Waste to Energy in Aalborg

A Historical Perspective of Global Warming Impact based on Life Cycle Assessment

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Master Thesis

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List of Abbreviations

APC	Air Pollution Control System
CHP	Combine Heat & Power plant
EU	European Union
FU	Functional Unit
GHG	Green House Gases
GWP_{100}	Global Warming Potential (100 years)
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCIA	Life Cycle Impact Assessment
LCT	Life Cycle Thinking
LCM	Life Cycle Management
LHV	Lower Heat Value
MSW	Municipal Solid Waste
MSWM	Municipal Solid Waste Management
tkm	tons kilometer

Abstract

Solid waste management all around the world is responsible for 3-5% of the total anthropogenic GHG emissions every year. This study has mainly focused on presenting the GWP_{100} from MSWM in Aalborg Municipality and a brief comparative analysis of accompanying waste management plans and strategies in Denmark from 1970s upto now. LCA has been used as a tool to get the GWP_{100} from different waste management options practiced from 1970 upto now taking the technological development and fuel value of MSW into account. The Comparative analysis of waste management plans at National level in Denmark has revealed that the common perception regarding environmental solutions has evolved from ''dilution'' in 1970s to ''cleaner products'' now a days where the whole life cycle of a product is considered in order to prevent any environmental damages at the source rather than end of pipe. At the local level in Aalborg, the waste management plans have focused on following the waste management hierarchy from the very first plan in 1989 upto now but the difference has been in making the targets for recycling, incineration and landfilling more strict every time. The LCA study has shown that in 1970, the GWP_{100} was highest as 586 kg CO_2 eq/ 1 ton of MSW treated per year in Aalborg because all the MSW was landfilled but in 2010 the GHG emissions leading to GWP_{100} have been saved as -1284 kg CO_2 eq/ 1 ton of MSW treated per year in Aalborg due to a combination of recycling, composting and incineration because recycling avoids the production of virgin materials, composting avoids the production of synthetic fertilizer and incineration process produce energy from waste which substitutes the energy produced from fossil fuels. Every person in Aalborg was responsible for 269 kg CO_2 eq from MSWM in 1970, which has reduced now upto -644 kg CO_2 eq / person. It reveals that Aalborg Municipality has shifted from a ''net polluter'' to ''net saver'' of global warming.

Key Words: Municipal Solid Waste, Life Cycle Assessment, Global Warming, energy from waste.

1. Introduction

’’Man is everywhere a disturbing agent. Wherever he plants his foot, the harmonies of nature are turned to discords’’.

George Perkins Marsh (1874)[1]

1.1. Waste Management

History reveals that the societies, who developed their industry rapidly, always faced the problem of solid waste management. For many of the developed and some developing countries with high rate of population growth, prosperity and urbanization, it is the big challenge to efficiently collect, treat and dispose of the waste. The developed world has this problem due to their heavy resource consumption and massive production, but the developing world is facing this problem due to inadequacy of proper resources and awareness for solid waste management (UN HABITAT 2010; Bogner et al. 2008).

European countries are also facing the issue of sustainable waste management as a result of heavy natural resource consumption, rapid industrialization and economic development. Approximately, 3 billion tons of waste is generated every year in EU and every single European citizen is responsible for 6 tons of waste every year. But this waste generation rate is not same all around the EU due to the difference in industrial structure and socio economic status of a country, as it very much depends on the living standards of inhabitants from country to country (European Environment Agency 2010a).

Municipal solid waste (MSW) generation also varies from country to country. But, according to the data available in 2008 it is clear that the average MSW generation rate per person in Europe is 524 kg. But European countries are very determined for the sustainable management of MSW and this is clear by the continuous decrease of waste going to landfills (European Environment Agency 2010a). Figure No. 1.1 shows that from 1995 till 2008, the waste going to landfills has reduced significantly whereas the waste going to recycling and composting has increased. The trend for incineration has also decreased during this time period in European countries.

[1] Source: Pichtel 2005

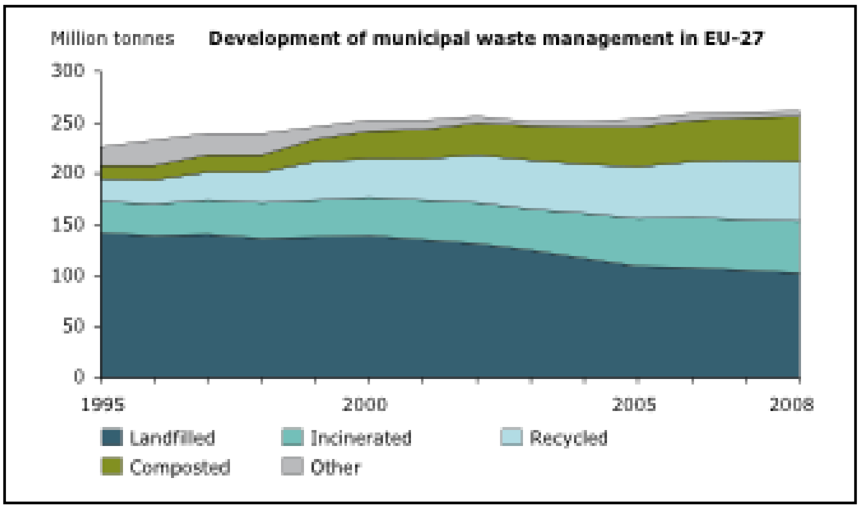

Figure No. 1.1: Waste management in EU- 27 from 1995 to 2008 (European Environment Agency 2010a).

1.2. History of Waste management Policy in EU

The history of waste management policy dates back to 1970s, when environmental policy makers became more concerned about the environmental and human health problems arising from the poor management of solid waste. At that time all the member states of EU started taking initiatives for waste management, which ultimately resulted in two directives namely *Waste Framework Directive* and *Hazardous Waste Directive* in 1975. These directives gave the early definition of waste and several key measures to ensure that waste is not handled in a poor way causing environmental or human health damage (European Commission 2005).

In the earlier stage of waste management policy, different emission parameters were not considered in order to select between different waste management options such as landfill, incineration and recycling in terms of their environmental hazards. As a result different environmental problems initiated because of pollution from landfills and incineration plants. In 1996, the *European Commission's Waste Strategy Communication* enforced the waste hierarchy to be followed in all the member states (European Commission 2005). This waste management hierarchy is shown in Figure No. 1.2.

