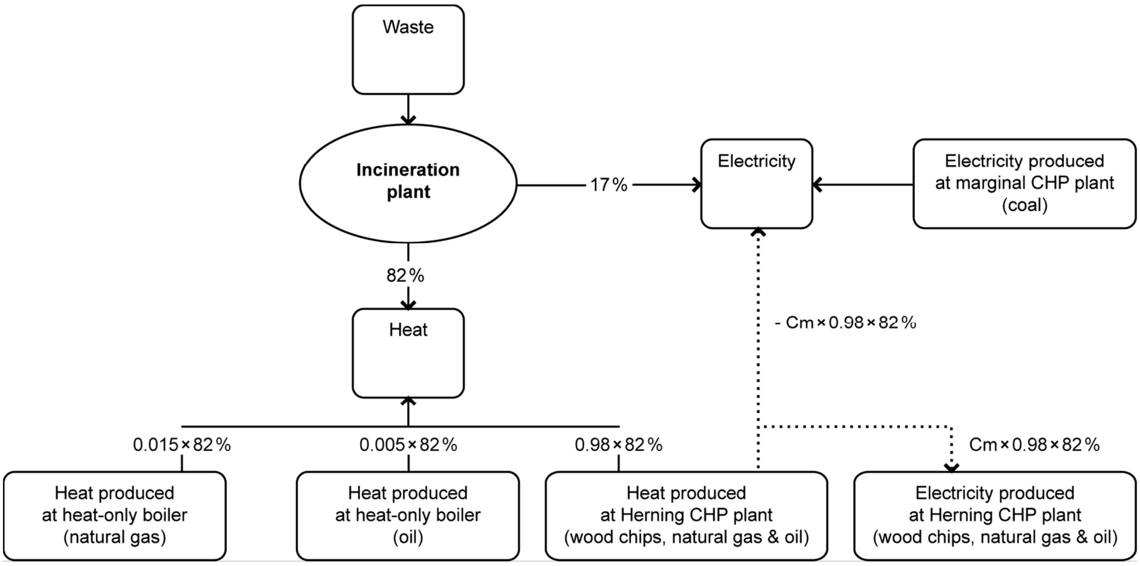

Figure 3. Heat and electricity substitution in Case 2 (Fruergaard et al., III).

The waste based electricity was assumed to substitute coal condensing electricity at the grid (termed marginal electricity in Figure 3), whereas waste based heat was send to the district heating network substituting mainly heat production at the large CHP plant. This was based on the assumption that heat from waste incineration (acting as base load in the district heating system) mainly substitutes other base load technologies. However, the analysis of the yearly heat production in Case 2 showed that reserve/peak load boilers in some months constituted a significant share of the total heat production, indicating that increased waste incineration may also influence these plants. This was accounted for in the modeling by including also heat substitution at two different heat-only boilers. The consequences of reduced heat production at the large CHP plant are illustrated by dashed lines in Figure 3. The electricity production at the CHP plant is reduced according to the C_m value, and to maintain a constant electricity production in the system the "missing" electricity must be produced at another plant, here assumed to be the marginal CHP plant.

4.4.1 Results

The energy and CO_2 accounts illustrated that it is insufficient to focus solely on plant efficiencies when evaluating the environmental performance of waste incinerators. More energy was substituted in Case 1 despite the efficiency of the waste incinerator in Case 2 being slightly higher. The smaller energy saving in

Case 2 was caused by the demand for extra electricity to compensate for the missing electricity when reducing the production at the CHP plant in Case 2. A more pronounced difference was seen with respect to CO_2 emissions: where waste incineration in Case 1 yielded a saving of 48 kg CO_2/GJ input to the incinerator, it provided a load of 43 kg CO_2/GJ input in Case 2. This corresponded to a saving of approximately 480 kg CO_2 and a load of 430 kg CO_2, respectively, per tonne of waste incinerated. This difference was caused by the fuels used in the networks. In Case 1, primarily coal based energy was substituted, whereas the substituted energy in Case 2 was comprised by biomass, natural gas and oil. The savings at the CHP plant in Case 2 were too low to counterbalance the load from the coal based electricity needed to compensate for the missing electricity in the system.

