

## **Alternatives for Future Waste Management in Denmark**

### **Final Report of TopWaste**

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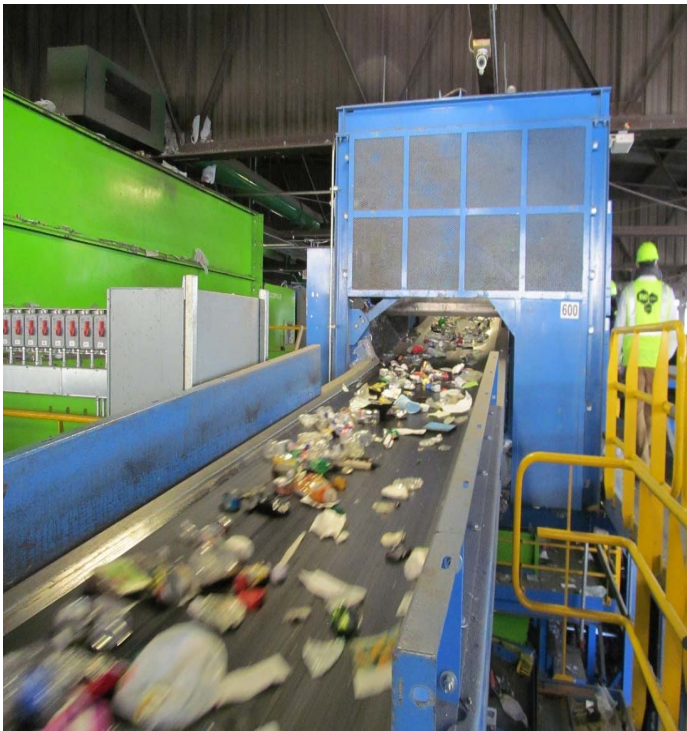
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# Alternatives for Future Waste Management in Denmark

Final Report of TopWaste



**System Analysis**

DTU Management Engineering

March 2016

Report

March 2016

By Frits Møller Andersen, Ciprian Cimpan, Ole Dall, Komal Habib, Birgit Holmboe, Marie Münster, Amalia Pizarro and Henrik Wenzel

Edited by Marie Münster

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## PREFACE

This report attempts to outline the results of the Danish strategic research project, TOPWASTE, to a broad audience. The project was funded by the Danish Innovation Foundation and has been running from 2011-2015.

The content of this report represents a brief summary of the findings related to some of the main research questions, which were addressed during the project. The report should however only be seen as an appetizer as many more analyses and documentation can be found in the references mentioned in the report as well as on the project home page ([www.topwaste.dk](http://www.topwaste.dk)), which we hope you will visit after having read the report.

We would like to thank all partners of the project for great cooperation and discussions during the project. We would in particular like to thank the industrial partners, Amager Resource Centre and RenoNord as well as the Consultant reference group (COWI, EA, Grontmij, Rambøll) for their participation in the project. Further thanks are extended to the members of the Advisory Board for great constructive criticism and suggestions.

Good appetite!

DTU Lyngby, March 2016

Marie Münster

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## SUMMARY

The TOPWASTE project has addressed the challenges of planning robust solutions for future waste management. The purpose was to identify economic and environmentally optimal solutions - taking into account different scenarios for the development of the surrounding systems, such as the energy system. During the project, four decision support tools were developed:

1. Frida - The EPA's tool for forecasting future waste generation
2. OptiWaste - a new tool for economic optimisation of investments and operation of the combined waste and energy system
3. KISS - a new lifecycle based model with focus on comparison of greenhouse gas emissions associated with different waste management alternatives
4. A new tool for techno-economic modelling of central sorting plants

The project has furthermore contributed with method development on evaluation of critical resources as well as analyses of economic and organisational factors with influence on the future waste management.

The results of the project clearly show the importance of taking scenarios for the future development of surrounding systems into account when deciding how the future waste management should be, both when it comes to the economic, environmental and resource efficiency of waste management solutions. The following chapters addresses these issues by answering some of the main research questions of the project.

# 1. HOW MUCH WASTE WILL WE HAVE IN THE FUTURE?

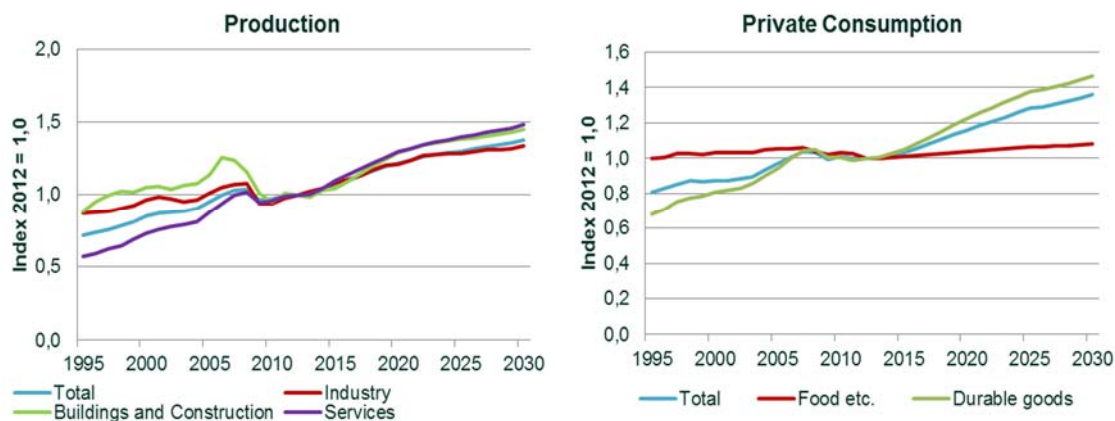
*” Based on the econometric model, FRIDA, the amounts of household waste will increase by 20% between 2012 and 2030. Daily collection will increase less than total waste from households, while combustible and garden waste is expected to increase more than total waste from households. Industrial waste is on the other hand expected to increase with 29% in the same period. Waste from the building and construction sector is expected to increase considerably over the coming years along with combustible and iron wastes, while waste from power-plants is expected to decrease slightly. In the Danish resource strategy, the main focus is on increasing recycling in the household sector (10% -points) decreasing incineration accordingly.”*

*Frits Møller Andersen (fman@dtu.dk)*

## INTRODUCTION

In order to plan future treatment of waste it is important to have an idea what the amounts and composition might be. In general, different economic activities and socio-economic developments generate different amounts and streams of waste. By analysing past changes in the generation of waste, the Frida model links the development of types of waste from different sources to economic and demographic changes<sup>1</sup>.

In order to use the model for forecasts, we assume that behaviour revealed in the past prevails in the future and forecasts of the socio-economic development are needed. The latest forecast by the Danish EPA is based on the official forecast of the economic development by the Ministry of Finance in relation to reporting to the European Convergence Program 2014. The anticipated developments in economic indicators, which are important in the Frida-model are shown in in Figure 1.1.

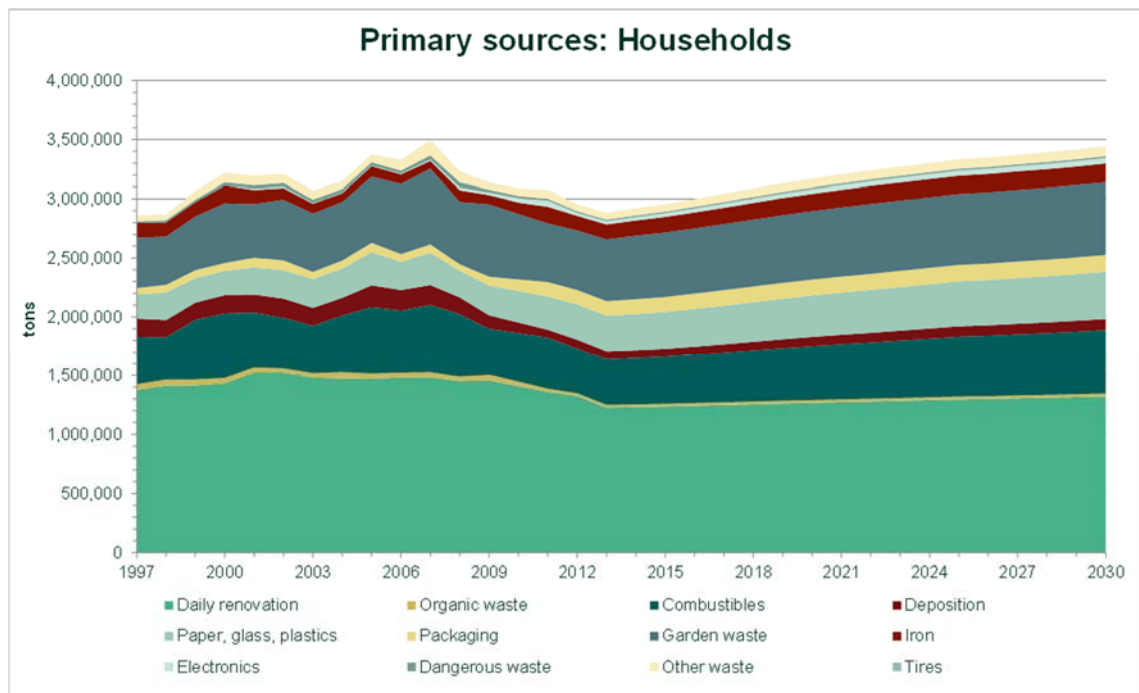


*Figure 1.1- The development of key economic indicators. Source: Ministry of Finance KP2014 and own calculations.*

<sup>1</sup> The Frida model is described in Andersen, F.M. and Larsen, H.V. (2012).

## RESULTS

Applying the model, Table 1.1 and Figure 1.2 shows a business-as-usual (BAU) projection of waste coming from households while Table 1.2 and Figure 1.3 displays waste from production sectors. Looking at waste from households, by far the largest fraction is daily collection accounting for little less than ½ of the waste generated by households. Next come the fractions "garden waste" and "combustible waste". Looking at the development in household waste, daily collection follows the private consumption of food, etc. implying a moderate increase in future amounts. Garden waste follows the development in the number of single family houses whereas combustible waste follows the consumption of durable goods. Both are expected to increase more than consumption of food, etc. Consequently, the amounts of daily collection increase less than total waste from households, and combustible and garden waste is expected to increase more than total waste from households.



**Figure 1.2 - Projected waste generation by households. Business-as-usual projection 2015.**

Looking at waste from production sectors in Figure 1.3, by far the largest amount is waste from building and construction which follows the building activity. Next come combustible waste and iron linked to the development of industrial production. As the economic projection expects a catching up of production within the building and construction sector, waste from this sector is expected to increase considerably over the coming years. This is also the case for the shares of combustible and iron wastes are expected to increase. On the other hand waste from power-plants is expected to decrease slightly due to a continued transformation from coal-fired power plants to renewable sources like wind and biomass<sup>2</sup>.

<sup>2</sup> Biomass power-plants produce some waste but less than coal-fired plants.



**Waste from households [1000 tons]**

	Daily renovation	Organic waste	Combustible waste	Deponeringse gnet	Paper, glass, plastics	Packaging waste	Garden waste	Iron	Batteries, electronics	Hazardous waste	Other waste	Total
<b>2000</b>	1.432	45	554	154	208	65	505	149		28	79	<b>3.219</b>
<b>2005</b>	1.470	44	569	186	282	78	557	89	6	27	66	<b>3.375</b>
<b>2012</b>	1.324	23	385	75	301	121	505	124	25	13	57	<b>2.954</b>
<b>2015</b>	1.336	23	401	70	313	128	546	133	32	13	64	<b>3.058</b>
<b>2018</b>	1.356	23	438	74	337	133	566	142	37	13	71	<b>3.190</b>
<b>2022</b>	1.381	24	483	83	364	137	591	152	41	14	77	<b>3.345</b>
<b>2030</b>	1.428	24	545	95	401	142	612	159	47	14	84	<b>3.551</b>
<b>2035</b>	1.457	25	578	101	421	144	628	163	50	15	88	<b>3.669</b>
<b>2040</b>	1.487	25	610	107	441	147	644	172	53	16	93	<b>3.794</b>
<b>2050</b>	1.555	26	695	122	491	155	680	201	61	17	107	<b>4.111</b>

Table 1.1 - Projected waste generation by households. Business-as-usual projection 2015.

**Waste from sectors [1000 tons]**

	Daily renovation	Organic waste	Combustible waste	Deponeringse gnet	Paper, glass, plastics	Packaging waste	Garden waste	Iron	Batteries, electronics	Hazardous waste	Other waste	Tires	Asphalt	Waste from power-plants	Waste from Building and construction	Total
<b>2000</b>	136	208	978	547	411	170	127	1.036		119	349	34	550,7296	1.189	1.685	<b>7.538</b>
<b>2005</b>	149	100	1.076	363	451	178	165	622	25	240	281	54	738,8419	1.190	2.203	<b>7.835</b>
<b>2012</b>	152	310	1.096	318	423	169	204	863	44	169	215	21	677,1367	802	2.173	<b>7.635</b>
<b>2015</b>	166	316	1.193	275	464	185	216	927	48	181	240	25	685,5273	646	2.321	<b>7.886</b>
<b>2018</b>	181	333	1.307	267	509	203	222	987	54	195	265	28	732,4611	637	2.640	<b>8.560</b>
<b>2022</b>	197	362	1.419	276	557	223	230	1.060	59	211	287	31	774,3376	648	2.913	<b>9.247</b>
<b>2030</b>	215	382	1.550	286	611	244	253	1.112	65	226	314	34	802,9758	676	3.106	<b>9.876</b>
<b>2035</b>	226	391	1.624	291	643	257	268	1.136	69	233	329	36	820,8439	676	3.229	<b>10.229</b>
<b>2040</b>	239	417	1.717	298	684	273	282	1.200	73	247	348	38	845,8672	676	3.405	<b>10.742</b>
<b>2050</b>	274	499	1.972	314	799	320	306	1.404	85	285	399	44	909,3527	676	3.872	<b>12.159</b>

Table 1.2 - Projected waste generation by production sectors. Business-as-usual projection 2015.

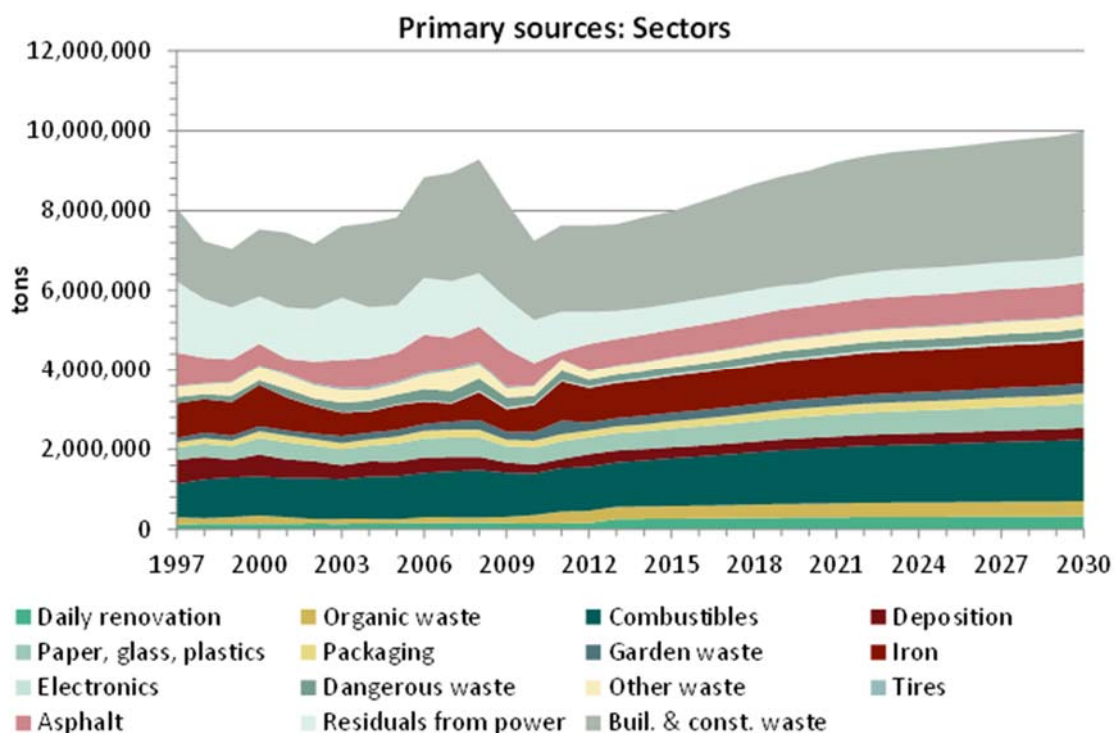


Figure 1.3 - Projected amounts of waste from production sectors. Business-as-usual projection 2015.

Assuming that treatment shares for the individual waste fractions are constant, the projected development in the generation of waste implies that all types of treatment capacities are needed to expand. However, due to changes in the relative weight of fractions, the aggregated share of recycled fractions is increased slightly at the expense of the share deposited. The expected development in treatment of waste in the BAU-projection is shown in Table 1.3 and Figure 1.4.

	Recycling	Incineration	Deposition	Special treatment	Other treatments	Sum
<b>2000</b>	6.784	2.743	1.131	17	82	<b>10.757</b>
<b>2005</b>	7.068	3.059	789	18	276	<b>11.209</b>
<b>2012</b>	6.840	3.045	541	75	87	<b>10.589</b>
<b>2015</b>	7.076	3.195	503	80	90	<b>10.944</b>
<b>2018</b>	7.652	3.395	519	87	98	<b>11.750</b>
<b>2022</b>	8.236	3.603	552	94	108	<b>12.592</b>
<b>2030</b>	8.758	3.864	586	100	119	<b>13.428</b>
<b>2035</b>	9.049	4.014	606	103	125	<b>13.898</b>
<b>2040</b>	9.476	4.190	630	109	132	<b>14.536</b>

Table 1.3 - Treatment of waste (million tons), BAU-2015.

