Energy 36 (2011) 1612–1622

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Optimization of use of waste in the future energy system

Marie Münster*, Peter Meibom

Risø-DTU, Technical University of Denmark, Frederiksborgvej 399, DK-4000 Roskilde, Denmark

ARTICLE INFO

Article history:
Received 3 February 2010
Received in revised form
17 December 2010
Accepted 30 December 2010
Available online 5 February 2011

Keywords:
Waste
Energy
System analysis
Biogas
Co-combustion
Thermal gasification

ABSTRACT

Alternative uses of waste for energy production become increasingly interesting when considered from two perspectives, that of waste management and the energy system perspective. This paper presents the results of an enquiry into the use of waste in a future energy system. The analysis was performed using the energy system analysis model, Balmorel. The study is focused on Germany and the Nordic countries and demonstrates the optimization of both investments and production within the energy systems. The results present cost optimization excluding taxation concerning the use of waste for energy production in Denmark in a 2025 scenario with 48% renewable energy. Investments in a range of waste conversion technologies are facilitated, including waste incineration, co-combustion with coal, anaerobic digestion, and gasification. The most economically feasible solutions are found to be incineration of mixed waste, anaerobic digestion of organic waste, and gasification of part of the potential RDF (refuse derived fuel) for CHP (combined heat and power) production, while the remaining part is co-combusted with coal. Co-combustion mainly takes place in new coal-fired power plants, allowing investments to increase in comparison with a situation where only investments in waste incineration are allowed.

1. Introduction

Use of waste for energy production becomes increasingly interesting, seen from an environmental as well as from the point of view of an energy system. When regarding waste as an environmental problem, a number of issues are important. First of all, waste amounts are increasing and so increasing amounts need to be treated [1]. Secondly, by 2014 the EU wishes to reduce the amount of landfilled biodegradable waste to a maximum corresponding to 35% of the biodegradable waste produced in 1995 [2]. Finally, the EU now accepts energy-efficient waste incineration as recovery, whereby it moves up the ladder of the waste hierarchy. The waste hierarchy prioritizes waste treatment in the following order from the top-down: waste prevention, re-use, recycling, recovery and safe disposal as a last resort [3].

Seen from an energy system perspective, it is interesting to include more organic waste in the energy system as this will increase the level of renewable energy in the system and hence decrease CO_2 emissions. In this way, including waste in the energy system becomes instrumental in achieving the goals of 20% renewable energy and 20% lower CO_2 emissions set by the EU for the year 2020[4]. Furthermore, 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 by 2020.

Compared to other countries, a very high proportion of the waste produced in Denmark is utilized for energy purposes i.e. 23%, and only 6% is landfilled [5]. There is, however, a lack of waste incineration capacity in the Danish system and old plants need replacement [6]. Currently, up to 20% of the electricity consumption in Denmark comes from wind power. Waste incineration has difficulties coping with the demand for flexible power production arising with increased shares of fluctuating wind power production. Waste is difficult to store and the plants have high investment costs which is why, preferably, they should run full time. Currently, in Denmark, waste incineration produces combined heat and power (CHP) with low electrical and high heat efficiencies, covering 4% of the electricity demand and 20% of the district heat production. All year round this heat is used in the district heating networks with first priority. However, heat produced from waste is still cooled off in cooling towers, particularly during summertime [7].

Due to the increased focus on reducing heat consumption in houses [4,8] even more heat may be cooled off in the future, unless the waste is used otherwise. Alternative uses of waste for energy production may potentially improve the energy efficiency and enable augmented shares of wind energy in the system by increasing the flexibility, e.g. through the production of bio-fuels from waste.

So far the use of waste for energy production has mainly been analyzed with a focus on environmental and, to some extent, economic

* Corresponding author. Tel.: +45 46775166; fax: +45 46775199.
E-mail address: marie.mynster@risoe.dk (M. Münster).

0360-5442/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.energy.2010.12.070

Nomenclature

Indices

i, I	Unit, set of units
I_a	Set of units in area a
$I^{ElecSto}$	Electricity storage units
$I^{HeatSto}$	Heat storage units
r, r', R	Region, neighboring region, set of regions
a, A	Area, set of areas
t, T	Time steps, set of time steps

Variables

C	New power capacity [MW]
P	Power generation [MW]
P^{Cur}	Wind curtailment [MW]
Q	Heat generation [MW]
S	Storage level in electricity storage [MWh]
SC	New heat storage capacity [MWh]
T	Electricity exchange between regions [MW]
U	Loading of heat storage [MW]

Parameters

av	Availability of the unit
c^{Loss}	Transmission loss
C^{Ex}	Existing power capacity [MW]
c^{Inv}	Annualized investment costs [Euro/MW]
c^{Fix}	Fixed operation and maintenance cost [Euro/MW]
$c^{Operation}$	Operation cost function of unit [Euro/h]
d	Electricity demand [MW]
h	Heat demand [MW]
l	Loading loss of heat storage
LC	Loading capacity of heat storage [MW]
R	Ratio between heat storage capacity and loading capacity
SC^{Ex}	Existing heat storage capacity [MWh]
w	Number of hours in each time period [h]

aspects using life cycle assessment (LCA) [9–14], cost–benefit analysis (CBA) [15–18], multi-criteria decision analysis (MCDA) [19–22] or various other tools, e.g. analyzing energy balances [23–25]. Here, waste incineration is mainly compared with non-energy waste treatment alternatives.

The LCAs have shown that the waste hierarchy, as established by the EU, by and large proves to be sound from an environmental point of view[10,26,27]; although, for some fractions, incineration has been found to outperform recycling [28]. This article uses the waste hierarchy as a starting point and aims at prioritizing between different future Waste-to Energy (WtE) uses of waste fractions which are not prevented, re-used or recycled.

Common to the above mentioned types of analysis is the fact that they fail to take into account the dynamic properties of the technologies and do not show the effect of changed use of waste for energy on the energy system. To account for this, it is necessary to perform energy system analysis (ESA).

Only few ESAs have focused on WtE technologies with representations of the variations in energy demand over the year. They use load duration curves and focus either on district heating systems or on national electric energy systems [29–34]. However, this does not make it possible to take the dynamic properties of the energy technologies fully into account, due to the loss of chronological time or give full justice to CHP technologies. In particular, full justice is not done to technologies which add flexibility to the energy system, such as storage technologies.

The above mentioned ESAs have all been performed on current energy systems or with a short-term view into the future, and the only WtE technology analyzed is waste incineration. As investments in plants, and particularly funding of research, have implications which reach further into the future, the aim of this study is to compare different WtE technologies, including their dynamic properties, in a medium term future energy system. Therefore comparisons are made of both commercialized technologies and pre-commercialized technologies in possible future scenarios of the Nordic and German energy systems in 2025 using the power system model Balmorel.

ESA of current and potential WtE technologies has recently been performed by Münster and Lund by use of the EnergyPLAN model for the current Danish energy system and a future energy system with 100% renewable energy [35–37]. However, using the Balmorel model makes it easy to assess possible future investments, as not only operation but also investments form part of the optimization [38]. By including the surrounding electricity markets of the other Nordic countries and Germany in the analysis, it is possible to identify the effects in these countries of changed use of waste for energy in Denmark, compared to a business-as-usual scenario. Hereby, the long-term affected (also called marginal) energy production plants can be identified. The importance of this has been highlighted by Mathiesen et al. [39] and calculated for illustrative cases by Münster and Meibom [40].

After taking into consideration the background and review of literature given above, the objective of the study presented here was to identify feasible WtE technologies for treatment of different waste fractions in a medium term future energy system. Their dynamic properties were taken into account and both production and investments were optimized.

2. Methodology

This chapter consists of a general description of the Balmorel model followed by a mathematical presentation of the model. Next a description is given of the modeling of waste in the model including the improvements made to the model by the authors. Then the data input of the model is given, and the model outputs and interpretation of results are shortly presented.