In conclusion, the district heating network, the interactions with the electricity system and the affected fuels showed to be crucial for the outcome. Additionally, the results suggest not locating new incineration capacity in a network dominated by back-pressure plants if the compensatory electricity would be based on fossil fuels.

4.5 Case study: LCA of waste-to-energy technologies

In the study of Fruergaard & Astrup (IV) referred to in section 4.2.2, LCAs of three waste-to-energy technologies (mass burn incineration, co-combustion in coal-fired power plant and anaerobic digestion) were conducted to evaluate the environmental impacts of energy production from two types of municipal solid waste: SRF and organic household waste. The modeled alternatives are outlined in Table 4.

To test the significance of the fuels identified as substituted energy substitutions were considered with respect to two different energy systems: a present-day system based on fossil fuels and a future system based on 100 % renewable energy. In a present-day perspective, the following fuels were assumed substituted:

- Waste incineration with energy recovery: mainly coal
- Co-combustion in coal-fired power plant: mainly coal
- Anaerobic digestion, biogas used for CHP: mainly natural gas, but also biomass and coal
- Anaerobic digestion, biogas used for transportation: petrol

Table 4. Waste-to-energy technologies assessed. “x” indicates the alternatives modeled for the two waste fractions.

	SRF	Organic waste
Waste incineration without energy recovery	x	x
Waste incineration with energy recovery	x	x
Co-combustion in coal-fired power plant	x	
Anaerobic digestion. Biogas for CHP production.		x
Anaerobic digestion. Biogas as transportation fuel.		x

The fuels identified as substituted in a present-day perspective were partly based on an energy system analysis of the Danish energy system (Münster, 2009). In modeling of a future system, electricity and heat was assumed to be produced exclusively from biomass, whereas liquid transport fuels were assumed to be biodiesel.

4.5.1 Results

Figure 4 shows the results of the LCA with respect to energy production from 1 tonne of organic household waste in a present-day perspective. For the majority of impact categories, incineration with energy recovery proved to be a better alternative than anaerobic digestion regardless whether the produced biogas was utilized for CHP production or as transport fuel. With respect to GW, the higher energy conversion rate of the waste incinerator compared with the rate of the anaerobic digestion plant was significant for the outcome. Also the fuel types substituted were significant, though.

