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Energy Systems Analysis of Waste to Energy Technologies by use of EnergyPLAN

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Risø DTU
National Laboratory for Sustainable Energy

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Abstract (max. 2000 char.):
Even when policies of waste prevention, re-use and recycling are prioritised, a fraction of waste will still be left which can be used for energy recovery. This report asks the question: How to utilise waste for energy in the best way seen from an energy system perspective? Eight different Waste-to-Energy technologies are compared with a focus on fuel efficiency, CO_2 reductions and costs. The comparison is made by conducting detailed energy system analyses of the present system as well as a potential future Danish energy system with a large share of combined heat and power and wind power. The study shows the potential of using waste for the production of transport fuels such as upgraded biogas and petrol made from syngas. Biogas and thermal gasification technologies are interesting alternatives to waste incineration and it is recommended to support the use of biogas based on manure and organic waste. It is also recommended to support research into gasification of waste without the addition of coal and biomass. Together, the two solutions may contribute to an alternate use of one third of the waste which is currently incinerated. The remaining fractions should still be incinerated with priority given to combined heat and power plants with high electrical efficiencies.

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Preface

This report forms part of the documentation of the research project "ENSUWE – Environmentally Sustainable Utilization of Waste resources for Energy production". The project is funded by the Danish Research Agency's programme for strategic funding within sustainable energy administered by the Danish Technical Research Council (STVF).

The report also forms part of the documentation of the PhD project of the author, entitled "Energy System Analysis of Waste Utilisation for Energy Production".

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April 2009

Contents

1 Introduction

In Denmark, 24% of the waste produced in 2005 was incinerated for heat and power production; 67% was recycled and only 8% land filled [3]. In 2006, waste supplied fuel for 5% of the Danish electricity production and 23% of the heat production[4].

In the EU, a waste hierarchy exists in which recycling is preferred to incineration, which is again preferred to landfill. This hierarchy should be kept unless a life cycle assessment (LCA) shows that other solutions would be preferable in concrete cases. In the EU, municipal waste is, at present, disposed of through landfill (49%), incineration (18%), and recycling and composting (33%) [5]. The EU has, however, introduced aims which significantly reduce the amounts of biodegradable waste to be landfilled. According to these aims, the amount of biodegradable waste deposited at landfills in 2014 must not exceed 35% of the amount of biodegradable waste produced in 1995 [6]. Consequently, at the EU level, great efforts are put into finding alternatives to landfill for biodegradable waste.

In January 2007, the Danish Government presented its vision for the Danish energy system towards 2025. According to the vision, the aim is to reach a level of 30% of energy consumption supplied by means of renewable energy in 2025, compared to 14% today, and to reach a share of 10% biofuel in the transport sector in 2020 [7]. Comparisons with similar European aims show a potential general increase in the level of renewable energy in the EU, from less than 7% today to 20% by 2020, and a minimum biofuels share of 10% by 2020 [8]. The utilisation of waste for energy can contribute to achieving these goals.

Furthermore, several trends make it interesting to use waste resources in a different manner:

- Waste amounts are increasing all over Europe. Recent analyses anticipate the amount of waste generated in Denmark to increase in the future. In these analyses, incinerable waste is projected to rise by 30% up to year 2020 and food and wood waste each by 40%. [9;10]
- The Danish waste incineration capacity is becoming insufficient for the growing amounts.
- The energy system needs flexibility to integrate more wind power.
- The demand for transport continues to increase [11]. As the transport sector is currently based on fossil fuels, CO_2 emissions from the sector continue to increase. This may be reduced by producing transport fuels from waste.
- A new building code makes it mandatory to reduce the energy consumption in houses, which may result in an overall decrease in the demand for heat [12]. Already at present, waste incineration

plants have insufficient heat markets and periodically need to cool off heat.

New technologies make it possible to utilise organic waste in a new way to achieve higher power efficiencies, to store energy or to produce fuels for transport. Technologies of interest include 2nd generation biofuel production, gasification/pyrolysis, anaerobic digestion and improved incineration. In a system perspective, the new technologies have potential benefits, such as the possibilities of regulating the production of electricity, heat and transport fuels and thereby increasing the flexibility of the system. It is, therefore, important to perform Energy System Analysis (ESA) as opposed to analysing the technologies at an individual level. Previously, energy system analyses have been made of various technologies, focusing on their ability to balance electricity supply and demand; but such studies have not included the potential contribution of waste technologies[13-19].

Particularly in societies with a large combined heat and power (CHP) production, in which electricity production is connected to heat demand, and with a large share of fluctuating energy sources, such as wind power, it is important to ensure that the production meets the demand at any given time. In order to analyse this, a dynamic model of the energy production and consumption must be made with hour-by-hour representation over a year. As CHP waste incineration is constant and produces a high percentage of heat, it may be interesting to look at more flexible alternatives which may facilitate integration of a larger share of wind power.

Environmental issues are in general analysed with a different focus than energy resource issues. The prioritisation between waste treatment options can be facilitated by a wide range of tools with different focus on economic and environmental impacts as well as impacts on society [20-22].

Energy system analysis (ESA) is used to assess the impact of particularly changes in energy production on e.g. national energy systems. This is an aspect which other assessment methods fail to address substantially. ESA focuses on one step of the life cycle (energy conversion), with simulation of all the interacting energy technologies, The cheapest energy production seen from the point of view of energy producers (including taxes) or society (excluding taxes) is found based on investment costs, operation and maintenance costs and fuel costs. CO_2 quota costs are often included, but further externalities are often omitted. The focus on environment is normally limited to CO_2 emissions and possibly also methane, sulphur and NOxes.

Table 1 shows the different focuses and approaches when performing LCA or ESA.

Table 1 Focuses and approaches when performing LCA or ESA

Life Cycle Assessment	Energy System Analysis
Functional unit: waste treatment	Functional unit: energy demand
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
Many types of emissions	CO_2 emissions
Allocation of environmental impacts according to energy quality or energy content/ use of one marginal energy-producing technology	Impacts on the whole energy system affect several marginal technologies and fuels
Current/ historical data	Current situation and future scenarios
Static model	Dynamic model
Results: - Environmental impacts (local and global)	Results: - Use of fuels - Percentage of renewable energy - Costs - CO_2 emissions from energy conversion

The results of ESA's can be used directly to prioritise between technologies according to an energy system perspective focusing on e.g. costs, fuel efficiency or percentage of renewable energy. CO_2 emissions from energy conversion represent the major part of the impact on global warming and ESA can hence be used as a parameter for decision-making seen from a climate perspective. The results can also be fed into LCA's if it is wished to prioritise from a broader and more detailed environmental perspective including the remaining parts of the life cycle. Assumptions regarding energy production is in many cases decisive for the outcome of the LCA's as shown by Ekvall [23] and more recently in an article regarding marginal energy production by Mathiesen, Münster and Fruergaard [24]. Furthermore, ESA can also contribute with results to other types of analysis focusing more on economy or the societal effects, such as cost benefit analysis (CBA) or multi criteria decision analysis (MCDA) [20].

Up to now a range of CBA's have been performed, particularly comparing incineration with landfilling [25-27]. A large number of LCA's have also been performed on waste management options [28-33]. and in the European Thematic Strategy on prevention and recycling of waste greater emphasis is now placed on life cycle thinking when evaluating waste management options [5]. In order to include the aspect of flexibility when prioritising between different WtE technologies it is, however, necessary to use a model which simulates the dynamic properties of the energy system. This is possible when conducting ESA in hourly simulations. Some ESA models operate without hour-by-hour simulations and use for example load duration curves instead or other simplifications with regard to distribution in time [34-39]. This, however, does not make it possible to include the benefits of increased flexibility in the system analysis.

In most of the different types of analyses presented above, waste incineration is compared with non-energy waste treatment [25;34;36-40] or with other fuel alternatives [31]. The analyses show that, from a general environmental point of view, incineration is better than disposal at landfills, but worse than recycling. However, although inconsistencies exist in the CBA's resulting in differing conclusions, in general the studies conclude that incineration is more costly than landfilling [25;26]. Furthermore, in some cases and for some waste fractions incineration may be preferred to recycling [36;39]. When incineration is compared with other WtE alternatives, the most common alternative is the production of biogas, as shown in a number of LCAs [28;30;33]. Here, the conclusions are unclear. Under some circumstances, the environmental consequences of biogas production used for CHP are comparable to those related to incineration [28;33] but combined with dedicated residual derived fuel (RDF) combustion, biogas production may have lower environmental impact [30].

The existing analyses have not encompassed the influence of increased flexibility in energy systems with large shares of wind power. Furthermore, the WtE technologies have not been analysed in the context of future energy systems. Finally, few technologies are compared and only established technologies. In order to assess if it is feasible to prioritise research, development and demonstration of new technologies such as waste gasification or waste-to-biofuel technologies, it is however important to analyse the technologies although data regarding costs and efficiencies may be less certain.

In this article, ESA with hour-by-hour simulations of energy demands, fluctuating renewable energy sources and fluctuating electricity prices is used to compare a number of technological alternatives using waste for energy production. In 2008 Münster and Lund performed another energy system analysis of WtE technologies [41], but with fewer technologies, without trade of electricity with neighbouring countries, and only in the current energy system with less wind power. Encompassing these features facilitates an explorative approach as defined by Borjeson et. al. [42] as opposed to the more normative approach of the former article. The result of this study showed that the largest CO_2 reduction was found with a manure-based biogas CHP alternative and the cheapest CO_2 reduction was achieved with a syngas transport alternative including co-gasification with coal. The results in the present article conclude that this alternative is feasible only if the co-gasification is omitted. This change in results is due to the improvements which have been added to the ESA model used. These improvements are described in the methodology section.

It is important to ensure that the characteristics of the new technologies are represented in the Energy System Analysis model, so that potential benefits, such as flexibility and multiple outputs are illustrated, and restrictions, for instance on storage, are taken into account.

The question arises:

- How can the Danish waste resource which cannot be recycled be utilised optimally for energy production in the current and potential future energy systems?

This report presents energy system analyses of a range of different Waste-to-Energy technologies performed by use of the EnergyPLAN model. In order to assess whether the technologies in question will function as planned or will obstruct the development of a desired future, they are analysed both in the current energy system as well as in a future energy system with 100% renewable energy. Hereby it becomes possible to recommend actions with regards to research in technologies. Positive results may also indicate that investments in infrastructure and built up of expertise will not be in vain. Furthermore, full CO_2 reduction potentials of the various technologies are established by applying the full resource potentials of today.

In Chapter 2 Waste Conversion Technologies, an overview is given of the range of technologies available and of the specific technologies chosen for the analyses. In Chapter 3 Model description, the energy system analysis model, EnergyPLAN, is briefly presented along with the alterations made to the model.

In Chapter 4 Scenarios, data used for the reference energy systems for 2006 and 2050 are described, and in Chapter 5, results of the energy system analyses are presented. In Chapter 6, the sensitivity analyses are presented and, finally, in Chapter 7, conclusions and recommendations are made.

2 Waste Conversion Technologies

In this Chapter, an overview is given of the range of technologies available or under development and of the specific technologies chosen for the analyses.

Using waste to produce e.g. transport fuel instead of combined heat and power (CHP) may imply a loss of energy efficiency at the plant level, but it may in turn increase the flexibility and thus facilitate an increased efficiency of the overall energy system.

To be able to analyse the effect of implementing these technologies into the national energy system, it is necessary to illustrate to which extent the technologies in question can contribute to an efficient and flexible energy system. Efficiencies, storage potential and flexibility with regard to producing electricity, heat or transport fuel are some of the features which are described.

Concrete examples of technologies will be 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)
- The technologies represent innovative Danish demonstration projects

2.1 Conversion Processes

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 and an environmental perspective.

Biomass conversion can be divided into thermo-chemical, bio-chemical and chemical processes, as illustrated in Figure 1 and Figure 2. The general processes and the specific technologies chosen are further described in the following sections.

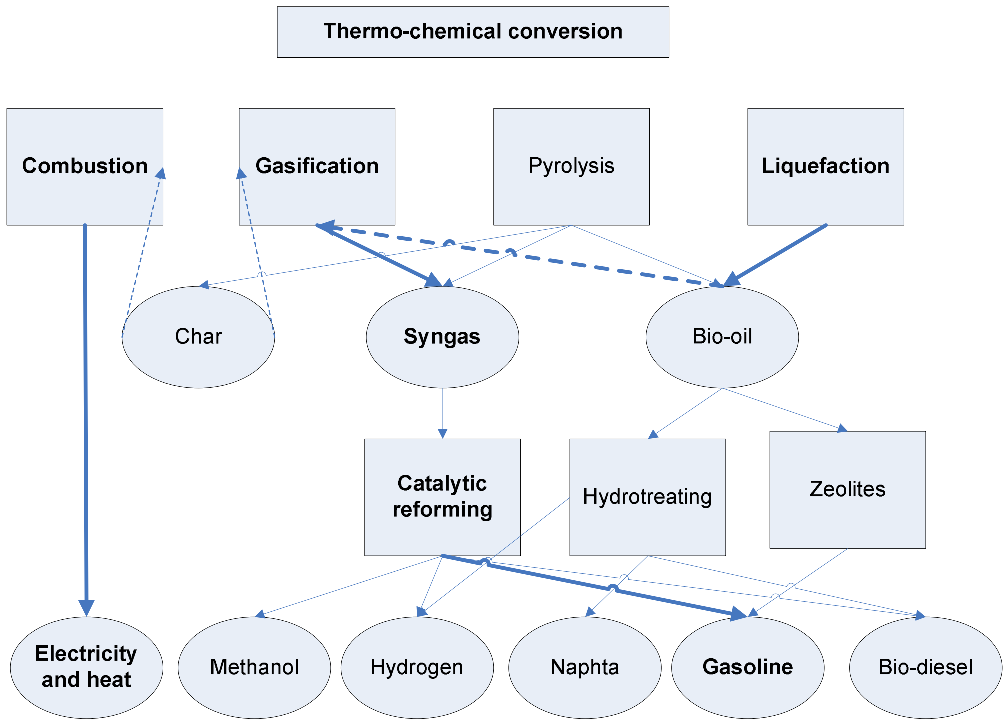


Figure 1 Thermo-chemical biomass conversion technologies

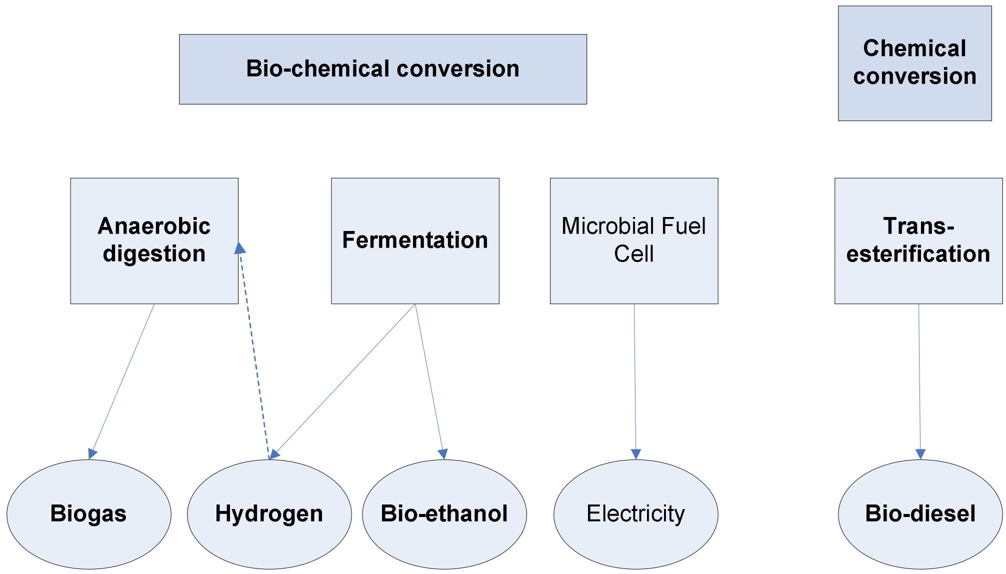


Figure 2 Bio-chemical and chemical biomass conversion processes

The technologies marked in bold in the figures above are chosen for the analysis as they represent a broad range of potential biomass conversion technologies. Furthermore, these technologies are considered to represent the various potential advantages and disadvantages of Waste-to-Energy conversion technologies seen from an energy system perspective. The technologies chosen are listed with their outputs in Table 2 below.

Table 2 Waste-to-Energy technologies

	WtE Technologies	DH area
Waste Incineration	CHP waste incineration with efficiencies of a new waste incineration plant. The technology is commercial. The waste fraction must be used continuously.	Central
Co-combustion	Residual derived fuel (RDF) is co-combusted with coal in a coal-fired power plant. The technology is at full-scale demonstration stage. RDF can be stored.	Central
Dedicated RDF	RDF is burnt in a dedicated CHP plant. The technology is commercial.	Central
Biogas CHP	Biogas from anaerobic digestion of organic household waste is used for CHP. The waste fraction must be used continuously. The fibre fraction from the manure is burnt in a CHP plant. The technology is commercial.	Decentralised
Biogas CHP+	As above, but it is assumed that the use of organic household waste facilitates the use of manure.	Decentralised
Biogas Transport	Biogas from anaerobic digestion of organic household waste is upgraded and used for transport in natural gas vehicles. The fibre fraction from the manure is burnt in a CHP plant. The technology is commercial.	Decentralised
Biogas Transport+	As above, but it is assumed that the use of organic household waste facilitates the use of manure.	Decentralised
Syngas	Municipal waste is liquidised and undergoes thermal gasification. The resulting syngas can be converted to biopetrol or used for CHP. The technology is at developmental stage. The waste fraction must be used continuously.	Central
Syngas+	As above, but it is assumed that the gasification of waste requires the co-gasification of coal in an entrained flow gasifier (75% of energy.	Central
Biodiesel	Animal fat, formerly used for industrial heat production, is converted to biodiesel in a trans-esterification process. The animal fat can be stored. The technology is commercial.	Decentralised
Bioethanol	Straw, grass and paper waste first undergoes pre-treatment and hydrolysis. Secondly, bioethanol is produced for transport through fermentation and thirdly biogas is produced through anaerobic digestion along with biofuel and hydrogen and used for CHP. The waste fractions can be stored. The technology is at developmental stage.	Decentralised

All technologies are commercial apart from Syngas and Bio-ethanol, which are still at the developmental stage and only being implemented at pilot plants or in demonstration plants. Data regarding these technologies are therefore the most uncertain and consequently sensitivity analyses have been performed for them on both efficiencies and investment costs.

It is chosen to include immature technologies as the technologies show great perspective in terms of conversion of waste to transport fuel, overall efficiency and flexibility. The specific technology design illustrates Danish projects, but similar projects are being developed worldwide. As predictions regarding efficiencies and investments costs tend to be optimistic for technologies under development the recommendations regarding these technologies can only be either 1) not to support further research in case the technologies are not competitive with current well proven technologies or 2) in case the results are positive, then to further investigate the matter and support further research in the technology.

As mentioned earlier, 24% of the waste collected in Denmark is incinerated for heat and power production. Waste combustion or incineration hence represents the reference case against which alternatives are tested. Co-combustion is an alternative which is discussed intensively in Denmark and which may become an important solution in the future. A dedicated RDF uses the same waste fraction and has the same storage advantage as co-combustion, but has a lower electrical efficiency.

Gasification of biomass is a technology which is gaining momentum in waste treatment around the world [43]. Pyrolysis is not analysed, since the technology is comparable to gasification, seen from a system perspective.

Trans-esterification of animal waste into bio-diesel is assessed to have a potential of around 5% of the current Danish diesel demand [2]. As this is considered to be an important contribution, the technology is analysed further.

Only a small percentage of the resources available for biogas production are used today. In recent studies, the technology is estimated to be able to deliver 16% of the electricity production, as compared to the current 0.8 % [44]. Furthermore, the technology is of great interest at the governmental level in relation to the coming national energy plan.

Second generation bio-ethanol production is considered to be a significant contributor to the reduction of the CO_2 emissions of the transport sector in the future. This production has no negative effects on food production as the technology relies on waste resources [45].

Microbial fuel cells are not analysed due to the fact that the technology is still at a very experimental stage and far from being competitive.

2.2 Thermo-chemical conversion

The thermo-chemical processes can be divided into combustion, gasification, pyrolysis and liquefaction, as illustrated in Figure 1. Differences in the processes and the outputs are shown in Table 3.

Table 3 Thermo-chemical processes [46]

	Process	Product
Combustion	Conversion of the intrinsic chemical energy in carbon with full oxidation	Hot gases at 800-1000ºC, which can be used to produce electricity and/or heat
Gasification	Partial oxidation which occurs at high temperatures (800-900ºC)	Syngas, mainly consisting of CO and H2
Pyrolysis	Conversion of biomass in the absence of air at temperatures of around 500ºC (carbonization or flash pyrolysis)	Syngas, bio-oil or char
Liquefaction	Conversion of biomass into short chain petroleum hydrocarbons in a wet environment at high pressure (hydrothermal) or using low temperature and high hydrogen pressure.	Bio-oil

In the following sections, an overview of combustion and gasification technologies is given together with data for the specific technologies chosen for the analysis.

2.2.1 Combustion

Combustion occurs at high temperatures and, for the flue gas from waste, it is necessary to ensure temperatures of at least 850 ºC for a minimum of 2 seconds to enable the breakdown of organic toxins [47]. The higher the temperature, the higher the electricity output, but too high temperatures in the boilers will cause corrosion.

Three combustion processes are chosen for the analysis:

- State-of-the-art Waste Incineration
- Co-combustion of coal and waste
- Dedicated residual derived fuel (RDF) plant

State-of-the-Art Waste Incineration

The combustion of waste is normally referred to as waste incineration. The Danish "Technology Data for Electricity and Heat Generating Plants" from 2005 [1] is used for data on incineration (See Table 4). Waste burnt in the incineration plants is assumed to have an average lower heating value (LHV) of 10.5 MJ/kg [48].

A recent research project has shown that the existing Danish waste incineration plants have a great potential for down-regulating the electricity production [49]. As waste incineration currently serves as base load which is a drawback to achieving a flexible system, the use of incineration plants for regulation is an interesting alternative. Downward regulation may be relevant if the heat demand is high and a surplus of electricity is created, e.g. due to a high wind power production.

It is estimated that up to 75% of the steam production can be by-passed and used for increased heat production. This adds up to 200 MW of downward regulation capacity, which is currently available in Denmark. Tests show the possibility of downgrading from 21 MW to 7 MW during only 120 seconds. Down and upward regulation must take place within 10-15 minutes, and typically lasts for a period between 45 minutes and 2 hours. The main potential is to be found in the period from October to May. The idea is that the incineration plants, through agreements, make available a certain amount of downward regulation capacity. The incineration plants will, however, not be competitive in the regulating power market, since compensation for actual downward regulation is costly as the waste still has to be burnt. [49]

In a normal week at an incineration plant, the waste is delivered by trucks during weekdays and the waste silo is filled. Some waste may come during the weekend from the municipal recycling centres, but basically, most of the waste which is accumulated during the week is burnt during the weekend. Most of the time, the plants are running at full load day and night all year round and heat is cooled off if excess heat is produced, as may be the case in summertime. Temporary storage is allowed for fractions which do not develop heat. The possibility of temporary storage has primarily been used for periods with a lack of incineration capacity or e.g. when lines have to be taken out for refurbishment. [50]

At the incineration plant, KARA, by Roskilde, 196.000 t of waste was incinerated in 2006. Of these, 15.000 t had been temporarily stored [51]. The temporarily stored waste mainly consists of combustible waste from industries or from waste handling stations. The waste primarily consists of plastic, some cardboard and small pieces of wood. The lower heating value is quite high (around 12-13 MJ/kg). The average heating value of waste incinerated at KARA is 10.6 – 10.7 MJ/kg. 60% of the waste at KARA is industrial waste and 40% comes from households (LHV 9 MJ/kg). The temporary storage is used when the main incineration line is taken out for service once a year during 3-8 weeks. The temporarily stored waste is subsequently burnt as fast as possible. Using the temporary storage is costly due to extra transport needs and the compression of the waste at the waste deposit. Combined with the fact that KARA normally has a sufficient heat market all year round, being as they are connected to the main district heating network of Copenhagen, VEKS, the temporary storage is used as little as possible. [52]

At the incineration plant, REFA, by Nykøbing Falster, 114.000 t of waste was incinerated in 2006 [53]. Around 10-15.000 t of the fraction of "large combustible" waste is temporarily stored each year. The waste fraction has to be brought to the deposit to be crushed and the temporary storage at the site will therefore generate a limited amount of extra costs of around 140 DKK/t. REFA has a limited heat market and, for some years, the CHP plant has had excess incineration capacity. The temporary storage has, therefore, been used during summertime, in which the incineration plant has run at part load. During the cold months of October/November to May, the plant has previously run at full load and burnt the temporarily stored waste. Currently, the plant is running at full load all year round. In 2006, 23% of the heat was cooled off [53]. This was both due to the increase in waste used for incineration, but in particular, to the fact that 2006 was an extremely warm year. By comparison, in 2004, only 13% of the heat produced was cooled off [53]. [54]

In the future, efficiencies are expected to increase to 29% electrical efficiency and 78% heat efficiency, assuming flue gas condensation and low temperature district heating [55].

Table 4. Waste incineration [1]

Technology	Waste to energy CHP plant			
	2004	2010-15	2020-30	Ref
Energy/technical data				
Waste treatment capacity (tonnes/h)	15	15	15	1
Thermal input (MW)	50.0	50.0	50.0	1
Own consumption (MW-e)	1.5	1.5	1.5	1
Generating capacity for one unit (MW-e), gross	11.3	13.5	14.5	1
Generating capacity for one unit (MW-e), net	9.8	12.0	13.0	1
Total efficiency (%) gross	87.9	98 A	100 A	1
Total efficiency (%) net	84.9	95 A	97 A	1
Electricity efficiency (%) gross - 100% load	22.5	26.9	29	1
Electricity efficiency (%) net - 100% load	19.5	23.9	26	1
75% load	19.5	23.9	26	1
50% load	n.a.	n.a.	n.a.	1
Start-up fuel consumption (GJ)	1080	1080	1080	1
Time for varm start-up (hours)	12	12	12	1
Cb coefficient	0.30	0.34	0.37	1
Cv coefficient (40°C/80°C)	n.a.	n.a.	n.a.	1
(50°C/100°C)	n.a.	n.a.	n.a.	1
Forced outage (%)	2	1	1	1
Planned outage (weeks per year)	3	3	3	1
Technical lifetime (years)	20	20	20	1
Construction time (years)	3	3	3	1
Environment (Fuel: Waste, 12 MJ/kg, 0.4%S)				
SO_2 (kg per GJ fuel)	0.027	0.014	0.011	1
SO_2 (degree of desulphurisation, %)	95.9	98.0	98.4	1
NO_X (kg per GJ fuel), note C	0.109	0.082	0.011	1
CH_4 (kg per GJ fuel)	~ 0	~ 0	~ 0	1
N_2O (kg per GJ fuel)	~ 0	~ 0	~ 0	1
Particles (mg per GJ fuel)	5500	2700	1100	1
Ashes (kg per GJ fuel), bottom ash	14	12	11	1
Other residuals (kg per GJ fuel)	1	1	1	1
Financial data				
Specific investment (M€/MW-e), note B	6.8	5.5	5.1	1
Fixed O&M (€/MW/year), note B	272,000	222,000	204,000	1
Variable O&M (€/MWh), note B	25	21	19	1
Regulation ability				
Fast reserve (MW per 15 minutes)	n.a.	n.a.	n.a.	1
Regulation speed (MW per sec.)	n.a.	n.a.	n.a.	1
Minimum load (% of full load)	75	75	75	1

References:

1 Rambøll Danmark, 2004

Remarks:

A With flue gas condensation
B Energy reference is net electrity production.
Total costs are included, including the ones relating to waste treatment and heat production
C NOx emissions are foreseen to be controlled by the SNCR process until 2015,
and in 2020-30 application of the SCR-process is foreseen.

