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IMPORTANCE OF FLEXIBLE USE OF WASTE FOR ENERGY FOR THE NATIONAL ENERGY SYSTEM

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SUMMARY: Marginal or affected energy production is often decisive for the outcome of consequential life cycle assessments. In this article the future long-term affected energy production when allowing investments in different Waste-to-Energy technologies is identified by use of energy system analysis. The technologies include co-combustion of coal and waste, anaerobic digestion and thermal gasification. The analysis is based on optimization of both investments and production of electricity, district heating and bio-fuel in an energy system in 2025 consisting of the countries in the Northern electricity market (Denmark, Norway, Sweden, Finland and Germany). Scenarios with high and low CO_2 quota costs are analyzed. It is shown that the waste incineration keeps on treating the largest amount of waste, but investments in new waste incineration capacity may be superseded by investments in new Waste-to-Energy technologies, particularly using sorted fractions such as organic waste and refuse derived fuel. The changed use of waste is shown always to affect a combination of technologies. What is affected varies among the different Waste-to-Energy technologies and furthermore depends on the CO_2 quota costs and on the geographical scope. Investments in flexibility measures such as heat and waste storage and expansion of district heating networks also vary with the different technologies. Finally, inflexible technologies are shown to be affected, as for several alternatives the production from nuclear power plants decreases.

1. INTRODUCTION

Due to demands on mitigation in CO_2 emission and increased shares of renewable energy in the energy production portfolio, the European countries are targeting significantly increased amounts of wind in the national energy systems. In order to facilitate this, higher flexibility is required from the remaining energy system. Denmark is an interesting case with up to 20% of the electricity coming from wind power. Currently a high percentage of waste is incinerated at combined heat and power (CHP) plants contributing 5% of the electricity production and 18% of the heat production. Albeit this is preferable to disposal at landfills the system is inflexible as only minor parts of the waste can be stored and that at considerable costs. As a result large amounts of heat (8% of the heat production from waste) are being cooled off, particularly during summertime. Alternative uses have the potential to improve energy efficiency and allow for increased shares of wind energy to the system. An important aspect of the analysis is the potential of producing bio-fuels from waste, thereby avoiding the large inflexible heat

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production and inflexible electricity production of the CHP at present.

Formerly, comparisons have primarily been made applying life cycle assessment (LCA) approaches (Baky & Eriksson 2003; Cherubini et al. 2008; Eriksson et al. 2007; Finnveden 1999; Kirkeby et al. 2006). However, to capture the significance of increased flexibility in the long term it is necessary to perform analysis with a model which incorporates the dynamic properties of the energy system. This has formerly been done by Münster and Lund (Münster & Lund 2008a; Münster & Lund 2008b) where different uses of waste were compared applying a national energy system analysis that optimizes the production of energy in the energy system. The studies showed good potential for thermal co-gasification and anaerobic digestion. They did, however, also illustrate that assumptions regarding the marginal electricity production plant are crucial for determining the environmental consequences when trading with the surrounding countries. Furthermore, reviews of a wide range of LCAs underline the importance of affected energy production (Finnveden et al. 2007; Sundberg et al. 2004; Villanueva & Wenzel 2007; Winkler & Bilitewski 2007).

Few energy system analyses (ESAs) have been made of Waste-to-Energy technologies. These use load duration curves and focus either on district heating systems or on national electric energy systems (Cosmi et al. 2000; Holmgren & Henning 2004; Knutsson et al. 2006; Ljunggren Soderman 2003; Sahlin et al. 2004; Salvia et al. 2002). Use of load duration curves, however, does not make it possible to take the dynamic properties of the energy technologies fully into account due to the loss of chronological time. Particularly technologies that add flexibility to the energy system, such as storage technologies, are not given full justice. The ESAs are all performed on the current energy system or with a short-term view into the future and the only Waste-to-Energy (WtE) technology analyzed is waste incineration.

In this study, long-term affected energy production for a wide range of uses of waste for energy is identified in an energy system analysis with optimization of both production and investments hour by hour towards 2025. The analysis incorporates the full North European (Denmark, Finland, Germany, Norway and Sweden) electricity market in the optimization and is performed with Balmorel (Ravn 2001).

In the subsequent sections it is first discussed how to identify marginal energy production and recommendations are made. Subsequently the energy system analysis model is presented as well as the technologies and main assumptions of the analysis. In the last sections the results are presented and conclusions are made with regard to the affected energy production.

2. IDENTIFYING MARGINAL ENERGY PRODUCTION

Energy system analysis (ESA) can be used to identify marginal or affected energy production. ESA is used particularly to assess the impact of 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 rather than focusing on one technology during the full life cycle (which is normally restricted to the phases from waste generation to final disposal in the case of waste LCAs).