2.1. Balmorel

Balmorel is a linear optimization model of a power system including district heating systems. It is open source and available on a home page along with a full model description and documentation of analyses (www.balmorel.com). Balmorel has been used for a wide range of analyses documented in project reports available on the model website and in journal papers, e.g. [41,42]. Based on the assumption that perfect market conditions exist, the model minimizes system costs consisting of operational costs of all plants and annualized investment costs. Operational costs include fuel costs, CO_2 quota costs as well as operation and maintenance costs. Taxes are not included in this analysis. Given a number of restrictions, the model may, in this way, optimize investments in new production as well as transmission capacity and the operation of plants. Prices such as the electricity price can be found from the marginal values of restrictions.

The model is designed to cover several countries within the same electricity market. Each country consists of one or more regions, between which electricity exchange is restricted due to limited transmission capacities. Each region, in turn, consists of one or more district heating areas, between which no exchange of heat is allowed. Time series for electricity demand and wind power production are given for regions, whereas time series for heat demand are given for areas. The time series provide hourly data for one year.

The model uses a two-level subdivision of time, which may be used to represent weeks and hours. When Balmorel is used to optimize investments it may be necessary to delimit either the number of hours or the number of weeks. When modeling energy systems with a high share of wind power it is recommendable to keep the hourly representation in order to capture the fluctuating nature of the wind and instead delimit the number of weeks.

By using the District Heating version of Balmorel, which facilitates investments in district heating networks, it is also possible to assess the impact of the changed use of waste for energy production on the need for expansion of the district heating networks [43]. Furthermore, The District Heating version has a more detailed representation of the district heating networks. The detailed representations of the district heating system and its possible expansions are assessed as important, although they require a reduction of the time steps analyzed down to 4 weeks of 168 h each. The inclusion of waste storage possibilities also improves the representation of dynamic properties connected to waste. Finally, Balmorel has the advantage that the electricity price is found by the model and does not have to be estimated. Depending on the size of the problem, calculations take from minutes to days. For this article, each run took approximately 15 h on a computer with an Intel Core2 Duo 3 GHz processor with 7.8 GB RAM using the CPLEX solver.

Some of the limitations of the model are that Balmorel is a deterministic model with perfect foresight and, hence, the wind speeds are "known" to the system in advance. As a result, the model underestimates system costs. Furthermore, decisions regarding investments are based solely on the costs calculated by the model in the year analyzed. In the real world, decisions on investments will normally include an analysis of trends, e.g. in the development of investment and fuel costs. As Balmorel is a linear model, it is not possible to include start-up costs of plants or to let scale be decisive of e.g. investment costs.

2.2. Mathematical framework

Balmorel is a linear programming model and as such consists of an objective function and some restrictions. The main equations of the model are given in this section in a simplified way in order to present the mathematical content of the Balmorel model.

The objective function (eq. (1)) minimizes system costs, which comprise the annualized investment costs of new investments, the fixed operation and maintenance costs of existing units and new investments, and the operational costs of units. Each time period is weighted to represent a longer time span in order to cover full-year costs. Electricity demand in each region taking into account export and import between regions (eq. (2)) and district heating demand in each area (eq. (3)) have to be fulfilled in each time period.

The marginal value of the electricity demand equation (eq. (2)) is the electricity price. Wind power production is treated as production following a fixed production time series with the possibility of curtailing wind power if cost optimal for the system.

Equation (4) influences the demand for capacity by ensuring that the power production from a unit either existing or new is lower than the capacity of the unit multiplied with an average availability. It simplifies the availability of power plants by assuming that a constant portion of each type of power plant is unavailable due to scheduled maintenance or forced outage. Availability of wind power is included in the wind power production time series. A restriction similar to eq. (4) applies for transmission limits although not shown here.

The Balmorel model includes restrictions specifying the technical capabilities of condensing and CHP plants, heat pumps and electric boilers, heat storages, and hydropower with reservoir. It also includes restrictions limiting the yearly usage of specific fuels, modeling the costs of expansions in the district heating networks and modeling the usage of waste for energy purposes. To shorten the model presentation, the technical restrictions of a heat storage are given as an example, while the rest of the restrictions are not shown here.

The investment decision for heat storage has been simplified by assuming a fixed relationship between storage size and loading capacity of the storage, and by assuming that the loading and unloading capacities are equal. In this study it is assumed that the storage content of all new heat storages corresponds to 12 h of maximum loading of the storage. Equation (5) is the balance equation for heat storage expressing that the storage content in the beginning of a time step is equal to the storage content in the beginning of the previous time step plus the loading of the storage minus the unloading during the previous time step. The maximum storage content is limited (eq. (6)) as well as the loading of the storage (eq. (7)).

$$\min\left(\sum_{i\in I} c_i^{Inv} C_i + \sum_{i\in I} c_i^{Fix}\left(C_i^{Ex} + C_i\right) + \sum_{t\in T} \times \sum_{i\in I} w_t c_i^{operation}\left(P_{i,t} Q_{i,t}\right)\right) \tag{1}$$

subject to

$$\sum_{a\in A(r)} \sum_{i\in I_a} P_{i,t} - P_{r,t}^{Cur} + \sum_{\bar{r}\in R}\left(\left(1 - c^{Loss}\right)\cdot T_{r,\bar{r},t}\right) = d_{r,t} + \sum_{\bar{r}\in R} T_{\bar{r},r,t}\,\forall t\in T; r\in R \tag{2}$$

$$\sum_{i\in I_a} Q_{i,t} = h_{r,t} + \sum_{i\in I_a^{HeatSto}} U_{i,t} \quad \forall t\in T; a\in A \tag{3}$$

$$P_{i,t} \le \left(C_i^{Ex} + C_i\right)\cdot av_i \quad \forall i\in I; t\in T \tag{4}$$

$$S_{i,t+1} = S_{i,t} + w_t\left(U_{i,t}(1 - l_i) - Q_{i,t}\right) \quad \forall i\in I^{HeatSto}; t\in T \tag{5}$$

$$S_{i,t} \le SC_i^{Ex} + SC_i \quad \forall i\in I^{HeatSto}; t\in T \tag{6}$$

$$U_{i,t}\cdot R_i \le SC_i^{Ex} + SC_i \quad \forall i\in I^{HeatSto}; t\in T \tag{7}$$

Different checks on the consistency of data inputs have been implemented in the Balmorel model and hence are performed automatically. Error checking by close inspection of the model output is still required.

2.3. Modeling waste

Waste can be considered an environmental problem or an energy resource, depending on the view of the beholder. When modeling waste in energy systems, a range of characteristics distinguish waste and waste treatment plants from many other energy sources and technologies:

Table 1
Input and output of Waste-to-Energy technologies.

WtE technology	Input	Output	Investment possibility
Waste incineration	Mixed waste, no storage, LHV 10.5 MJ/kg [45]	Low electricity output and high heat output.	All areas with current waste incineration
Co-combustion with coal	Sorted, pre-treated RDF[a], storable, LHV 16.5 MJ/kg [46] or straw, requires min. 93% coal [47]	High electricity output and heat	Larger city areas in Denmark with current coal-fired power plants
Thermal co-gasification with coal for CHP and bio-fuel production	Mixed pre-treated waste, no storage, LHV 10.5 MJ/kg, requires min. 75% coal [48]	Choice between bio-petrol or CHP production with high electricity output and heat	Larger city areas in Denmark with current coal-fired power plants
Thermal gasification for CHP	Sorted, pre-treated RDF[a], storable, LHV 16.5 MJ/kg	High electricity output and heat	Larger city areas in Denmark
Thermal gasification for bio-fuel production	Sorted, pre-treated RDF[a], storable, LHV 16.5 MJ/kg	Di-methyl ether (DME)	Rural areas in Denmark with current waste incineration
Anaerobic digestion for CHP	Sorted, pre-treated organic waste[b], not storable, LHV 2.5 MJ biogas per kg organic waste [49]	High electricity output and heat	Rural areas in Denmark with natural gas-fired CHP plants
Anaerobic digestion for bio-fuel production	Sorted, pre-treated organic waste[b], not storable, LHV 2.5 MJ biogas per kg organic waste	Cleaned, upgraded and compressed biogas	Rural areas in Denmark with natural gas-fired CHP plants

[a] RDF consists mainly of paper, cardboard, plastic and waste wood. RDF is assumed to amount to maximum 19% of the energy content of the total waste resource [6].
[b] Organic waste, which can feasibly be sorted out and used for biogas production, is estimated to amount to 4% only in energy terms [47]. It is assumed that half of the energy input for biogas plants comes from manure, which is made available at no cost. The current anaerobic digestion of manure amounts to 10% of the potential [48]. The manure is assumed to contribute with 0.5 MJ of biogas per kg of manure [50].

