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Use of Waste for Heat, Electricity and Transport – Challenges when performing Energy System Analysis

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Abstract

This paper presents a comparative energy system analysis of different technologies utilising organic waste for heat and power production as well as fuel for transport. Technologies included in the analysis are 2nd generation biofuel production, gasification, fermentation (biogas production) and improved incineration. It is argued that energy technologies should be assessed together with the energy systems of which they form part and influence. The energy system analysis is performed by use of the EnergyPLAN model, which simulates the Danish energy system hour by hour. The analysis shows that most fossil fuel is saved by gasifying the organic waste and using the syngas for combined heat and power production. On the other hand, least greenhouse gases are emitted if biogas is produced from organic waste and used for combined heat and power production; assuming that the use of organic waste for biogas production facilitates the use of manure for biogas production. The technology which provides the cheapest CO_2 reduction is gasification of waste with the subsequent conversion of gas into transport fuel.

Keywords: Waste; Energy System Analysis; Gasification; Anaerobic digestion; Incineration; CHP; Transport fuel

1. Introduction

In Denmark, 27% of the waste produced in 2004 was incinerated for heat and power production. Of the remaining amounts, 64% was recycled and only 8% deposited at landfills [1]. In the EU, municipal waste is, at present, disposed of through landfilling (49%), incineration (18%), and recycling and composting (33%) [2]. The EU has, however, introduced aims which intend to significantly reduce the amount of landfilled biodegradable waste. 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 [3]. Furthermore, landfilling of certain types of waste such as combustible waste or untreated organic waste is illegal in some member states, e.g. Denmark, Sweden and Germany. Consequently, at the EU level, great efforts are made to identify alternatives to the landfilling of biodegradable waste.

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In Denmark, 34 waste incineration plants contribute with 4% of the electricity production and 18% of the heat production. 75% of the waste incinerated is biodegradable waste. 70 Danish biogas plants contribute with a mere 1% of the electricity production and 1% of the heat production. [4]

In January 2007, the Danish Government presented its vision for the Danish energy sector towards 2025. According to the vision, 30% of the energy consumption should be supplied by means of renewable energy in 2025, compared to 14% today, and a share of 10% of biofuel should be reached in the transport sector in 2020 [5]. Comparisons with similar European aims show a planned increase in the level of renewable energy in the EU as a whole, from less than 7% today to 20% by 2020, as well as a biofuel share of minimum 10% [6]. The utilisation of waste for energy can contribute to 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 project the amount of waste generated in Denmark to increase in the future. In these analyses, incinerable waste is expected to rise by 30% up to year 2020 and food and wood waste each by 40%. [1]
- The Danish waste incineration capacity is becoming too low for the growing amounts.
- The energy system needs flexibility in order to integrate more wind.
- The demand for transport continues to increase [7]. As the sector is currently based on fossil fuels, CO_2 emissions from the sector continue to increase. This may be altered 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 [8]. Already today, 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 efficiency, to store energy or to produce fuels for transportation. 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 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 [9,10,11,12,13,14,15].

A number of Life Cycle Assessment (LCA) and Well-To-Wheel studies have been performed which illustrate the environmental effects - particularly the greenhouse gas emissions - of different technologies utilising renewable energy, including biomass for transport purposes, such as [16,17]. Likewise, LCA studies have been performed of the use of waste for energy, e.g. [18,19,20,21]. These studies compare strings of technologies involving e.g. the production of biofuels, upgrading, distribution and the utilisation of fuels in vehicles. However, the studies do not analyse the technologies and their advantages and disadvantages seen from an energy system perspective or their influence on the energy system of which they form part. Some energy system analyses have been made of Waste-to-Energy technologies mainly focusing on district heating systems and using load duration curves[22,23,24]; or on local regions using linear programming without hour-by-hour simulations of the energy system[25,26]. The energy system analysis presented in this article includes heat, power and energy for transport. It takes into account the intermittent nature of renewable energy production technologies with hour-by-hour simulations and it considers both new and established Waste-to Energy technologies.

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.

In Table 1,, some of the main differences between traditional fossil-fuelled combined heat and power (CHP) plants and Waste-to-Energy technologies are illustrated.

Table 1. Differences between traditional fossil-fuelled CHP plants and Waste-to-Energy technologies

In this Energy System Analysis of the Danish energy system, it is attempted to take these characteristics into account. Through the analysis, it is assessed how the utilization of 10 TWh waste for incineration, fermentation or gasification producing electricity, heat and transport fuel may contribute to reducing the dependence on fossil fuels and to reducing greenhouse gas emissions in the most cost-effective way.

In the Methodology chapter, the use of the Energy System Analysis model is explained and the scenarios used are presented. In the Results chapter, the results are illustrated and recommendations are made for the future use of organic waste in the Danish energy system. Subsequently, in the Sensitivity Analysis chapter, sensitivity analyses of different parameters are presented. Finally, in the Conclusions and Discussion chapter, conclusions are drawn with respect to the use of the model for the purpose of evaluating different technologies and suggestions are made for future analysis.

2. Methodology

In the following sections, the model which was used for the analysis is described and, subsequently, the technical alternatives are analysed.

The Energy System Analysis was made by use of the EnergyPLAN model, which is developed at Aalborg University. The model can be downloaded free of charge together with documentation on www.energyplan.eu. On the webpage, examples can be seen of analyses made by use of the model, including a comparison of results with other models as in Lund et al. 2007 [27]. A brief description of the model is presented below. For more thorough explanations, please consult [28,29].

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

- Demands for electricity, heat, cooling, industry, individual households and transport
- Renewable Energy Supply
- Capacities and efficiencies of, among others, CHP and power plants
- Technical limitations and definition of external power market
- 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 share of renewable energy in the system.

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 II – 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 [30].

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 improving the fuel efficiency of the system or a market optimisation focusing on improving the financial output of the individual plants.

Previously, waste has been treated in the model as a fuel along with biomass resources. However, as a part of this study, the utilisation of waste in the EnergyPLAN computer model has 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, excess electricity production 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.

