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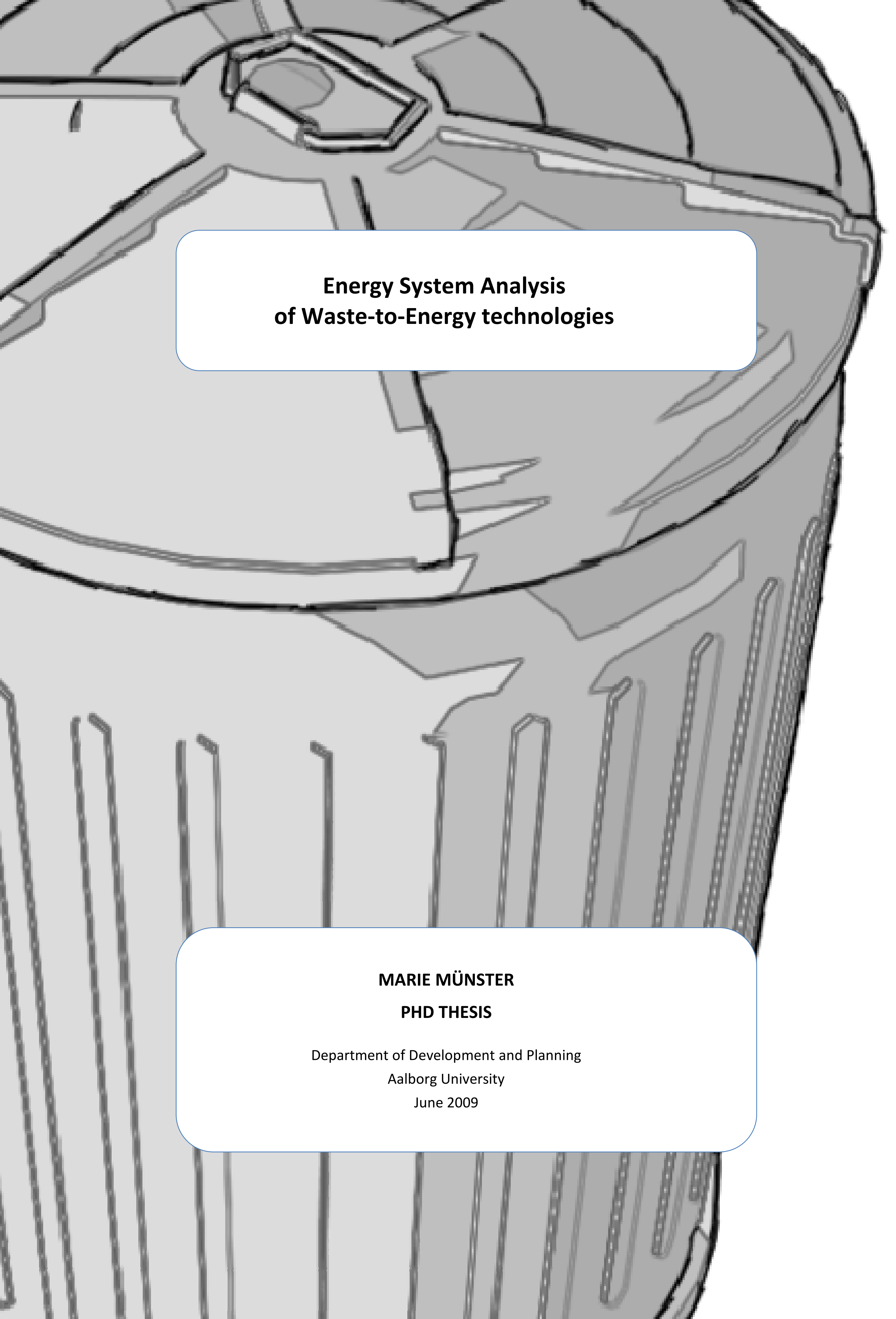
Publication date:
2009

Document Version
Publisher's PDF, also known as Version of record

Link to publication from Aalborg University

Citation for published version (APA):
Münster, M. (2009). *Energy System Analysis of Waste-to-Energy technologies*. Aalborg Universitetsforlag. ISP-Skriftserie No. 2009-12



Energy System Analysis of Waste-to-Energy technologies

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PHD THESIS

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June 2009

Energy System Analysis of Waste-to-Energy technologies

1. Edition

June 2009

Publication Series 2009-12
ISSN 1397-3169
ISBN 978-87-91830-36-5

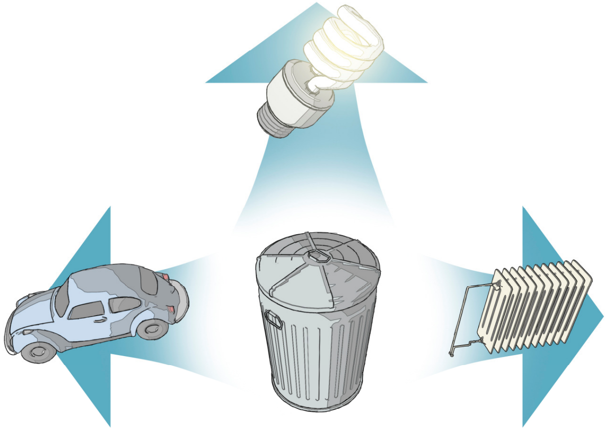
Department of Development and Planning, Aalborg University

Proofreading: Mette Reiche Sørensen

No. of pages: 73

Abstract

Alternative uses of waste for energy production becomes increasingly interesting both from a waste management perspective - to deal with increasing waste amounts while reducing the amount of waste deposited at landfills – and from an energy system perspective – to improve the flexibility of the energy system in order to increase the share of renewable energy and reduce greenhouse gas emissions.



The focus of this PhD thesis is the analysis of the optimal use of waste for energy production in Denmark, now and in the future. The object of analysis is waste which is not reused or recycled, but can be used for energy production. Different Waste-to-Energy technologies are analysed through energy system analysis of the current Danish energy system with 13-14% renewable energy, as well as possible future Danish energy systems with 43% (2025) and 100% renewable energy (2050), respectively. The technologies include combustion, thermal gasification, anaerobic digestion, fermentation, and transesterification technologies producing electricity, heat, or transport fuel. The influences on and from the surrounding countries Norway, Sweden, Finland and Germany are included in some of the analyses.

The analyses are performed in two Danish energy models: the EnergyPLAN model developed at Aalborg University and the Balmorel model developed at the former TSO, ElkraftSystem. A set of important aspects related to the modelling of waste and Waste-to-Energy technologies have been identified, and both models have been developed and improved in this respect in the course of the PhD project.

Given the assumptions applied, an optimal use of waste in the current and future Danish energy systems is mainly for combined heat and power (CHP) production. It is assessed as feasible to sort out 4% of the mixed combustible waste as a wet organic waste fraction and 19% as refuse derived fuel (RDF) consisting of paper, plastic, and waste wood.

The following combination of Waste-to-Energy technologies is found to be optimal:

1) Incineration for CHP of the main amount of waste (77% of total) with the highest possible electricity and heat efficiencies.
2) Biogas production from the full potential of organic household waste and manure, assuming that untreated manure is available equal to 5% of the current untreated potential and that a treatment price of 3 EUR/GJ can be obtained for organic waste. The biogas should be used for CHP or transport fuel, depending on the CO_2 quota costs and declared goal (reduced costs or reduced CO_2 emissions).
3) Thermal gasification of RDF for CHP combined with co-combustion of the remaining RDF with coal in new coal-fired power plants, if reduced CO_2 emissions are not the main goal. This is under the assumptions that the new coal-fired plants would, to a large extent, be built anyway; that the efficiencies of the waste incineration plants do not decrease due to a decreased heating value of the mixed waste used for incineration, and RDF is available for free.

Affected or “marginal” energy production has been identified as input to life cycle assessments. The main conclusion in this respect is that the affected energy production always consists of a combination of energy technologies, which can be identified by the use of energy system analysis. Which technologies are affected depends on the time perspective (short-term or long-term), the energy system analysed, the area analysed (Denmark or Nordic and German electricity markets), as well as on assumptions regarding capacities, efficiencies, costs, and prices.

When modelling Denmark along with its surrounding countries and including investments as part of the optimisation, technologies located outside Denmark are affected by the changed uses of waste in Denmark. Furthermore, not only flexible technologies, such as coal-fired power plants, which are capable of reacting to short-term changes in demand, are affected, but also inflexible technologies, such as nuclear power.

Resumé

Alternativ anvendelse af affald til energiproduktion har en stigende interesse både fra et affaldsplanlægningsperspektiv – for at håndtere stigende mængder affald og mindske mængden af affald der bliver deponeret – og fra et energisystemsperspektiv – for at forbedre fleksibiliteten af energisystemet med det mål at øge andelen af vedvarende energi og reducere udledningen af drivhusgasser.

Fokus i denne afhandling er analyser af optimal udnyttelse af affald til energiproduktion i Danmark nu og i fremtiden. Objektet for analyserne er affald, der ikke genanvendes, men som kan udnyttes til energiproduktion. Forskellige affaldsteknologier er analyseret i energisystemanalyser af det eksisterende danske energisystem med 13-14% vedvarende energi såvel som fremtidige mulige energisystemer med henholdsvis 43% (2025) og 100% vedvarende energi (2050). Teknologierne inkluderer forbrænding, anaerob afgasning, fermentering, trans-esterificering og termisk forgasning med produktion af varme, el og transportbrændsler. Indflydelsen på og fra de omkringliggende lande, Norge, Sverige, Finland og Tyskland, gennem el-markederne er inkluderet i nogle af analyserne.

Analyserne er udført på to danske energimodeller: EnergyPLAN-modellen, udviklet på Aalborg Universitet, og Balmorel-modellen, udviklet af den tidligere systemoperatør, ElkraftSystem. En række vigtige aspekter relateret til modellering af affald og affaldsenergiteknologier er blevet identificeret og begge modeller er blevet udviklet og forbedret under hensyntagen til disse i løbet af PhD projektet.

En optimal anvendelse af affald, primært til kraftvarme produktion, i det eksisterende og fremtidige danske energisystem er fundet ud fra de givne antagelser. Det er antaget, at det vil være muligt at udsortere 4% af det blandede forbrændingsegnede affald som en våd organisk affaldsfraktion og 19% som RDF (refuse derived fuel), bestående af papir, plastik og affaldstræ. Den følgende kombination af energiteknologier til behandling af affald er fundet optimal:

1) Affaldsforbrænding til kraftvarme af størstedelen af affaldet (77% af den fulde mængde) med den højest mulige el og varme-effektivitet.
2) Biogasproduktion fra det organiske husholdningsaffald og gylle ud fra den antagelse, at ubehandlet gylle er tilgængeligt i en mængde svarende til 5% af den nuværende uudnyttede ressource, og at en behandlingspris på 3 EUR/GJ kan opnås for organisk affald. Biogassen bør anvendes til kraftvarme eller transportbrændsel afhængigt af CO_2 kvote-priser og definerede mål (reducerede omkostninger eller reducerede CO_2 udledninger).
3) Termisk forgasning af RDF til kraftvarme kombineret med medforbrænding af RDF i nye kulfyrede kraftværker, hvis CO_2-reduktion ikke er det primære mål. Dette bygger på den antagelse, at de nye kulfyrede kraftværker i det store hele ville blive bygget alligevel; at effektiviteten på de eksisterende affaldsforbrændingsanlæg ikke falder som følge af en nedsat

brændværdi af blandet affald til affaldsforbrænding, samt at RDF kan fås gratis.

Påvirket eller "marginal" energiproduktion er i projektet blevet identificeret som input til livscyklusanalyser. Den primære konklusion i denne henseende er, at den påvirkede energiproduktion altid består af en kombination af energiteknologier, som kan identificeres ved hjælp af energisystemanalyser. Hvilke teknologier, der er påvirket, afhænger af tidsperspektivet (kort eller langsigtet), det energisystem der analyseres, det område der analyseres (Danmark eller det nordiske og tyske el-marked), så vel som af antagelser vedrørende kapaciteter, effektivitet, omkostninger og priser.

Når Danmark modelleres med sine omkringliggende lande, og investeringer inkluderes som del af optimiseringen, bliver teknologier uden for Danmark påvirket af forandringer i udnyttelsen af affald i Danmark. Derudover påvirkes ikke kun fleksible teknologier, som fx kulfyrede kraftværker, som kan reagere på korttidsforandringer i forbrug, men også ufleksible teknologier som atomkraft.

Publications

Primary Publications

Paper I
Modelling Waste-To-Energy Technologies in National Energy Systems
Münster, M.
Peer reviewed conference proceeding. The 17th IASTED International Conference on Applied Simulation and Modelling, Corfu, Greece June 23rd – 25th, 2008

Paper II
Use of Waste for Heat, Electricity and Transport - Challenges when performing Energy System Analysis. Münster, M. & Lund, H.
Published in Energy – The International Journal. vol. 34, no. 5, pp. 636-644, May 2009.

Paper III
Comparing Waste-to-Energy Technologies by applying Energy System Analysis. Münster, M. & Lund, H.
Accepted subject to revisions by the International Journal of Integrated Waste Management March 2009. Resubmitted April 2009

Paper IV
Optimal Use of Waste in the Future Energy System. Münster, M. & Meibom, P.
To be submitted to Energy – The International Journal

Paper V
Uncertainties related to the identification of the marginal
energy technology in consequential life cycle assessments. Mathiesen, B.V. Münster, M. & Fruergaard, T.
Accepted by Journal of Cleaner Production April 2009. In Press, Corrected Proof.

Paper VI
Importance of Flexible Use of Waste for Energy for the National Energy System. Münster, M. & Meibom, P.
Conference proceeding. Abstract accepted March 2009. Final paper submitted June 2009. Twelfth International Waste Management and Landfill Symposium 5 - 9 October 2009 S. Margherita di Pula (Cagliari), Sardinia, Italy

Report
Energy Systems Analysis of Waste-to-Energy Technologies using EnergyPLAN. Münster, M.
Risø Report. Risø-R-1667(EN). April 2009

Secondary Publications

Conference proceedings (peer-reviewed and later expanded and submitted to international scientific journals):

Risø International Energy Conference
Optimal Use of Organic Waste in Future Energy Systems - the Danish case.
Münster, M. and Lund, H. 2007. 12 p.
Risø International Energy Conference, Roskilde, Denmark, 22nd – 24th May 2007.

Dubrovnik Conference on Sustainable Development of Energy, Water and Environmental Systems
Use of Waste for Heat, Electricity and Transport - Challenges when performing Energy Systems Analysis
Münster, M. 2007. 17 p.
4th Dubrovnik Conference on Sustainable Development of Energy, Water and Environmental Systems, nr. 4, Dubrovnik, Croatia, 4th – 8th June 2007

European Meeting Point - Energy for Development
Production of bio-fuel, electricity and heat through gasification of waste
Münster, M. 2007. 3 p.
European Meeting Point - Energy for Development 2007, Beja, Alentejo, Portugal, 10th – 12th October 2007

SETAC Europe LCA Case Studies Symposium
Energy system analyses of the marginal energy technology in life cycle assessments
Mathiesen, B.V. Münster, M. and Fruergaard, T. 2007. p. 15-18
SETAC Europe 14th LCA Case Studies Symposium, Göteborg, Sweden, 3rd-4th December 2007

Contribution of author to papers with co-writers

In Papers II and III, the author of this thesis participated in the conceptual modelling of waste and Waste-to-Energy (WtE) technologies in EnergyPLAN and tested the model, after it was finally programmed in EnergyPLAN by Henrik Lund. The author of this thesis, furthermore, performed the energy system analyses and wrote the articles, apart from the parts describing how waste and WtE technologies are modelled in EnergyPLAN, which were written by Henrik Lund. Henrik Lund, furthermore, contributed with quality assurance of the results and comments to the articles.

In Papers IV and VI, the author of this thesis did the modelling and programming of waste and WtE technologies in Balmorel. The author, furthermore, performed the energy system analyses and wrote the articles. Peter Meibom contributed with supervision and guidance in the process as well as with quality assurance of the results and comments to the articles.

In Paper V, the authors contributed with even shares of the article. The author of this thesis contributed with a case study of affected electricity and heat technologies when increasing waste incineration in ten specific energy system analyses with different energy systems, different types of district heating areas, and different possibilities of storing waste. Brian Vad Mathiesen contributed with an analysis of the application of the consequential life cycle assessment (LCA) methodology at different specific points in time, contemporary and historical, in order to identify the marginal electricity technology and, furthermore, he contributed with a description of consequential LCA methodology. Thilde Fruergaard contributed with a review of the "state-of-the-art" practice in LCA studies in order to identify the marginal electricity and heat technologies. The introduction, methodology description, as well as conclusions and recommendations were written jointly.

Acknowledgements

First, I would like to thank Prof. Henrik Lund from Aalborg University, my main supervisor, for originally inviting me to apply for this PhD project, for introducing me to EnergyPLAN, and for providing continuous guidance and encouragement throughout the process as well as always giving quick replies. Likewise, I would like to thank Prof. Poul Erik Morthorst, my supervisor at Risø-DTU, for sharing his overview of the energy sector and for skillful advice and inspiring discussions. It has been a very enjoyable journey with both of you, from which I have learned a lot. I would also like to thank my supervisor, Thomas Astrup, from DTU Environment, for constructive comments and discussions.

I would like to express my gratitude to Peter Meibom from Risø-DTU, for collaboration and guidance on the use of Balmorel as well as for our highly spirited and humorous exchanges of opinion. Furthermore, I wish to thank Hans Ravn from Ram-løse edb as well as Jesper Werling, Lars Bregnbæk and Anders Kofoed-Wiuff from EA Energy Analysis for patient consulting on data and model characteristics of Balmorel.

Thanks are also extended to my other co-authors, Brian Vad Mathiesen from Aalborg University and Thilde Fruergaard from DTU Environment, for inspiring discussions and great collaboration.

I would like to thank my colleagues at the Energy Systems Analysis research programme at Risø-DTU for inspiration, support and companionship and the Systems Analysis Division for hosting me. Especially, I would like to thank the great food club and my room-mate Stephanie Ropenus for good company, not least during our GAMS course, and for all the chocolate and concern. Thanks are also extended to Michael Nyboe for great assistance in IT matters.