Co-combustion of coal and waste

Co-firing waste with coal is currently considered an interesting alternative. Benefits of this process may be an increased electrical efficiency, less need for expanding waste incineration capacity and more flexibility in the system. The main advantage for the coal-fired power plants may be to gain access to a fuel which is taxed as CO_2 neutral and which may have a negative cost. The taxes and refunds applied will be determining whether the concept will prove economically feasible for coal-fired power plants and for society.

The solution may, however, also have some drawbacks. When co-firing waste with coal, the waste of high energy value, such as plastic, may be moved from decentralised CHP plants to central plants. Here, less heat can be utilised and the total energy efficiency may hence decrease. Furthermore, the heating value of the waste burnt at the waste incineration plants may decrease. To some of the older plants, which are optimised to burn waste at low heating values (8-9 MJ/kg), this may be an advantage; but to the newer plants optimised to higher heating values (11-13 MJ/kg), this may constitute a problem as they already have difficulties in obtaining waste with a sufficiently high heating value. Finally, co-firing waste with coal may lead to increased emissions of heavy metals and dioxins, as no limit has currently been defined for the emission level of the coal-fired plants. Hence, these plants do not have the same flue gas cleaning equipment as the waste incineration plants. Consequently, the emissions from the waste can be diluted with emissions from coal, and may still meet the emission levels for waste incineration measured in mg/m3 flue gas. [56]

Efficiencies for 2006 are taken from the Green Accounts for the plant Studstrupværket [57]. Apart from that, data from the Technology Catalogue is used [1] (See Table 5).

Table 5. Coal-fired power plant [1]

Technology	Steam turbine, coal fired, advanced steam process			
	2004	2010-15	2020-30	Ref
Energy/technical data				
Generating capacity for one unit (MW)	400			
Total efficiency, back-pressure mode, net (%) (B)	93	93	93	1
Electricity efficiency, condensation mode, net (%)				
100% load	48.5	52.5	55	1
75% load	48	52	54.5	1
50% load	47	51	53.5	1
Cb coefficient (40°C/80°C) (50°C/100°C)	0.78	0.95	1.08	1
Cv coefficient (40°C/80°C) (50°C/100°C)	0.15	0.15	0.15	1
Availability (%)	91	91	91	2;2;3
Technical lifetime (years)	30	30	30	2;2;3
Construction time (years)	4.5	4.5	4.5	2;2;3
Environment (Fuel: hard coal, 1% sulphor content)				
SO_2 (kg per GJ fuel) (A)	0.03	0.03	0.03	2;2;3
SO_2 (degree of desulphoring, %) (A)	95-97	95-97	95-97	1
NO_X (kg per GJ fuel) (A)	0.04	0.04	0.04	2;2;3
Particles (mg per GJ fuel), (C)	3.600-18.000	3.600-18.000	3.600-18.000	2;2;3
Ashes (kg per GJ fuel)	4.0	4.0	4.0	2;2;3
Other residuals, gypsum (kg per GJ fuel)	2.30	2.30	2.30	2;2;3
Financial data				
Specific investment (M€/MW) (B)	1.1	1.2	1.2	1
Fixed O&M (€/MW/year)	16000	16000	16000	4
Variable O&M (€/MWh)	1.8	1.8	1.8	4
Regulation ability				
Fast reserve (MW per 15 minutes)				
Regulation speed (% per sec.)	4	4	4	1
Minimum load (% of full load)	20	20	20	1

References:

1 Elsam, November 2003
2 Elsam's and Elkraft's update of the Danish Energy Authority's 'Teknologidata for el- og varmeproduktionsanlæg', December 1997
3 Eltra, September 2003
4 Energi E2, October 2004

Remarks:

A The data for SO2 and NOx emissions assume flue gas desulphurisation (wet gypsum) and DeNOx equipment of the “high dust” SCR type.
B The cost excludes infrastructure, such as habour, district heating transmission, and electricity transmission. The unit cost refers to the capacity in full condensation mode.
C Calculated from from 10-50 mg/Nm³ assuming this interval refers to dry flue gas at 6% oxygen

Dedicated RDF plant

A dedicated RDF plant incinerates only RDF for CHP production. The plant has the same advantage as co-combustion plants with regard to the ability to store waste, but it has a lower electrical efficiency. Furthermore, dedicated RDF plants placed in district heating areas and connected to central plants are assumed to substitute the average plant in such an area. Hence, RDF plants substitute a range of fuels and not only coal, as may be the case with co-combustion.

The efficiencies and costs of a dedicated RDF plant are assumed to be similar to those of a straw-fired steam turbine, and the data presented in Table 6 is taken from the Technology Catalogue [1].

Table 6 Data for dedicated RDF plant [1]

Technology	Steam turbine, grate firing, straw combustion			
	2004	2010-15	2020-30	Ref
Energy/technical data				
Generating capacity for one unit (MW)	8 - 10			
Total efficiency (%) net	88 - 90	90	90	1
Electricity efficiency (%) net - 100% load	29 - 30	29 - 30	29 - 30	1
75% load	29 - 30	29 - 30	29 - 30	1
50% load				
Time for varm start-up (hours)	2			4
Cb (50°C/100°C)	0.5	0.5	0.5	
Availability (%)	91	91	91	2
Planned outage (weeks per year)				
Technical lifetime (years)	20	20	20	5
Construction time (years)	2 - 3	2 - 3	2 - 3	2
Environment (Fuel: straw; LHV 14.2 GJ/t; ashes 4%; sulphur 0.2%)				
SO_2 (kg per GJ fuel)	0.047			3
NO_X (kg per GJ fuel)	0.131	0.09		3;2
CH_4 (kg per GJ fuel)	< 0.0005			3
N_2O (kg per GJ fuel)	< 0.0014			3
Particles (mg per GJ fuel)	40	40	40	2
Ashes (kg per GJ fuel)	2-4	2-4	2-4	2
Financial data				
Specific investment (M€/MW) (A)	4.3-5.5	3.5-4.6	2.9-3.7	1
Total O&M (% of investment per year)	4	4	4	1
Fixed O&M (€/MW/year)				
Variable O&M (€/MWh)				
Regulation ability				
Fast reserve (MW per 15 minutes)				
Regulation speed (MW per second)				
Minimum load (% of full load)				

References:

1 Danish Energy Authority, September 2004
2 Elsam's and Elkraft's update of the Danish Energy Authority's 'Teknologidata for el- og varmeproduktionsanlæg', December 1997
3 Eltra PSO project 3141: "Kortlægning af emissionsfaktorer fra decentral kraftvarme", 2003
4 Danish Technology Institute: "Udvikling af computerbaseret værktøj, energyPRO, til simulering og optimering af driftsstrategi for biobrændselsfyrede kraftvarmeværker", September 2001
5 Elkraft System, October 2003

Remarks:

A A cost reduction of 2 % per year cost is assumed

Gas engine

For both the Bioethanol and the Biogas plants, a gas engine is needed to convert the gas into CHP.

Data for the gas engine (*Table 7*) is taken from the Technology Catalogue [1].

Table 7 Gas engine [1]

Technology	Spark ignition engine, natural gas			
	2004	2010-15	2020-30	Ref
Energy/technical data				
Generating capacity for one unit (MW)	1 - 5			
Total efficiency (%) net (D)	88 - 96	88 - 96	88 - 96	4
Electricity efficiency (%) net - 100% load	40 - 44	41-44	43-46	5
75% load	40 - 43			1
50% load	38 - 40			1
Cb (50°C/100°C)	0.9			
Availability (%) (A)	95	95	95	1+3
Technical lifetime (years) (B)	20 - 25	20 - 25	20 - 25	1+3
Construction time (years)	< 1	< 1	< 1	1
Environment (Fuel: Natural gas)				
NO_X (kg per GJ fuel)	0.17	0.08-0.2		2/3
CH_4 (kg per GJ fuel) (F)	0,26-0,58	0-0,26		2; 5
N_2O (kg per GJ fuel)	0.0013			2
Particles (mg per GJ fuel), (E)	0-3000	0-3000	0-3000	3
Ashes (kg per GJ fuel)				
Lubricating oil (kg per GJ fuel)	0.012			2
Financial data				
Specific investment (M€/MW)	0.8 - 1.2	0.8 - 1.2	0.8 - 1.2	1
Total O&M (€/MWh)	6-9	6-9	6-9	5
Fixed O&M (€/MW/year)				
Variable O&M (€/MWh)				
Regulation ability				
Fast reserve (MW per 15 minutes)	From cold to full load within 15 minutes			1
Regulation speed (MW per sec.)				
Minimum load (% of full load) (C)	50			1

References:

1 Danish Energy Authority, September 2003
2 Eltra PSO project 3141: "Kortlægning af emissionsfaktorer fra decentral kraftvarme", 2003
3 Elsam's and Elkraft's update of the Danish Energy Authority's 'Teknologidata for el- og varmeproduktionsanlæg', December 1997
4 Danish Association of District Heating Companies (DFF), December 2003
5 Danish Gas Technology Centre (DGC), September 2004

Remarks:

A Regular service typically every 1,000 hours. Extra service usually every 2,000, 5,000 and 10,000 hours. Major overhauls usually at 20,000 and 40,000 hours.
B Continual more rigorous environmental regulations offen shorten the practical lifetime.
C The minimum load can be lower, but this is usually not advisable due to lower efficiency
D May be higher than 100% (flue gas condensation), if hydrogen rich fuels are used.
E Calculated from from 0-10 mg/Nm³ assuming this interval refers to dry flue gas at 5% oxygen
F Mean values for open chamber and precombustion chamber technologies respectively.

2.2.2 Thermal Gasification

In several countries, such as the UK, thermal gasification of waste has been attempted with little success. However, recently, more attention is given to the solution and several new technologies are being developed.

Different types of technologies are available for gasification. Differences regarding demands to moisture content and particle size of the fuel as well as efficiencies and contents of tar and particulates in the gas are shown in Table 8.

Table 8. Gasification processes

Processes	Moisture	Particle size	Efficiency	Tar	Dust	Source
Fixed bed						
- Down-draft	<25%	5-50 mm	<90%	Very low	Moderate	[58]
- Up-draft	<50%	Dispensable	<75%	Very high	Moderate	[58]
Fluidized bed						
- Circulating	<50%	Up to 20 mm	75-80%	Low	High	[58]
- Bubbling				Low		[59]
Entrained flow	<10%	0.4-1.1 mm	81% [60]			[61]
Super critical water	>40%	Pulverized	72%	Medium*	Low*	[62]

Gasification plants have high investment costs and high potential efficiencies. The investment costs are highly dependent on the size of the plant, and measured in MW, the large plants are more cost-efficient than the smaller ones. A general problem related to the gasification of biomass is to ensure that sufficient biomass is available at a reasonable cost. This means that either biomass with a high energy content can be transported to the plant, given that the transport costs do not outweigh the benefits, or low energy biomass from a location near the plant can be used. One way to overcome this problem is to mix the biomass with fossil fuel, such as coal. Other problems are energy use during pre-treatment and the avoidance of corrosion. Currently no commercial energy plants exist which gasify waste alone.

Table 9. Examples of costs of gasification plants

Plant type	Fuel	Capacity	Investment cost (MEUR/PJ)	O&M costs, fixed	O&M costs, Variable (EUR/MWh)	Source
Two stage down-draft gasifier with gas engine	Biomass	0.1-0.6 MWel	340 (2004)	150000 (EUR/MW/ year)	15	[1]
Gasification + Fischer Tropsch (syn-diesel)	Black Liquor	9.6 PJ/a	33 (2010-20)	17.3 (EUR/ year)		[63]
Single stage entrained flow gasifier, IGCC	Coal	500 MWel	1.1 (2004)	43000 (EUR/MW/ year)		[64]

As can be seen, the differences in costs are enormous and depend on the type but, in particular, on the size of the plant.

REnescience

Gasification of waste has been attempted earlier with little success, e.g. in the UK. Today, only few projects attempt to gasify waste unless it comes from forestry or agriculture. In Denmark, a new research project named "Renewables, Science and renaissance of the energy system", in short "REnescience", utilises municipal solid waste for gasification. The purpose of the project is to develop and verify a technology for flexible and integrated production of electricity, heat and synthetic petrol through gasification of biomass/waste together with coal. [65]

The process is illustrated in Figure 3. Household waste will arrive to the pre-treatment plant unsorted. Then the waste will be liquefied by use of heat and enzymes and will be put through a sieve to sort out non-liquefied parts for incineration or reuse. Subsequently, the liquefied mass will be gasified. Two different gasification technologies will be tested: Gasification with coal in an entrained flow gasifier under high pressure (up to 400 bars) and high temperature (1700ºC) and supercritical wet gasification, which occurs in water under supercritical conditions.

The produced syngas will be used either for CHP production, when the electricity price is high (and the wind power production low), or for producing petrol, when the electricity price is low. Petrol will be produced in a catalytic process, which was originally developed for the conversion of natural gas under a constant flow. The process will now have to be adapted to the conversion of syngas with varying flows.

In order obtain economic feasibility of the plant, it is necessary to run the gasification unit full time. However, for the entrained flow gasifier, it may not always be necessary to add waste to the process. Most likely it can run on coal alone. The capacity of the entrained flow gasifier will be around 1000 MWth.

The conversion efficiency of the liquefaction and gasification is assumed to be 77.8%. The efficiency of the catalysis is assumed to be 100%, with a maximum gas conversion of 70%, and the efficiencies of the CHP plant are assumed to be 47% in terms of electricity and 45% in terms of heat [66].

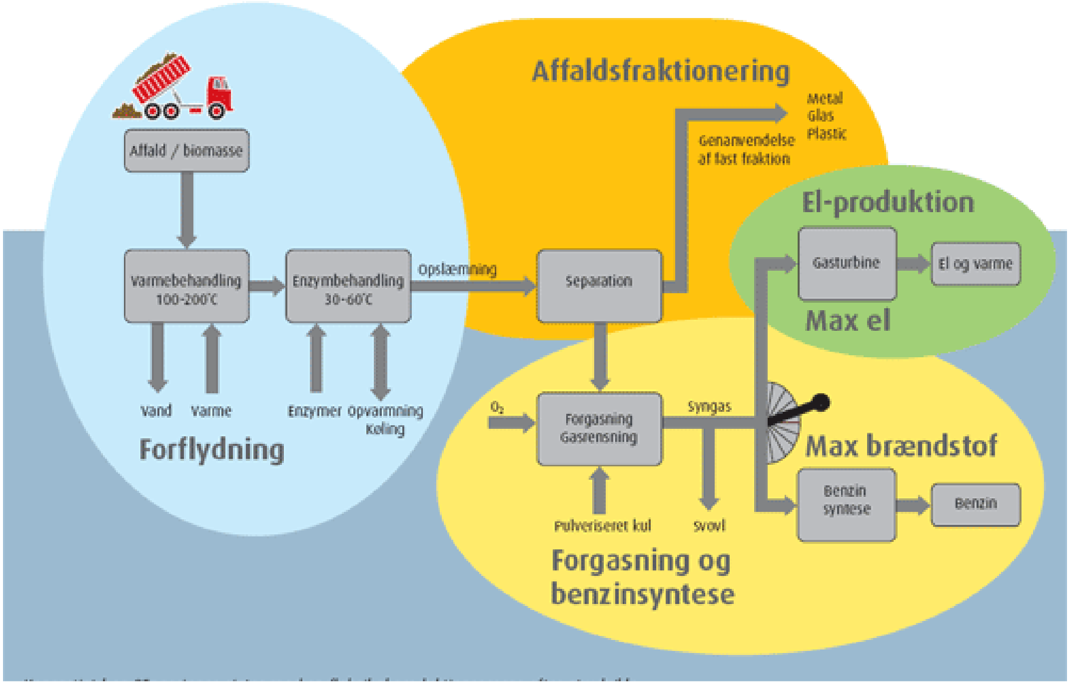


Figure 3. The REnescience process [65]

2.3 Bio-chemical conversion

The bio-chemical conversion of biomass occurs when different micro-organisms convert biomass into gases or liquids typically under anaerobic conditions and by addition of heat.

A number of bio-chemical conversion processes exist which will be introduced in the following sections:

- Bio-ethanol production
- Dark fermentation producing bio-hydrogen
- Photo-fermentation producing bio-hydrogen
- Biogas production
- Microbial Fuel cell
- Biological water-gas shift reaction

In the end data for the two chosen technologies, the Biogasol project and a centralised biogas plant are presented. The Biogasol project is a bio-refinery which produces bio-ethanol, hydrogen through dark fermentation, biogas, as well as a solid bio-fuel.

2.3.1 Bio-ethanol production

The production of bio-ethanol occurs when sugars are fermented by yeasts under anaerobic conditions. 1st generation plants use starch (e.g. sugar cane, corn and grain) and 2nd generation plants utilise lignocellulosic biomass (e.g. straw, wood etc.). Lignocellulosic biomass includes residues, and is hence relevant for this study.

Lignocellulosic biomass requires pre-treatment to break down the lignin and make the biomass accessible for enzymes. The pre-treatment could e.g. be wet oxidation at 180 ºC and 12 bar oxygen pressure. Subsequently, enzymatic hydrolysis can be used to convert cellulose and starch into sugars (saccharification), which can be used by yeasts to produce ethanol. [45]

Yields between 0.30 and 0.49 g/g of initial sugar input are reported [67].

2.3.2 Dark fermentation producing bio-hydrogen

Anaerobic bacteria and microalgaes can produce hydrogen from carbohydrate-rich substrates in dark conditions at 30-80 ºC [68]. The product is a gas consisting of hydrogen in combination with other gases, e.g. CO_2 and methane as well as volatile fatty acids (VFAs) and/or alcohols [69]. Through dark fermentation of sweet potato, a starch up to 2.7 mol H2/mol glucose can be obtained [70]. Dark fermentation of sugarcane juice has been reported to have an energy efficiency of 9.6 %, when excluding by-products (methane, bagasse etc.) [71].

2.3.3 Photo-fermentation producing bio-hydrogen

Some bacteria are capable of converting organic acids to hydrogen and CO_2 under anaerobic conditions using light as an energy source. As VFAs can be converted in the process, the process combines well with dark fermentation, which has VFAs as a by-product. One important issue is, however, the large areas needed for the process. It has hence been estimated that a reactor for photo-fermentation would need 149 m3, whereas a reactor for dark fermentation would only require 0.2-1.14 m3 to produce the same amount of hydrogen. [69]

Photo-fermentation of sugarcane juice can have an energy efficiency of 25.6% and a sequential dark photo-fermentation of 27.2%, when excluding by-products (methane, bagasse etc.) [71].

2.3.4 Biogas production

Biogas production is a process in which the digestion of biomass by bacteria occurs under anaerobic conditions with heat supplied. The process can take place under thermophilic (~55 ºC) or mesophilic (~35 ºC) conditions. Especially biomasses with high moisture contents, such as manure and organic household waste, are well suited for this type of treatment.

The main outcome of the process is biogas, consisting primarily of methane and CO_2. Furthermore, in a two stage process hydrogen may be produced through dark fermentation and removed before being absorbed by methane bacteria[72]. Finally, digested biomass is produced, which may be used as fertilizer, depending on the cleanness of the biomass resource used. Average heating values and biogas yields are shown in Table 10.

Table 10. Lower heating values and biogas output. *Based on LHV of dry matter content in the manure

Fuel	LHV	Biogas output
Mixed waste	10.5 MJ/kg [73]	
Organic waste	5.7 MJ/kg [74]	108 Nm3/t [74]
Manure	0.9 MJ/kg* [75]	21 Nm3/t [1]
Fibre fraction from biogas plant	3.8 MJ/kg [76]	
Biogas	23 MJ/m3 [1]	

2.3.5 Microbial Fuel cell

Studies have shown that bacteria present in waste water produce electricity in a microbial fuel cell (MFC) by transferring electrons gained from an electron donor towards an anode. The electrons are led over a resistance toward a cathode, where e.g. oxygen is being reduced to form water.

The power output of a microbial fuel cell is considerably lower than the one achieved by anaerobic digestion, as reported by Pham et.al. "In practice, anaerobic digestion allows 1 kg of COD[1] to be converted to an energy amount of roughly 1 kWh and on average, the power density obtained is about 400 W/m3 when the technology is applied to treat about 5 to 25 kg of COD per m3 of the reactor per day. In the case of MFCs, theoretically, 1 kg of COD can be converted to 4 kWh of electrical energy. However, the current generated by MFCs, until now, has not exceeded 0.1 A. The average power density of MFCs is about 40 W/ m3. Recently, stacked configurations of MFCs have reached power densities of 250 W/m3, implying that an improvement of MFC performance is underway." [77]

An energy recovery of 65% has been demonstrated[78]. However, only 20% COD removal for sewage sludge has been found [77]. Furthermore, studies have shown very high investment costs of 900 USD/W [79]. The technology still has a long way to go before it is commercially competitive, but may have a potential in combination with e.g. biogas production or dark fermentation in the future [77;80].

2.3.6 Biological water-gas shift reaction

In a biological water-gas shift reaction, CO and water is converted to CO_2 and hydrogen by bacteria under dark anaerobic conditions. The biological water-gas shift process could be added to the gasification or pyrolysis processes, which produce syngas with a high amount of CO.

Biological water-gas shift processes prove to be competitive with conventional water-gas shift reactions when methane concentrations are below 3%. The lower cost is due to the elimination of a reformer and associated equipment. Hydrogen production costs are expected to be around 14.6 – 18.8 USD/GJ for methane concentrations between 1 to 10%. The process is, however, still only at the laboratory stage and a limited amount of work has been reported in the field. [68]

BioGasol

In Denmark, two companies are promoting different 2nd generation plants: DONG Energy is promoting the Integrated Biomass Utilization System (IBUS) and BioGasol is developing its own process. In the IBUS concept, straw is used as feedstock and the bio-ethanol plant is operated in conjunction with a biomass CHP plant. BioGasol is building a plant on the island of Bornholm, where the feedstock is expected to be grass, straw, paper waste and garden waste. This feedstock can, to a large extent, be stored if needed, e.g. due to seasonal variations. The BioGasol process includes a biogas plant, which is used to clean the process water. The BioGasol process is chosen for the analysis, as it combines a number of

1 Chemical Oxygen Demand (COD) is used as a measure of the amount of organic compounds.

processes, i.e. the production of bio-ethanol, hydrogen and biogas, and as the process has been much less analysed than the IBUS process.

The BioGasol process is illustrated in Figure 4

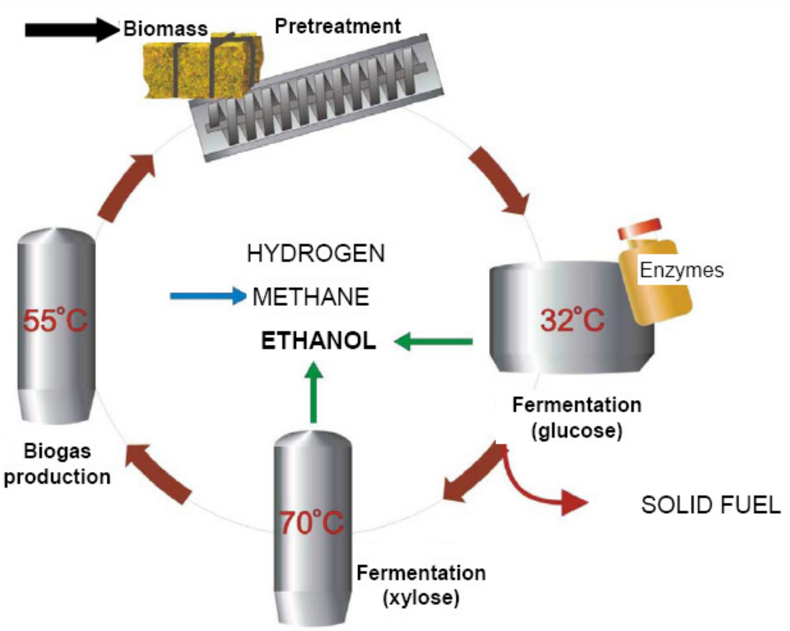


Figure 4. The BioGasol process [45]

The biomass is pre-treated through wet oxidation (180 ºC at 12 bar oxygen pressure) and subsequently fermented with the addition of enzymes and yeast at 32 ºC. Ethanol and solid bio-fuel is a result of the glucose fermentation. Subsequently, a second fermentation happens at 70 ºC. The xylose fermentation produces ethanol and hydrogen. After that, the biomass is distilled to sort out the ethanol. Finally, the waste waters are treated in a biogas plant at 55 ºC. The power and heat used for the process is produced by use of biogas. Around 35% of the energy of the feedstock is estimated to be retrieved as bio-ethanol, 25% as the solid fuel lignin, 8% as low-temperature heat, 2% as electricity and 1% as hydrogen. Summing up, this adds up to 72% energy efficiency. [45]

The construction of the plant will cost around 275 MDKK. Each year, the plant is planned to convert 90-100.000 t of wet biomass (equal to around 40.000 t of dry matter) to bio-ethanol. 10 million litres of bio-ethanol will be produced and around 10.000 t of solid fuel (pellets). Apart from that, the plant will produce 4 million m^3 of biogas, which will be converted to electricity and heat. [45]

Biogas production

Around 0.8 % of the electricity consumption and 0.7 % of the heat production in Denmark comes from biogas, mainly produced at centralised biogas plants which utilise both manure and organic waste [4]. Data regarding costs for anaerobic digestion (Table 11) is taken from the Technology Catalogue [1].

Table 11. Centralized anaerobic digestion [1]

Technology	Centralised Biogas Plant			
	2004	**2010-15**	**2020-30**	**Ref**
Energy/technical data				
Daily input of manure & organic waste in tonnes	**800**			1
Biogas output Nm3/m3 raw material (C)	25 - 30		24 - 28	2
Generating capacity for one plant (MW)	3			3
Electricity efficiency (%) net - 100% load	39.3			4
Availability (%)	98			4
Technical lifetime (years)	20			2
Construction time (years)	1			2
Own electricity consumption, kWh per ton biomass	4			1
Own heat consumption, kWh per m3 of raw material	34			5
Environment, emissions from co-generation plant				
SO_2 (g per GJ fuel)	0.019			8
NO_X (kg per GJ fuel)	0.54			8
CH_4 (kg per GJ fuel)	0.323			8
N_2O (kg per GJ fuel)	> 273			8
Financial data				
Total plant investment, excl. transport equipment and co-generation plant (M€) (A+B)	9.1	8.2	7.3	1;7;7
Total investment, co-generation plant (M€)	0.40	0.40	0.40	1
Specific investment, incl. co-generation plant (M€/MW)	3.2	2.9	2.6	
Total O&M (€/tonnes supplied raw material), excl. transport	1.75	1.75	1.75	1;7;7
Total O&M (€/MWh)	26	26	26	
Regulation ability				
Fast reserve (MW per 15 minutes)				
Regulation speed (MW per sec.)				
Minimum load (% of full load)				

References:

1 Samfundsøkonomiske analyser af biogasfællesanlæg 2002. Fødevareøkonomisk Institut. Rapport 136
2 "Teknologidata for vedvarende energianlæg, Del 2, Biomasseteknologier. Danish Energy Authority, 1996.