The improvement of the model has resulted in an increase in total annual costs of the energy system of 1100 MDKK with a decrease in fuel costs of 700 MDKK, although fuel consumption has increased by 2.4 TWh. Finally, the change resulted in an increase in the annual CO_2 emissions of 1.4 Mt.

2.1. Technical alternatives

Eight different scenarios illustrating different ways of utilising waste for energy production are modelled. The scenarios focus on incineration, biogas and gasification technologies:

- **NoWaste**. Waste is not used for energy but either deposited at landfills or composted
- **WasteHeat**. Waste is used only for heat in new heat-only boiler (HOB) plants with efficiencies of a new plant
- **WasteCHP (today).** Waste is incinerated in today's plants, where 96% are CHP plants and just 4% produce only heat [31].
- **WasteCHP (new).** Waste is incinerated in new plants with efficiencies from 2004 without flue gas condensation
- **BiogasCHP**. An organic fraction of 1 TWh is used for producing biogas, which is used for CHP production. 0.6 TWh manure is added to the organic fraction with a weight distribution of 80% manure to 20% organic waste. The biogas is produced in large-scale centralised biogas plants with a capacity of 800t/d. When fermented the biomass is separated and the fibre fraction is burned in a waste incineration plant.
- **BiogasTransport**. Again the organic fraction produces biogas, but the biogas is upgraded to natural gas quality and used in natural gas vehicles. Manure is added as above.
- **SyngasCHP**. The Syngas scenarios use the planned REnescience process as case [32]. For this analysis, the process is split into a CHP and a transport scenario. The REnescience project, however, plans to produce both CHP and transport fuel. In the SyngasCHP scenario, 1 TWh organic fraction is gasified and used for CHP production. The waste is first liquefied by non-pressurised heat treatment and subsequently gasified in an entrained flow gasifier with 25% organic waste and 75% coal. The syngas is then used in a single cycle gas turbine.
- **SyngasTransport**. Again the waste is gasified and then 70% is converted into petrol and used in petrol vehicles. The remaining 30% is used for CHP

The total amount of waste considered equals 10 TWh, which was the amount of waste used for energy purposes in Denmark in 2004. The 10 TWh waste is treated using the above-mentioned technical alternatives, sometimes in combination. For the biogas and the syngas scenarios, 1 TWh organic waste is used in the respective plants. This amount is comparable to the total amount of organic waste from households [19]. The remaining waste fraction of 9 TWh is incinerated in new plants with efficiencies of 2004. The waste amounts used as well as the efficiencies of the plants are illustrated in Table 2. Furthermore, 0.6 TWh manure is facilitated in the biogas scenarios. Energy from manure is only included in these scenarios, since biogas plants based solely on manure are economically unfeasible under Danish conditions[33]. Finally, 3 TWh coal is induced in the syngas scenarios, as the gasification of coal is assumed to take place only to facilitate the gasification of waste.

Table 2 Efficiencies and waste amounts used for the scenarios.*Including 0.6 TWh manure.

The electric efficiency of incineration CHP plants increases from 14.4% of today's average to an average of 19.5% in the case of new plants [34]. Fuel efficiency refers to the amount of energy retrieved in the fuel seen in relation to the energy input. Biogas plants have a lower efficiency than gasification plants, but have the advantage of facilitating the use of manure in the energy system. The main difference is due to the high difference in the efficiency of conversion into gas. Biogas plants have an efficiency of 48.4% when converting to biogas and the CHP plants have an electric efficiency of 40% and a heat efficiency of 50%. Furthermore, a 94.3% efficiency is assumed for the purification and upgrading process from biogas to transport fuel. For the gasification process, the conversion efficiency is high, i.e. 78%. For the CHP plant, 47% efficiency is assumed for electricity and 45% for heat. The catalysis process efficiency is assumed to be 100% with the described setup, but 30% of the gas cannot be converted and is used for CHP.

The CO_2 content of the waste related to fossil parts is assumed to be 24 kg/GJ [35]. In Table 3, the Lower Heating Values and biogas yields are illustrated.

Table 3. Lower heating values and biogas output. *Based on LHV of dry matter content in the manure

2.2. Reference Energy System

The reference energy system, in which the technologies are used, is the Danish energy system in 2004. Compared to other countries, the Danish energy system has a high total energy efficiency with a high level of CHP (55% of the thermal electricity production and 82% of district heating) and a high percentage of wind (18.5% of total electricity production) [36]. In all scenarios, the same amounts of electricity, heat and transport fuel are supplied at the same hours throughout the year.

The system is analysed with no transmission to neighbouring countries and a technical optimisation is chosen in which the model seeks to find solutions with the lowest fuel consumption. In order to ensure this, CHP plants operate according to both heat and electricity demands.

3. Results

In this chapter, differences in fuel substitution, CO_2 emissions and costs are illustrated when utilising the waste in different ways.

3.1. Fuel consumption

Figure 1 shows the fossil fuel substituted with waste in the various scenarios.

Figure 1. Fossil fuel substituted when utilising 10 TWh waste per year. Including 2.5 Mt manure for biogas and 3 TWh coal for syngas

In the WasteHeat scenario, the heat replaces heat produced at a CHP plant. Consequently, more electricity has to be produced at other plants including coal-fired power plants, and hence, a consumption of coal is induced. If more wind turbine capacity would be installed in the future and the needed electricity would be produced from wind power instead, the large coal consumption would be avoided. The remaining scenarios do not induce fossil fuel consumptions, but rather substitute approx. the same amount of fossil fuel, namely 8-9 TWh each.

The scenario which provides the largest fossil fuel reduction is the SyngasCHP scenario, followed by the new WasteCHP scenario and the biogas scenarios. The SyngasTransport scenario substitutes most oil, whereas the WasteHeat scenario substitutes most natural gas and the BiogasCHP scenario substitutes the largest amount of coal.

3.2. CO_2 emissions

Utilising waste in the energy system results in reduced CO_2 emissions from energy conversion in the Danish energy system, as illustrated in Figure 2.