- The storage of waste is complicated depending on the moisture and organic content.
- The transportation of waste over long distances may not be feasible due to the low energy content and the odurs of waste.
- Waste is inhomogeneous and consists of various fractions which can be treated in different plants and have different potentials in terms of storage.
- Benefit may be drawn from using waste together with other fuels in energy plants.
- Prices for treating waste vary depending on local factors and national taxes.
- Potential exists to produce bio-fuel for transport as well as electricity and large amounts of heat.

In this model, the issues of storage and transportation are dealt with through a restriction which requires that all waste available for energy production in each region must be used within a year. It is possible to store part of the waste (here assumed to be 40%) within the year subject to a transportation cost (8.4 EUR/t) and a weekly fee to the deposit (23.6 EUR/t) [44]. It is assumed that the waste flow is constant and that on average waste is stored for half a year.

Furthermore, a restriction has been added as the waste fractions used by the various plants differ. This ensures that the combined use of a given fraction by the relevant plants does not exceed the share which this fraction constitutes out of the total in each region.

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 fueling with one fuel to fueling with multiple fuels. In this manner, it is possible to model, e.g. co-combustion of waste and coal in existing coal-fired plants.

Finally, the production of transport fuels has been facilitated by introducing revenue of the fuels produced to the objective function and by adding the use of waste for transport 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 plant capable of using multiple fuels and of optimizing by changing between producing transport fuel or electricity and heat, depending on the fluctuating electricity prices.

In combination the above mentioned alterations to the model ensure that the model now has improved the understanding of the restrictions and possibilities connected to the use of waste for energy production in the future. With the wide range of technologies modeled, it is assumed that it will now be possible to analyze most possible WtE technologies within the existing framework.

2.4. Data input

In order to answer the question of how we should use waste for energy in a future energy system, a range of technologies are chosen which may be feasible in a medium long perspective. The chosen WtE technologies have all proven interesting in former ESAs of WtE technologies [35–37]. The technologies and their inputs and outputs as well as assumed investment possibilities are presented in Table 1. As data for technologies under development are naturally uncertain and may be optimistic, results of the analysis can mainly be used to recommend whether further funds should be invested in the development of the technology.

Investment costs as well as operation and maintenance costs and efficiencies of the WtE technologies are shown in Table 2.

For reasons of simplicity, potential increased costs related to changed method for waste collection, sorting and transportation procedures as well as changed distribution of transport fuel and other vehicles are not included in the analysis.

As it is impossible to predict the future, it is important to look at different possible scenarios. When analyzing WtE technologies, a number of parameters have great influence on the outcome of the results. Six scenarios (Table 3) are, therefore, analyzed in which the energy demands (Table 4), waste amounts (Table 5) as well as fuel prices (Table 6) and CO_2 quota costs vary. The scenarios represent possible futures for Denmark in 2025. The CO_2 quota price is expected to be 32 EUR/t in the Base scenario and 25 EUR/t in the low CO_2 quota price scenario [61].

Table 4 shows the expected electricity and heat demands for the Nordic countries and Germany and the number of regions and areas modeled. Electricity demand is defined at the region level and heat demand at the area level. The Danish district heating system consists of around 450 separate networks. The number of networks

Table 2
Technologies available for investment in 2025.

	Fuel	Fuel eff[a]	CB	CV	Inv cost	VO&M cost	FO&M cost	Life-time	Source
					MEUR/MWel	EUR/MWhel	kEUR/MWel	Years	
WtE technologies									
Gasification	Coal/Mixed waste	0.78			0.69		43.4	20	[51]/[52]/[53]
Combined cycle, back pressure	Syngas	1.04	1.31		0.89	2.8	10.2	20	[51]/[52]/[54]/[50]
Syngas Catalysis	Syngas	0.79			0.13		81.7	20	[51]/[52]
Integrated gasification and combined cycle, extraction	RDF	0.49	0.93	0.13	2.06		92.9	20	[51]/[52]/[53]
Gasification and DME production	RDF	0.67			1.98		118.6	20	[53]
Biogas Plant and Engine, back pressure	Organic waste and manure	0.60	0.8		1.86		170.8	20	[53]
Biogas Plant incl. cleaning and upgrading	Organic waste and manure	0.56			1.93		170.8	20	[53]
Co-combustion upgrade, steam turbine, extraction	Coal/RDF/Straw	0.37–0.47	0.59–4.76	0.15–0.2	0.15	2.7/4.5	56.4	30	[50]/[46]/[55]
Co-combustion steam turbine, extraction	Coal/RDF	0.53/0.52	0.95/0.94	0.15	1.39	4.5	23.5	30	[50]
Incineration steam turbine, back pressure	Mixed waste	0.97	0.37		5.44	20.3	217.8	30	[50]
Other energy technologies									
Condensing (only FI and SE)	Uranium	0.37			2.81	7.7	55.5	40	[56]
Condensing	Coal	0.46			1.35	6.0	42.7	35	[56]
Open cycle, condensing	Nat. gas	0.37			0.34	2.6	17.1	25	[56]
Combined cycle, extraction	Nat. gas	0.62	1.7	0.13	0.96	1.6	13.3	25	[50]
Extraction	Coal	0.53	0.95	0.15	1.28	1.9	17.1	35	[50]
Steam turbine, back pressure	Straw	0.9	0.5		4.62	15.4	92.3	20	[50]
Steam turbine, back pressure	Wood	0.9	0.5		4.62	13.5	80.8	20	[50]
Wind turbine	Onshore	1			1.20	2.0	15.5	20	[50]
Wind turbine	Offshore	1			1.62	3.5	40.6	20	[50]
Heat boiler	Wood	0.91			0.27	2.1	16.0	35	[50]
Heat boiler	Nat. gas	0.93			0.05	1.1	2.1	40	[50]
Heat Pump	Electricity (35 °C water)	3.6			0.48		7.1	20	[57]
Electric Heater	Electricity	0.97			0.03	0.01		20	[50]
Central heat storage	Heat	0.99			1.78[b]			20	[58]
Individual heat boiler	Nat. gas	0.97			0.59		22.8	15	[59]
Individual heat boiler	Oil	0.92			0.52		22.8	15	[59]
Individual heat boiler	Wood pellets	0.9			0.82		22.8	15	[59]
Individual heat pump (water–water)	Electricity (Ground water)	3.4			1.99		0.01	20	[60]
Individual heat pump (Air–air)	Electricity	1.5			1.26		0.02	15	[60]

[a] For extraction plants, the fuel efficiency illustrates the electrical efficiency. For the remaining plants, it illustrates the total fuel efficiency.
[b] The investment cost for heat storage is given in kEUR/MWh.

continues to decrease as networks get connected. In the Balmorel model, Denmark is represented by two regions, East and West, and by 21 areas of which 8 are based on geography and 13 on the main type of energy-producing technology.

The assumed resource potentials are illustrated in Table 5. With regard to waste resources available for energy, two scenarios are analyzed; one with an increase in the amount of waste of 1.3% per year, resulting in 47 PJ/year [6], and one in which the amount of energy in the waste as a minimum remains stable at 37 PJ/year, corresponding to the level in 2006 [67]. The waste resources of countries other than Denmark are maintained at the same level in all scenarios.