The resource strategy "Denmark without waste", recently published by the Danish government, focuses on recycling and material recovery, setting increasing targets for increasing recycling and material recovery of waste coming from households and the service sector. Comparing the resource strategy and the BAU scenarios, the main difference is that, due to increased sorting of waste, the composition of fractions and, therefore, the treatment differ.

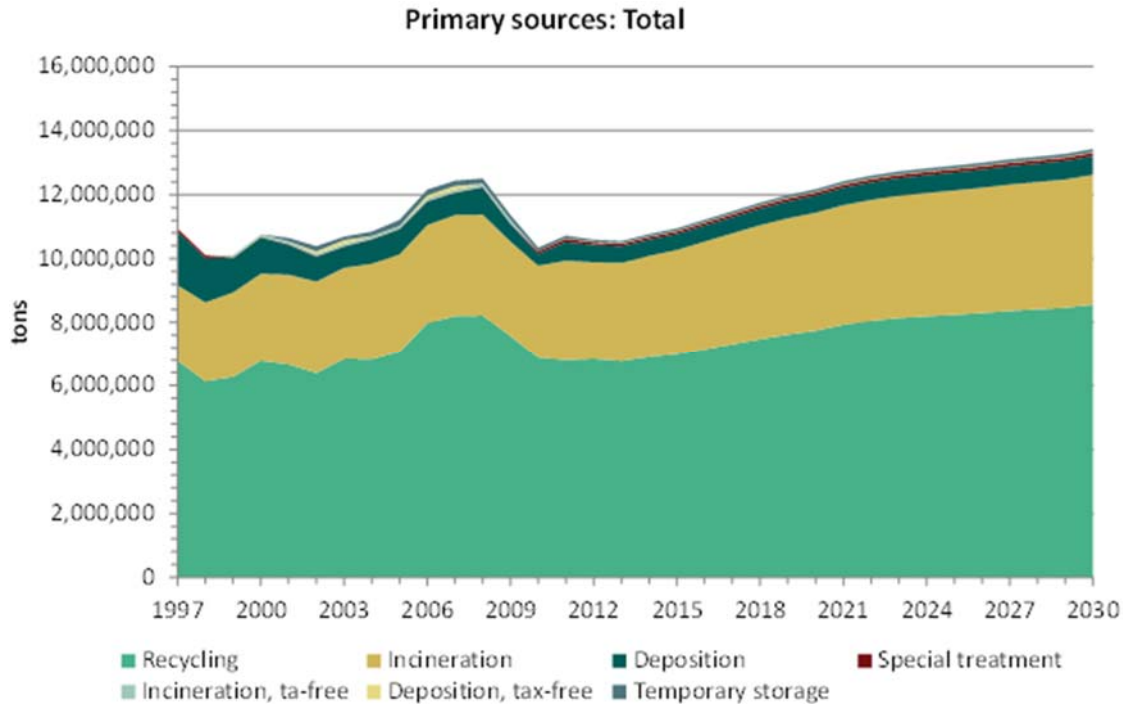


Figure 1.4 - Treatment of waste, BAU-2015.

Looking at the development in treatment shares, Table 1.4 shows their values in the base-year 2012 and in 2030 for both the BAU and the resource strategy projections. In 2030 the major difference between the BAU-scenario and the resource strategy is that the aggregated share going to recycling is 3% larger in the resource strategy scenario than in the BAU-scenario, with a consequent equal reduction in the share going to incineration. Most of this difference is due to changes in the treatment of household waste where especially organic waste is planned to be separated from the daily renovation and wood waste moved from incineration to recycling. In total, the share of household waste being recycled is increased with 10% -points and incineration decreased accordingly.

Looking at waste from production sectors the strategy mainly focuses on separating recoverable materials from incineration, but the relative magnitude of the targets are limited and the aggregated treatment shares of waste from sectors are only changed marginally. Towards 2050 the same trends are expected to continue.

	Total			Households			Production sectors		
	Waste statistics	BAU	Ressource strategy	Waste statistics	BAU	Ressource strategy	Waste statistics	BAU	Ressource strategy
	2012	2030	2030	2012	2030	2030	2012	2030	2030
<b>Recycling</b>	64,6	65,2	68,8	39,8	42,0	51,5	74,2	73,6	74,2
<b>Incineration</b>	28,8	28,8	25,3	55,5	53,0	43,5	18,4	20,1	19,5
<b>Deposition</b>	5,1	4,4	4,4	2,9	3,0	3,5	6,0	4,9	4,8

Table 1.4 - Treatment shares in the business as usual and the resource strategy scenarios.

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## CONCLUSION AND RECOMMENDATIONS

By linking waste generation to economic indicators, a model forecasting national waste generation and treatment has been developed. The model is open source and is used for analysis and planning by the Danish Environmental Protection Agency.

A further development of the model will include insights into forecasting waste development in local areas, a further detailing of waste sources, e.g. different production sectors and municipal waste.

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## 2. WHAT IS THE IMPACT OF DIFFERENT ENERGY FUTURES ON THE OPTIMAL WASTE TREATMENT?

*“ In different 100% renewable energy scenarios for the future Danish energy system, residual waste will still mainly be incinerated in CHP plants in central district heating areas. Only a limited capacity of boilers and RDF fired plants will be installed due to comparably high electricity prices and limited need for storage of waste between seasons, combined with high investment costs associated with central sorting.”*

Marie Münster (maem@dtu.dk)

### INTRODUCTION

As waste incineration currently provides 21% of the Danish district heating demand and 5% of the electricity demand, the optimal use of waste is affected by the surrounding energy system and the possible future development. The socio-economic feasibility of waste treatment has been analysed in four distinct scenarios representing different possible futures for the energy system:

- **Biomass** - High biomass consumption for power, heat and transport fuels - with bio-refineries placed in central district heating areas in Denmark (**BioDK**) or outside Denmark (**BioNotDK**)
- **Wind** - High wind power share for power, heat and transport fuels - with flexible production of hydrogen in Denmark (**WindFlexH2**) and without (**WindNoFlexH2**). Hydrogen production is assumed placed close to either biogas production in rural areas (37%) or to bio-refineries (63%)

### RESULTS

The associated primary energy demands are illustrated for Denmark in Figure 2.1. The main difference relates to the use of biomass and wind, where particularly the supply of the transport sector differs. Biofuels are mainly used in the Bio scenarios and more electric vehicles and hydrogen in the Wind scenarios. For the Nordic region a similar difference is assumed. A description of the data used is given in the TOPWASTE Background Energy Scenarios Report [5].

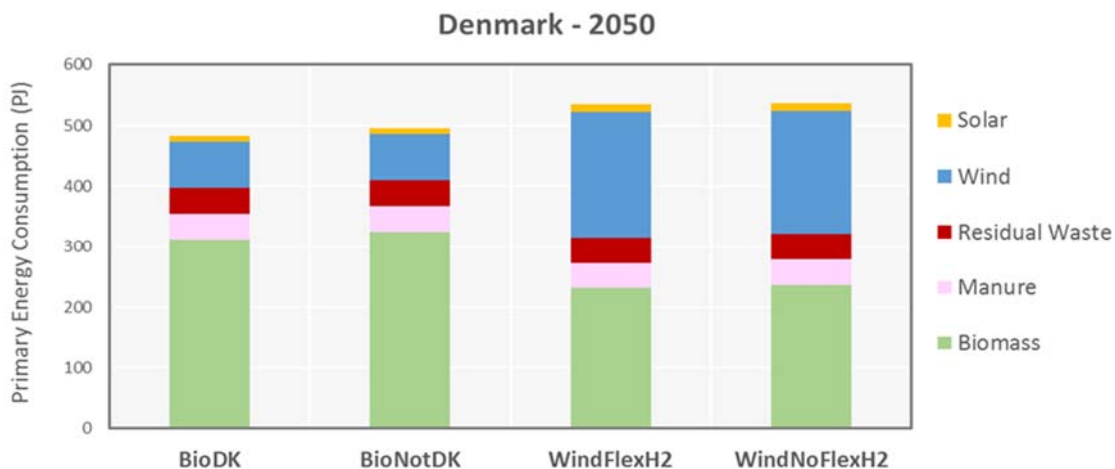


Figure 2.1 - Primary energy consumption (PJ) in Denmark in 2050

The differences in electricity demand are illustrated in Figure 2.2 for four different weeks, where it can be seen that the demand is much lower and with similar timing in the Biomass scenarios, whereas the timing of the demand differs greatly in the wind scenarios, depending on whether hydrogen production is assumed to be flexible or not.

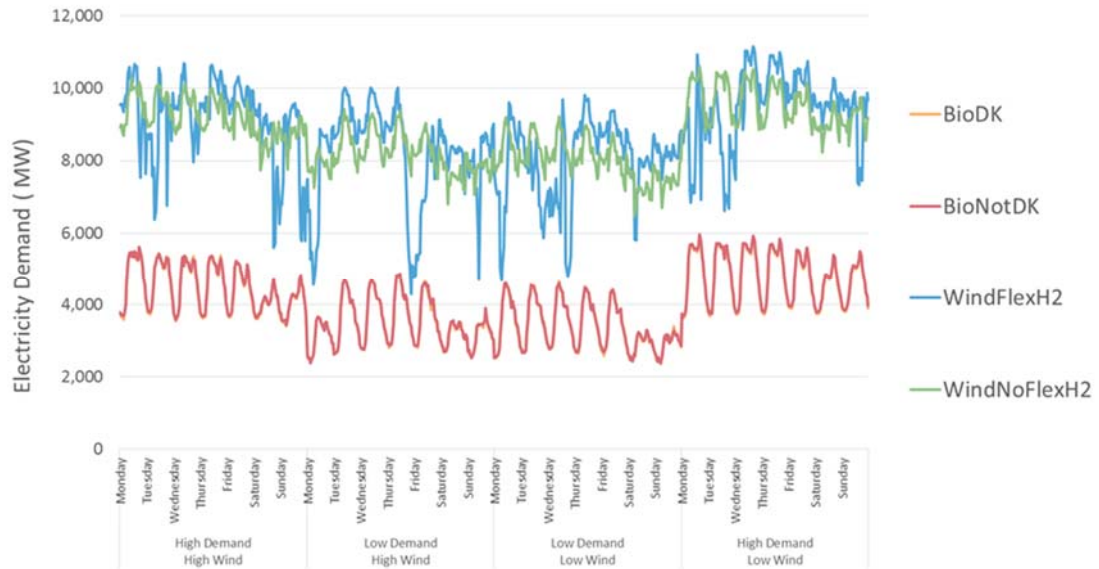


Figure 2.2 - Electricity demands (MW) in Denmark in 2050

The four scenarios have different fluctuations in the electricity prices with the Wind scenarios having the highest prices in average and the biggest variations as shown in Figure 2.3. Electricity prices are generated in the Nordic energy system model, Balmorel, and exported to the Danish waste and district heat optimisation model, OptiWaste.



Figure 2.3 - Electricity prices in Denmark in 2050

When allowing the optimisation model, OptiWaste, to optimise between different types of plants in different types of areas, and taking transport costs into account, results show that the main incineration capacity will be large scale CHP plants in central district heating areas, while less small scale plants will be built as illustrated in Figure 2.4. More investments are seen in decentralised areas in the BioDK and the WindNoFlexH2 - due to the comparably higher share of bio-refineries and biomass CHP plants in the central areas in the respective scenarios. Furthermore, only a limited amount of heat only boilers will be used, as electricity prices are found to be sufficiently high to pay back the investment in steam turbines.

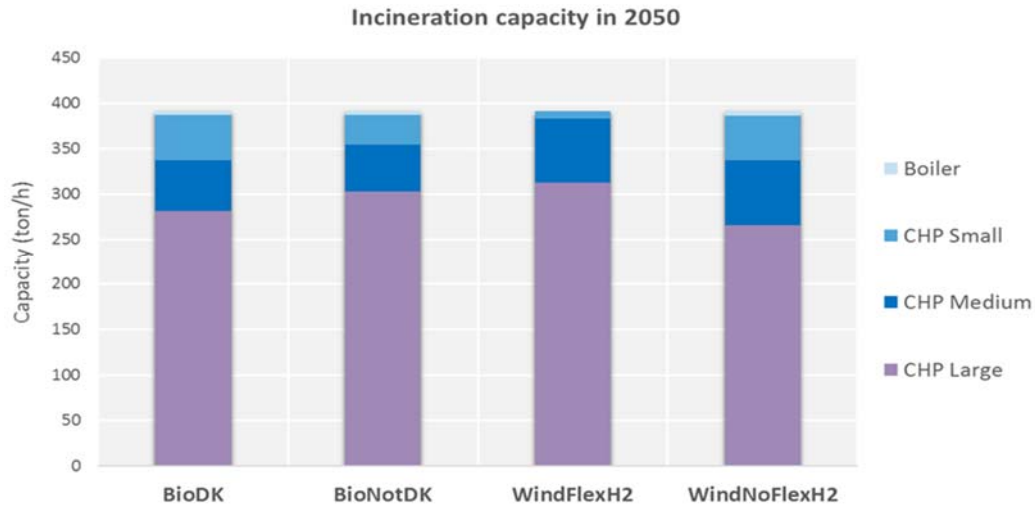


Figure 2.4 - Incineration capacities in 2050

The total costs of treating mixed residual waste is comparable between the different scenarios, with the main difference being whether income is mainly generated through sales of electricity or district heat as seen in Figure 2.5. The lowest total cost is found in the BioNotDK, where a relatively high income is generated from sales of district heat, as bio-refineries are assumed placed outside Denmark, and thereby do not compete with the waste incineration plants. Increased costs of importing bio-fuels are not included in the analysis.

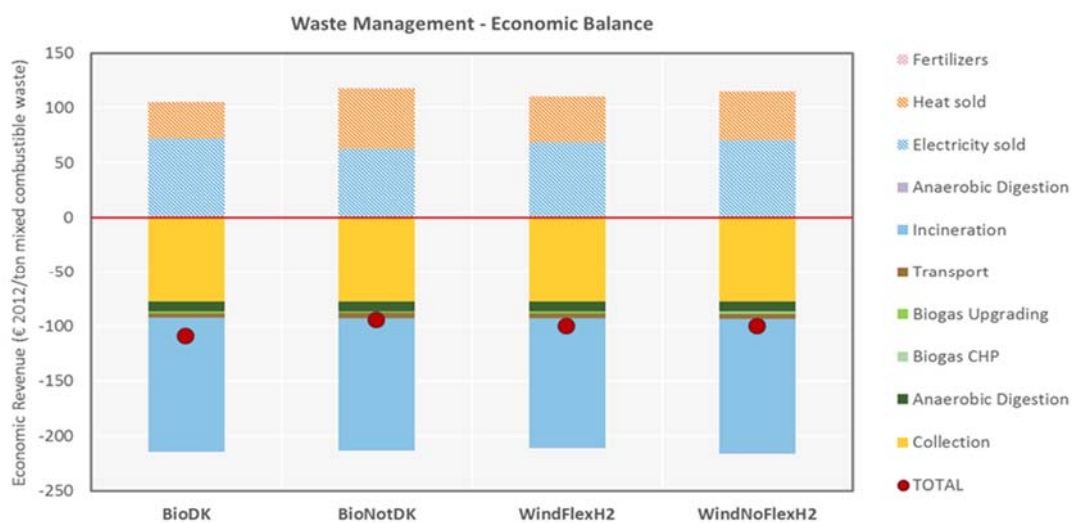


Figure 2.5 - Economic revenue of waste management (minus administration costs) in 2050

Results were found using the OptiWaste model, which is a generalized linear programming network model developed during the TOPWASTE project. The model takes different waste fractions into account and minimizes costs of waste treatment, heat production and waste transport between 66 different areas in Denmark. The model is soft-linked with the linear optimization model, Balmorel, which is used to provide least-cost optimization of the electricity and district heating sectors of the Nordic energy systems and Germany.

Electricity prices and capacities of heat producing plants not using waste are transferred to OptiWaste in a first step, subsequently OptiWaste is used to optimize investment and operation of waste treatment plants as well as operation of other district heating plants. Finally, results from OptiWaste are fed into Balmorel. The main difference between the two models is the level of detail in the OptiWaste model with many waste fractions and areas represented, and with transport of waste integrated along with recycling options competing with Waste-to-Energy plants. The model is hence able to provide the optimal socio-economic waste treatments for the integrated waste, waste transport and district heating sectors. Further information regarding results, the OptiWaste model, combined energy and waste scenarios, the background energy scenarios etc. can be found in the publications named in the reference list below.

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## CONCLUSION AND RECOMMENDATIONS

Incineration of residual waste in combined heat and power plants (CHP) will continue being a socio-economic feasible solution in different 100% renewable energy scenarios. By installing bypasses, the plants will be able to take advantage of periods with high heat prices compared to the electricity prices thereby covering the higher investments in CHP versus heat only boilers. The scale and placement of the CHP plants will depend on the competing heat technologies. It is therefore important to take the heat production from the transport sector (bio-refineries and electrolyzers) into account when planning for future waste incineration capacity. Unless investment costs decrease or material recycling prices increase, it will not be socio-economically feasible to invest in the complex central sorting system and subsequent dedicated incineration of RDF, which was modelled in this analysis. Further analyses of central sorting is shown in section 5 and 6.

It would be beneficial with further research in the field of soft or hard-linking OptiWaste and Balmorel as well as soft-linking OptiWaste to LCA tools - such as the KISS tool also developed in the TOPWASTE project. Analyses of more scenarios with increased fluctuations in electricity prices as well as of seasonal storage of dry waste fractions and heat, and other technical solutions e.g. with regard to central sorting, boilers and cooling including related costs would also be interesting.



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### 3. WHAT IS THE FUTURE POTENTIAL FOR IMPORTS OF COMBUSTIBLE WASTE TOWARDS DENMARK?