Figure 2. Reduction of CO2 emissions from energy conversion in the various scenarios.

Seen from a CO_2 perspective, the worst solution would be not to utilise waste for energy purposes. When waste is utilised only for heat production, only a negligible reduction in CO_2 emissions is achieved. Moreover, today's use of waste for energy may save the Danish society from approximately 1 Mt CO_2 eq. every year due to the reduced use of fossil fuels in the energy sector. The highest reduction in CO_2 emissions is achieved by utilising organic waste in biogas plants for CHP, closely followed by the new WasteCHP, SyngasCHP and BiogasTransportation scenarios.

If seen in a lifecycle perspective, the main differences in emissions of greenhouse gases between the scenarios, which are not already accounted for, are based on the fact that more methane will be emitted in the NoWaste scenario and less methane and N_2O will be emitted in the biogas scenarios. If waste is e.g. deposited at landfills in the NoWaste scenario, methane emissions from landfill sites should be added to the emissions. The accumulated amount of emissions from the extra waste deposited each year would be around 7 Mt CO2 eq.[37]. Around 20% of the landfill gas could however be recovered for energy purposes [38].

The reduced methane and N_2O emissions in the biogas scenarios are the results of digested manure used in the fields as opposed to raw manure. An increase in the transport of manure is expected, but emissions from this are heavily outweighed by the reduced methane and N_2O emissions achieved [33]. The net reduced methane and N_2O emissions amount to 0,2 Mt CO_2 equivalents [16]. If the biogas scenarios were credited for further net reduced greenhouse gas emissions, the BiogasCHP scenario would provide even better results and the second best solution would be the BiogasTransport scenario.

3.3. Economic Analysis

In this section, the costs of the energy system in the different scenarios are presented. The costs are calculated as annual socio-economic costs including fuel, operation and maintenance costs as well as annualised investment costs[1], discounted with a rate of 3%. In Table 4, the cost inputs to the analysis are illustrated. The WasteCHP (today) scenario is not included in the analysis, since the rate of depreciation of the existing plants is not known. Fuel prices for Denmark in 2004 are used with a crude oil price of 36 USD/bbl [39]. For waste, a fuel price of minus 20 DKK/GJ[2] is used.

Alternative investment costs are analysed for the BiogasTransport and syngas scenarios, as these are the newest technologies and data for these technologies are most uncertain.

Table 4. Investment and Operation and Maintenance Costs as well as normal plant capacities, availability and lifetimes.

Data for the syngas scenarios are taken from a European Well-To-Wheel study [16]. As exact data for similar plants are not available in the study, it is attempted to use data of plants with similar technologies and capacities. For SyngasCHP, data of a Coal-based Integrated Gasification Combined Cycle (IGCC) plant are used. For SyngasTransport, data of a Black Liquor-based gasification plant producing synthetic diesel are used. For the Syngas High scenarios, data of an IGCC plant are used and taken from a report from the United States' Environmental Protection Agency [41]. It is assumed that the costs of the combined cycle are comparable to those of the catalyst converting syngas to petrol. All syngas data are expectations for the future (2010-20) as the technology is not commercially available at the moment.

For the BiogasTransport scenario, the additional cost of natural gas cars compared to conventional cars is included, but no costs related to transmission and filling stations. A natural gas car is assumed to cost 25% more than a conventional car [42]. In the BiogasTransport Low scenario, the natural gas car is assumed to cost only 10% extra.

Figure 3 illustrates the increased total annual costs of the energy system when utilising the waste for energy. It should, however, be noted that alternative costs of treating the waste will be generated elsewhere in society if the

[1] Annualised investment costs make it possible to compare the feasibility of technologies with different lifetimes.

[2] In Denmark the cost of incinerating waste in 2004 was around 633DKK/t and the income from energy services was 419 DKK/t leaving 214 DKK/t equivalent to 20 DKK/GJ to be paid by the municipalities for the waste treatment service as waste incineration plants are by law non-profit organizations in Denmark [40]. The income from energy services is furthermore regulated by a maximum price on the heat delivered.

waste is not used for energy production. These costs are not included in the present analysis. Neither are CO_2 quota costs.

Figure 3. Difference in annual costs between the NoWaste scenario and various other scenarios.

As can be seen, the use of waste results in increased annual costs of the energy system for all scenarios compared to not using waste for energy, even when investments in additional coal-fired power plants (Coal PP) are included, as seen in the right bars (NoWaste and WasteHeat scenarios). If the waste was not used for energy, but instead deposited at landfills[3], the cost of landfilling would amount to around 1400 MDKK, making it the most expensive solution apart from the biogas solutions[43].

The largest difference between the reference and the alternative technology is seen in the SyngasTransport scenario where the annual costs compared to the NoWaste scenario are five times as high as in the reference. The large differences in the syngas scenarios illustrate the uncertainty in investment costs.

The increased annual costs should be compared to the CO_2 reduction potential, as in Figure 4.

Figure 4. Increased annual cost versus CO_2 reduction potential.

The biogas scenarios are the most expensive solutions in absolute terms, but since they also have high CO_2 reduction potentials, they do not have the highest CO_2 reduction costs[4]. On the other hand, WasteHeat has the highest CO_2 reduction costs, since it has a very low CO_2 reduction potential. The SyngasTransport scenario has the lowest CO_2 reduction costs, if the cost data of the reference prove to hold. If waste incineration plants would keep the costs of the reference and improve the efficiencies to 30% electric efficiency and 67% heat efficiency, they would constitute the most efficient technology in terms of CO_2 reduction, but SyngasTransport would still have the lowest CO_2 reduction costs.

A more precise calculation of CO_2 reduction cost can be performed on the basis of a life cycle assessment using the results from the energy system analyses, but it is outside the scope of this study. When including the methane emissions from landfilling or from composting, the calculation of CO_2 reduction costs would make a difference in favour of using waste for energy, but it would not change the ranking of the scenarios.