Expected fuel prices are shown in Table 6. The mixed waste price is calculated as the cost of waste incineration deducted the income from the sale of electricity and heat. The cost is negative as the treatment plants receive money to treat the waste. Great uncertainty exists regarding the costs of other waste fractions, as this is determined by local circumstances. The price of sorted organic household waste is here assumed to be the same as for mixed waste, but, in reality, municipalities may be willing to pay more, as shown in Münster and Lund [37]. If competition for RDF (refuse derived fuel) increases, the price may converge with biomass prices. As more competition is assumed in the future, the price here is increased so that the plants receive RDF for free. This issue is further dealt within the sensitivity analysis.

The remaining fuel prices are from the Danish Energy Agency. The high oil price is equivalent to 119 USD/bbl and the low price is equivalent to 87 USD/bbl. All monetary values (e.g. investment costs and fuel prices) are given in EUR in year 2007.

Lower heating values and fossil CO_2 content of the fuels are also shown in Table 6. To be able to compare, 7 kg/GJ from refining petrol is added to the fossil carbon content [72].

Table 3
Scenarios.

Name	Description
BAU	Business as usual. Only investments in waste incineration
Ref	Reference. Investments in new WtE technologies are also allowed
Low fuelp	Low fuel price
Low CO_2p	Low CO_2 quota price
Low energy	Low energy demand
Low energy and waste	Low energy demand and low waste amount

Table 4
Projected energy demands in the Nordic countries and Germany in 2025 and modeled areas.

	Denmark –Ref	Denmark –Low	Germany	Finland	Norway	Sweden
Electricity demand (TWh)[a]	35[62]	21[63]	543[64]	106[64]	145[64]	148[64]
District heat demand (PJ)[a]	67[62]	47[63]	337[65]	266[66]	9[65]	166[65]
Electricity regions/DH areas	2/21	2/21	2/2	1/1	1/1	1/1

[a] Excluding transmission losses.

Table 5
Resource potentials in 2025.

	Denmark	Germany	Finland	Norway	Sweden
Wind turbine (GW)	9,5[a]	78,4[b]	16,4[b]	19,7[b]	22,9[b]
Agricultural solid waste (PJ)	36 [48]	200 [68]/[69]	91 [68]/[69]	17 [70]	237 [68]/[69]
Forestry residues and energy crops (PJ)	18 [48]	592 [68]	52 [68]	160 [70]	154 [68]
Municipal waste for energy (PJ)	47 [6]/37 [67]	591[1]	29 [1]	40 [71]	56 [1]

[a] Max 60% of electricity consumption in 2025 assumed.
[b] Max 50% of electricity consumption in 2025 assumed.

The electricity-generating technologies which are expected still to be in operation in 2025 are shown in Fig. 1, with total capacities given in GW. The capacities are a result of an analysis where 3% of the existing fossil fueled plants are decommissioned per year, whereas new renewable and nuclear plants are assumed to replace existing plants, to allow the capacity to remain the same. No other new investments occur before 2025. The new Finnish nuclear plant of 1600 MWe at Olkiluoto is included in the existing capacity. Furthermore, based on the age of the existing waste incineration plants, Denmark is still expected to have a waste incineration capacity equal to around 25 PJ input in 2025.

Apart from the WtE technologies, a wide range of technologies are made available for investment, as shown in Table 2. An interest rate of 6% without inflation is utilized to calculate the costs of investments.

2.5. Model output and interpretation of results

In general the model output consists of the level of each variable and the marginal value of each restriction. Hence for each time step the following are given: fuel usage, electricity production and heat production of each unit, wind curtailment, electricity transmission between regions and loading and unloading of heat storages. These values are summed up over units and time steps to achieve yearly values. The fossil CO_2 content in each fuel type is combined with the yearly fuel usage and used to calculate yearly CO_2 emissions.

Yearly model output consists of the size of the investments in new production units, heat and waste storages and transmission lines, and in the yearly investment and operation costs.

As mentioned, the marginal values of the electricity balance equation give the electricity prices.

Results are derived by comparing the model output between different input data scenarios. Sensitivity analysis is performed by varying some of the assumptions to which the results may be most sensitive:

- Investment costs
- Inclusion of free manure for biogas production
- Possibility to invest in nuclear plants.

The investment costs of energy technologies under development are highly uncertain. Hence an analysis has been performed with increased investment costs depending on the development stage of each technology and the sensitivity to local conditions.

3. Results

Based on the input data the model first provides results for the Reference scenario. Due to the high fuel prices in general, the relatively low coal price and the high CO_2 quota costs, the main resources utilized for heat and power production in the Reference scenario for the whole region are coal (46%), uranium (33%), and wind power (11%). Municipal waste only constitutes 4% in this area and the share of renewable energy amounts to 17%. On the other hand, in Denmark the expected increase in waste amounts and decrease in energy consumption leads to utilization of mainly coal (41%), municipal waste (32%), and wind (14%), and the share of renewable energy adds up to 48%.

The utilization of waste for energy production varies in the different scenarios as shown in Fig. 2, where existing and new waste incineration plants are shown on the left axis and the remaining plants on the right.

In the scenarios in which investments in new WtE technologies are allowed, the full resource of organic waste is converted to biogas and used for CHP, apart from the scenario with low CO_2 quota costs, in which the biogas is used for transport instead, as less is earned on substituting fossil fuels in the heat and power sectors. The organic waste is assumed to be co-digested with manure. The corresponding manure amounts to 5% of the current untreated manure potential. RDF is both used for co-combustion in coal-fired power plants and for gasification with subsequent use for CHP

Table 6
Projected fuel prices in 2025, lower heating values and CO_2 content of fuels.

	Fuel oil	Petrol	Natural Gas	Coal	Bio-mass	Bio-pellets	Uranium	Mixed waste	RDF	Organic waste
Base price (EUR/GJ)[61]	11.1	25.0	10	3.4	6.4–6.9	10.2–11.5	0.7	–3[a]	0	–3[a]
Low price (EUR/GJ) [73]	8.5	15.6	7.7	2.7	7.3	13.4	0.7	–3[a]	0	–3[a]
Lower Heating Value (GJ/t) [61]	40,7	43,8	39,6	25,2	14,5	14,5-17,5	500000	10,5	16,5[b]	2,5[c]
Fossil CO_2 content (kg/GJ) [61]	78	73	57	95	0	0	0	34[b]	37[b]	0

[a] Renosam benchmarking [74].
[b] Møller et al., 2008 [46].
[c] Christensen et al., 2003. Based on biogas output [49].

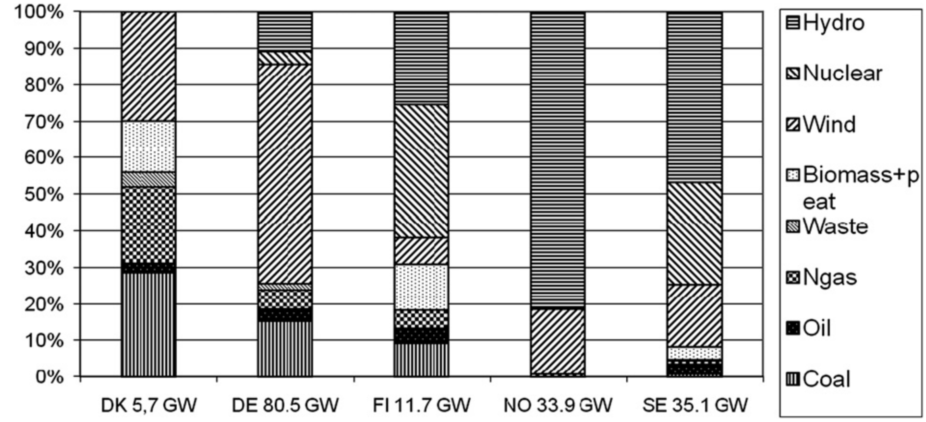

Fig. 1. Assumed remaining electricity production capacity in 2025.