In 2007, Ekvall, Assefa, Björklund, Eriksson and Finnveden discussed the fact that "a traditional LCA model has several inherent characteristics that prohibit it from giving adequate answers to many significant questions" in the article ""What life-cycle assessment does and does not do in assessments of waste management"(Ekvall et al. 2007). A number of issues are raised:

1. With regard to the **functional unit** it is identified as problematic when static assumptions regarding the waste amount are employed and e.g. one tonne of waste is used as the functional unit. An amendment to this might be to have the amount of waste produced in an area as the functional unit, thus making it possible to include waste reduction as a strategy.
2. Along the same line, the **system dynamics** is considered problematic as traditional LCA models do not provide answers to how much waste treatment capacity is needed. The static nature is criticized further: "Perhaps more seriously, the system structure and the input data in a traditional LCA both reflect the recent past. This means that, at the best, traditional LCA provides basis for identifying what waste strategies are best served to solve the needs of the current society." It is suggested to conduct studies regarding the future and to use dynamic models which may answer the question of when the appropriate time for investments is.
3. Concerning **spatial information,** the problem is addressed that emissions have different impacts depending on where they are emitted. It is suggested to amend this by using site-dependent modelling on regional level and combining local studies with environmental assessment.
4. Furthermore, information on **specific pollutants** and the practice of aggregating substances of the same type using sum parameters is addressed as the environmental impacts of these substances may vary greatly. It is suggested to avoid sum parameters and use specific data when possible.
5. Regarding **non-linear relationships,** the problem is addressed that LCA models are linear while the reality may be nonlinear. Using linear programming with partially linear functions is suggested as amendment.
6. With regard to **effects on background systems**, in the article it is considered a problem that average data are often used for effects on energy systems and production of materials and fertilizers. It is recommended to identify long term marginal effects using dynamic optimizing models.
7. Concerning inclusion of **non-environmental impacts** it is recommended to combine or supplement analyses with e.g. cost benefit analysis. Pros (such as simple answers or transparency) and cons (such as lack of information) for the two approaches are discussed.

Combining LCA with ESA may alleviate some of the inherent problems. Particularly with regards to points 2 and 6 ESA may have something to offer, as future studies are made possible using dynamic modelling and identifying long-term marginal effects on the energy system. This can be done with linear programming which addresses point 5. The ESA modelling district heating systems include spatial data, which makes it possible to identify in broad terms the areas in which an investment in a WtE technology would be most feasible.

Although ESAs in general do not include non-energy waste treatment, in particular waste prevention, it is uncomplicated to perform analyses of scenarios with different waste amounts such as shown in (Münster & Meibom 2009). Furthermore, if non-energy treatments are represented by prices it will be possible to include these technologies in the optimization thereby allocating the waste amounts, where it is most economically feasible.

Apart from improving the assessment of environmental impacts ESA may also improve assessment of non-environmental impacts by estimating when and where and in which technologies investments may occur. It may be possible to combine LCA with ESA in one model, but as both types of models are complex and require extensive training, practice and data collection, it is here recommended to keep the models apart and if deemed necessary, to perform manual iterations between the models. ESAs normally only include CO_2 emissions and possibly also methane, sulphur and NOxes but they may e.g. be extended to include more emission factors, which LCAs show to be important, or results from ESAs may be included in LCAs in which affected energy production is decisive for the results.

In Ekvall & Weidema 2004 (Ekvall & Weidema 2004) 5 steps are presented to identify a "marginal"1 technology:

1. Firstly, the relevant time aspect is discussed. It is argued that "In reality, any change can be expected to have a combination of short term and long term effects." In energy terms short term effects refer to changes in production and long term effects refer to changes in capacity.
2. Secondly, the relevant markets must be identified and "If the decision influences a market it is necessary to identify the marginal technology of this market." In energy system terms markets may be electricity or district heating markets. As an established electricity market exists among e.g. the Nordic countries and Germany, affected energy technologies may be found in these countries rather than in Denmark.
3. Thirdly, it is necessary to "identify the overall trend in the demand on the relevant market segment" and "the replacement rate of existing production capacity". Hence, it is important to assess the trend with regard to demand for electricity and heat and decommissioning of existing plants. Furthermore the waste amounts available for energy production must be assessed.
4. Fourthly, the flexibility of technologies must be assessed. This argument is often used to discard wind or hydropower as marginal technologies. In the short term, technologies which are affected by a change must be able to adjust the production and in the long term, technologies must be able to adjust capacity. When looking at an energy system in the long term, all types of energy technologies may in practice be flexible in terms of either production or capacity and should therefore be included in an analysis. Natural, political and market constraints are mentioned as important, but these are often not fixed entities and may change e.g. as technologies develop.
5. Fifthly, the marginal technology is said to be determined by the short term or long term cost per unit depending on whether the technologies are to be phased out or installed.

ESAs may be conducted either with a short term perspective optimising only production or with long-term perspective including both investments and production in the optimisation. Often optimisations are done with focus either on heat markets or on electricity markets, maybe representing the heat markets as just one aggregate district heating area. For short term ESAs, current data regarding energy demand and waste production are used, whereas it is a necessary part of all ESAs of future scenarios to estimate the trends in this respect. When modelling energy systems, all technologies in the respective systems regardless of their short term or long term flexibility will be represented. Energy system models optimising production and investments will normally do that according to both short term and long term costs and are hence built under the same assumptions as mentioned above.