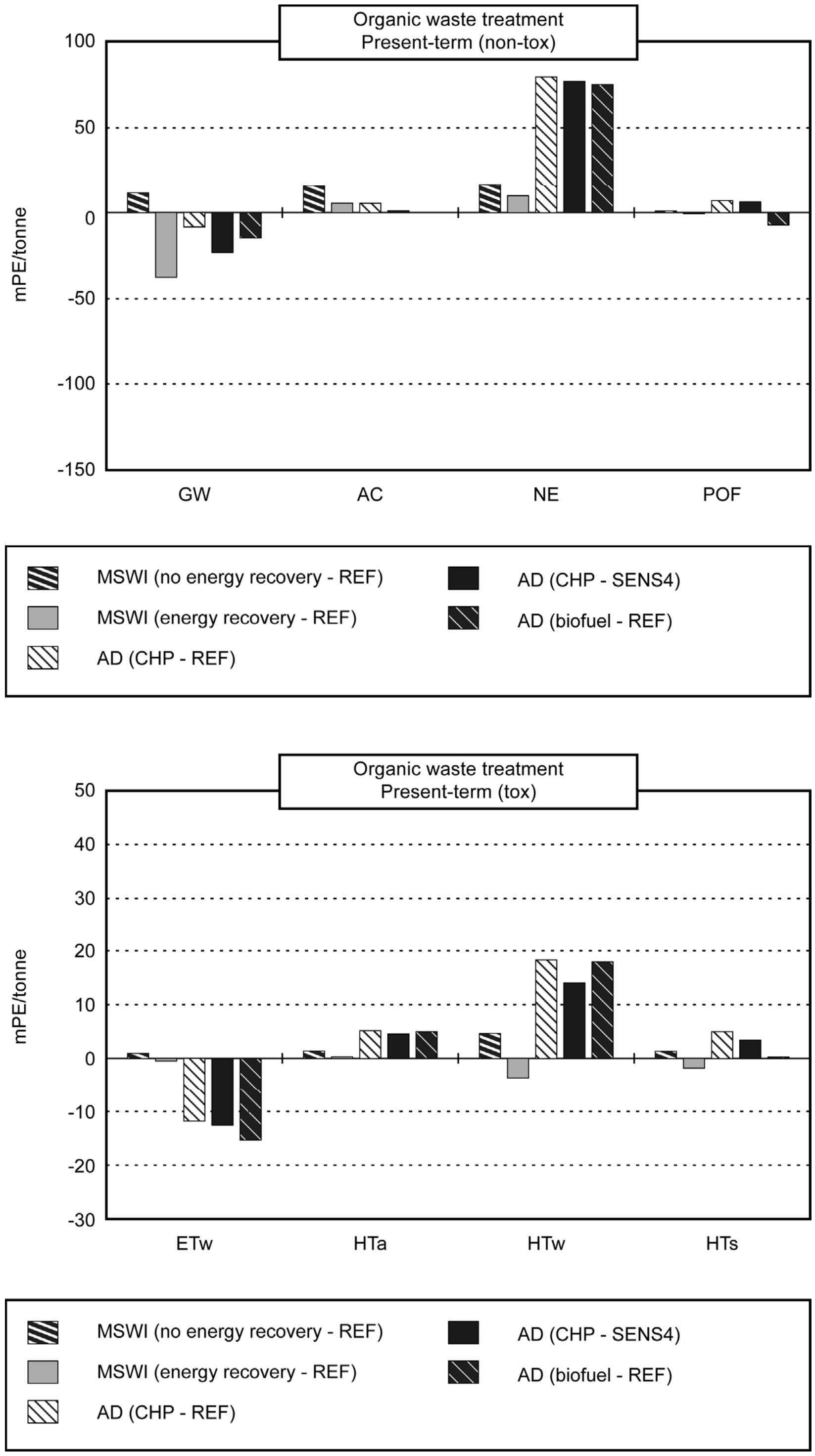

Figure 4. Environmental impacts from treatment of 1 tonne of organic household waste in a present-day perspective. The graphs include results based on the original assumptions (referred to as REF) as well as results from the sensitivity analysis (referred to as SENS). SENS4: coal substitution instead of the mix of natural gas, biomass and coal substitution.

A sensitivity analysis (referred to as SENS4 in Figure 4) was conducted evaluating the effects of substituting coal instead of the mix of natural gas, biomass and coal when biogas was utilized for CHP production. This improved the environmental performance of anaerobic digestion within some impact categories; however, waste incineration with energy recovery was still superior in the majority of categories. With respect to utilization of biogas, use as transport fuel proved to be slightly better than CHP production. In a future perspective; however, these small differences were evened out.

The results of the LCA concerning energy production from SRF showed co-combustion to have benefits over waste incineration with energy recovery with respect to the non-toxicity impact categories, whereas the opposite was the case with respect to the toxic impacts. Both alternatives caused environmental savings with respect to the non-toxic impacts, whereas this was only the case for waste incineration when considering the toxic impacts. As mentioned in section 4.2.2 co-combustion generated significant loads primarily caused by air emission of Hg, highlighting the importance of efficient flue gas cleaning systems at co-combustion facilities. In the modeling of waste incineration not all the generated heat was assumed utilized to illustrate the reality for many waste incinerators. However, as it would not make sense to increase incineration capacity in an area where the produced heat could not be utilized a sensitivity analysis was performed to evaluate the consequences of 100 % heat utilization. Given all the produced heat could be utilized the two alternatives would be comparable with respect to the non-toxic impact categories.

As aforementioned the assessment was also performed with an energy system based 100 % on biomass to model to consequences of the changes that may happen in the future as the energy system is expected to change from a system primarily based on fossil fuels to a system more based on renewable energy. The modeling of the waste-to-energy technologies using two different energy systems as reference showed that the overall ranking of the technologies was not significantly affected by the choice of fuels in the system. This suggests that the results of the assessment are robust also in the future. However, with respect to

GW all alternatives contributed with loads as opposed to the savings obtained in the present-day energy system based on fossil fuels.