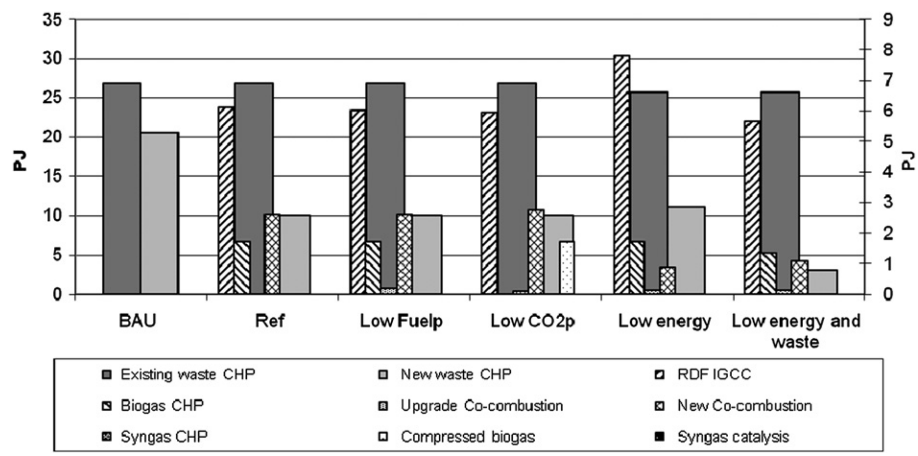

Fig. 2. Use of waste for energy production in Denmark. Waste CHP are shown on the left axis and new WtE technologies on the right.

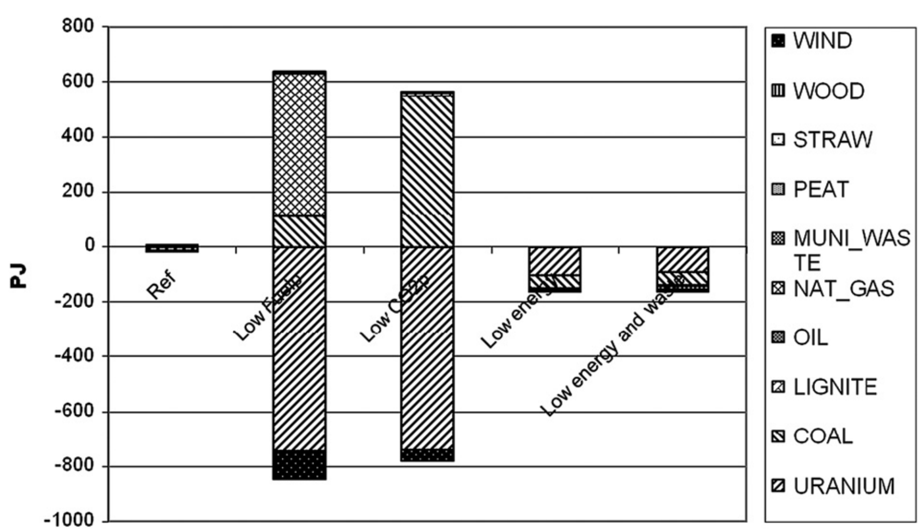

Fig. 3. Differences in fuel use for all countries compared to the BAU scenario.

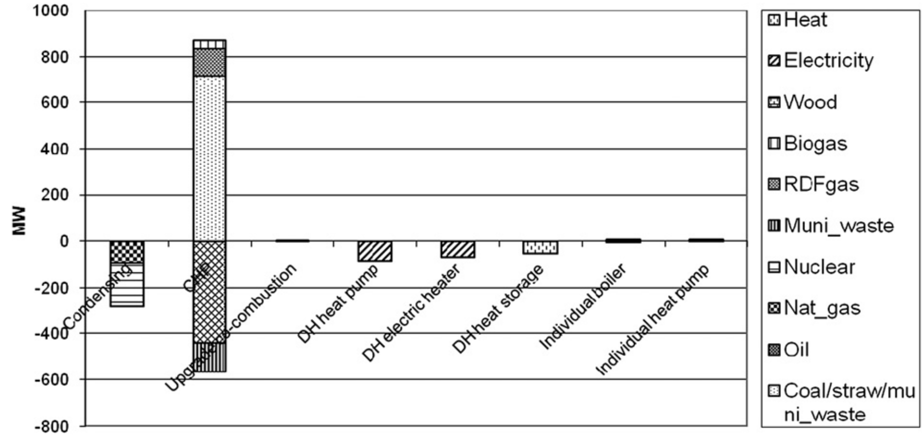

Fig. 4. Differences in investments for all countries between the BAU and the reference scenarios.

production. In all scenarios, the full RDF potential is utilized. No mixed waste is co-gasified with coal in the syngas plant in any of the scenarios.

RDF is mainly gasified and used for CHP production or co-combusted in new coal-fired power plants. RDF is only co-combusted in existing coal-fired plants to a limited degree, and only when these have high total efficiencies.

Hardly any difference can be found between the BAU scenario and the Reference scenario with regard to the fuel use in all countries, as shown in Fig. 3. In the remaining scenarios, less uranium for nuclear power is found to be used. In the low fuel price scenario, nuclear power plants are replaced by natural gas and coal-fired plants and in the low CO_2 quota price scenario; they are replaced by coal-fired plants.

When looking at the differences in investments between the BAU and the Reference scenario in Fig. 4, the main change is that there is an increase in investments in coal-fired power plants co-combusting RDF replacing investments in coal-fired CHP plants. In Denmark investments in 240 MW coal-fired CHP plants are replaced by 720 MW of the same type of plants capable of co-combusting RDF.

Apart from altering the division between producing heat and electricity, increasing heat storage or producing transport fuel, three flexibility options exist in order not to create a surplus of heat or electricity: 1) increasing the transmission capacity of electricity or 2) the size of district heating networks or 3) the capacity of waste storage.

With regard to investments in heat networks and electricity transmission capacity, minor differences also exist between the scenarios, as shown in Fig. 5. Heat consumption in new networks ranges from 18.6 PJ in the low energy and waste scenario with less heat production and demand up to 22.4 PJ in the BAU scenario in which the maximum amount of heat is produced from waste. Total investments in electricity transmission in the Nordic and German energy system are lowest in the low fuel price scenario (18 GW) and in the low CO_2 price scenario (21 GW). This is due to increased electricity production capacity in the central German region in these scenarios. In the remaining scenarios the investments are of 26 GW.

The storage of waste is also used to increase the flexibility of the energy system. As shown in Fig. 6, most waste is stored in the BAU scenario (5.5 PJ), where waste is used more inflexibly and in the scenario with low energy consumption (5.1 PJ), where it is more difficult to balance production due to lower demands.

Differences in CO_2 emissions are shown in Fig. 7, when comparing the various scenarios with the BAU scenario. The columns show differences in CO_2 emissions for electricity, heat and transport in Denmark on the left axis and the dots show the difference for electricity, heat and transport in all countries on the right axis. Overall, when allowing investments in new WtE

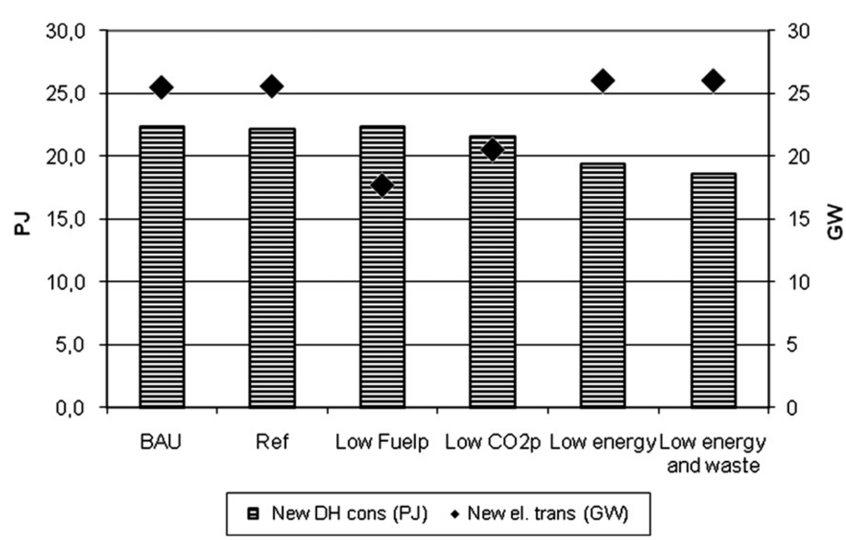

Fig. 5. Heat consumption in new district heating networks in Denmark (left axis) and new electricity transmission in whole region (right axis).