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

In the article “Uncertainties related to the identification of the marginal energy technology in consequential life cycle assessment” by Mathiesen et. al. (Mathiesen et al. 2009) problems in the current practise of identifying marginal energy technologies are illustrated. As illustrated in the article through a review of current consequential LCAs, one single technology, either a coal or natural gas fired CHP plant is in general assumed to be the “marginal” energy production plant. The “marginal” energy production plant is chosen based on a range of varying arguments, but only in one case does energy system analysis form part of the identification. Furthermore the recommendations are based on a historical analysis of the “marginal” energy production technology in Denmark and on an energy system analysis of increased waste incineration. In the energy system analysis waste incineration is increased in different district heating areas, in different energy systems and with different flexibility. The energy system analysis in the article shows great differences with regard to fuel substitution in the different scenarios. Based on the three types of analyses in (Mathiesen et al. 2009) three recommendations for identifying marginal energy technologies are presented:

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

The first and third recommendations follow logically when performing a national energy systems analysis. The second recommendation relates to the time perspective and to trends. As illustrated in the abovementioned article, energy technologies perform differently in different energy systems and hence, in order to evaluate the technology, it is necessary to perform energy system analysis of WtE technologies not only in current energy systems, but also in medium and long term. In an LCA context the significance of doing this has also been illustrated by Klang et. al. (Klang et al. 2008).

Based on the above three articles the following five recommendations can be made when identifying long-term affected energy production:

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

3. ENERGY SYSTEM ANALYSIS MODEL

The energy system analysis is performed in Balmorel, which is a linear optimization model that optimises investments as well as production with regard to electricity and heat production and also storage and transmission. The model is open source and is available at the homepage (www.balmorel.com) along with documentation and examples of use. A GAMS license and linear programming software is required to run the model.

The model incorporates several countries participating in an electricity market. Each country is divided into one or several regions between which electricity is traded, restricted by electricity transmission capacity. Each region is divided into one or several district heating areas between which no heat may be traded. The model has flexible time division modelling a year divided into seasons (e.g. 52 weeks) and time periods (e.g. 168 hours). In the analysis presented in this article it has been necessary to settle for 4 seasons and 168 time periods. Thereby hourly presentations of one week for each season are achieved. By being able to run hour-by-hour as opposed to using load duration curves the model maintains the chronology of the demand and production, and it facilitates modelling of e.g. short-term energy storage. The Balmorel model has been applied to a wide range of countries analyzing a broad spectrum of technologies as well as market conditions (Ball et al. 2007; Jensen & Meibom 2008; Karlsson & Meibom 2008).

4. TECHNOLOGIES AND MAIN ASSUMPTIONS

The technologies and energy system analysed in this article are the same as used to identify the optimal combination of WtE technologies in the article “Optimal Use of Waste in the Future Energy System” by Münster and Meibom. Further explanations of the technologies and documentation of the assumptions may be found in the article (Münster & Meibom 2009).

In order to identify the affected energy technology, alternatives are analysed by allowing investments in waste incineration as well as in each type of WtE technologies in turn in Denmark. The same amount of waste is used in all alternatives, apart from the Less waste alternative, where the use of waste for energy production is decreased by 1 PJ. To show the effects of the optimal combination a combined alternative is also analysed. The alternatives are listed below:

- Inc: Existing and new waste incineration CHP (Mixed waste)
- Co-comb: Upgraded and new co-combustion plants (Coal and RDF)
- Biogas: Biogas for CHP or transport fuel (Organic waste and manure)
- RDF gas: Thermal gasification for CHP or transport fuel (RDF)
- Syngas: Syngas for CHP and transport fuel (Mixed waste and coal)
- Combined: All WtE technologies
- Less waste: 1 PJ less waste in Inc alternative

Refuse derived fuel (RDF) mainly consists of paper, plastics and wood. The efficiencies and costs of the WtE technologies along with the waste fractions and additional fuels are illustrated in Table 1.

Table 1 Efficiencies and costs of WtE technologies

	Fuel	*Fuel eff**	*CB*	*CV*	*Inv cost*	*VO&M cost*	*FO&M cost*	*Life-time*	*Source*
					MEUR/ MWel	*EUR/ MWhel*	*kEUR/ MWel*	*Years*	
WtE technologies									
Mixed waste gasification (Syngas)	Coal/ Mixed waste	0.78			0.69		43.4	20	a/b/c
Combined cycle, back pressure (CHP)	Syngas	1.04	1.31		0.89	2.8	10.2	20	a/b/d/e
Syngas Catalysis (Transport)	Syngas	0.79			0.13		81.7	20	a/b
Integrated gasification and combined cycle, extraction (CHP)	RDF	0.49	0.93	0.13	2.06		92.9	20	a/b/c
Gasification and DME production (Transport)	RDF	0.67			1.98		118.6	20	c
Biogas Plant and Engine, back pressure (CHP)	Organic waste and manure	0.60	0.8		1.86		170.8	20	c
Biogas Plant incl. cleaning and upgrading (Transport)	Organic waste and manure	0.56			1.93		170.8	20	c
Co-combustion upgrade, steam turbine, extraction (CHP)	Coal/ RDF/ Straw	0.37-0.47	0.59-4.76	0.15-0.2	0.15	2.7/4.5	56.4	30	e/f/g
Co-combustion steam turbine, extraction (CHP)	Coal/ RDF	0.53/ 0.52	0.95/ 0.94	0.15	1.39	4.5	23.5	30	e
Incineration steam turbine, back pressure (CHP)	Mixed waste	0.97	0.37		5.44	20.3	217.8	30	e

[a] (DONG Energy 2007)
[b] (Rostrup-Nielsen et al. 2007)
[c] (EUCAR et al. 2007)
[d] (Ahrenfeldt et al. 2005)
[e] (Danish Energy Authority et al. 2005)
[f] (Møller et al. 2008)
[g] (Danish Energy Authority 2008b)

Further energy technologies, in which the model is allowed to invest, encompass biomass and fossil fuelled condensing and CHP plants as well as nuclear plants. Furthermore, investments are allowed in wind power, heat boilers, heat pumps, heat storage and new district heating networks.