One possible source of error from the model could arise from the fact that the energy system is divided into three areas. In this way, district heating demands are combined and district heating plants may supply networks which seem greater than they really are. This may lead to a more flexible modelling of the energy system than what would

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[3] Landfilling combustible waste is currently not legal in Denmark, so it is an academic comparison.

be possible in reality. However, as the EnergyPLAN model is regularly compared to the official energy statistics and checked to give similar results, the issue is assessed to be of minor importance to the results of this article.

4. Sensitivity Analysis

Sensitivity analyses are performed in terms of the fuel price, the organic waste handling cost, the interest rate and the fossil CO_2 content of waste.

4.1. Fuel price

In the reference scenarios, Danish fuel prices from 2004 with a crude oil price of 36 USD/bbl are used [39]. Fuel prices have, however, gone up since then and, consequently, fuel prices from Denmark from 2006 with a crude oil price of 68 USD/bbl are used [45]. Furthermore, crude oil prices of 100USD/bbl have been tested with the other fuel prices kept in the same relation to the crude oil price, as assumed in the recommendations for socio-economic energy analysis as issued by the Danish Energy Authority in 2008 [46].

The SyngasTransport scenario results in a reduction in annual costs already when the oil price rises to 68 USD/bbl, as can be seen from Figure 5. Difference in annual costs between the NoWaste scenario and various other scenarios with 36, 68 and 100 USD/bbl, respectively.

With the increased fuel price, the WasteHeat scenario achieves reduction costs below 150 DKK/t CO_2 when oil prices are 68 USD/bbl and a reduction in annual costs with 100 USD/bbl without considering investment in additional power plants.

Figure 5. Difference in annual costs between the NoWaste scenario and various other scenarios with 36, 68 and 100 USD/bbl, respectively.

4.2. Handling cost of organic household waste

A report from the Danish Environmental Agency from 2003 analyses Danish pilot projects in the field of sorting organic household waste for anaerobic digestion and composting. A broad spectrum of handling and transportation costs were identified in the analysis; i.e. 1754-3415 DKK/t of organic waste in single-family houses and 1640-1830 DKK/t of organic waste in multi-storey houses [47]. For the reference scenario, an average of each category is used. For the sensitivity analysis, the lowest prices are combined to form low-cost biogas scenarios and likewise in the case of high costs.

[4] The term CO2 reduction cost is here used when referring to the increased annual costs of the energy system divided by the CO2 reduction potential due to energy production, as done by Morthorst, P.E. [44]

In the high cost scenario, the annual costs of the biogas scenarios are even higher than previously defined and although the low-cost scenario reduces the costs considerably, the CO_2 reduction costs of the biogas scenarios remain higher than the reduction costs of the WasteCHP and syngas scenarios.

4.3. Interest rate

In the reference scenarios, an interest rate of 3% is used. If the interest rate is increased to 6%, the SyngasCHP, WasteCHP (New) and SyngasTransport scenarios are highly affected. This is due to the fact that the investment constitutes a relatively large share of the total annual cost. For these scenarios, the increased annual costs are all above 260 MDKK. The NoWaste scenario is not affected, but apart from that, the WasteHeat scenario has the lowest increase in annual costs of around 170 MDKK. However, the ranking of the scenarios does not change.

4.4. CO_2 content of waste

The Danish Energy Authority recommends the use of a CO_2 content of 18 kg/GJ, originating from the fossil part of the waste [45]. This is equivalent to a plastic content of 6.6% [48]. The figure originally came from the Danish Government’s Waste Plan 1998-2004 [49]. A more recent Danish analysis, however, shows a plastic content of minimum 9.1% [50]. If this figure is used, a fossil CO_2 content of 24 kg/GJ is found, which is the figure used for the reference here. Furthermore, Waste Centre Denmark calculates with a figure of 33 kg/GJ [51].

Varying the contents of CO_2 in the waste does not change the ranking of the scenarios as the same amount of waste is used in each scenario. However, 0.23 Mt CO_2 less than in the reference is emitted when calculating with 18 kg/GJ and 0.32 Mt more CO_2 is emitted when applying 33 kg/GJ. Consequently, if the high content is used, the minor CO_2 reduction of 0.15 Mt obtained in the WasteHeat scenario is converted into an increase in CO_2 emissions of 0.17 Mt.

5. Conclusion and Discussion

The results of the Energy System Analysis are useful in two respects:

- They support decision-making directly, when the dependence on fossil fuels is in focus.
- They supply input, both in terms of CO_2 emissions from conversion in the energy system and fuel consumption, to further environmental assessment e.g. using Life Cycle Assessment (LCA) methodology

The clearest conclusion of the analysis is that waste should be used for energy purposes. When comparing the energy options, the less feasible solution is to use the waste for heat production only. Furthermore, if the main political aim is to reduce the dependence on fossil fuels, the best solution is to produce syngas for CHP, closely followed by upgrading the CHP incineration plants. The reduction of oil dependence is best achieved by using syngas for transport.

If, on the other hand, the main political aim is to reduce greenhouse gas emissions, the best solution is to utilise organic waste for biogas production and, subsequently, use the biogas for CHP production. In this case, the worst solutions would be to incinerate the waste for heat production or not to utilise the waste for energy production, at all. This conclusion should, however, be substantiated by performing LCAs for the remaining life cycles of the scenarios.

The cheapest reduction of CO_2 in the energy system is obtained with the SyngasTransport scenario when compared to the NoWaste scenario. Traditionally, the utilisation of waste for CHP production has been regarded the most efficient technology; but the SyngasTransport solution seems promising both in terms of costs, CO_2 reduction potential and the waste use potential for transport. This conclusion does, however, depend heavily on whether it will be possible to achieve the low investment costs used.

It has proven valuable to perform energy systems analysis of Waste-to-Energy technologies with a model which takes into account the dynamic effects of the Waste-to-Energy technologies on the whole energy system, including the supply of heat and electricity as well as transport fuels for domestic use. This is particularly important in a system with a high co-production of electricity and heat, such as the Danish one, and when considering technologies which have a number of possible outputs. Waste incineration has many advantages, but in an energy system, such as the Danish one, with an increasing supply from intermittent energy sources, it is necessary to be able to simulate the benefits of the flexibility supplied by other Waste-to Energy technologies and thus be able to compare the technologies on a fair basis. The inclusion of new Waste-to-Energy technologies in the analysis has also been valuable and has pointed to the prospective potential of syngas solutions and the production of transport fuels from waste.