5 Discussion

This chapter discusses the issues found to be associated with the largest uncertainties related to energy substitution: identification of the long-term marginal technology and fuel for electricity production and identification of the long-term effects of heat substitution. Based on these discussions the results of the two case studies are evaluated and recommendations for treatment of combustible waste in a Danish context are provided.

5.1 Long-term marginal electricity production

The long-term marginal technology and fuel for electricity production depend on the trend in demand, but is also affected by political considerations as described in section 3.8.2. This chapter discusses possible alternatives for identification of the long-term marginal technology and fuel, and provides various suggestions in this regard.

Recommendations with respect to identifying the long-term marginal energy technology and fuel depend on the geographical scope of the LCA. Electricity is distributed via large, interconnected grids across national borders, and identification of the long-term marginal technology for electricity should therefore be based on the expected development of the grid in the concerned area. For Denmark (and the other Scandinavian countries) this involves development in the Nordic grid, which is also connected to Germany, Poland, Holland, Estonia and Russia. As these connections are assumed to become stronger in the future it is relevant to focus on the entire Baltic Sea Region when evaluating the future. A projection of the development in this region could be used to identify the long-term marginal electricity. An example of such a projection was developed for the Nordic Council of Ministers and the Baltic Development Forum (EA Energianalyse, 2009). The projection focused on identifying how the electricity sector in the Baltic Sea Region could develop until 2030 while complying with the EU targets for 2020 (renewable energy constituting 20 % and a CO_2 reduction of 20 %) and a target of 50 % CO_2 reduction in 2030 (compared with 1990). The energy system analysis models Stream and Balmorel were used.

The analyses showed an increasing trend in electricity production and that investments would be made primarily in new efficient coal-fired power plants and wind power. A few investments would be made in new biogas plants, but these investments were small compared with investments in coal and wind technologies. This suggests the long-term marginal technology for electricity could be constituted by two fundamentally different technologies: coal and wind power.

A different way of identifying the long-term marginal technology and fuel would be by assuming a target of achieving environmental sustainability as the underlying basis for the discussion. Focusing on EU, such a target is linked to the overall goal of security of supply. To achieve this goal the EU Commission has proposed different measures, among others to improve cross-border infrastructures and to improve the energy efficiency in especially buildings and industry (European Commission, 2008). The vision for 2050 is to become independent of fossil fuels and reduce the dependency of fuel import. This is anticipated to involve a reduced energy demand, introduction of electric cars and new technologies (e.g. fuel cells), expanded use of CHP, and a more intelligent energy system than the current capable of adjusting production to the actual demand and vice versa. A reduced energy demand would render the long-term marginal technology the least preferred technology (se section 3.8.2). This would most likely be technologies using fossil fuels (e.g. old, inefficient coal-fired power plants or oil technologies).

The abovementioned approaches for determining the marginal technology are both uncertain, but both of them suggest coal as a possible long-term marginal fuel for electricity. However, the coal technologies are not identical in the different examples. In the example where projections were made for the Baltic Sea Region, new, efficient plants would be affected while in the example based on political visions, old plants would be affected. The difference in electricity conversion efficiency may be significant. In real life, the political framework, fuel prices, CO_2 quota prices, etc. may likely affect decommissioning rates of old plants and investments in new plants. In any case; however, coal combustion is a likely long-term marginal technology.

As it is not possible to conclude which approach will yield the most correct result, it is recommended to base the LCA modeling on two significantly different long-term marginal technologies: coal and wind power. To account for the fact that the technologies for coal utilization can be very different, it is recommended to either use two different data sets or to use data representing a medium efficient coal-fired power plant.

5.2 Long-term effects of heat substitution

Fruergaard et al. (III) focused on evaluating the importance of local conditions for waste incineration with energy recovery: as the aim was to provide an understanding of the effects of interactions between the waste management system and the existing energy system only the short-term marginal effects were assessed. This was considered reasonable for that specific purpose; however, as argued in the previous chapters the consequences of a decision should also account for the long-term effects. Fruergaard et al. (III) used 10 GJ of energy input (corresponding to approximately 1 tonne of waste) as basis for the calculations, but in reality a decision may involve several thousand tonnes of waste. According to the definitions in Chapter 3.3 and the recommendation in section 3.8.2, this could significantly affect the district heating network and should therefore be modeled with data reflecting these effects. To identify the actual effects one could ask: which fuels would have been utilized if waste was not available? Sahlin et al. (2004) addressed this issue and found the answer for Sweden to be biomass. If waste was not available, the demand for district heating would most likely have been met by investments in facilities using biomass.