The fuel prices, lower heating values and fossil CO_2 content assumed are illustrated in Table 2. It is assumed that organic waste equivalent of 4% of the mixed combustible waste may be sorted out and used for biogas production (Fruergaard 2008). For RDF the equivalent figure is 19%

(Ramboll 2008). Manure is assumed to be available from outside the energy system at no cost. Currently, 10% of the Danish manure resource is treated at biogas plants.

Table 2. Projected fuel prices in 2025, lower heating values and CO_2 content of fuels

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

[a](Danish Energy Authority 2009)
[b](Danish Energy Authority 2008c)
[c] (RenoSam 2006)
[d] (Møller et al. 2008)
[e] (Christensen et al. 2003)

The CO_2 quota price is expected to be 32 EUR/t in the high scenario. In the low CO_2 quota price scenario the price is only assumed to reach 25 EUR/t. (Danish Energy Authority 2009)

The percentage of renewable energy in the energy system analysed reaches 43% in Denmark, mainly due to a high contribution from wind. The assumed energy demands and electricity production capacity are shown in Table 3. The electricity production capacities shown are the capacities which are assumed to remain after decommissioning if no investments are made in the period until 2025.

Table 3. Projected energy demands and remaining electricity production capacity in the Nordic countries and Germany

	DK	*DE*	*FI*	*NO*	*SE*
Electricity demand (TWh)*	35[a]	543	106 [b]	145 [b]	148 [b]
District heat demand (PJ)*	67 [a]	337 [c]	266 [d]	9 [c]	166 [c]
Remaining electricity production capacity and main fuel (GW)	5.7 (Coal, wind, ngas)	80.5 (Wind, coal, hydro)	11.7 (Nuclear, hydro, oil)	33.9 (Hydro, wind)	35.1 (Hydro, nuclear, wind)

* Excluding transmission losses
[a] (Danish Energy Authority 2008a)
[b] (Papageorgi 2006)
[c] (Danish Energy Authority 2007)
[d] (Kiviluoma & Meibom 2009)

5. RESULTS

Comparisons are carried out for the alternative uses of waste for energy in terms of both:

- Use of waste for energy in different WtE technologies
- CO_2 emissions
- Fuel consumption
- Flexibility measures (Heat and waste storage and expansion of heat and electricity transmission)

- Total yearly costs of the energy system

The changed use of waste is illustrated in Figure 1. Overall most of the waste continues to be incinerated regardless of the possible investments in new WtE technologies as shown in the left axis. The Combined alternatives, in which the model optimizes among choices of investments in all plants, have investments in a combination of all new WtE technology types. These are also the alternatives where the full potentials of organic waste and RDF are used, where least waste is used for waste incineration and where the investments in new WtE technologies exceed the investment in new waste incineration capacity. The full amount of organic waste is also sorted out and used for the biogas alternatives. For RDF the full amount is furthermore sorted out and used in the RDF gasification alternatives. Most, but not all RDF is used in the co-combustion alternatives. Here the use in existing plants is limited to plants with high total efficiencies and by increased operation and maintenance costs combined with costs of upgrading as well as decreased electrical efficiencies. Co-combustion in new plants is on the other hand correlated with the demand for new coal-fired power plants in general. Competition for RDF is seen in the Combined alternatives between the co-combustion plants and RDF gasification plants. Of the two technologies co-combustion of waste with coal is the most developed, and RDF gasification may be more relevant in a longer time horizon as is the case with gasification of mixed waste in the syngas plant.

When optimizing between the choice of producing CHP or transport fuel, then production of transport fuel is most feasible in the Syngas alternative and in the Biogas alternative with low CO_2 prices, whereas production of CHP is most feasible in the RDF gasification alternatives.

In the Co-combustion alternative, co-combustion of waste with coal mainly takes place in new coal-fired power plants, but upgrade of existing plants is also found in plants with high total efficiencies. The main difference between the two scenarios in terms of use of waste is that investments in Syngas are only found with the low CO_2 price and biogas is used for CHP with high CO_2 prices and for transport fuel with low CO_2 prices. This is due to the fact that the CO_2 emissions increase in the Syngas alternative due to increased use of coal. Furthermore, when using biogas to replace fuels for heating or electricity production, costs of CO_2 quotas are reduced at these plants. This is not the case when replacing transport fuels.