*“Presently, imports of combustible waste towards Denmark, diverting from landfilling, and using the existing incineration over-capacity is socioeconomically beneficial for the waste management and energy system, creating a value, and substituting the use of fossil fuels for electricity and district heating production.*

*In the long term, imports of combustible waste towards Denmark would require an investment in over-capacity and will depend on the evolution of electricity and district heating markets, the availability of waste and the willingness of countries to pay to get rid of it. Waste with high calorific value might be seen as a resource, a cost-effective way to provide electricity and district heating. On the other hand, waste with low calorific content will require expenditures to burn it that are not surpassed by electricity and district heating revenues, and a higher incineration gate fee would be needed to make it socioeconomically feasible.”*

*Amalia R. Pizarro (aroyal@dtu.dk)*

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#### INTRODUCTION

The European Union continuously tightens waste management policy, promoting the use of waste as a resource, shifting towards re-use and recycling primarily, and also towards energy recovery. On the European country level, differences in waste management systems are significant. Landfilling is still the dominating method for managing municipal solid waste in most countries; however, Switzerland, Germany, the Netherlands, Sweden, Austria, Denmark, Norway and Belgium have reported MSW landfill rates below 5%.

Particularly, Denmark has a high incineration capacity: in 2012 it experienced an over-capacity of 20% (in terms of mass) due to decreased domestic waste amounts sent to incineration, as a result of higher recycling rates and lower waste generation. In 2012, ten out of twenty-seven incineration plants in Denmark imported waste, amounting to 4.5% of incinerated waste or 167,000 tons (primarily from the United Kingdom and Germany but also from Ireland and Norway). The amount of imports of combustible waste has increased since then and it is expected soon to rise up to 400,000 tons/year.

During the next decade, available waste for incineration in Denmark is predicted to decrease due to the adoption of more stringent recycling targets until 2022, overall related to paper, plastic and biowaste recycling which would divert around 18% of waste that is currently combusted (see Section 1 for further information). Imports of waste for incineration could be a way of utilizing already installed capacities, meeting district heating demand, balancing intermittent electricity production in Denmark and avoiding hindering recycling measures. Furthermore, from the perspective of exporting countries, incineration in high thermal efficiency plants could be an opportunity to divert waste from landfilling during an interim period until they develop the required infrastructure, which has been pointed out as potentially environmental beneficial by Life Cycle Assessments (LCA).

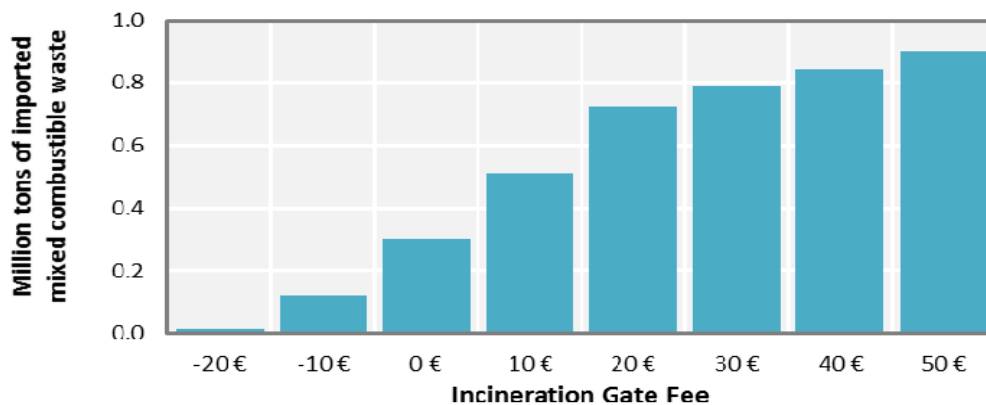
In the long term, the role of trading waste for incineration is more uncertain and is viewed differently between actors. The revised European Waste Framework Directive opens up for community level solutions, complementing the prevailing principle of proximity for waste treatment. The question arises whether, in the long term, countries with extensive district heating networks, such as Denmark, with a very high thermal efficiency (more than 90%), should plan their incineration capacity relying on waste imports, taking the European, rather than the national, perspective. On the other hand, the system can be locked in to large investments which might negatively impact recycling and/or the economy of incineration plants [1].

## RESULTS

This study optimizes through least-cost minimization the mixed combustible waste management system and the district heating supply in Denmark nowadays, and in 2050 under several carbon-regulated scenarios [2], as described in the previous section, with the possibility to import combustible waste attending to different gate fees for incineration plants.

In the present, socio-economic profitability from importing combustible waste from foreign countries (United Kingdom in this study as it is the main exporter to Denmark) will compete against landfilling. Denmark would import waste as long as running costs of incineration plants and transport costs minus revenues from electricity and heat selling surpass the gate fees of their facilities. United Kingdom would export waste whenever the gate fee of the plant located abroad plus conditioning and administrative expenditures related to shipment (around 15 €/ton) are lower than the cost of disposing the waste in their country.

Least cost minimization of the district heating supply and waste system shows that import of combustible waste (assuming a Lower Heating Value (LHV) of 12.5 GJ/ton) is presently profitable under a range of different gate fees, as depicted in Figure 3.1.



**Figure 3.1 Optimal import of combustible waste at an annual level – Present system**

Currently, the maximum landfill gate fee in United Kingdom, without including taxes, is around 51 €/ton; therefore, in order to compete from a socioeconomic point of view against landfilling, Danish incineration plants should have a gate fee lower than 36 €/ton, as conditioning costs are around 15 €/ton and considering that the transport cost is covered by the incineration plant. Export of near 800,000 tons of mixed combustible waste per year from United Kingdom to Denmark would be optimal, if diverting this amount from landfills with high gate fees (51 €/ton).

The annual socioeconomic impact from importing mixed combustible waste to Denmark is represented in Figure 3.2. For Denmark, it is profitable to import small amount of waste even at negative gate fees (plants would pay for importing waste), as there is presently an incineration over-capacity and marginal costs for running some plants are lower than the revenues from electricity and district heating supply [3]. However, in order to cover most of the existing incineration over-capacity, higher gate fees are needed, as otherwise, running costs of the plants and shipment expenditures are not covered by revenues from electricity and district heating.

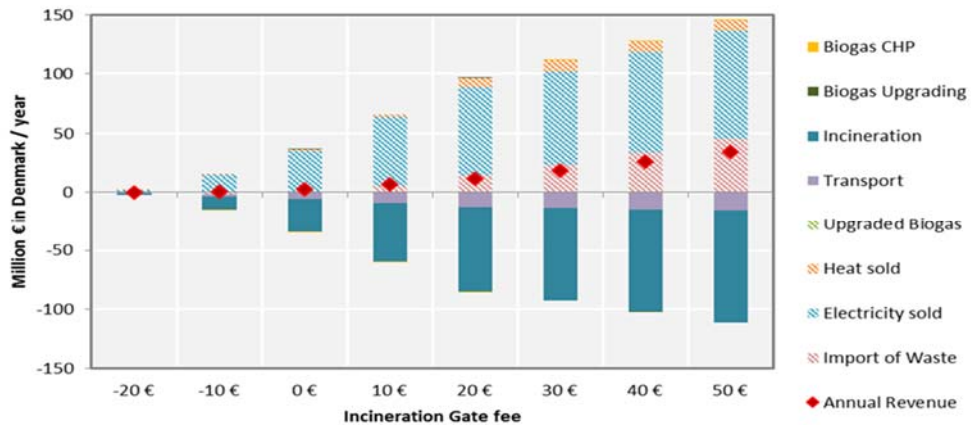


Figure 3.2 Socioeconomic annual impact from importing combustible waste for the incineration plants - Present

When importing more waste into the system, most of the socioeconomic benefits for incineration plants come from receiving the gate fee and selling electricity. Benefits from covering a higher District Heating demand are limited, as District Heating prices would decrease when increasing waste incineration, as potential expansion of district heating markets is not considered as part of the optimization here. However, apart from the socioeconomic earnings for incineration plants depicted in Figure 3.2, there will be further socioeconomic benefits for the energy sector, as District Heating will be supplied at a lower cost. This is shown in Figure 3.3, where import of combustible waste is favored during winter time, when District Heating demand and prices are higher, showing it also is an important driver for import of combustible waste, in addition to the level of the gate fee and revenues from selling electricity.

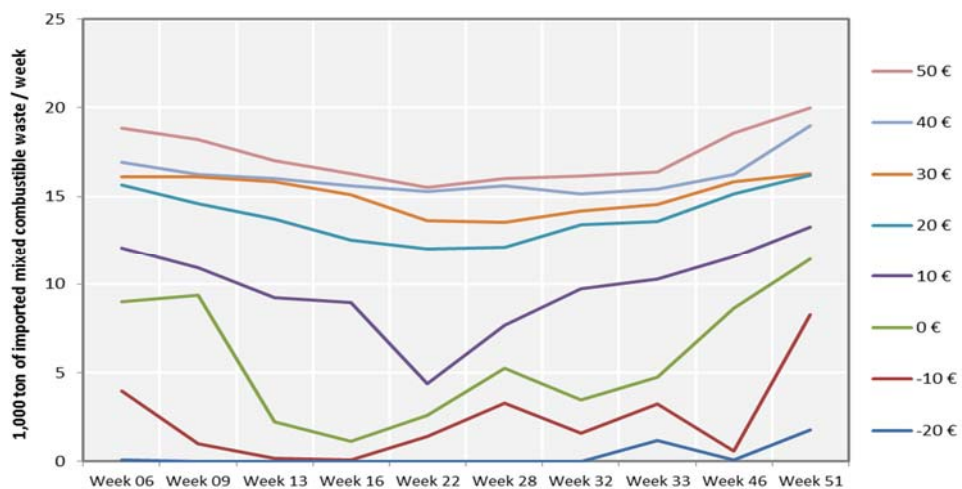


Figure 3.3 Optimal import of combustible waste at a weekly level depending on different gate fee levels - Present

From a private economic point of view, trade of combustible waste would also depend on taxes for landfilling in United Kingdom and taxes for incineration in Denmark, heat tax and CO<sub>2</sub> tax related to the fossil content of the combustible waste. If landfill taxes in United Kingdom are higher than energy-related taxes in Denmark, export of combustible waste would be even more favored; but further private economic analysis would be required to evaluate it.

In 2050, the energy system is assumed to unfold following the description of the four scenarios stated in the previous section and characterized by the electricity and district heating prices depicted in Figure 3.4. Here it can be seen, that the lowest electricity prices are found in the BioOutDK scenario whereas the highest heat prices are found in the same scenario, particularly in the medium size district heating areas.

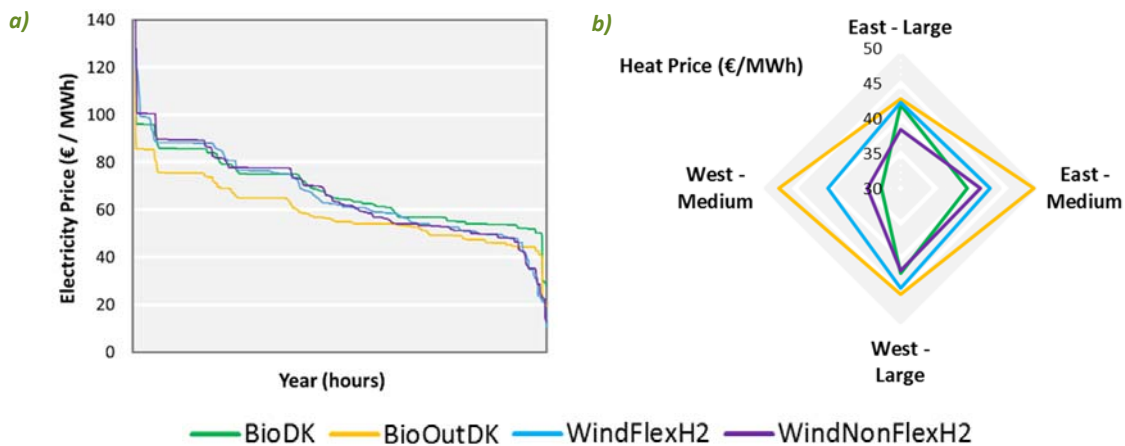


Figure 3.4. 2050 Energy scenarios: a) Power Price duration curve b) Average District Heating price during winter time in large and medium District Heating networks, where incineration plants are mainly located

Least cost minimization of the district heating supply and waste system in 2050 for the different scenarios shows that import of combustible waste, implying an investment in incineration over-capacity, could be profitable under a range of different gate fees, as depicted in Figure 3.5. The study has been conducted considering two different types of combustible waste, which could be imported throughout all the year: one with a high lower heating value (LHV) (16.5 GJ/ton) and one with a low LHV (12.5 GJ/ton).

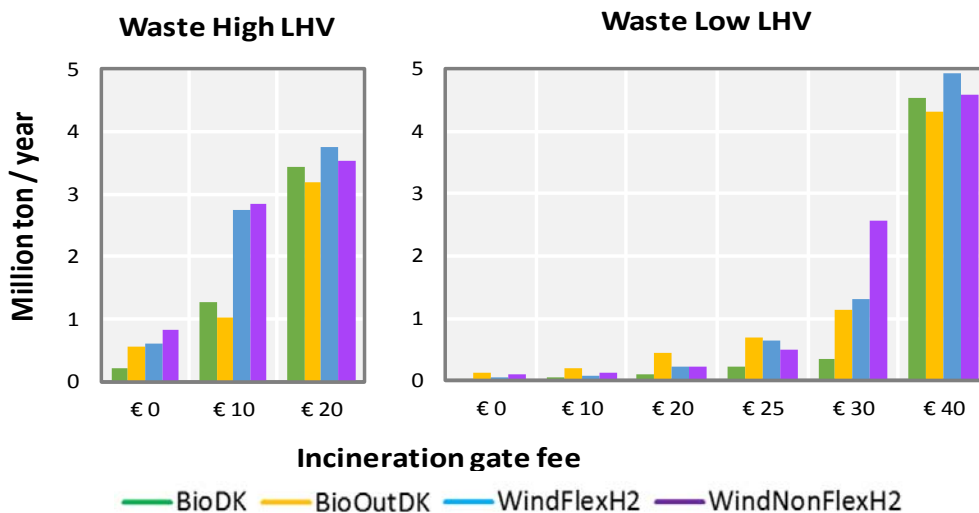


Figure 3.5 Optimal import of combustible waste - 2050 Scenarios

When combustible waste has a high LHV it can be seen as a valuable resource, and in spite of high investment costs associated to incineration plants, it might pay off for Denmark to import it and to burn it to produce electricity and district heating even without receiving a gate fee. However, when the LHV of the waste is low, receiving a gate fee is necessary to make imports profitable for the Danish waste management and energy system.

For both cases, high and low LHV combustible waste, at low gate fees, import of waste in the BioDK scenario is lower because electricity prices are lower than for the Wind scenarios and district heating prices are also lower than for the BioOutDK scenario.

Combustible waste is mainly imported to large incineration CHP plants, which benefit of economy of scale, and the district heating generated will compete with excess heat from bio-refineries in the BioDK scenario and from electrolyzers in the Wind scenarios. Therefore, even if small amounts of waste is imported, part of the heat produced by the incineration plants might be cooled down at a low cost, and most of the benefits for the three scenarios come from selling electricity and the gate fee itself. At higher incineration gate fees, when a significant amount of waste is imported in the four scenarios, heat that has to be cooled down also increases in the BioOutDK scenario and import of waste is lower than for the other three scenarios, as electricity prices are generally lower.

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## CONCLUSION AND RECOMMENDATIONS

Import of combustible waste in the present system in order to tackle an existing incineration over-capacity is socioeconomically beneficial for the Danish waste management and energy system, even at low gate fees for the plants with low operational expenditures. Plants with higher running costs require receiving a gate fee to create socioeconomic revenues. Environmentally, as waste could be assumed to be diverted from landfilling and the Danish system still has a high share of fossil fuel technologies, it might be beneficial, although further specific analyses are required.

Socioeconomic profitability of importing waste in the longer term will depend on the surrounding energy system, such as electricity and District Heating prices, the heating value of the combustible waste available for import and the willingness of countries to pay to get rid of it. Waste with a high LHV is seen as a resource, and it could be a cost-effective way of providing district heating and electricity to the system. On the contrary, incineration of waste with lower LHV implies extra expenditures, as district heating and electricity production can be supplied in cheaper ways. Uncertainty associated to availability of waste and willingness of countries to pay to treat it should be further analysed when planning investments in over-capacity.

Waste incineration plants, will mainly be located in central areas, as stated in Section 2. However, when importing high amounts of combustible waste, incineration plants might cover more than the base district heating demand during summer time. Hence they will only substitute electricity in the energy system, which might have an important impact when evaluating the environmental benefits of importing waste. In addition, the Danish energy system is predicted to be fully decarbonised; therefore, avoided electricity and district heating production will not substitute fossil-fuels but mainly biomass. The environmental performance of importing waste will depend on: 1) the avoided treatment in the country of origin; such as landfill with or without gas recovery and use, incineration with electricity production, etc. 2) the affected energy technologies in Denmark when substituting electricity and District Heating production and 3) the global marginal emissions associated to the avoided biomass use. Analyses of the environmental impacts are presented in the Sections 4, 5 and 6.

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## 4. IN WHICH WAY DO BOUNDARY CONDITIONS INFLUENCE FUTURE WASTE MANAGEMENT?