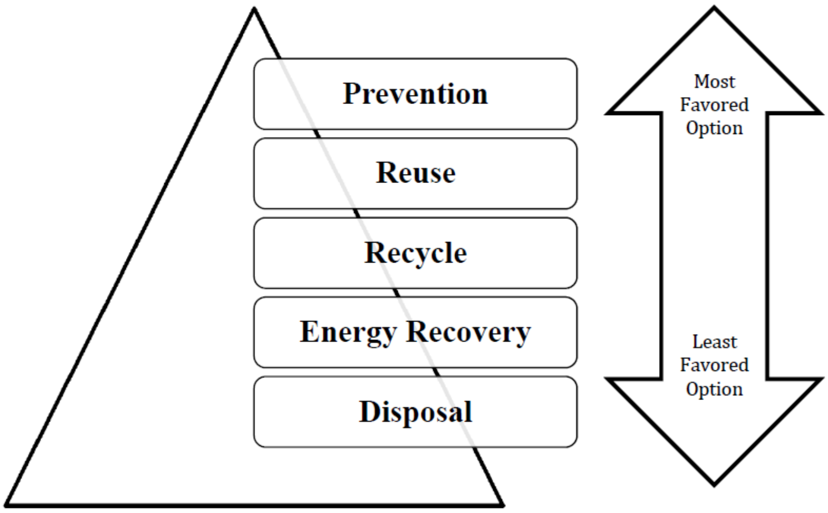

Figure No. 1.2: Waste Management Hierarchy (European Commission 2008)

Finally in 2000, EU adopted the *Waste Incineration directive* and in 2001, *Landfill Directive* was developed. The next step was to encourage the trend of recycling as compared to landfill or incineration of waste in order to avoid the waste management issue and resource depletion problems and this trend of preferring recycling over other waste treatment options is now a part of EU waste management policies (European Commission 2005).

1.3. Country Situation – Denmark

In Denmark, waste generation is increasing continuously with a constant upward trend. From 2000 to 2008, total waste has increased from 13 to 15.6 million tons (20%). Similarly, waste management has also improved in Denmark as in 2008; the amount of waste being recycled has increased. On the other hand, amount of waste going to landfills has decreased. Figure No. 1.3 is showing the waste generation patterns from different sectors, whereas Figure No. 1.4 is showing the waste management options from 1994 to 2008 in Denmark (European Environment Agency 2010b).

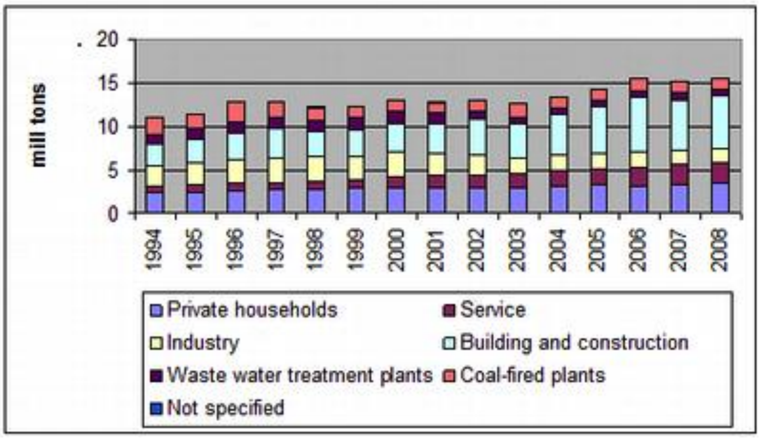

Figure No. 1.3: Development of waste generation in Denmark from different economic sectors (European Environment Agency 2010b)

The above figure shows the composition of solid waste and it is clear that the waste from building and construction industry constitutes the highest amount of this waste in total. The second highest amount of waste comes from the private households and the waste from service sector ranks at third position.

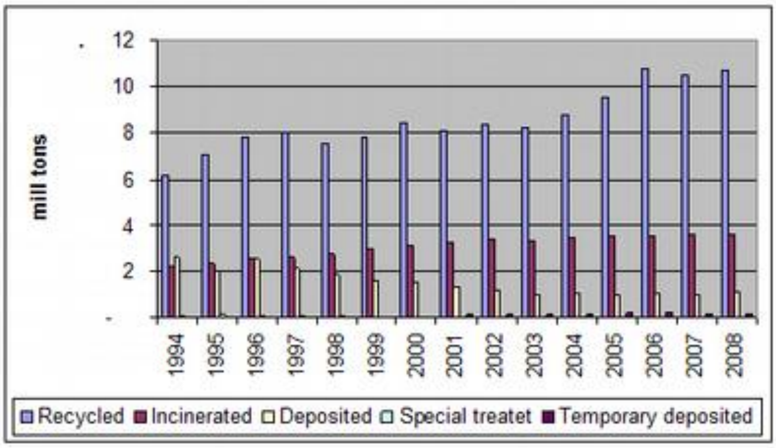

Figure No. 1.4: Waste Management in Denmark (European Environment Agency 2010b)

The above Figure No. 1.4 shows very clearly that recycling is the most common practice in Denmark and has increased overtime. Incineration is the second best waste management option in Denmark as heat and electricity is produced from this process. On the other hand, solid waste going to landfills has significantly decreased over the last years from 1994 to 2008.

1.4. Energy Recovery from Waste

Waste hierarchy shows very clearly the preference order of managing the waste problem (See Figure No. 1.2). According to this hierarchy, landfill is the least priority option and energy recovery from waste stands one step higher than landfill in this hierarchy though less prioritized than recycling. The appropriate way of waste management is still a big concern regarding the difficult choice between recycling and incineration options embedded in strong political and socio cultural context of a country.

Throughout the world, the waste management and energy use sources and patterns are changing depending on the threat from global warming impacts. In EU and other developed countries, focus is mainly to shift from coal and oil based energy system to renewable energy systems to not only lessen the global warming impacts but also for the security of non-renewable resources. Waste is sometimes considered as a renewable fuel (Finnveden et al. 2005). MSW contains significant amount of energy that can be utilized using different waste management technologies.

According to Poulsen & Hansen (2009), the upper and lower fuel values of MSW vary from 18- 20 to 8- 12 GJ /ton. These amounts are equal to approximately two- third and one- third fuel value recovered from anthracite coal respectively. So, the old definition of waste where waste was considered as something not able to be used again has changed considering the high energy value of MSW. The theme of current report also takes its point of departure from here considering the fuel value of MSW. The point of focus in current report will be to look into the historical development of waste management plans and strategies and treatment options depending on the latest technology available during all the time periods from 1970 onwards and then to see the overall GWP_{100} from this MSWM in different time periods from 1970 onwards in Denmark by putting more emphasis on the case study of Aalborg Municipality.

1.5. Life Cycle Assessment (LCA) in Waste Management

Life Cycle Assessment can be described as evaluation of environmental impacts throughout the life cycle of a product. This approach is beneficial in terms of improving the environmental conditions such as resource use and environmental burdens at different stages of a product manufacturing. Life Cycle Assessment has been extensively used in comparison of different waste management options all over the world to decide about the best management practice and also to improve the existing waste management practices.