3 Ramboll estimate based on data from Lemvig Centralised Biogas Plant (Daily input app. 500 tonnes)
4 Lemvig Biogas Plant
5 Ramboll estimates based on monthly biogas data from Danish Energy Authority
6 Varme Ståbi
7 Danish Energy Authority, September 2003.
8 Eltra PSO project 3141: "Kortlægning af emissionsfaktorer fra decentral kraftvarme", 2003

Remarks:

A Transport is typically 1.6-2.4 €/tonne; average distance between farms and plant 4-8 km.
B The deceasing investment costs presume an escalated market
C The output figures are estimated avarages for Danish conditions, recognizing the limited availability of industrial wastes

2.4 Chemical conversion

In this section, bio-diesel production through esterification is described.

2.4.1 Esterification

Bio-diesel consists of methyl esters, which are most frequently formed by a catalyse reaction of the glycerides in vegetable oil or animal fat with a short-chain alcohol such as methanol or ethanol. The challenges met in the bio-diesel production are contaminants in the feedstock, such as water, or free fatty acid and impurities in the final product, such as methanol, free glycerol and soap. Free fatty acids (FFA) comprise 2-7% of used cooking oil and 5-30% of animal fats and up to 100% of trap grease. At FFA levels above 5%, it may be necessary to convert the FFA into methyl esters in a separate step using an acid catalyst (e.g. sulphuric acid H_2SO_4) and adding methanol (CH_3OH) and heat (e.g. 69 ºC for 1 hour). Subsequently, the transesterification based on a base catalyst and adding methanol and heat can be done at e.g. 50 ºC. [81]

The transesterification results in a stream of methyl esters and a glycerol stream consisting of around 50% glycerol. The glycerol has a low solubility and can be removed using a settling tank or a centrifuge. Following the transesterification, the glycerol may be refined by adding acid to split the soaps into FFAs and salt. After the transesterification, the methyl esters pass through a neutralisation step at which acid is added. Frequently, the base potassium hydroxide (KOH) is used as reaction catalyst and phosphoric acid (H_3PO_4) is used for neutralization, so that the salt formed is potassium phosphate (K_3PO_4), which can be sold as fertilizer. Afterwards, the methyl esters pass through a methanol stripper before water washing. Water washing removes remaining catalyst, soap, salts, methanol and free glycerol. The remaining water is removed from the bio-diesel in a vacuum flash process. To reuse the methanol, the water must be removed by distillation. [81]

DAKA

In Denmark, a large plant is being built by DAKA which converts animal fat into bio-diesel. This conversion makes it possible to utilise a waste fraction. When produced from vegetable fat, bio-diesel utilises biomass which could otherwise be used for food production. Currently, the animal fat at DAKA is used for heat production in industrial boilers, which run 5 days a week, 24 hours a day. Natural gas will substitute the animal fat for heating purposes when the plant is finished. [2]

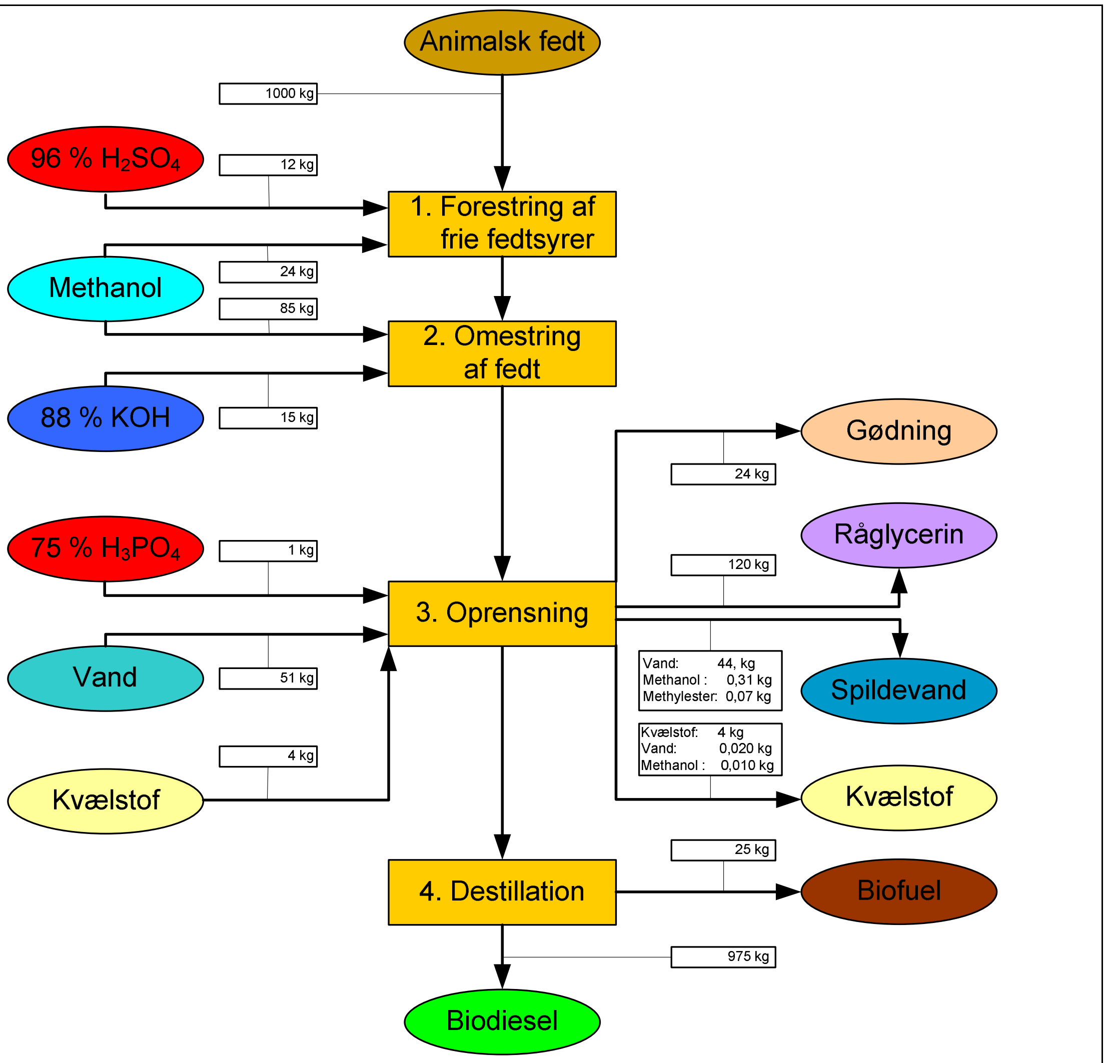
The construction of the plant will cost 180 MDKK and its operation and maintenance costs will correspond to around 2-3 MDKK/year. The plant will have a capacity of 50,000 t/year equivalent to 1.75 PJ/year. The feedstock can be stored for ½-1 year by adding chemicals, but currently, storage capacity for one month is available and, as the feedstock is delivered regularly all year round, further storage capacity needs are not foreseen. [82]

Table 1: Input and output data for esterification of animal fat

Animal fat based biodiesel production - Esterification		Substance	Original data		Energy units[a]	
			Unit	Quantity	Unit	Quantity
Inputs	Raw materials	Animal fat	kg	1000	GJ	35.0
		Methanol (natural gas based)	kg	109	GJ	2.17
	Catalysts, additives	H_2SO_4 (96%)	kg	12	-	-
		KOH (88%)	kg	15	-	-
		H_3PO_4 (75%)	kg	1	-	-
		Nitrogen	kg	4	-	-
		Water	kg	51	-	-
	Energy	Power	MJ	148	GJ	0.148
		Power (water treatment)	MJ	3.6	GJ	0.0036
		Natural gas (for heat production)	MJ	2574	GJ	2.574
Outputs	Products	Biodiesel	kg	975	GJ	36.2
		Catalyst residue (fertiliser use)	kg	24	-	-
		Glycerin (fuel use)	kg	123	GJ	2.07
		Distillation residues (fuel use)	kg	25	GJ	0.88
	Emission to water	Water	kg	40.6	-	-
		Methanol	kg	0.19	-	-
		Methylester	kg	0.04	-	-
		COD	kg	0.5	-	-
	Emission to air	Nitrogen	kg	3.96	-	-
		Methanol	kg	0.01	-	-

Source: Andreasen (2007). The data have been verified by Daka A/S.
[a] Lower heating values applied: Animal fat: 35 MJ/kg; Bio-diesel: 37.11 MJ/kg; Glycerin: 16.8 MJ/kg, Distillation residues: 35 MJ/kg. Source: Andreasen (2007).
Methanol: 19.9 MJ/kg. Source: JRC et al. (2006a).

An overview of the process is illustrated in Figure 5.



Kemiske reaktioner: Procestrin 1: Forestring af frie fedtsyre til methylester:

$$R\text{-}COOH + CH_3OH \xrightarrow[Q]{H_2SO_4} R\text{-}COOCH_3 + H_2O$$

Procestrin 2: Omestring af triglycerider til methylester:

$$\begin{array}{l} R\text{-}COOCH_2 \\ \quad | \\ R\text{-}COOCH \\ \quad | \\ R\text{-}COOCH_2 \end{array} + 3CH_3OH \xrightarrow[Q]{KOH} 3R\text{-}COOCH_3 + \begin{array}{l} CH_2OH \\ \quad | \\ CHOH \\ \quad | \\ CH_2OH \end{array}$$

Figure 5 DAKA Esterification process [83]

2.5 Efficiencies and perspectives

In Table 13, the efficiencies assumed for the various technologies in 2006 and 2050 are shown.

Table 13 Efficiencies of WtE technologies in 2006 and 2050

	Conversion	Electricity	Heat	Transport fuel	Ref
			New waste incineration		
2006		19,5 %	65,4%		[1]
2050		29,0%	78,0%		[55]
			Co-combustion		
2006		34,4%	26,0%		[57]
2050		48,5%	41,5%		[1]
			Dedicated RDF		
2006		30,0%	60,0%		[1]
2050		30,0%	60,0%		[1]
			Biogas CHP		
2006	40,9%*	42,0%	50,0%		[84]+ [1]*/ [1]
2050	40,9%*	46,0%	50,0%		[84]+ [1]*/ [1]
			Biogas Transport		
2006	40,9%*			94,3% eff	[84]+ [1]*/ [85]
2050	40,9%*			94,3% eff	[84]+ [1]*/ [85]
			Syngas		
2006	77,8%	47,0%	45,0%	(70% of converted gas, rest for CHP)	[66]
2050	77,8%	47,0%	45,0%	(70% of converted gas, rest for CHP)	[66]
			Biodiesel		
2006	90,4%			100%	[2]
2050	90,4%			100%	[2]
			Bioethanol		
2006	76,0%*	42,0%	50,0%	(46% of converted amount, rest for CHP)*	[45]*/ [1]
2050	76,0%*	46,0%	50,0%	(46% of converted amount, rest for CHP)*	[45]*/ [1]

3 Model description

The energy system analysis was made by use of the EnergyPLAN model, which is developed at Aalborg University. The EnergyPLAN model is a computer model designed for energy systems analysis. The main purpose of the model is to assist the design of national or regional energy planning strategies on the basis of technical and economic analyses of the consequences of implementing different energy systems and investments.

The model can be downloaded free of charge together with documentation from www.energyplan.eu. On the webpage, examples can be seen of analyses made by use of the model, including a number of case studies by Lund and others [19;86] as well as comparisons of results with other models as in Lund et al. 2007 [87]. A brief description of the model is presented below. For more thorough explanations and references, please consult [88;89]

The EnergyPLAN model is a deterministic input/output simulation model. Inputs to the model may be divided into five sets of data:

1. Demands for electricity, heat, cooling, industry, individual households and transport
2. Renewable Energy Supply
3. Capacities and efficiencies of, among others, CHP and power plants
4. Technical limitations and definition of external power market
5. Fuel costs and CO_2 emission factors

The fluctuating demands, production and prices are fed in as hourly distributions over a year. The input data are regulated by a number of strategies illustrating e.g. how CHP plants are operated on the market and how critical excess electricity production is reduced. Results involve, among others, heat and power production, import/export of electricity, forced excess electricity production, fuel consumption, CO_2 emissions and the share of renewable energy in the system. See Figure 6.

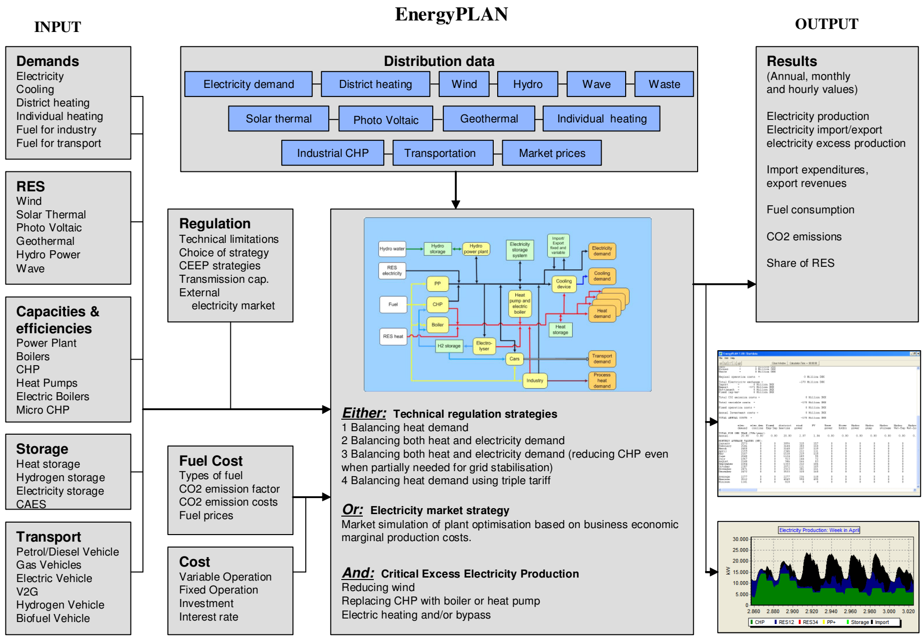


Figure 6 Input-Output structure of the EnergyPLAN model

The model is a simplified model in which the energy system is divided into three groups:

- Group I – supplied by district heating plants only
- Group II – supplied by decentralised CHP plants and boilers
- Group III – supplied by centralised CHP plants, condensing power plants and boilers

Each group represents areas supplied by the mentioned technologies. The geographical distribution is hence not included in the analysis and this aspect would have to be dealt with by a supplementary analysis, e.g. using Geographical Information Systems [90].

The model can simulate both a closed system with no electricity exchange and an open system. It is interesting to simulate a closed system in order to evaluate whether the energy system can utilise the energy produced at a given hour and thus ensure an efficient system. This can facilitate the trade of electricity at times when the Danish actors wish to do so - and not when they are forced to do it. Likewise, the model can perform either a technical optimisation focusing on the fuel efficiency of the system or a market optimisation focusing on the financial output of the individual plants.

EnergyPLAN includes a large number of traditional technologies, such as power stations, CHP and boilers, as well as energy conversion and technologies used in renewable energy systems, such as heat pumps, electrolysers, and heat, and also electricity and hydrogen storage technologies, including Compressed Air Energy Storage (CAES) [91]. The model can also include a number of alternative vehicles, for instance sophisticated technologies such as V2G (Vehicle to grid) in which vehicles supply the electric grid [92]. Moreover, the model includes various renewable energy sources, such as solar thermal and PV, wind, wave and hydro power.

The model encompasses the whole national or regional energy system including heat and electricity supplies as well as the transport and industrial sectors. With regard to electricity supply, the model emphasises the analysis of different regulation strategies with a focus on the interaction between CHP and fluctuating renewable energy sources.

Previously, waste has been treated in the model as a fuel along with biomass resources. However, the analysis of waste utilisation in the EnergyPLAN computer model has now been made more detailed and is now conducted in the way described below.

The following input must be given to the model:

- The energy content of the waste resource divided into the three types of district heating systems mentioned above. Other resources can be included, but the cost and the CO_2 content of the waste will then have to be adjusted accordingly.
- Efficiencies specifying the energy output in the following 4 energy forms: Heat for district heating, electricity, fuel for transport, and fuel for CHP and boilers. Moreover, one can specify an additional non-energy output (such as animal food), which will then be given an economic value in the feasibility study. In this way, multiple products are taken into account.
- An hour-by-hour distribution of the waste input (and hence heat and electricity output).

Basically, the model assumes that waste is converted at a constant rate in accordance with the specified hour-by-hour input. This is due to the difficulties associated with the storage of waste and the high investment costs. The energy outputs are treated in the following way:

- Heat production from waste for district heating is given priority along with solar thermal and industrial waste heat production. If such input cannot be utilised because of limitations in demand and heat storage capacity, the heat is simply lost. Electricity production from waste is fed into the grid and given priority along with renewable energy resources such as wind power. Other units, such as CHP and power plants, will adjust their production accordingly, if possible (given the specified regulation strategy); and if this cannot be done, the excess electricity produced will be exported.
- The amount of transport fuel produced is calculated and the user can subtract it from the total use of the relevant fuel in the reference and, at the same time, adjust for differences in car efficiencies, if such differences exist. Fuel for CHP and boilers is automatically

subtracted in the calculation of fuel in the relevant district heating groups.

As part of this study, the model has been expanded in order to include Syngas technologies in the regulation strategies, as explained below. A mathematical representation of the extension is presented in Appendix A.

The Syngas unit is defined in the model as a unit which converts waste, coal and biomass into biopetrol, electricity and heat, as shown in the principle diagram in Figure 7:

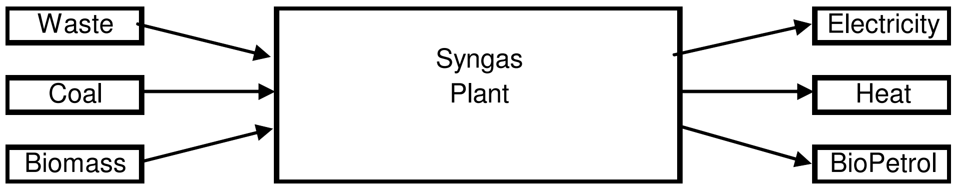


Figure 7 Diagram of Syngas plant

The Syngas utilises waste which cannot be stored. Coal and/or biomass may be added to facilitate the energy conversion process. Consequently, the input to the plant is simply defined by the annual amount of fuels in combination with the hourly distribution data set of waste. All three fuel inputs (coal, biomass and waste) follow the same distribution.

The Syngas plant can choose to produce either primarily biofuel (Operation mode 1) or primarily CHP (Operation mode 2). The plant typically cannot operate 100% in CHP mode or 100% biofuel mode. The plant normally has a minimum biofuel output in order to avoid on/off operation, and a minimum share of the syngas is surplus from the biofuel production and is consequently used for CHP. Such operation possibilities are, in the EnergyPLAN model, defined by 6 inputs, as illustrated in the diagram below.

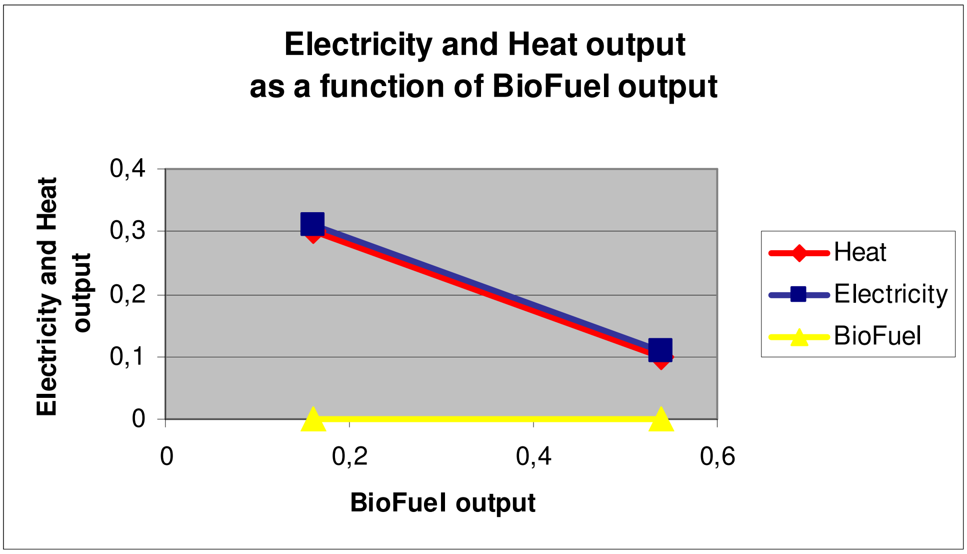


Figure 8 Electricity, heat and bio-fuel output

The plant is assumed to be able to operate linearly between the two modules, as shown in Figure 8.

Based on the annual fuel amounts and the hourly distribution of waste, the Syngas plant can choose between the modules of operation defined by the input efficiencies.

- Heat is supplied to district heating
- Biopetrol is replacing petrol for transport
- Electricity is supplied to the public grid

Initially, the plant is set to operate according to module 1. The marginal cost of increasing electricity production by operating the Syngas plant in module 2 instead of 1 is calculated in two situations. One in which the heat replaces heat from the boiler and one in which it replaces heat from the CHP units.

The technical regulation is based on the principle that, if the total fuel consumption of the system can be reduced by replacing electricity at a power plant and heat in the district heating system instead of producing petrol, the operation will be changed. The market economic regulation is based on the principle that, if the marginal production cost of producing electricity is lower than the market price (in competition with all the other units), the Syngas unit will change to module 2.

4 Scenarios

In order to assess whether the technologies in question will function as planned or will obstruct the development of a desired future, they are analysed both in the current energy system as well as in a future energy system with 100% renewable energy. Hereby it becomes possible to recommend actions with regards to research in technologies. Positive results may also indicate that investments in infrastructure and built up of expertise will not be in vain. Furthermore, full CO_2 reduction potentials of the various technologies are established by applying the full resource potentials of today.
This chapter includes description of the resources as well as the reference energy systems and scenarios analysed.

4.1 Resources

First, the current resource potential is described. Fruergaard has identified the resource potential of the various fractions used by the Waste-to-Energy plants described in Chapter 2 [93]. Table 14 is based on the findings of Fruergaard and illustrates the full potential. Furthermore, the table shows the types of waste resources which can be used in each plant. It is worth noticing that, in all cases, the majority of the waste which is currently incinerated must still be incinerated, as only minor fractions can be sorted out and used in the different technologies.

Table 14 Potential waste resources

PJ	New Incine-ration	Co-com-bustion	RDF	Biogas CHP	Biogas Transport	Syngas	Bio-diesel	Bio-ethanol
Resources used for waste incineration								
Paper		6,0	6,0			6,0		6,0
Plastic		1,0	1,0			1,0		
Org waste				1,4	1,4	3,4		
Mixed waste	10,4/27,0	30,4	30,4	36,0	36,0	27,0	37,4	31,4
Resources used for industrial heating								
Animal fat	3,2	3,2	3,2	3,2	3,2	3,2	3,2	3,2
Resources currently not used for energy								
Straw	12,2	12,2	12,2	12,2	12,2	12,2	12,2	12,2
Wood	5,4	5,4	5,4	5,4	5,4	5,4	5,4	5,4
Industrial waste				2,0	2,0			
Sludge				5,1	5,1			
Manure				32,5	32,5			
Grass								1,4
Extra resources needed to run process								
Coal						31,2		

The resources in each column are used in the technical alternative mentioned in that column. When the resource is marked in bold, it is taken from its normal use and used for the technology mentioned in the column instead. When the resource is not marked in bold, it is converted in a waste incineration plant (mixed waste), in an industrial heating plant (animal fat) or in a biomass CHP plant (straw and wood).

The same resource is used for each alternative apart from the Biogas+ and the Bioethanol alternatives. In the case of these alternatives, the construction of a plant of such type is assumed to facilitate the utilisation of unused resources. Furthermore, the Syngas+ alternative requires an addition of coal to run the process. In the future, it may be possible to co-gasify with biomass instead. Some resources can only be used for energy in the specific technologies mentioned in the respective columns (industrial waste, sludge, manure and grass). The largest resource which is made available for energy production in WtE plants is manure, which corresponds to almost the same energy amount as the waste which is currently incinerated.

The table reflects the amounts used for the scenario where the full resource potential is used. For the scenarios in which 4 PJ of waste is added, 4 PJ of the resource needed for that specific technology is added. This illustrates a situation in which the resources are not already used for energy or are imported. For the Biogas scenarios, only organic household waste is included and, in the Biogas+ scenarios, manure is also added (80% of volume). For Syngas, only paper and plastic are added and, for Syngas+, coal is also added (75% of energy content). For Bioethanol straw, paper and grass resources are used in the same relation as shown in the table.

In the scenarios in which 4 PJ of waste is moved, the fractions are taken from the current use, such as incineration, and added to the respective technologies. Again, for the Biogas+ alternatives, manure is added and, for Syngas+, coal is added in 2006 and biomass in 2050. For simplicity, only the straw and paper fractions are used in the Bioethanol alternative. This scenario, hence, illustrates a situation in which both straw and paper are already being used and the negative consequences of removing the resources from their current use is included in the analysis.

Table 15 shows the characteristics of the different fuels and waste fractions.

Table 15 Characteristics of fuels and waste fractions

Process	Input	Current use	LHV (MJ/kg)	Waste storage
Combustion	Mixed waste	C	10.5 [4]	Only dry fractions e.g. industrial
Co-combustion	Coal RDF	C C	24.8 [4] 16.5 [94]	RDF and coal
RDF	RDF	C	16.5 [94]	RDF
Gasification	Coal Household waste	C C	24.8 [4] 9.0 [95]	Only coal
Trans-esterification	Animal fat	C	35.0 [2]	Possible
Biogas production	Manure Organic waste Waste water	F C F 53%, C 43% [86]	0.9 [75] 5.7 [74] 1.3 [95]	Only manure - can be stored at farms
Fermentation	Straw Grass and garden-waste Paper	F 66%, C 34% [96] F R	14.5 [4] 13.6 [95] 15.3 [95]	Possible

C=Combustion, F=Fertilizer, R=Reuse

4.2 Reference Energy System 2006

In this section, the assumptions and principles of the reference energy system are described. To a large extent, the same reference energy system is used as in the Heat Plan Denmark project [55]. The reference energy system is based on the latest base forecast of the energy system of the Danish Energy Authority from January 2008 [97]. Taking the figures for 2006 as starting point, the energy consumption and energy supply have been converted to inputs to the EnergyPLAN model. Further information about the base forecast can be found in [97].

The Danish Energy Authority operates with two different versions of the forecast: One with corrected gross energy consumption and one including the electricity export. The corrected version is here chosen as a starting point, as focus is put on the national energy supply. In the calculation in EnergyPLAN, the installed power plant capacity is set to be 9400 MW-e. The wind turbine capacity is 3100 MW.

When reconstructing the base forecast of the Danish Energy Authority, assumptions regarding the development of fuel prices have been taken from the latest description of assumptions for socio-economic analysis in the energy sector of the Danish Energy Authority [98].