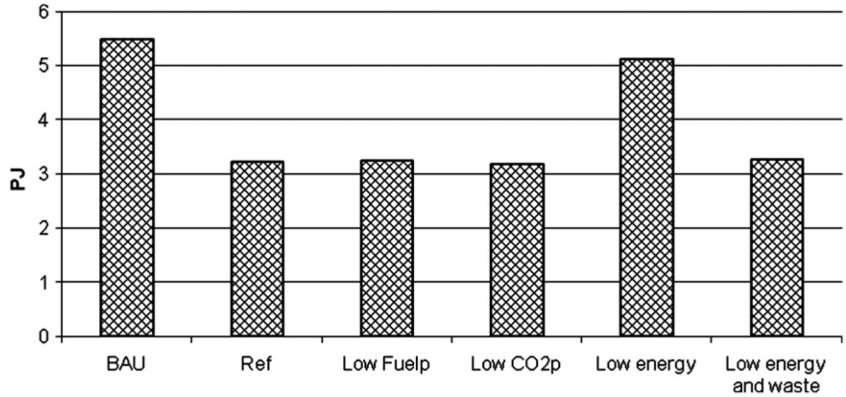

Fig. 6. Waste storage in Denmark.

technologies, CO_2 emissions increase very slightly due to increased use of coal and natural gas. The highest CO_2 emissions are found in the low CO_2 price scenario in the whole region, whereas it is found in the low fuel price scenario in Denmark. This is due to less electricity import and more inland production with natural gas-fired CHP plants. The share of renewable energy in the Danish energy system decreases slightly from 48% in the BAU scenario to 46% in the Reference.

3.1. Sensitivity analyses

The investment costs of waste incineration were raised by 10% and of co-combustion by 25%. The figures for the remaining technologies were raised by 50%. The main change in the use of waste compared to the reference is a decrease in the use of RDF in new co-combustion plants, corresponding to 20% of the total RDF. Instead, the main part of the unused RDF is used for gasification for CHP and the rest for co-combustion in existing coal-fired power plants.

The sensitivity of the assumption that manure is available for free was analyzed in a scenario where biogas was produced from organic household waste alone. Basically the use of waste does not change in this scenario and the full organic waste resource is still used for the production of biogas for CHP.

When comparing the BAU scenario with and without the possibility for new investments in nuclear power, new nuclear capacities are substituted by coal-fired power plants, offshore wind turbines and natural gas-fired power plants. When allowing investments in new WtE technologies in a scenario with no new nuclear investments, there is a slightly higher use of RDF in new co-combustion plants and less gasification of RDF for CHP than in a scenario with nuclear investments. This follows the trend of more coal-fired capacity in general. Furthermore, also due to increased coal-fired power production, the investments in wind power and natural gas-fired power capacity decrease, however only marginally.

A recent study of Münster and Meibom illustrates the significance of combining the WtE technologies by comparing this approach to modeling the technologies individually[40]. Here, high potential was also found for using organic waste for biogas production and RDF for co-combustion or gasification.

4. Discussion

In some studies, incineration has been compared with the production of biogas using LCA [9,11,14]. Here, the conclusions are unclear. Under some circumstances, the environmental consequences of biogas production used for CHP are comparable to those related to incineration [9,14]. Combined with dedicated RDF combustion, however, biogas production has been found to have a lower environmental impact [11]. In this study the production of biogas and use of RDF for energy production are shown to be feasible from an economic viewpoint and changed use of waste for energy production results in an increase in CO_2 emissions mainly due to increased co-combustion with coal.

Few comparisons have been made in which gasification or bio-fuel production has been compared with other waste treatment alternatives. In Murphy and McKeogh [23], digestion with a subsequent production of biogas for transport was the best option for the organic fraction; whereas for the non-organic fraction, gasification was found to be superior to incineration. The analysis showed high sensitivity to the use of thermal output. The results are well in accordance with the results of the analysis in this article where there is a relatively high demand for district heating.

In Dornburg et al. [25], 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 shows good results for integrated gasification combined cycle plants (primarily utilizing municipal solid waste and sewage sludge) and co-combustion (utilizing organic domestic waste, swill and waste from food industry after hydrothermal upgrading). These results also support the results from this study where co-combustion and integrated combined cycle plants show high potential.

In future studies it would be relevant to analyze the optimal use of waste for energy including taxes and tariffs in the optimization and testing the significance on assumptions regarding costs of e.g. nuclear and wind power. It could also be interesting to analyze the WtE technologies in substantially different energy systems, such as one supplied by 100% renewable energy. Finally, it would be

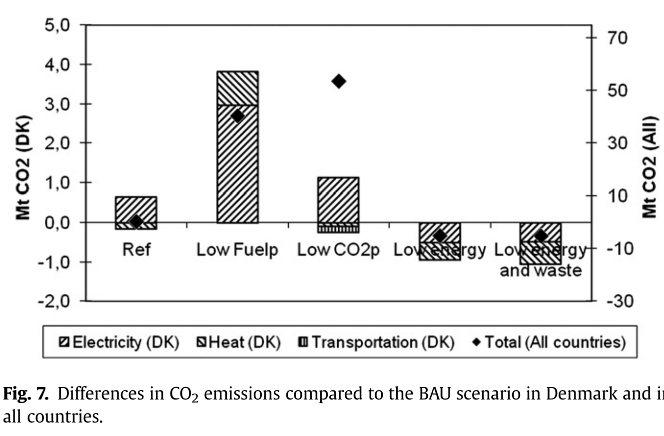

Fig. 7. Differences in CO_2 emissions compared to the BAU scenario in Denmark and in all countries.

interesting to include a more detailed representation of waste fractions, and non-energy waste treatment measures and conservation measures could be represented in the model, e.g. by costs and by greenhouse gas emissions.

5. Conclusion

The main objective of the analysis was to identify feasible WtE technologies for treatment of different waste fractions in a medium term future energy system taking into account their dynamic properties and optimizing both production and investments. To summarize, the results of the analysis show that waste incineration will continue to have an important role to play also in the future. Hence it can be recommended to incinerate mixed waste primarily in dedicated waste incineration plants producing CHP at high efficiencies. As co-gasification in syngas plants leads to higher CO_2 emissions it may be relevant from an economic perspective, but only with low CO_2 quota prices. Furthermore, organic household waste should be co-digested with manure, if free untreated manure is available and a treatment price of organic waste of 3 EUR/GJ can be obtained. The biogas should be used for CHP or transport fuel, depending on the CO_2 quota costs.

Under the given assumptions, it is most economically feasible to use RDF for co-combustion with coal in plants with high efficiencies today, whereas, in the future, RDF should be used for gasification combined with CHP production, assuming that the sorting out of the full RDF potential does not decrease the efficiencies of the existing waste incineration plants and that RDF is available for free.

Overall, it can be concluded that the main objective of the article has been met and the results are supported by other studies.

Acknowledgements

The authors 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 consultancy on data and model characteristics of Balmorel. Thanks are also extended to Henrik Lund from Aalborg University and Poul Erik Morthorst from Risø-DTU for comments and discussions. Finally, the authors wish to thank Tore Hulgaard from Rambøll as well as the staff from Swedish Gas Centre, Waste Centre Denmark, DONG Energy, Danish Energy Authority, AV Miljø, KARA and L90 for contributing with data to the analyses.