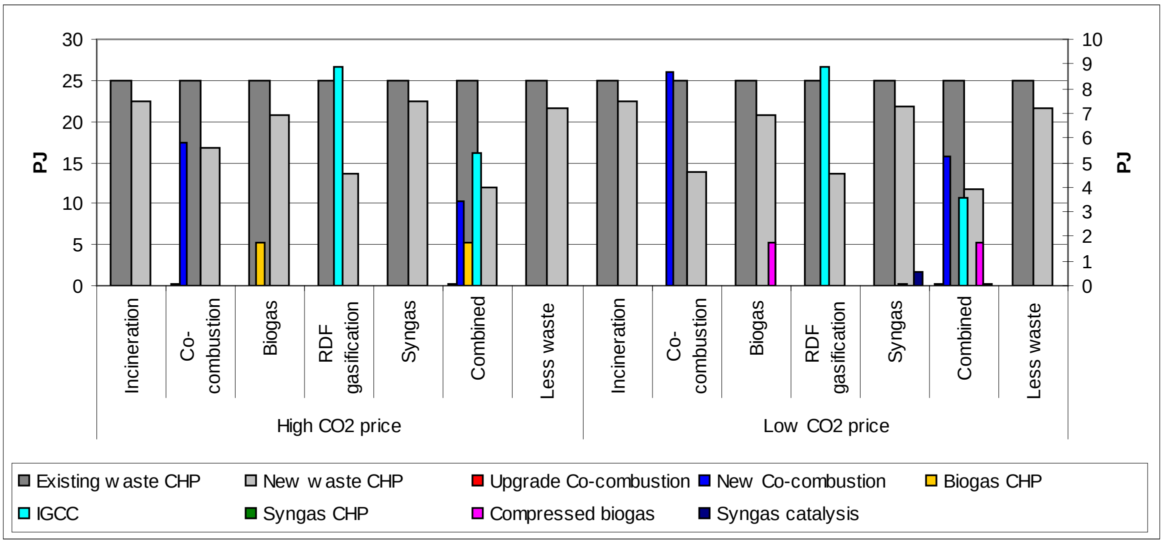

Figure 1. Use of waste for energy in Denmark. Waste CHP is shown on the left axis and the remaining WtE technologies on the right

In Figure 2 the changed CO_2 emissions compared to the incineration alternatives are shown. The most significant change is increased CO_2 emissions in the co-combustion alternatives due to increased use of coal. For most alternatives, the CO_2 emissions increase compared to waste incineration. Decreases are only seen when producing biogas for transport fuel in a low CO_2 price scenario and when using less waste for energy production in a situation with high CO_2 prices. Overall an increase in CO_2 emissions in Denmark is followed by increased CO_2 emissions in the whole region.

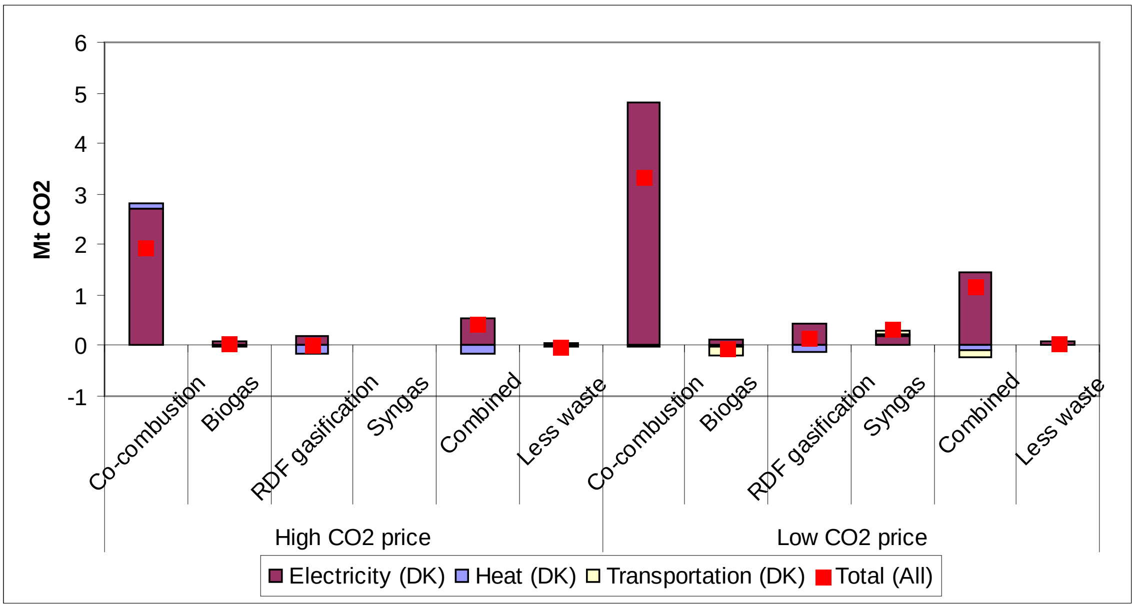

Figure 2. Changed CO_2 emissions in Denmark and in all countries for all technologies compared to the Incineration alternative with high or low CO_2 prices respectively

When comparing with the incineration alternative, the differences with regard to fuel use vary in Denmark as shown in Figure 3. The main change in use of fuel is seen in the Co-combustion alternatives, where the use of coal increases by respectively 30 PJ and 51 PJ in the high and low CO_2 price scenarios. Coal CHP is in close competition with coal in the scenarios. With the possibility of using RDF as free fuel, coal-fired CHP becomes more feasible and investments in coal-fired CHP increase in Denmark from 900 MW to 2150 MW, thereby replacing investments in nuclear power capacity in Sweden. When gasifying RDF and producing biogas for CHP, the main effects are seen abroad, as shown in Figure 4. Due to investments in a syngas plant in the low CO_2 price scenario, biomass use decreases in existing biomass co-combustion plants in the area where the investments are made. With different fuel prices, different effects would be seen.