In future research, it would be interesting to perform further Energy System Analyses of a system with open borders facilitating the trade with electricity, and to assess the economy of the various scenarios. Furthermore, it would be interesting to assess the performance of the technologies in possible future energy systems with higher shares of wind power. Finally, in order to give full credit to the flexibility of the systems when choosing between the production of electricity and heat or transport fuels, the model will be developed further to reflect these features. Syngas is for example currently modelled as two separate plants producing either electricity and heat (SyngasCHP) or biofuel, electricity and heat (SyngasTransport), and not as one plant determining its production according to the feasibility of each product at a given time.

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References

[1] Møller Andersen F, Larsen HV. A Model for Projection of Isag Data – FRIDA. Roskilde. Risø National Laboratory, 2006

[2] European Commission. Taking sustainable use of resources forward: A Thematic Strategy on the prevention and recycling of waste. Brussels, 2005

[3] Council Of The European Union. Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste Official Journal L 182, 1999:0001-0019

[4] Danish Energy Authority. Energy Statistics 2004. Copenhagen. Danish Ministry of Transport and Energy, 2005

[5] Danish Government. A Visionary Danish Energy Policy. Copenhagen, 2007

[6] European Commission. An Energy Policy For Europe. Brussels, 2007

[7] Danish Energy Authority. Energy Statistics 2004 (In Danish). Copenhagen, 2005

[8] Danish Government. Law about increasing energy savings in buildings. LOV no 585 of 24/06/2005. Copenhagen, 2005(In Danish

[9] Salgi G, Lund H. System behaviour of compressed-air energy-storage in Denmark with a high penetration of renewable energy sources. Applied Energy 2007.

[10] Mathiesen BV, Lund H, N°rgaard P. Integrated transport and renewable energy systems. Utilities Policy 2008;16:107-116.

[11] Lund H. Large-scale integration of optimal combinations of PV, wind and wave power into the electricity supply. Renewable Energy 2006;31:503-515.

[12] Blarke MB, Lund H. The effectiveness of storage and relocation options in renewable energy systems. Renewable Energy 2008;33:1499-1507.

[13] Lund H. Large-scale integration of wind power into different energy systems. Energy 2005;30:2402-2412.

[14] Lund H, Munster E. Integrated transportation and energy sector CO2 emission control strategies. Transport Policy 2006;13:426-433.

[15] Lund H. Renewable energy strategies for sustainable development. Energy 2007;32:912-919.

[16] EUCAR, CONCAWE, Joint Research Centre of the EU Commission. Well-To-Wheels Analysis Of Future Automotive Fuels And Powertrains In The European Context - WELL-to-WHEELS Report Version 2c. Joint Research Centre of the EU Commission, 2007http://ies.jrc.ec.europa.eu/WTW

[17] Hamelinck CN, Faaij APC. Outlook for advanced biofuels. Energy Policy 2006;34:3268-3283.

[18] Finnveden G. Methodological aspects of life cycle assessment of integrated solid waste management systems. Resources, Conservation and Recycling 1999;26:173-187.

[19] Baky A, Eriksson O. Systems Analysis of Organic Waste Management in Denmark. Environmental Project no. 822, 2003. Copenhagen. Danish Environmental Agency, 2003

[20] Kirkeby JT, Birgisdottir H, Hansen TL, Christensen TH, Bhander GS, Hauschild M. Evaluation of environmental impacts from municipal solid waste management in the municipality of Aarhus, Denmark (EASEWASTE). Waste Management & Research 2006;24:16-26.

[21] Eriksson O, Finnveden G, Ekvall T, Bjorklund A. Life cycle assessment of fuels for district heating: A comparison of waste incineration, biomass- and natural gas combustion. Energy Policy 2007;35:1346-1362.

[22] Ljunggren Soderman M. Recovering energy from waste in Sweden--a systems engineering study. Resources, Conservation and Recycling 2003;38:89-121.

[23] Sahlin J, Knutsson D, Ekvall T. Effects of planned expansion of waste incineration in the Swedish district heating systems. Resources, Conservation and Recycling 2004;41:279-292.

[24] Knutsson D, Sahlin J, Werner S, Ekvall T, Ahlgren EO. HEATSPOT--a simulation tool for national district heating analyses. Energy 2006;31:278-293.

[25] Cosmi C, Cuomo V, Macchiato M, Mangiamele L, Masi S, Salvia M. Waste management modeling by MARKAL model: A case study for Basilicata Region. Environmental Modeling & Assessment 2000;5:19-27.

[26] Salvia M, Cosmi C, Macchiato M, Mangiamele L. Waste management system optimisation for Southern Italy with MARKAL model. Resources, Conservation and Recycling 2002;34:91-106.

[27] Lund H, Duic N, ic G, Graτa Carvalho Md. Two energy system analysis models: A comparison of methodologies and results. Energy 2007;32:948-954.

[28] Lund H, Munster E. Modelling of energy systems with a high percentage of CHP and wind power. Renewable Energy 2003;28:2179-2193.

[29] Lund H. EnergyPLAN, Advanced Energy System Analysis Computer Model version, Documentation version 7.0. Aalborg. Aalborg University, 2007www.Energyplan.eu

[30] Möller B. Urban mass and energy flow analysis by means of cost surfaces : the example of combustible household waste 2006.