The EU policies also support and recommend the use of LCA as the basic aim of EU policies is to ensure the resource security by carefully handling the waste issue. Although EU stressed on following the waste management hierarchy in its Directive 2008/98/EC but in addition, it also suggests taking the measures that result in best environmental conditions justified by LCT (European Commission 2008). As described earlier (See Section 1.2), the 3 billion tons of solid waste produced every year by the European inhabitants not only leads to different environmental problems such as pollution and global warming but also ends up in resource depletion. Policies and legislation in EU stress upon the efficient use of resources, so that the amount of waste generated every year can be reduced. Although the European Commission stress on following the waste management hierarchy, but the waste management policies in different EU countries depend on local conditions, e.g. in some countries incineration is the most favorable option like in Denmark but on the other hand in UK, landfill is preferred over incineration. Here, the LCA can have a great role to develop a policy based on proper scientific evidence to facilitate the sustainable waste management according to the waste hierarchy.

In the current report, use of LCA will help to sort out the best available MSWM technique in different time periods from 1970 till now considering the fuel value of this waste.

1.6. Problem Formulation and Research Questions

The current report will focus on MSWM in Aalborg as MSW is the most difficult waste stream to manage not because of its quantity but due to its complex composition for example kitchen waste, yard waste, paper, plastic, glass, waste from institutions and construction sites etc. Due to its mixed and complex nature, in many countries MSW is landfilled to avoid the complications. But due to landfilling of this waste, the fuel value of MSW is not recovered at all and hence the pressure on fossil fuels is increasing all the time based on ever increasing population growth and rapid industrialization.

In Denmark, incineration has been a very popular waste management practice from 1903 as at that time availability of landfill places was a big problem. From that time onwards, incineration has a share in national energy production. On the other hand we see a constant change in energy picture of Denmark shifting from fossil fuel based power plants in 1970s and 1980s to more and more renewable energy production such as windmills in current age. According to the 2009 Energy statistics, 27.4% of the Danish domestic electricity supply comes from the renewable energy sources. Following Figure No. 1.5 is showing the renewable energy production from different sources during 1980 – 2009. It is clear from the figure that over the time waste consumption for energy production has increased up to 149% from 1990 to 2009 (Danish Energy Agency 2009).

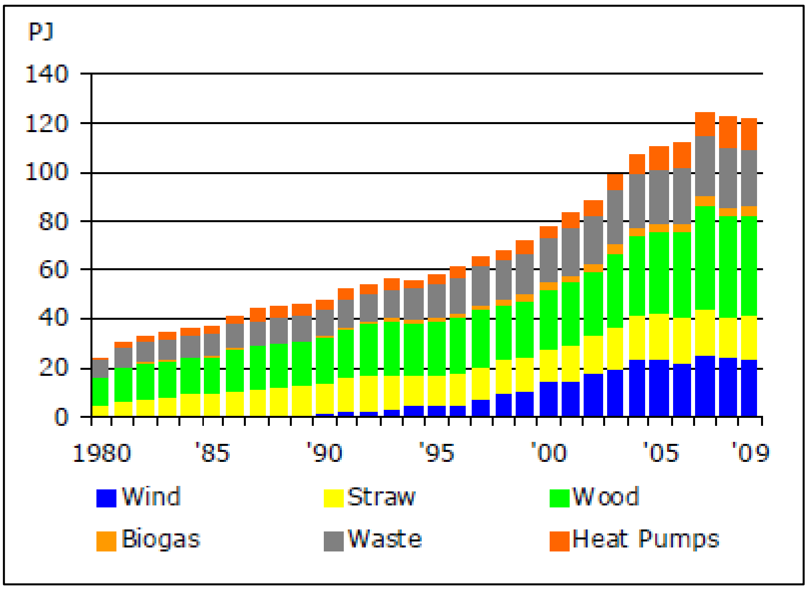

Figure No. 1.5: Production of Renewable Energy by Renewable Energy sources in Denmark from 1980 – 2009 (Danish Energy Agency 2009)

The above figure related to role of waste consumption for energy production reveals the importance of waste for its fuel value. In 2009, the total renewable energy production was noted as 121.6 PJ, out of which wind power share is 24.2 PJ and the share of energy produced from waste is 22.7 PJ. Out of this total renewable energy, highest amount is produced from biomass such as only wood is responsible for 40.8 PJ of renewable energy out of 121.6 PJ. Following is the more detailed figure explaining the growth of waste consumption for energy production:

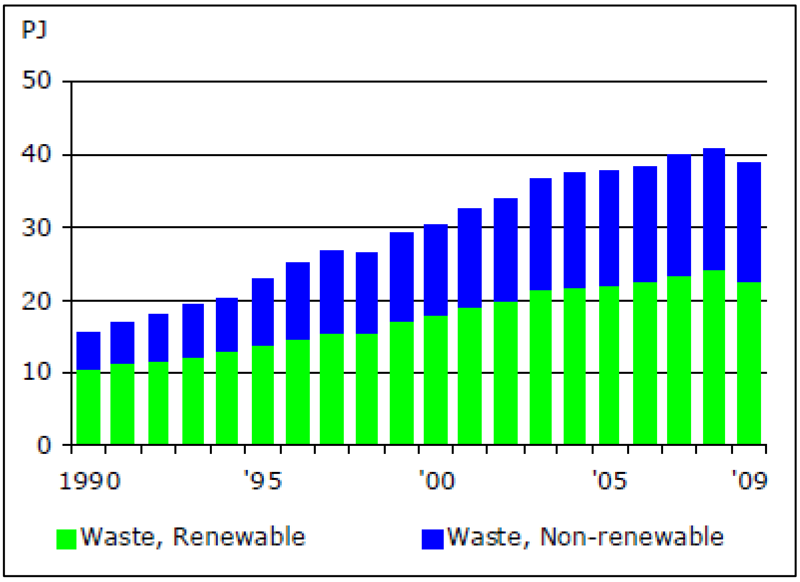

Figure No. 1.6: Energy produced from Waste from 1990- 2009 (Danish Energy Agency 2009)

The above figure reveals that the consumption of waste for energy production has increased from 15.5 PJ in 1990 to 38.6 PJ in 2009, which shows an increase of 149% in energy produced from waste. Now we see that renewable energy especially the waste has a significant role in overall energy picture of Denmark. But it is worthwhile to see that which factors actually initiated the use of waste for energy production in 1980; either it was fossil fuels deficiency, the overwhelming climate change and global warming problem or the issue of waste management. So, these overarching questions make the base of my report. To know the environmental burden of different waste management practices from 1970 upto now, LCA will be used as an assessment tool.