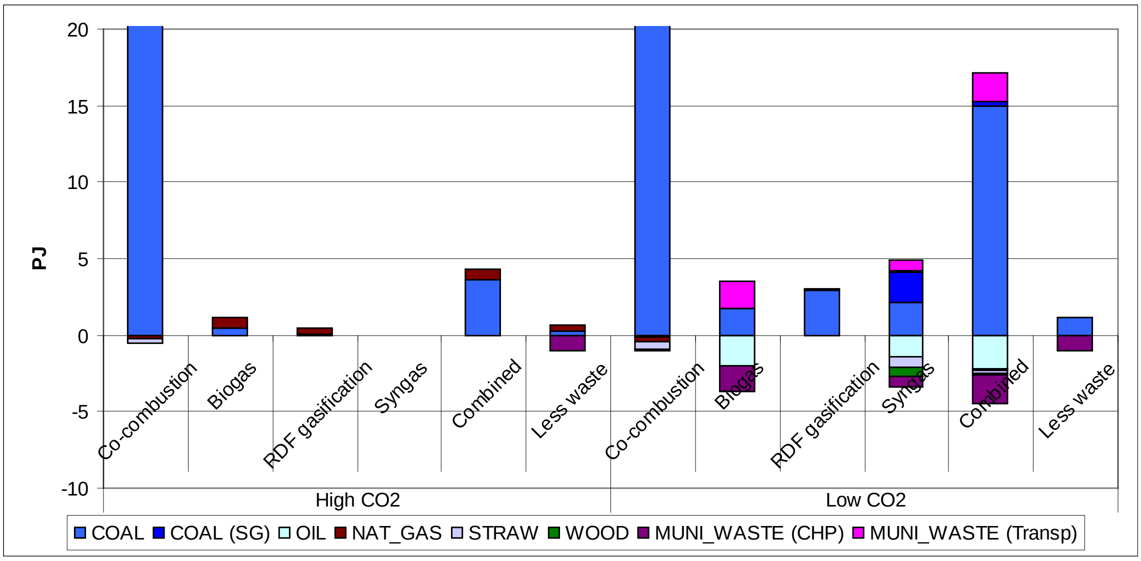

Figure 3. Changed fuel use for Denmark for all technologies, when compared to the Incineration alternative with high or low CO_2 prices respectively (max 20 PJ shown)

When looking at the affected fuel use in the whole region shown in Figure 4, use of coal in general increases while nuclear power decreases. The most significant effects are again seen in the Co-combustion alternatives, where coal increases with 20 PJ and 36 PJ in the high and low CO_2 quota price scenarios respectively, while use of uranium simultaneously decreases by 36 PJ and 65 PJ.

For all alternatives a mix of fuels is affected. Furthermore, it is noteworthy that for the whole region, effects are seen on nuclear power, which is an inflexible technology in terms of capability to react to short-term changes in demand. Inflexible production technologies are generally not considered, when LCA practitioners determine the affected energy production.

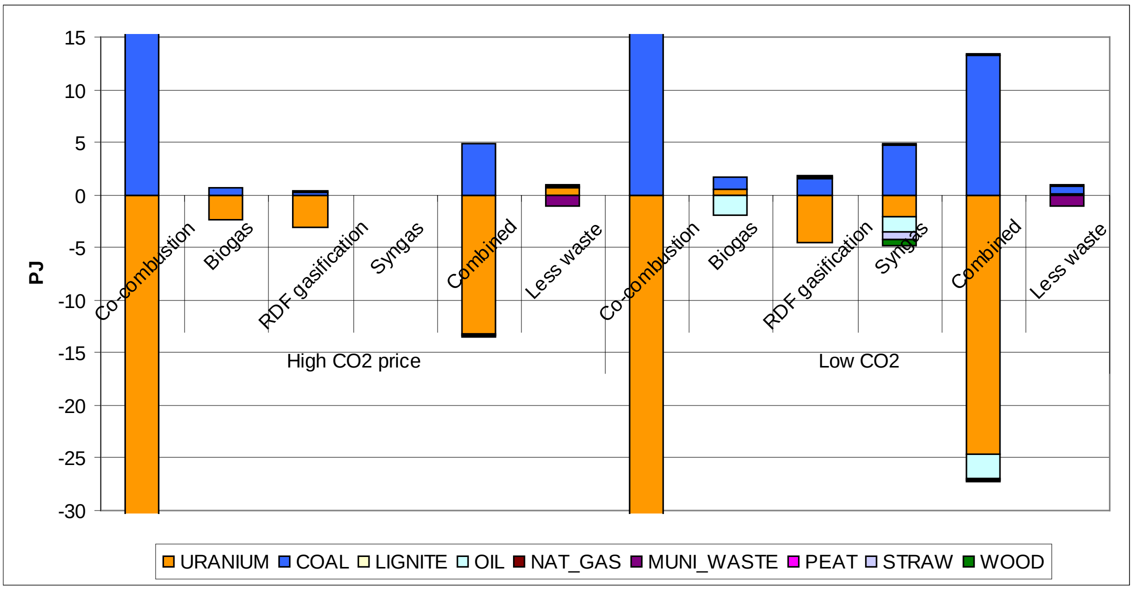

Figure 4 Changed fuel use for the whole region for all technologies, when compared to the Incineration alternative with high or low CO_2 prices respectively (max 15 PJ and min -30 PJ shown)