At Aalborg University, I would like to thank my colleagues of the Sustainable Energy Planning Research Group for great inspiration and also my other colleagues at the Department of Development and Planning for welcoming me in an always warm and friendly atmosphere. Special thanks to Mette Reiche Sørensen for providing excellent proofreading.

Many persons have helped and supported me along the way and although I cannot mention all, at least I would like to thank Tore Hulgaard from Rambøll as well as the staff from Swedish Gas Centre, Waste Centre Denmark, DONG Energy, Danish Energy Authority, DAKA, Lemvig Biogas Plant, AV Miljø, KARA, L90, and PlanEnergi for contributing with data to the analyses. I would also like to thank Mikkel Juul from Penalhuset for the illustration on the front page and Rikke Gottrup from the University of Southern Denmark for great company and encouragement during the final writing phase.

Finally, I would like to thank my friends and, especially, my lovely family for continuous encouragement and practical support, particularly at the last stage of the project.

Last but not least, I would like to thank my husband, Andrew, for loving and supporting me, and my daughters, Matilda and Monica, for bringing so much joy and meaning into my life.

Abbreviations

Energy and monetary units

bbl	Barrel (5.8 GJ/bbl petrol)
DKK	Danish kroner
EUR	Euro (7.45 DKK in June 2009)
MW	Mega Watt
t	tonne
PJ	Peta Joule
TWh	Tera Watt hour (3.6 PJ)
USD	US dollar (5.28 DKK in June 2009)

Countries

DE	Germany
DK	Denmark
FI	Finland
NO	Norway
SE	Sweden

Other abbreviations

CBA	Cost Benefit Analysis
CHP	Combined Heat and Power
CO_2	Carbon dioxide
DH	District Heating
DME	Di-methyl ether
ENSUWE	Environmentally Sustainable Utilization of Waste resources for Energy production
ESA	Energy System Analysis
IGCC	Integrated Gasification Combined Cycle
LCA	Life Cycle Assessment
MCDA	Multi Criteria Decision Analysis
N_2O	Nitrous Oxide
Ngas	Natural gas
NOx	Nitrogen Oxides
RDF	Refuse Derived Fuel
RE	Renewable Energy
SO_2	Sulphur dioxide
TSO	Transmission System Operator
WtE	Waste-to-Energy

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Report

1 Introduction

Using waste for energy production becomes increasingly interesting seen both from a waste management and an energy supply perspective.

Seen from a waste management perspective, a number of issues have made it more and more topical for the EU countries to consider the treatment of waste in Waste-to-Energy (WtE) plants:

- Waste amounts are increasing and thereby increasing amounts need to be treated [1].
- The EU aims at reducing the amount of biodegradable waste which is landfilled, so that by 2014, a maximum amount corresponding to 35% of the biodegradable waste produced in 1995 is landfilled [2]. In several European countries, the legislation has been followed up by a ban on landfilling of biodegradable waste fractions.
- The EU now accepts energy-efficient waste incineration as a method of recovery, whereby it moves up the ladder of the waste hierarchy [3].

In Denmark, a very high proportion of municipal waste is utilised for energy purposes (54%) and only 4% is deposited at landfills. At the EU-25 level, much less is incinerated (17%) and much more deposited at landfills (45%). Comparable percentages are recycled in Denmark and at the EU level. [1]

Similarly, the energy sector has an increasing interest in utilising waste as fuel, for a number of reasons:

- The use of waste will increase the level of renewable energy in the system and decrease CO_2 emissions. In this way, including waste in the energy system contributes to the achievement of the goals of 20% renewable energy and 20% lower CO_2 emissions in the EU in 2020[4]. Furthermore, the dependence on fossil fuel is reduced.
- If waste is used to produce bio-fuel for transport this could contribute to the EU goal of having 10% of the transport sector supplied with sustainable fuels in 2020[4].
- At the global level, biomass is becoming a scarce resource and the production of biomass for energy purposes is considered to compete with food production. For this reason, there is a growing awareness of using biomass residues and waste for energy production.

Currently in Denmark, waste incineration produces combined heat and power (CHP) covering 4% of the electricity demand and 20% of the district heating production [5]. In Denmark, CHP is well developed and covers, in total, 43% of the electricity demand. To exploit the heat, a wide-spread district heating network exists that supplies 60% of the households, corresponding to 46% of the heat market. The use of heat produced from waste is currently given priority in the district heating networks all year round, but still heat produced from waste must be cooled off, particularly during summertime. The EU has a goal of increasing the share of CHP [6] and expanding district heating networks. In Denmark, a possible decrease in the demand for district heating in the future is discussed due to the political goal of improving the energy efficiency of buildings [4;7]. However, if the efficiency of waste incineration and district heat distribution increases, the percentage of waste incineration in the district heating system may increase to around 33% of the current consumption [8]. In Denmark, a current lack of waste incineration capacity exists and old plants need replacement [9].

Denmark has a high percentage of wind power in the energy system, which covers up to 20% of the electricity production. The Danish Government aims at achieving a 100% renewable energy supply in the long run and a 30% renewable energy share before 2025 [10]. This will require a significant increase in the share of wind power and thus an increased flexibility in the energy system.

To sum up, the integration of waste into energy systems represents a range of challenges. Denmark is an interesting case of analysis in this respect, for a number of reasons:

- The Danish system has a high percentage of combined heat and power (CHP) production, in which the electricity production is tied to the heat demand with some flexibility added by heat storages.
- The system has a high percentage of wind power production, in which the electricity production is tied to the wind speed. Denmark has defined even higher wind power goals in the future.
- Denmark focuses on improving the energy efficiency of buildings, thereby potentially reducing the heat demand considerably.

Combining an energy system with the above-mentioned characteristics with waste incineration - where the main product is heat and where electricity production is determined by the difficulty of storing waste - is complicated. It is, therefore, interesting to consider other Waste-to-Energy[1] (WtE) options which have more flexibility in terms of facilitating the storage of waste or derived fuels. Furthermore, it may be interesting to consider technologies which produce less heat and more power or transport fuel.

Other countries throughout Europe wish to increase the share of CHP [6] as well as the wind power capacity with the aim of improving the energy efficiency of their systems. Few countries incinerate as high a degree of waste as Denmark [1], but, as mentioned above, new solutions are sought in order to decrease the amount of biodegradable waste deposited at landfills.

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[1] The term Waste-to-Energy is often used to refer to the incineration of municipal waste. In this thesis, WtE refers to all technologies that convert any type of waste to any type of energy.

Following the issues raised above, two research questions arise:

1. What is the optimal use of waste for energy production in the Danish energy system in the future?
2. What is the affected energy production with changed uses of waste for energy production?

Whether a particular use of waste is optimal is measured in terms of the effects on the energy system with regard to costs, CO_2 emissions and fossil fuel consumption. Decreasing fossil fuel consumption is interesting, both from an environmental and a security of supply perspective.

Overall, the PhD project aims to contribute to three goals:

1. Improving the national decision-making with regard to future WtE technologies in Denmark.
2. Improving the modelling of waste in existing energy system analysis models.
3. Improving the understanding of affected energy production when implementing WtE technologies to be used for consequential life cycle assessments of these technologies.

To achieve the goals and answer the research questions, the PhD project represents an interdisciplinary effort to unite energy system analysis, waste technology analysis and the identification of affected energy production for life cycle assessment. The PhD is part of the project "ENSUWE – Environmentally Sustainable Utilization of Waste resources for Energy production", which is financed by the Danish Council for Strategic Research under the Danish Agency for Science, Technology and Innovation. The identification of waste resources which are available for energy purposes is an important task. This issue is, however, not covered by this PhD project, but is the focus of another PhD project under the ENSUWE project, which also performs life cycle assessments of WtE technologies based on identified affected energy production. This PhD project analyses the optimal way to convert fixed amounts of waste to energy using Denmark as case.

1.1 Content overview

The thesis includes 6 papers and a Report (see Primary Publications). The first four papers and the Report deal with the modelling of waste and analyse the optimal use of the waste resource for energy production. The last two papers handle the issue of affected energy production. Throughout the thesis, references are made to the papers and the Report, when relevant.

Paper I "Modelling Waste-To-Energy Technologies in National Energy Systems" is a conference proceeding with graphic models of WtE technologies. The graphic models provide a first step of the conceptual modelling of the technologies for energy system analysis models.

Paper II “Use of Waste for Heat, Electricity and Transport - Challenges when performing Energy System Analysis”, Paper III “Comparing Waste-to-Energy Technologies by applying Energy System Analysis“, and the Report “Energy Systems Analysis of Waste-to-Energy Technologies using EnergyPLAN” demonstrate energy system analysis of WtE technologies in the model, EnergyPLAN. Paper III is an article based on the Report, which includes more analyses as well as a thorough description of WtE technologies. The analyses in EnergyPLAN encompass the optimisation of energy production in Denmark. Paper II deals with the optimisation of fuel consumption, while Paper III and the Report focus on minimising the marginal operation costs of the energy providers in the current system and on decreasing fuel consumption in a future 100% renewable energy scenario. Furthermore, in Paper III and the Report, a more detailed modelling of a “syngas” plant is included. In the plant, waste is co-gasified with coal and is subsequently used for transport fuel or CHP production. This type of plant is referred to as a syngas plant.

In Paper IV “Optimal Use of Waste in the Future Energy System”, an energy system analysis is made in the Balmorel model. In this analysis, the costs of the energy system are minimised and both investments and production are optimised. Again, a detailed model of a syngas plant is included. Furthermore, Denmark is modelled together with its neighbouring countries.

Paper V “Uncertainties related to the identification of the marginal energy technology in consequential life cycle assessments” presents the problems related to the current practise of identifying marginal energy production for consequential life cycle assessments. Paper VI “Importance of Flexible Use of Waste for Energy for the National Energy System” identifies the long-term affected energy production for different WtE technologies on the Nordic and German electricity market by conducting energy system analysis, including the optimisation of both investments and production.

The contents of the remaining part of the thesis are presented as follows: After the introduction, Chapter 2 discusses methods of analysing WtE technologies and identifying affected energy production and identifies a set of requirements to energy system analysis models. The requirements form the basis for choosing two energy system models, EnergyPLAN and Balmorel, which are further described in Chapter 3. Moreover, the main challenges when modelling waste in energy system models are outlined. Chapter 3 describes the main characteristics of the two energy models and presents the improvements added to the models with regard to the modelling of waste. Chapter 4 encompasses a description of the WtE technologies, which are analysed in terms of system characteristics, input and output as well as assumed costs. Chapter 5 presents the main results with regard to both the optimal use of waste for energy production and the affected energy production. Finally, Chapter 6 presents conclusions and discussions and outlines possible further research.

2 Methods

This chapter discusses the methods needed to answer the research questions. Furthermore, requirements for modelling tools are identified.

First, the differences between using life cycle assessment (LCA) or energy system analysis (ESA) approaches to analyse Waste-to-Energy (WtE) technologies are described. Then a literature review of ESAs of WtE technologies is presented. The review leads to the identification of a number of requirements to the energy system model which is to be used. Then the identification of affected energy production through ESA is discussed and further requirements are defined. At the end of the chapter, two energy system models are chosen for the analyses based on these requirements. Finally, challenges related to the modelling of waste in energy systems are discussed.

2.2 Analysing WtE technologies

Waste management solutions - including WtE solutions - have so far primarily been analysed using a life cycle assessment (LCA) approach with a focus on the environmental impact of the different waste management solutions, from the production to the disposal of waste. Cost benefit analysis (CBA) [11-14], multi criteria decision analysis (MCDA) [15-18] and various other tools, e.g., analysing energy balances [19-21], have also been applied, albeit to a lesser degree. The use of a life cycle approach to prioritise between waste treatment methods has been acknowledged by the EU, as only results from this method are accepted if deviations from the defined waste hierarchy are desired [3].

A number of reviews have been made of the long list of LCAs conducted of waste [22-25]. Overall, the reviews support the waste hierarchy applied in the EU. The waste hierarchy prioritises waste treatment in the following order: waste prevention, re-use, recycling, recovery (including energy recovery) and safe disposal as a last resort[3]. Exceptions do, however, exist; for some fractions, incineration has for example been found to outperform recycling [26]. This thesis takes the waste hierarchy as a starting point and aims at prioritising between different future Waste-to Energy (WtE) applications of waste fractions which are not prevented, re-used or recycled. Apart from a general agreement on confirming the waste hierarchy, the reviews identify different factors which have a great significance on the outcome of the LCAs. All reviews, however, identify affected energy substitution as one of the key factors.

Ekvall et. al. have discussed the fact that “a traditional LCA model has several inherent characteristics that prohibit it from giving adequate answers to many significant questions”[27]. The issue of how to identify effects on the background system such as the energy system is also brought forward here as well as the historical and static nature of LCAs. It is recommended to conduct studies involving the future and identify long-term[2] marginal effects using dynamic optimisation models. Apart from that, spatial information is discussed. Emissions have different impacts depending on where they take place, and this problem is addressed as well as the issue of how to determine where plants should be erected. All issues are further discussed in Paper VI.

Whereas LCAs focus on one technology during the full life cycle (which is normally restricted to the phases from waste generation to final disposal in the case of waste LCAs), ESA focuses on one step of the life cycle (energy conversion), with a simulation of all interacting energy technologies. Figure 1 is a simplified illustration of the system boundaries of ESA and traditional waste LCAs.

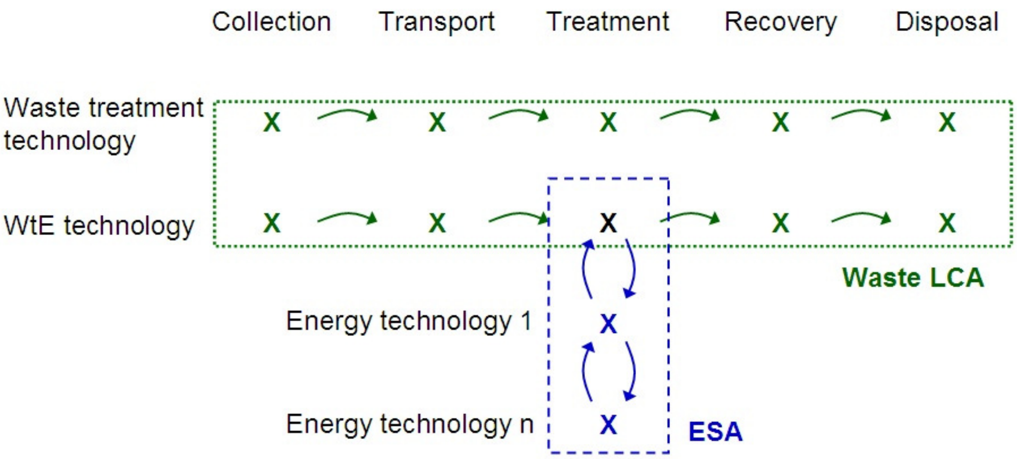

Figure 1 System boundaries of Energy System Analysis (ESA) and Waste Life Cycle Assessment (LCA)

The different elements included in the analysis can be illustrated as in Figure 1, where the green dotted line marks waste technologies and the blue dashed line marks energy technologies. The waste treatment technology does not form part of the energy system, while the remaining technologies do. Apart from the WtE technology, the remaining energy technologies in the energy system do not form part of the LCA. Concerning recovery, material recovery may also take place before or during treatment, but, for simplicity, it is here placed after treatment. Furthermore, depending on energy efficiency, WtE plants may be considered as energy recovery plants.

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[2] Long-term is here defined as including effects on investments and not only production.

The different focuses and approaches of LCA and ESA of WtE technologies are illustrated in Table 1.

Table 1 Focuses and approaches when performing LCA or ESA

Life Cycle Assessment	Energy System Analysis
Functional unit: e.g. treatment of 1t waste	Functional unit: e.g. energy demands in 1 country or region
Uses of waste for energy and non-energy purposes	Use of waste for energy
Life cycle (stages from generation of waste to final disposal)	Energy conversion stage
Comparison of few technologies	Technologies and their impact on the whole energy system
Current/ historical data	Current situation and future scenarios
Static model	Static or dynamic models
Normally non spatial	Divided into district heating areas and electricity markets
Many types of emissions	Primarily CO_2 emissions
Results: - Environmental impacts	Results: - Use of fuels - Percentage of renewable energy - Costs - CO_2 emissions from energy conversion

The results of ESAs can be used directly to prioritise between technologies according to an energy system perspective focusing on e.g., costs, fuel efficiency, CO_2 emissions from energy production, or percentage of renewable energy. The results can also be used in LCAs, if one wishes to prioritise according to a broader and more detailed environmental perspective, including the remaining parts of the life cycle. This is particularly relevant when analysing energy technologies using waste or biomass, in which the environmental impact of the remaining lifecycles may be relatively high. Furthermore, ESA can also contribute with results to other types of analyses focusing more on economy or societal effects, such as cost-benefit analysis (CBA) or multi-criteria decision analysis (MCDA) [15].

2.2.1 Energy system analysis of WtE technologies

The prioritisation of energy technologies is commonly done on the basis of energy system analysis which minimises the costs or maximises the income of the energy system studied [28-30]. For various reasons, little emphasis has so far been placed on modelling waste in energy systems. Primarily, due to the fact that waste has provided a marginal input to the energy production. Secondly, incineration has been the main WtE technology available and the main question has been whether to apply incineration or non-energy waste treatment, rather than prioritising between different WtE technologies. As more WtE technologies become available and new demands arise regarding both waste treatment and energy production, the prioritisation between different WtE technologies does, however, become interesting.

Methods

Only in few cases has waste been the focus of energy system analyses. A literature review of the studies made has been conducted to assess how waste is modelled in these cases. Table 2 below gives an overview of some of the ESAs made of WtE in recent years[3]. Large overlaps can be found among the authors of the papers and several of the papers are based on the same studies, such as 1+2, 3+4 and 8+9.