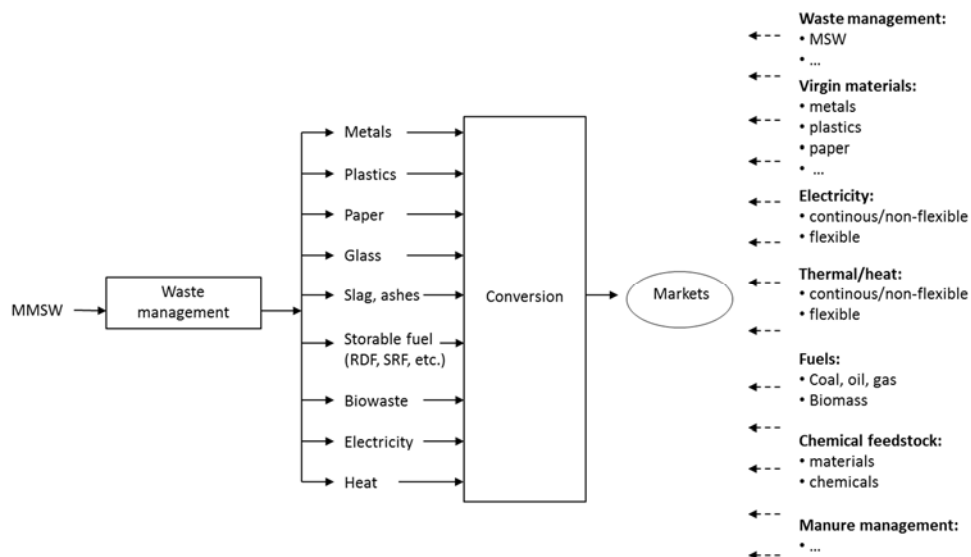
*“The interactions with background systems are of key importance to both the economic and environmental performance of any waste management system, and therefore the assumed nature of the background systems is decisive to the results. We also know that these background systems change over time, and some of the key systems such as the energy system, virgin biomass production and waste management systems in general (including landfilling) are expected to change very significantly over the next decades. In order to ensure a robust comparison of alternative waste management systems and to provide a robust assessment for investment decisions, we must, thus, compare alternatives against these background systems as they can be expected to develop over time.”*

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### INTRODUCTION

When studying waste management, it is generally found that it leads to reduction in environmental impacts. The key reason for this is that the generation of waste is not a function of the waste management system, as waste is generated independent of the way in which it is managed. No management system, or the most basic and least cost system like uncontrolled landfilling, thus, leads to significant impacts on the environment. Most other management systems leads to less impacts, and many systems will end up leading to even net overall reduction in environmental impact.

The key characteristic of a waste management system is the way it interacts with the background system in which it resides. Economically and especially environmentally, the nature of these interactions is decisive for the performance of the system.



**Figure 4.1 : A general model of waste management illustrating the conversion of various waste fractions into secondary products sold on markets thereby substituting other products on the market**



The primary function and service of a waste management system is the service of legally compliant waste management itself, but almost any waste management system creates secondary services in term of products sold to markets, e.g. recovered energy or materials. Figure 4.1 illustrates a general model of a waste management system.

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## RESULTS

The essential background systems comprise:

- Virgin material production systems of recovered material fractions
- The energy systems (grids) of heat and electricity
- Manure biogas systems, agricultural soil systems and mineral fertilizer productions
- Virgin biomass production and the origin of this biomass
- Alternative waste management in landfill in scenarios with waste import

Virgin material production systems of recovered material fractions are routinely dealt with in life cycle assessments. The other background systems are however not. In this section we illustrate the assumptions regarding marginal impacts used for the studies in Section 5 and 6 of the four remaining background systems.

### CONTINUOUS AND FLEXIBLE PRODUCTION OF HEAT AND ELECTRICITY

Supplementary to the economic optimisation approach described in Section 2 and 3, in TOPWASTE project a consequential life cycle assessment approach has been employed, focusing on greenhouse gas impacts and taking into account different marginal emissions based on different scenarios for the development of the background systems. With regard to the latter, energy production from waste has been grouped in two categories: continuous and flexible. This categorization is important because both the heat and electricity systems respond differently to continuous and flexible outputs to the grids. A continuous production will replace one type of electricity or heat, whereas a flexible production (i.e. a production specifically supplied to the grids in time intervals of higher demand) will replace a different type of heat/electricity. Definitions for energy from waste:

- **Continuous electricity** or baseload power production is associated with power plants with continuous operation and supply of electricity throughout the year, with breaks only for planned maintenance or service. Power produced by waste incineration plants falls largely under this category. However, modern incineration plants can adjust their operation considerably in a matter of hours by lowering or raising their capacity (between 70 % and 100 % load) and sometimes by adjusting the ratio between heat and electricity (condensing plants). For this reason, a flexibility factor has been associated with the waste CHPs in the systems.
- **Flexible electricity** represents a balancing power production, and is associated with power plants which can operate based on market demand, i.e. can fully start or shut down in a matter of minutes. Biomethane stored in the natural gas grid, or otherwise, is assumed to be used in the future for electricity production in this way.
- **Continuous heat**, accounts for non-flexible heat production, e.g. from waste incineration.
- **Flexible heat** here accounts for heat generation from combustion of RDF in waste incineration plants. RDF is assumed prioritized (stored) for heat generation in the cold part of the year, and therefore flexible heat avoids the production of the respective heat marginal. If electricity is generated together with heat from RDF, it is categorized similarly to regular electricity from incineration (i.e. continuous).

**Time perspectives**

As previously introduced, the background systems surrounding Danish waste management systems are undergoing important structural changes, most importantly the gradual transition from fossil-based to renewable-based energy. Waste management infrastructure changes imply considerable capital investment, which is typically recovered by maximizing lifetimes. For example, lifetimes of plants can be extended from 20 years (sorting plants) to 30-40 years (WtE facilities). It is therefore crucial to consider future changes in the background systems when taking decisions regarding waste management in order to avoid lock-in effects.

The time scope considered in this work goes from 2012 to just beyond 2050. The timeline was broken down into four periods in accordance with the key milestones of Danish energy policy, i.e. 2012-2020, 2020-2035, 2035-2050 and beyond 2050. The key milestones considered were: (1) wind power makes up 50 % of electricity consumption in 2020, (2) coal is completely phased out in 2030, and (3) all heat and power is renewable in 2050.

However, these milestones are expected to be relaxed to some extent by the new Danish Government (autumn 2015) and therefore the related background electricity and heat marginal in the four time periods were modified, compared to the work by Wenzel et al. [1], to include a small portion of fossil energy until 2050 (Table 4.1). The Beyond 2050 time perspective then represents a fully renewable energy scenario.

		Electricity	Heat
<b>Present (2012-2020)</b>	<i>Continuous</i>	100 % coal power	100 % natural gas
	<i>Flexible</i>	100 % coal power	100 % natural gas
<b>Mid-term (2020-2035)</b>	<i>Continuous</i>	10 % coal, 5 % natural gas, 18 % biomass <sup>3</sup> , 2 % solar and 64 % wind power	50 % heat pumps and 50 % natural gas
	<i>Flexible</i>	100 % coal power	100 % natural gas
<b>Long-term (2035-2050)</b>	<i>Continuous</i>	5 % coal, 5 % natural gas, 15 % biomass <sup>6</sup> and 75 % wind and solar power	50 % heat pumps, 25 % biomass and 25 % natural gas
	<i>Flexible</i>	25 % coal, 25 % natural gas, 50 % biomass <sup>4</sup>	50 % biomass and 50 % natural gas
<b>Beyond 2050</b>	<i>Continuous</i>	100 % wind and solar power	80 % heat pumps and 20 % biomass
	<i>Flexible</i>	100 % biomass	100 % biomass

**Table 4.1 : The four time periods and associated background electricity and heat marginals**

<sup>3</sup> The biomass marginal is used in direct combustion CHP

<sup>4</sup> The biomass marginal is used in wood gasification with syngas reforming to SNG stored and used for flexible power

The flexibility factors associated to waste incineration denote how much of the power produced is assumed to replace other regulating power on the energy market. The factors were: 30% in the Mid-term, 15% in the Long-term and 5% in the Beyond 2050 time perspectives. These factors are rough estimates which consider the decreasing “window of opportunity” over time, i.e. time intervals when incineration can contribute with flexible power. These time intervals decrease as renewable (wind and solar) cover more of the early power consumption.

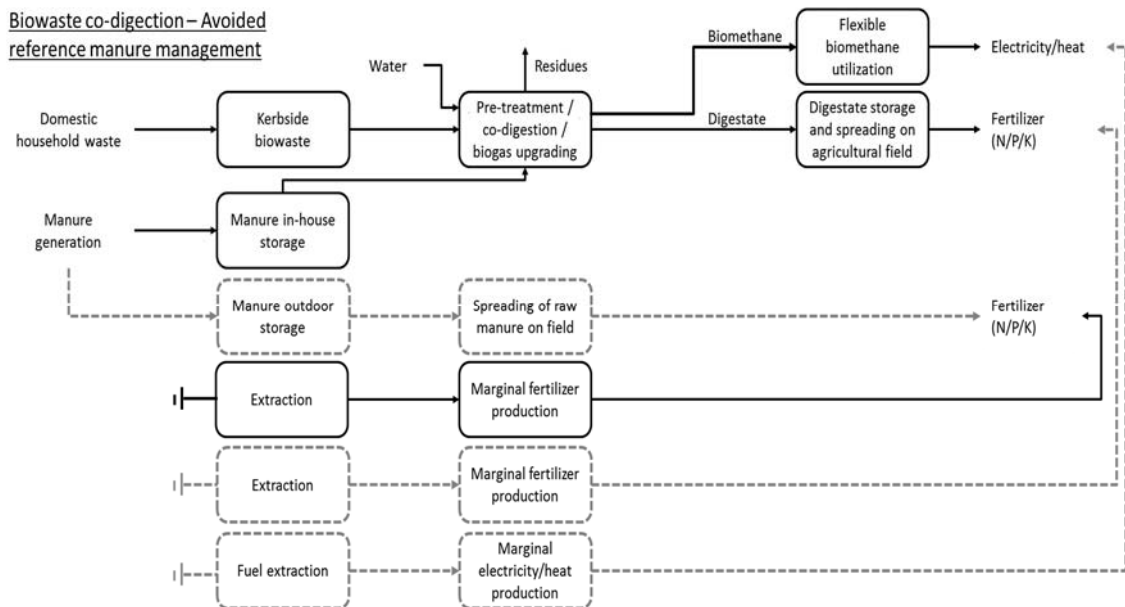
**BIOWASTE FROM SEPARATE COLLECTION AS A CO-SUBSTRATE IN MANURE-BIOGAS**

As a baseline, the biowaste collected separately from households is digested in dedicated plants. However, considering the Danish targets on boosting manure-biogas, it is valuable to quantify possible benefits assuming that biowaste can contribute to achieve these targets.

In Denmark a target has been launched to reach 50 % use of animal manure for biogas by 2020, as compared to the present use of 7- 8 %. Under the current framework conditions, projections show that the share at 2020 will most likely be only between 20 and 35 % [2]. One of the main barriers to a wider expansion is related to biomass, i.e. it is increasingly difficult to find suitable biomass to supplement slurry in order to achieve adequate and economically feasible gas production.

In a consequential perspective, the biowaste made available by source separation of food waste from households can constitute a co-substrate to manure, thereby enabling extra manure quantities to be digested and/or substituting other marginal co-substrates, such as energy crops.

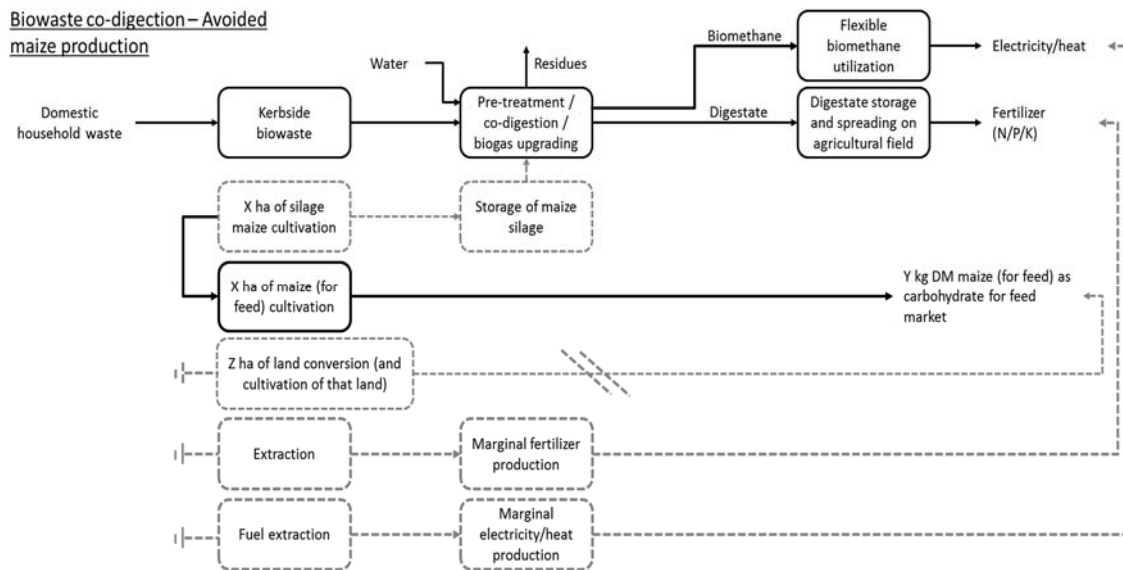
The model of co-digestion with manure has been used to produce system results, avoiding reference manure management (Figure 4.2), or replacing the production of an alternative co-substrate for manure-biogas, namely maize (Figure 6.1Figure 4.3). The results have been compared with a baseline with biowaste mono-digestion.



*Figure 4.2: Process flow diagram cut-out illustrating co-digestion of biowaste with manure leading to avoided reference manure management; full lines indicate foreground and induced system flows and processes while dotted lines indicate avoided flows and processes (in the background system)*

Based on consequential LCA rationale, the benefits and burdens of the extra manure-biogas production were weighted against the burdens and savings associated with conventional manure management, with storage and application on land without any additional treatment, in the way described by Hamelin in [3].

Although the use of energy crops as co-substrates is already being restricted, it is still expected that energy crops may have a role even in long-term: in this study maize was used as a representative of energy crops. Thus, the burdens and benefits of use of biowaste as a co-substrate were weighted against the use of maize, which is associated with both direct and indirect land use changes. The substitution ratio between biowaste and maize was based on methane yield.



**Figure 4.3: Process flow diagram cut-out illustrating co-digestion of biowaste with manure leading to avoided production of maize; full lines indicate foreground and induced system flows and processes while dotted lines indicate avoided flows and processes (in the background system).**

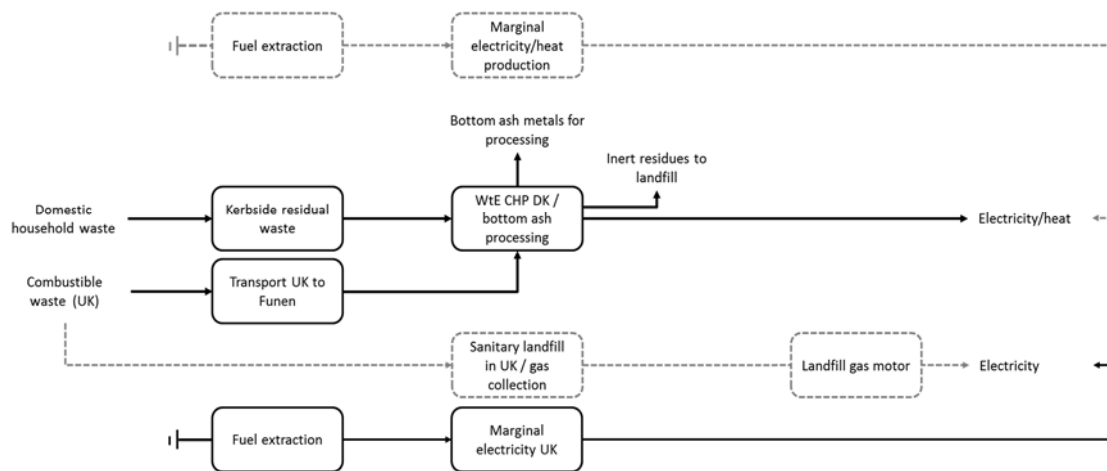
#### CASCADING EFFECTS – COMBUSTIBLE WASTE IMPORTS

Under the assumption that the reference waste management system in the region is functioning under stable conditions (i.e. the current infrastructure is fully utilized), any diversion of waste towards recycling, by increased source separation, or processing of residual waste in central sorting facilities would liberate combustion capacity in the WtE plants in the system. This, in turn, induces a “demand” for combustible waste at the incineration plants, or rather a capacity to receive more waste at a given market based gate fee.

Cimpan et al. identified combustible waste import from countries which still landfill large shares of MSW as the most probable response to a released WtE capacity in Denmark [4]. In this study, cascading effects were included in connection with the Present (2012-2020) and the Mid-term time period (2020-2035).

Cascading effects were modelled effectively as preparation of combustible waste for export in the UK (here UK is used as a representative for a country which still landfills MSW), sea and land transport to Funen, and combustion in the Danish incineration facilities (Figure 4.4). The GHG impact of these operations was essentially measured against the benefits of electricity and heat production from imported waste in DK and the avoided reference management of combustible waste in the UK.

## Cascading effect – Combustible waste import



**Figure 4.4: Process flow diagram cut-out illustrating effects pertaining to waste import; full lines indicate foreground and induced system flows and processes while dotted lines indicate avoided flows and processes (in the background system)**

In order to capture a possible range in efficiency (and therefore environmental effects) related to management of combustible, two options have been modelled:

- (1) Combustible waste is landfilled in a sanitary landfill with high gas collection and utilization in a gas motor with recovery of electricity;
- (2) Combustible waste is landfilled in a sanitary landfill with average gas collection, followed by flaring of the collected gas.

The two options were modelled as described by Cimpan et al. in [5].

#### MARGINAL BIOMASS FOR FUTURE ENERGY PRODUCTION

Biomass marginals are used in the construction of mid-term, long-term and beyond 2050 energy mixes and in the estimation of electricity and heat marginals. The carbon footprint factors used in this work are presented in Table 4.2, and are taken from [1] by Wenzel et al.