There have been many studies where LCA has been used as a decision making tool in order to identify the most environmentally favorable waste management option (Eriksson et al. 2007; Finnveden and Ekvall 1998; Finnveden et al. 2005). LCA studies have also been made in order to compare different renewable energy options and more specifically a comparison of energy produced from waste and other renewable energy sources. Poulsen & Hansen (2009) also did a study focusing on development of waste management technologies from 1970 and their impact on global warming considering the fuel value of this waste in Aalborg. But in this study, they have assumed the same waste composition throughout history from 1970 till 2020; though we are aware that the waste composition has always been changing. As a result, following major issues rise on which the current report will focus:

1. Tracing the change in fractions of MSW from 1970 up to now
2. Co- relation of Waste management policies with the ever changing waste management options and technologies from 1970 till now
3. Role of LCA in comparing different MSWM options (described in waste management hierarchy) from 1970- 2020 regarding global warming by taking the fuel value of this waste into account

These issues lead to the formulation of following main research question to be dealt in the current report:

What is the Global Warming impact of MSWM options having main focus on ''Waste to Energy'' in Aalborg Municipality from 1970 to 2020?

To answer this main research question, two sub questions have been formulated in order to get more insight and outcome of the main research question. These two sub questions are as follows:

1. How the waste management strategies in Denmark especially in Aalborg have developed regarding waste handling and treatment options over time from 1970 up to now?
2. What is the GWP_{100} from MSWM in Aalborg from 1970 – 2020 considering the technological development regarding waste management?

Following table is giving a brief overview of working questions and outcomes related to both sub questions:

Table No. 1.1: Research Questions with Working Questions and Expected Outcomes with their Chapter of Appearance

Research Question	Working Questions	Outcomes	
How the waste management strategies in Denmark especially in Aalborg have developed regarding waste handling and treatment options over time from 1970 up to now?	What is the pattern of changes in waste generation and regarding treatment methods during this time? What was the main focus area of these plans and strategies?	History of waste management plans in Denmark and Aalborg Resource management ways from waste in different periods	**Chapter 3 & 4**
What is the GWP_{100} from MSWM in Aalborg from 1970 up to 2020 considering the technological development regarding waste management?	What kind of data is required to make a comparative LCA study of waste management in different time periods? How the incineration technology regarding its efficiency and APC system has developed over time? What about the vehicular emissions and fuel consumption by transport sector from 1970 upto now?	Complete picture of GWP_{100} from MSWM in Aalborg from 1970 – 2020 Future perspectives for waste management policy development	**Chapter 5 & 6**

1.7. Contents of Report

Contents of the current report are given as follows:

- **Chapter 2** presents the theoretical and methodological framework of current report.
- **Chapter 3** gives an overview of historical development of ‘’waste to energy’’ phenomenon and waste management plans & strategies in Denmark from 1970 up to now.
- **Chapter 4** describes the case study of Aalborg Municipality regarding the city profile, history of local waste management plans, waste and energy situation.
- **Chapter 5** is LCA of MSWM options from 1970- 2020 in terms of global warming considering the fuel value of this waste.
- **Chapter 6** will present the results of LCA study and try to give the complete picture of global warming rising from waste management throughout the history.
- **Chapter 7** concludes the report by presenting the most important findings.
- **Chapter 8** describes the Perspectives about future.

2. Theory and Methods

The aim of this chapter is to provide the theoretical and methodological framework of the current study to present the analysis of how the chosen theory fits with the chosen methodology.

2.1. Theoretical Framework

2.1.1. Waste Management Hierarchy and Global Warming

Global warming and its impacts are the major concern of current era all over the world and solid waste also has its share in global warming. The greenhouse gas emissions arising from the waste management activities are approximately 1.3 Gt of CO_2eq and nearly 3- 5% of the total anthropogenic emissions according to 2005 statistics (IPCC 2007a). Waste Management hierarchy also reveals that the order of preference between different waste management options is supported by their global warning potential respectively.

Landfill is placed at the base of waste management hierarchy, as it is the least preferred option. Considering the Global warming impacts, CH_4 arising from landfills and wastewater only is responsible for 18% of anthropogenic CH_4 emissions globally in 2004 (Bogner et al. 2008). In developed countries CH_4 emissions are decreasing progressively because of increased landfill CH_4 recovery, less land filling and less waste production due to more recycling and incineration. On the other hand in developing countries of especially east and south Asia, CH_4 emissions are expected to grow upto 50% from 1990 to 2020 due to high rates of population growth and urbanization (US EPA 2006).

With the technology advancements, now it is possible to decrease the GHG emissions arising from landfill by recovery of landfill gas, increased recycling and incineration. But these mature technologies depend on a number of different factors such as local and national driving forces for waste management and global warming mitigation (Bogner et al. 2008). The recovery and use of landfill gas as a renewable energy first came to light in 1975 and is practiced now a days in approximately 1150 plants all around the world with reduction of more than 105 Mt CO_2eq per year (Bogner and Matthews 2003; Willusmen 2003). For the EU- 15 alone, CH_4 emissions from landfill have decreased by nearly 30% from 1990 to 2002 mainly due to the implementation of Landfill Directive 1999/31/EC and by 2010, GHG emissions from waste in EU have decreased by 50% considering the 1990 levels (Deuber et al. 2005; EEA 2004).

Landfills are not only the source of CH_4 but they are sink for carbon as well in long term perspective (Barlaz 1998). All the organic carbon landfilled is not converted into CH_4 but some of it (nearly 50%) is stored in landfill due to the reluctant nature of cellulosic fractions to natural decomposition. This makes the landfills as a potential competitive alternative considering the GWP_{100}, especially in conditions where landfill gas is used as energy source (Flugsrud et al. 2001). But the carbon fraction stored can vary depending on the composition of waste and landfill conditions (Hashimoto and Moriguchi 2004).

According to waste management hierarchy, *Incineration* is the next preferred option to landfill. Incineration is very useful waste management option as it reduces the amount of waste and in return heat is produced which can be used as electricity or district heating ultimately resulting in less fossil fuel burning and less global warming. Although the GWP_{100} from waste incineration has decreased but still a little amount of CO_2 escapes in environment contributing to global warming (Consonni et al. 2005). For EU- 15, CO_2 emissions from waste incineration are approximately 9 Mt CO_2eq per year and globally this amount is 40 Mt CO_2eq per year (EIPPC Bureau 2006). Incineration rates are high in European countries due to the Landfill Directive 1999/31/EC , limited landfill place and also because it is evident that waste incineration cause less global warming as compared to land filling of waste.

Recycling of waste is placed higher than incineration and land fill because it reduces the need for production of virgin materials and ultimately leads to less GHG emissions due to the avoided production. Although there is energy required for recycling purpose as well but it is still lower than the energy required to produce the virgin materials; hence proving recycling as the appropriate waste management option (ISWA 2009).

Reuse and reduce stand at the highest level in waste management hierarchy as reuse delays the release of GHG emissions to environment and finally postpones the global warming impacts. Reduction or avoidance of waste generation is at the top of waste hierarchy as avoiding the unnecessary waste decreases the demand of producing virgin materials and in return it reduces GHG emissions arising from every life cycle stage of virgin materials production, use and disposal. Finally, waste hierarchy is not only favorable to manage the waste issue in a sustainable way but also to combat the challenge of global warming and its impacts.