Whether a similar situation would apply also for Denmark is unclear. According to the statistics of the Swedish District Heating Association biomass constituted around 30 % of the fuels used for district heating in Sweden (SDHA, 2004). The similar figure for Denmark was 16 % (DEA, 2008). The large availability of biomass due to large forest areas in Sweden is a main reason for the current difference between Sweden and Denmark, but this may not be case in the future. Denmark is according to the EU directive on promotion of renewable energy obliged to increase the share of renewable energy to 30 % in 2020 (European Parliament, 2009). This requires a significant increase in the use of wind power and biomass. Today, biomass in the Danish energy system is constituted mainly by wood, straw and the biodegradable part of waste, but in the future biogas produced from manure is expected to increase. This indicates that if waste was not available for energy production more investments would have to be made in facilities utilizing biomass. Wind power cannot realistically be considered the only solution for increasing the renewable energy share with the current design of the energy system and the needs for a stable electricity supply. The situation would then be similar to the one in Sweden and biomass would be the affected fuel. This conclusion may be true for an average situation, considering the more than 400 self-contained district heating networks as one interconnected system. However, for the individual district heating networks the situation may still be very different. LCA modeling involving specific networks should include evaluation of individual investment plans in order to properly account for local conditions.

In the discussion above the consequences of waste not being available for heat production were evaluated for an average situation. Different situations are discussed in the following.

1. Introducing waste incineration in a newly established residential area without alternative heating facilities:

Which fuels would have been utilized in this case if waste was not available? As previously discussed, the answer could be biomass. It may; however, also be natural gas, since gas is generally considered a relatively clean fuel and Denmark has rather expanded natural gas distribution networks. Investments in coal and oil technology are unlikely, as Denmark needs to reduce CO_2 emissions significantly to meet the political reduction targets (according to the Danish Energy Agency, Denmark has a CO_2 deficit of 8-13 million tonnes of CO_2 per year for the period 2008-2012).

2. Introducing waste incineration in an area where the heat demand is supplied by a coal-fired CHP plant

If the demand for heat is constant, the coal-fired CHP plant will have to decrease its production, as waste is a cheaper fuel than coal. This is a short-term effect, though. If the demand for heat is increasing in the area (and the coal plant cannot supply the extra heat) this demand would possibly have been met by investments in facilities utilizing biomass or perhaps natural gas as discussed above. This investment would be avoided by introducing waste incineration. If the demand for heat is decreasing, introduction of waste incineration will reduce the need for coal at a faster rate than if waste incineration was not introduced. This could eventually lead to decommissioning of the coal-fired CHP plant. Finally, heat production at the CHP plant is linked to its electricity production. If electricity prices are high the CHP plant may still choose to produce electricity and instead cool off the extra heat. In this case, the benefits of waste incineration are significantly reduced. This must; however, be regarded as a short-term effect.

The consequences of introducing waste incineration in this situation depend heavily on the framework conditions. Biomass and natural gas are expected to be affected if the demand for heat is increasing, whereas coal is expected to be affected if the demand for heat is decreasing.

3. Introducing waste incineration in an area where the heat demand is supplied by a natural gas-fired or an oil-fired CHP plant

The consequences will be similar to the consequences in situation 2, but with substitution of natural gas or oil instead of coal.

Summing up, the outcome depends on the framework conditions. Increasing the capacity of waste incineration is expected to affect investments in biomass (or natural gas) technology when the demand for heat is increasing. If the demand for heat is decreasing, this is expected to affect the existing plants (e.g. coal, natural gas, and oil).

The discussion above shows that a range of fuels may be affected by increased waste incineration. In the future, even more technologies such as solar heat, heat pumps and geothermal heat are expected to replace fossil fuels, bringing even more technologies into play. Blurring the results even more is the discussion whether biomass should be considered constrained or not. If not, it is reasonable to assume that waste incineration will substitute biomass when this fuel type is expected to be affected. If biomass is considered a constrained resource; however, it will most likely be used for energy production in another area, possibly substituting fossil fuels there. As such biomass cannot be considered an affected fuel.