The need for flexibility measures differs when allowing investments in different WtE technologies as shown in Figure 5. Overall, the use of waste storage decreases. The expansion of new district heating networks is virtually the same in all alternatives, apart from with Co-combustion in the low CO_2 price scenario, where a larger expansion is seen. Here the need for central waste storage decreases and the electricity and heat production increases significantly reducing the need for import of electricity, and thereby the need to expand electricity transmission, and increasing the need both for new district heating networks and for heat storage. In the Co-combustion alternative with high CO_2 costs, less increase in Danish production is seen and consequently, the slight increase in district heating networks reduces the need for heat storage.

The results show that it would not be sufficient to aggregate all district heating grids into one, as illustrated by the changes concerning heat storage and expansion of district heating networks. This is due to the fact, that these flexibility measures are not necessary, when assuming that heat can be transferred freely among the many district heating networks.

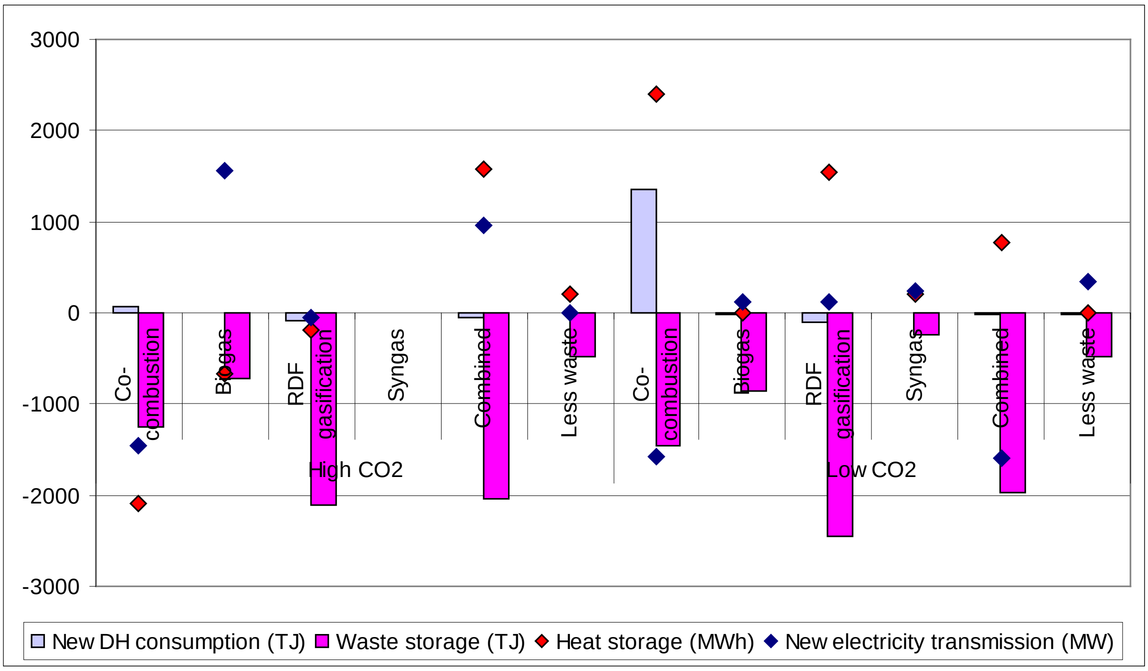

Figure 5. Changes in new DH consumption due to investments in DH networks, electricity transmission and heat storage as well as use of central waste storage compared to the Incineration alternative.

When comparing the yearly costs of the total energy system of the whole region in the incineration alternative with the other alternatives, savings are found in all alternatives apart from Syngas in the high CO_2 cost scenario, as shown in Figure 6. The largest total saving is achieved with the Combined alternatives and the largest saving per PJ waste moved are found in the Biogas alternatives. The red diamonds illustrate the negative CO_2 reduction cost i.e. saved costs per reduced t CO_2, for the two alternatives which reduce CO_2 emissions, namely the Biogas for transport with low CO_2 price and the Less waste alternative with high CO_2 price. However, as shown in Figure 2 the reductions are minor, particularly for the Less waste alternative.