2.1.2. Energy Recovery from waste and Global Warming

Municipal solid waste is a significant source of renewable energy and this energy can be utilized by a number of different ways such as incineration, recovery of landfill gas, industrial co combustion and biogas produced as a result of anaerobic treatment of waste (ISWA 2009). As far as waste hierarchy is considered which will be followed and analyzed throughout the report, only incineration[2] and recovery of landfill gas are direct means of renewable energy based on their fossil or biogenic carbon content[3].

According to ISWA (2009), 1400 PJ of energy was produced from post- consumer waste in 2006, which can be a sufficient amount of energy for 14 million EU citizens (average consumption 100 GJ per year). Some of the waste projection studies (Monni et al. 2006) show that if some new policies and economic incentives are established now for waste management; then by 2030, energy derived from waste at global level can be sufficient for 130 million EU citizens as the total waste derived energy in 2030 will increase upto 13, 000 PJ. If we put focus on specific waste management techniques then by only incineration, 1000 GJ of electricity is produced per year from 130 million tons of waste being incinerated at more than 600 *waste to energy* plants all over the world. Likewise, the landfill gas recovered is also used for heating and electricity purposes depending on the amount of CH_4 in it as this gas has CO_2 and some trace elements that need to be removed before its use as a substitute to natural gas. These practices also lead to significant reductions in GHG emissions from the avoided burning of fossil fuels.

In Denmark, history of energy recovery from waste is very old as the first incinerator was built in 1903. At that time, the purpose of incineration was just to burn the waste but later it became a significant source of energy in 1980s (See chapter 3 for detail). The current report also focuses on solid waste management in Denmark especially energy recovery from the incineration process. Life Cycle Assessment approach will also be used in order to quantify the global warming impacts form waste management options after following the waste hierarchy.

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[2] Incineration will be considered as non- renewable energy source if plastic or other waste fractions having ‘’fossil C content’’ are incinerated.

[3] Biogenic C content is considered as responsible for no GWP_{100} in LCA.

2.1.3. Is Global warming the appropriate indicator for waste management?

Indicator is a very useful tool to communicate the scientific results to the non-scientific community as they change the very complex phenomenon and results into simple and easy to understand results. In environmental research, indicators can be used for different purposes such as comparison of environmental performance of different products or processes, identification of improvement potentials and as a decision support tool. So, for decision making process indicators should be understandable and relevant (Merrild 2009).

For LCA studies, indicators can be of two types:

1. Mid-point indicators: *A midpoint indicator can be defined as a parameter located on the impact pathway at an intermediate position between the life-cycle inventory results and the ultimate environmental damage e.g, global warming or acidification* (Jolliet et al. 2004).
2. End-point indicators: *Endpoint indicators express the damage at the end of the cause-effect chain, e.g. damage to the natural environment and damage to human health* (Merrild 2009).

Use of multiple indicators makes the decision making process very complex as then the decision makers or the researchers have to use the weighting factor in order to compare the significance of different indicators. On the other hand using only one indicator such as global warming makes the results even simpler, easy to understand and ready to be used for decision-making process (Merrild 2009). In many LCA studies related to waste management, only global warming has been used as an indicator because it provides some advantages over other indicators such as:

1. Global warming indicator has a higher comparability rate across different impact assessment methods as the categorization methods are based on the GWP_{100} by IPCC (2007b). This shows that whichever assessment method is used, the results should be the same for assessments of the same inventory data. Other indicators are more difficult to compare according to different impact assessment methods because they use different characterization methods (Merrild 2009).
2. Global warming indicator is analyzed on a global level, so it can be used as a general impact category but the other indicators such as ozone depletion, acidification,

eutrophication etc are analyzed at a more local or regional level. This is shown in the table below:

Table No. 2.1: Environmental impact categories included in EDIP 97 method (black) and other relevant impact categories (light blue)

	Environmental Impacts	Resource Consumption	Other related impacts
Global	• Global Warming • Ozone Depletion	• Depletion of non-renewable resources	
Regional	• Photochemical ozone formation • Acidification • Nutrient enrichment • Ecological toxicity • Human toxicity	• Depletion of renewable resources at regional scale	• Radiation
Local	• Ecological toxicity (acute) • Human toxicity (acute) • Waste • Damage to the seabed • Land use	• As above but local scale	• Occupational H&S • Animal welfare • Noise • Odor • Accidents • Aesthetics • Radiation

Source: Thrane and Schmidt (2007)

For waste management options, global warming is the important indicator for one more reason, as waste is a significant source of renewable energy such as energy can be recovered by incineration process and through the landfill gas recovery. It ultimately affects the picture of global warming coming from fossil fuel's energy. For all these reasons, it has been decided to analyze only global warming indicator in this report.

2.1.4. How Life Cycle Thinking, Assessment and Management help in Reducing GWP_{100}?

"Life cycle thinking(LCT) implies that everyone in the whole chain of a product's life cycle, from cradle to grave, has a responsibility and a role to play, taking into account all relevant external effects''.(UNEP 2003). Hence it becomes clear that the role of manufacturing industries does not starts at just getting the raw materials and does not ends at just producing the goods, but their role extends to ensure the environment safety throughout the product

chain from raw material extraction to the disposal of goods. The whole life cycle of a product can be explained in the following figure:

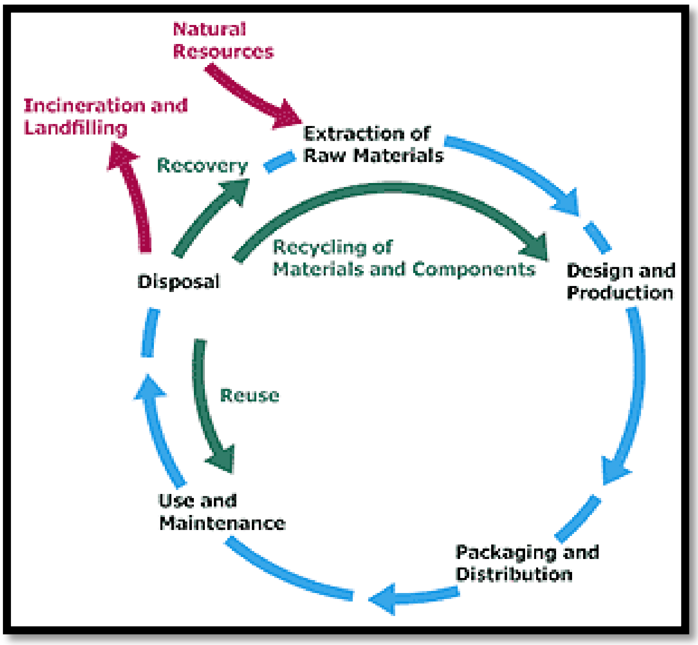


Figure No. 2.1: Life Cycle of a product (UNEP 2007)