If no knowledge is available about the specific district heating network and the development in the area, it is recommended to use two different types of fuels in the LCA. Biomass should (for now) be used in one scenario, and natural gas, oil or coal in the other scenario. However, it is recommended that as much information as possible is gained with respect to local conditions for assessing whether coal rather than oil or natural gas to be affected.

5.3 Evaluation of previous results

The discussions in the two previous chapters demonstrated the uncertainties related to identifying the long-term marginal technology for electricity as well as the long-term effects of heat substitution. The question is how these recommendations provided above relate to the conclusions from the studies outlined in Chapter 4.4 (Fruergaard et al. (III)) and Chapter 4.5 (Fruergaard & Astrup (IV)).

5.3.1 Energy substitution

In the study investigating the consequences of waste based heat substitution in two specific district heating networks (Chapter 4.4) the short-term effects were assessed, i.e. changes affecting the existing production capacity. If changes affecting investments were considered not only the fuel types but also the technologies (and thus the ratio between heat and electricity production) could be different. The recommendations from above are in the following only discussed with respect to the affected fuel type. The same is the case for the study outlined in Chapter 4.5.

Pure coal production was assumed affected in Case 1 and a mixture of biomass, natural gas and oil in Case 2 when heat production from waste incineration was increased. The benefits of heat substitution in Case 1 would be significantly reduced if biomass instead of coal was assumed substituted. The effects would be smaller for Case 2 due to the mix of fuels already employed in modeling. Larger savings would be obtained if only oil was assumed affected, whereas the opposite would be the case if solely biomass was affected. The results of the two cases were highly affected by the interactions with the electricity system, and for Case 2 in particular the interactions were critical. Heat substitution in Case 2 caused an extra demand for electricity originally causing an environmental load with respect to CO_2 emissions as the marginal electricity was assumed to be based on coal. If this electricity production was based on wind, the difference between the two cases would decrease. The ranking of the two cases is therefore expected to be highly affected by the choice of marginal electricity. This is in line with the original conclusions where an evaluation of different scenarios for electricity substitution showed to have significant effects on the results. The original conclusions concerning the importance of the district heating network, the interactions with the electricity system and the type of affected fuels would; however, not be altered.

In the study reported in Chapter 4.5, LCAs of different waste-to-energy technologies were conducted. Heat substitution from waste incineration was in this study modeled similar to heat substitution in Case 1 in the previous study acknowledging the fact that waste as a resource is utilized best in such an area. The LCAs were conducted with substitution of fossil fuels as well as renewable fuels which were in line with the recommendations from Chapter 5.2. The results with respect to ranking of the scenarios were shown to be robust towards changes in the substituted fuels.

5.3.2 Final recommendations

The fact that the results were robust with respect to changes in the substituted fuels illustrates other contributions besides energy substitution to be significant for the results. These contributions relate as discussed in section 4.2.2 to the technologies (e.g. emissions of heavy metals contributing to the toxic impact categories), the composition of the waste and in the case of anaerobic digestion to the assumptions concerning management of digestate. This illustrates the importance of balancing the time and resources spent on determining the substituted energy technology relative to the time spent on identifying and quantifying other significant contributions.

Finally, it should be considered whether the findings above allow for recommendations of a specific waste-to-energy technology in Denmark. An answer to this depends to some extent on how different impacts are weighted. If recirculation of nutrients is important, anaerobic digestion of the organic household waste should be the preferred solution. If focus instead is on efficient energy recovery, waste incineration and co-combustion of (suitable) waste fractions should be preferred. The findings in Fruergaard & Astrup (IV) indicated that waste incineration (in comparison with co-combustion and anaerobic digestion) yields the best results in most impact categories provided all of the produced heat can be utilized.

6 Conclusions

To evaluate the environmental consequences of energy recovery from waste, the interactions with the energy system have to be accounted for as these may have profound effects on the results. This also applies for the issues related to defining the framework of the assessment, i.e. definition of the goal and scope.