The model allows using different biomass marginal. For this study two different perspectives have been considered:

- (1) A **progressive biomass marginal**, which reflects an increasing demand for biomass over time. In this perspective the marginal is forest thinning in the Present and Mid-term time perspectives, plantation on high C-stock savannah in Long-time and harvest from existing tropical forests in the Beyond 2050 time perspective.
- (2) A **“dirty” biomass marginal**, which reflects the use of biomass with a high carbon footprint in all four time perspectives, namely harvest from existing boreal forests.

Reprocessing waste paper and cardboard into secondary pulp leads to a reduction in the use of primary paper pulp. The biomass marginal used for primary pulp production, and thus avoided, was considered coming from “tropical plantations on forest land”, in accordance with Reinhard et al. [6].

	Progressive biomass marginal		Dirty biomass marginal	
	100 years amortisation (kg CO <sub>2</sub> per MJ)	20 years amortisation (kg CO <sub>2</sub> per MJ)	100 years amortisation (kg CO <sub>2</sub> per MJ)	20 years amortisation (kg CO <sub>2</sub> per MJ)
<b>Present (2012-2020)</b>	0	0	0.074	0.153
<b>Mid-term (2020-2035)</b>	0	0	0.074	0.153
<b>Long-term (2035-2050)</b>	0.009	0.043	0.074	0.153
<b>Beyond 2050</b>	0.041	0.123	0.074	0.153

*Table 4.2 : Carbon footprint factors for the biomass marginal used in the four time perspectives*

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## CONCLUSION

Environmental impacts of affecting marginal emissions differ depending on the assumed development of the background systems. This section illustrates the background scenarios which were used in the following sections, where it is shown that the environmental impact of a waste management system depends heavily on the time perspective and the scenarios assumed for the background systems.

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## 5. HOW SHOULD WE SORT OUR WASTE AND WHAT COULD THE ROLE OF CENTRAL SORTING BE?

*“Current and future targets for municipal and household waste recycling require comprehensive programs, such as kerbside collection schemes. This investigation explored the possibilities of separate collection and additional material recovery by central sorting of residual waste. The main findings suggest that kerbside collection of recyclable material alone will probably not be sufficient to achieve the 50% target of the Danish Government. Central sorting and separate collection of biowaste are essential options to achieve current and future higher targets.”*

*Ciprian Cimpan (cic@kbm.sdu.dk)*

### INTRODUCTION

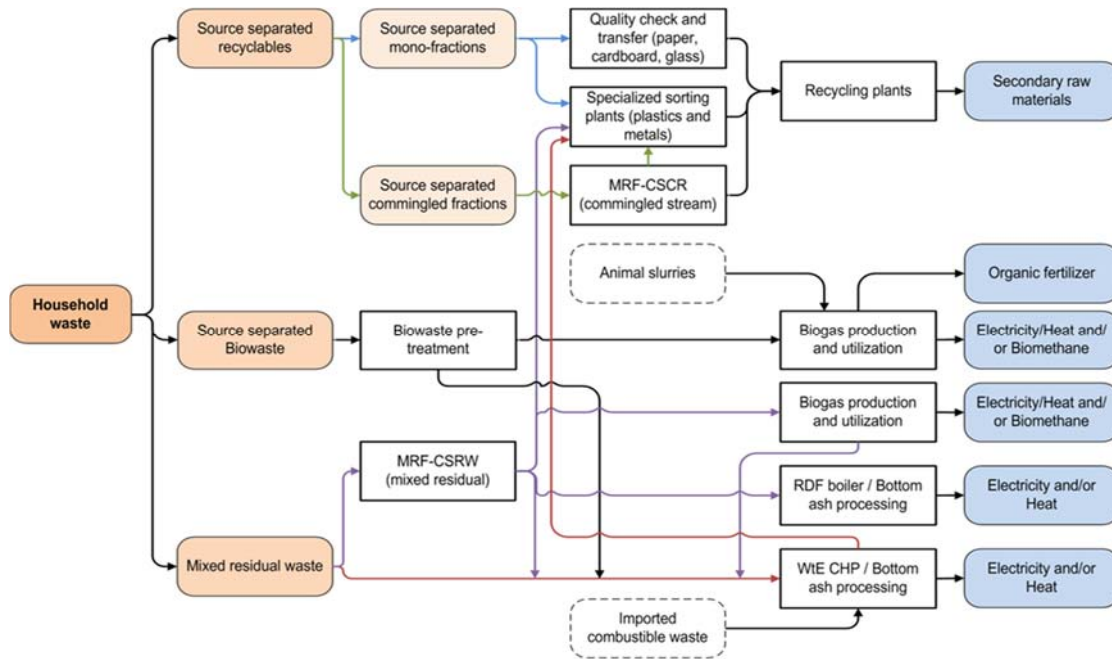
Recent data shows that by 2012, recycling and biological treatment together accounted for more than 50% of Municipal Solid Waste (MSW) treatment in Germany (65%), Austria (62%), Belgium (57%) and the Netherlands (50%). The UK (46%) and Ireland (45%) were the countries which most dramatically increased recycling from their 2001 levels of 12% and respectively 11% ([4], [5]). In this regard, Denmark is facing great challenges, as municipal waste recycling in 2012 stood at only 42%. As a result, the Danish Government has released a new National Waste Plan, calling for immediate and comprehensive action (the Danish Government, 2013). In this release, the lack of more comprehensive separate collection programs and use of other complementary alternatives is given as possibly the main reason for the low performance of recycling in Denmark.

Materials can be recovered for recycling by source separation (e.g. in the household as shown in Figure 5.1) followed by separate collection or by sorting of mixed/residual MSW (from herein referred to as Central Sorting of residual MSW). Although the EU's waste legislation regarding MSW and packaging waste clearly mandates source separation and separate collection as the main recovery path, it still allows for alternative schemes in which recyclable materials are sorted directly from residual MSW. Another form of central sorting can also occur after separate collection if recyclable materials are commingled (from herein referred to as Central sorting of commingled recyclables). In a comprehensive review, [1], we conclude that physical processing and sorting technology today has reached a high level of maturity and can now support both efficient central sorting of commingled recyclables and residual MSW.

Central Sorting of residual MSW today contributes significantly to the recycling rates of MSW and packaging waste in countries such as Spain, France and Greece. Additionally, in Austria this approach is used to supplement separate collection (for plastics) in four large cities, which display lower household participation in source separation programs. Finally, around 10% of municipalities in the Netherlands have chosen a form of central sorting as the main route to recovery of plastic packaging. Much of the reasoning behind implementation of central sorting has to do with inherent difficulties with source separation, i.e. overall cost of systems, various local implementation issues, and in general the disappointing results from urban areas in terms of responses and contamination levels. Therefore, the strongest motivation for central sorting is found for areas where source separation and separate collection is difficult, such as urban agglomerations, and can in such areas contribute to increasing recycling rates, either complementary to- or as a substitute for source separation of certain materials, such as plastics and



metals. To further support this, recent research in the Netherlands on the quality in terms of composition and mechanical properties, of plastics originating from both separate collection and recovered directly from MSW, [6], concluded that there were no observable quality differences between the two recovery paths to affect recycling.



**Figure 5.1 - Foreground system options for management of MSW from households; arrow colour denotes path dependencies, orange boxes are options for collected streams and blue boxes are functional outputs.**

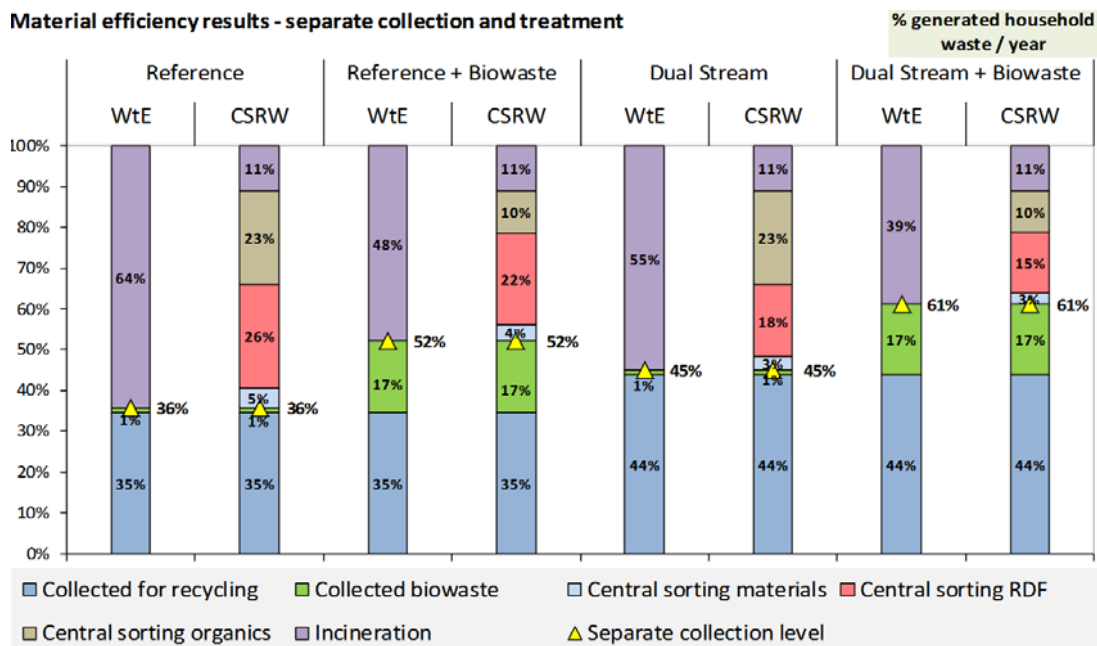
Within the primary scope of the TOPWASTE project, meeting obligations on resource recovery and recycling under environmentally and economically feasible conditions was central for evaluating alternative systems of managing Danish MSW. A much greater challenge was to design alternative systems which enable synergies between the waste sector and other societal sectors such as the energy production sector and agriculture. In this regard, alternative systems were designed to provide a contribution to the needs of the future, namely production of electricity and heat with a greater degree of control and flexibility, and also contribute to increased utilization of animal manure for biogas and recycling of plant nutrients.

In this sense, central sorting can do much more than just contribute to recovery of materials for recycling. It could be the missing link that facilitates some of the synergies mentioned above. Today in Denmark all residual MSW and parts of commercial and industrial waste are being used for energy production in 28 waste-to-energy (WtE) facilities. The technical and economic demands governing the operation of these facilities limit the flexibility of the energy production considerably. Residual waste in itself contains high shares of biodegradable materials which if not processed immediately will result in emissions. Future demand of flexible production of electricity (to balance increasing reliance on fluctuating renewables) and heat (to cover peak demand during winter) can be addressed by the waste sector through conversion of unstable residual MSW into storable energy carriers. Central sorting can be used to separate wet MSW fractions from dry MSW fractions, whereby wet fractions (biodegradable) can be directed to biogas production and dry fractions can be stored as Refuse Derived Fuel (RDF). Biogas, once upgraded, can be stored in the natural gas grid, and used for electricity production according to needs, while RDF could be used primarily to cover part of the heat demand during the cold season.

## RESULTS

Results supported by empirical data from two case studies are presented below. The studies were performed using the methods of mass flow analysis (MFA) and carbon footprint analysis in a consequential LCA perspective, both of which are the foundation for the KISS tool. Both case studies included the detailed characterization of existing waste management systems, the conceptual design of alternative systems, and the modelling of these systems in terms of mass and substance transfer from waste generation until final recovery, disposal and interaction of functional outputs with the background systems. Alternative management systems reflected different separate collection and treatment of remaining residual waste.

In the first case study, the implementation of a commingled collection system for recyclables (a Dual Stream) was monitored for the duration of one year, in the Danish municipality of Sønderborg, [2]. This kerbside system replaced less comprehensive collection of recyclables in drop-off points, and resulted in a collection efficiency increase of around 40% at the end of the first year. The system included six types of materials (paper, cardboard, plastic foils, hard plastics, metals and glass) collected mixed, which are then sorted centrally into individual materials before being traded to recycling plants.



*Figure 5.2 - Separate collection levels, material recovery and treatment in the region of Funen (10 municipalities), all fractions included in the calculation of recycling rates according to the Danish Resource Strategy [3]*

In the second case study, we looked at the entire region of Funen, comprising of 10 municipalities with a total of 486,000 inhabitants. The region generated a total of 209,611 tonnes of municipal household waste in 2013 - according to the definition in the Danish Resource Strategy. The breakdown according to management of this waste in 2013 is illustrated in Figure 5.2 as the Reference system with incineration of residual waste (WtE). The region achieved an overall material recovery for recycling of 36% with the existing, quite diverse, separate collection systems.

Among modelled alternative systems, we included the introduction of biowaste separate collection and changing the existing collection systems for dry recyclables with a uniform Dual Stream thorough the

region (Figure 5.2). Biowaste separate collection showed the potential to increase overall material recovery (collected separately) to around 50%, which would satisfy the 2022 target set by the Danish Government. The Dual Stream alone could raise the overall material recovery up to 45%, while a combination of the Dual Stream and biowaste separate collection could potentially raise this figure to around 60%.

In terms of treatment of remaining residual waste, two main options were investigated: (1) incineration (WtE) and (2) central sorting. In terms of material recovery, sorting of metals from incineration ash was shown to contribute an additional 1 % to material recovery in the region, while central sorting could contribute between 3 % and 5 %, with recovery of metals and plastics (depending of the source separation in the system). Central sorting also recovers a concentrated stream of organics, however this has not been considered to contribute to material recovery because digestion residues after biogas production would more than likely not be accepted as an organic fertilizer in Denmark.

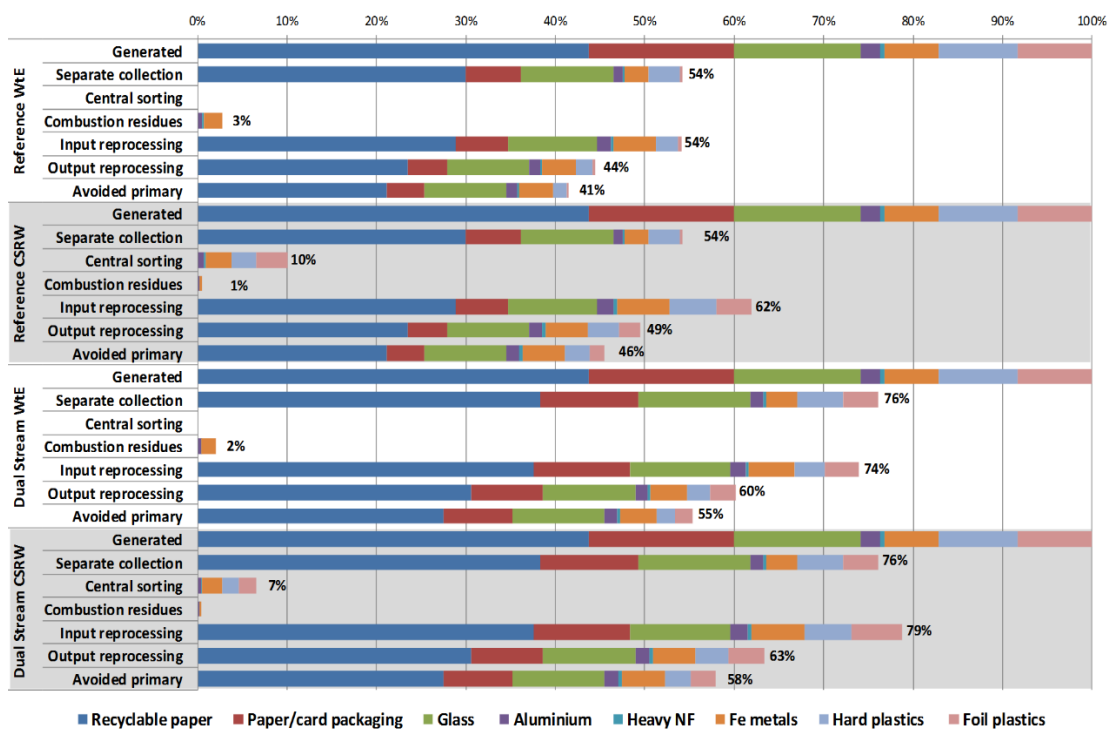


Figure 5.3 - Material recovery and recycling in relation to total amounts of generated dry recyclables, without wood and large metals collected at recycling centres [3]

The total potential for dry recyclable materials in the region was estimated at 108,000 tonnes (including paper, cardboard, glass, plastics, metals and wood). Without recyclable wood and what is collected as municipal iron (large items) at the recycling centres, this potential was estimated at 79,000 tonnes. On the basis of this second calculated potential, results from modelling material transfers are illustrated in Figure 5.3, showing recovery (separate collection, central sorting and incineration ash), reprocessing/recycling and potential primary raw materials replaced for the four alternative systems. Not surprisingly, the highest share of avoided primary production was obtained when the dual stream option was combined with central sorting (58%). This was however only marginally better than implementing the dual stream option alone (55%). A more important difference was to the system without dual stream, where the system with central sorting achieved only a 46% share and the reference system only 41%. From

the perspective of material recovery for recycling, carbon footprint results (presented in Figure 5.4) suggest strong benefits by changing the existing collection schemes for dry recyclables, and by means of application of central sorting on remaining residual waste in the system, with a difference of 63 Mt saved in the reference system and 84 Mt in the dual stream and CS system.