Table 16 Fuel prices and waste resource prices

Fuel	DKK/GJ	Ref	Waste resource	DKK/GJ	Ref
Coal	15,8	[98]	Mixed incinerable waste	-20	[99]
Fuel oil	54,0	[98]	RDF	39	[100]
Diesel	96,5	[98]	Organic household waste	-112	[101;102]
Petrol	102,7	[98]	Manure	-10	[103]
Natural gas	48,0	[98]	Organic industrial waste	5	[103;104]
Straw	22,9	[98]	Sludge	-1024	[102;104]
			Animal fat	114	[105]
			Grass	-7	[106-108]

In Table 16, negative prices represent payment received for treating waste. The positive costs of the waste fractions - e.g. RDF - represent the increased cost of transportation as well as pre-treatment of the waste in order to achieve the required size and quality or alternatively of purchasing the equivalent.

For conventional fuels, a world market exists and, for straw, a Danish market helps establishing the prices for these fuels with a fair amount of certainty. The same cannot be said about waste resources, which have prices ranging from positive to negative depending on energy content, ease of handling, content of harmful substances etc. A European market does, to some extent, exist for RDF and a Danish market for animal fat. An average price can be established for receiving incinerable waste and, to a lesser extent, manure; but when it comes to organic industrial and household waste, sludge and grass, the data are much more uncertain and have been established through averages of prices found at biogas plants or other plants currently treating the fractions. Sensitivity analyses are performed of both fuel and waste resource prices.

The base forecast and the reference used for Heat Plan Denmark does not distinguish between the fuels and efficiencies of energy plants connected to central district heating grids and to decentralised grids. To develop a reference which uses different efficiencies and fuels for the central and decentralised CHP plants, a methodology has been applied in which the base forecast corrected for electricity export is maintained as the main source of data, while efficiencies and distributions of fuels are found in other official statistical sources and applied to the base forecast corrected for electricity export [97].

4.3 Waste Incineration Efficiencies

Using the Energy Producer Statistics from 2006 [109], efficiencies and distribution of waste have been found for the waste incineration plants connected to central district heating grids (Cen CHP), to decentralised grids (Dec CHP) and to district heating grids with heat-only-boilers (DHP).

Cen CHP plants are plants connected to district heating grids into which central condensing plants also feed [110]. DHP plants are boilers not placed at central or decentralised CHP plants. Dec CHP plants are the remaining plants. The efficiencies of the plants in Dec CHP and Cen CHP entail the efficiencies of the CHP plants and boilers connected to these groups. Electrical efficiencies are calculated on the basis of the electricity delivered, and heat efficiencies are calculated on the basis of the heat produced. Only plants using 90% waste or more were included in the analysis.

Table 17 Efficiencies of waste incineration plants and distribution of waste in 2006

Waste Incineration	Electrical efficiency	Heat efficiency	Waste distribution
DHP		79,76%	2%
Dec CHP	13,20%	67,30%	36%
Cen CHP	16,43%	70,75%	62%

4.4 Efficiencies for Dec CHP and Cen CHP

The efficiency of the CHP plants when running in condensing mode has been found from the forecast including export made by the Danish Energy Authority [97]. The Danish Energy Statistics 2006 have been used to identify the power production in 2006 [4]. The power production and the efficiency have been used to identify the consumption. Subsequently, the production and the consumption have been removed from the production and consumption of the other central CHP plants [4] (excel tables) to identify the efficiencies of the central plants when producing both heat and power.

To find the efficiencies of Dec CHP, the waste incineration efficiencies described above were used together with the waste consumption figures from the Energy Statistics [4] (excel tables). The production and consumption were subtracted to get the efficiencies of the plants in group II which do not use waste. The plants which use less than 90% waste constitute part of the remaining fossil and biomass plants and the efficiencies found. For simplicity, in the model, the total amount of waste is used by the waste incineration plants with the efficiencies shown above.

Table 18 Efficiencies of fossil and biomass plants in 2006

Fossil and biomass plants	Electrical efficiency	Heat efficiency
DHP		90%
Dec CHP	35,97%	43,19%
Cen CHP	29,87%	60,06%
Condensing mode Cen CHP	39,8%(exp)/39,4%(corr)	

4.5 Validation

The fuels used for condensing plants in Cen CHP have been identified by applying the distribution of fuels found in the base forecast [97] to the figures of the statistics [4] (excel tables). The distribution of fuels between Dec CHP and Cen CHP has been found by subtracting the fuels used for condensing plants in Cen CHP. The amount of oil and biomass used in the different types of plants has been fixed. This is due to the fact that oil is either primarily used for start-up purposes or is waste oil. Furthermore, the amount of biomass used is, to a large extent, independent of market mechanisms; it rather depends on capacities and permissions. The input of fuels to the plants has been distributed, to match the proportion of fuels in each plant type.

Two types of analysis have been made based on the reference energy system developed. One analysis focuses on a technical optimisation in which the model seeks to find the lowest fuel consumption and does not include electricity trade (Closed). A second analysis has been made in which the model optimises on the basis of short-term marginal business-economic production costs and trades on the Nordic energy market (Open). For the Open analysis, an average electricity price of 362 DKK/MWh, as found on the NordPool in 2006, has been used [111]. Furthermore, a CO_2 price of 160 DKK/t has been used to match the consumption of fuels and net electricity export in 2006 [4].

The fuel consumptions and some key figures of the reference are compared in Table 19. The Closed analysis is comparable with the corrected base forecast [97] and the Open analysis with the Energy Statistics 2006 [4], as can be seen below.

Table 19 Energy production and consumption

	Unit	2006 forecast	2006 Closed	2006 Open	2006 Statistics	2050 Open
			Input			
Electricity consumption	TWh/year	36,3	36,3	36,3	36,4	33,4
District heat consumption	TWh/year	35,8	35,8	35,8	35,6	26,0
Individual heating (fuel)	TWh/year	23,1	23,1	23,1	24,0	6,4
Industry, service and refining	TWh/year	39,6	39,6	39,6	37,4	26,2
Transport incl. aviation and shipping	TWh/year	59,8	59,8	59,8	60,0	35,08
North Sea losses etc.	TWh/year	16,2	16,2	16,2	16,2	-
			Primary energy supply			
Wind and solar	TWh/year	6,2	6,2	6,2	6,2	44,0
Coal	TWh/year	49,6	49,6	65,6	64,7	-
Oil	TWh/year	95,6	95,5	95,5	96,3	-
Natural gas	TWh/year	51,7	51,5	52,8	53,1	-
Biomass and waste	TWh/year	31,6	32,1	31,7	33,1	104,9
Total incl. electricity export	TWh/year	234,7	234,8	251,8	253,2	148,8
			Key figures			
Condensing power	%	32	31	49	58	24
Boilers	%	16	12	11	14	47
Net electricity export	TWh/year	0,11	0,11	24,48	24,97	19,78
Corrected total	TWh/year	234,4	234,8	234,5	-	117,9

The main deviations are to be found in the amounts of biomass used. This deviation may also be the main reason for the difference in total fuel consumption between the Open analysis and the Energy Statistics 2006. Furthermore, some deviations can be seen between the percentage of electricity produced on condensing plants and the percentage of heat produced on boilers. As condensing plants produce most of the power exported, this percentage increases significantly when export increases. In the Energy Statistics 2006, both the import and the export are significantly higher than in the model, which may be the reason for the higher percentage of electricity produced on condensing plants here. However, as the fuel consumptions match well, the model is still assessed to produce a sufficiently valid picture of reality.

4.6 Reference Energy System 2050

It is impossible to forecast how future energy systems will be, but the energy system used for this analysis represents one possible combination of technologies, which can supply Denmark with electricity, heat and transport fuels with a massive utilisation of both wind power and biomass. The Reference Energy System for 2050 is based on the 2050 vision of The

Danish Society of Engineers' Energy Plan, which is a system with 100% renewable energy [112;113]. The system has the following capacities: 9200 Mw-e power plants, 10.000 MW wind power, 500 MW-e heat pumps, 1500 MW photovoltaic power, 900 MW hydro power and 6800 MW electrolysers.

In the 2050 vision of The Danish Society of Engineers' Energy Plan, waste is not included in the analysis. It is, for simplicity, assumed that the waste for incineration stabilises at the current level. Therefore, the reference energy system is the same as the 2050 vision of The Danish Society of Engineers' Energy Plan. The same amount of waste is added as in the reference for 2006 and with the same distribution, but with a higher efficiency as in Heat Plan Denmark [55] (See Table 20). The energy consumption and fuel use for 2050 are shown in Table 19.

Table 20 Efficiencies of waste incineration plants, biomass plants and distribution of waste in 2050

	Electrical efficiency	Heat efficiency	Waste distribution
	Waste Incineration		
DHP		97,6%	2%
Dec CHP	29%	78%	36%
Cen CHP	29%	78%	62%
	Biomass plants		
DHP		90%	
Dec CHP	54%	36%	
Cen CHP	64%	26%	
Condensing mode Cen CHP	64%		

The biomass price is expected to increase to 53,7 DKK/GJ in 2025 [114].The price has been found by taking the coal price and adding a CO_2 price element. It is assumed that this will be the minimum biomass price. For simplicity, the price is assumed to remain at this level until 2050. The increase in the biomass price is 16 % and the waste fractions prices have increased by the same percentage.

The average electricity price in 2025 has been analysed in the energy system analysis model Balmorel and found to be approximately 550 DKK/MWh, with coal power plants as the prime marginal electricity-producing technology [114]. The price is used for 2050 under the assumption that the price will remain at that level. Furthermore, it is assumed that Denmark will trade electricity with countries which still have coal-condensing plants, although Denmark is supplied 100% by renewable energy. A CO_2 price of 225 DKK/t has been applied, which is the CO_2 quota price expected by the Danish Energy Authority from 2013 [97].

5 Results

Four types of analyses have been performed and key assumptions as well as results from the analyses are presented in the following sections.

- Add/remove 4 PJ 2006
  First, an analysis is made of a system in which 4 PJ of different types of waste are either added to or removed from the corresponding WtE plants in the energy system of 2006. This exercise is mainly done to illustrate the effects of various actions on the energy system.
- Move 4 PJ 2006
  Secondly, an analysis is made of a system in which 4 PJ are moved by taking them from the current use and using them in the respective WtE plants instead. In this way, it is possible to ensure that the alternatives are comparable in the sense that each alternative treats the same amount of waste. Furthermore, the major part of the potential waste is already being used for energy purposes and, in most cases, it therefore also seems more realistic to include the drawbacks of removing the waste from its current utilisation.
- Full resource 2006
  Thirdly, an analysis is made of the CO_2 reduction potential when utilising the full resource available.
- Move 4 PJ 2050
  Finally, an analysis is made of the performance of WtE technologies in a future 100% renewable energy system. This is done to ensure that the technologies recommended will not hinder the path to a desired 100% renewable energy future.

For 2006, a market optimisation is used in which the model optimises on the basis of the short-term marginal business-economic production costs and trades on the Nordic energy market. Taxes are included in the prioritisation in the operation of the plants, but not in the economic results. For 2050, a technical optimisation with electricity trade is performed. As it is a technical optimisation focusing on the reduction of fuel consumption, no taxes are included in this analysis.

5.1 Add/ remove 4 PJ 2006

In this section, the results of adding 4 PJ of waste to various technical alternatives are presented. The analyses are primarily made to illustrate the mechanisms of the energy system when adding the production of the various technologies. It is, hence, mainly an academic exercise as waste will normally have to be removed from another use in the Danish case. However, the analysis can also provide an answer to the question "How low CO_2 emissions can we achieve when importing wastes for use in different WtE plants?" Furthermore, it is analysed what happens when 4 PJ of waste is removed from different uses in order to illustrate the resulting energy production.

Table 21 Resource use for the WtE alternatives when adding or removing 4 PJ in 2006

PJ	Specific plant	Waste inc.	Biomass CHP
Reference		37	46
Incineration (Cen.)	4	37	46
Co-combustion/ Ded. RDF (Cen)	4	37	46
Biogas (Dec)	4+2*	37	46+1*
Syngas (Cen)	4+12*	37	46
Biodiesel (Dec)	4	37	46
Bioethanol (Dec)	4	37	46
Remove Waste (Dec/Cen)		33	46
Remove Animal Fat (Dec)		37	42

*Extra resource used only in this type of plant – included in the ”+” alternatives.

The different plants utilise different types of waste. In the case of Incineration, mixed combustible waste is used. For Co-combustion and dedicated RDF plants, refuse derived fuel (RDF) consisting of paper and plastic is utilised. Sorted organic household waste is used for the biogas plants and, for the Biogas+ alternatives, the use of 2 PJ of manure is assumed to be facilitated by anaerobic digestion of organic waste. Furthermore, 1 PJ of fibre from the digested manure is assumed to be combusted in a biomass CHP plant. For the Syngas alternative, organic waste is used and, for the Syngas+ alternative, 12 PJ of coal is assumed to be required to run the gasification process. The Biodiesel alternative requires animal fat and Bioethanol utilises straw, paper and grass. The distribution can also be seen in Figure 9.

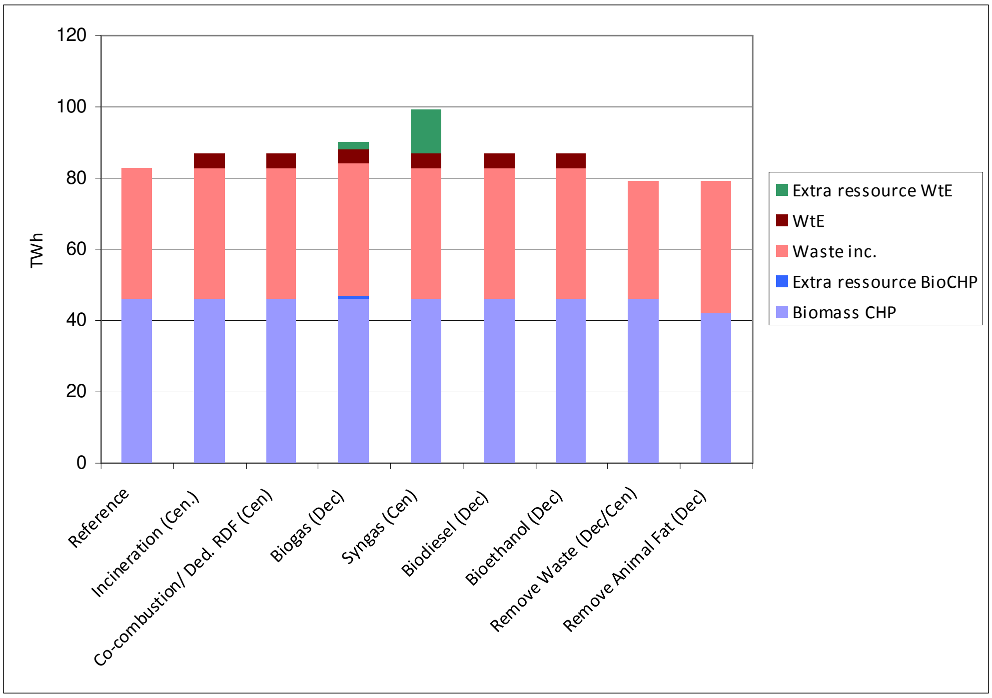


Figure 9 Resource use for the WtE alternatives when adding or removing 4 PJ in 2006

Table 22 Investment and Operation and Maintenance Costs as well as availability and lifetimes for 4 PJ

WtE technologies	Investment (MEUR/PJ)	O&M (%)	Availability (%)	Lifetime (years)	Year	Source
Waste Incineration	52.2	7	98	20	2004	[1]
Co-combustion	1.7	10	98	30	2004	[1]
Dedicated RDF	51.1	4	91	20	2004	[1]
Biogas CHP	5.9/18.3*	7	98	20	2004	[1]
Biogas Transport	24.1/34.1*	2/4	98	20	2004	[1]
Syngas	50.9	4	80	20	2010-20	[63]
Biodiesel	13.9	1	98	20	2006	[82]
Bioethanol	65.0	10	98	20	2006	[45]

* Biogas Plus alternatives

Table 22 shows the investment and operation and maintenance costs assumed for the technical alternatives. Bioethanol has the highest investment costs per PJ input. Waste incineration, RDF and Syngas are at the same level, whereas Co-combustion is by far the cheapest, as only the extra cost of co-firing with RDF in an existing coal-fired power plant is taken into consideration.

In general, data has been found for plants of sizes similar to the required and from there, the investment costs have been adjusted linearly to fit the required input capacity. Data have been adjusted to 2004 prices.

Data for Co-combustion are taken from the data sheet on large-scale biomass plants with 20% co-firing of straw in a coal-fired steam turbine in the Technology Catalogue [1]. For RDF, data for a straw-fired steam turbine of 8-10 MW is used. For biogas used for transport, data regarding the costs of cleaning and upgrading the biogas to natural gas quality has been taken from Swedish Gastechnical Centre [85] and data regarding extra natural gas vehicle costs come from the energy system model of the project "The Future Danish Energy System" of the Danish Board of Technology [115]. Costs regarding distribution have not been included in any of the alternatives. Costs for the Syngas alternative are from the Well-to-Wheel Report by EUCAR et.al. regarding an integrated gasification combined cycle plant [63], which is assumed to cover the costs of gasification and catalysis combined with the costs of the CHP unit (10-100 MW-e gas turbine combined cycle) from the Technology Catalogue [1]. Data regarding Biodiesel is provided by the owner of an existing plant [82], while data on Bioethanol is from a producer of a plant, which is only being planned [45].

The figures below show the differences between the reference – today's energy system – and the alternative uses of waste. The figures show the substituted fuel or decreased consumption as positive values and the induced fuel or increased consumption as negative values. The figures illustrate the plant types and sectors in which changes occur due to the different uses of waste in the various alternatives. Furthermore, the figures illustrate the differences in heat surplus and net electricity export compared to the Reference. For both, an increase is shown as a negative value and a decrease as a positive value. To be able to compare sizes with fuel consumption, the net electricity export is divided by the electrical efficiency of a coal-fired power plant (40%) in this type of figures, thereby assuming that the marginal electricity production unit is coal-fired power plants.

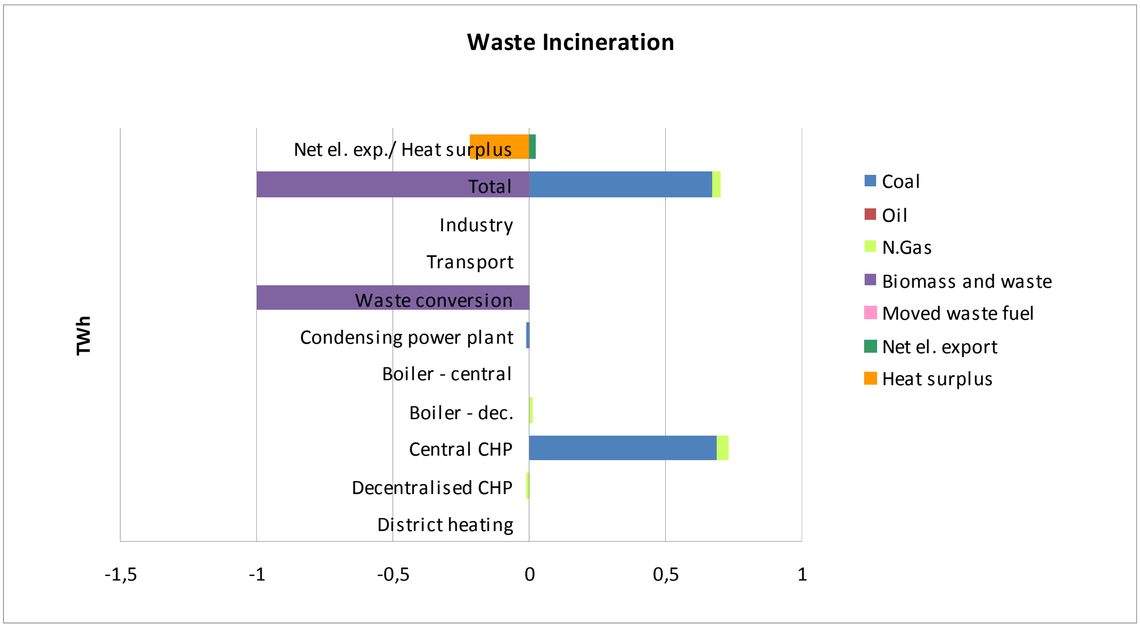


Figure 10 Substituted fuel when adding 4 PJ of mixed waste to new waste incineration in a central DH area

When 4 PJ of mixed waste is added to a central area, around 0.7 TWh of coal is displaced in central CHP plants. The net electricity export decreases and the heat surplus increases as the flexibility of the system is reduced.

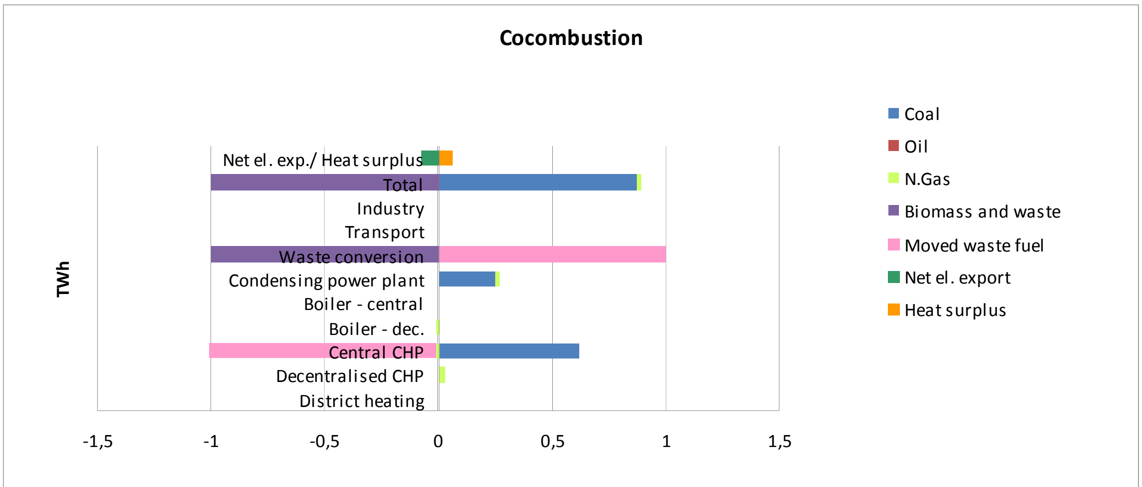


Figure 11 Substituted fuel when adding 4 PJ of RDF to Co-combustion in a coal-fired power plant in a central DH area

When co-combusting RDF with coal in a coal-fired power plant by adding 4 PJ of RDF, around 0.8 TWh of coal is substituted. The pink column illustrates the conversion of the waste to another fuel – here from mixed waste to RDF – and the input of the fuel to another energy use – here central CHP. The substitution of coal occurs both in condensing power plants and in central CHP plants. The substitution of fuels in the condensing power plants is due to the increased electrical efficiency of this system compared to the reference. As a result of the change, net electricity export increases and heat surplus decreases, indicating a better flexibility than in the reference.

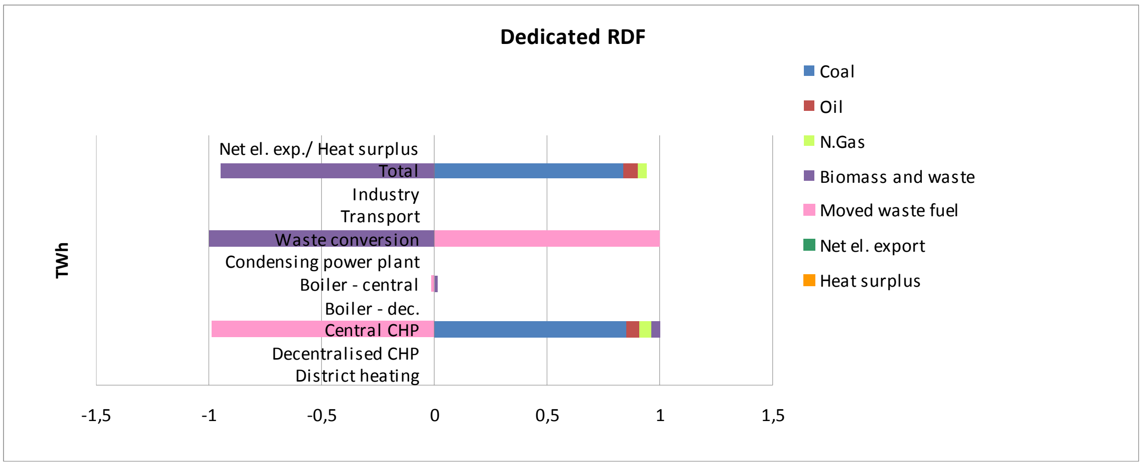


Figure 12 Substituted fuel when adding 4 PJ of RDF to a dedicated RDF CHP plant in a central DH area

When adding 4 PJ of RDF to a dedicated RDF plant in a central area, mainly coal is substituted and mainly in central CHP plants. Some biomass is, however, also substituted resulting in a reduced net increase in biomass and waste consumption, compared to the Co-combustion alternative. The difference between the dedicated RDF alternative and the Co-combustion alternative is related to the efficiencies of the RDF and the Co-combustion plant, respectively. In the RDF alternative, the electrical efficiency does not increase and, hence, no substitution occurs in the condensing power plants. Furthermore, in the Co-combustion alternative, only coal is substituted in the central CHP area, whereas an average of the fuels used in central CHP plants is substituted in the RDF alternative. No changes occur with regard to net electricity export or heat surplus.

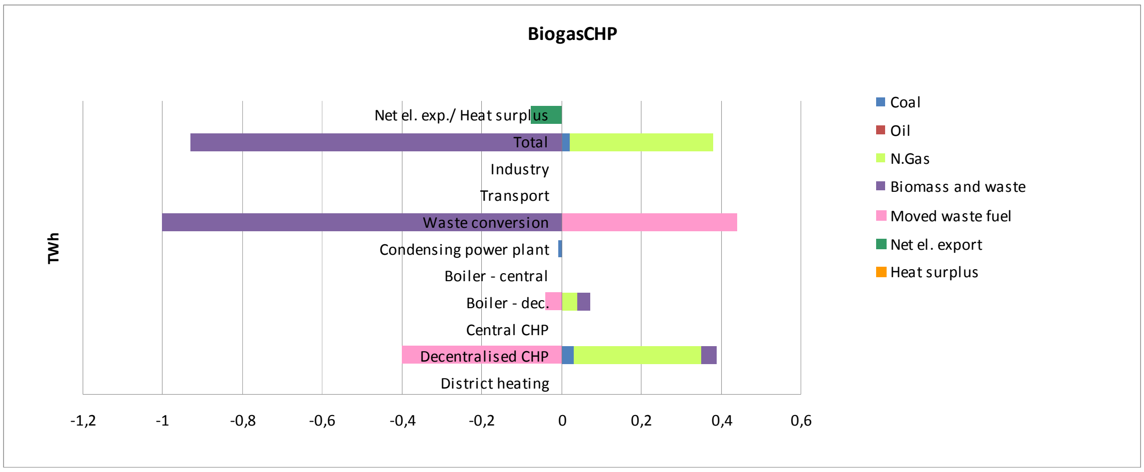


Figure 13 Substituted fuel when adding 4 PJ of organic waste to anaerobic digestion in a biogas plant with subsequent use of the biogas for CHP production in a decentralised DH area

Converting organic waste to biogas and subsequently utilising it for CHP has a low total efficiency and, hence, only around 0.4 TWh are substituted when adding 4 PJ of organic waste to a biogas plant in a decentralised area. The main part of the substituted fuel consists of natural gas used for CHP in decentralised areas. Some coal is also substituted in boilers in decentralised areas and some biomass in both CHP plants and boilers. Furthermore, the net electricity export increases.