The following goal and scope related factors were identified as critical to ensure transparency and consistency in LCA studies: 1) goal definition, 2) the LCA approach, 3) the scale of the change, 4) the time perspective, 5) the technological and 6) the geographical scope, and 7) the effects of the CO_2 emission trading scheme. Also the type of effects (short-term or long-term) included in the LCA was identified as critical for the outcome. Each of these factors was evaluated based on examples or general discussions and recommendations provided regarding how they should be addressed and quantified in a Danish context. As an example, it was recommended applying the consequential LCA approach, as the purpose of an LCA of waste management solutions in the majority of cases would be to evaluate the consequences of a decision.

Based on specific studies, it was evaluated which contributions were important for the environmental performance of waste-to-energy technologies. Although the significance of the technologies and fuels identified as affected was indisputable, especially for global warming, other contributions were significant as well. The toxic impact categories were in general more affected by direct emissions caused by the chemical composition of the waste rather than the substituted energy. The impacts from anaerobic digestion of organic household waste were strongly related to assumptions concerning the final destination and use of the digestate.

The type of energy indentified as substituted was found to be highly related to the type of effects included in the LCA and the interactions between the waste management system and the energy system. It was recommended to focus on the long-term effects, i.e. decisions affecting investments in production capacity, as these effects were identified as most representative for modeling of changes in the waste system. This recommendation may give rise to increased uncertainty in the LCA; however, systematic arguments for selecting the affected technologies will reduce this uncertainty and at the same time provide valuable insights in system interactions and substitution mechanisms. Well founded arguments are a prerequisite for choosing one technology over another; nevertheless, as future effects are associated with substantial uncertainties, it was recommended to test the importance of energy substitution for the LCA results by using two significantly different technologies. Based on two different approaches, it was argued that investments in both coal and wind technology could potentially be affected due to changes in electricity production. For heat production, investments in biomass and coal technology (or another type of fossil fuel) could potentially be affected. The technologies and fuels identified as affected with respect to heat production were; however, highly related to local conditions.

The significance of interactions between the waste management system and the energy system was assessed in a case study with two specific district heating networks. The high level of CHP production in the Danish energy system was found to be crucial for the environmental performance of incineration plants, as reduced heat production at the CHP plant also affected electricity production. The effects on electricity production were related to the design of the CHP plant, as lowering heat production as some plants also results in reduced electricity production. Consequently, the type of plants as well as affected fuel types should be addressed when evaluating the environmental impacts of heat substitution.

Recommendations for treatment of combustible waste in Denmark depended to some extent on the focus of the assessment and how the various impacts were weighted. Anaerobic digestion of organic household waste was the preferred solution, if recirculation of nutrients were considered important. If energy recovery was prioritized, waste incineration was the preferred solution. Provided all heat could be utilized, waste incineration with energy recovery proved to be the best alternative in the majority of impact categories, suggesting waste incineration as a robust solution for treatment of combustible waste.

7 Future work

The work included in this thesis provides a basis for continued investigation within the following topics:

- **Evaluation of new and emerging waste-to-energy technologies.** Focus of this thesis was especially on waste incineration, anaerobic digestion and co-combustion as these technologies were considered most relevant from a Danish perspective. In the future; however, new and emerging technologies (e.g. for production of liquid biofuels) may be relevant for treatment of some parts of the waste. The data available for evaluating these technologies are often poor as the technologies are still under development emphasizing the importance of establishing inventory data for these technologies.
- **Flexibility of waste-to-energy technologies.** Waste incinerators act as base load technologies in the energy system as the possibilities of storing waste over longer periods of time are limited. To increase the share of wind in the energy system the remaining technologies need to be capable of acting flexibly to ensure security of supply. Some of the emerging waste-to-energy technologies have this ability (potentially), e.g. as multi-output processes generating either CHP or liquid fuels depending on the need of the system. The impacts of this ability need to be included and addressed as waste incineration otherwise tend to be superior in most LCAs due its high energy recovery efficiency.
- **The chemical composition of waste.** For some of the impact categories the chemical composition of waste is critical, e.g. when evaluating co-combustion of waste where the air pollution control system is less efficient than at incineration plants. Also the fossil carbon content is significant with respect to global warming. To enhance the general robustness of the results more focus should be allocated to improving these data.

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9 Appendices

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