[31] ISWA. Energy from Waste State-of-the-Art-Report 5th Edition August 2006. Copenhagen. ISWA Working Group on Thermal Treatment of Waste, 2006;5th Edition August 2006

[32] DONG Energy. Personal Communication regarding REnescience. Skærbæk, 2007

[33] Nielsen LH, Hjort-Gregersen K, Thygesen P, Christensen J. Socio-economic Analysis of Centralised Biogas Plants - with technical and corporate economic analysis (In Danish) Report no. 136. Copenhagen. Institute of Food and Resource Economics, 2002;Report no. 136

[34] Danish Energy Authority, ElkraftSystem, Eltra. Technology Data for Electricity and Heat Generating Plants. Copenhagen. Danish Energy Authority, 2005

[35] Petersen C, Domela I. Composition of municipal waste and schemes for homecomposting (In Danish) Miljøprojekt 868. Danish Environmental Protection Agency, 2003;Miljøprojekt 868). See also: http://www2.mst.dk/common/Udgivramme/Frame.asp?pg=http://www2.mst.dk/Udgiv/publikationer/2003/87-7614-001-6/html/default.htmhttp://www.mst.dk/

[36] Danish Energy Authority. Energy Statistics 2004 (In Danish). Copenhagen, 2005

[37] Skovgaard M, Hedal N, Villanueva A, Andersen FM, Larsen H. Municipal waste management and greenhouse gases. Copenhagen, Denmark. European Topic Centre on Resource and Waste Management, 2008

[38] Pipatti R, Svardal P. 2006 IPCC Guidelines for National Greenhouse Gas Inventories Volume 5 Chapter 3. Institute for Global Environmental Strategies (IGES), Hayama, Japan, 2007 http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol5.html.

[39] Danish Energy Authority. Guidelines in socioeconomic analysis in the field of energy. Appendix: Assumptions for socioeconomic analysis in the field of energy. Copenhagen. Danish Energy Authority, 2005

[40] RenoSam. Still more efficient waste treatment - Benchmarking 2006 (In Danish), 2006). See also: http://www.renosam.dk/media/filebank/org/RenoSam_Benchmarking_2006.pdf

[41] Nexant I. Final Report Environmental Footprints and Costs of Coal-Based Integrated Gasification Combined Cycle and Pulverized Coal Technologies EPA-430/R-06/006. U.S. Environmental Protection Agency Office of Air and Radiation, 2006;EPA-430/R-06/006). See also: http://epa.gov/air/caaac/coaltech/2007_01_epaigcc.pdf

[42] Jørgensen K. Natural gas car costs - Personal communication, 2007

[43] Waste Centre Denmark. Danish Landfill Gate Fees. 2005. See also: http://www.affaldsinfo.dk/Affald+i+Danmark/%c3%98konomi/Modtagepriser/Deponeringspriser.

[44] Morthorst PE. Constructing CO2 reduction cost curves The case of Denmark. Energy Policy 1994;22:964-970.

[45] Danish Energy Authority. Guidelines in socioeconomic analysis in the field of energy. Appendix: Assumptions for socioeconomic analysis in the field of energy. Copenhagen. Danish Energy Authority, 2007). See also: http://www.ens.dk/graphics/Energipolitik/dansk_energipolitik/oekonomiske_analyser/vejledning_110405/beregningsforudsaetninger_jan07.pdf

[46] Danish Energy Authority. Assumptions for socioeconomic analysis in the field of energy. Copenhagen. Danish Energy Authority, 2008

[47] Damsgaard C, Strandmark L. Should the foodwaste of households be burned or recycled? (In Danish). Socioeconomic analysis of increased recycling of organic municipal waste. Miljøprojekt nr. 814. Danish Environmental Protection Agency, 2003). See also: http://www2.mst.dk/common/Udgivramme/Frame.asp?pg=http://www2.mst.dk/Udgiv/publikationer/2003/87-7972-685-2/html/default.htmhttp://www.mst.dk

[48] Illerup JB, et.al. Denmark's National Inventory Report 2006 - Submitted under the United Nations Framework Convention on Climate Change, 1990-2004. NERI Technical Report No. 589. National Environmental Research Institute, Ministry of the Environment, 2006). See also: http://www2.dmu.dk/1_viden/2_Publikationer/3_fagrapporter/rapporter/FR589.pdf

[49] Danish Environmental Protection Agency. Waste 21. The Government's Waste Plan 1998-2004. Danish Environmental Protection Agency, 1999http://www.mst.dk/

[50] Petersen C, Domela I. Composition of municipal waste and schemes for homecomposting (In Danish) Miljøprojekt 868. Danish Environmental Protection Agency, 2003;Miljøprojekt 868). See also:

http://www2.mst.dk/common/Udgivramme/Frame.asp?pg=http://www2.mst.dk/Udgiv/publikationer/2003/87-7614-001-6/html/default.htmhttp://www.mst.dk/

[51] Waste Centre Denmark. Fossil CO_2 content in waste - Personal communication, 2007

[52] Persson M. Assessment of upgrading techniques for biogas (In Swedish). Rapport SGC 142 . Svenskt Gastekniskt Center, 2003

[53] DONG Energy. REnescience, 2007.

[54] Danish Environmental Protection Agency. Status on organic municipal waste (in Danish). Orientation from the Environmental Protection Agency No. 4 2003. Copenhagen, 2003

[55] Moller HB, Sommer SG, Ahring B. Methane productivity of manure, straw and solid fractions of manure. Biomass & Bioenergy 2004;26:485-495.

[56] Hjort-Gregersen K, Christensen J. Burning of fibre fraction from separated manure - Corporate and socio-economic analyses (In Danish). Copenhagen. Institute for Food and Economy, 2005). See also: http://www.foi.life.ku.dk/upload/foi/docs/publikationer/udredninger/2005/30.%20maj.pdf

Table Captions

Table 1. Differences between traditional fossil-fuelled CHP plants and Waste-to-Energy technologies

Table 2. Efficiencies and waste amounts used for the scenarios.*Including 0.6 TWh manure.

Table 3. Lower heating values and biogas output. *Based on LHV of dry matter content in the manure

Table 4. Investment and Operation and Maintenance Costs as well as normal plant capacities, availability and lifetimes.

Figure Captions

Figure 1. Fossil fuel substituted when utilising 10 TWh waste per year. Including 2.5 Mt manure for biogas and 3 TWh coal for syngas

Figure 2. Reduction of CO_2 emissions from energy conversion in the various scenarios

Figure 3. Difference in annual costs between the NoWaste scenario and various other scenarios

Figure 4. Increased annual cost versus CO_2 reduction potential.