All studies, apart from one, focus on incineration and only few studies go beyond short-term scenarios. As the aim of this thesis is to make recommendations regarding the future and as investment in energy technologies in general have implications in the longer run, the technologies should also be tested in future possible energy systems. Furthermore, it is also within the scope of this thesis to assess the possible future role of WtE technologies which are not yet completely mature.

The studies identified are either from Italy or Sweden. In Sweden, the modelling of district heating has been in focus, which is not the case of the Italian studies. This reflects the nature of the energy systems of the regions involved. None of the studies perform national ESA including both electricity and district heating (DH) areas. In the future, more electricity may, however, be produced from waste in DH areas and more DH may be produced in countries such as Italy. Furthermore, the displacement of CHP plants in district heating areas influences the overall electrical energy system. For these reasons, an energy system model which provides recommendations for national policy should ideally encompass both electricity and heat in several DH areas.

None of the studies focus on wind power integration. Consequently, all the models used apply load duration curves. In load duration curves, the required energy loads are ranked according to size and represented by a varying number of steps. For each step, the energy production technologies with the cheapest marginal production costs are identified and used to supply the required energy. However, by ranking the loads according to size, the chronology of when they appear is lost. This is normally not a problem, but when simulating energy systems with a significant contribution of storage technologies, it is. Storage technologies become increasingly important to ensure flexibility in energy systems with a high share of fluctuating energy sources, such as wind energy. Here, the challenge becomes to match the energy demands with the production or unloading of storage hour-by-hour. The Danish energy system represents such an example and to model the dynamics of the Danish energy system, it is therefore preferable to use models with hour-by-hour representations of loads.

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[3] A further reference was found by Eriksson et. al., but it was an LCA using data from an ESA made for another purpose, which did not analyse waste technologies specifically [31].

Table 2 Energy System Analyses of WtE technologies

Literature	WtE technology/ model	Energy system	Area/ time perspective
1 Cosmi et. al. 2000 [32]	Incineration (MARKAL WAMMM)	Local ESA with no DH*	Basilicata region, Italy (medium term)
2 Salvia et. al. 2002 [33]	Incineration (MARKAL WAMMM)	local ESA with no DH*	Basilicata region, Italy (medium term)
3 Sahlin et. al. 2001 [34]	Incineration (MARKAL)	National/ regional ESA with one DH* area	Sweden (2050)
4 Olofsson et. al. 2003 [35]	Incineration, pyrolysis and gasification (MARKAL)	National/ regional ESA with one DH* area	Sweden (2050)
5 Ljunggren Söderman 2003 [36]	Incineration (Marginal cost ordering procedure)	National DH analysis with one DH* area	Sweden (short term)
6 Lundin et. al. 2004 [37]	Incineration with and without phosphorus recovery (MARTES)	Local DH* analysis	Göteborg, Sweden (short term)
7 Holmgren & Henning 2004 [38]	Incineration (MODEST)	Local DH* analyses	Skövde and Linköping, Sweden (short term)
8 Sahlin et. al. 2004 [39]	Incineration (HEATSPOT)	National DH* analysis, 164 DH* areas	Sweden (short term)
9 Knutsson et al. 2006 [40]	Incineration (HEATSPOT)	National DH* analysis, 164 DH* areas	Sweden (short term)

* DH: District heating

To identify the optimal use of waste for energy production in the future Danish energy system, the energy system model should be able to perform the following:

- Analysis of future scenarios with high shares of wind power and energy storage.
- Hour-by hour representation of loads.
- Simulation of both DH and electrical energy system.
- Analysis at national level.
- Analysis of both commercialised and pre-commercialised WtE technologies.

2.3 Identifying affected energy production

As mentioned earlier, the results from ESA may be used as input to LCA. Overall, two types of LCAs exist: attributional LCA, which uses average data and aims at describing "environmentally relevant physical flows to and from a life cycle and its subsystems", and consequential LCA which is "designed to generate information on the consequences of actions" and uses marginal data.[41]

The common LCA approach with regard to energy substitution is based on one of the following assumptions:

1. the energy substituted equals the average energy production at national scale, or
2. the energy substituted is produced by one "marginal" energy production plant.

Finding the average data for attributional LCA in the current system is not complicated. If future scenarios are analysed it may, however, be necessary to perform ESA to estimate the future average.

Finding the “marginal” is more complex. Paper V of this thesis illustrates problems related to the current practice of identifying the “marginal” energy production for consequential LCA. As illustrated in the article, through a review of current consequential LCAs, one single technology, either a coal or natural gas-fired CHP plant, is in general assumed to be the “marginal” energy production plant. The “marginal” energy production plant is chosen on the basis of a range of varying arguments, but only in one case, does energy system analysis form part of the identification. [42]

In an article from 2004, Ekvall & Weidema recommend that 5 steps are followed to identify a “marginal”[4] technology [41]. It is stated that the effects of a change are most likely to be both short-term and long-term. In energy terms, short-term effects refer to changes in production and long-term effects refer to changes in capacity. The relevant markets should also be analysed. In energy system terms, markets may be electricity or district heating markets. Furthermore, trends including the increase or decrease in energy demand as well as the flexibility of technologies should be identified. In the long term, all types of energy technologies may in practice be flexible in terms of either production or capacity, particularly when combined with storage technologies. Finally, short-term or long-term costs per unit - depending on the scope - can be used to determine the affected technology. Further discussion of the article and its relation to energy system analysis is presented in Paper VI.

In Paper V, recommendations are made concerning the identification and use of the affected energy production for consequential LCA. Apart from the LCA review mentioned earlier, the recommendations are based on a historical analysis of the “marginal” energy production technology in Denmark and on an energy system analysis of increased waste incineration. In the energy system analysis, waste incineration is increased in different district heating areas, in different energy systems, and with different degrees of flexibility. The analysis shows great differences with regard to fuel substitution among the different scenarios. At the end, the following recommendations could be made:

1. Use fundamentally different affected technologies, including production technologies unable to adjust to changes in demand, such as wind power generation;
2. Use long-term perspectives by identifying affected technologies in several possible and fundamentally different future scenarios, i.e. both fossil and renewable energy technologies; and
3. Identify the affected technologies on the basis of energy system analysis taking into account the technical characteristics of the technologies and the energy system involved.

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[4] In the article, an effect is defined as marginal if “the effect of a decision on the total production volume of a product is small enough to be approximated as infinitesimal”. As effects of long-term changes in the future use of waste for energy may not be infinitesimal - and hence not “marginal” - the term “affected” is used hereafter.

The first and third recommendations are natural consequences of performing a national energy systems analysis. The second recommendation relates to time perspective and trends. As illustrated in Paper V, energy technologies perform differently in different energy systems and, hence, in order to evaluate the technology, it is necessary to perform energy system analysis of WtE technologies not only in the short term, but also in the medium and long term. As mentioned before, only few of the papers in Table 2 do that. In an LCA context, the significance of looking at several time perspectives has also been illustrated by Klang et. al. [43].

To identify the effects which changed uses of waste for energy production have on the energy system, further performance requirements to an energy system analysis model arise. The model should be able to perform:

- Analysis of electricity market and local DH markets.
- Optimisation of investments and production according to cost.
- Analysis of fundamentally different scenarios.

Apart from contributing with input to LCAs, the affected energy production may also serve as an input to analyses such as CBA or MCDA.

2.4 Choice of energy system analysis models

To sum up, the energy system model which is able to identify the optimal use of waste for energy in the Danish energy system in the future must meet the following performance requirements:

- Analysis of future scenarios with high shares of wind power and energy storage.
- Hour-by hour representation of loads.
- Simulation of both DH and electrical energy system.
- Analysis at national level.
- Analysis of both commercialised and pre-commercialised WtE technologies.

Further requirements were identified in order for the model to be able to find the affected energy production units when the use of waste for energy production changes:

- Analysis of electricity market and local DH markets.
- Optimisation of investments and production according to cost.
- Analysis of fundamentally different scenarios.

On the basis of these requirements, two models have been chosen:

1) EnergyPLAN, which is developed at Aalborg University.
2) Balmorel, which is developed at the former Danish TSO, ElkraftSystem, and is now used and further developed at Risoe DTU and the consultants Ramløse and EA Energy Analysis.

Both models are continuously applied to new cases and improved. Both models are available for free and, in both, it was possible to work with the modelling environment and apply changes in order to improve the modelling of waste. Both models live up to the requirements listed to answer the first research question and, furthermore, Balmorel readily fulfils the requirements related to the optimisation of investments and trade on an international electricity market. EnergyPLAN, in turn, has the advantage of being fast and user-friendly as well as enabling the analysis of a full year hour-by-hour. A more detailed description of the models is presented in Section 3.1.

2.5 Modelling waste in energy systems

The modelling of waste in energy systems involves a series of challenges, as WtE technologies differ from other energy technologies in a number of ways (See Table 3). Most of the challenges were originally identified in Paper II of this thesis [44]. Each of these challenges should be met when performing ESA of WtE technologies. In Section 3.2, it is illustrated how EnergyPLAN and Balmorel, respectively, deal with these challenges.

Table 3 Differences between traditional fossil-fuelled CHP plants and Waste-to-Energy technologies

	Fossil fuel CHP	Waste-to-Energy technologies
Products	Electricity and heat	Multiple products such as heat, electricity, gaseous or liquid fuels, waste treatment and by-products (e.g. fodder and fertilizer)
Fuel quality	Homogenous	Heterogeneous, consisting of many fractions and dependent on e.g. time, location and source
Fuels	Predominantly single fuel plants (e.g. coal or gas)	Multiple fuels possible (e.g. waste, coal, biomass, manure, straw etc.)
Storage	Storage possible	Not allowed to store, household waste and wet biomass rapidly degrade
Geographical distribution	Fuel can be stored and transported easily	Location of fuel is important as fuel is not easily stored and has low energy content per volume
Fuel prices	Determined by world market prices	Waste price determined by e.g. national taxes
CO_2 emissions	CO_2 content of fossil fuels	CO_2 content based on fossil vs. organic fractions

New WtE technologies have the potential to produce not only heat and electricity but also transport fuels, waste-derived fuels for CHP and other products such as fertilisers. The plants may use multiple fuels mixing waste with fuels with higher energy content.

Whereas average CHP plants use homogenous fuels which can easily be stored and are often available on the world market, this is not the case of WtE technologies, in which the resource may consist of different fractions varying over time, location and source. Mixed waste is not easily stored as the organic, wet fractions rapidly decay. Furthermore, as waste in general has a low energy content per volume and emits odour, it is expensive and difficult to transport over long distances. It therefore becomes important to locate the origins of the waste.

Also, as opposed to most fuels, waste may be assumed to have a negative cost, as treatment of the waste involves a cost. The waste is stabilised and its volume is reduced before it is deposited or landfilled. The price of this treatment may vary depending on factors such as energy content, purity of the fraction, and ease of storing and handling. Local factors such as competing waste treatment capacity may, however, also influence the prices. The prices of specific fractions are therefore highly uncertain. In Denmark, an average negative price of mixed combustible waste may be found by taking the costs of the waste incineration and subtract the incomes from sales of electricity and heat.

A final issue is CO_2 emissions from waste. Many energy models do not take into account the fossil content of waste. Several arguments can be made in favour of this approach: 1) The fossil part of waste would otherwise end at a landfill where the same emissions would occur over time, or 2) The fossil part of the fuel is or should be burdening the producers of the waste products, or 3) Waste used for energy is not part of the CO_2 quota system. When analysing the energy system from a societal point of view it does, however, seem appropriate to include all fossil CO_2 emissions in the energy system. Additionally, although the use of waste for energy is not part of the CO_2 quota system today, there is a good chance that it may be in the future, particularly if it enters into competition with other fuels in multiple fuel plants, which are not dedicated to waste. The approach of including the fossil content in the calculations is furthermore similar to the approach normally applied for other fuels in energy system models.

When modelling the specific WtE technologies in ESA models, a first step has been to make simplified graphic models of the technologies, taking into account only the characteristics which are relevant for the ESA models.

An example of a graphic model is illustrated in Figure 2. A multi-fuel and multi-product plant such as co-gasification with the utilisation of syngas for either CHP or for transport is a complex technology to model, and detailed descriptions of the model including mathematical representations have been included in Papers III and IV.

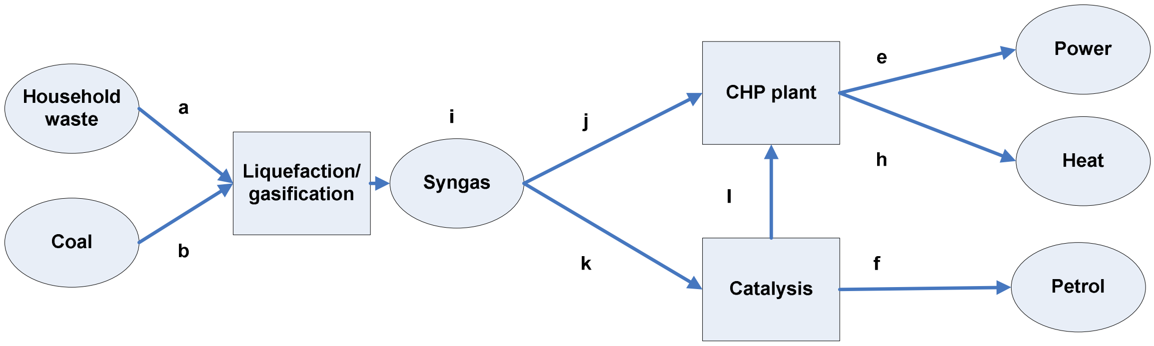


Figure 2 Gasification with use for CHP and transport

Full representations of the WtE technologies have been developed and are described in Paper I.

3 Models

Both EnergyPLAN and Balmorel have formerly been compared to a large number of energy system analysis models [45;46]. This chapter describes and compares the two models to each other. First, the general characteristics of both energy models are described and differences and similarities are identified. Subsequently, improvements of the models with regard to waste are described and compared.

3.1 Model Characteristics

Below, the models are characterised in terms of type of optimisation, model aggregation and coverage, as well as outputs, run-time and accessibility. The characteristics of both models are summarised in a table in Section 3.1.3.

3.1.1 EnergyPLAN

The EnergyPLAN model is developed and maintained at Aalborg University, Denmark. The model is available for free on the homepage www.energyplan.eu, where documentation of the model, case studies and comparative studies with other models can also be found [47-51]. The model is windows-based and programmed in Delphi Pascal with a user-friendly interface, which enables changes in input data, but not in the model structure.

The model is a deterministic model based on analytical programming and a selection of regulation strategies[45]. The model performs optimisation of energy production while meeting electricity and heat demands in each time period and each area. Optimisation of investments must be performed manually through iterations. The model can either perform technical optimisation, i.e. identifying the least fuel consuming and least import/export demanding solution, or market-economic optimisation, i.e. identifying the least-cost solution based on the business-economic costs of the individual plant owners. The model delivers results in a matter of seconds and re-runs are therefore uncomplicated to make. Output from the model entails energy production by unit, fuel consumption, CO_2 emissions and electricity import/export as well as excess electricity production (See Figure 3).

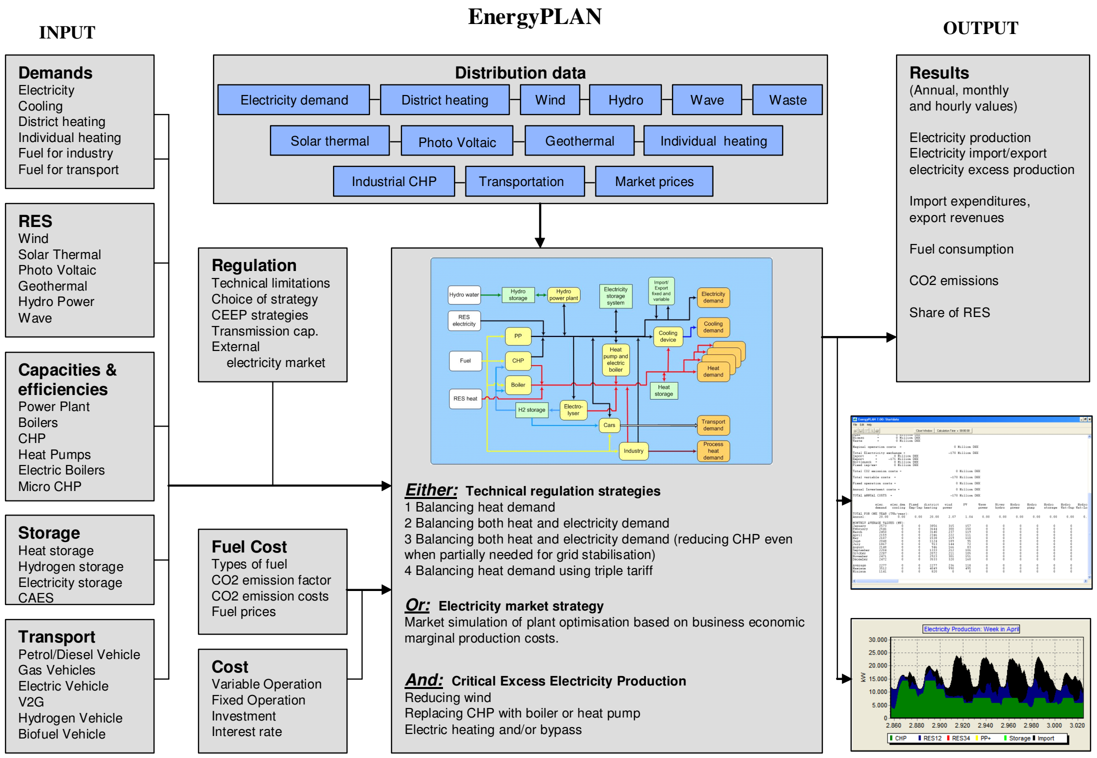


Figure 3 The EnergyPLAN model

EnergyPLAN performs hour-by-hour analyses of one full year, thus requiring time distribution data of demands, fluctuating production, such as wind, and market prices. The model integrates demands for individual heating and district heating, electricity and transport as well as fuel demands for industry.