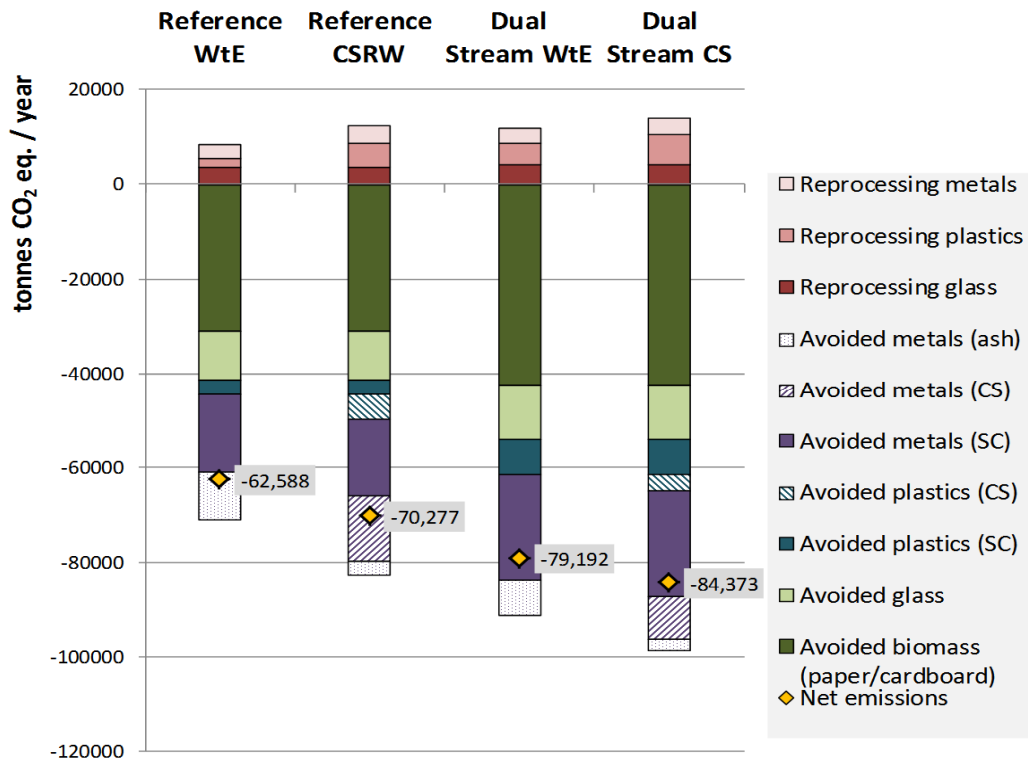


Figure 5.4 - Burdens (positive) related to reprocessing to secondary materials, and benefits (negative) due to avoided primary material production, excluding wood and large metals collected at recycling centres [3]

## CONCLUSION AND RECOMMENDATIONS

The target to recover 50% of waste from households by 2022 for recycling is realistic and can be achieved by introduction of more comprehensive separate collection systems. In most cases, even well working collection of dry recyclables will not be enough to reach the target, and separate collection of biowaste will probably be necessary. Central sorting of dry recyclables from residual waste, and the accounting of these materials towards recycling, could potentially raise material recovery to around 50%, when supplementing a well working kerbside system (even without separate collection of biowaste).

The mass modelling and carbon footprint analysis capabilities are incorporated in the developed KISS model. Future research should be invested into better estimation of the realisable potential found in waste from households in Danish communities, in terms of dry recyclables and their quality.

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## 6. HOW DO WE OPTIMIZE THE MANAGEMENT OF THE MAIN WASTE FRACTIONS UNDER FUTURE FRAMEWORK CONDITIONS?

*"Our analysis indicated that, under prevailing future framework conditions, strategies which should be prioritized include increased material recovery and recycling combined with waste-to-energy solutions which maximize the flexible integration of waste-derived energy in the energy systems of the future. Pre-treatment of residual household waste by central sorting, compared to direct incineration as done today, was found preferable because it can contribute both to material recycling and increased flexibility in heat and electricity production. Biowaste source separation is another strategic management option which showed high benefits due to synergy with manure-biogas production in Denmark."*

*Ciprian Cimpan (cic@kbm.sdu.dk)*

### INTRODUCTION

The foreground systems options mentioned in Section 5 were evaluated and compared based on their carbon footprint. The benefits related to increased materials recovery and recycling were presented in the same section. Therefore this section is dedicated to presenting results in connection with indirect effects and energy recovery under future framework conditions. A detailed description of the assessment methods and results is available in [1]. The results presented here are based on the case study which evaluated waste management system alternatives for the region of Funen (10 municipalities).

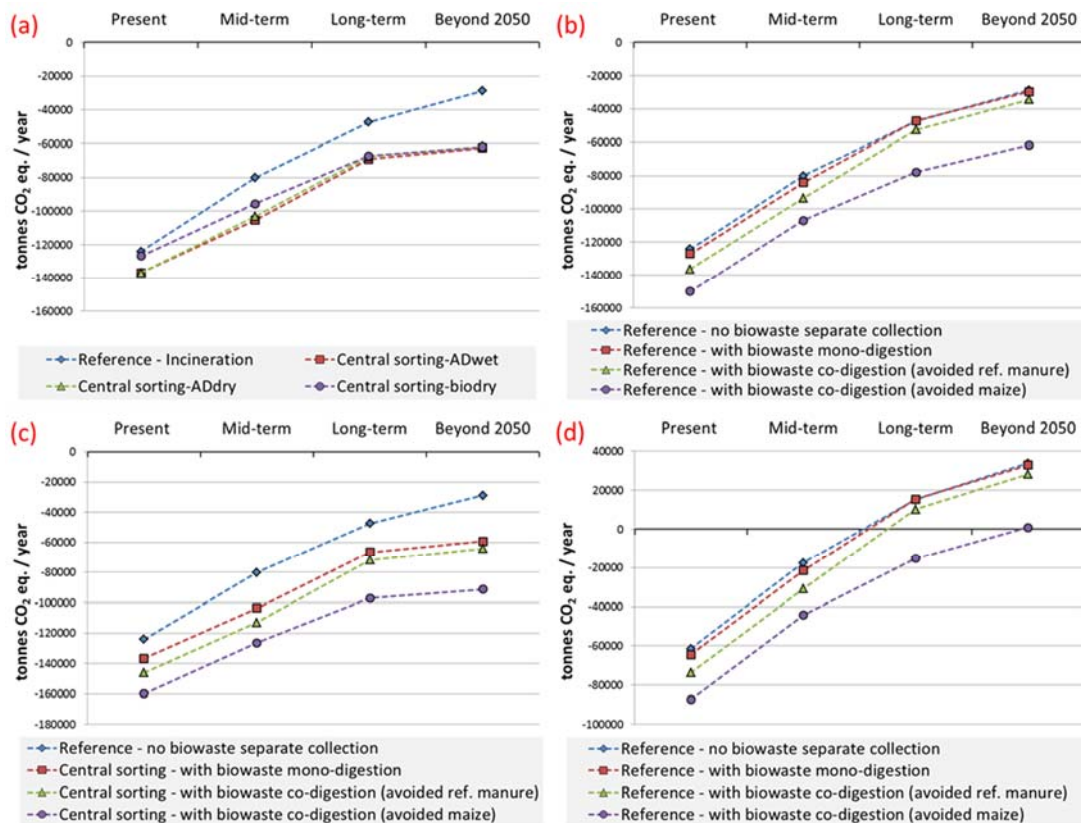
In order to look beyond the present background framework condition and include an assessment of the significance of the changes in background conditions, such as overall Danish policy, strategies and ambitions for future renewable energy integration and climate change mitigation, we modelled the foreground waste management systems in four progressive background time perspectives/periods: the Present (2012-2020), Mid-term (2020-2035), Long-term (2035-2050) and Beyond 2050. The timeline was broken in accordance with key milestones of the Danish energy policy [3]. The marginals for electricity and heat were based on energy system analyses by the Danish Energy Agency, and can be found in the study [4] by Wenzel et al.

In the progression of the Danish energy system from now until beyond 2050, biomass plays a role in both electricity, heat and transport fuel production. On the marginal, this biomass is modelled as being imported. But the global biomass marginal is not necessarily a constant, but may well be dynamic/progressing as time goes and global biomass demand increases. In order to show the influence of assuming a fixed biomass marginal compared to a progressive one, both modelling options were included in the assessment.

Cascading effects which lead to combustible waste imports were included in the first two time periods (up to 2035) and modelled as first described by Cimpan et al in [2]. Interactions between the waste sector and background manure-biogas systems were included in all future perspectives, under the assumption that 100% use of manure for biogas will not be achieved even in 2050.

## RESULTS

Net carbon footprint results for the management of municipal household waste (the functional unit represents the whole waste generated in the region of Funen – 10 municipalities) are illustrated in Figure 6.1 and Figure 6.2. GHG emission savings attributed to all systems decreased in background scenarios considering future background development perspectives (Figure 6.1). All systems, including variants with WtE, followed a pattern of decreasing savings which was dependent especially on the diminishing share of fossil-based energy and the increasing role of biomass in the future energy system (and the source of the biomass marginal). Residual waste management specifically, which is the energy recovery part of the systems, became a net contributor to Global Warming (GW) in the Long-term and Beyond 2050 perspectives (Figure 6.1.d)



**Figure 6.1: Carbon footprint results (relaxed energy targets and progressive biomass marginal): (a) reference system: residual WtE vs. central sorting; (b) reference system: no vs. separate collection of biowaste; (c) Reference collection with Incineration vs. Reference collection + biowaste and central sorting (ADwet); and (d) same as (b) but without the material recycling part of the system.**

The change from residual waste incineration to central sorting (both with the current separate collection system and the alternative dual-stream), was shown beneficial from a GW perspective in all four background time periods (Figure 6.1.a, Figure 6.2). This was due to a threefold contribution by central sorting to: (1) GHG savings by material recovery for recycling, (2) GHG savings by contributing to flexible power and heat production, and (3) GHG savings from combustion of imported combustible waste, due to liberated incineration capacity. The latter contributes to increased savings in the Present perspective, but adds negligible savings in Mid-term. From Mid-term to Beyond 2050, increased flexibility due to

production of RDF and biomethane determined a widening gap in savings between systems with WtE and central sorting (Figure 6.1.a).

Co-digestion of separately collected biowaste from households with animal slurries (manure) showed large potentials for GHG savings, compared to mono-digestion (Figure 6.1.b,c). Potentially large GHG emissions savings could be achieved due to: (1) intrinsic support to increasing manure-based biogas production while avoiding some of the burdens associated with reference manure management, and/or (2) avoiding the utilization of other (marginal) high-C co-substrates, which most likely are energy crops, the production of which comes in direct land use competition with food or feed crops, thus implicitly leading to indirect land use changes through the food/feed crop displacements into land use change somewhere else in the world.

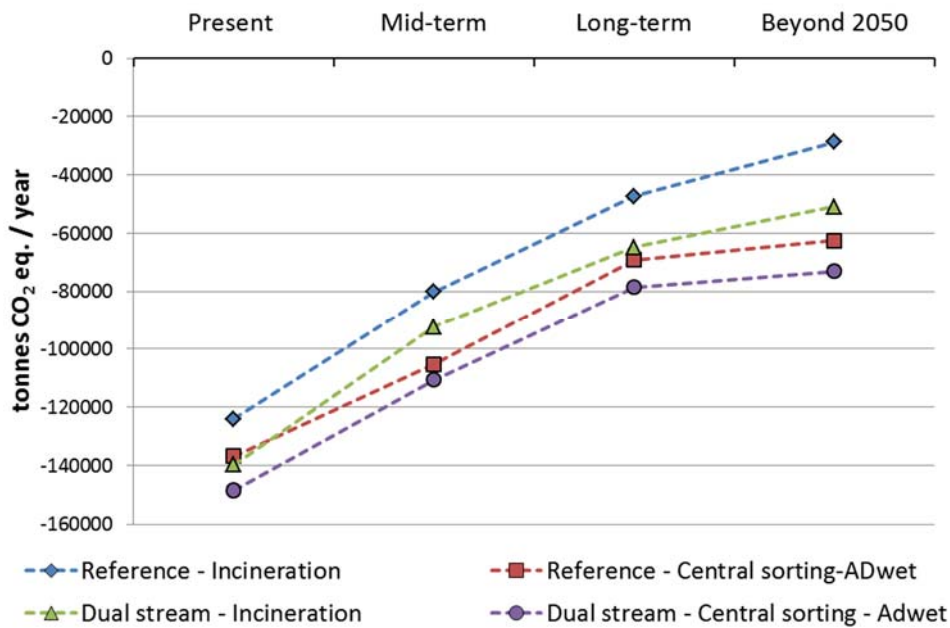


Figure 6.2: Carbon footprint results (relaxed energy targets and progressive biomass marginal): reference collection system with residual waste incineration/central sorting and dual stream collection with waste incineration/central sorting.

## CONCLUSION AND RECOMMENDATIONS

The evaluation by carbon footprint (based on consequential LCA methodology), of reference (WtE) and alternative strategies to waste-derived energy integration (biomethane and RDF), against different sets of background conditions, which represent the most probable future development of the Danish energy system, yielded a number of meaningful conclusions.

In short-to-medium term, MSW management would see a decrease in GHG savings, consistent with the diminishing share of fossil fuels in the energy system. The ability to maintain net waste-derived GHG savings from waste energy recovery in a longer term perspective is found to be determined by the ability to integrate energy production in the surrounding energy system, and therefore the ability to displace other peak energy production, based on remaining fossil fuels or increasingly biomass. In a fully renewable background energy system, the marginal source for biomass utilization, would determine the magnitude of savings related to flexible waste-derived energy production.



Systems based on central sorting, with production of storable RDF for intended utilization in the cold season in district heating networks were indicated as especially relevant, and consistently attained net GW benefits in all modelled background situations superior to direct WtE.

Synergy-based effects strongly advocate for the source separation of household organic waste as this waste management strategy/decision would support the wider strategy to expand bioenergy while at the same time have significant GHGs savings by avoiding the reference management of animal manure in Denmark and/or reduce the utilization of energy crops as a high-C co-substrate in manure-biogas plants. This takes into account potential contamination risks with the alternative central sorting of organics from residual MSW, which despite the possible higher recovery rates, cannot be applied to soils.

While the first steps to integrate waste systems models and energy system analysis models have been confidently taken within this project, further research efforts are still necessary in order to properly capture system dynamics and to integrate tools.

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## 7. WHAT IS THE ROLE OF RECYCLING IN MANAGING SUPPLY RISK OF CRITICAL RESOURCES?

*“Supply risk can arise from a number of underlying factors e.g., geological scarcity, increased market concentration where only a few suppliers are responsible for global supply of a resource, the political stability and governance conditions of the producing countries, etc. Recycling can play a major role in managing the geological supply risk by decreasing the burden on virgin resources. It can also help to reduce the geopolitical supply risk by diversification of supply originating from a number of different countries.”*

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### INTRODUCTION

Critical resources can be defined as the resources which perform an essential function in their end-use products, and at the same time are subject to high level of supply risk. Increased recycling may offer an opportunity to reduce the supply risk. Recently, the term critical resources got wider attention globally regarding their potential supply disruption for a future large-scale implementation of clean energy technologies e.g., wind turbines, electric and hybrid vehicles etc. In [2], a number of different underlying constraint factors causing supply risk are enlisted, such as:

- a) *Geological availability* of a resource is considered, the principal concern being the geological presence and availability of a resource. This indicator is often quantified by calculating the ratio of identified geological reserve<sup>5</sup>/reserve base<sup>6</sup> of a resource to its annual consumption, which results into the lifetime or depletion time of the identified reserve of the resource in question.
- b) *Geopolitical availability* of a resource is considered, the principal concern being geographically related political barriers to supply and availability of the resource in question. Furthermore, this often covers two concerns, the first being the *share of global supply* a given supplying nation represents, the second being the *state of political governance* and stability of the nation in question:
  - *Global supply share* is an indicator representing the degree of monopoly or oligopoly one or a few nations has/have, i.e. the degree to which one or only few countries dominate the global supply of a resource. This parameter is assessed with the help of the widely used Herfindahl Hirschman Index (HHI) indicator, which shows the risk of potential supply constraints originating from a single or a few countries controlling the global supply of resources. A high HHI score shows highly concentrated supply, few producers and hence the greater supply risk; whereas a low HHI score shows less concentrated supply, more producers and hence less supply risk.
  - *Worldwide Governance Indicators (WGI)* – a set of six sub-indicators has been used in a number of studies to assess the supply risk related to politically unstable countries being dominant producers of a resource. This indicator is provided by the World Bank and is aggregated based on a set of sub-indicators: e.g. voice and accountability, political stability, absence of violence etc.

<sup>5</sup> According to USGS, reserve is that part of reserve base (part of the total geological resource of a metal) which could be extracted or produced economically at the point of determination. (<http://minerals.usgs.gov/minerals/pubs/mcs/2009/mcsapp2009.pdf>).

<sup>6</sup> According to the USGS, reserve base is that part of an identified resource that meets specific minimum physical and chemical criteria related to current mining and production practices (<http://minerals.usgs.gov/minerals/pubs/mcs/2009/mcsapp2009.pdf>).

In [3], we have estimated the future geological and geopolitical supply risk of two Rare Earth Elements (REEs): neodymium (Nd) and dysprosium (Dy), and we have highlighted the role of recycling in managing this supply risk. In our study, we developed four different future demand scenarios for neodymium and dysprosium, ranging from business as usual (Baseline) to the ultimate renewable energy scenarios (100% REN), and compared these with the projected primary supply by 2050, estimated from historical trends.

The four demand scenarios offer varying degrees of renewable energy shares in the future electricity demand (among changing demand from other sectors), e.g., the Baseline scenario assumes a 22% share of renewable energy, where wind power represents 5% of the total electricity demand by 2050. In comparison to this, the 100% REN scenario assumes a very ambitious target of achieving 100% renewable energy, with 33% share of wind power by 2050. The demand in all the four scenarios has been further projected at a rather stable annual growth rate (0.5-1%) by 2100 to address the issue of lifetime/depletion time of the geological Reserve2011 (i.e. the value of geological reserve in 2011) of neodymium and dysprosium. By considering various end-of-life (EoL) recycling rates for different end-use sectors, we estimated the secondary supply (originating from recycling) of neodymium and dysprosium [1].