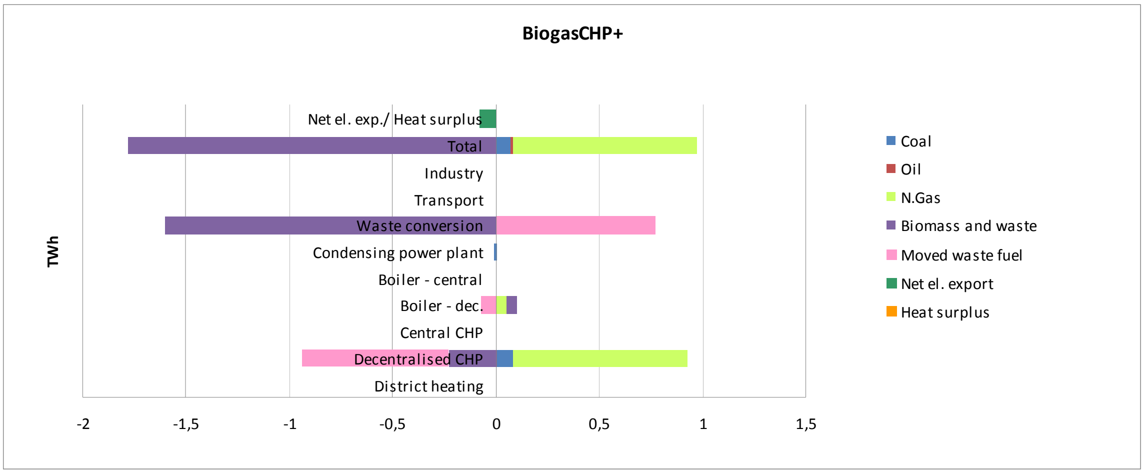


Figure 14 Substituted fuel when adding 4 PJ of organic waste and 2 PJ of manure to anaerobic digestion in a biogas plant with subsequent use of the biogas for CHP production in a decentralised DH area. Includes 1 PJ of fibre fraction from manure burnt in a biomass CHP plant.

In the BiogasCHP+ alternative, 2 PJ of manure is added apart from the 4 PJ of organic waste. The anaerobic digestion of the organic waste in a biogas plant is assumed to facilitate the treatment of manure. Furthermore, it is assumed that the fibre fraction of manure remaining after the anaerobic digestion is used in biomass CHP plants in a decentralised area. The result is an increased displacement of primarily natural gas from decentralised CHP plants and a net increase in the use of biomass in decentralised CHP plants. Again, the net electricity export increases.

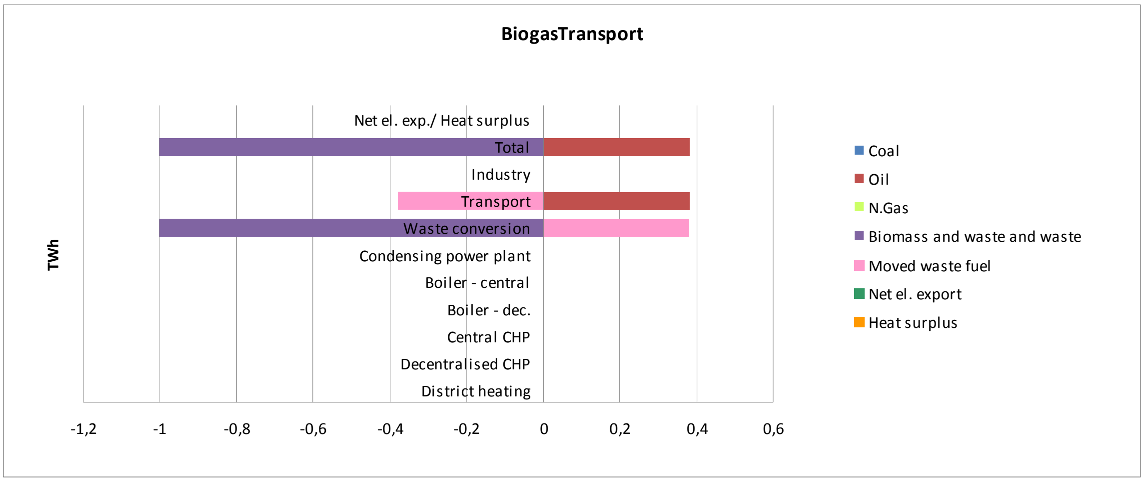


Figure 15 Substituted fuel when adding 4 PJ of organic waste and 2 PJ of manure to anaerobic digestion in a biogas plant with subsequent use of the biogas for transport.

When converting the 4 PJ of organic waste to biogas and subsequently utilising the biogas for transport, around 0.4 TWh of oil is substituted. No changes occur with regard to net electricity export or heat surplus.

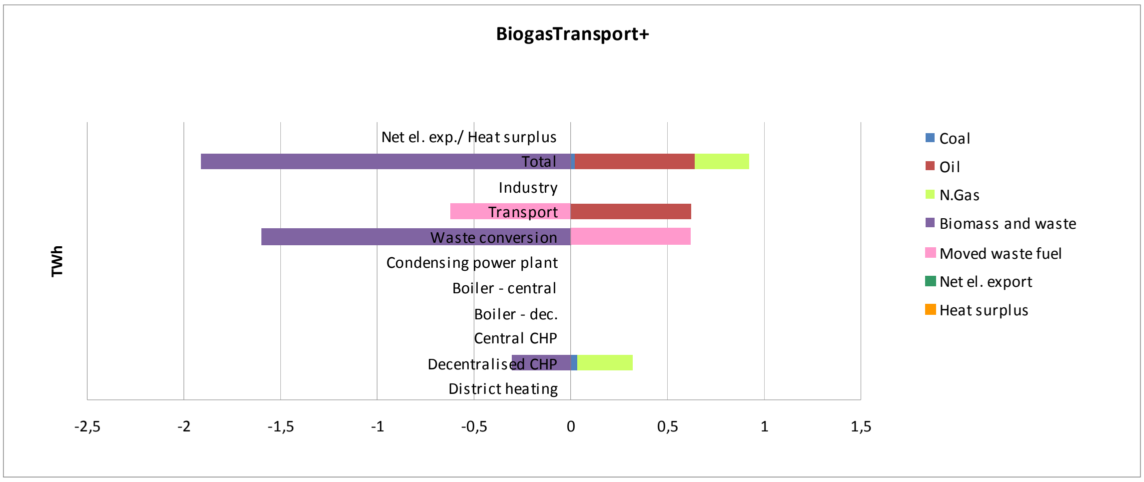


Figure 16 Substituted fuel when adding 4 PJ of organic waste and 2 PJ of manure to anaerobic digestion in a biogas plant with subsequent use of the biogas for transport. Includes 1 PJ of fibre fraction from manure burnt in a decentralised biomass CHP plant.

In the BiogasTransport+ alternative, 2 PJ of manure is added along with the 4 PJ of organic waste, and again, the fibre fraction is burnt in biomass CHP plants in a decentralised area. The result is a substitution of around 0.6 TWh of oil from transport and 0.3 TWh of natural gas from decentralised CHP plants. Again, no changes occur with regard to net electricity export or heat surplus.

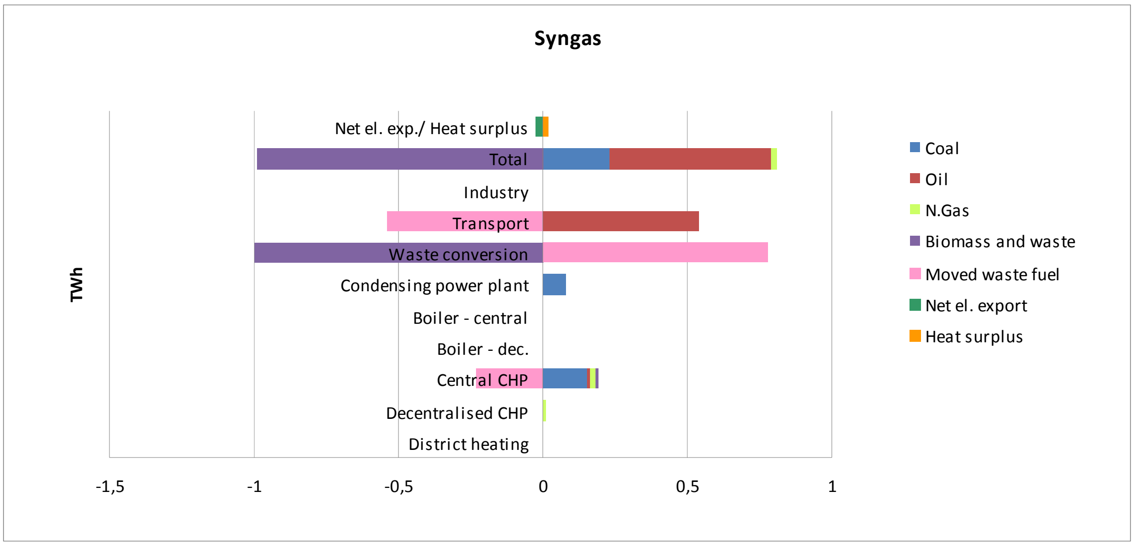


Figure 17 Substituted fuel when adding 4 PJ of mixed waste to gasification with subsequent use of the syngas for transport and CHP in a central DH area

In the syngas alternative, 4 PJ of mixed waste is converted to syngas. Part of it is catalysed to biopetrol and used for transport while another part is used directly in a CHP plant placed in a central area. The result is the substitution of around 0.6 TWh of oil from transport and around 0.2 TWh of coal. A minor increase in net electricity export and a minor decrease in surplus heat occur.

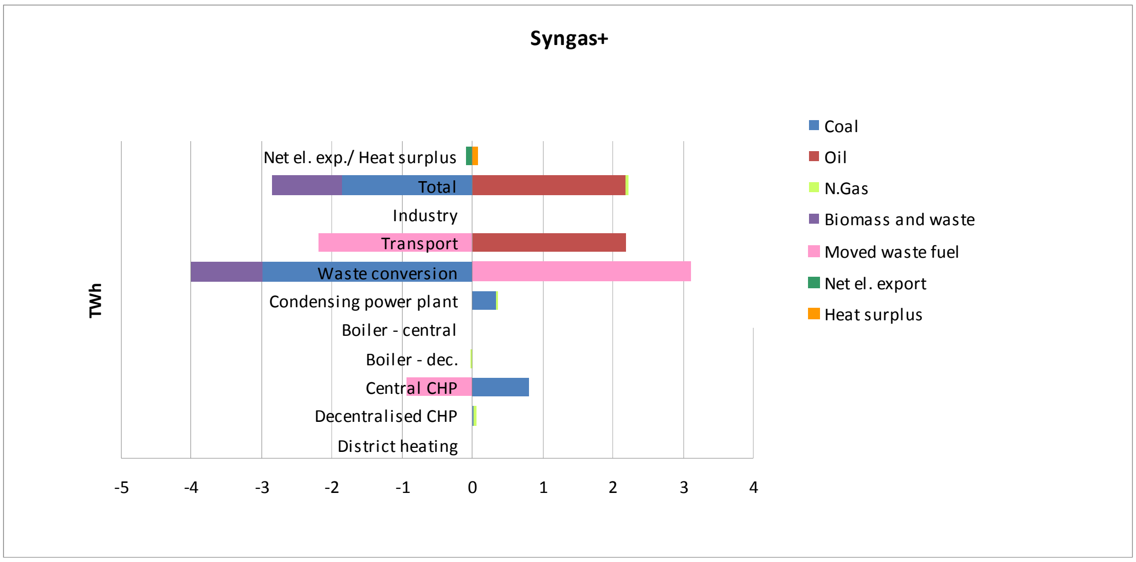


Figure 18 Substituted fuel when adding 4 PJ of mixed waste and 12 PJ of coal to gasification with subsequent use of the syngas for transport and CHP in a central DH area.

In the Syngas+ alternative, the gasification of 4 PJ of waste is assumed to result in the gasification of 12 PJ of coal, presuming that the gasification of coal would otherwise not take place in the current Danish energy system. Around 2.2 TWh of oil is now substituted from the transport sector, while a net increase in the consumption of coal of around 1.9 TWh occurs. Again, a minor increase in net electricity export and a minor decrease in surplus heat take place.

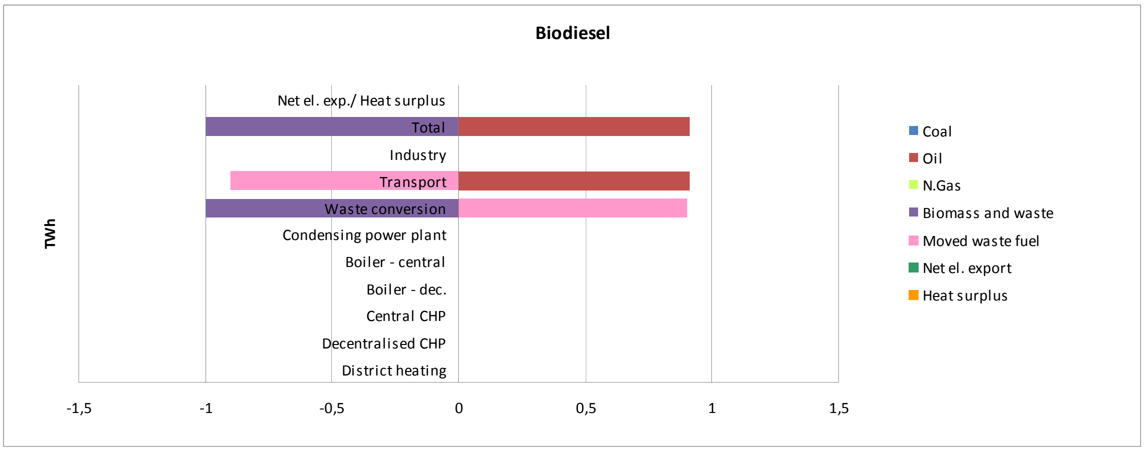


Figure 19 Substituted fuel when adding 4 PJ of animal fat transesterification with subsequent use of the biodiesel for transport

In the Biodiesel alternative, 4 PJ of animal fat is converted to biodiesel and used in the transport sector, thereby substituting around 0.9 TWh of oil. No other changes occur.

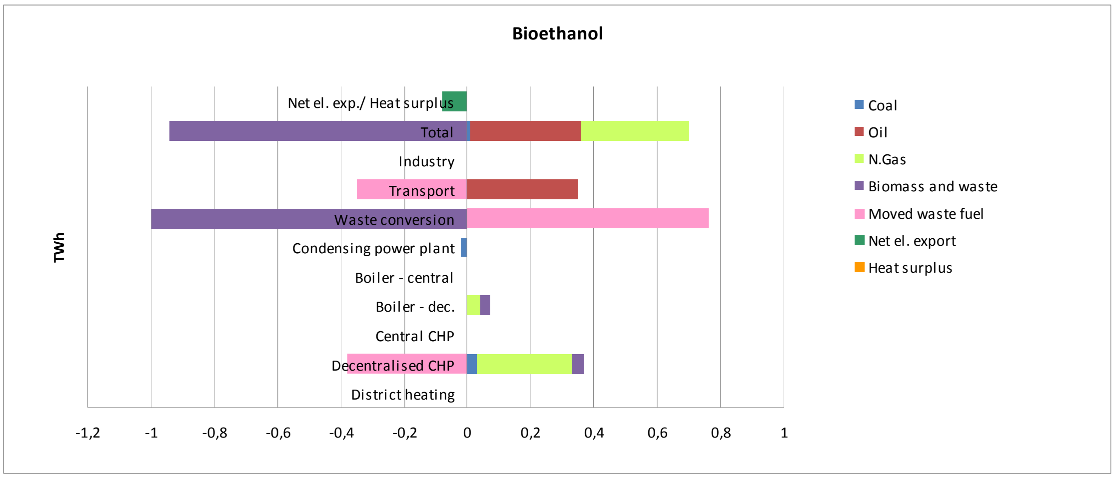


Figure 20 Substituted fuel when adding 4 PJ of organic wastes to fermentation with subsequent use of the bioethanol for transport and by-products for CHP in a decentralised DH area.

In the Bioethanol alternative, organic wastes are converted to bioethanol used for transport and to biogas, solid biomass and hydrogen used for CHP production in a decentralised area. As a result, around 0.4 TWh of oil is substituted in the transport sector together with 0.3 TWh of natural gas from primarily CHP plants but also boilers in a decentralised area. The change results in an increase in the net electricity export.

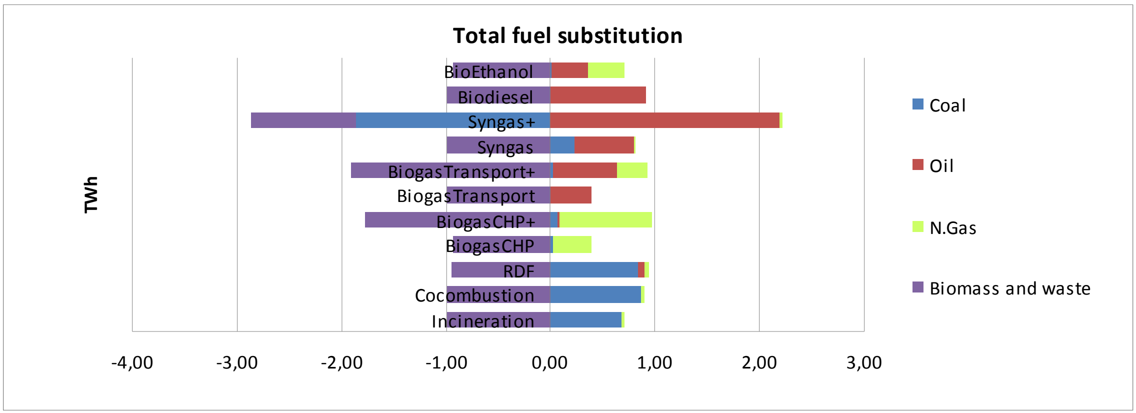


Figure 21 Total substituted fuel for all WtE technologies when adding 4 PJ waste (and 2 PJ manure in the Biogas+ alternatives and 12 PJ coal in the Syngas+ alternative)

Figure 21 illustrates the results of the alternatives subtracted from the reference. From the figure, it can be seen that the RDF, Co-Comb, Biogas+, Syngas and Biodiesel alternatives perform more or less equally well in terms of substituting fossil fuels. The Biogas+ scenarios do, however, use more biomass (primarily manure) to achieve the same fossil fuel substitution. The Biodiesel alternative substitutes mostly oil, whereas the RDF and Co-Comb alternatives substitute mainly coal, and the BiogasCHP+ mainly natural gas. The Syngas+ alternative substitutes the highest amount of oil, but increases the use of coal at the same time.

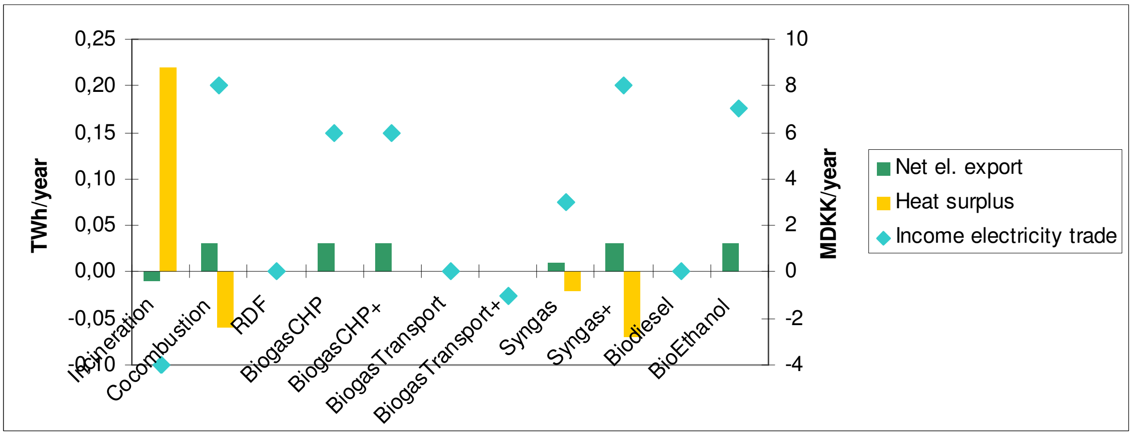


Figure 22 Difference in electricity export, heat surplus and electricity trade income when adding 4 PJ in 2006

In Figure 22, an increase compared to the Reference is shown as a positive value and a decrease as a negative value. In this type of figures, the net electricity export is not divided by the efficiency of a possible marginal electricity-producing plant.

To sum up, the figure shows an increase in the electricity trade income for most alternatives apart from Incineration and, to a lesser degree, Biogas Transport+. Incineration is the only alternative in which the net electricity export decreases and the heat surplus increases. As more waste is added to the system, the flexibility decreases. The highest electricity trade income is found with the Co-combustion and Syngas+ alternatives, which are also the alternatives with the highest net electricity export and the lowest heat surplus.

After having looked at the consequences of adding 4 PJ of waste to different technologies, the consequences of removing 4 PJ of waste from the current use are now analysed. It is analysed what happens when 4 PJ are removed from decentralised or central DH areas and what happens when animal fat removed from the current use for industrial heating.

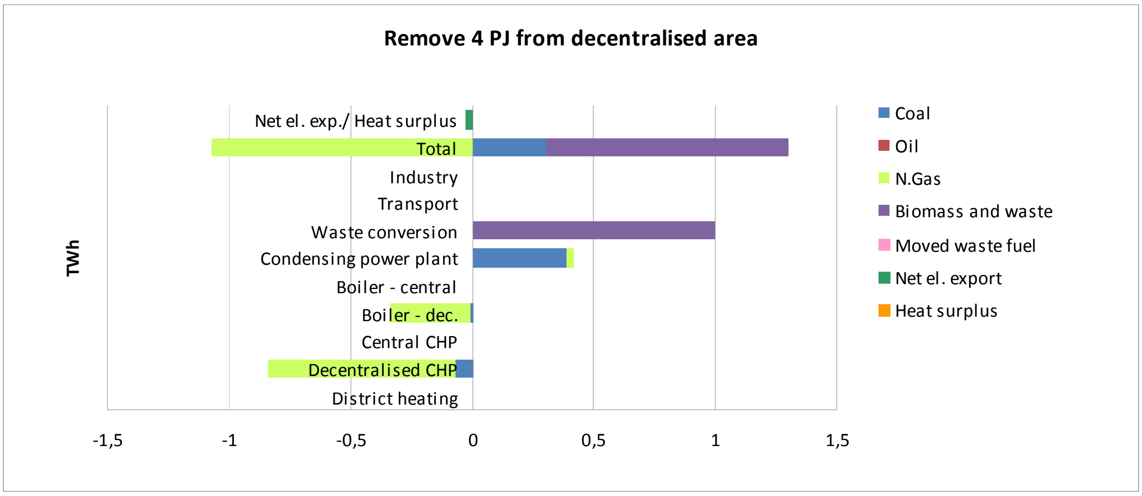


Figure 23 Substituted fuel when removing 4 PJ of mixed waste from waste incineration for CHP in a decentralised DH area.

In Figure 23, it can be seen that the removal of 4 PJ of waste from decentralised CHP results in an increase in the natural gas consumption of CHP plants in decentralised areas. As the natural gas plants have higher electrical efficiencies than waste incineration, coal is substituted in the condensing power plants and an increased consumption of natural gas occurs in the boilers in the decentralised areas to cover the heat demand. A minor increase in the net electricity export also occurs.

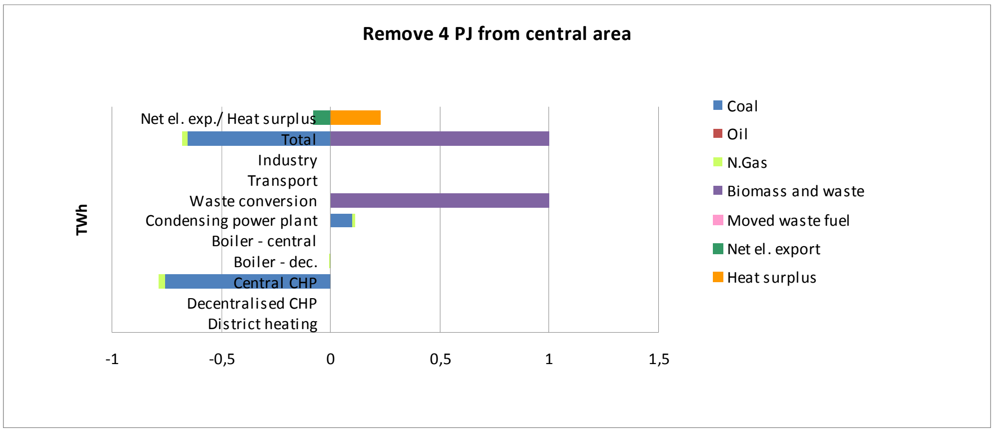


Figure 24 Substituted fuel when removing 4 PJ of mixed waste from waste incineration for CHP in a central DH area.

Figure 24 shows that the removal of 4 PJ of waste from central CHP results in an increase in the coal consumption of CHP plants in central areas. As the coal-fired CHP plants have higher electrical efficiencies than waste incineration, coal is substituted in the condensing power plants. The change results in an increased flexibility in the system and, hence, the heat surplus decreases and the net electricity export increases.

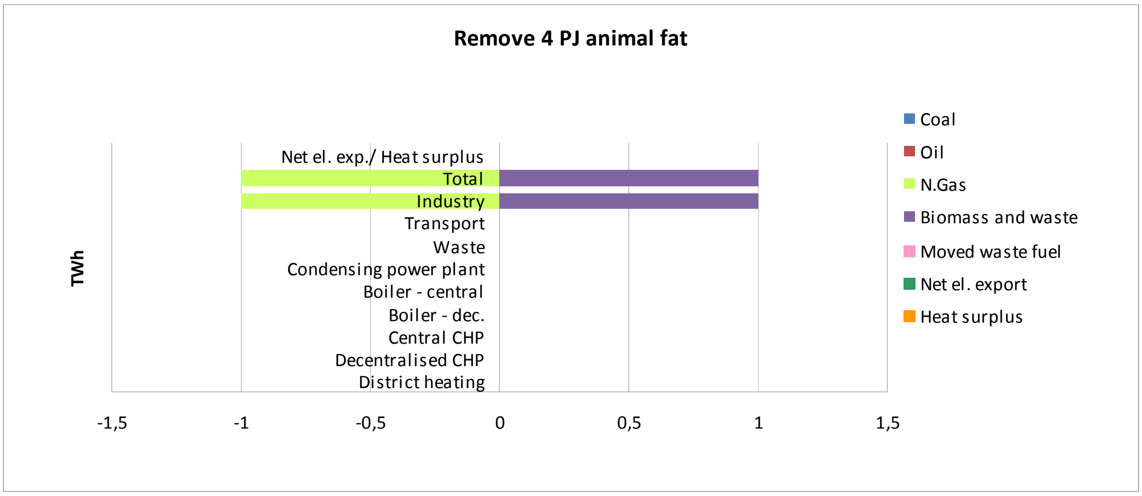


Figure 25 Substituted fuel when removing 4 PJ of animal fat from industrial heating.