The paper was partially funded by the programme for strategic funding within sustainable energy administered by the Danish Council for Strategic Research under the Danish Agency for Science, Technology and Innovation and is part of the research programme "ENSUWE – Environmentally Sustainable Utilisation of Waste resources for Energy production".

References

[1] Skovgaard M, Hedal N, Villanueva A, Andersen FM, Larsen H. Municipal waste management and greenhouse gas emissions. ETC/RWM Working paper 2008/1. Copenhagen, Denmark: European Topic Centre on Resource and Waste Management. Available from: http://scp.eionet.europa.eu/publications/wp2008_1; 2008.
[2] Council Of The European Union. Council directive 1999/31/EC of 26 April 1999 on the landfill of waste. Official Journal L 1999;182:0001–19.
[3] European Commission. Taking sustainable use of resources forward: a thematic strategy on the prevention and recycling of waste; 2005. Brussels.
[4] European Commission. An energy policy for Europe; 2007. Brussels.
[5] Danish Environmental Protection Agency. Danish waste statistics 2006. Orientation from the Danish Environmental Protection Agency, 2/2008 (In Danish). Copenhagen, Denmark: Danish Environmental Protection Agency. Available from: http://www.mst.dk/; 2008.
[6] Ramboll. Vurdering af mængden af forbrændingsegnet affald i Danmark [(Assessment of the amount of incinerable waste in Denmark). 834–071572] (In Danish). Copenhagen, Denmark: Waste Denmark. Available from: http://affalddanmark.dk/; 2008.
[7] Lund H, Münster E. Modelling of energy systems with a high percentage of CHP and wind power. Renewable Energy 2003;28:2179–93.
[8] Government Danish. Law about increasing energy savings in buildings. LOV no 585 of 24/06/2005; 2005 (In Danish). Copenhagen.
[9] Baky A, Eriksson O. Systems analysis of organic waste management in Denmark. Environmental project no. 822, 2003. Copenhagen: Danish Environmental Agency; 2003.
[10] Finnveden G, Bjorklund A, Reich MC, Eriksson O, Sorbom A. Flexible and robust strategies for waste management in Sweden. Waste Management 2007;27:S1–8.
[11] Cherubini F, Bargigli S, Ulgiati S. Life cycle assessment of urban waste management: energy performances and environmental impacts. The case of Rome, Italy. Waste Management 2008;28:2552–64.
[12] Eriksson O, Finnveden G, Ekvall T, Bjorklund A. Life cycle assessment of fuels for district heating: a comparison of waste incineration, biomass- and natural gas combustion. Energy Policy 2007;35:1346–62.
[13] Finnveden G. Methodological aspects of life cycle assessment of integrated solid waste management systems. Resources, Conservation and Recycling 1999;26:173–87.
[14] Kirkeby JT, Birgisdottir H, Hansen TL, Christensen TH, Bhander GS, Hauschild M. Evaluation of environmental impacts from municipal solid waste management in the municipality of Aarhus, Denmark (EASEWASTE). Waste Management & Research 2006;24:16–26.
[15] Eshet T, Ayalon O, Shechter M. A critical review of economic valuation studies of externalities from incineration and landfilling. Waste Management & Research 2005;23:487–504.
[16] Dijkgraaf E, Vollebergh HRJ. Burn or bury? A social cost comparison of final waste disposal methods. Ecological Economics 2004;50:233–47.
[17] Moutavtchi V, Stenis J, Hogland W, Shepeleva A, Andersson H. Application of the WAMED model to landfilling. Journal of Material Cycles and Waste Management 2008;10:62–70.
[18] Tietze-Stockinger I, Fichtner W, Rentz O. A model to minimize joint total costs for industrial waste producers and waste management companies. Waste Management & Research 2004;22:466–76.
[19] Morrissey AJ, Browne J. Waste management models and their application to sustainable waste management. Waste Management 2004;24:297–308.
[20] El Hanandeh A, El-Zein A. Strategies for the municipal waste management system to take advantage of carbon trading under competing policies: the role of energy from waste in Sydney. Waste Management 2009;29:2188–94.
[21] Shmelev SE, Powell JR. Ecological-economic modelling for strategic regional waste management systems. Ecological Economics 2006;59:115–30.
[22] Longden D, Brammer J, Bastin L, Cooper N. Distributed or centralised energy-from-waste policy? Implications of technology and scale at municipal level. Energy Policy 2007;35:2622–34.
[23] Murphy JD, McKeogh E. Technical, economic and environmental analysis of energy production from municipal solid waste. Renewable Energy 2004;29:1043–57.
[24] Luoranen M, Horttanainen M. Feasibility of energy recovery from municipal solid waste in an integrated municipal energy supply and waste management system. Waste Management & Research 2007;25:426–39.
[25] Dornburg V, Faaij APC. Optimising waste treatment systems: part B: analyses and scenarios for The Netherlands. Resources, Conservation and Recycling 2006;48:227–48.
[26] Winkler J, Bilitewski B. Comparative evaluation of life cycle assessment models for solid waste management. Waste Management 2007;27:1021–31.
[27] Villanueva A, Wenzel H. Paper waste – recycling, incineration or landfilling? A review of existing life cycle assessments. Waste Management 2007;27:S29–46.
[28] Luoranen M, Soukka R, Denafas G, Horttanainen M. Comparison of energy and material recovery of household waste management from the environmental point of view – case Kaunas, Lithuania. Applied Thermal Engineering 2009;29:938–44.
[29] Ljunggren Soderman M. Recovering energy from waste in Sweden – a systems engineering study. Resources, Conservation and Recycling 2003;38:89–121.
[30] Cosmi C, Cuomo V, Macchiato M, Mangiamele L, Masi S, Salvia M. Waste management modeling by MARKAL model: a case study for Basilicata Region. Environmental Modeling & Assessment 2000;5:19–27.
[31] Holmgren K, Henning D. Comparison between material and energy recovery of municipal waste from an energy perspective – a study of two Swedish municipalities. Resources Conservation and Recycling 2004;43:51–73.
[32] Salvia M, Cosmi C, Macchiato M, Mangiamele L. Waste management system optimisation for Southern Italy with MARKAL model. Resources, Conservation and Recycling 2002;34:91–106.
[33] Sahlin J, Knutsson D, Ekvall T. Effects of planned expansion of waste incineration in the Swedish district heating systems. Resources, Conservation and Recycling 2004;41:279–92.
[34] Knutsson D, Sahlin J, Werner S, Ekvall T, Ahlgren EO. HEATSPOT – a simulation tool for national district heating analyses. Energy 2006;31:278–93.
[35] Münster M, Lund H. Use of waste for heat, electricity and transport – challenges when performing energy system analysis. Energy 2009;34:636–44.
[36] Münster M. Energy systems analysis of waste to energy technologies by use of EnergyPLAN. R1667(EN). Risoe, Denmark: Risoe DTU. Available from: http://130.226.56.153/rispubl/reports/ris-r-1667.pdf; 2008.
[37] Münster M, Lund H. Comparing Waste-to-Energy technologies by applying energy system analysis. Waste Management 2010;30:1251–63.