The above figure also clears one of the big misunderstandings about LCT that life cycle of a product ends with the disposal but on the other hand here starts another life cycle thinking approach starting when the goods become waste until their sustainable end solution such as recycling, incineration etc and hence the life cycle thinking goes on. The overall difference between the product life cycle and waste management life cycle can be explained with the help of following figure:

Product Life Cycle

Raw Material Acquisition	**Production**	**Use**	**End of Life Treatment**	**Recycling**	**Disposal**

Waste Management Life Cycle

Collection	**Treatment**	**Final Disposal**

Figure No. 2.2: Product Life Cycle and Waste Management Life Cycle (Merrild 2009)

In the above figure it is clear that waste management life cycle starts when product life cycle ends by turning product into waste. The overall situation where both, product life cycle and waste management life cycle merge is explained in the following figure:

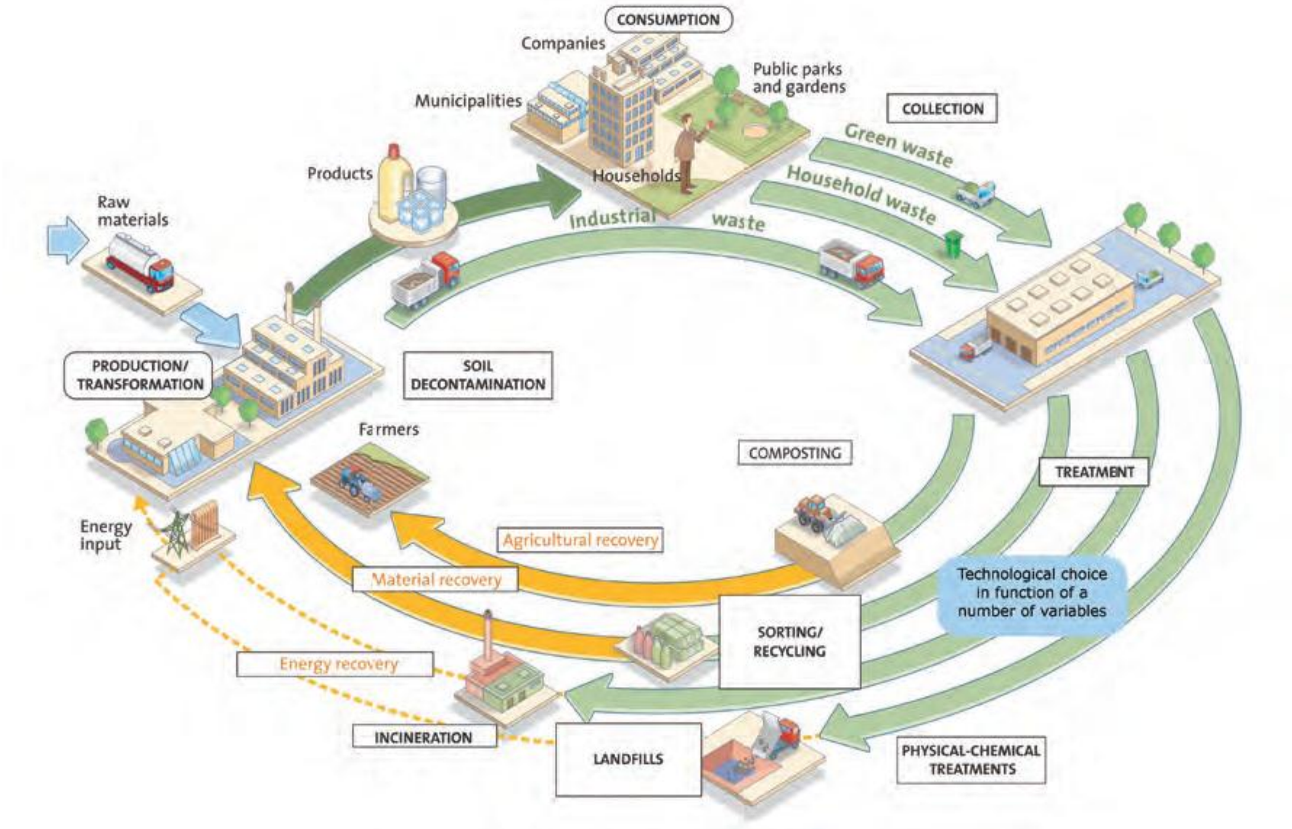


Figure No. 2.3: Integrated solid waste management approach (ISWA 2009)

The above figure not only describes the combination of product life cycle and waste management life cycle but also it focuses on the choice of waste management technology and resulting situation as in case of recycling, material is recovered and in case of incineration, energy is recovered.

Life cycle thinking, assessment and management in case of waste management helps to identify the global warming hotspots using different waste management techniques according to waste management hierarchy and ultimately supports in evidence based strategy formulation. This waste management strategy based on LCT and LCA will pave the way for

LCM i.e. efficient management of loopholes at source identified by the LCIA approach ultimately resulting in less global warming in future.

2.2. Use of Research Strategy and Theory

2.2.1. Waste Management Plans and Strategies Analysis

The main purpose of this section is to present the research strategy and theory for *Waste Management Plans and Strategies analysis* to answer the sub question 1 (See Section 1.6). The objective behind the analysis of waste management plans and strategies in Denmark and particularly in Aalborg is to go back in history and try to find in what ways the waste management strategy in Denmark has developed from time to time from 1970s till now. The purpose is also to see the factors behind these strategies and also the relation between the waste management hierarchy and waste management strategy.

The research strategy used to answer this research question is *qualitative research* as for this purpose qualitative data is used and *inductive theory* is used as it allows the researcher to develop some ideas and concepts about the case study and then conclude in some theory or statement (Bryman 2008). Using the inductive theory, researcher first observes the realities around him and the pattern of their occurrence. After this exercise the researcher is able to develop some hypothesis ending in a valuable theory or the findings are fed back into stock of theories.

2.2.2. LCA

Life Cycle Assessment is the approach to assess the environmental burdens of a product during its entire life cycle including raw material extraction, processing, distribution, use and final disposal (ISO 14040 2006) (See Figure No. 2.1). As a result of LCIA study, different potential environmental impacts can be assessed such as global warming, ozone depletion, nutrient enrichment and acidification (ISO 14040 2006).

LCA is chosen as the tool to answer the sub question 2 to reach the outcomes (See Section 1.6). The research strategy used for this research question is *quantitative* as it deals with the quantification of global warming impacts from different waste management options in different time periods and for this purpose numerical data is used. The theory used for this section is *deductive theory* as the purpose of LCA study in current report is to check the validity of theory of waste management hierarchy regarding different waste management options during different time periods from 1970 - 2020. This theory allows the researcher to deduce a hypothesis based on some observations or findings, that is then subjected to empirical scrutiny (Bryman 2008).