The model is aggregated into three district heating groups, which are defined by the type of plants supplying them:

1. Areas supplied by district heating plants only
2. Smaller town areas supplied by CHP plants and boilers
3. Larger city areas supplied by CHP plants, condensing power plants and boilers

The three district heating groups exist in one area, which can represent a region or a country. Heat is traded without restrictions within each DH group and electricity is traded without restrictions within the area represented, which is typically a country. The exchange of electricity with neighbouring countries is modelled on the basis of a price interface, which includes price elasticity so that prices increase if exchange increases.

Data of the existing energy system can be found from publicly available sources, in particular the national energy statistics and the official projections of energy demand and production supplied by the Danish Energy Authority [52;53]. Heat boilers, CHP plants, and condensing power plants are divided into the three DH groups and represented by an average efficiency and an average fuel share for each type of plant. Furthermore, the model includes data on renewable energy plants, storage, electric heating and transport, which are independent of the district heating areas.

3.1.2 Balmorel

The Balmorel model was originally developed within the framework of the Balmorel project hosted by the former Danish TSO ElkraftSystem. The model is today used and developed at the research institute Risoe-DTU and at the consultants RAM-løse edb and EA Energy Analysis. RAM-løse edb also maintains the model. The model is open source and is available on www.balmorel.com, where documentation and case studies may also be found [28;29;54]. The model is programmed in GAMS and is operated without user-interface with direct access to the code. A user-interface is currently under development. A GAMS license and linear programming solver is needed to operate the model.

Balmorel is a deterministic model based on linear programming. The model optimises investments in production, storage and transmission units while meeting the demands for electricity and heat in each time period and area. The model minimises costs in the energy system, consisting of annualised investment costs for new investments, operation and maintenance costs of existing and new units, as well as fuel costs and CO_2 quota costs. Taxes and tariffs may be included in the optimisation. It would also be possible to programme the model to optimise according to other criteria, such as minimising CO_2 emissions or fossil fuel consumption.

Depending on the size of the problem to be solved (number of areas, technologies, time steps, etc.) the model requires from minutes to days to complete an optimisation. Apart from producing results on energy production by unit, fuel consumption, CO_2, SO2 and NOx emissions, and electricity import/export, the model also produces results on investments in energy plants and transmission as well as electricity prices.

The time division in Balmorel is flexible. The year is divided into seasons, which may be used to represent weeks, and into time periods, which may represent hours. When optimising both investments and operation, the model is often aggregated into less time steps either by reducing the number of time periods or the number of seasons. To be able to capture the fluctuating production from wind, it is necessary to perform hourly analyses and it is hence more desirable to reduce the number of seasons (e.g. to 26 weeks with 168 time periods) rather than the number of time periods. Each season is then weighted to ensure the representation of a full year. Investments and operation may be modelled for one year or development paths may be unfolded by performing yearly analysis and transferring the results, e.g., regarding investments, to subsequent analyses. This can for example be done in five-year steps as done by Karlsson and Meibom [28].

As EnergyPLAN, Balmorel requires time series for demands and for production from fluctuating sources, such as wind. Balmorel normally only integrates demands for electricity and district heating. Further demands, such as for individual heating, transport and fuel for industry, may, however, be added.

The geographical aggregation in Balmorel is also flexible. Countries consist of regions, which in turn consist of areas. Electricity demand is defined on a regional basis and exchange occurs between regions. Borders of regions should be defined by bottlenecks in the electricity transmission system. Heat demand is defined on an area basis and exchange is not allowed between areas. When analysing Danish conditions, the model often encompasses the Nordic countries – excluding Iceland – and Germany. Denmark is normally represented by two regions – East and West – as no electricity transmission exists between the two regions. The district heating areas have been represented by two areas – Urban and Rural - in each region [28], but also by 21 areas in total, of which 8 are based on geography and 13 on the main type of energy-producing technology, as in Paper IV. Neighboring countries are often modelled with one or few regions and district heating areas.

Data regarding existing energy plants is less aggregate than in EnergyPLAN, which makes the access to data more complicated. In Denmark, the data must be found via, e.g., the official green accounts of the major energy plants or the Danish Energy Producer Statistics [55]. For neighbouring countries, the data collection becomes even more complicated; however, some official sources do exist, such as the statistics and prospects for the European electricity sector by Eurelectric [56]. All existing plants are divided into the relevant areas. Technologies for new investments are also made available on an area basis. Plants are, among other things, characterised by fuel type, efficiencies, costs, and emissions. As with EnergyPLAN, the model includes renewable energy technologies, storage, and electric heating, which are also assigned to areas. The exchange of electricity with countries which are outside the model is based on a price interface and potentially a fixed import/export.

3.1.3 Summary of model characteristics

The characteristics and differences between EnergyPLAN and Balmorel are summarised in Table 4.

Table 4 Characteristics of EnergyPLAN and Balmorel

Characteristics	EnergyPLAN	Balmorel
Time aggregation	Hourly representation of one year	Flexible representation of one year (typically aggregated e.g. to 26 weeks or less with 168 hours).
Area represented	National	Several countries
System aggregation	3 DH groups, 1 region (e.g. a country)	Flexible at three levels (e.g. 21 DH areas and 2 regions in DK and one or few regions and DH areas in neighbouring countries)
Demand	Electricity, heat, transport and fuel for industry	Electricity and heat (and potentially transport and fuel for industry)
Optimisation type	Analytical/ strategy-based (market or technical)	Linear programming (market)
Optimisation focus	Minimising fuel consumption or marginal production costs	Minimising annualised costs of energy system
Optimisation object	Operation	Operation and investment
Output	Energy production by unit, fuel consumption, CO_2 emissions, electricity import/export	As EnergyPLAN, but also including investments in plants and transmission, as well as electricity price
Model run-time	Seconds	Depending on size of problem, varying from minutes to days
Access	Free, windows-based interface	Open source (demands GAMS license and linear programming software), direct access to code

Both models are deterministic and assume perfect foresight. Hence, they do not take into account the uncertainty related to, e.g., wind forecasts. Both models can also perform analyses with or without taxes.

Furthermore, none of the models take into account start-up costs or varying costs depending on scale. Balmorel assumes that the energy market is a perfectly competitive market where - among other things – no monopolies or skewed market power exist, where producers and consumers have perfect access to information, and where all actors act economically rational seeking to maximise their own profit. This is also the case with EnergyPLAN, when run in market optimisation mode. To clarify other aspects, which may influence future energy systems, such as institutional settings, market power and hegemony, further analysis will have to be made.

Finally, both models include investment costs annualised subject to an interest rate, as well as operation and maintenance costs, fuel costs, and CO_2 quota costs. In EnergyPLAN, investment costs are used to determine the total costs of the energy system, whereas they form part of the optimisation in Balmorel. Balmorel also includes taxes on SO2 and NOx. No further externalities are currently included in the models, such as other greenhouse gas emissions, health effects from energy production, etc.

3.2 Modelling waste

In this section, the modelling of waste in the two models is presented. The challenges which were previously identified are used as a starting point of the presentation. A summary of how the energy models handle waste is presented in a table in Section 3.2.3.

3.2.1 Waste in EnergyPLAN

As mentioned earlier, a range of challenges are related to the modelling of waste in energy systems. Formerly, waste was basically modelled as biomass in EnergyPLAN, as is the case in many other energy models. In this section, the improvements of EnergyPLAN with regard to waste are presented. The improvements have been made in a collaborative effort. Based on descriptions of the WtE technologies (Paper I), I have first identified the needed changes. Henrik Lund and I have subsequently, in an iterative process, discussed and modelled the changes; Henrik Lund has encoded the changes to the model and I have tested the model.

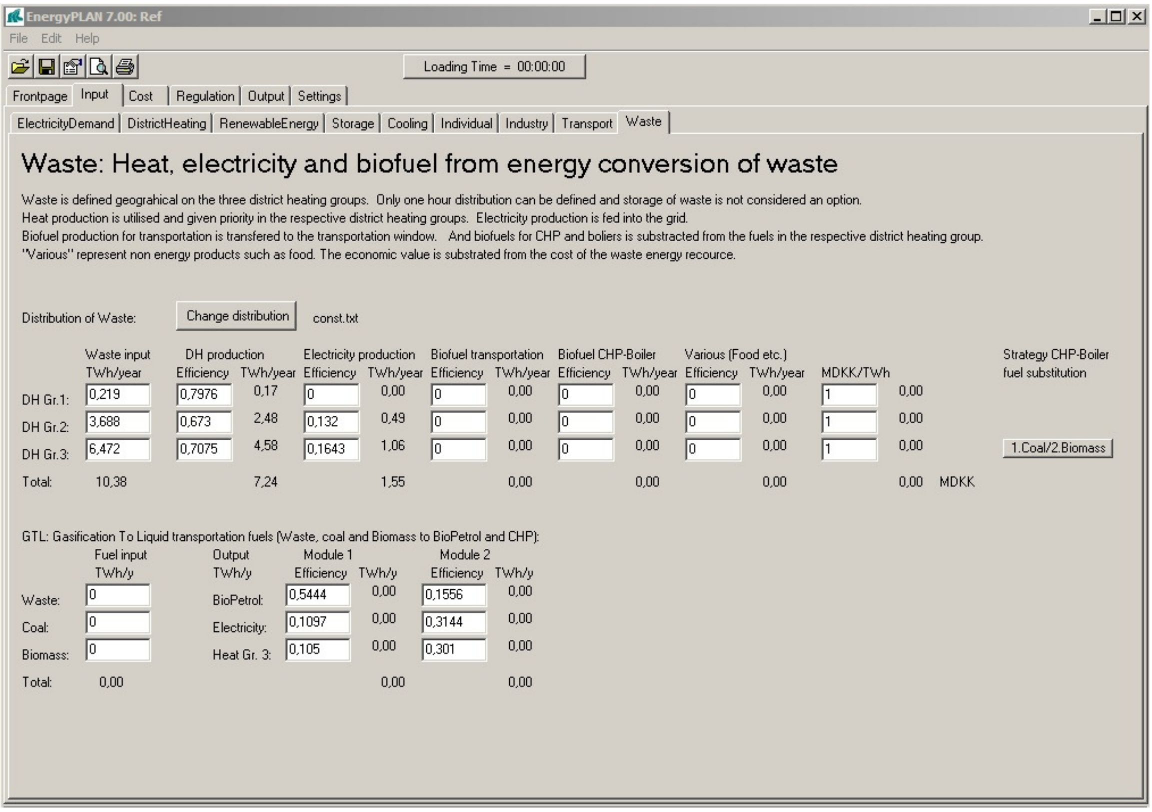
First, the need to distinguish between biomass and waste with regard to storage, price and CO_2 content was identified. Secondly, the need for more products, such as fuel for CHP and transport, was found, along with the need to choose which fuels to substitute when co-firing with a waste-derived biofuel. After having analysed a number of WtE technologies (Paper II), a need was identified to model a waste plant which can co-fire with other fuels and optimise between production of electricity/heat and transport fuel. This was done in the syngas module, which is described in detail in Paper III. Full documentation of the modelling of waste in EnergyPLAN can furthermore be found in the documentation on the model homepage (www.energyplan.eu).

The challenges when modelling waste have in EnergyPLAN been dealt with as illustrated in Table 5.

Table 5 Modelling waste in EnergyPLAN

Challenges	EnergyPLAN
Products	Electricity, heat, fuels for transport and CHP and other products can be produced. The Syngas plant optimises production of electricity/heat and fuel for transport, respectively.
Fuel quality	Waste is represented by energy content. Different fractions are modelled in different scenarios.
Fuels	Waste substitutes first coal then biomass in coal-fired plants. The Syngas plant may utilise coal, waste and biomass.
Storage	Constant production
Geographical distribution	Divided into three DH areas
Fuel prices	A negative waste price is used. Varying prices on different waste fractions are calculated after simulation in a spreadsheet.
CO_2	Fossil carbon content of waste is included

With the new representation of waste in EnergyPLAN, it is possible to choose between the production of electricity, heat, fuels for transport and for CHP, as well as other products, such as fertiliser (See Figure 4). Waste is represented by energy content. To simulate different waste fractions the corresponding energy amount must be added to or subtracted from technologies which utilise the fraction in question. To move refuse derived fuel (RDF) from incineration to coal-fired power plants, the efficiencies of the current use in incineration should be decreased and the efficiencies of the bio-fuel for CHP should be increased accordingly. It should then be chosen whether the bio-fuel should replace the average fuel used for the respective CHP plant, or first replace coal and then biomass. Modifications of CO_2 emissions from WtE technologies must be calculated and entered in a separate tab sheet and waste fraction prices likewise.



Waste: Heat, electricity and biofuel from energy conversion of waste

Waste is defined geograhical on the three district heating groups. Only one hour distribution can be defined and storage of waste is not considered an option.
Heat production is utilised and given priority in the respective district heating groups. Electricity production is fed into the grid.
Biofuel production for transportation is transfered to the transportation window. And biofuels for CHP and boliers is substracted from the fuels in the respective district heating group.
"Various" represent non energy products such as food. The economic value is substrated from the cost of the waste energy recource.

Distribution of Waste: const.txt

	Waste input	DH production		Electricity production		Biofuel transportation		Biofuel CHP-Boiler		Various (Food etc.)					Strategy CHP-Boiler
	TWh/year	Efficiency	TWh/year	Efficiency	TWh/year	Efficiency	TWh/year	Efficiency	TWh/year	Efficiency	TWh/year	MDKK/TWh			fuel substitution
DH Gr.1:	0,219	0,7976	0,17	0	0,00	0	0,00	0	0,00	0	0,00	1	0,00		
DH Gr.2:	3,688	0,673	2,48	0,132	0,49	0	0,00	0	0,00	0	0,00	1	0,00		
DH Gr.3:	6,472	0,7075	4,58	0,1643	1,06	0	0,00	0	0,00	0	0,00	1	0,00		1.Coal/2.Biomass
Total:	10,38		7,24		1,55		0,00		0,00		0,00		0,00	MDKK	

GTL: Gasification To Liquid transportation fuels (Waste, coal and Biomass to BioPetrol and CHP):

	Fuel input	Output	Module 1		Module 2	
	TWh/y	TWh/y	Efficiency	TWh/y	Efficiency	TWh/y
Waste:	0	BioPetrol:	0,5444	0,00	0,1556	0,00
Coal:	0	Electricity:	0,1097	0,00	0,3144	0,00
Biomass:	0	Heat Gr. 3:	0,105	0,00	0,301	0,00
Total:	0,00			0,00		0,00

Figure 4 Waste sheet in EnergyPLAN

The WtE technologies are divided into the three district heating groups in the model. Data regarding existing waste incineration plants can be extracted from the Danish Energy Producer Statistics [55], which are made available for research purposes. From this, the existing plants have been grouped according to the three areas and average efficiencies have been found. The division into the three areas ensures that waste is, to some extent, used close to the source where it is produced.

The time distribution of production can be set at constant, in order to simulate that no storage can take place. The use of waste as biofuel for CHP and transport is flexible and storage is thus allowed.

3.2.2 Waste in Balmorel

In Balmorel, waste has formerly mainly been modelled as waste incineration with full storage possibility, with no restrictions regarding the use of waste produced, with no CO_2 emissions, and with zero cost [28]. This section presents improvements to the model with regard to waste. I have implemented all phases of the modelling and programming with the supervision and guidance of Peter Meibom, unless otherwise stated.

After having performed the energy system analysis by use of EnergyPLAN, as reported in Paper III and the Report, the importance of identifying the long-term affected energy production on a regional electricity market was clarified. It was therefore chosen to perform further analyses in Balmorel in order to encompass neighbouring countries and optimise investments along with production. A version of the model which includes the possibility of investment in district heating networks was chosen [57]. The understanding of how to model the WtE technologies was again based on the diagrams which are presented in Paper I.

First, the model was improved with regard to storage, price and CO_2 content. Subsequently, the syngas module was implemented. This implementation along with a mathematical representation of the module is described in Paper IV. Subsequently, the possibility to produce transport fuel was extended to other WtE technologies and, finally, investment in the upgrade of existing single-fuel plants to multiple-fuel plants was implemented.

The challenges when modelling waste have in Balmorel been dealt with as illustrated in Table 6.

Table 6 Modelling waste in Balmorel

Challenges	Balmorel
Products	Electricity, heat and transport fuel can be produced. The Syngas plant optimises production of electricity/heat and fuel for transport, respectively.
Fuel quality	Waste is represented by energy content. Different fractions are defined as a percentage of the total, which the relevant plants can use.
Fuels	Multiple fuels can be used in WtE plants. Syngas plant may, e.g., utilise coal and waste.
Storage	A percentage of the waste may be stored within a year
Geographical distribution	Waste is made available in the two regions in Denmark. Existing plants are divided into the 21 DH areas.
Fuel prices	A negative waste price is used. Treatment prices of fractions are identified based on shadow prices of restrictions on use of the fractions.
CO_2	Fossil carbon content of waste is included

The production of bio-fuels for transport has been facilitated by introducing revenue from the fuels produced for that purpose and by adding the use of waste for bio-fuel production to the restriction ensuring that all waste is used each year. A larger extension to the model has been added in order to model a syngas plant which can optimize between use of multiple fuels and optimise between producing transport fuel or electricity and heat, depending on the fluctuating electricity prices.

The model facilitates the use of various fuels in one plant. This feature has been expanded to accommodate investments in the upgrading of existing plants from fuelling with a single fuel to fuelling with multiple fuels. In this manner, it is possible to model, e.g., the co-combustion of waste and coal in existing coal-fired plants.

As only certain waste fractions can be used for some plants, a restriction has been added which ensures that the combined use of a given fraction in these plants does not exceed the share which this fraction constitutes out of the total. As a starting point, the model treats waste as one fuel with one price. Feasible treatment prices of waste fractions have been identified based on the shadow prices of the restrictions on use of the fractions.

In this model, the issue of storage and transportation is dealt with through a restriction, which requires that all waste available for energy production in each region must be used within a year. Existing WtE plants are placed in the various areas. It is possible to store part of the waste (e.g. 40%) within the year; this storage is subject to a cost for waste transportation and a weekly fee to the deposit. The waste flow is assumed to be constant and stored waste is on average stored for half a year. The waste storage function was originally developed by EA Energy Analysis for a simulation of Copenhagen [57].