When removing animal fat from industrial heating, the heat is instead assumed to be produced on natural gas-fired boilers and, hence, the demand for natural gas increases. No other changes occur.

Although it may be tempting to combine the results of adding 4 PJ of waste in one area with the results of removing 4 PJ in another area, it may not always give the same results as moving 4 PJ of waste from one use to another in the same area.

The table below shows the total fuel consumption and net electricity export for the different technical alternatives when adding or removing 4 PJ of waste.

Table 23 Fuel consumption and net electricity export with the different WtE alternatives when adding or removing 4 PJ in 2006

TWh/year	Total fuel	Coal	Oil	Ngas	Bio	Waste	Other RE	Net el. export
No waste	248,84	68,88	95,49	56,99	21,24	0	6,24	6,94
Reference	251,77	65,64	95,49	52,79	21,23	10,38	6,24	6,80
Incineration	252,07	64,97	95,49	52,76	21,23	11,38	6,24	6,79
Co-combustion	251,88	64,77	95,49	52,77	21,23	11,38	6,24	6,83
RDF	251,78	64,80	95,43	52,75	21,18	11,38	6,24	6,80
BiogasCHP	252,32	65,62	95,49	52,43	21,16	11,38	6,24	6,83
BiogasCHP+	252,58	65,57	95,48	51,90	22,01	11,38	6,24	6,83
BiogasTransport	252,39	65,64	95,11	52,79	21,23	11,38	6,24	6,80
BiogasTransport+	252,76	65,62	94,87	52,51	22,14	11,38	6,24	6,80
Syngas	251,95	65,41	94,93	52,77	21,22	11,38	6,24	6,81
Syngas+	252,41	67,50	93,31	52,75	21,23	11,38	6,24	6,83
Biodiesel	251,86	65,64	94,58	52,79	21,23	11,38	6,24	6,80
BioEthanol	252,01	65,63	95,14	52,45	21,17	11,38	6,24	6,83
Remove waste Dec	251,54	65,34	95,49	53,86	21,23	9,38	6,24	6,81
Remove waste Cen	251,45	66,30	95,49	52,81	21,23	9,38	6,24	6,83
Remove animal fat	251,77	65,64	95,49	53,79	20,23	10,38	6,24	6,80

Table 23 shows the total fuel consumptions of the Danish energy system with the different alternatives. The alternative with the highest fossil fuel consumption is the alternative in which no waste is used. This is also the alternative with the lowest total fuel consumption and the highest net electricity export. Apart from that, the highest fuel consumption is found in the BiogasTransport+ alternative in which extra manure is utilised and a relatively high amount of coal is also used. The highest use of coal is seen in the Syngas+ alternative, where coal is added to gasify waste. This is also the alternative with the lowest oil consumption. The lowest coal consumption is found in the Co-combustion alternative and the lowest natural gas consumption is seen in the BiogasCHP+ alternative.

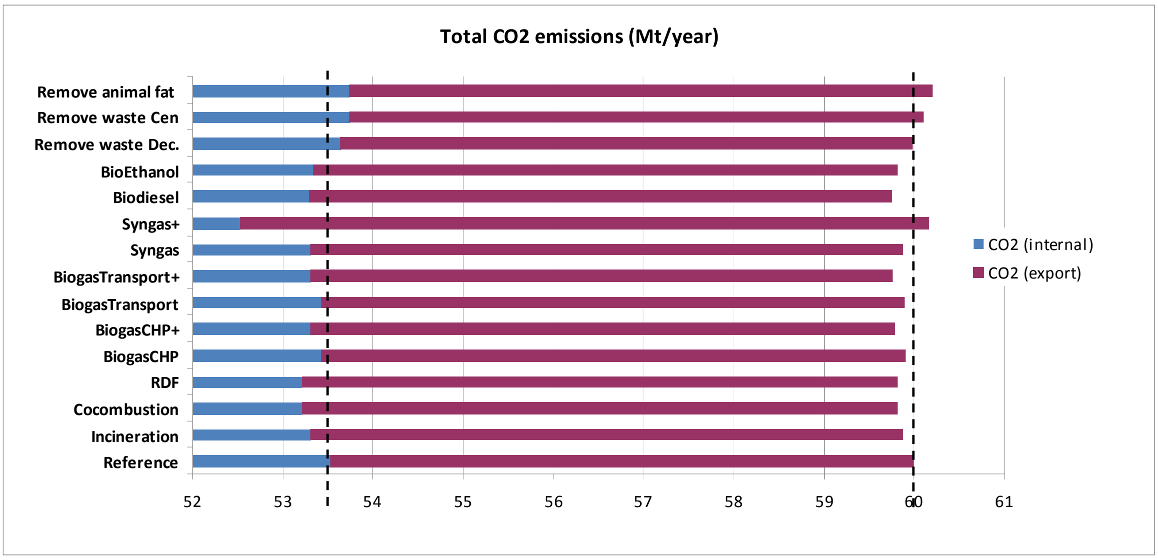


Figure 26 Total CO_2 emissions when adding or removing 4 PJ of waste (and adding 2 PJ of manure in the Biogas+ alternatives and 12 PJ of coal in the Syngas+ alternative). The dotted line illustrates the level of CO_2 emissions in the Reference for total CO_2 emissions and for emissions related to internal electricity consumption.

Figure 26 illustrates the differences in CO2 emissions from the Danish energy system between the reference and the various alternatives. When regarding the total CO_2 emissions including emissions related to export, in most cases, a reduction of CO_2 emissions occurs compared to the Reference. Only the removal of waste from a central district heating area, the removal of fat from industrial heating as well as the Syngas+ scenario emit more than the Reference. The alternatives with least CO_2 emissions are the Biodiesel, the BiogasTransport+ and the BiogasCHP+ alternatives.

When only internal emissions are taken into account, the picture changes slightly. When assuming that condensing coal-fired power plants constitute the marginal power-producing unit, the emissions from the internal use of electricity can be estimated by subtracting emission figures equivalent to those of a coal-fired power plant with an efficiency of 40% which produces the electricity exported. The results will now show that the removal of waste and animal fat from the energy system leads to an increase in CO_2 emissions. Syngas+ is now by far the alternative which substitutes most CO_2 followed by Co-combustion and RDF.

As Syngas+ changes from being one of the worst to the best alternative, depending on the perspective, the results illustrate the importance of identifying the correct marginal electricity-producing unit when attempting to isolate the CO_2 emissions related to internal electricity consumption. Assuming this is always coal-fired power plants is a crude simplification. Finding the marginal electricity-producing unit is best done in an energy model which incorporates the entire surrounding electricity market, in this case the Nordic electricity market.

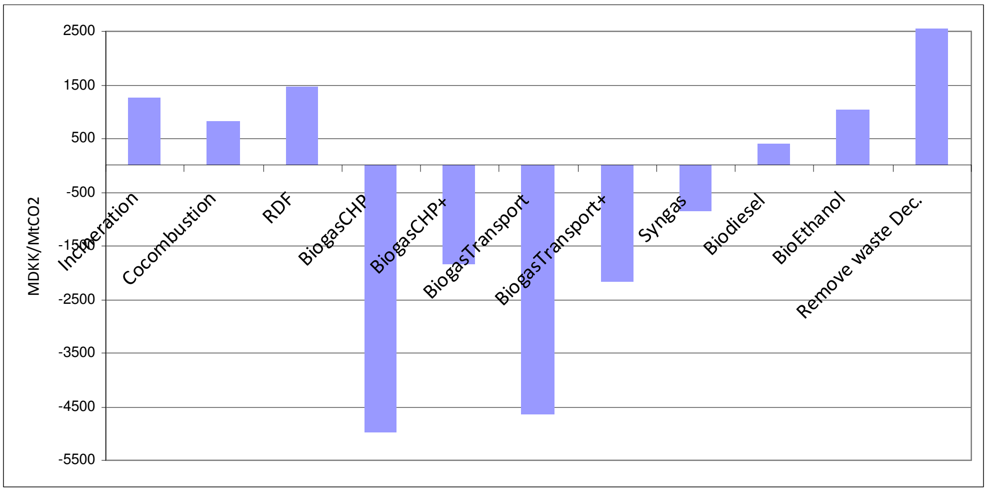


Figure 27 CO_2 reduction cost when adding 4 PJ of waste. RemoveWasteDec is almost 20000 MDKK/Mt CO_2 and is cut off in the figure.

Figure 27 illustrates the CO2 reduction costs measured as the increase in costs divided by the total CO_2 reduction achieved for the alternatives providing a CO_2 reduction. Removing waste from a decentralised district heating area is very expensive, corresponding to a price of almost 20000 DKK/t CO_2, and the column is cut off to illustrate the other reduction costs. Five of the alternatives result in lower annual costs of the energy system than today, resulting in negative reduction costs. Here, Biogas results in the lowest CO_2 reduction costs, followed by the Syngas alternative. It should be noted that, if distribution costs for biogas were included in the BiogasTransport initiative, the CO_2 reduction costs could be altered considerably.

5.2 Move 4 PJ 2006

In this section, results are presented for analyses of scenarios in which 4 PJ of waste is moved from its present use and added to the various technical alternatives. The question to be answered is “How low CO_2 emissions can we achieve when changing the uses of waste for energy?”

Table 24 Resource use for the WtE alternatives when moving 4 PJ in 2006

PJ	Specific plant	Waste inc.	Biomass CHP
Reference		37	46
Incineration (Cen.)	4	33	46
Co-combustion/ Ded. RDF (Cen)	4	33	46
Biogas (Dec)	4+2*	33	46+1*
Syngas (Cen)	4+12*	33	46
Biodiesel (Dec)	4	37	42
Bioethanol (Dec)	4	36	43

*Extra resource used only in this type of plant – included in the ”Plus” scenarios

Table 24 is similar to Table 21 apart from the fact that, in Table 25, 4 PJ is both added and removed. The distribution can also be seen in Figure 28.

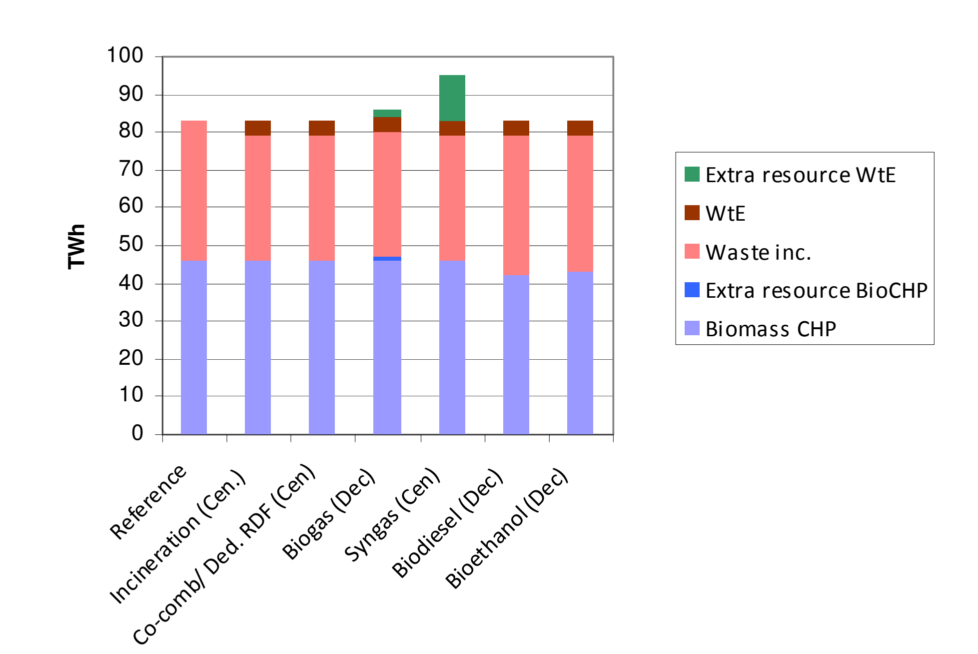


Figure 28 Resource use for the WtE alternatives when moving 4 PJ in 2006

The investment and O&M costs as well as the lifetimes are the same for the moving of 4 PJ of waste in 2006 (Move 4 PJ scenario) as for the addition of 4 PJ of waste in 2006 (Add 4 PJ scenario) and are displayed in Table 22.

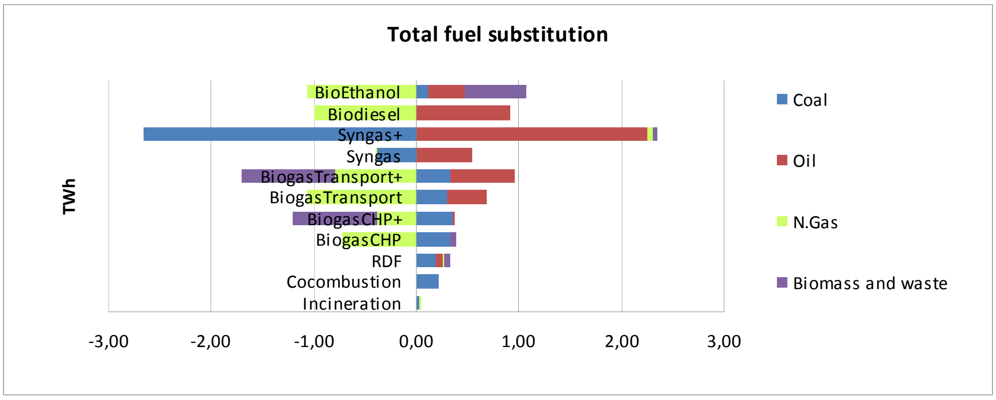


Figure 29 Total substituted fuel for all WtE technologies when moving 4 PJ of waste (and adding 2 PJ of manure in the Biogas+ alternatives and 12 PJ of coal in the Syngas+ alternative)

In Figure 29, results from the technical alternatives are again subtracted from the reference. As can be seen, the total fuel substitution achieved by moving 4 PJ of waste is significantly different from the one resulting from the addition of 4 PJ, as the benefit from adding waste is reduced by the disadvantage of removing 4 PJ. The same amounts of oil are substituted, whereas the consumption of natural gas increases in the alternatives placed in a decentralised DH area (Biogas, Biodiesel and Bioethanol). The same is the case of the coal consumption of the alternatives placed in a central area (Incineration, Co-combustion, RDF and Syngas). Biomass is substituted in the Bioethanol alternative, as it is here assumed that straw is moved from biomass CHP to the bioethanol plant. Furthermore, the coal consumption increases in condensing power plants when less electricity is produced as a result of moving the 4 PJ of waste.

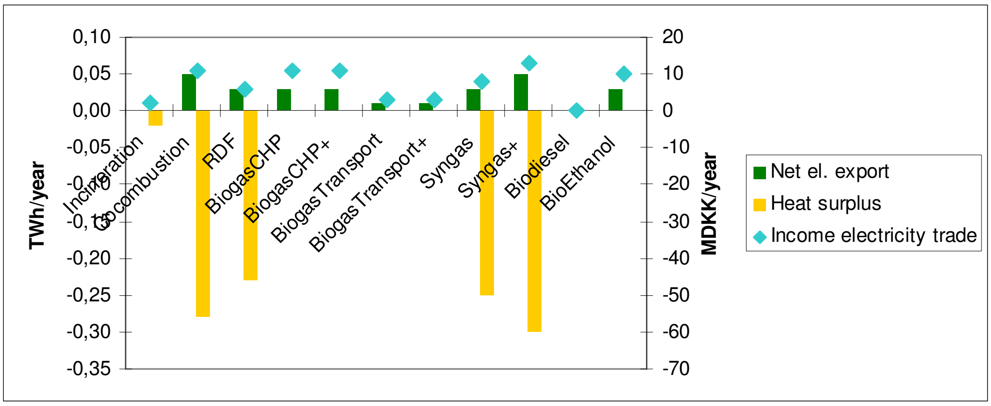


Figure 30 Difference in net electricity export, heat surplus and electricity trade income when moving 4 PJ in 2006

Figure 30 shows that the Syngas alternatives as well as the Co-combustion and RDF alternatives increase the flexibility of the energy system, resulting in increased electricity export and decreased heat surplus. The Biodiesel alternative has no influence on the electricity export, heat surplus or electricity trade income. The highest electricity trade income is found in the Syngas+ alternative. The electricity trade income follows the difference in electricity export; apart from in the BiogasCHP and the Bioethanol alternatives, which are able to gain more by the increased electricity export. The improved electrical efficiency of the Incineration alternative decreases the heat surplus but has no effect on the net electricity export.

In Table 25, the total fuel consumption and net electricity export are shown for each alternative.

Table 25 Fuel consumption and net electricity export with the different WtE alternatives when moving 4 PJ in 2006

TWh/year	Total fuel	Coal	Oil	Ngas	Bio	Waste	Other RE	Net el. export
Reference	251,77	65,64	95,49	52,79	21,23	10,38	6,24	6,80
Incineration	251,73	65,61	95,49	52,78	21,23	10,38	6,24	6,80
Co-combustion	251,55	65,42	95,49	52,79	21,23	10,38	6,24	6,85
RDF	251,45	65,45	95,43	52,77	21,18	10,38	6,24	6,83
BiogasCHP	252,10	65,31	95,49	53,51	21,17	10,38	6,24	6,83
BiogasCHP+	252,61	65,28	95,48	53,17	22,06	10,38	6,24	6,83
BiogasTransport	252,16	65,34	95,11	53,86	21,23	10,38	6,24	6,81
BiogasTransport+	251,77	65,64	95,49	52,79	22,14	10,38	6,24	6,81
Syngas	251,63	66,03	94,95	52,80	21,23	10,38	6,24	6,83
Syngas+	252,08	68,30	93,25	52,72	21,19	10,38	6,24	6,85
Biodiesel	251,86	65,64	94,58	53,79	21,23	10,38	6,24	6,80
BioEthanol	251,77	65,52	95,14	53,85	20,64	10,38	6,24	6,83

The highest fuel consumption occurs in the BiogasCHP+ alternative, whereas the lowest is found in the RDF alternative. The Syngas+ alternative is the alternative which results in the highest coal consumption and the lowest oil and natural gas consumption. The lowest coal consumption is found in the BiogasCHP alternatives. The highest oil consumption is found in the Reference and CHP alternatives and the highest natural gas consumption in the BiogasTransport alternative.

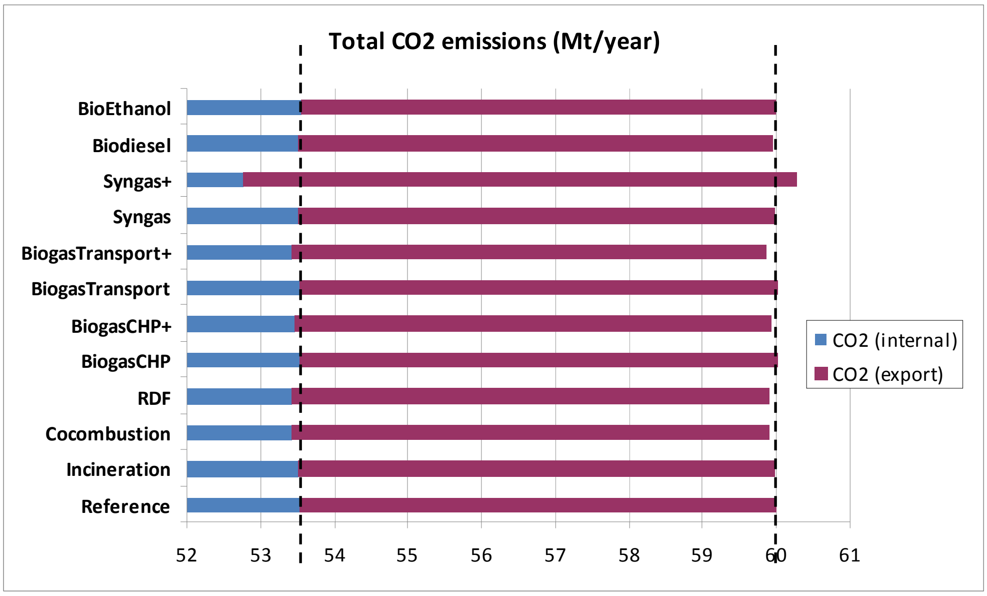


Figure 31 Total CO_2 emissions when moving 4 PJ of waste (and adding 2 PJ of manure in the Biogas+ alternatives and 12 PJ of coal in the Syngas+ alternative). The dotted line illustrates the level of CO_2 emissions in the Reference for total CO_2 emissions and for emissions related to internal electricity consumption.

As seen in Figure 31, the reduced CO2 emissions achieved by moving 4 PJ of waste are also different from the reductions achieved by adding 4 PJ. When adding 4 PJ, only the Syngas+ alternative and the removal of waste resulted in increased CO_2 emissions. When including the drawback of removing the 4 PJ from their current usage, the BiogasCHP and the BiogasTransport alternatives also result in increased emissions. Now the BiogasTransport+, the Co-combustion and the RDF alternatives give the highest CO_2 reductions, and no differences can be found between the CO_2 emissions of the Bioethanol alternative and those of the Reference, respectively. Below, the CO_2 reduction costs for the alternatives resulting in CO_2 emissions reductions are illustrated.

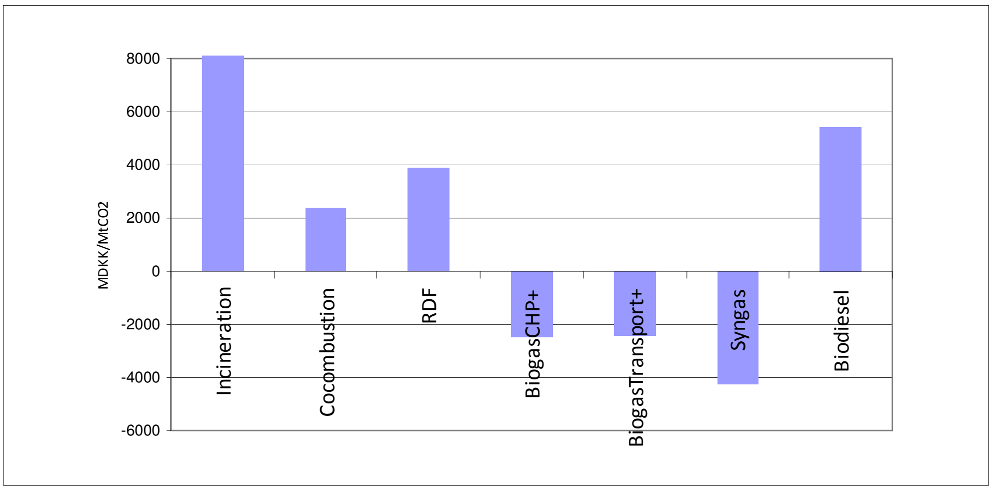


Figure 32 CO_2 reduction cost when moving 4 PJ of waste. The cost of Incineration is almost 20000 MDKK/Mt CO_2 and is cut off.

From Figure 32, it can be seen that the Biogas+ and Syngas alternatives represent savings compared to today's system. Incineration is the most expensive alternative in terms of CO_2 reduction at a price of almost 20000 DKK/t CO_2.

5.3 Full resource potential in 2006

Fruergaard [93] has identified the existence of an unused biomass resource potential in Denmark. In this section, results are presented of analyses of the full resource use. If not used in other ways, waste is incinerated primarily for CHP as today, biomass is used for CHP and boilers and animal fat is used for industrial heating. The question to be answered is "How high CO_2 emission reductions can we achieve when using the full resource potential?"

In Table 26, the resource use of the various alternatives is shown. As can be seen, the potentials vary significantly for the different alternatives. It is particularly noteworthy that an unused potential of 17 PJ of manure is identified for biogas production. Furthermore, a potential of 10 PJ of waste is identified for gasification. The gasification of this waste together with coal would require the use of 31 PJ of coal.

Table 26 Resource use for the WtE alternatives when using full resource potential in 2006

PJ	Specific plant	Waste inc.	Biomass CHP
Reference		37	46
Reference - Extra		37	46+19
Incineration (Dec/Cen)	10**	27	46+19
Co-combustion/ Ded. RDF (Cen)	7+3**	27	46+19
Biogas+ (Dec)	4+40*+6**	27	46+19+17*
Syngas (Cen)	10+31*	27	46+19
Biodiesel (Dec)	3+10**	27	46+16
Bioethanol (Dec)	18+5*+4**	27	46+7

*Extra resource used only in this type of plant
**10 PJ of waste is used in new waste incineration plants (35% in the decentralised and 65% in central DH areas) unless it is used in the other conversion plants.

In the Biogas+ alternatives, the full potential of organic household waste, manure, organic industrial waste and sludge is used. In the Syngas+ alternative, coal is included and, in the Syngas alternative, it is not. The resource use is also illustrated in Figure 33.

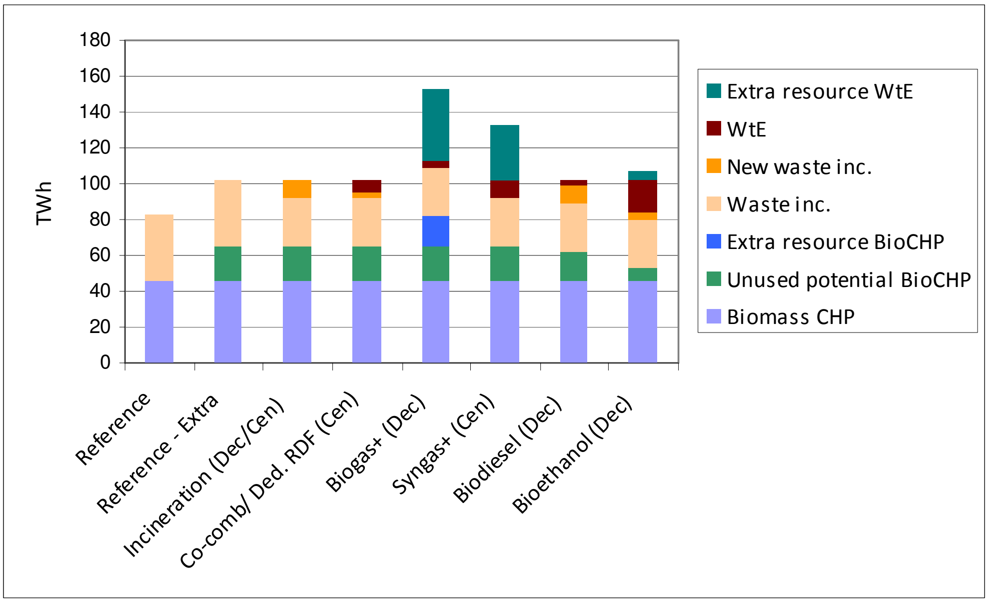


Figure 33 Resource use for the WtE alternatives when using the full resource potential in 2006

Table 27 Investment and Operation and Maintenance Costs as well as availability and lifetimes when using the full resource

WtE technologies	Investment (MEUR/PJ)	O&M (%)	Availability (%)	Lifetime (years)	Year	Source
Waste Incineration	52.2	7	98	20	2004	[1]
Co-combustion	1.7	10	98	30	2004	[1]
Dedicated RDF	51.1	4	91	20	2004	[1]
BiogasCHP+	18.3	7	98	20	2004	[1]
BiogasTransport+	34.1	4	98	20	2004	[1]
Syngas	50.9	4	80	20	2010-20	[63]
Biodiesel	13.9	1	98	20	2006	[82]
Bioethanol	65.0	10	98	20	2006	[45]

Only the biogas alternatives in Table 27 have other investment costs measured in MEUR/PJ input than when adding 4 PJ.