[38] Ravn H. Balmorel: a model for analyses of the electricity and CHP markets in the Baltic Sea region. Denmark: ElkraftSystem. Available from: http://balmorel.com/; 2001.
[39] Mathiesen BV, Münster M, Fruergaard T. Uncertainties related to the identification of the marginal energy technology in consequential life cycle assessments. Journal of Cleaner Production 2009;17:1331–8.
[40] Münster M, Meibom P. Long-term affected energy production of waste to energy technologies identified by use of energy system analysis. Waste Management 2010;30:2510–9.
[41] Karlsson K, Meibom P. Optimal investment paths for future renewable based energy systems – using the optimisation model Balmorel. International Journal of Hydrogen Energy 2008;33:1777–87.
[42] Ball M, Wietschel M, Rentz O. Integration of a hydrogen economy into the German energy system: an optimising modelling approach. International Journal of Hydrogen Energy 2007;32:1355–68.
[43] EA Energy Analysis. Efficient district heating in the future energy system – final report [(Effektiv fjernvarme i fremtidens energisystem - Slutrapport)] (In Danish). Copenhagen, Denmark: EA Energy Analysis. Available from: http://www.ea-energianalyse.dk/reports/625_Effektiv_fjernvarme.pdf; 2009.
[44] AV Miljø; KARA, L90. Prices of temporary waste storage. Personal communication; 2009.
[45] Danish Energy Authority. Energy Statistics 2004. Copenhagen: Danish Ministry of Transport and Energy; 2005.
[46] Møller J, Fruergaard T, Riber C, Astrup T, Christensen TH. Environmental assessment of waste incineration and alternatives. Lyngby, Denmark: DTU Environment; 2008 [In Danish].
47] Fruergaard T. Assessment of waste resources for energy production – fractions, quantities, segregation potentials and energy content. Lyngby, DK: Danish Technical University, Department of Environmental Engineering; 2008.
[48] Danish Energy Agency. Biomass resourcer (Biomass resources). Copenhagen, Denmark: Danish Energy Agency; 2006.
[49] Christensen TH, Hansen TL, Kirkerby JT, Jansen JlC, Svärd Å, Toudal JK, et al (In Danish). Basisdokumentation af biogaspotentialet i organisk dagrenovation [(Base documentation for the biogas potential in organic municipal waste)], vol. 802. Copehagen, Denmark: Danish Environmental Protection Agency. Available from:, http://www.mst.dk; 2003.
[50] Danish Energy Authority. ElkraftSystem, Eltra. Technology data for electricity and heat generating plants. Copenhagen: Danish Energy Authority; 2005.
[51] DONG Energy. REnescience. Personal communication. Skærbæk, Denmark; 2007.
[52] Rostrup-Nielsen T, Nielsen PEH, Joensen F, Madsen J. Polygeneration – integration of gasoline synthesis and IGCC power production using Topsoe's TIGAS process. Energy solutions for sustainable development. Proceedings 2007;Risø-R-1608(EN).
[53] Eucar, Concawe, Joint Research Centre of the EU Commission. Well-to-wheels analysis of future automotive fuels and power trains in the European context – well-to-wheels report version 2c: Joint Research Centre of the EU Commission; 2007. Available from: http://ies.jrc.ec.europa.eu/uploads/media/WTW_Report_010307.pdf.
[54] Ahrenfeldt J, Bain RL, Beld BVD. Handbook biomass gasification BTG biomass technology group BV; 2005.
[55] Danish Energy Authority. Energiproducenttælling 2006 (Energy Producer Statistics 2006); 2008 (Not publicly available).
[56] IEA. Tackling investment challenges in power generation in IEA countries. Online bookshop: OECD/IEA. Available from: http://www.iea.org/w/bookshop/add.aspx?id=321; 2007.
[57] Marcus-Møller C. Surplus heat from AGA with transcritical CO_2 heat pump; 2008.
[58] Ellehauge K, Pedersen TE. Solar heat storages in district heating networks. Energinet.dk project no. 2006-2-6750: ieea EC. Available from: http://www.iee-library.eu/images/all_ieelibrary_docs/preheat_solar-heat-storage_district-heat-netwks.pdf; 2007.
[59] Danish Energy Authority. Perspektiver for den danske varmeforsyning frem mod 2025-Teknisk Baggrundsrapport til Energistrategi 2025 [(Perspectives for the Danish heat supply towards 2025-Technical background report for the Energy Strategy 2025)] (In Danish). Copenhagen, Denmark: Danish Energy Authority. Available from:, http://130.226.56.153/rispubl/NEI/nei-dk-4484.pdf; 2005. Available from: http://193.88.185.141/Graphics/Publikationer/Energipolitik/Perspektiver_for_den_danske_varmefors.pdf; 2005.
[60] Danish Technological Institute. Economy of heatpumps (In Danish). Danish Technological Institute. Available from: http://www.varmepumpeinfo.dk/18578; 2009.
[61] Danish Energy Authority. Guidelines in socio-economic analysis in the field of energy. Copenhagen: Danish Energy Authority. Available from: http://www.ens.dk/graphics/Publikationer/Energipolitik/Beregningsforudsaetninger_Maj_samlet.pdf; 2009.
[62] Danish Energy Authority. Basisfremskrivning af Danmarks Energiforbrug frem til 2025 [(Forecast of the Danish energy supply until 2025)] (In Danish). Available from: Copenhagen, Denmark: Danish Energy Authority http://www.ens.dk/graphics/Publikationer/Energipolitik/basisfremskrivning_2008/index.htm; 2008.
[63] Kofoed-Wiuff A, Werling J, Markussen P, Behrmann M, Pedersen J, Karlsson K. The future Danish energy system – technology scenarios. 2007/2. Copenhagen, Denmark: The Danish Board of Technology. Available from: http://www.tekno.dk/pdf/projekter/STOA-Energy/p07_The_Future_Danish_Energy_System.pdf; 2007.
[64] Papageorgi A. Statistics and prospects for the European electricity sector. 2006-030-1086. Bruxelles, Belgium: Eurelectric; 2006.
[65] Danish Energy Authority. Basisfremskrivningen til CO_2-kvotealloker-ingsplanen for 2008-12 og regeringens energistrategi: En visionær dansk energipolitik [(Base Forecast for the CO_2-quota Allocation Plan for 2008-12 and the energy Strategy: a Visionary Danish energy policy)]. Copenhagen, Denmark: Danish Energy Authority; 2007 [In Danish].
[66] Kiviluoma J, Meibom P. Influence of wind power, plug-in electric vehicles, and heat storages on power system investments. Energy – the International Journal; 2009.
[67] Danish Energy Authority. Energy statistics 2006. Copenhagen: Danish Energy Authority. Available from: http://www.ens.dk/graphics/Publikationer/Statistik/Energistatistik%20_2006_t_internet.pdf; 2007.
[68] Wiesenthal T, Mourelatou A, Petersen J-E, Taylor P. How much bioenergy can Europe produce without harming the environment. No 7/2006. Copenhagen, Denmark: European Environment Agency; 2006.
[69] Resch G. Database on potentials and costs for RES-E. Vienna, Austria: Energy Economics Group (EEG), Vienna University of Technology. Available from: http://www.green-x.at/; 2009.
[70] Fornybar.no. Bioenergiressurser i Norge. Norway: Fornybar.no. Available from: http://www.fornybar.no/imagecache/43.OriginalImageData.20070320085549.jpg; 2009.
[71] Statistics Norway. Avfallsregnskap for Norge [(Waste accounts for Norway)]. Statistics Norway; 2008.
[72] Eucar, Concawe, Joint Research Centre of the EU Commission. Well-To-Wheels Analysis Of Future Automotive Fuels And Powertrains In The European Context – WELL-TO-TANK Report Version 3.0. Description and detailed energy and GHG balance of individual pathways: Joint Research Centre of the EU Commission; 2008. Available from: http://ies.jrc.ec.europa.eu/uploads/media/WTT%20App%202%20v30%20181108.pdf.
[73] Danish Energy Authority. Guidelines in socio-economic analysis in the field of energy. Copenhagen: Danish Energy Authority. Available from: http://www.ens.dk/graphics/Energipolitik/dansk_energipolitik/oekonomiske_analyser/vejledning_110405/Beregningsforudsaetninger_08_final.pdf; 2008.
[74] RenoSam. Still more efficient waste treatment – benchmarking 2006 [Stadig mere effektiv affaldsbehandling (In Danish)]. Available from: http://www.renosam.dk/media/filebank/org/RenoSam_Benchmarking_2006.pdf; 2006.