3.2.3 Summary of waste modelling

To sum up, the challenges when modelling waste have, in the two models, been dealt with as illustrated in Table 7.

Table 7 Modelling waste in EnergyPLAN and Balmorel

Challenges	EnergyPLAN	Balmorel
Products	Electricity, heat, fuels for transport and CHP and other products can be produced. The Syngas plant optimises production of electricity/heat and fuel for transport, respectively.	Electricity, heat and transport fuel can be produced. The Syngas plant optimises production of electricity/heat and fuel for transport, respectively.
Fuel quality	Waste is represented by energy content. Different fractions are modelled in different scenarios.	Waste is represented by energy content. Different fractions are defined as a percentage of the total, which the relevant plants can use.
Fuels	Waste substitutes first coal then biomass in coal-fired plants. The Syngas plant may utilise coal, waste and biomass.	Multiple fuels can be used in WtE plants. Syngas plant may, e.g., utilise coal and waste.
Storage	Constant production	A percentage of the waste may be stored within a year
Geographical distribution	Divided into three DH areas	Waste is made available in the two regions in Denmark. Existing plants are divided into the 21 DH areas.
Fuel prices	A negative waste price is used. Varying prices on different waste fractions are calculated after simulation in a spreadsheet.	A negative waste price is used. Treatment prices of fractions are identified based on shadow prices of restrictions on use of the fractions.
CO_2	Fossil carbon content of waste is included	Fossil carbon content of waste is included

All of the challenges have been met in the two energy models and comparable functionalities have been achieved. The most important difference between the modelling of WtE technologies in the models is the fact that Balmorel, unlike EnergyPLAN, facilitates investments in both new WtE technologies and district heating networks, as well as models the surrounding electricity market. This difference is, however, related to the general characteristics of the models. The other most important difference is the possibility to store part of the waste in Balmorel. As EnergyPLAN already encompasses storage technologies, this should easily be implemented in EnergyPLAN. EnergyPLAN, on the other hand, facilitates the production of fuel for CHP and other products, but this may also be easily implemented in Balmorel on an ad hoc basis. Finally, the possibility to optimise between the shares of different fuels in multiple-fuel plants is only fully represented in Balmorel, as EnergyPLAN as a rule operates with fixed fuel shares in the aggregated plants.

In both models, waste fractions, which form part of mixed combustible waste, are analysed. In EnergyPLAN, other fractions, which form part of the biomass fraction, have also been included in the analysis. The issue of fractions is quite complicated as, e.g., combustible waste can be divided into an infinite number of fractions with varying energy and chemical contents, storage and handling properties, etc. With regard to energy system analysis, it is important to identify which waste fractions may be used in WtE technologies. The current use of the waste fractions, for example, whether they are currently incinerated in waste incineration plants or are used outside the energy system, must also be identified. Each waste fraction may then be regarded as part of the mixed combustible waste, or a separate fuel type with separate fuel price and CO_2 content may be created for that particular fraction.

4 Technologies

In this chapter, an overview is given of the WtE technologies analysed. A whole range of technologies are relevant, when considering how to convert waste into energy in the most efficient way, seen from an energy system perspective.

Biomass conversion can be divided into thermo-chemical, bio-chemical and chemical processes, as illustrated in Figure 5 and Figure 6. The figures represent a wide range of possible conversion routes, but do not intend to include all. Some of the processes require further fossil additives, which are not included in the figures.

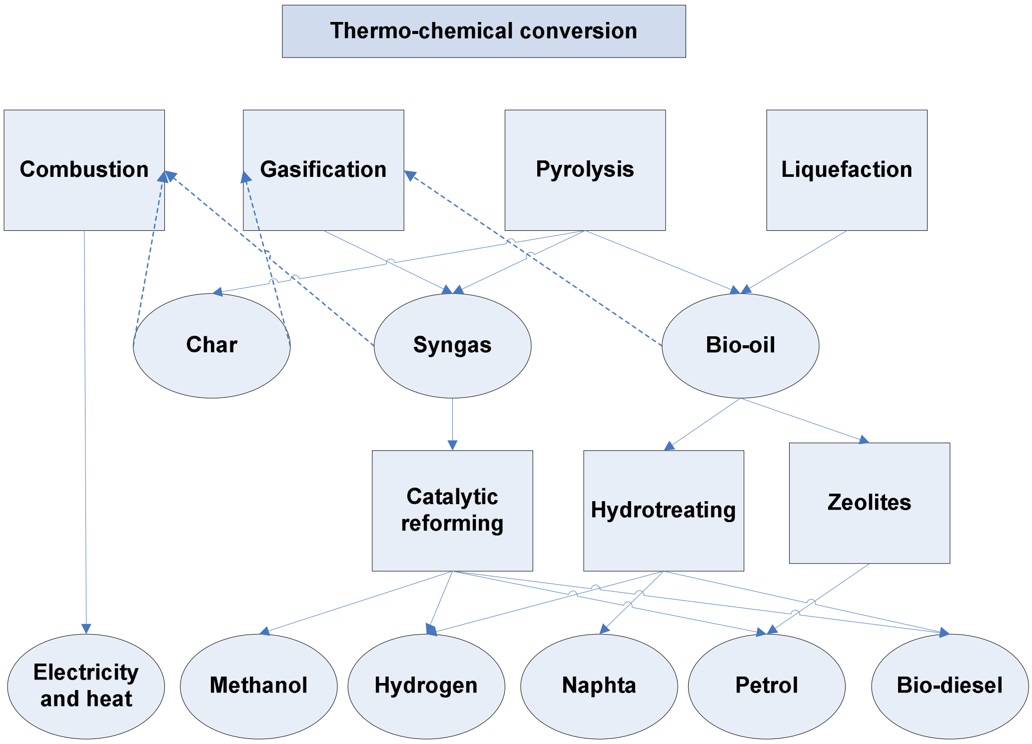


Figure 5 Thermo-chemical biomass conversion technologies

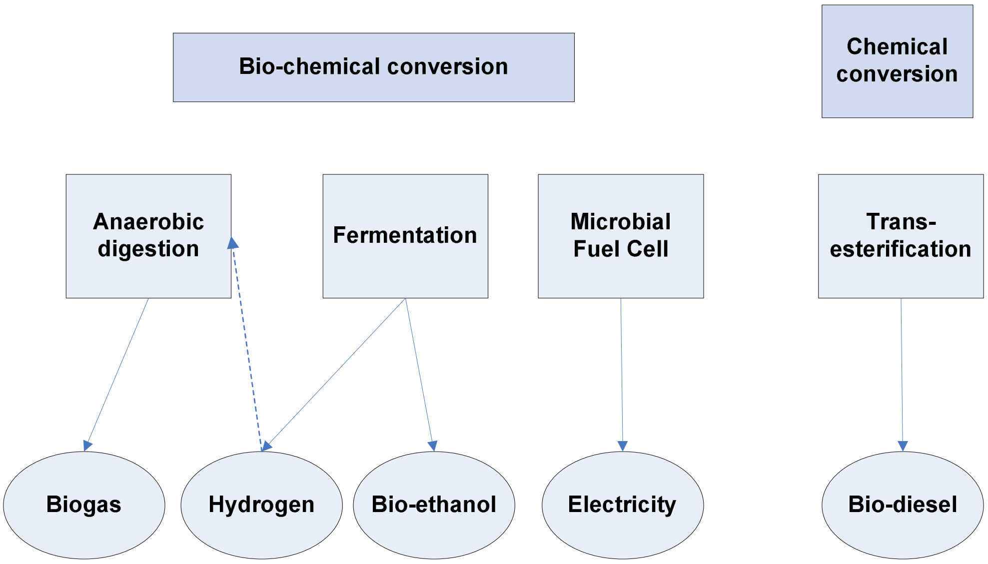


Figure 6 Bio-chemical and chemical biomass conversion processes

As can be seen from the figures, a wide range of fuels can be produced and many combinations are possible. It is not possible to analyse all potential combinations, but a number of concrete examples of technologies are chosen for a detailed analysis on the basis of a set of criteria:

- The technologies utilise household waste, waste from the service sector and industry or residues from agriculture as a resource to produce electricity, heat or transport fuel.
- The technologies have a good potential for increasing the flexibility of the energy system and thus increasing the amount of renewable energy in the system (Decoupling electricity from heat production. Producing transport fuels instead of electricity. Facilitating storage of waste or produced fuels).
- The technologies represent the main different types of WtE technologies, seen from an energy system perspective.
- The technologies are interesting in a Danish context, e.g., by representing innovative Danish demonstration projects.

From these criteria, the technologies presented in Table 8 have been chosen.

Three parameters may make other WtE technologies more feasible than waste incineration:

- Lower costs
- Higher efficiencies
- Increased flexibility

Efficiencies and costs are documented in Papers II, III, IV, VI and the Report and are shown in Table 9. System diagrams of most technologies are presented in Paper I. In Table 8, the characteristics of the technologies in terms of conversion processes, input, output, and possibilities of storage are shown.

When considering combustion, three possible combinations have been analysed. For future waste incineration plants, there is a potential for increase in the electricity and heat production and the storage of some waste fractions may be utilised more. With co-combustion of RDF in coal-fired power plants, there is a potential for substituting coal (or straw), for increasing electricity production and for storing the RDF. Dedicated RDF incineration plants may yield higher total efficiencies and store the RDF.

When co-gasifying pre-treated municipal waste with coal, there is a potential for optimising between producing electricity and heat when required or for converting to petrol, which is storable. As some of the gas is not converted to petrol, a minimum amount of gas must, however, be burnt in the CHP plants. Likewise, in order to keep the plant in operation, a minimum amount of gas is required for the catalytic process. Furthermore, it is possible to optimise between the use of coal, waste or biomass for the process. The gasification of RDF facilitates the storage of RDF and may yield high electricity production. Likewise, RDF for di-methyl ether (DME) may be stored, as may the DME.

When looking at the bio-chemical processes, the production of biogas through anaerobic digestion of the organic fraction of municipal waste may facilitate the treatment of more manure, whereby a fossil free energy resource may be included in the energy system. Currently, only 10% of the available manure for biogas production is used in Denmark[58]. Biogas can be used for either CHP production or the production of compressed biogas for transport. In that way, the biogas may be stored. The wide range of efficiencies illustrates the different assumptions of different references.

The production of bio-ethanol by fermentation of organic wastes represents another possibility of producing transport fuel. The concrete technology example also produces fuel for CHP. Finally, an example of chemical conversion by the production of bio-diesel from animal fat through transesterification has been included. Again transport fuel is produced which may be stored. The energy content of methanol used for the process is subtracted from the energy output, thereby reducing the fuel efficiency of the plant.

Table 8 Characteristics of WtE technologies

Technology	Description	Input	Output[a]	Papers
Waste incineration	Waste incineration with efficiencies of a new or existing waste incineration plant. The technology is commercialised. Part of the waste fraction may be stored.	Mixed waste (limited storage)	Low electricity output and high heat output or only heat (26-29% el. and 71-78% heat) [8;59]	II, III, IV and VI
Co-combustion	Refuse derived fuel (RDF) is co-combusted with coal in a coal-fired power plant. The technology is at full-scale demonstration stage.	Coal and sorted, pre-treated RDF (storable)	High electricity output and heat (34-53% el. and 26-55% heat) [59-61]	III, IV and VI
Dedicated RDF	RDF is burnt in a dedicated CHP plant. The technology is commercialised.	Sorted, pre-treated RDF (storable)	High total efficiency (25% el. and 80% heat) [59]	III, IV and VI
Syngas	Municipal waste is liquidised and treated with enzymes. Solid fractions are removed and recycled and the remaining fraction undergoes thermal gasification. The resulting syngas can be converted to petrol or used for CHP. The technology is at the developmental stage. The waste fraction must be used continuously. In the Syngas+ alternative, it is assumed that the gasification of waste requires the co-gasification of coal in an entrained flow gasifier (minimum 75% of energy).	Coal (storable) and mixed pre-treated waste (no storage)	Choice between bio-petrol or CHP production with high electricity output and heat (Max. 79% fuel or max. 46% el. and 35% heat) [62;63]	(II), III, IV and VI
IGCC	Thermal gasification of RDF for CHP in an integrated gasification combined cycle (IGCC). The technology is at full-scale demonstration stage.	Sorted, pre-treated RDF (storable)	High electricity output and heat (48% el. and 45% heat) [64]	IV and VI
DME	Thermal gasification of RDF producing di-methyl ether (DME) using methanol synthesis. The technology is at full-scale demonstration stage.	Sorted, pre-treated RDF (storable)	DME for transport (67% fuel) [64]	IV and VI
Biogas CHP	Biogas from anaerobic digestion of organic household waste and manure is used for CHP. The fibre fraction from the manure may be burnt in a CHP plant. The technology is commercialised for uncomplicated waste fractions.	Sorted, pre-treated organic waste and manure (no storage)	Electricity and heat (20-24% el. and 18-30% heat) [59;64;65]	II, III, IV and VI
Biogas Transport	Biogas from anaerobic digestion of organic household waste and manure is cleaned, upgraded, compressed and used for transport in natural gas vehicles. The fibre fraction from the manure may be burnt in a CHP plant. The technology is commercialised for uncomplicated waste fractions.	Sorted, pre-treated organic waste and manure (no storage)	Compressed biogas for transport (39-56% fuel) [59;65;66]	II, III, IV and VI
Bio-ethanol	Straw, grass and paper waste first undergoes pre-treatment and hydrolysis. Secondly, bio-ethanol is produced for transport through fermentation and, thirdly, biogas is produced through anaerobic digestion along with bio-fuel and hydrogen and used for CHP. The technology is at the developmental stage.	Straw, grass paper and waste (storable)	Bio-ethanol and fuel for CHP (35-42% transport fuel and 34-41% CHP fuel) [64;67]	II and III
Biodiesel	Animal fat, formerly used for industrial heat production, is converted to biodiesel in a trans-esterification process. The technology is commercialised.	Animal fat (storable)	Biodiesel (90% fuel) [68]	II and III

[a] Efficiencies are calculated as energy output per energy input for each energy type

Technologies

In Table 9, costs are shown with prices in EUR2007. All data are for future plants assuming the same prices in 2025 and 2050. If data could not be found for the specific technology, data from similar technologies has been used. The sources are shown in the table.

Table 9 Investment and operation and maintenance costs of WtE technologies

Technology	Investment costs (MEUR/MW)*	Variable Operation and maintenance costs (EUR/MWh)*	Fixed Operation and maintenance costs (kEUR/MW)*	Source
Waste incineration	5.44	20.3	217.8	[59]
Co-combustion	Upgrade 0.15 New 1.39	4.5	Upgrade 56.4 New 23.5	[59]
Dedicated RDF	3.5		141	
Syngas***	Gas 0.69**		Gas 43.4	[64]
	CHP 0.89	CHP 2.8	CHP 10.2	[59;64;69]
	Cat 0.13**		Cat 81.7	[63;64]
	Gas+cat 1.46**		65.7	[64]
	CHP 0.7	CHP 2.8	CHP 10.2	[59]
IGCC**	2.06		92.9	[64]
DME***	1.98		118.6	[64]
Biogas CHP	1.86		170.8	[64]
	2.78	27.8		[59]
Biogas Transport	1.93		170.8	[64]
	3.24	27.8		[59]
Bio-ethanol	2.63		262.7	[64;67]
Biodiesel	0.47		6.6	[70]

* Data are per MW fuel or MW electricity depending on the technology, likewise for MWh.
**Cost is per MW produced fuel
*** Gas = Gasification unit, CHP = CHP unit, Cat = Catalysis unit

The ranges of efficiencies and costs taken from different sources illustrate the inherent uncertainties of determining future data. Most uncertainty is found with the least developed technologies, such as thermal gasification of waste and production of second generation bio-ethanol. The most developed technologies are the combustion technologies with waste incineration as the most mature WtE presented. Anaerobic digestion is also a well-established technology, but not in terms of the utilisation of organic household waste. Some sources use data from existing plants as a starting point, while others reflect optimistic future expectations. Furthermore, efficiencies also depend on local conditions, such as, for example, the temperature needed for district heating. Sensitivity analyses have been made to take these uncertainties into account.

5 Results of Energy System Analyses

This chapter first describes the scenarios analysed. In the following sections, the results of the energy system analyses of WtE technologies presented in the Report and in Papers II, III, IV and VI are summarised and compared. In Paper I, graphic models of the WtE technologies are presented and Paper V includes energy system analysis of increased waste incineration with different degrees of flexibility, in different energy systems, and in different district heating groups, but not comparing different WtE technologies.

In broad terms, three types of energy systems have been analysed: the current system with a Danish renewable energy (RE) share for heat and power of 13-14%, a possible future system in 2025 with a Danish RE share of 43%, as well as a future system with 100% renewable energy in Denmark. The 100% RE share is a declared target of the Danish government. The different scenario characteristics of the energy system analyses are outlined in Table 10.

Coal is one of the main fuels used for heat and power production in Denmark in all scenarios, apart from the 2050 scenario. Natural gas is also one of the main fuels in the current energy system. Wind power plays a major role in 2050, but also contributes considerably to the production in 2025. Waste plays a major role in the Danish energy system of 2025, which has a lower total consumption and uses higher amounts of waste. In 2025, the main energy sources used in Denmark and its neighbouring countries combined are uranium (50-56%), coal (24-30%), and wind power (10%), depending on the CO_2 quota price.

During the period in which the analyses were made, assumptions regarding fuel prices have changed. The used fuel prices are represented in Table 10 by the crude oil price and, in the 100% renewable energy scenario, by the biomass price.