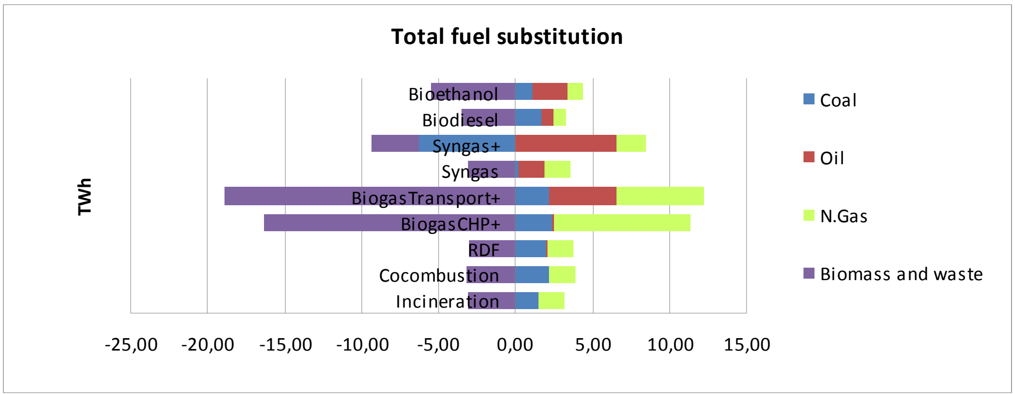


Figure 34 Total substituted fuel for all WtE technologies when moving the full potential

In Figure 34, the technical alternatives utilising the full resource potential have been subtracted from the reference (today's energy system). The results, therefore, mainly illustrate the benefit of utilising the resource potential and, to a less degree, the drawbacks of moving waste from waste incineration or from combustion in biomass CHP plants, which are the default solutions when the resources are not utilised in the various alternatives. In that sense, the figure resembles the results of adding 4 PJ more than the results of moving 4 PJ. It should be noted that the potential resources are greatest for the Biogas alternatives, which is one of the primary reasons that the substituted consumption is largest here.

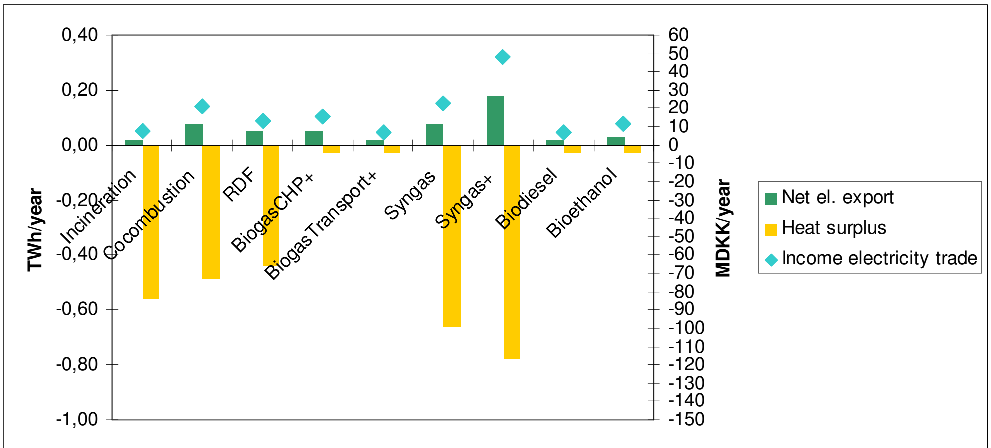


Figure 35 Difference in electricity export, heat surplus and electricity trade income when moving the full resource potential in 2006

From Figure 35, it can be seen that all alternatives increase the flexibility of the system with reduced heat surplus, increased electricity export and increased income from electricity export. The Syngas+ alternative results in the lowest heat surplus and the highest electricity export as well as the largest electricity trade income. For the Incineration alternative, the increased substitution of the incineration plants with new plants with higher electrical efficiency, compared to moving 4 PJ, results in both a decrease in heat surplus and an increase in net electricity export.

Table 28 Fuel consumption and net electricity export with the different WtE alternatives when moving the full resource potential in 2006

TWh/year	Total fuel	Coal	Oil	Ngas	Bio	Waste	Other RE	Net el. export
Reference	251,77	65,64	95,49	52,79	21,23	10,38	6,24	6,80
Reference Extra	251,77	64,17	95,45	51,16	24,37	10,38	6,24	6,80
Incineration	251,58	63,98	95,45	51,14	24,39	10,38	6,24	6,82
Co-combustion	251,14	63,51	95,45	51,14	24,42	10,38	6,24	6,88
RDF	251,05	63,72	95,34	51,09	24,28	10,38	6,24	6,85
BiogasCHP+	256,80	63,24	95,42	43,95	37,57	10,38	6,24	6,85
BiogasTransport+	258,50	63,52	91,03	47,19	40,14	10,38	6,24	6,82
Syngas	251,36	65,42	93,83	51,12	24,36	10,39	6,24	6,88
Syngas+	252,75	71,97	88,98	50,89	24,29	10,38	6,24	6,98
Biodiesel	252,02	63,98	94,64	52,03	24,75	10,38	6,24	6,82
BioEthanol	252,92	64,53	93,22	51,78	26,77	10,38	6,24	6,83

As can be seen in Table 28, the highest fuel consumption occurs in the BiogasTransport+ alternative, and the lowest in the RDF alternative. Again, the Syngas+ alternative results in the highest coal consumption and the lowest oil consumption. The highest oil and natural gas consumption are, again, to be found in the Reference. The lowest natural gas consumption is also to be found in the BiogasCHP+ alternative. The highest net electricity export is found in the Syngas+ alternative, and the lowest in the Reference.

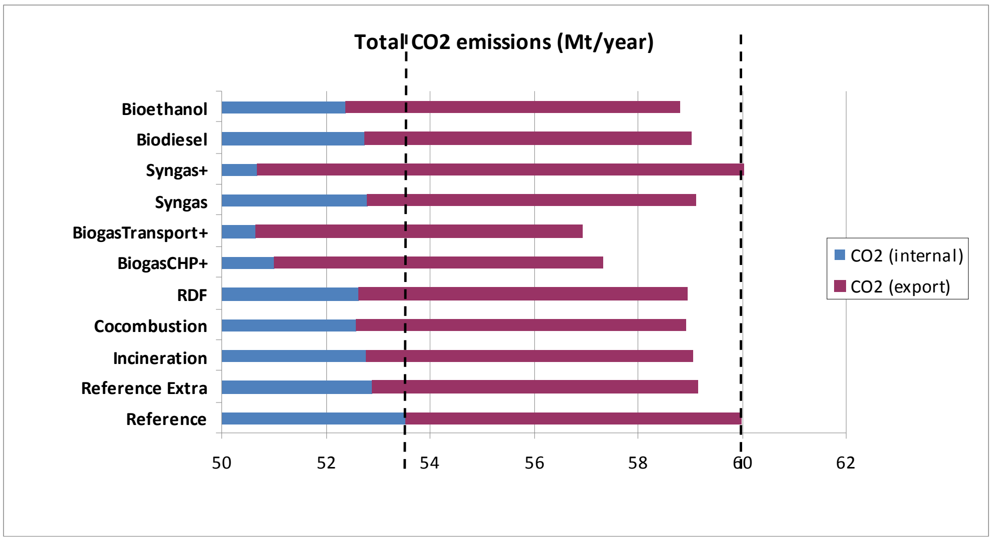


Figure 36 Total CO_2 emissions when moving the full resource potential. The dotted line illustrates the level of CO_2 emissions in the Reference for total CO_2 emissions and for emissions related to internal electricity consumption.

With regard to the CO_2 emission saving potential, the BiogasTransport+ alternative is the best, but only marginally better than the BiogasCHP+ alternative. The Syngas+ is marginally worse than the Reference in terms of total CO_2 emissions, including emissions from export, and as good as the BiogasTransport+ alternative when only looking at emissions from internal consumption.

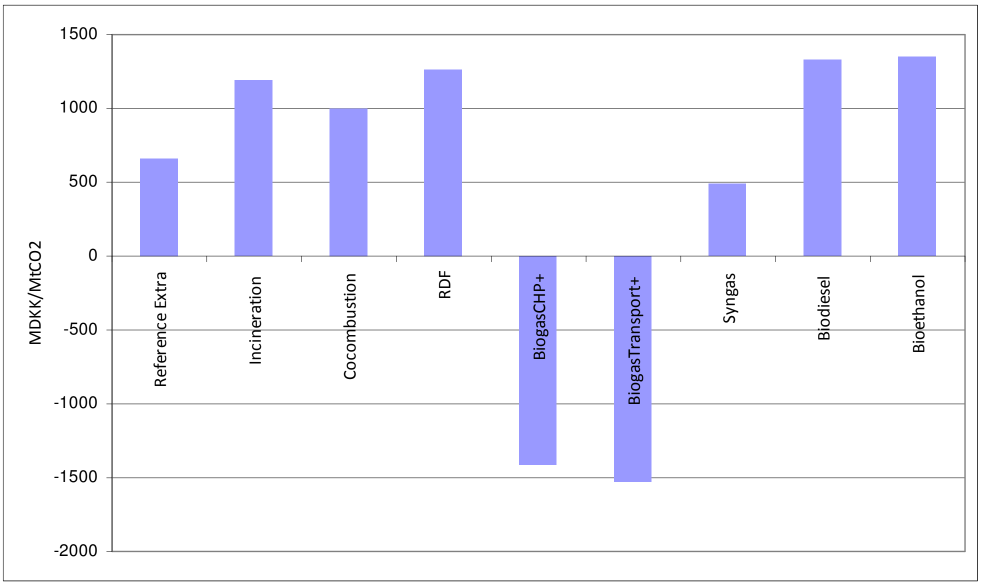


Figure 37 CO_2 reduction cost when moving full resource potential

The annual cost of the energy system with the various alternatives has been calculated in the way that all alternatives are assumed to carry the full burden of the investments needed to handle the extra resource. Only the ReferenceExtra alternative does not include costs for the upgrade required to incinerate up to 10 PJ of waste in new waste incineration plants. Only the Incineration and the Biodiesel alternatives carry the burden of investing in new waste incineration plants which can incinerate the full potential of 10 PJ.

The Biogas+ alternatives result in net savings in annual costs. The most expensive alternatives are the Bioethanol and Biodiesel alternatives.

5.4 Move 4 PJ 2050

In this section, results are presented of analyses of scenarios in which 4 PJ of waste is moved from where it is used in the reference and added to the various technical alternatives in a 100% renewable energy system. As the system is relying 100% on renewable energy, the only CO_2 emissions from energy conversion stems from the fossil part of the waste utilised. This is the same in all alternatives, apart from the Reference system in which no waste is used. As biomass will be a limited resource in a 100% RE system, the focus on reducing CO_2 emissions changes to a focus on reducing biomass consumption. The question to be answered here is therefore "How can we reduce biomass consumption by changing the use of waste for energy?"

Table 29 Resource use for the WtE alternatives when moving 4 PJ in 2050

PJ	Specific plant	Waste inc.	Biomass CHP
Reference		37	132
Incineration (Cen.)	4	33	132
Co-combustion/ Ded. RDF (Cen)	4	33	132
Biogas (Dec)	4+2*	33	132
Syngas (Cen)	4+12*	33	132
Biodiesel (Dec)	4	37	128
Bioethanol (Dec)	4	36	129

*Extra resource used only in this type of plant – included in the ”Plus” scenarios

For simplicity, the same amount of waste is used in the reference in 2050 as in the 2006 reference, as can be seen in Table 29. A much larger amount of biomass is, however, used to cover the energy demand by renewable energy. For the Syngas+ alternative, it is assumed that the waste is co-gasified with biomass. The resource use is illustrated in Figure 38.

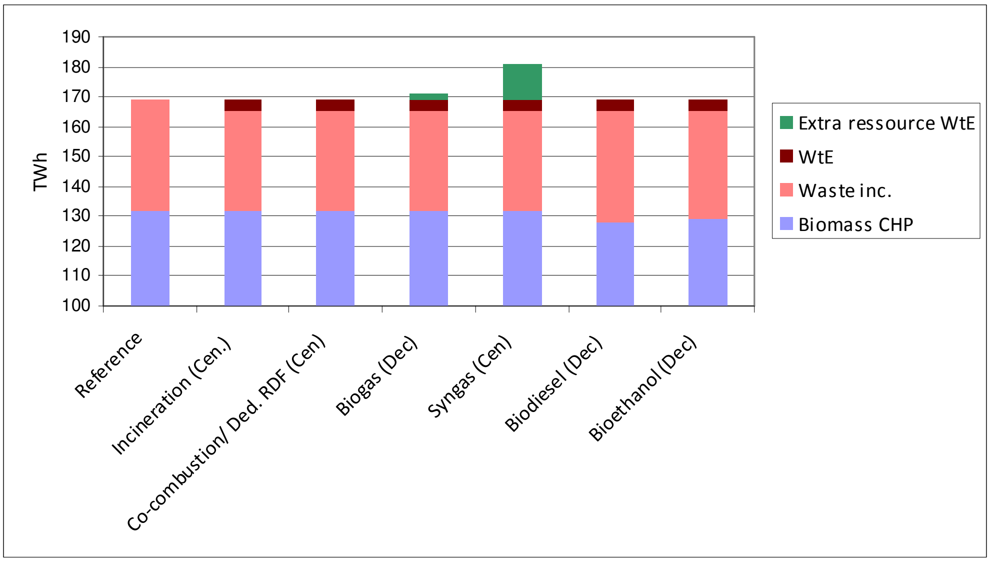


Figure 38 Resource use for the WtE alternatives when moving 4 PJ in 2050

Please note that, due to the large biomass consumption assumed in 2050, the figure starts at 100 TWh.

Table 30 Investment and Operation and Maintenance Costs as well as availability and lifetimes when moving 4 PJ in 2050

WtE technologies	Investment (MEUR/PJ)	O&M (%)	Availability (%)	Lifetime (years)	Year	Source
Waste Incineration	51.4	7	99	20	2020-30	[1]
Co-combustion	22.2	4	90	30	2020-30	[1]
Dedicated RDF	34.4	4	91	20	2020-30	[1]
Biogas CHP	4.7/14.8*	7	98	20	2020-30	[1]
Biogas Transport	15.4/25.4*	5	98	20	2020-30	[1]
Syngas	50.9	4	80	20	2010-20	[63]
Biodiesel	13.9	1	98	20	2006	[82]
Bioethanol	29.0	10	98	20	2010-20	[63]

* Biogas Plus alternatives

With regard to the investment costs shown in Table 30, the first five alternatives on the list have been assigned the prices of 2020-2030, as given in the Technology Data for Electricity and Heat Generating Plants from the Danish Energy Authority et. al. 2005. The Syngas investment costs have been kept at the same level, as the prices were already future prices including expectations of decreases in costs and increases in efficiencies. The Biodiesel investment costs have also been maintained, as production of biodiesel from animal fat is a fairly mature technology, which is not expected to change significantly in the future. Finally, the investment costs have been replaced by costs from the Well-To-Wheels Report by EUCAR et. al. 2007, as these represent an estimation of future costs and a significant reduction in costs compared to the costs used for 2006.

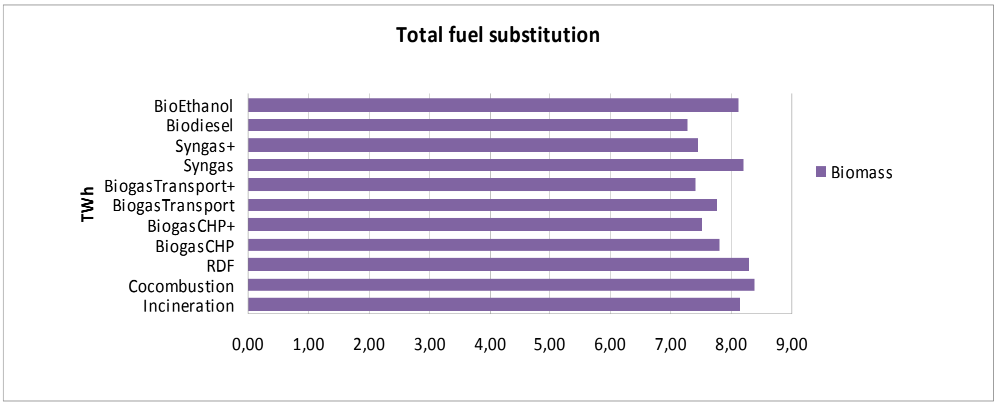


Figure 39 Total substituted fuel for all WtE technologies when moving 4 PJ of waste (and adding 2 PJ of manure in the Biogas+ alternatives and 12 PJ of biomass in the Syngas+ alternative)

In Figure 39, results from the analysis of technical alternatives are subtracted from a scenario in which waste is not used for energy. As can be seen, the only type of fuel use which alters is the biomass consumption. The results of the analysis of alternatives are compared with a reference case in which no waste is used and, hence, all alternatives substitute biomass. Furthermore, for the Biogas+ scenarios, it is assumed that an unused resource of manure is still available, and this resource is added to the system. Co-combustion, RDF and Syngas use less biomass than Incineration. The Biodiesel alternative results in a high use of biomass, as the efficiency of producing transport fuel is lower than the efficiency of the alternative technologies of the model, such as hydrogen and electric cars.

The highest substitution occurs with Co-combustion. This alternative does, however, require large-scale combustion of biomass and it is not certain whether this will take place in a future with 100% RE. The high competition on biomass resources and the need for energy efficiency may instead result in a gasification of the biomass. If this technology exists, it may be possible to co-gasify waste with biomass in existing biomass gasification plants, making the Syngas alternative, in which no extra biomass is required, more likely. The Syngas alternative could also use other technologies, such as super critical water gasification based on the gasification of waste only. These technologies are, however, still at the developmental stage.

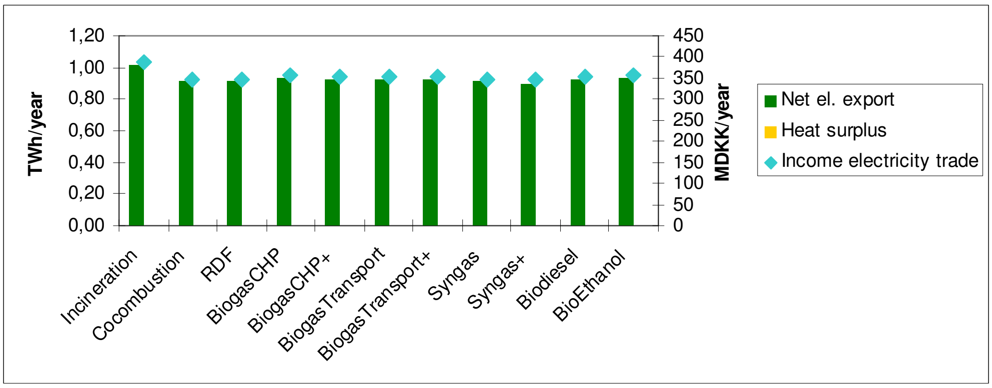


Figure 40 Differences in electricity export, heat surplus and electricity trade income when moving 4 PJ in 2050

Figure 40 shows little difference in the electricity export and in the income from trade with electricity. Increased electricity trade income follows increased electricity export. The highest net electricity export and the highest income from electricity trade are found in the Incineration alternative. No difference can be seen between the heat surplus in the reference alternative with no waste and the heat surplus in the other alternatives. This is due to the assumed existence of a large heat market, which can use the full heat from CHP, also during summertime.

Table 31 Fuel consumption and net electricity export with the different WtE alternatives when moving 4 PJ in 2050

TWh/year	Total fuel	Biomass	Waste	Wind	Other RE	H2	Net el. export
Reference	119,84	75,82	0	34,30	9,72	12,23	3,45
Incineration	122,08	67,69	10,38	34,29	9,72	12,25	4,47
Co-combustion	121,84	67,45	10,38	34,29	9,72	12,25	4,36
RDF	121,92	67,53	10,38	34,29	9,72	12,25	4,36
BiogasCHP	122,41	68,02	10,38	34,29	9,72	12,25	4,38
BiogasCHP+	122,71	68,32	10,38	34,29	9,72	12,25	4,37
BiogasTransport	122,46	68,07	10,38	34,29	9,72	12,25	4,37
BiogasTransport+	122,82	68,43	10,38	34,29	9,72	12,25	4,37
Syngas	122,01	67,62	10,38	34,29	9,72	12,25	4,36
Syngas+	122,76	68,37	10,38	34,29	9,72	12,25	4,35
Biodiesel	122,94	68,55	10,38	34,29	9,72	12,25	4,37
BioEthanol	122,09	67,70	10,38	34,29	9,72	12,25	4,38

The highest resource consumption is found in the Biodiesel alternative. Apart from the reference, in which no waste is used for energy purposes, this is also the alternative with the highest biomass consumption, as can be seen in Figure 39. The lowest biomass consumption occurs in the Co-combustion alternative. The Reference is also the alternative with the highest wind power integration, due to the higher flexibility of the system which does not have waste utilisation. No differences are found in the utilisation of wind power, other RES and H2 of the remaining alternatives. All alternatives export more than the Reference. Only minor differences are found with regard to net electricity export of the other alternatives, apart from the Incineration alternative which results in the highest net export. One may expect that the system is forced to export due to lower flexibility, but as the income based on electricity trade is also the largest among the alternatives, this is not the case.

To compare the alternatives, a cost of reducing biomass consumption has been calculated. The results are illustrated in Figure 41.

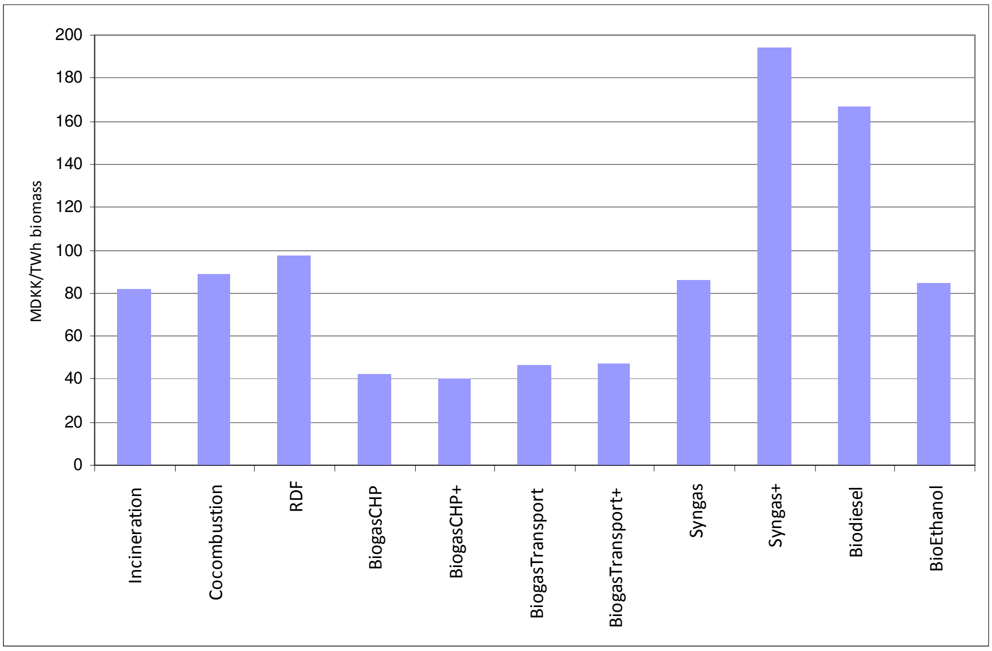


Figure 41 Biomass reduction cost when moving 4 PJ waste in 2050

The lowest biomass reduction cost is found in BiogasCHP+ with 40 DKK/TWh or 11 DKK/GJ of biomass. The costs of the other biogas alternatives are similarly low. The Incineration, Co-combustion, RDF, Syngas and Bioethanol alternatives follow with CO_2 reduction costs between 82 and 98 DKK/TWh. The highest reduction costs are found in the Biodiesel and Syngas+ alternatives. Compared to a biomass cost of 54 DKK/GJ, even the highest biomass reduction cost of 194 DKK/TWh is, however, feasible.

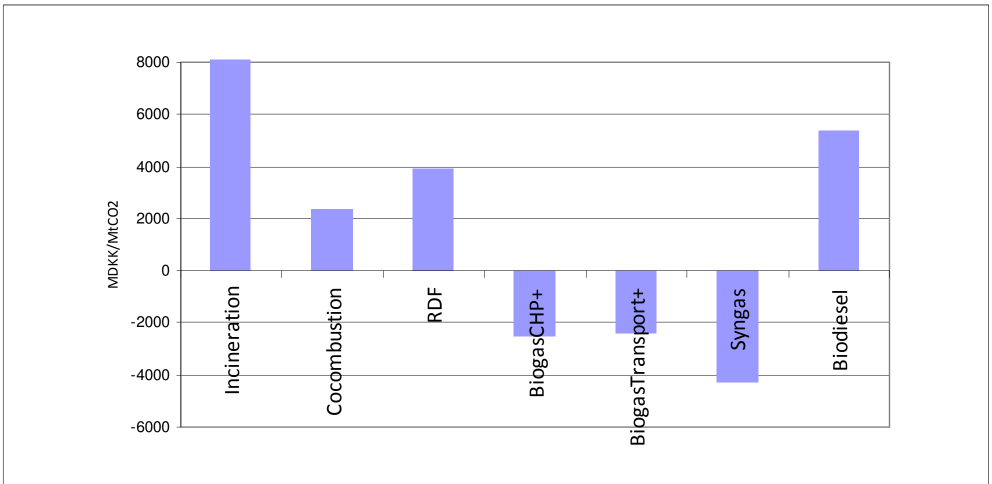


Figure 42 CO_2 reduction cost when moving 4 PJ of waste in 2006. The cost of Incineration is almost 20000 MDKK/Mt CO_2 and is cut off.

When comparing the biomass reduction costs of moving 4 PJ of waste in 2050 (Figure 41) with the CO2 reduction costs of moving 4 PJ of waste in 2006 (Figure 42), some of the results are similar. First of all, the Biogas alternatives seem promising in both scenarios. The Biogas+ alternatives result in negative CO_2 reduction costs in 2006, and in 2050, the Biogas alternatives are the cheapest in terms of biomass reduction costs. It may therefore seem like a good idea to invest in the capacity to produce manure-based biogas for CHP or transport today. If, in the future, the manure resource is utilised, it may still be economically feasible to invest in biogas production capacity to digest sorted organic household waste.

The Syngas alternative also seems feasible in both scenarios with high negative CO_2 reduction costs in 2006 and medium biomass reduction costs in 2050. This does, however, depend on the development of the relevant technologies, as previously mentioned. The Syngas+ alternative does, on the other hand, not seem to be a feasible technology to rely upon when considering CO_2 reduction or biomass substitution. In 2006, it does not produce a CO_2 reduction and, in 2030, it has the highest biomass reduction cost bordering the expected cost of biomass.