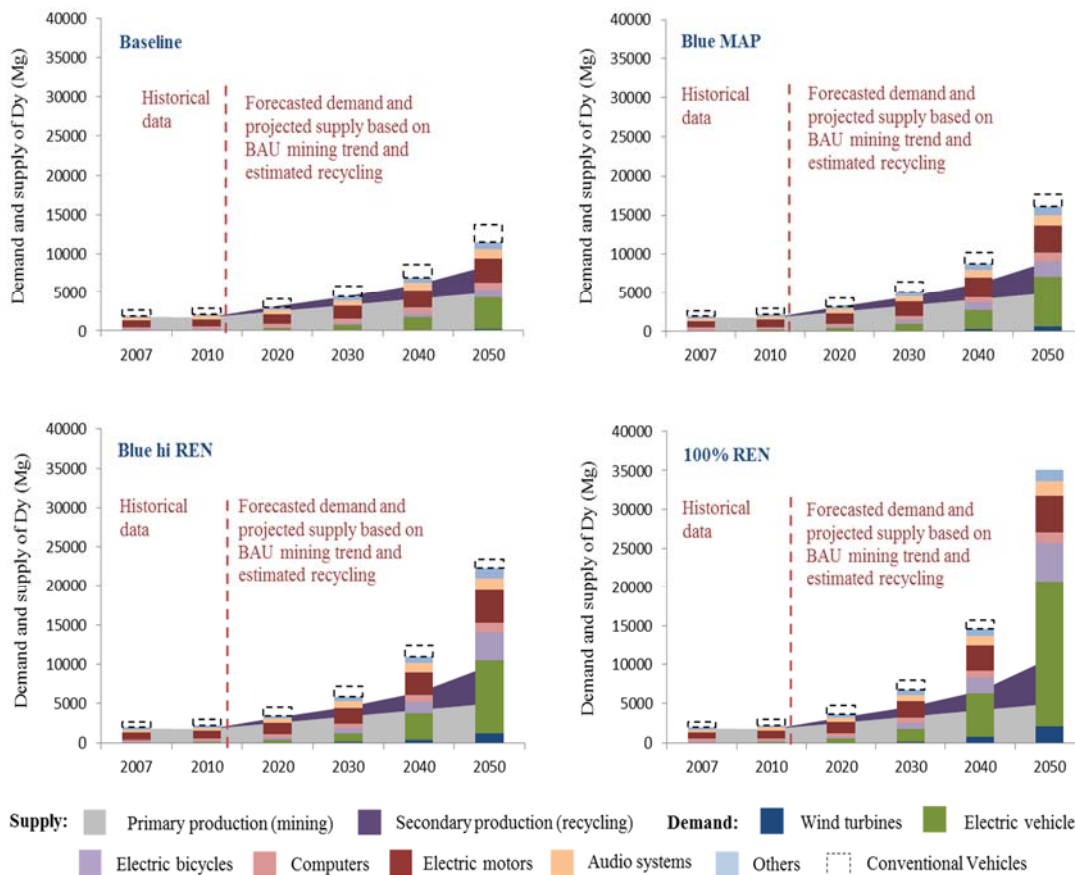
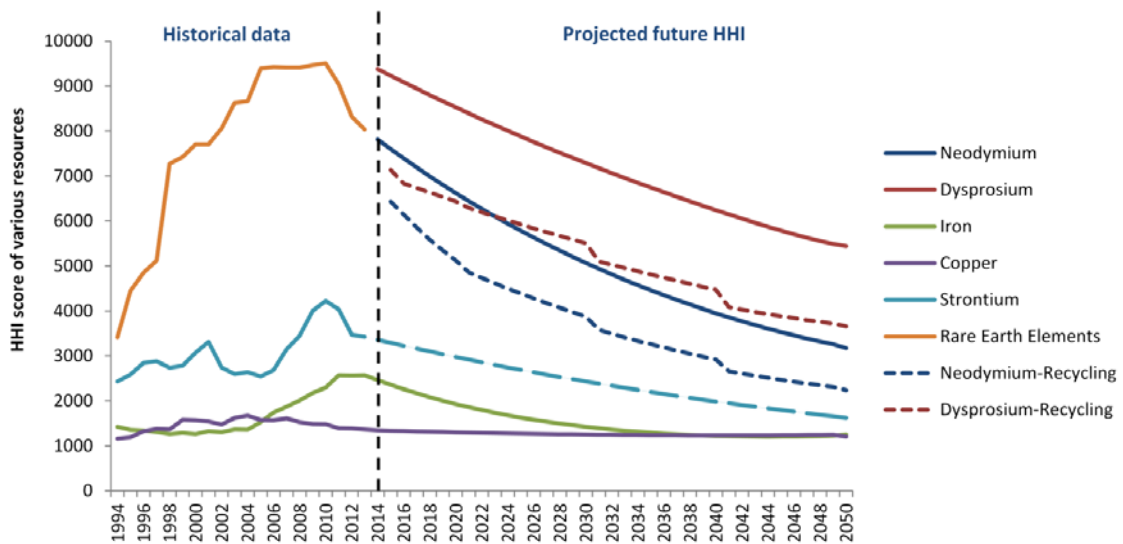


Figure 7.1 - Comparative overview of forecasted future annual demand vs. the business as usual (BAU) projected primary supply and scenario dependent secondary supply of Dy in four different scenarios up to 2050. The bars show the forecasted annual demand and the slopes show the projected primary and secondary supply of Dy [1].

## RESULTS

Figure 7.1 shows a detailed overview of the projected demand and supply of dysprosium in four different scenarios, where it becomes evident that the forecasted demand of dysprosium exceeds the projected supply in all scenarios. The demand ranges from 2.6 Gg year<sup>-1</sup> in 2007 to 13.6 Gg year<sup>-1</sup> in the Baseline scenario and 35 Gg year<sup>-1</sup> in the 100% REN scenario by 2050. On the other hand, the projected primary supply of dysprosium is estimated to reach approximately 5 Gg by 2050, which can only meet 38% of the forecasted demand in the Baseline scenario and 14% in the 100% REN scenario in 2050. The results regarding secondary supply originating from recycling of EoL products show that the amount of dysprosium secondary supply is estimated to reach 3.5 Gg year<sup>-1</sup> in the Baseline scenario and 5.8 Gg year<sup>-1</sup> in the 100% REN scenario by 2050. This means that recycling can help to reduce the demand and supply gap from 62% to 37% in the Baseline scenario, and from 86% to 69% by 2050.

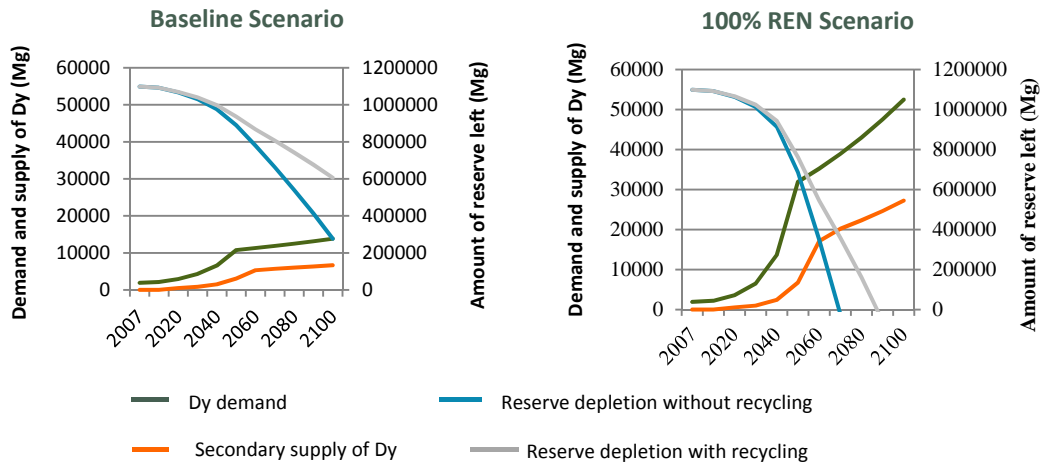
Figure 7.2 shows that recycling is also found to play a significant role in lowering the geopolitical aspect of supply risk (estimated based on the HHI) from 7,812 to 2,237 for neodymium and from 9,647 to 3,656 for dysprosium in the Blue MAP scenario by 2050. This is foreseen mainly because of the increasing secondary production and thus the diversification of REEs supply (both primary and secondary) originating from a number of different countries in the future, [1].



*Figure 7.2 - The estimated historical and future Herfindahl Hirschman Index (HHI) of Rare Earth Elements (REEs), neodymium, dysprosium, copper, iron and strontium from 1994 to 2050. The HHI score of REEs has been differentiated between neodymium and dysprosium from 2013 onward. Moreover, the dashed trend line for strontium after 2013 reveals the data limitations regarding strontium reserves [2].*

Figure 7.3 shows the results for geological supply risk of dysprosium, where in the Baseline scenario it is clear that almost 25% of Dy Reserve<sub>2011</sub> seems to be available by 2100 (orange line, secondary vertical axis), even if the secondary supply is not considered. If we consider the share of secondary supply, then this amount of Reserve<sub>2011</sub> available by 2100 increases from 25% to nearly 55% (grey line, secondary

vertical axis). In the extreme scenario of 100% REN, the Reserve2011 seems to deplete already by 2070 (orange line, secondary vertical axis) although recycling helps to delay this depletion for almost two decades (grey line, secondary vertical axis) [3].



**Figure 7.3 - Overview of the annual demand of Dy, secondary supply and the resulting Reserve2011 depletion in the Baseline scenario (left) and the 100% REN scenario (right) [3]**

## CONCLUSION AND RECOMMENDATIONS

Neodymium and dysprosium recycling is found to play a major role in reducing the gap between the forecasted supply and trend based projected supply in the long term, i.e. beyond 2050. It is also shown that recycling can help to reduce the burden on the virgin resources, and thereby increase the lifetime of geological resources. In [2] and [3], recycling is also found to play a significant role in lowering the geopolitical aspect of supply risk (estimated based on the HHI). This is foreseen mainly because of the increasing secondary production and thus the diversification of REEs supply (both primary and secondary) originating from a number of different countries in the future. Finally, this study recommends further research in identifying the potential waste streams for the efficient recovery of critical resources from urban mines, as well as to estimate the recovery potential of these resources from the current and future waste flows in order to manage any supply risk in a well-planned manner.

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## 8. ARE WE RUNNING OUT OF METALS FOR FUTURE RE TECHNOLOGIES?

*"Access to metals has always been crucial for human development throughout history. As a matter of fact, the major societal development periods of human history have been named after metals, e.g., the Copper and Iron Ages. The massive exploitation of metals during the past two centuries has raised the concern of their long-term availability, especially for the full-scale development of clean energy technologies in future. We have shown, with the help of Rare Earth Elements – considered as critical resources by the European Commission, that there are enough geological resources of REEs to meet the exponential demand by renewable energy technologies e.g., wind turbines and electric vehicles in the long-term future i.e., 2050."*

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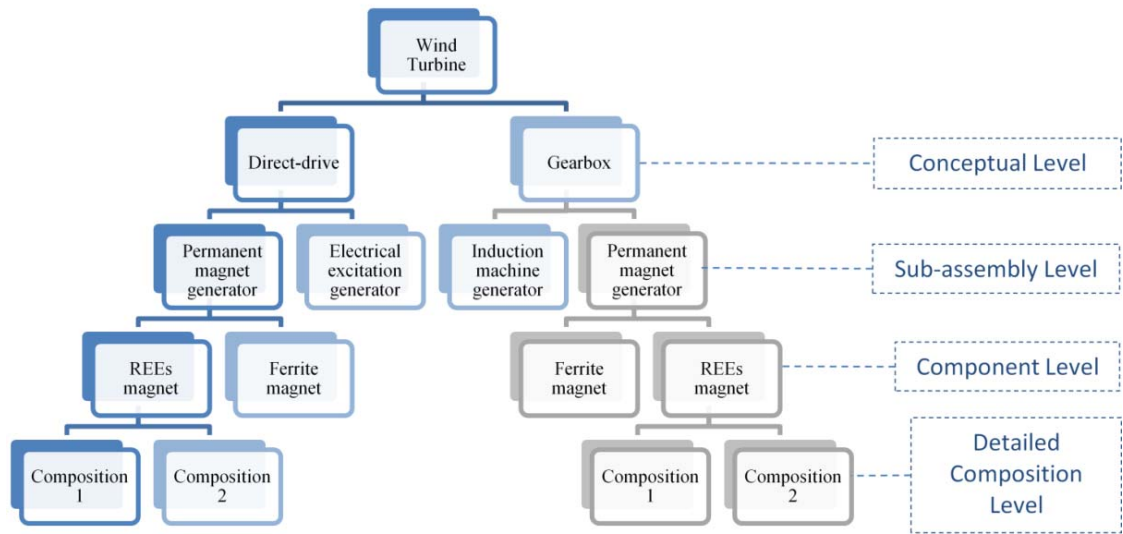
### INTRODUCTION

The industrial revolution, starting in the 18<sup>th</sup> century, followed by the exponential economic growth during the last two centuries, has been accompanied by a heavy reliance on fossil fuels, but also by a growing concern of their future scarcity along with the overwhelming global warming issue. The oil crisis of 1973 further highlighted the rising threat of future supply risk of fossil fuels. The increasing concern of fossil fuels depletion has led the global society to devise other renewable means of energy and transport, to reduce dependency on the fossil fuels as well as to reach ambitious goals for meeting the climate change challenges of the future. This enormous transition from the current fossil based society to the future non-fossil society might, however, be constrained by the decreasing availability of other non-renewable resources such as metals – an issue that has been highlighted in several recent studies [1].

A future non-fossil society needs to be built on emerging clean energy and transport technologies such as wind turbines, solar panels, electric cars etc. The existing state-of-the-art clean energy technologies such as the direct-drive wind turbines and electric vehicles use significant amounts of the so-called *specialty metals* such as rare earth elements (REEs) for the specific functionalities required. These specialty metals are relatively new in use compared to the major industrial metals such as aluminum, iron, copper, nickel and zinc etc. [1]. In [3], the growing concern with respect to risk of supply disruption of the two key REEs namely neodymium and dysprosium and the resulting implications for the wider implementation of clean energy technologies in the future has been explicitly addressed. The major use of these two elements is neodymium-iron-boron (NdFeB) magnets which are the strongest permanent magnets developed so far. NdFeB magnets are further used in various end-use products ranging from body care and home appliances, and information technology and telecommunication (IT & Telecom) to transport and energy sectors, [3]. The current state-of-the-art direct-drive wind turbine technology and the electric and hybrid vehicles are two major clean energy technologies which are as yet highly dependent on these magnets for the performance and size reduction benefits offered.

We have explicitly addressed the issue of geological resource limitations for future renewable energy technologies in [2]. In the study, we have stressed on assessing the potential resource constraints in a technology and dynamic perspective. Considering the case of current state-of-the-art direct drive wind turbine technology, we have developed a so-called *product design tree* (see Figure 8.1). This product

design tree ensures the same functionality for a range of design alternatives, from the very conceptual level to the detailed composition level, given the condition of associated resource trade-offs.



*Figure 8.1 - A hierarchical product design tree of wind turbines illustrating design alternatives from bottom to top. An analysis of the feasibility of design substitutions at each level forms the basis of assessing the vulnerability to risks of resource supply constraints (dark blue boxes show the reference product i.e. the direct-drive turbine design assessed in the current study, light blue boxes show the design alternatives assessed in the current study, and the grey boxes show other design alternatives which are not considered in the current study) [2].*

Since the case of the current study is direct-drive wind turbines, we have selected neodymium, dysprosium, copper, iron and strontium from a wide array of metals used in a wind turbine to illustrate our approach and to capture some of the key resource trade-offs when comparing alternative designs. Data regarding resource consumption of the selected resources was collected with the help of a wind turbine manufacturer, and

Table 8.1 presents this actual resource trade-off between the available substitutes at all the four levels of product design tree, [1].

Level	Design substitute	Normalized installed capacity (MW)	Nd	Dy	Fe for Magnet	Fe for Turbine	Cu	Sr
<b>Detailed Composition</b>	Composition 1	1	200	13.33	440	76160	4700	-
	Composition 2	1	203.33	10	440	76160	4700	-
<b>Component</b>	REEs magnet	1	200	13.33	440	76160	4700	-
	Ferrite magnet	1.03	-	-	2435	78445	4700	346
<b>Sub-assembly</b>	Permanent magnet generator	1	200	13.33	440	76160	4700	-
	Electrical excitation generator	1.07	-	-	1155	80729	4982	-
<b>Conceptual</b>	Direct-drive turbine	1	200	13.33	440	76160	4700	-
	Gearbox turbine	1.17	-	-	-	84900	1500	-

*Table 8.1 - Resource trade-off (kg/equivalent functional output of 2190 MWh year-1 for a period of 20 years) for different substitutes along the product design tree [2].*

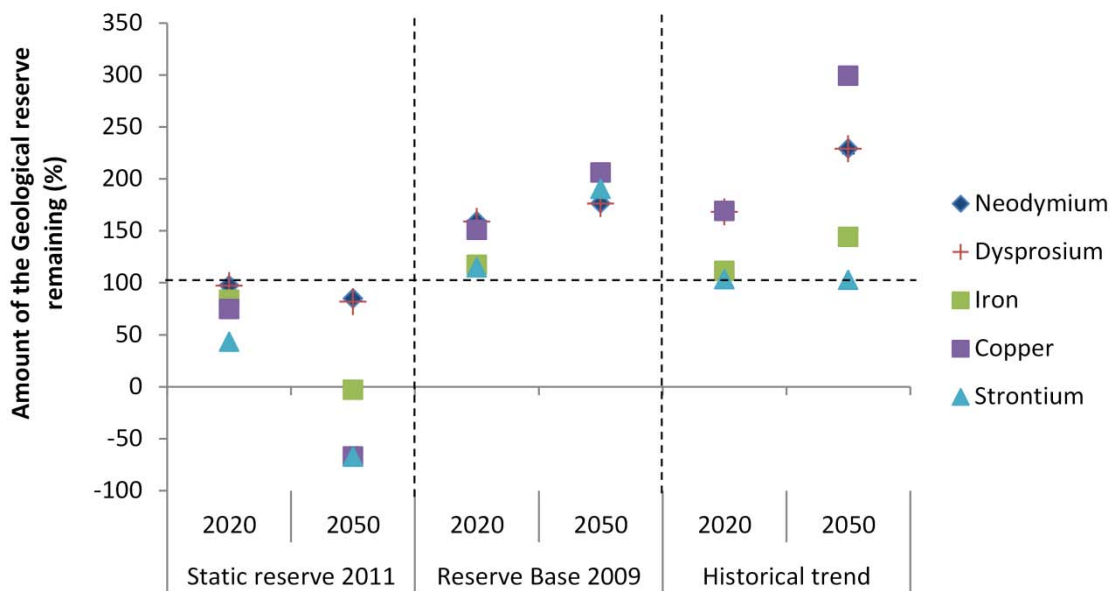


## RESULTS

Figure 8.2 shows the amount of geological reserve available by 2050, by taking into account the depletion of geological resources using two different geological reserve estimation approaches: first, a static reserve approach where the geological reserve of 2011 for all the resources considered in this study is assumed to be static, meaning that the geological reserve does not grow over time resulting from any new discoveries or economic reasons; second, a dynamic reserve approach where the currently known reserves are assumed to grow over time until 2050.