2.3. Methodological Framework

2.3.1. Data Collection

As describes in Section 1.6, the main research question has been further divided into two sub questions. To answer the first sub question related to analysis of waste management plans and strategies, qualitative data has been collected from the following two correspondents:

1. Søren Dalager – Consultant at Rambøll, Copenhagen
2. Dorte Ladefoged – Civil Engineer at Aalborg Municipality

Furthermore, the policy documents by Danish Government and Aalborg municipality have been analysed. To answer the second sub question, quantitative data has been obtained from the following correspondents:

1. Thomas Lyngholm – Environmental Manager at Reno Nord, Aalborg
2. Dorte Ladefoged - Civil Engineer at Aalborg Municipality
3. Tjalfe Gorm Poulsen – Associate Professor at Department of Biotechnology, Chemistry and Environmental Engineering, Aalborg University

Moreover, the scientific articles have been consulted in order to get the appropriate data to perform the LCA study.

2.3.2. Types of LCA

There are two basic kinds of LCA described as follows:

1. Process LCA – is a bottom up approach. It applies cut off criteria and for that reason, it must be decided to whether include aspects such as capital goods, services, business travelling or some less significant inputs from feedstock (Thrane and Schmidt 2007).

2. Input Output LCA – has its roots in the field of economics where it deals with links between industry sectors and households from a national economy perspective in the

form of supply and demand of goods and services, capital development and exchange of income and labour as well (Finnveden et al. 2009).

For the current study Process LCA is used. Moreover in the current report Consequential modelling is used which avoids the cut off criteria by system expansion (See Chapter 5).

2.3.3. Structure & Components of LCA

LCA has a wide range of application areas such as product development and improvement, strategic planning, marketing and public policy making. So, it cannot only be used at company level but also at policy and sector level by NGOs and other organizations. When it is used at company level, it is primarily for specific products, while at societal level, it is more generic in its purpose e.g. for societal action plans and legislation. LCA can be further divided into two types depending on its intended application e.g. It can be used just for documentation purpose as a response or demand from different stakeholders. It can also be used for strategic purpose for policy making (Thrane & Schmidt 2007).

According to ISO 14040 (2006), LCA study includes four phases as illustrated in Figure 2.4, the detail of these phases is given in the following section.

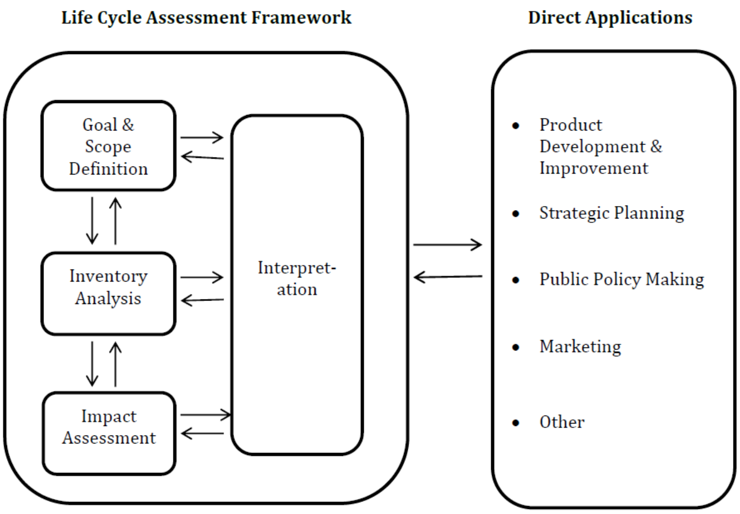


Figure No. 2.4: Life Cycle Assessment Framework and its Application Areas (ISO 14040 2006).

2.3.4. Phases of LCA

2.3.4.1. Phase 1: Goal & Scope

In the 1st phase of LCA purpose of study, definition of functional unit, system boundary, cut off criteria, co product allocation, an overview of applied methods (impact categories, method for impact assessment and key assumptions), the relevant processes such as system boundary are described. For System delimitation two methods can be used i.e. consequential and attributional modelling. The main difference between both modelling approaches is given below in Table No. 2.2.

Table No. 2.2: Differences between Consequential &Attributional Modelling

Feature	Consequential modelling	Attributional modelling
Nature of the approach to modeling	Attempts to predict to responses to a change in demand	Describes how existing production is taking place
Included processes / suppliers	Marginal (i.e. actual affected supplier)	Average of present suppliers
Co – product allocation	Co – product allocation is avoided by system expansion	Co – product allocation is most often treated by using allocation factors, and in some cases system expansion may be applied

Source: Schmidt 2007 & based on Weidema 2003

2.3.4.2. Phase 2: Life Cycle Inventory

Second phase of LCA study describes data collection, calculation, data quality assessment and finally handling of co- product allocation. Data collection may be the collection of both kinds of data e.g. qualitative and quantitative, and it is probably the most time consuming job. For calculation purpose data is validated and related to the functional unit defined in Goal and Scope of study. Data can be verified for its accuracy by different data triangulation methods. Finally life cycle inventory is developed with a complete inventory of elementary flows, which is then used as an input for the third phase of LCIA. In inventory phase, handling of co product allocation can be a key challenge because sometimes one unit process delivers more than one product.

2.3.4.3. Phase 3: Life Cycle Impact Assessment

Life cycle impact assessment phase includes characterization and valuation. In characterization, Life Cycle Inventory results in different impact categories. Whereas in valuation, two steps are carried out i.e. normalization and weighting (See Section 5.3). Normalization is basis for comparing categories by dividing the points to some normalization reference. Weighting step is the evaluation of the relative importance of each impact category. Normalization and Weighting both are optional (Thrane and Schmidt 2007).

2.3.2.4. Phase 4: Interpretation

The interpretation is the final phase of LCA study. It includes the presentation of results, critical reflection about the study, sensitivity analysis and evaluation of results. At the end, key results are described and discussed on the basis of consistency, completeness and sensitivity analysis (Thrane and Schmidt 2007).

3. ‘’Waste to Energy’’ in Denmark

The aim of this chapter is to present the historical development of ‘’incineration’’ in Denmark as the focus of this report is ‘’Waste to Energy’’. Moreover, a brief history and comparative analysis of waste management plans and strategies in Denmark will be presented which will help to answer the 1st research sub question.

3.1. History of ‘’Waste to Energy’’ in Denmark

During 1850s, increasing population and growing urbanization in Denmark led to strong emphasis on urban sanitary conditions in control. An act from 1858 demanded that all the provincial towns in Denmark should adopt the sanitary regulations. This led to the present system in which all the municipalities take care of their sanitary conditions such as water supply, sewerage and solid waste management. In the same time, Denmark built its first gas works. By the end of 19th century, the first electricity works were constructed and municipalities owned these both systems. Later, district heating was also a big municipal task and these all activities were named a joint term called ‘‘The municipal works’’ (Dalager 2006, 2011).