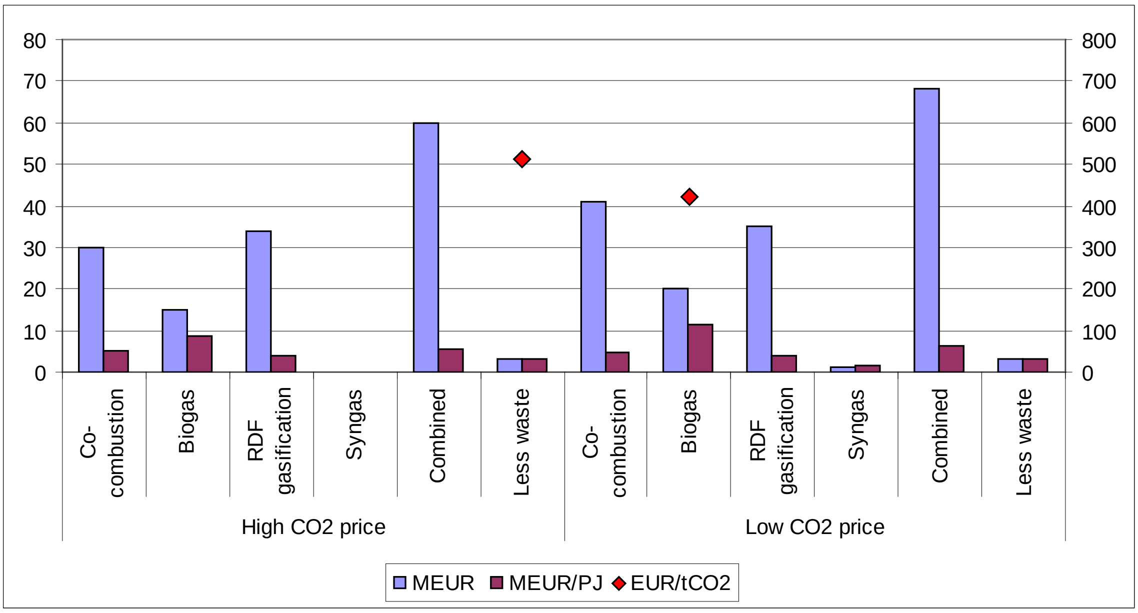

Figure 6. Saved total costs (MEUR) and saved costs per PJ waste moved (left axis) and saved costs per t CO_2 less emitted in the whole region (right axis), when comparing to the Incineration alternative.

6. CONCLUSION

In all scenarios waste incineration treats by far the largest amount of waste, but investments in new waste incineration capacity may be superseded by investments in new WtE technologies, particularly using sorted fractions. When allowing investments in new WtE technologies it is feasible to move some waste from waste incineration to other WtE technologies in all scenarios apart from the “Syngas” alternative in the high CO_2 price scenario. The full potential for sorting out the organic waste fraction is utilized in the Biogas alternatives and for RDF it is fully utilized with gasification for CHP production. Mixed waste is only used in a new WtE technology (Syngas) in the scenario with low CO_2 costs.

The only two alternatives, which provide CO_2 reductions are the Biogas alternative producing transport fuel and when using less waste in the high CO_2 price scenario. The lowest of these is the Biogas alternative. The two alternatives have the lowest CO_2 emissions, both when looking at Denmark or the whole region. The highest CO_2 reduction earning is found in the Less waste alternative, but this is due to division with a very low CO_2 reduction.

The affected fuel consumption consists of a mix of fuels in all cases, but depends on the CO_2 price, the technology and the region in question. In Denmark the main fuel affected is coal, for which use increases. When looking at the whole region, the main fuel affected is uranium for which use decreases. With other fuel prices, the results would change

When comparing use of waste for energy with other types of waste treatment one should be aware that reducing the amount of waste for energy may result in either decreased or increased CO_2 emissions depending on the CO_2 quota costs, but that in both scenarios it has the benefits of reducing the costs of the energy system and reducing the need for waste storage.

Overall, the need for waste storage decreases when allowing investments in new WtE technologies. Expansion of district heating networks changes little among the different alternatives apart from the co-combustion alternative with low CO_2 price, where there is a significant increase. The highest amount of heat storage is also found here. The Co-combustion alternatives furthermore result in the lowest expansion of electricity transmission.

7. DISCUSSION

The question now remains whether the analysis supports the recommendations for identifying the long-term affected energy production which were brought forward in the introduction?

The first recommendation was:
1. Identify affected energy production with energy system analysis

One single marginal energy production plant is normally assumed when performing LCAs. The analyses presented above consistently show that the affected energy production consists of a combination of energy technologies. By using ESA it is possible to identify the combination of affected energy technologies.

The second recommendation was:
2. Include the full electricity market in the analysis along with local district heating markets

The analyses show different results with regard to affected energy production for Denmark and for the whole region (DK, NO, FI, SE, DE). When highly integrated markets for electricity exist, the changed energy production in one country may just as well result in effects in another country. The whole electricity market should therefore be included in the analysis. With regard to district heating the benefit of not aggregating all district heating grids into one, is illustrated by the changes in heat storage and expansion of district heating networks.

The third and fourth recommendations were:
3. Optimise both investments and production according to cost
4. Include investments in both flexible and inflexible energy production technologies, as well as storage technologies in the optimization

The analyses show investments in “inflexible” energy technologies such as nuclear power and wind power, as well as effects on use of flexibility measures. This underlines the importance of optimizing both investment and production and of including both flexible and inflexible production technologies as well as flexibility measures in the optimization.

5. Analyse fundamentally different future scenarios

Only by reducing the CO_2 quota price by 22%, different conclusions are found in the analyses with regard to affected technologies. As it is impossible to predict the future, it is therefore important to assess the affected energy production in different future scenarios for the energy system.

In conclusion all five recommendations have been shown to be important with the analyses presented in this article.

In future it would be interesting to use the affected energy production identified in this article in life cycle assessments of the WtE and compare with use of single marginal affected energy production such as coal or natural gas fired CHP plants.

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