In the Report and in Papers II and III, the analysis is made of Denmark only and by the use of EnergyPLAN. The optimisation focus of Paper II and of the 2050 scenario in the Report and Paper III is low fuel consumption in the energy system. In the other scenarios analysed in EnergyPLAN, the optimisation focus is low marginal production costs. Electricity trade is included in the Report and Paper III and is simulated based on a price interface with the neighbouring countries. In Papers IV and VI, the analysis is made of the Northern electricity market, including Denmark and its neighbouring countries, and is made in Balmorel. Here, the optimisation focus is low energy system costs. Taxes and tariffs are only included in the analysis of the current Danish energy system with the optimisation focus of achieving low marginal production costs. In the remaining analyses, the aim is to achieve the best solution for society, and taxes and tariffs are therefore not included. In all analyses, different uses of waste are modelled in the Danish energy system.

Table 10 Scenario characteristics

	Paper II	Report and Paper III	Report and Paper III	Paper IV	Paper VI
Year	2004	2006	2050	2025	2025
Model	EnergyPLAN	EnergyPLAN	EnergyPLAN	Balmorel	Balmorel
Optimisation focus	Low fuel consumption	Low marginal production costs	Low fuel consumption	Low energy system costs	Low energy system costs
Area	Denmark (excl. electricity trade)	Denmark (incl. electricity trade)	Denmark (incl. electricity trade)	Denmark, Sweden, Norway, Finland and Germany	Denmark, Sweden, Norway, Finland and Germany
Oil price	36 USD/bbl	95 USD/bbl	7 EUR/GJ biomass*	119 USD/bbl	119 USD/bbl
CO_2 quota price	-	25 EUR/t	32 EUR/t	32 EUR/t	32 EUR/t
% RE in DK	13%	14%	100%	43%	39-43%
Main fuel consumption for electricity and heat in DK	500 PJ ngas 38%, coal 32%, biomass 15%, waste 7%	575 PJ coal 42%, ngas 33%, biomass 13%, waste 6%	240 PJ wind 51%, biomass 33%, waste 16%	215 PJ coal 39%, waste 28%, wind 18%, ngas 5%	215-230 PJ coal 46-50%, waste 26-28%, wind 12-13%, ngas 5%

* Biomass price in 2050
Ngas: natural gas

Table 11 WtE technologies and waste fractions

	Paper II	Report and Paper III	Papers IV and VI
Technology			
Waste incineration	X	X	X
Co-combustion		X	X
Dedicated RDF incineration		X	
Biogas	X	X	X
Syngas	X	X	X
Integrated gasification combined cycle (IGCC)			X
Di-methyl ether (DME)			X
Bio-diesel		X	
Bio-ethanol		X	
Waste fraction			
Mixed waste	X	X	X
Organic household waste	X	X	X
Manure	X	X	X
RDF		X	X
Animal fat		X	
Straw		X	
Grass		X	

Table 11 shows the WtE technologies and the waste fractions analysed in the various papers. Waste incineration, biogas and syngas technologies are analysed in all papers along with the use of mixed waste, organic waste, and manure.

An overview of the results of the energy system analyses is given in a table in each section and in a combined table in Section 5.5. Main results are presented in terms of costs, CO_2 emissions, and percentage of renewable energy. Furthermore, in order to give an overview of the affected energy production plants, the main changes in fuel consumption are reported.

5.1 Results of Paper II

The first energy system analysis made in the PhD project was the analysis presented in Paper II. The analysis is made of the current Danish energy system (2004) and by the use of EnergyPLAN. It presents an analysis of the Danish energy system with reduced fuel consumption and self-reliance as the optimisation focus. Consequently, no electricity trade with surrounding countries is simulated. Alternative uses of organic waste (4 PJ) are modelled. The technologies analysed are: waste incineration plants with heat-only or with CHP production as well as a syngas plant and a biogas plant producing either transport fuel or CHP. In terms of biogas, it is assumed that use of more manure in the energy system is facilitated. Furthermore, a scenario with no use of waste for energy production is analysed.

The reference energy system utilises 13% renewable energy and a large share of natural gas and coal. The oil price is assumed to be 36 USD/bbl and no CO_2 quota price is included in the calculation.

Three alternatives are among others compared; one in which waste is not used for energy production; one in which waste is used for only heat production, and one in which waste is used for CHP production. The results of the analyses show that the use of waste for energy production is beneficial, and that the production of CHP outperforms the production of heat alone from an energy perspective. The other main results are summarised in Table 12.

Table 12 Main results from Paper II

Result	Paper II 2004 (EnergyPLAN)
Cheapest CO_2 reduction	Syngas for transport
Least CO_2 emission	Biogas for transport
Most renewable energy	Syngas for CHP
Main affected energy production	Coal, oil and natural gas

CO_2 emissions are reduced, mainly by using organic waste in biogas plants, assuming that the treatment of organic waste in biogas plants leads to the treatment of manure. Most fossil fuel is replaced and the highest percentage of renewable energy is achieved by converting the organic waste in a syngas plant to CHP production. This result is due to the high efficiencies assumed. All alternatives displace fossil fuel when compared to the alternative of not using waste for energy production. Mainly natural gas is displaced as shown in Figure 7, but in most alternatives, waste also substitutes oil for transport as well as coal.

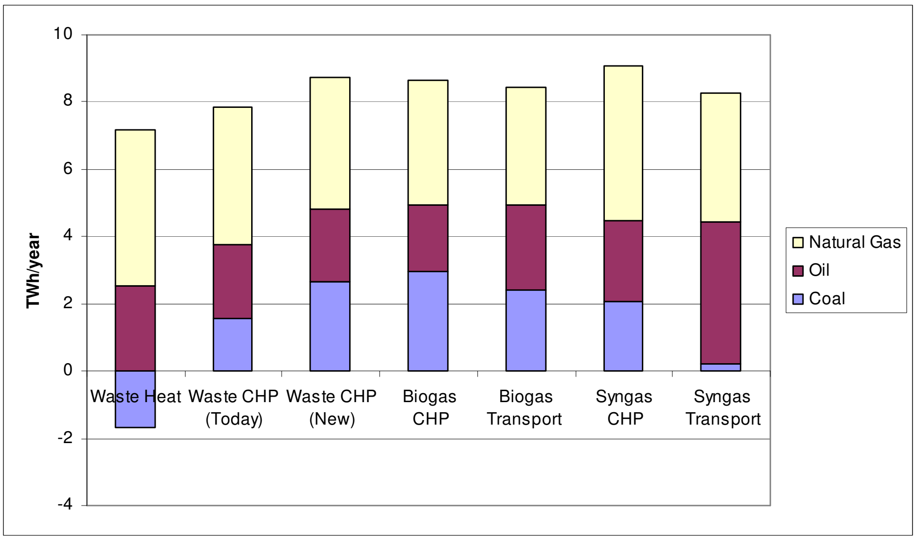


Figure 7 Fossil fuel substituted when utilising 10 TWh waste per year. Including 2.5 Mt manure for biogas and 3 TWh coal for syngas

The cheapest alternative in terms of CO_2 reduction cost is the production of syngas with conversion to transport fuel. This is, however, heavily dependent on assumptions on investment costs, as shown in the Paper. Assumptions regarding investment prices for syngas are most uncertain, as syngas is the least developed technology, and references with differences in investment costs up to a factor 3 have been found. However, sensitivity analyses of fuel prices, handling cost of organic waste, interest rate, and CO_2 content of waste show no differences in the ranking of the technical alternatives.

5.2 Results of Report and Paper III

The good prospects of the syngas technology found in Paper II made it interesting to go into more detail with the modelling of this technology, and hence, the model was improved to model a syngas plant which could optimise between the production of transport fuel and CHP, depending on fluctuating electricity prices. The good prospects of producing bio-fuel from waste led to the inclusion of bio-ethanol and bio-diesel production in the analysis. Thereby, the fractions of straw, grass and animal fat also needed to be included. Incineration with heat-only production was omitted, whereas the co-combustion of coal and RDF in new plants and dedicated RDF incineration in CHP plants were included. The analysis of biogas with and without co-digestion of manure was modelled as well as syngas production with and without co-gasification with coal. Again, the analysis was performed by the use of EnergyPLAN.

In the Report, four scenarios are analysed and documented:

1. Add/remove waste (2006)
2. Move waste (2006)

3. Use full waste resource potential (2006)
4. Move waste (2050)

Different waste fractions, but all with the same amount of waste (4 PJ), are affected in all scenarios, apart from in scenario 3 in which different potentials are exploited. In the first scenario, waste is either added to or removed from the energy system, illustrating import/ export or increased/decreased sorting of the various waste fractions for energy production. The analysis of this scenario makes it possible to single out the effects of adding or removing waste and thereby achieve an understanding of the effects on the remaining energy system. The Report therefore contains detailed figures on fuel substitution in different types of plants for each technical alternative in this scenario. In the remaining scenarios, waste fractions are moved from one use to another. Drawbacks of removing waste from its current utilisation are therefore included. In scenario 2, the same amount of waste is subtracted from one plant and added to another. Usually, waste will be moved from one use to another, and when this is done with the same amount in each analysis, it is possible to compare the effects of the various technologies. In scenario 3, the full waste resource potential for each technology is utilised to illustrate the full potential benefits. In scenario 4, the technologies are analysed in a future 100% renewable energy system, in order to assess whether the technologies may be beneficial to or stand in the way of such a system. All results are presented in the Report and the results from the three last scenarios are also summarised in Paper III.

For 2006, a market optimisation with focus on the short-term marginal production costs is used and trade is allowed on the Nordic and German electricity markets. For 2050, a technical optimisation focusing on the reduction of fuel consumption, also including electricity trade, is performed.

The existing Danish energy system with 14% renewable energy is used as a reference scenario for 2006 (main fuels are coal and natural gas); whereas the energy system in 2050 is an example of a possible future energy system with 100% renewable energy (main energy sources are wind and biomass). The Reference Energy System for 2050 is based on the 2050 vision of The Danish Society of Engineers' Energy Plan [71;72]. For 2006, an oil price of 95 USD/bbl is used and, for 2050, a biomass price of 7 EUR/GJ is used. CO_2 quota prices of 25 EUR/t and 32 EUR/t are used for 2006 and 2050, respectively. Different prices are used for the various waste fractions. The main results of the analyses are summarised in Table 13. Overall, the biogas alternatives are seen to perform well.

Table 13 Main results from Report and Paper III

	Report and Paper III (EnergyPLAN)			
Scenario	1 Add/remove waste (2006)	2 Move waste (2006)	3 Full waste potential (2006)	4 Move waste (2050)
Cheapest CO_2 reduction	Biogas	Syngas (without coal)	Biogas (incl. manure)	Biogas (incl. manure)
Least CO_2 emission	Biogas (incl. manure), Bio-diesel	Biogas (incl. manure)	Biogas (incl. manure)	-
Most renewable energy	Biogas (incl. manure)	Co-combustion	Biogas (incl. manure)	Co-combustion (with biomass)
Main affected energy production	Coal, oil and natural gas	Coal, oil and natural gas	Coal, oil and natural gas	Biomass

In scenario 1, the addition of organic waste for biogas production without co-digestion with manure provides the cheapest CO_2 reduction. The inclusion of manure adds considerably to investment costs as these are defined in terms of input. Least CO_2 is emitted when adding animal fat to a bio-diesel plant or adding organic waste and manure to a biogas plant, and the highest percentage of renewable energy is found when adding organic waste (as well as manure) to a biogas plant with CHP production. This is due to the high efficiency of the bio-diesel plant and the inclusion of additional biomass in the biogas alternatives.

In scenario 2, the cheapest CO_2 reduction is achieved by moving mixed waste to a syngas plant, assuming that gasification can take place in the future without coal at the same efficiencies and costs. Least CO_2 is emitted when moving organic waste to a biogas plant and including emissions due to export of electricity. Here, co-digestion with manure, and use of biogas for transport fuel, is assumed. Most CO_2 is emitted when co-gasifying waste with coal in a syngas plant. This result, however, changes completely if only CO_2 emissions from domestic energy consumption are taken into account and if the marginal power production is coal-fired condensing power plants. In this case, co-gasifying waste with coal in a syngas plant leads to the lowest CO_2 emissions. Least fossil fuel is used when moving RDF to co-combustion in a coal-fired power plant, due to a high total efficiency and an increased flexibility. Compared to Scenario 1, the benefit achieved by adding waste is reduced by the disadvantage of removing it elsewhere. The fuel substitution is shown in Figure 8 with positive figures while induced fuel consumption is shown as negative

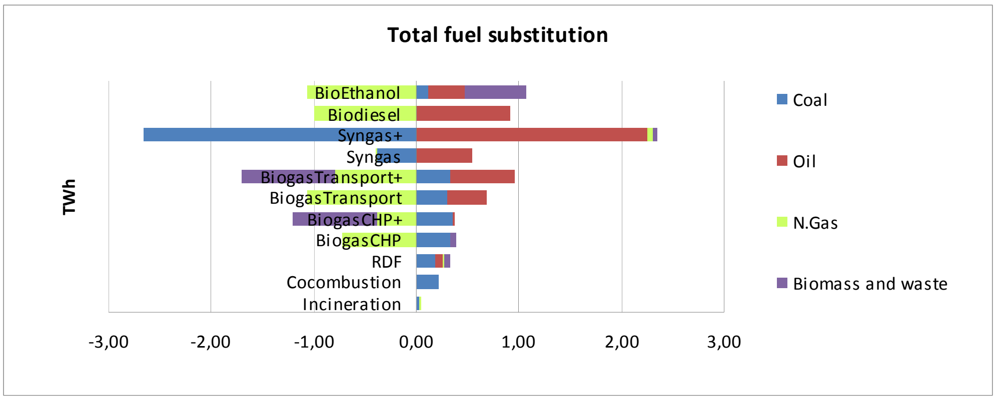


Figure 8 Total substituted fuel for all WtE technologies when moving 4 PJ of waste (and adding 2 PJ of manure in the Biogas+ alternatives and 12 PJ of coal in the Syngas+ alternative)

In scenario 3, the biogas solutions which include the digestion of manure provide the cheapest CO_2 reduction, the lowest CO_2 emissions, and the highest percentage of renewable energy. This is due to the high potential amounts of manure which are included in the biogas alternatives. Apart from that, the substitution of fuel resembles the results of Scenario 1.

In scenario 4, the reduced consumption of biomass in the 100% renewable energy system is in focus rather than CO_2 emissions. Co-combustion of waste with biomass provides the highest biomass reduction. It is, however, uncertain whether large-scale biomass combustion plants will be built in a 100% renewable energy system, in which a more effective use of biomass, e.g., in gasification plants, may be more prevalent. The second best option is dedicated RDF incineration. Biogas production provides the cheapest biomass reduction.

Sensitivity analyses of waste resource prices, investment costs, fuel prices, CO_2 quota prices, and interest rate have been made. Waste resource prices and investment costs are found to have a high sensitivity. Waste resource prices are difficult to estimate, as prices are dependent on local conditions. Investment costs are particularly difficult to estimate for technologies which are at the early stages of development such as the syngas technology.

The main differences compared to the results of Paper II is that the syngas plant provides the cheapest CO_2 reduction only in one scenario, and only when assuming that gasification takes place without coal. This is due to the use of different data on the efficiencies of converting syngas to transport fuel and to the changed optimisation focus of the scenarios combined with the inclusion of CO_2 quota costs. Considering the percentage of renewable energy, the syngas plant is outperformed by the biogas solutions, which facilitate the digestion of manure, and by the co-combustion of waste with coal, due to the high total efficiency and flexibility assumed for this type of plant. Furthermore, when adding animal fat to a bio-diesel plant without subtracting it elsewhere in the energy system, least CO_2 is emitted.

Currently, animal fat is, however, fully utilised, and the use for bio-diesel production does require removing it elsewhere.

5.3 Results of Paper IV

The differing conclusions regarding CO_2 emissions related to the co-gasification of waste with coal in a syngas plant illustrated the need for an identification of the “marginal” or affected production unit on the electricity market. To be able to find the long-term affected production unit, a model which includes the optimisation of investments was chosen. The analysis of Paper IV was therefore performed in the Balmorel model, which includes the neighbouring countries in the optimisation. Again, a detailed model of the syngas plant optimising between the production of CHP and transport fuel was included. The syngas plant in Balmorel, furthermore, optimises between the use of coal and waste. In order to achieve a better simulation of the dynamic properties, the storage of waste was made possible and a model was chosen which facilitates the investment in new district heating networks and electricity transmission apart from energy production and storage.

The good prospect of gasification without coal led to the inclusion of two types of WtE technologies with gasification of refuse derived fuel (RDF): integrated gasification combined cycle (IGCC) and a di-methyl ether (DME) production plant. Furthermore, the upgrade of existing coal-fired power plants to co-combustion with straw or waste was included. On the other hand, dedicated RDF incineration, bio-ethanol and bio-diesel production and the associated waste fractions were omitted due to the discouraging results encountered.

To supplement the former analyses of the current Danish energy system and a future Danish energy system with 100% renewable energy, it was chosen to analyse a possible intermediary step with an energy system of 2025. The 2025 scenario is based on the assumptions of the Danish Energy Authority regarding fuel prices, CO_2 costs, and energy demands, and on prospects regarding electricity demand for the surrounding countries from Eurelectric. Assumptions regarding the remaining existing energy production capacities and renewable energy potentials also form part of the analysis, as described in Paper IV.

The focus of the analysis is still on the use of waste for energy production in Denmark, but the energy systems of the neighbouring countries Sweden, Norway, Finland and Germany are part of the optimisation. The aim is to minimise the total costs of the combined energy systems. The fuel price and the CO_2 quota price are assumed to be 119 USD/bbl and 32 EUR/t, respectively. The business as usual (BAU) scenario only facilitates the investment in waste incineration and in energy technologies using other fuels than waste. In the BAU scenario, 43% renewable energy is utilised in Denmark. The main energy sources used in Denmark are coal, waste and wind. The results of the analysis are summarised in Table 14.

Table 14 Main results from Paper IV

Result	Paper IV 2025 (Balmorel)	
	DK	DK, DE, FI, NO, SE
Cheapest technologies	-	RDF gasification for CHP, Co-combustion, Biogas for CHP, Incineration
Main affected energy production	Coal	Nuclear power and coal

The optimal combination found, when allowing the investment in all WtE technologies is shown in Figure 9. The first choice is to use the existing waste incineration capacity and then build new waste incineration capacity. Furthermore, investments are made in biogas plants for CHP or transport fuel production, in IGCC plants with gasification of RDF for CHP, and in the co-combustion of waste with coal mainly in new coal-fired power plants. The full resources of both organic waste and RDF are used. In total, this adds up to around 23% of the waste available for energy production. The remaining waste is incinerated in existing and new waste incineration plants producing CHP. The manure used for co-digestion with organic waste equals 5% of the current Danish untreated manure potential.