Figure 5. Difference in annual costs between the NoWaste scenario and various other scenarios with 36, 68 and 100 USD/bbl, respectively

Table 1. Differences between traditional fossil-fuelled CHP plants and Waste-to-Energy technologies

	Fossil fuel CHP	Waste-to-Energy technologies
Products	Electricity and heat	Multiple products such as heat, electricity, gaseous or liquid fuels, waste treatment and by-products (e.g. fodder and fertilizer)
Fuel	Single fuel plants (typically coal or gas)	Multiple fuels possible (e.g. waste, coal, biomass, manure, straw etc.)
Storage	Storage possible for infinite time	Not allowed to store, household waste and wet biomass rapidly degrade
Geographical distribution	Fuel can be stored and transported easily	Location of fuel is important as fuel is not easily stored and has low energy content per volume
Fuel prices	Determined by world market prices	Waste price determined by national taxes

Table 2 Efficiencies and waste amounts used for the scenarios.*Including 0.6 TWh manure.

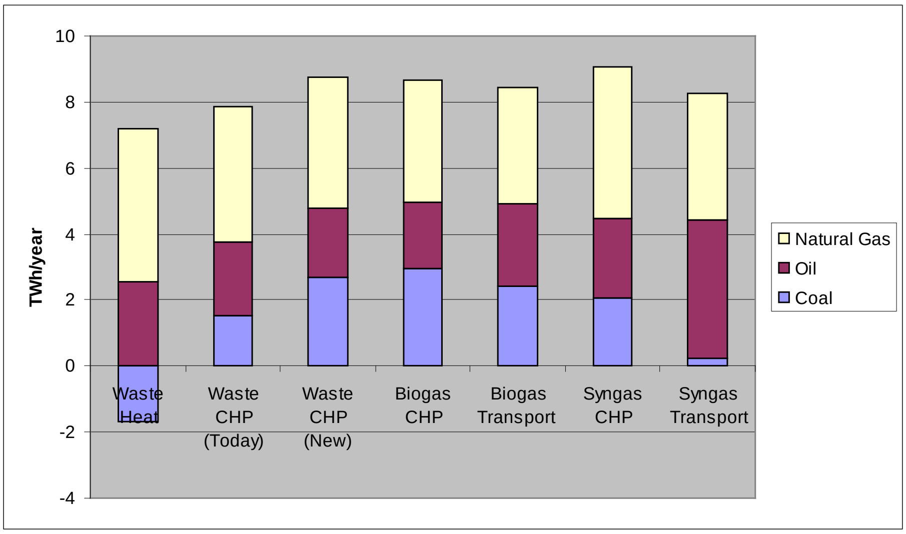
	Waste incineration				Biogas or gasification				
Technical alternatives	Mixed waste	Electric eff. (CHP)	Heat eff. (CHP)	Heat only eff. (HOB)	Org. waste	Electric eff. (CHP)	Heat eff. (CHP)	Fuel eff.	Source
	TWh	%	%	%	TWh	%	%	%	
NoWaste	0				0				[34]
WasteHeat	10			85.5	0				[34]
WasteCHP (today)	10	14.4	70.9	75.0	0				[31]
WasteCHP (new)	10	19.5	65.4	85.5	0				[34]
BiogasCHP	9	19.5	65.4	85.5	1.6*	18.6	17.5		[34]
BiogasTransport	9	19.5	65.4	85.5	1.6*			38.6	[52]
SyngasCHP	9	19.5	65.4	85.5	1	36.6	35.0		[53]
SyngasTransport	9	19.5	65.4	85.5	1	11.0	10.5	54.4	[53]

Table 3. 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 [4]	
Organic waste	5.7 MJ/kg [54]	108 Nm3/t [54]
Manure	0.9 MJ/kg* [55]	21 Nm3/t [34]
Fibre fraction from biogas plant	3.8 MJ/kg [56]	
Biogas	23 MJ/m3 [34]	

Table 4. Investment and Operation and Maintenance Costs as well as normal plant capacities, availability and lifetimes.

Reference technologies	Capacity	Investment	O&M	Avai-lability	Lifetime	Year	Source
	PJ/a	MEUR/PJ	%	%	Years		
WasteHeat	1.3	33.5	9	98	20	2004	[34]
WasteCHP (new)	1.3	52.2	7	98	20	2004	[34]
BiogasCHP	3.0	355.6	7	98	20	2004	[34]
BiogasTransport	3.0	573.2	7	98	20	2004	[34]
SyngasCHP	27.5	44.0	5	80	20	2010-20	[16]
SyngasTransport	9.6	33.1	5	85	20	2010-20	[16]
Technical alternatives							
BiogasTransport Low	3.0	480.6	7	98	20	2004	
Syngas High	4.6	120.8	4	80	20	2010	[41]
Coal PP	3.0	148.2	3	91	30	2004	[34]



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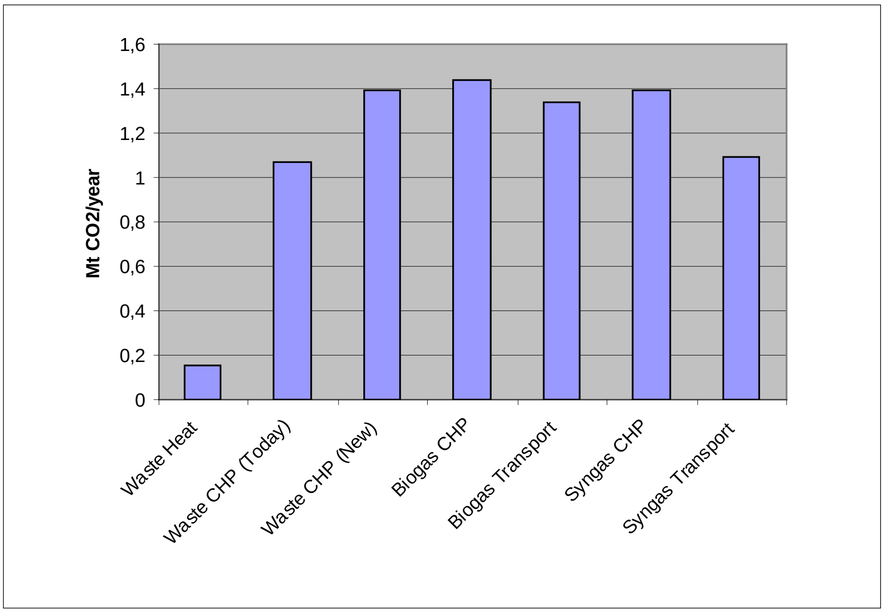