In the dynamic reserve approach, reserve growth is projected until 2050 using two different ways: first, the currently known geological reserves are projected to grow up to the reserve base 2009 estimates provided by the U.S. Geological Survey by 2050; second, by 2050 the current known geological reserves are projected to follow a historical growth pattern from 1994 to 2014, [1]. Furthermore, the results presented in Figure 8.2 are for the so-called Blue MAP scenario developed by the International Energy Agency ([5]-[6]). This scenario is chosen from four scenarios assessed in [3], as it offers the minimum initiatives global community has to take in order to stay within the limit of 2°C temperature rise, and avoid the resulting climate change implications.

The results presented in [2] highlight that even with the pessimistic Static Reserve 2011 approach, the reference design case of direct-drive wind turbine with permanent magnet generator containing NdFeB magnet is not likely to face neodymium and dysprosium supply constraints due to depletion of geological resources by 2050, considering the given scenario. The amount of remaining geological Reserves<sub>2011</sub> after considering the cumulative demand of neodymium and dysprosium by the reference wind turbine design case and the background end-use sectors by 2050, is estimated to be more than 80%, thus posing no geological supply disruptions in medium-to-long term future (see Figure 8.2).



*Figure 8.2 - Comparative reserve depletion estimates of neodymium, dysprosium, copper, iron and strontium for the present state-of-the-art direct-drive wind turbine design in the Blue MAP scenario, by considering the currently available geological reserves*

*known static as well as projected future reserve estimates by 2050. Note that the figure presents the resource demand in both the wind turbine and the background uses [2].*

Substituting the reference design case of NdFeB magnet generator with a ferrite magnet generator (see Figure 8.1) shows that the ferrite magnet generator is less efficient compared to the reference design case (see

Table 8.1). In order to compensate this performance loss, a clear resource trade-off can be seen among both of the design options, where the NdFeB permanent magnet generator is dependent on neodymium and dysprosium whereas the ferrite magnet generator consumes a significantly larger amount of iron in addition to strontium. Regarding the geological supply risk of choosing the ferrite magnet generator, the Reserve2011 for strontium seems to be already depleted by 2033 in the Blue MAP scenario (using the Static reserve 2011 approach), even without considering the consumption of strontium by the ferrite magnet design alternative for direct-drive wind turbine (see Figure 8.2). This indicates a warning of potential supply constraints of strontium to the wind turbine manufacturers. On the other hand, using the dynamic reserve approach (Reserve base2009 approach) reveals that the amount of strontium reserve available by 2050 is subject to grow by almost a factor of 2 by 2050 compared to Reserve2011, instead of getting depleted as in case of static reserve approach. Moreover, according to the U.S. Geological Survey, the total resources of strontium are more than 1 billion tons, equivalent to 147 times higher than the current identified reserve. This means that the depletion of strontium reserves is not realistic at least in the foreseeable future, [1].

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## CONCLUSION AND RECOMMENDATIONS

By evaluating the geological resource availability, in both static and dynamic perspectives, for the future renewable energy technologies, it can be concluded that we are not running out of resources for a broader implementation of clean energy technologies by 2050. Also, by studying the current state-of-the-art wind turbine technology in a detailed technology perspective, it was found that their dependency on rare earths based permanent magnets is not strong enough to pose an actual risk for the full-scale deployment of wind turbines in future, as these magnets can be substituted by a number of commercially available alternatives at different levels of product design tree, though with varying degree of efficiency and resource trade-offs. Hence, we can conclude that we are not running out of resources for future renewable energy technologies - at least not in the case of rare earth elements for wind turbines and background uses.

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## 9. WHAT ARE THE MOST IMPORTANT COST ELEMENTS OF MSW MANAGEMENT?

*“ The net cost of MSW in DK is about evenly distributed on administration & information, curbside collection and recycling centres. The income is mainly related to sale of recycling paper and metals.”*

*Ole Dall (old@kbm.sdu.dk)*

### INTRODUCTION

The economy of waste management plays a fundamental role in political decisions about changes in the waste management systems and the related regulation schemes.

The cost of waste management in Odense has been estimated basing on the information from the Odense Renovation (see Figure 9.1). The employed approach has been to match the overall waste management fee for a single family household: including curbside collection of one 190 litre waste bin every 2nd week and one paper bin every 4th week. The use of recycling centres including hazardous waste from households when needed has also been included in the model. Nine cost groups have been identified, hence the distribution of the global cost is based on detailed information about the cost per ton for different waste types for an average waste volume per single family household, [1]. The income from sale of recycling materials is shown, but the income from energy sale from incineration is included in the net cost for treatment.

Administration, collection and incineration, and recycling centres roughly costs 1/3 each when final waste treatment is included (see Figure 9.2). The administration and information cost is an approximation based on the fee for a company in Odense (2012 level), but verified by comparing to waste fee's in several municipalities.

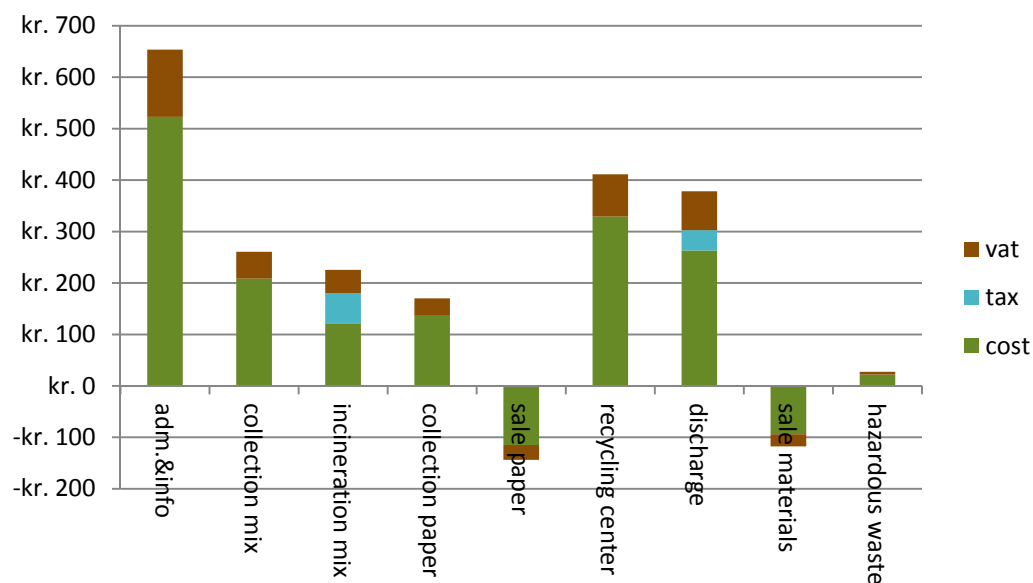


Figure 9.1 – Cost distribution in Odense for waste management in 2012.

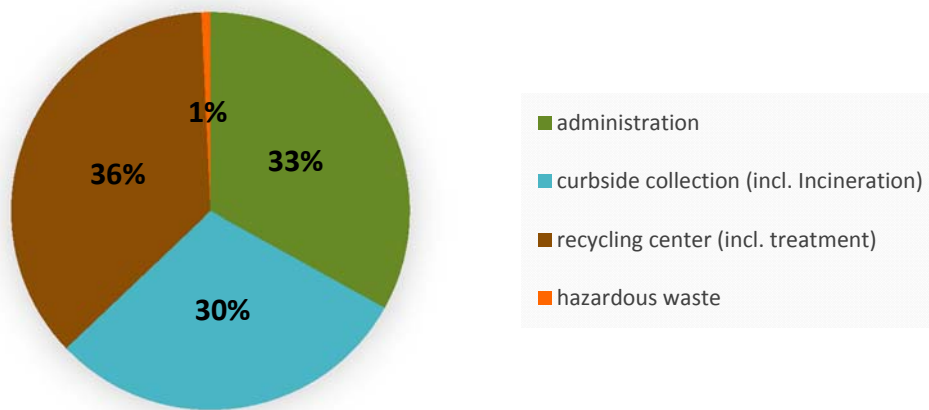


Figure 9.2 - The circle diagram aggregate values from Figure 9.1, column 2-5 as “collection and incineration” and column 6-8 as “recycling centre”

In Figure 9.1 it should be noticed, that the taxes on waste management related to incineration of mixed waste from recycling centres are relative small (about 5% of the total cost). From curbside collection almost all costs are related to collection and incineration of mixed waste (column 2+3), whereas the cost of collection and sale of paper almost evens up (column 4+5). The running costs of recycling centres and discharge of waste from those is quite costly due to the high share of mixed waste. The incomes at recycling centres represent about 15% of the running costs (including waste disposal) and originate from metals and paper/cardboard.

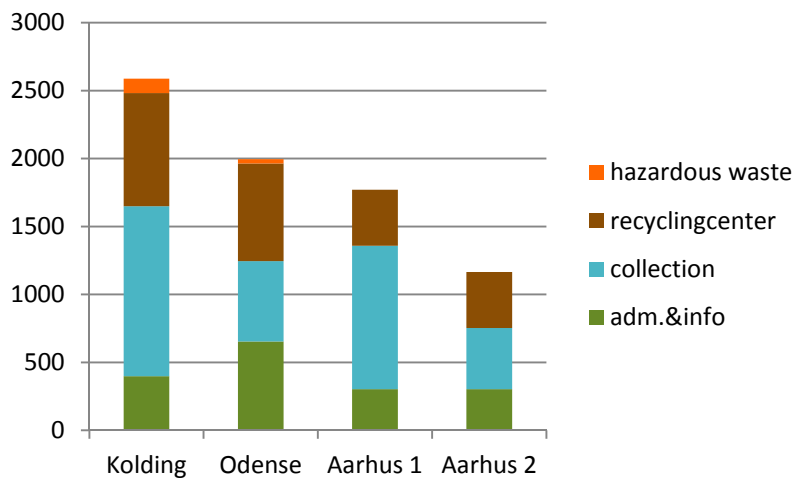


Figure 9.3 - Waste management costs (kr.) in 3 different Danish cities (2015)

Figure 9.3 shows cost of municipal waste management, using data from the municipal waste management system in Odense (2015 level) and official waste fees from websites in Kolding and Aarhus 1 for similar service for a single family household. Aarhus 2 represents the new system in the inner city with extended use of road side bins for mixed waste: the main difference is the use of roadside bins for mixed waste in Aarhus, where Odense and Kolding collects mixed waste from every household.

Interesting differences are found in the administration and information cost, where Odense seems to have the highest cost. It is however not well defined what is included (could be all administration or only shares not related to collection etc., information activities, planning activities, material sale etc.).

For the cost of recycling centres, the three examples differ with a factor of 2, which might be explained by different levels of service. Another, and more likely, explanation relates to the higher efficiency of the recycling centres in Aarhus due to the high volumes they normally treat – partly originating from an extended use of these facilities by private companies, as a consequence of the historic fee policy for companies in Aarhus.

The curbside collection fees are the lowest in Odense, which may be partly explained (but only partly, since collection distances could be different) by the fact that this service is provided by the municipal organisation and not outsourced to a private operator as in Kolding and Aarhus. Public service is in this case very competitive. The low cost for collection in Aarhus 2 is due to the new system, mentioned above, introduced in densely populated areas, where the collection is done by a large number of underground collection bins. This has radically lowered the costs for collection and covers paper and glass collection, besides mixed waste.

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## CONCLUSION AND RECOMMENDATIONS

In the decision making process for the future management waste system, 5 issues should be considered:

- 1) The taxation is less than 10% on waste management (mainly related to incineration), and might have to be increased to encourage higher recycling rates.
- 2) Administration of waste management systems and information campaigns are costly and can increase if the collection becomes more diversified.
- 3) The strategy of outsourcing waste collection should be critically evaluated since it seems not to be the most cost efficient compared to municipal owned collection fleet and organisation as in Odense.
- 4) Collection costs can be reduced radically by replacing collection from individual households to local waste bins where users bring the waste – at least in cities this could be an important future development.
- 5) The income from recycling of waste is a fundamental feature to analyse. Especially for paper, cardboard and metals; an increase of future prices of recyclables could imply a radical change in the economy of waste management.

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## 10. WHICH ORGANIZATIONAL MEASURES MAY SUPPORT THE ACHIEVEMENT OF THE POLITICAL GOALS AS SPELLED OUT IN “DENMARK WITHOUT WASTE”?

*“From the 70's up to today the perception of waste has changed from being an environmental problem into a resource potential. Interviews carried out amongst main stakeholders within the energy sector on the Danish island of Funen indicate that cross municipality cooperation and establishment of supply companies while leaving the authority tasks to the local authorities could be one of the main institutional developments, supporting the initiatives to be taken to achieve the political goals. The survey is not comprehensive but gives some indications that establishment of supply companies could be one of several drivers needed”*

*Birgit Holmboe (birgit@birgitholmboe.dk)*

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### INTRODUCTION

The question of how to organize the waste sector is fundamental, since the transition needed to achieve 50% recycling of the household waste before 2022 – as set up by the Danish Government - not only depends on technical, environmental and economic issues, but also on the stakeholders’ ability to adjust to the changed framework and to develop their organizations according to the new responsibilities and conditions.

In order to illustrate the challenges faced by the stakeholders, a memorandum has been developed [1], aiming to give an overview of the historic development of the organizational set-up – from the period where waste was considered an environmental problem (1970’ties-) until today, where waste is frequently regarded as a raw material for new production.

Furthermore, the significance of recent trends, such as further market based waste management, is highlighted. The global trends will have influence on the organization of the household waste management in Denmark. The memorandum, [1], seeks to summarize the prospects for the waste sector.

To concretize the problems faced by the stakeholders now and in the years to come, interviews with key stakeholders have been carried out. The aim of the interviews has mainly been to get an understanding of the considerations concerning the institutional development of handling household waste. To narrow the scope of the interviews, the island of Funen has been chosen as geographical boundary.

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### RESULTS

The results of the survey carried out show a waste sector that has undergone huge transformations since the late 1970’ties. The technical, economic and regulatory conditions have called for changes in the institutions taking care of the municipal waste management services. From the 1970’ties the awareness of the environmental problems of the growing waste amounts launched a cascade of legal regulations giving the environmental framework for the stakeholders.

The existing legal framework with two tiers of government is partly set up by the EU and partly by the Danish Government. The growing focus on circular economy, recycling and efficiency has led to technical improvements. The increasing exposure to rely on a further market based sector has called for considerations by the local authorities concerning cooperation and changes in the institutional set-up. Cooperation is expected to take place not only between the private and the public sector, but also between the waste sector and other service sectors, for example the energy sector and the waste water sector. The combination of interviews with key players in the 1980'ties -1990'ties and a desk study, have been the background for the results given in the memorandum.

The knowledge gained from the historic examination of the waste sector and the overview of the perspectives for the future development of the sector institutions was used as basis for interviews with main stakeholders in the island of Funen (Denmark). The interviews took place during the period in which the compulsory strategic energy planning took place. The strategic energy planning for the region of Funen included waste management as an important issue in their scope of work, which gave the interviews perspectives when talking about coordination between service sectors.

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## CONCLUSION AND RECOMMENDATIONS

The changes in the framework conditions for handling of household waste and the technological and environmental breakthroughs achieved in recent years have called for changing the institutional set-up of the sector.

Coordination and partnerships have to be established in order to reach the goal of 50% recycling of municipal solid waste within 2022. New EU draft regulations even indicate that the future EU goal will strive to reach 65% recycling of municipal waste in 2030.

The Danish Government has chosen to rely on voluntary agreements and partnerships developed by the local governments themselves. Due to the limited timeframe in which the development of the new institutional framework has to be in operation, it is important to follow the development closely the coming years to avoid sub-optimization.

If progress is not seen, actions should be taken to ensure adequate drivers to ensure a sustainable development of the waste sector so private and public sector initiatives can be properly coordinated. Future research should focus on these issues.

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The TOPWASTE project has addressed the challenges of planning robust solutions for future waste management. The purpose was to identify economic and environmentally optimal solutions - taking into account different scenarios for the development of the surrounding systems, such as the energy system. During the project, four decision support tools were developed:

- Frida - The EPA's tool for forecasting future waste generation.
- OptiWaste - a new tool for economic optimisation of investments and operation of the combined waste and energy system.
- KISS - a new lifecycle based model with focus on comparison of greenhouse gas emissions associated with different waste management alternatives.
- A new tool for techno-economic modelling of central sorting plants.

The project has furthermore contributed with method development on evaluation of critical resources as well as analyses of economic and organisational factors with influence on the future waste management.

The results of the project clearly show the importance of taking scenarios for the future development of surrounding systems into account when deciding how the future waste management should be, both when it comes to the economic, environmental and resource efficiency of waste management solutions.

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