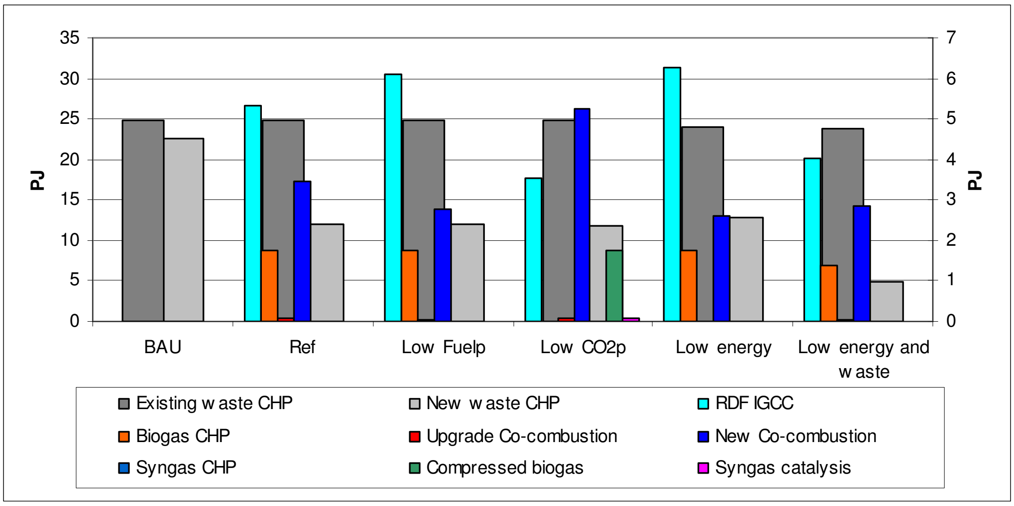


Figure 9 Use of waste for energy production in Denmark. Waste CHP are shown on the left axis and new WtE technologies on the right.

A slight increase in CO_2 emissions as well as a decrease in total costs occur both in Denmark and in the whole region, when allowing investments in new WtE technologies. The co-combustion of RDF improves the feasibility of coal-fired plants, leading to increased investments in these plants at the expense of investments in nuclear power plants. The changes in fuel consumption are consistent with the changes in investments in both regions. Co-combustion is only undertaken to a low degree in existing coal-fired power plants, as the costs are assumed to increase significantly and efficiencies are assumed to decrease slightly.

If no investments in nuclear power are allowed, and a BAU scenario is compared to one with investments in new WtE technologies, investments in new co-combustion units still increase, while investments in wind power and natural gas-fired power plants now decrease.

When increasing the investment costs, in particular of the least developed technologies, high sensitivity is found particularly with regard to the use of RDF for co-combustion or in gasification plants with CHP production. Low sensitivity is, however, found concerning co-digestion with manure, as, even when manure is not included in the biogas production, the model still chooses to invest in biogas for CHP. Negative shadow prices of 3-4 EUR/GJ are found for organic waste and 1-2 EUR/GJ for RDF. This indicates that it could be feasible to pay the biogas plants a slightly higher treatment fee in order to receive more waste, and it would also be feasible to pay the plants using RDF a slight compensation for treating more.

The investment in biogas for transport and co-combustion of waste and coal is in accordance with the former analyses, in which biogas was found to be an optimal solution in terms of low CO_2 emissions, low CO_2 reduction costs and high percentage of renewable energy.

The investment in new waste incineration plants is, however, a new result, as in the former analyses it has been found to be expensive compared to the alternatives. From the results, it can be seen that the treatment of organic waste is cheaper in biogas plants; that the treatment of RDF in CHP gasification plants is competing with co-combustion plants for the resource, and that it is cheaper to treat mixed waste in waste incineration plants than in syngas plants, unless the CO_2 quota price is low and then only for a minor part. In the former analyses, new waste incineration plants were assumed to replace existing plants in operation. In this analysis, new waste incineration plants replace decommissioned plants. As mixed waste can only be treated in waste incineration plants or syngas plants, and that requires a considerable use of coal, the major waste fraction must be treated in waste incineration plants.

5.4 *Results of Paper VI*

The analysis of Paper IV showed the combined effects of implementing various energy technologies. In order to identify the affected energy technology, as discussed in Paper IV and Paper V, alternatives are analysed by allowing investments in waste incineration together with each type of WtE technologies, which are modelled in the Danish system one by one, also in Balmorel. The following alternatives were analysed:

1. Existing and new waste incineration CHP (Mixed waste).
2. Upgraded and new co-combustion plants (Coal and RDF).
3. Biogas for CHP or transport fuel (Organic waste and manure).
4. Thermal gasification of RDF for CHP or transport fuel (RDF).
5. Syngas plant with thermal gasification of pre-treated mixed waste. for CHP and transport fuel (Mixed waste and coal).
6. Combined alternative with possible investments in all WtE technologies.

7. Less waste in the incineration alternative (1 PJ).

To show the effects of the optimal combination, a combined alternative is analysed, and to show the effects of removing waste from the incineration alternative, an alternative is also analysed with slightly less waste. The biogas alternative assumes the availability of untreated manure and, for the thermal gasification technologies, a further development of the technologies is assumed.

The analysis of Paper VI is made by use of the same model and is based on the same assumptions as Paper IV. The affected energy technologies are found in a long-term perspective with investments included as part of the optimisation. Furthermore, the affected technologies are identified taking into account the full electricity market as well as heat markets in the respective countries. Finally, analyses have been made in different energy systems by analysing the alternatives in two different scenarios: a high cost scenario (Scenario 1) and a low cost scenario (Scenario 2), assuming CO_2 quota prices of 32 and 25 EUR/t, respectively.

In each scenario, investments in new WtE technologies are made and waste is moved from waste incineration. Investments in Syngas, however, only occur at a low CO_2 quota price. The main results are summarised in Table 15.

Table 15 Main results from Paper VI

	Paper VI 2025 (Balmorel)	
Result	DK	DK, DE, FI, NO, SE
Cheapest CO_2 reduction	-	Biogas for transport^2
Least CO_2 emission	Biogas for transport^2	Biogas for transport^2
Most renewable energy	Incineration^1, Biogas for transport^2	Co-combustion^{1,2}
Main affected energy production	Coal	Nuclear power, coal

^{1} High CO_2 price
^{2} Low CO_2 price

CO_2 emissions increase for all alternatives in both scenarios, apart from the production of biogas for transport, which occurs in the low CO_2 price scenario, or the reduction of the amount of waste for energy production in a high CO_2 cost scenario. These two alternatives, of which only one represents a WtE technology, consequently also provide the cheapest CO_2 reductions. As the model minimises the costs of the total energy system, costs are not determined for the Danish energy system, and hence, the cheapest CO_2 reduction is not found for Denmark alone.

In the given energy system analysed, the main affected fuel is found to be coal in Denmark. In the whole region, nuclear power is also found to be affected as shown in Figure 10. At the level of the whole region, co-combustion results in the highest percentage of renewable energy in both scenarios. It does, however, also provide the highest percentages of fossil energy. This is due to the fact that the total fuel consumption is reduced, as coal consumption for CHP increases at the expense of fossil free uranium-fuelled condensing power.

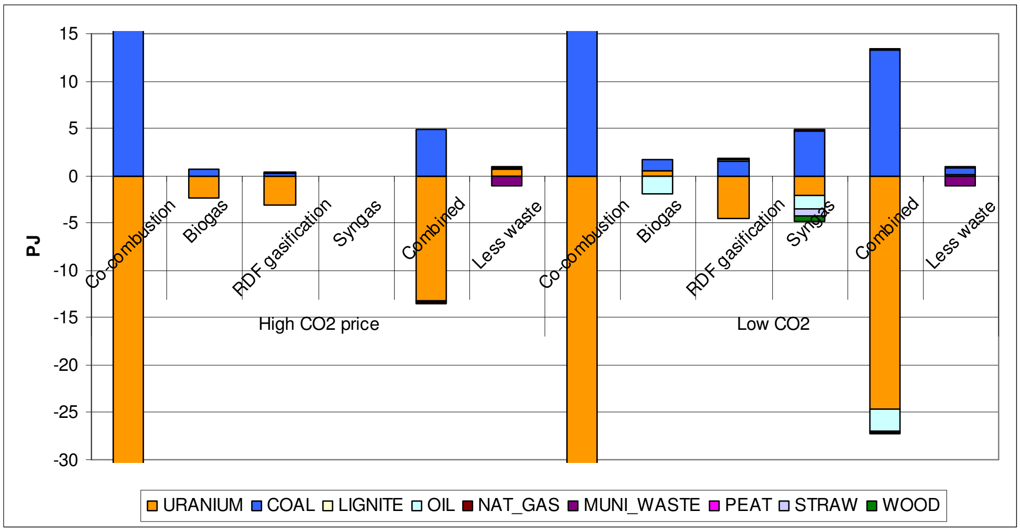


Figure 10 Changed fuel use for the whole region for all technologies, when compared to the Incineration alternative with high or low CO2 prices respectively (max 15 PJ and min -30 PJ shown)

In Denmark, the highest percentage of renewable energy is provided in the incineration alternative in the high CO_2 cost scenario and in the biogas alternative in the low CO_2 cost scenario in which biogas is used for transport fuel. In the scenario with high CO_2 quota costs, biogas is used for CHP and hereby substitutes fossil fuels in the energy system, which are burdened by the high CO_2 quota costs.

The good results achieved by the use of organic waste for biogas production to transport are confirmed by the former analyses. However, this is again based on the assumptions that untreated manure is available, equal to 5% of the current untreated potential, and that a treatment price equivalent to the treatment fee of mixed waste (3 EUR/GJ) can be obtained. Co-combustion performs better when looking at the effects on the whole Northern electricity market, than when looking at the effects in Denmark, based on the assumptions that new co-combustion plants, to a large degree, replace coal-fired power plants which would be built anyway and that RDF can be obtained for free.

With regard to the main affected energy production, coal is also affected in Denmark, in the other analyses. Furthermore, oil is affected, when transport fuels are produced. Natural gas is also affected in the other analyses. The main difference here is that natural gas, in this scenario, only contributes with a minor part of the fuel consumption in Denmark (5%) and the whole region (2%), as hardly any investments are made in natural gas to replace decommissioned plants. This result would be different with other fuel price assumptions, as used in the former analyses with EnergyPLAN. When looking at the whole region, nuclear power production is also affected, as investments in nuclear power are allowed in Finland and Sweden.

5.5 *Summary of results*

After the separate review of the results of each scenario, the main results of the energy system analyses comparing WtE technologies are here summarised. The main results are shown in Table 16.

Table 16 Main results of the energy system analyses

	Paper II	Report and Paper III	Report and Paper III	Paper IV	Paper VI
Year	2004	2006	2050	2025	2025
Model	EnergyPLAN	EnergyPLAN	EnergyPLAN	Balmorel	Balmorel
Main fuel in DK (el. and heat)	ngas, coal, biomass	coal, ngas, biomass	wind, biomass	coal, waste, wind	coal, waste, wind
Cheapest CO_2 reduction	SG(T)	BG^{1,3}, SG^{2} (without coal)	BG	BG, IGCC, CC, INC**	All: BG(T)
Least CO_2 emission	BG(T)	BG^{1,2,3}, BD^{1}	-	-	DK:BG(T)
Most renewable energy	SG(CHP)	BG^{1,3}, CC^{2}	CC (with biomass)*	-	All: CC^{1,2}. DK: INC^{1}, BG(T)^{2}
Main affected energy production	Coal, oil and ngas	Coal, oil and ngas	Biomass	Coal (DK, all) Nuclear power (All)	Coal (DK, all) Nuclear power (All)

el: electricity, ngas: natural gas, INC: Waste incineration, CC: Co-combustion, SG: Syngas, BG: Biogas, BD: Biodiesel, IGCC: Integrated Gasification Combined Cycle, (T): Transport, (CHP): Combined Heat and Power

^{1,2,3}: Scenarios 1,2 and 3, respectively.

* Least biomass consumption in 2050

** Cheapest in terms of total energy system costs

Overall, new WtE technologies can be said to offer advantages primarily in terms of reduced costs. Waste incineration of mixed waste with CHP production is cheaper and emits less CO_2 than co-gasification with coal, and waste incineration will thus continue to play an important role in Denmark in the future, when using waste for energy production. When co-gasifying mixed waste with coal, the coal consumption increases, which results in increased CO_2 emissions and makes the technology unfeasible at high CO_2 prices. Co-gasifying waste with biomass may be a good possibility when moving towards a future with 100% renewable energy, but it remains to be developed.

The new WtE technology, which consistently offers the best performance in terms of CO_2 emissions, percentage of renewable energy in Denmark, and CO_2 or biomass reduction costs through the various analyses, is biogas production from organic household waste. However, this assumes that untreated manure equal to 5% of the current untreated potential is used and that a treatment price of 3 EUR/GJ can be obtained. In a 100% renewable energy future, biogas production may also be advantageous without manure. Overall, the best use of biogas in terms of reducing CO_2 emissions is to clean and upgrade biogas to transport fuel use.

Thermal gasification of RDF is also found to have good prospects in terms of economic feasibility. This will, however, depend on whether further development of the technology makes it possible to achieve the costs and efficiencies assumed for 2025.

Co-combustion of RDF with coal also shows good prospects in terms of costs and the increase of the renewable energy share. This is due to the substitution of coal with waste in Denmark, assumed in the Report and in Paper III, and to a decrease of the total fuel consumption in the whole region, described in Paper VI, as condensing power plants are replaced by CHP plants. In Paper VI, co-combustion, however, also leads to increased investments in coal-fired power plants and in the highest fossil fuel consumption. Co-combustion in existing plants only occurs to a minor degree due to increased costs and decreased efficiencies assumed if upgrading to co-combustion. Constructing more new coal-fired power plants may, however, not be the right path to choose when aiming at a future energy system with 100% renewable energy. In such a system, it may still be advantageous to co-combust waste, but with biomass instead, if large-scale combustion of biomass is still a sufficiently efficient use of biomass to be used then. The positive results with regard to the use of RDF is based on the assumption that RDF is available for free and that the efficiencies of the waste incineration plants do not decrease due to decreased heating values of the remaining mixed waste fraction.

In general, the main fuels of the energy systems are affected, apart from wind power and waste. This is due to the fact that the amount of waste for energy production is not flexible and that wind turbines are used fully when installed, as the marginal production costs are low. The use of inflexible technologies such as nuclear power is, furthermore, only affected when investments are included in the optimisation. Heading towards the future, a more flexible use of waste for energy production may result in increased production from coal-fired power plants and a decrease in nuclear power, depending on costs prices and efficiencies, if the cheapest solution from the point of view of society is chosen. Other political goals may, however, be promoted, e.g., through the use of taxes, tariffs and bans resulting in different effects of more flexible uses of waste for energy.

6 Conclusion and discussion

In this chapter, the two research questions are answered and the conclusions are discussed. Subsequently, the use of energy system analysis to compare WtE technologies is assessed. After that, it is assessed whether the three goals of the PhD project have been achieved. Finally, areas for further research are suggested.

6.1 Research question 1

The first research question is:

1. What is the optimal use of waste for energy production in the Danish energy system in the future?

The short answer to this question is: 1) incineration of the main amount of waste for CHP, 2) biogas production from organic waste and manure, if untreated manure is available equal to 5% of the current untreated potential and a treatment price of 3 EUR/GJ can be obtained, and 3) co-combustion of RDF with coal in mainly new coal-fired power plants, when new coal-fired plants would to a large extent be built anyway, and gasification of RDF for CHP to reduce costs when fully developed. Co-combustion and gasification of RDF is however only optimal if reduced CO_2 emissions is not the main goal and under the assumptions that the efficiencies of the waste incineration plants do not decrease due to a decreased heating value of the mixed waste used for incineration; that gasification of RDF in the future achieves the efficiencies and costs assumed, and that RDF can be obtained for free.

The main part of the waste used for energy production is, in all analyses, incinerated in waste incineration plants. It is only feasible to sort out waste, such as RDF and organic waste, to a smaller degree (around 19% and 4%, respectively). The best utilisation of waste in incinerators is in plants producing CHP with the highest possible electricity and heat efficiencies. Waste incineration will therefore continue to be the main WtE technology, also in the future.

For all waste fractions, it is generally preferable to produce CHP with as high efficiencies as possible, but in some situations, the conversion to transport fuel, particularly from biogas, may also have a role to play, especially when aiming at reducing CO_2 emissions.

CO_2 reduction costs, CO_2 emissions and renewable energy percentage
From the analyses presented above, the cheapest WtE alternative in terms of CO_2 reduction costs appear to be the utilisation of organic waste for biogas production when including the digestion of manure and receiving a treatment price of 3 EUR/GJ. Similar results are found with regard to the use of biogas for CHP or transport fuel. If biogas production for transport was also burdened by the costs of building the infrastructure required to

distribute the compressed biogas, these results may change for the benefit of using biogas for CHP.

The WtE technology contributing with the largest decrease in CO_2 emissions in most scenarios in Denmark is the biogas for transport solution including manure. If the benefits of digesting manure were included, even better results would be achieved, due to decreased emissions of methane and N2O when manure is spread in the fields.

With regard to increasing the percentage of renewable energy in the system, the biogas solution is the best alternative when including manure. Co-combustion of coal and RDF, however, also performs well in this respect.

The syngas solution with co-gasification of coal and waste provides the cheapest CO_2 reduction, when producing transport fuel in a 2004 scenario. In the same scenario, least fossil fuel is used by the syngas for CHP. Later analyses do, however, not show the same good results for the technology. This is due to the use of lower efficiencies of the conversion of syngas to transport fuel and to the changed focus on decreasing costs combined with the inclusion of CO_2 quota costs in the optimisation.