Improved incineration is a very costly way of reducing CO_2 emissions in 2006. However, if, in the future, an amount of waste which is not incinerated can be found, improved incineration will provide a feasible solution to substituting biomass. Co-combustion and RDF, on the other hand, present considerable CO_2 reduction costs in 2006, but feasible biomass reduction costs in 2050. As mentioned before, Co-combustion may, however, not be an option in 2050, as it requires large-scale biomass combustion. Dedicated RDF plants are comparable but their reduction costs are slightly higher than the biomass reduction costs achieved with Incineration.

6 Sensitivity analyses

Four sensitivity analyses have been made to examine the sensitivity of the results with regard to fuel prices, CO_2 quota prices, interest rate, investment costs, efficiency, and waste prices. The sensitivity analyses have been made of the scenario of moving 4 PJ in 2006.

Compared to the scenario of moving 4 PJ in 2006, the fuel cost has been increased by 20% to a level around 119 USD/bbl in order to test the sensitivity of the results to this parameter. This is also the alternative tested in the base forecast of the Danish Energy Authority [97]. The electricity price on the Nordic Energy Market can be expected to rise together with the fossil fuel price and, hence, the electricity price has also been increased, for simplicity also by 20% to 434 DKK/MWh. This is done in order to ensure that the system does not simply import cheap electricity to compensate for high fuel prices.

Secondly, the CO_2 quota price has been increased to 225 DKK/t CO_2. This is also the CO_2 quota price expected by the Danish Energy Authority from 2013 [97]. Thirdly, the interest rate has been checked. In the socio-economic analyses presented here, an interest rate of 3% has been used. The sensitivity of changing the interest rate to 6% has been examined.

Furthermore, as the investment costs of the non-commercial WtE technologies are associated with great uncertainty, the investment costs of the syngas and the bioethanol solutions have been compared to the investment costs of other sources, which results in an increase in the syngas and a decrease in the bioethanol investment cost. The figures can be seen in Table 32.

Table 32 Investment and Operation and Maintenance Costs as well as availability and lifetimes for 4 PJ

WtE technologies	Investment	O&M	Avai-lability	Lifetime	Year	Source
Reference costs	MEUR/PJ	%	%	Years		
Syngas	50.9	4	80	20	2010-20	[63]
Bioethanol	65.0	10	98	20	2006	[45]
Alternative costs						
Syngas	116.7	4	80	20	2006	[64]
Bioethanol	29.0	10	98	20	2010-20	[63]

As the efficiencies of the technologies under development are also highly uncertain, sensitivity analyses have been performed for these. For Syngas the efficiency of liquefaction has been reduced in accordance with Goudiraan et. al [116] and the efficiency of gasification has been slightly raised in accordance with the European Well-to-Wheel study [63] resulting in a combined efficiency decrease of 22%. For BioEthanol the efficiency of fuel production has been raised to 45% at the cost of producing biofuel for CHP, in accordance with production of bioethanol from straw in the Well-to-Wheel study [63]. A sensitivity analysis has also been introduced for Cocombustion. Here the efficiency of the coal power plants is reduced by 1% point due to use of electricity for pre-treatment [94] and assuming that the heating value of the remaining waste fraction drops 4 MJ/kg, the efficiencies of the remaining waste incineration plants decrease with 3% points, and the CB value is decreased by 0.02 [117].

Finally, another important factor is the cost of the different waste fractions. As mentioned before, these figures are very uncertain as, in many cases, there is no larger market established for the fractions and prices depend on local conditions and treatment capacities. To assess the sensitivity of the results to the costs of the waste fractions, an analysis has been made in which an amount of 30 DKK/GJ has been added and subtracted from the price of the waste fraction used for the respective technologies. For RDF the decrease results in a price of 9 DKK/GJ, which represents a negative cost combined with a moderate expense for pre-treatment and extra transport.

The operation of the energy system only changes when the fuel prices and the CO_2 quota prices change. It does not change when alternative interest rates or investment costs are introduced. The fuel consumption of the alternative varies a little, but the figures of the changes in CO_2 emissions are corrected for electricity trade and for CO_2 reduction costs.

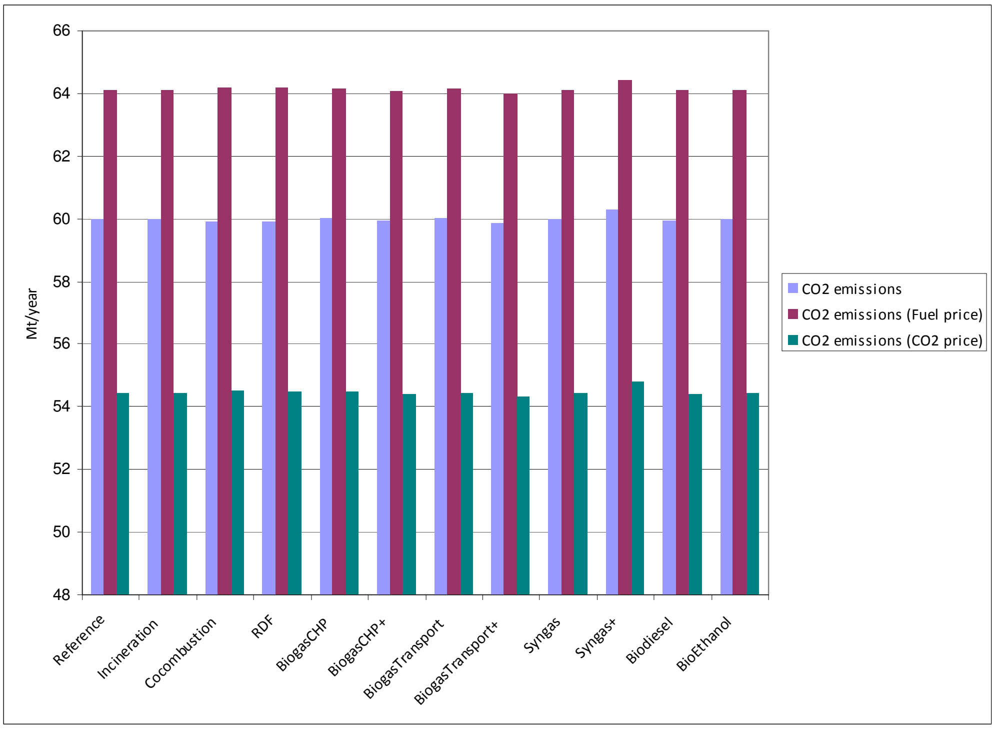


Figure 43 CO_2 emissions for the different technical alternatives with increased fuel prices and increased CO_2 quota prices

As it can be seen, the ranking of the alternatives has a low sensitivity to changes in fuel prices and CO_2 quota prices. In all cases, the alternative with the highest CO_2 emissions is the Syngas+ alternative, whereas the alternative with the lowest CO_2 emissions is the BiogasTransport+ alternative.

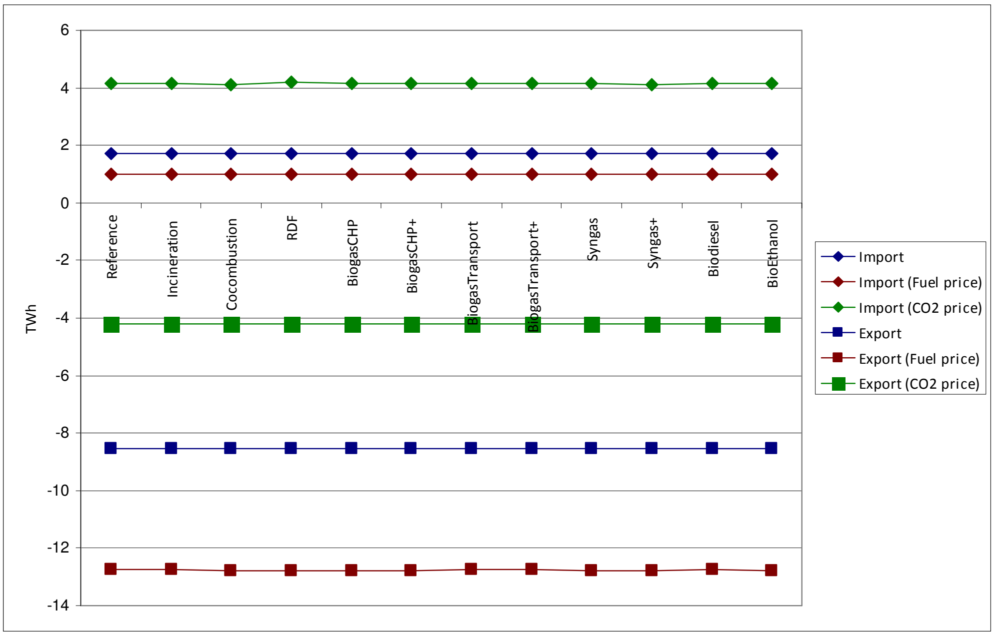


Figure 44 Electricity trade with the different technical alternatives compared with increased fuel prices and increased CO_2 quota prices

With regard to electricity trade, it is obvious that the import increases and export decreases considerably when the CO_2 quota price in Denmark increases, whereas the opposite is true when the fuel prices and the electricity price on NordPool rise. Only small differences can be found in the overall electricity trade between the alternatives, as only marginal amounts of waste are moved.

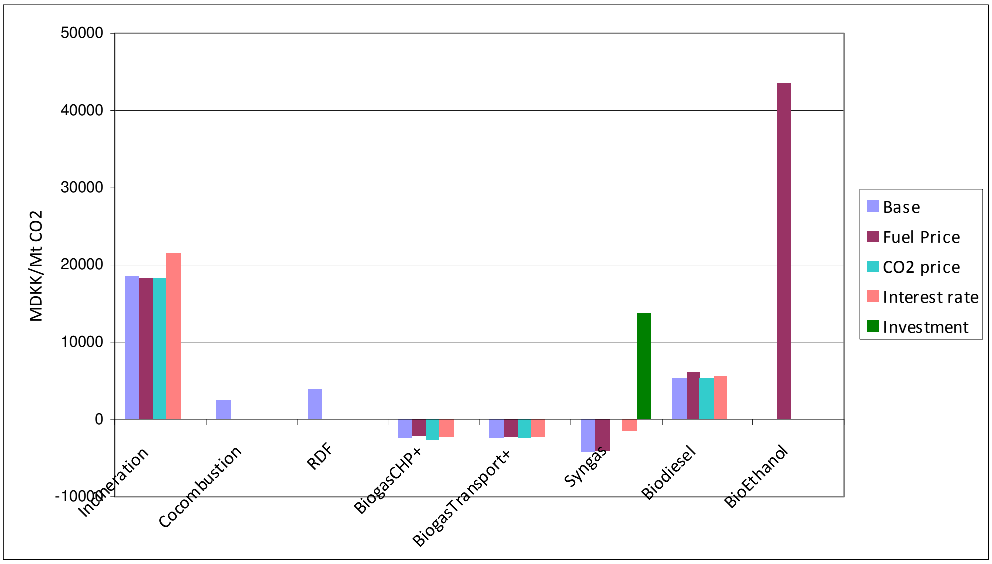


Figure 45 CO_2 reduction price for the technical alternatives which reduce CO_2 emissions, with increased fuel prices, increased CO_2 quota prices, increased interest rate and changed investment costs for syngas and bioethanol

When comparing the CO_2 reductions in Figure 45, it can be seen that the Bioethanol alternative only results in CO_2 emissions in the scenario with high fuel and electricity prices. Apart from that, the results demonstrate a low sensitivity to changes in fuel price, CO_2 quota price and interest rate, whereas they are highly sensitive to changes in investment costs. The Syngas alternative changes from representing savings in annual costs of the energy system to a high increase in costs. The costs used for the original analysis are for entrained coal gasifiers, which have large sizes and hence lower costs per MW. Biomass gasifiers are typically smaller and more expensive per MW. The high investment cost identified in the sensitivity analysis may therefore be the most likely cost for the Syngas alternative, whereas the investment costs used in the original analysis may be the most likely for the Syngas+ alternative, which includes the use of coal.

When checking the sensitivity to changes in efficiency, the decreased overall efficiency of the Syngas plant results in increased CO_2 emissions as less oil is displaced and more coal is consumed. The same is the case for Syngas+ which now results in an even greater increase in CO_2 emissions. BioEth on the other hand now results in a decrease in CO_2 emissions. Although less coal is displaced for CHP, more oil is displaced. The CO_2 reduction cost is however almost 2.5 times the reduction cost of Incineration. With regards to co-combustion the decrease in efficiency now results in a net zero decrease in CO_2 emissions illustrating high sensitivity to minor changes in efficiency.

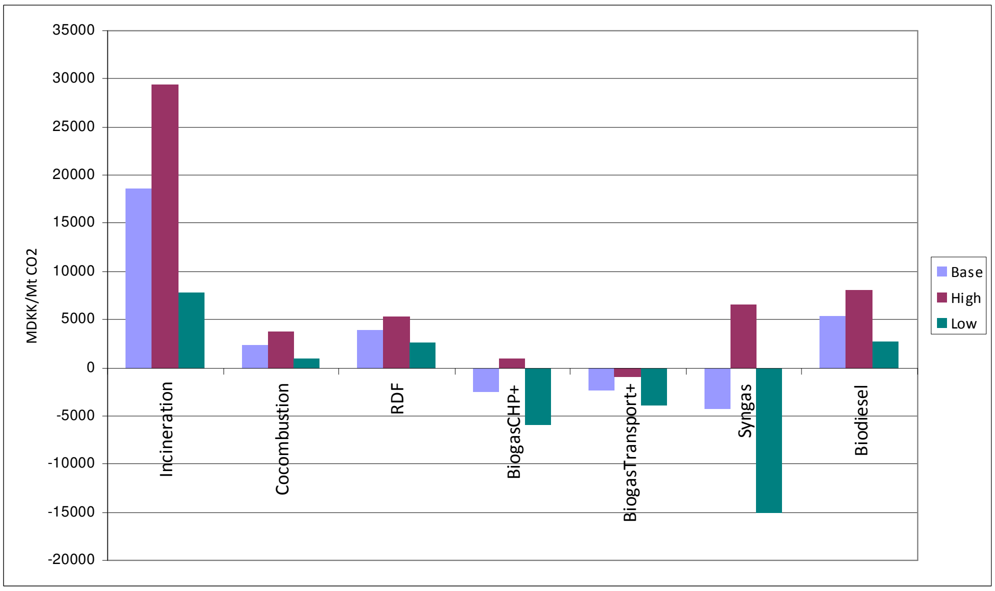


Figure 46 CO_2 reduction prices in situations with high waste prices (+30 DKK/GJ) and with low waste prices (-30DKK(GJ) compared to the reference prices.

As can be seen in Figure 46, the results are highly sensitive to changes in waste prices. Particularly the Syngas and Incineration alternatives vary considerably with variations of almost 22500 DKK/t CO_2 in reduction prices. Syngas varies between highly positive and highly negative CO_2 reduction costs. BiogasCHP also varies between positive and negative CO_2 reduction costs although with lower variation. BiogasTransport+ has low variations and remains with negative CO_2 reduction prices, as the only alternative.

7 Recommendations and conclusions

Which technology to choose, when converting unrecyclable waste into energy, depends on the objectives of the decision-maker. When analysing the influence of the various technologies on the Danish energy system in 2006 and in a renewable energy future, two parameters are chosen: the CO_2 or biomass reduction potential and the costs related to the reduction.

With regard to the total CO_2 reduction potential, BiogasTransport+ gives the best results and only Syngas+, BiogasCHP and BiogasTransport result in increased emissions.

Assuming that coal power plants with an electrical efficiency of 40% supplies the marginal electricity when exporting, and thus subtracting the CO_2 emissions due to export, Syngas+ becomes the best alternative. This illustrates the fact that determining the marginal electricity production unit on the Nordic electricity market is important, if the aim is to determine which technology emits least CO_2, considering the internal consumption of energy.

When looking at year 2050, on the other hand, RDF and Co-combustion provide the highest biomass substitution, closely followed by Syngas, Bioethanol and Incineration. The Biodiesel, Syngas+ and Biogas+ alternatives provide least biomass substitutions.

Taking economy into account, the analyses show that biogas and syngas plants are interesting alternatives to waste incineration. In today's energy system, the utilisation of organic waste in manure-based biogas production provides a negative CO_2 reduction cost; i.e. today, it is a cheaper solution than incineration and it provides a CO_2 reduction. It seems less important if the biogas is used for transport or CHP. When comparing these two alternatives, the use of biogas for transport provides the largest CO_2 reduction, while biogas used in CHP production gives the lowest CO_2 reduction cost. However, if anaerobic digestion of waste does not facilitate the use of manure, the results change and the biogas plants have increased CO_2 emissions. In a future 100% renewable energy system, biogas production is also a feasible solution providing the cheapest biomass reduction costs, even without manure.

The results concerning biogas are supported by the conclusions of other studies. Other studies show that biogas may be as good a solution as incineration or even a better alternative, depending on the concrete design of the system. It is here concluded that, in today's energy system, biogas production reduces CO_2 emissions only if this production also leads to an increased anaerobic digestion of manure.

Syngas plants provide the lowest CO_2 reduction cost in today's energy system, when it is assumed that co-gasification with coal is not necessary.

If the waste is co-gasified with coal, total CO_2 emissions increase. Currently, plants which co-gasify waste with other resources are, however, only at the developmental stage and the gasification of waste alone is even further from becoming a commercial technology. In a 100% renewable energy future, Syngas with gasification of only waste provides a biomass reduction cost only slightly higher than that of incineration and still lower than the expected biomass cost. This alternative can also represent co-gasification of waste with biomass, in which waste replaces biomass in an existing biomass gasification plant.

If focusing only on CO_2 emissions related to domestic electricity consumption, the Syngas+ alternative provides the largest CO_2 reduction. This large difference in results illustrates the significance of determining the marginal electricity-producing unit correctly.

If the current resource potential is fully utilised, the BiogasTransport+ solution alone may contribute with a CO_2 reduction of 3.1 Mt/year and the Syngas with 0.9 Mt/year. Even higher CO_2 reductions may be achieved by combining several technologies, as they do, to some extent, utilise different waste fractions. Furthermore, a significant reduction in other greenhouse gases occurs due to reduced emissions of methane and nitrous oxide achieved by spreading treated manure instead of raw. This factor is not included in the analysis, as it is not part of the energy conversion stage. If included, this factor will only support the conclusion of prioritising manure-based biogas production.

Energy system analysis with hour-by-hour representation of demands and production takes the flexibility of the various technologies into account. Thus, it improves the results of the technologies which increase the flexibility compared to the current system, partly in terms of changed income from electricity trade, but also in terms of changed fuel consumption and reduced CO_2 emissions.

As Denmark is one of the countries in the world with the highest wind power share in the electricity production, one of the highest shares of CHP as well as one of the highest shares of waste incineration, it is an interesting case to analyse. Many countries are moving in the direction of Denmark with regards to wind and district heating and considering how to treat their waste in the future. They can learn from analyses of Denmark with regards to e.g. which challenges their energy system may face. In countries with little heat demand or little coverage with district heating the WtE technologies which produce transport fuel or high degrees of electricity will be the most feasible.

The conclusions are mainly sensitive to changes in investment costs, waste resource prices and efficiencies and special attention should therefore be given to these parameters e.g. when performing feasibility analyses of projects, particularly for immature technologies and markets. The largest uncertainty about investment costs is related to the technologies which are yet at the development stage, such as Syngas and Bioethanol. There is, in particular, uncertainty about the waste resources, which do not have a well developed market. High sensitivity is found for the Incineration and Syngas alternatives and low sensitivity for BiogasTransport+. High sensitivity is also found when changing efficiencies of Syngas (decrease in total efficiency), Bioethanol (higher transport fuel production and no CHP) and Co-combustion (low decrease in efficiency at coal power plants and at remaining waste incineration plants). To assess whether the conclusions are also valid from a broader environmental perspective, the results regarding fuel substitution can be used for detailed life cycle assessment.

In general, the study shows that there is potential in using waste for the production of transport fuels from an energy system perspective. Unless the processes facilitate anaerobic digestion of manure or gasification of waste alone (which is a technology that still has to be developed) it is, however, an expensive solution compared to the current incineration. If the technologies are compared to other technologies producing biofuels they may, however, prove superior from an environmental, resource and economic perspective.

The second best solution seems to be to improve the electrical efficiency and the flexibility of the energy system by sorting out RDF and co-combusting it with coal or burning it in a dedicated RDF plant. The combustion of coal in existing large-scale power plants must, however, take place in order for Co-combustion to be a feasible alternative. It is doubtful whether more coal-fired power plants will be built in the quest for a 100% renewable energy future and Co-combustion should therefore be regarded a short-term initiative, e.g. to overcome the lack of incineration capacity. When considering the investment in new plants, dedicated RDF plants provide a higher CO_2 reduction and a lower CO_2 reduction cost than new incineration plants. RDF does, however, only constitute 19% of the waste which is currently incinerated.

As a significant fraction of mixed waste will still be left no matter which alternative is chosen, waste incineration will still form part of the solution when converting waste to energy in the future. Today, the Incineration alternative is an expensive solution in terms of reduced CO_2, but it represents the replacement of existing waste incineration plants only with the aim of improving efficiency. If the plants are replaced when needed due to age or lack of capacity, the solution will not be nearly as expensive. In a 100% renewable energy future, waste incineration appears to be marginally cheaper in terms of biomass reduction than the Co-combustion and RDF alternatives.

To sum up, a recommendation to decision-makers could be to support investments in utilisation of sorted organic household waste for biogas production today if this facilitates anaerobic digestion of manure. In the future biogas based on sorted organic household waste also appears to be a cheap way of saving biomass. Investments in infrastructure etc. facilitating this technology therefore appears to be beneficial also in the future. For paper and plastic a feasible option may in the short run be to co-combust in existing coal fired plants or in dedicated RDF plants. For the longer run it can be recommended to support research into gasification of both organic waste, paper and plastic without addition of coal or biomass. The remaining incinerable waste fractions should be incinerated in increasingly efficient and flexible waste incineration plants.

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Appendix A - Syngas Module in EnergyPLAN

The model is operated with market economic regulation, which is based on the principle that if the marginal production cost of producing electricity is lower than the market price (in competition with all the other units) the Syngas plant will produce the maximum amount of electricity possible otherwise it will produce the maximum amount of biofuel for transportation.

Input

- $F_{GTL\text{-}Waste}$ - Annual amount of Waste input (TWh/year)
- $F_{GTL\text{-}Coal}$ - Annual amount of Coal input (TWh/year)
- $F_{GTL\text{-}Biomass}$ - Annual amount of Biomass input (TWh/year)
- $f_{GTL\text{-}Biofuel}$ - Annual production of biofuel (TWh/year)
- $\mu_{GTL\text{-}M1}$ - Electric output module 1
- $\rho_{GTL\text{-}M1}$ - Thermal output module 1
- $\eta_{GTL\text{-}M1}$ - Biofuel output module 1
- $\mu_{GTL\text{-}M2}$ - Electric output module 2
- $\rho_{GTL\text{-}M2}$ - Thermal output module 2
- $\eta_{GTL\text{-}M2}$ - Biofuel output module 2
- $P_{VOC\text{-}GTL\text{-}M1}$ - Variable operation costs in module 1 (DKK/MWh fuel)
- $P_{VOC\text{-}GTL\text{-}M2}$ - Variable operation costs in module 2 (DKK/MWh fuel)
- $P_{UNIT\text{-}GTL}$ - Investment pr. Unit (Mio.DKK/TWh fuel)
- n_{GTL} - Lifetime of Investment (Years)
- $P_{FOC\text{-}GTL}$ - Fixed operation costs (% of investment/year)
- VOC – Variable operation costs (DKK/MWh)

Output:

- Δq_{GTL} – Change in heat production (MWh)
- Δe_{GTL} – Change in electricity production (MWh)

- MC – Marginal costs (DKK/MWh)

Initial calculations

The fuel input is defined by the annual amounts and the distribution of waste input. All three fuel inputs (coal, biomass and waste) are following the same distribution.

$$F_{GTL\text{-}Total} = F_{GTL\text{-}Waste} + F_{GTL\text{-}Coal} + F_{GTL\text{-}Biomass}$$

The hourly fuel input ($F_{GTL\text{-}Total}$) is found by using the hourly distribution of waste (δ_{Waste}) specified in the waste input tab sheet.

$$f_{GTL\text{-}Total} = F_{GTL\text{-}Total} * \delta_{Waste} / \Sigma\delta_{Waste}$$

Based on such input the Syngas plant can choose between the modules of operation defined by the input efficiencies.

- Heat is supplied to the district heating system of larger city areas
- Biofuel is replacing fossil fuel (e.g. petrol) for transportation
- Electricity is supplied to the public grid

Initially the plant is set to operate according to module 1

The marginal cost of increasing electricity production by operating the plant in module 2 instead of 1 is calculated in two situations. One in which the heat replace heat from the boiler (B3) and one in which it replaces heat from CHP3.

In both situations the change in variable operation costs (ΔVOC), the decrease in Biofuel production ($\Delta f_{GTL\text{-}Petrol}$) and the cost of not producing Petrol ($\Delta Cost_{Petrol}$) is:

$$\Delta VOC = (P_{VOC\text{-}GTL\text{-}M2} - P_{VOC\text{-}GTL\text{-}M1})$$

$$\Delta f_{GTL\text{-}Petrol} = F_{GTL\text{-}Total} * (\eta_{GTL\text{-}M1} - \eta_{GTL\text{-}M2})$$

$$\Delta Cost_{Petrol} = \Delta f_{GTL\text{-}Petrol} * (P_{Petrol\text{-}WM} + CO2_{Oil} * P_{CO2\text{-}trade})$$

In the case of replacing boiler heat production the saved costs are calculated as follows:

$$\Delta q_{GTL} = F_{GTL\text{-}Total} * (\rho_{GTL\text{-}M2} - \rho_{GTL\text{-}M1})$$

$$\Delta F_{B3} = \Delta q_{GTL} / \rho_{B3}$$

$$\Delta Cost_{Heat} = \Delta F_{B3} * (P_{Fuel\text{-}B3} + CO2_{B3} * P_{CO2\text{-}trade}) + VOC_{B3} * \Delta q_{GTL}$$

The increase in electricity production and the marginal costs are then found:

$$\Delta e_{GTL} = F_{GTL\text{-}Total} * (\eta_{GTL\text{-}M2} - \eta_{GTL\text{-}M1})$$

$$MC_{IncGTLdecB3} = (\Delta VOC + \Delta Cost_{Petrol} - \Delta Cost_{Heat}) / \Delta e_{GTL}$$

In the case of replacing CHP3 heat production the saved costs are calculated as follows:

$$\Delta F_{CHP3} = \Delta q_{GTL} / \rho_{CHP3}$$

$$\Delta e_{CHP3} = \Delta F_{CHP3} * \eta_{CHP3}$$

$$\Delta Cost_{Heat} = \Delta F_{CHP3} * P_{Fuel\text{-}CHP3} + VOC_{CHP3} * \Delta e_{CHP3}$$

The increase in electricity production and the marginal costs are then found:

$$MC_{IncGTLdecCHP3} = (\Delta VOC + \Delta Cost_{Petrol} - \Delta Cost_{Heat}) / (\Delta e_{GTL} - \Delta e_{CHP3})$$

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