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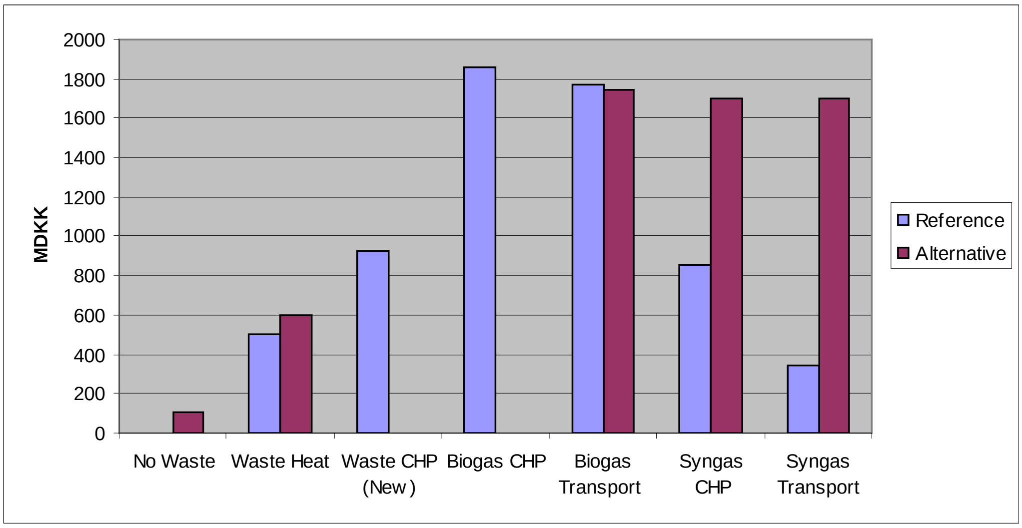

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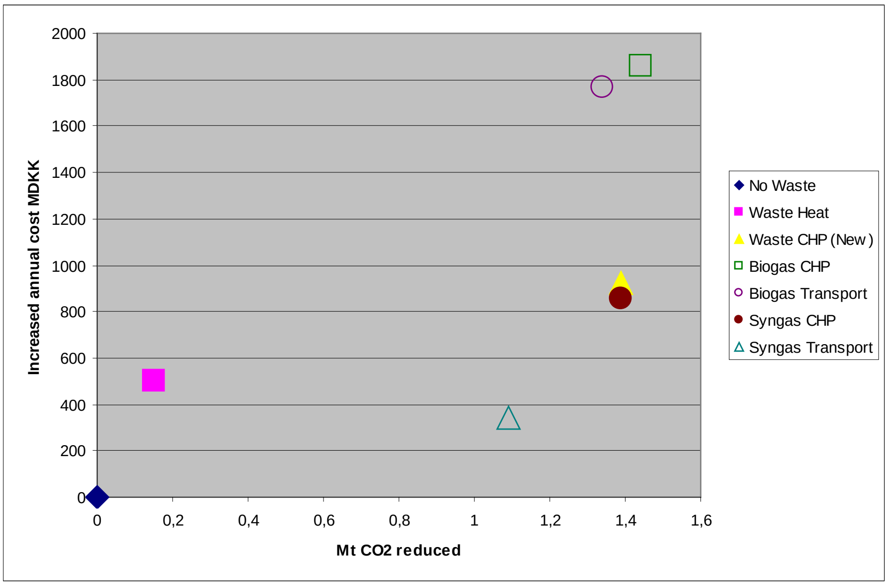

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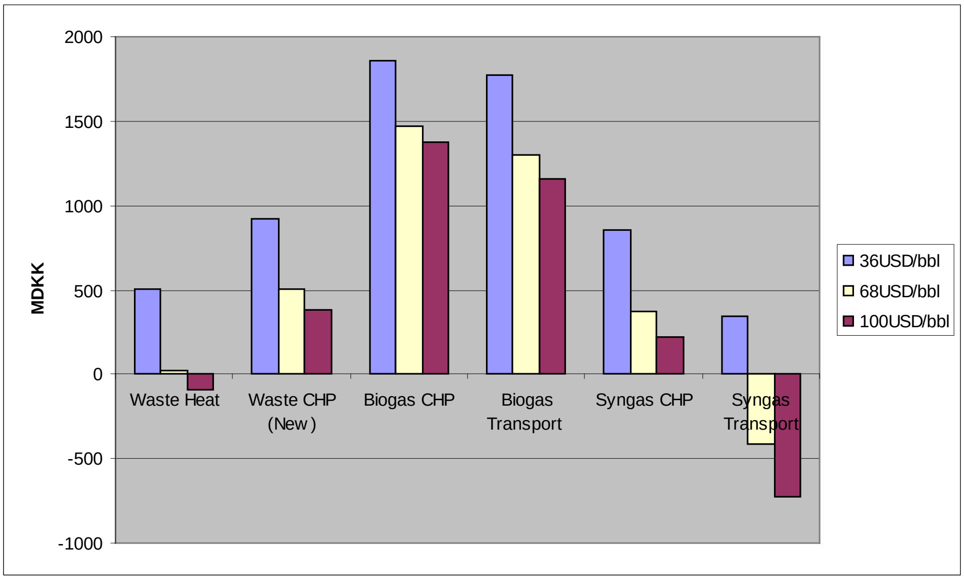

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