Use of waste fractions

Overall, the following conclusions can be drawn with regard to the use of the various waste fractions for energy production:

- The main part of the waste, namely mixed waste, should continue to be used for waste incineration. The only technology analysed which may also use mixed waste is thermal gasification. If mixed pre-treated waste can be gasified without co-gasification with coal in the future, this may also be beneficial, but it will not change the use of waste for energy production dramatically.
- Organic waste should be sorted out and co-digested with manure for biogas production, preferably for transport, if a treatment fee of 3 EUR/GJ can be obtained for the waste fraction. Currently, 90% of the manure potential in Denmark is unused, and hence, untreated manure may be available in a foreseeable future. In the long term, producing biogas from organic household waste without manure is a feasible way of saving biomass, as shown in the analysis of a 100% renewable energy system. The benefits of producing biogas for transport fuel may also be achieved through the anaerobic digestion of other biomass sources, particularly sources which are not currently part of the energy system.
- If the goal is to reduce costs or increase the percentage of renewable energy on the Nordic and German electricity markets, RDF should be co-combusted with coal in new plants, but only when these would by and large be built anyway. This conclusion is based on the assumption that the co-combustion of RDF does not result in decreased efficiencies at the waste incineration plants from which the RDF is removed; that the content of organic material in the RDF

is high, and that it is available for free. In the long term gasification of RDF for CHP should be developed and used, particularly if RDF does not substitute coal in coal-fired power plants.

- In terms of reduced CO_2 emissions, it is beneficial to convert animal fat to bio-diesel. The CO_2 reduction cost is, however, high, particularly if the fat is already used for energy production, which is currently the case.
- Reduced CO_2 emissions are only achieved with the bio-ethanol technology, if it facilitates the inclusion of waste fractions which are not currently used in the energy system, such as grass, straw or paper. The CO_2 reduction costs are, however, high.

Discussion

Most uncertainty exists regarding the costs and efficiencies of the WtE technologies which are least developed, namely the thermal gasification technologies and bio-ethanol production from waste. Here gasification of RDF for CHP shows the greatest prospects if developed as predicted. Biogas production, particularly for CHP production, is a well established technology, but its costs, treatment prices, and efficiencies are highly dependent on local circumstances and so is the availability of untreated manure.

The largest difference when modelling the WtE technologies in different future energy systems is found when modelling waste in a 100% renewable energy future. In the other scenarios, CO_2 emissions are reduced by including biomass which is not already part of the energy system. In a 100% renewable energy future, biomass is, however, a limited resource, which must be assumed already to be in use, and the goal is not to reduce CO_2 emissions but rather to reduce biomass consumption. Biogas production without manure and co-combustion with biomass still come out with positive results in such an energy system. Overall, the differences seen when comparing WtE technologies in the different analyses appear to be a result of changing assumptions rather than differences between the energy system analysis models.

When comparing the results with other analyses, the results are both confirmed and contradicted. Life cycle assessments of biogas production compared to incineration have, e.g., had varying results. In some analyses, the environmental consequences of biogas production used for CHP are comparable to those related to incineration [73;74] and in others biogas production has shown to have lower environmental impacts when combined with dedicated residual derived fuel (RDF) combustion[75].

The conclusion that gasification of RDF is preferable to waste incineration is supported by the conclusions of Murphy and McKeogh [19] and Dornburg et. al. [21]. However, it contradicts the results of Sahlin in the article "Gasification or Pyrolysis – future treatment methods for municipal solid waste in Sweden?"[76]. In Murphy and McKeogh [19], digestion with subsequent production of biogas for transport was concluded to be the best option for the organic fraction, whereas for the non-organic fraction, gasification was found to be superior to incineration. The analysis showed a high sensitivity to the use of thermal output. In Dornburg et. al. [21], a large number of waste treatment technologies are compared including incineration, gasification, digestion, co-combustion in a coal power plant, and the production of bio-fuel. The analysis also shows good results for integrated gasification combined cycle plants (utilising primarily municipal solid waste and sewage sludge) and co-combustion (utilising organic domestic waste, swill and waste from the food industry after hydro-thermal upgrading).

6.2 Research question 2

The second research question of the thesis is:

2. What is the affected energy production with changed uses of waste for energy production?

The main conclusion here is that the affected or "marginal" energy production always consists of a combination of energy technologies (also called complex or composite marginal energy production), which can be identified by applying energy system analysis. Which technologies are affected depends on the time perspective (short-term or long-term), the energy system analysed, the area analysed (Denmark or Nordic and German electricity markets), as well as on assumptions regarding capacities, efficiencies, costs, and prices.

When modelling Denmark along with its surrounding countries and including investments as part of the optimisation, technologies located outside Denmark are affected by changed uses of waste in Denmark. Furthermore, not only technologies capable of reacting to short-term changes in demand are affected, but also inflexible technologies[5].

The results of the analyses conducted with the two energy models mainly differ with regard to the affected fuel consumption. Both models agree that coal consumption is affected in Denmark. The same is the case of oil when transport fuel is produced. Natural gas is only found to be affected in the current Danish energy system, as it makes up a large and flexible part of the fuel consumed in this system.

Balmorel identifies changes in nuclear and coal as the most important changes on the Nordic and German electricity markets, apart from the changes in the use of waste. These results naturally depend on fuel prices, CO_2 quota costs, and assumptions regarding possible investments in, e.g., nuclear power. As establishment of new nuclear and coal power capacities is highly controversial, measures may be taken to prevent development of

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[5] Inflexible energy technologies are here defined as energy technologies which can not readily react to short-term changes in demand.

an energy system such as the one analysed and in such a case the affected energy technologies will be different.

Discussion

The energy production affected by the introduction of WtE technologies one by one has been modelled in both EnergyPLAN and in Balmorel. In both models, it is important to distinguish between the use of the models illustrated in this PhD thesis and their potentials. With EnergyPLAN, it has proved possible to find the short-term effects on production in Denmark in future potential energy systems. The full Nordic and German electricity system may also be modelled, but without restrictions on electricity transmission. Optimisation of investments would have to be made manually through iterations. In Balmorel, it is possible, in one optimisation, to find the long-term effects including investments and production on the Nordic and German electricity markets of which Denmark forms part. This has here been done for aggregated time periods. It is, however, straightforward to optimise the production for a full year hour by hour and it is also possible to improve the hourly simulation of the year significantly, including the optimisation of investments, but only if omitting some of the features modelled, such as investments in new district heating networks.

As the affected energy productions are significantly different among the scenarios analysed with the two models, it is important to determine whether the objective is to identify the short-term effects on production in Denmark or the long-term effects on the Nordic and German electricity markets assuming perfect market conditions.

Nuclear power would normally not be regarded as possible “marginal” energy production technologies by LCA practitioners, as the technologies cannot easily adjust their production to changes in demand. This assumption implies two problems. Firstly, when combining inflexible energy production technologies with storage technologies or flexible energy demand, the combined system may still be able to react to changes in demand. Secondly, when removing an inflexible energy production technology, such as waste incineration, other inflexible technologies, such as nuclear, may replace it or an inflexible technology may be replaced by a flexible. It is therefore necessary to include inflexible technologies when identifying the long-term affected energy technologies.

6.3 Use of energy system analysis

When comparing WtE technologies, a good starting point is to compare efficiencies and costs or environmental impacts in a life cycle perspective. If, however, the objective is to include the dynamic properties of the technologies and the synergies with other energy technologies in the comparison, energy system analysis has shown to be an efficient tool.

Conclusion and discussion

If one wishes to analyse new WtE technologies in an energy model which, from the offset, basically simulates waste as if it was biomass, the model should be improved to be able to simulate the following:

- Multiple products
- Heterogeneous waste fuel quality consisting of many fractions
- Multiple fuels
- Storage restrictions on waste
- Geographical distribution of waste
- Waste prices
- CO_2 emissions from fossil fractions

The following can be recommended when performing energy system analysis of WtE technologies to find optimal future WtE solutions:

- Analyse future scenarios with both commercialised and pre-commercialised technologies.
- Perform hour-by-hour analysis when analysing systems with significant shares of short-term energy storages and fluctuating energy sources.
- Analyse district heating and electrical system jointly, when analysing systems with significant shares of CHP and while paying attention to ensure an acceptable level of detail when aggregating the district heating areas.

The energy system analyses may contribute to improved decision-making also by supplementing other analyses, such as life cycle assessments or cost benefit analyses.

With regard to identifying the long-term affected energy production with changed uses of waste for energy, it can further be recommended to:

- Optimise both investments and production according to cost.
- Include the full electricity market in the analysis along with local district heating markets.
- Include investments in both flexible and inflexible energy production technologies, as well as storage technologies in the optimisation.
- Analyse fundamentally different future scenarios.

Affected energy production may serve as input to other analyses and particularly to consequential life cycle assessments.

6.4 PhD goals

Three goals of the PhD project were outlined in the introduction. The question is now whether it has been possible to achieve the three goals? The first goal is:

1. To improve national decision-making with regard to future WtE technologies in Denmark.

Previously, WtE technologies have primarily been analysed using life cycle assessment or cost benefit analysis. The effects of changed uses of waste on the energy system, however, represent an important piece of the puzzle. In the course of this PhD project, energy system analyses have been performed of different energy systems (current, 2025, 100% renewable energy), for different areas (DK and the Nordic and German electricity markets) and with different assumptions with regard to fuel prices, CO_2 quota costs, energy demands, and waste amounts for energy production. The analyses are assessed to improve the knowledge about the WtE technologies, which is required for national decision-making regarding potential future uses of waste for energy.

The second goal is:

2. To improve the modelling of waste in existing energy system analysis models.

The modelling of waste in general, and a wide range of potential WtE technologies in particular, in both EnergyPLAN and Balmorel is assessed as considerably improved. This will have a positive influence on future energy system analyses, including different WtE technologies, performed in the two models.

The third goal is:

3. To improve the understanding of affected energy production when implementing WtE technologies to be used for consequential life cycle assessments of WtE technologies.

For the purpose of this PhD project, the current method of identification of affected energy production for consequential LCA has been questioned. Both Danish short-term and Nordic and German long-term energy productions affected by changing uses of waste for energy production have been identified in future energy systems on an hour-by-hour basis. Hereby, significant improvements regarding the understanding of affected energy production have been achieved.

Many countries in the EU aim to increase the use of CHP and wind power in their energy systems. Denmark is in front in both areas with the present electricity demand covered by 43% CHP production and up to 20% wind power. Alternatives to depositing waste at landfills are also sought all over the EU. In this respect, it may be interesting to learn from the Danish case with a high degree of waste incineration used for CHP. In countries with less demand for heat or with less developed district heating networks, the WtE technologies which have high electric efficiencies or which produce transport fuel should prove more interesting. In the other countries included in the analyses performed with Balmorel, similar affected energy productions can be expected with regard to changed uses of waste for energy production.

The two energy models can easily be used to model other countries, and the improved simulation of waste as well as the respective WtE technologies modelled in the two energy models may be useful in the analysis of different uses of WtE in other countries. Alternatively, the recommendations presented in the former section, regarding the use of energy system analysis as a method to analyse WtE technologies, should be applicable to all countries and can be used to improve existing models. In countries with a low electricity trade with neighbouring countries or with a low percentage of CHP in the current and foreseeable future energy systems, it is, however, less important to be able to model these aspects in detail.

6.5 Further research

The results of this thesis lead to a whole range of new questions, which could be interesting to look into.

First of all, it would be interesting to analyse anaerobic digestion more thoroughly, including all possible biomass fractions and all competing technologies as well as aspects regarding the distribution of transport fuels and prices/ sorting costs of fractions.

Furthermore, it would be interesting to analyse other aspects of co-combustion of waste and coal, such as the effects on dedicated waste incineration plants of the removal of RDF and the decreased heating value of the remaining mixed waste fraction. Waste incineration plants are dimensioned to operate optimally with a given heating value. If the value decreases, so does the efficiency of the plant. Furthermore, if RDF is traded freely on a market, it may be necessary to pay to receive the fraction in the future; it may enter into competition with biomass, the necessary treatment capacity may not always be ensured for the fraction, and the question is to which heating value future waste incineration plants should be dimensioned?

It could also be interesting to look into further possibilities of improving the flexibility in the use of waste for energy production. One possibility is to combine waste incineration with geothermal heat pumps and storage. Furthermore, a more detailed modelling of different waste fractions and technologies using them could be interesting, along with the modelling of waste treatment technologies and by-products outside the energy system represented, e.g., through prices and emissions. Use of learning curves to predict costs of pre-commercialised technologies could also be interesting.

An analysis in which the surrounding countries, apart from Denmark, would be allowed to invest in different WtE technologies, and in which they were also required to use a certain amount of waste for energy production or pay for alternative waste treatment, would also be relevant. Furthermore, the analysis of years with different precipitation and varying amounts of hydro power available on the Nordic electricity market would be interesting to analyse, as would the effects of assuming perfect foresight, e.g., of wind speeds, instead of using stochastic programming.

The analysis of a 100% renewable energy system in Balmorel could also be interesting and, in general, to perform an analysis of the same scenario and technologies in both EnergyPLAN and Balmorel in order to compare the results. Also, it could be interesting to make analyses of the use of waste for energy production, applying the two models to other energy systems in terms of fuel consumed and in significantly different countries, e.g., without significant shares of CHP.

The focus of this thesis is on energy system analyses primarily excluding taxes. It could, however, also be interesting to assess the effects of possible changes in taxes and tariffs. Furthermore, it could be interesting to supplement this analysis with more qualitative analyses of the organisation of the overlap between waste management and energy sectors.

Finally, it would be interesting to analyse the significance of using data from energy system analysis for life cycle assessments, as opposed to the current practise. Also, it could be interesting to include emissions of other greenhouse gases from the remaining lifecycles and perform analyses with CO_2 caps or fixed renewable energy targets as well as optimisation with regard to minimising greenhouse gases as opposed to fuel consumption or costs.

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Appendices

Paper I

Modelling Waste-To-Energy Technologies in National Energy Systems
Münster, M.
Peer reviewed conference proceeding
The 17th IASTED International Conference on Applied Simulation and Modelling
June 23rd – 25th, 2008 Corfu, Greece
http://www.actapress.com/Abstract.aspx?paperId=33401

Paper II

Use of Waste for Heat, Electricity and Transport - Challenges when performing Energy System Analysis. Münster, M. & Lund, H.
Published in Energy – The International Journal. vol. 34, no. 5, pp. 636-644, May 2009.
http://dx.doi.org.globalproxy.cvt.dk/10.1016/j.energy.2008.09.001

Paper III

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Paper IV

Optimal Use of Waste in the Future Energy System. Münster, M. & Meibom, P.
To be submitted to Energy – The International Journal

Paper V

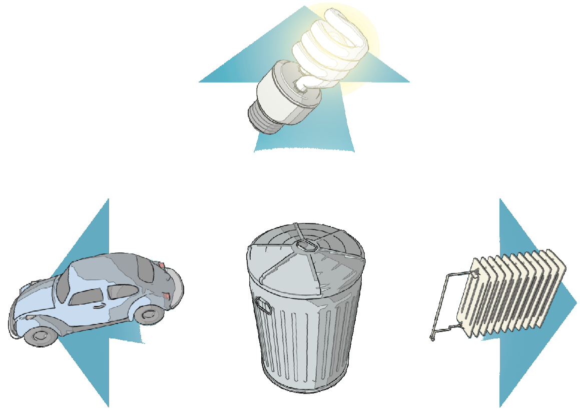
Uncertainties related to the identification of the marginal energy technology in consequential life cycle assessments. Mathiesen, B.V. Münster, M. & Fruergaard, T.
Published in Journal of Cleaner Production, April 2009. Volume 17, Issue 15, October 2009, Pages 1331-1338
http://dx.doi.org.globalproxy.cvt.dk/10.1016/j.jclepro.2009.04.009

Paper VI

Importance of Flexible Use of Waste for Energy for the National Energy System. Münster, M. & Meibom, P.
Conference proceeding. Abstract accepted March 2009. Final paper submitted June 2009
Twelfth International Waste Management and Landfill Symposium
5 - 9 October 2009 S. Margherita di Pula (Cagliari), Sardinia, Italy
http://iwwg.eu/publications/conference-proceedings

Report

Energy Systems Analysis of Waste-to-Energy Technologies using EnergyPLAN. Münster, M.
Risø-DTU Report. Risø-R-1667(EN). June 2009
http://130.226.56.153/rispubl/reports/ris-r-1667.pdf



Alternative uses of waste for energy production becomes increasingly interesting both from a waste management perspective - to deal with increasing waste amounts while reducing the amount of waste deposited at landfills – and from an energy system perspective – to improve the flexibility of the energy system in order to increase the share of renewable energy and reduce greenhouse gas emissions.

The focus of this PhD thesis is the analysis of the optimal use of waste for energy production in Denmark, now and in the future. Different Waste-to-Energy technologies are analysed through energy system analysis of the current Danish energy system with 13-14% renewable energy, as well as possible future Danish energy systems with 43% (2025) and 100% renewable energy (2050), respectively.

Given the assumptions applied, the following Waste-to-Energy technologies show good prospects:

1) Incineration for CHP of the main amount of waste (77% of total) with the highest possible electricity and heat efficiencies
2) Biogas production from the full potential of organic household waste and manure for production of CHP or transport fuel
3) Co-combustion of refuse derived fuel (RDF) with coal in new coal-fired power plants today and thermal gasification of RDF for CHP in the future when fully developed, if reduced CO_2 emissions are not the main goal

Affected or “marginal” energy production has been identified as input to life cycle assessments. The main conclusion in this respect is that the affected energy production always consists of a combination of energy technologies, which can be identified by the use of energy system analysis. Which technologies are affected depends on the time perspective (short-term or long-term), the energy system analysed, the area analysed (Denmark or Nordic and German electricity markets), as well as on assumptions regarding capacities, efficiencies, costs, and prices. Furthermore, not only flexible technologies, such as coal-fired power plants, which are capable of reacting to short-term changes in demand, are affected, but also inflexible technologies, such as nuclear power.