By 1900, all the waste collected was going to landfills, and sometimes it was burnt as well at the end of the day. In the meantime, the availability of places for landfills became a problem as in Frederiksberg; an enclave located in the middle of Copenhagen had not a single available site for landfill. As a result, the municipality of Frederiksberg built the first waste incineration plant in Denmark in 1903 (Kleis et al. 2003). Figure No. 3.1 is showing this first incinerator in Denmark.

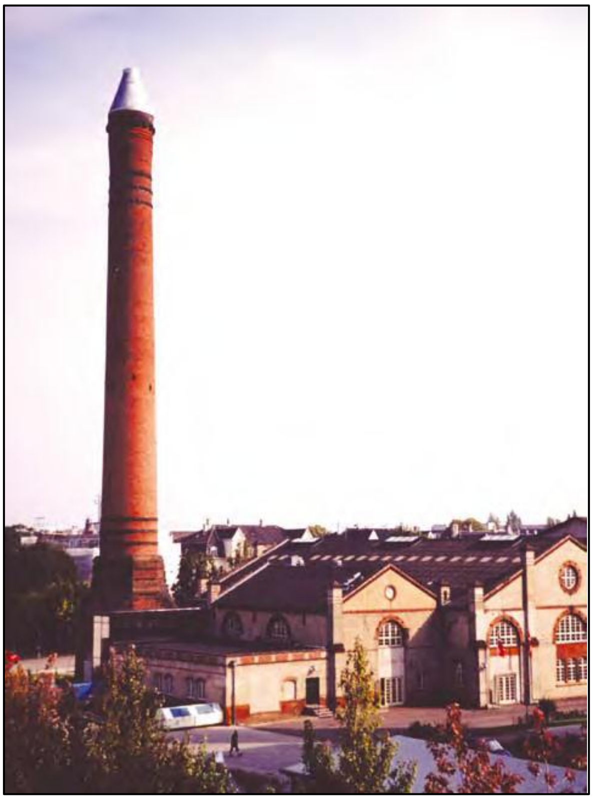


Figure No. 3.1: Denmark's first Incineration plant in Frederiksberg in 1903 (Dalager 2006; Kleis et al. 2003)

The energy generated during the process of incineration was used for the production of both heat and electricity and the heat produced was sold to a nearby hospital. In this way, Frederiksberg also became the first municipality in Denmark to establish a district heating system. Before the Second World War, there were 3 incineration plants in Denmark with energy recovery. During the war and the immediate after war years delayed the further development in the waste incineration field, but in 1960s it was started again. At that time, the economy of Denmark was improved and the women started working as labor. This development resulted in changed family patterns and also had an impact on the waste composition as people became more affluent. It was the time when, Denmark became a 'use-and-throw-away' society, and this changed the waste composition patterns dramatically (Dalager 2006, 2011).

This economic growth resulted also in large number of newly built towns and the main focus at that time was to provide these areas with district heating system instead of having an oil burner in every house. Growing environmental awareness and concern in public also supported this solution as by this way waste was also handled in an appropriate way ending in energy recovery. So, in 1965 the first inter-municipal companies were established with the aim of building and operating an incineration plant for the burning of waste generated in the owner municipalities (Dalager 2006).

‘’Waste to Energy’’ phenomenon got more encouragement in Denmark when the first oil crisis happened in October 1973. At that time, 92% of Denmark’s total energy consumption was dependent on oil. Thus the oil crisis came as a shock to the country, and a strong focus developed on making a long-term energy policy. The power stations were asked to reconvert to coal firing, and big district heating transmission networks were built to ensure the maximum possible use of the surplus heat produced at the local power stations. This new energy policy proved a plus point for incineration plants as well because now it became easy for them to sell district heating. After the introduction of oil and coal taxes, the incineration plants got economic benefit as well because they could demand higher heat prices correspondingly due to lack of any tax. As a result, the number of incineration plants got higher upto 48 in 1982 (Dalager 2006, 2011).

During the late 1980s, the greenhouse gas effect got high political attention and focus, which resulted in encouragement of cogeneration of heat and power in 1990. As a result, municipalities who were having district heating and incineration plants were asked to convert to combined heat and power production plants. Today, Denmark has a total of 29 incineration plants with modern incineration technology capable of converting the waste to heat and power according to the environmental requirements such as EU Waste Incineration Directive 2000 (Dalager 2006).

3.2. History of Waste Strategies in Denmark

The main purpose of this section is to give a baseline narration of all the Government strategies, action plans and policies related to waste management in Denmark from 1970s onwards. This interpretation will especially focus on development of waste management plans depending on waste handling and treatment options from 1970 upto now. Finally the section will present a comparative analysis of different waste management plans in a tabular form and the marginal energy source in the respective time period.

3.2.1. Waste Strategies from 1970 – 1987

During the early 70s, the issue of handling the toxic chemical's waste was highly discussed and it got the attention of Government as well. This resulted in the formulation and promulgation of ''Law on Toxic Chemicals'' in 1972. The main focus of this law was to devise ways to carefully collect this waste to avoid any accidental damages. During the same period a Danish company named '' Kommunekemi'' established, having such treatment plants that could treat highly toxic waste. Later in 1973, the Danish Environmental Protection Act came having a special section on waste. This act mainly stressed on establishing the Sanitary landfills as before that, the landfills were not having the impermeable lining to protect the waste water leaching into ground water. This act also focused on the requirement of Environmental permits by the operating companies of these landfills to assure that environment is not compromised in the whole process. The operating companies were asked to treat the leachate from landfills to avoid any kind of ground water pollution (Christensen 2011).

In 1982, the Act of 1973 was amended and a number of new provisions on waste management were introduced. The new rules were about the consideration of not only the collection system of waste and siting of new sanitary landfills, but also the arrangements and planning of various other waste stages such as transport, treatment and final disposal (including recycling). Later in 1983, the Chemical Waste Sites Act was formulated to provide the legal basis for cleaning up the old waste sites used for dumping of chemical waste upto 1976 (Ministry of Environment 1987).

3.2.2. Danish Waste Policy in 1987

Danish government's waste policy in 1987 had two main aspects to be focused upon:

1. Actions to repair damages in the past
2. To prevent pollution problems in the future waste management

Hence from the above two main aims of Waste Policy 1987, it becomes clear that at that time, Government was more focused to cover up the pollution problems made in the past due to land filling of waste having certain environmentally hazardous chemicals and also to make sure that in future such problems do not happen again. This policy stressed basically upon the issue of chemical waste sites both old and planning the new ones to avoid the future environmental hazards (Ministry of Environment 1987).

3.2.3. Action Plan on Waste and Recycling from 1993 – 1997

Danish Government action plan on waste and recycling from 1993 – 1997 (Danish Environment Protection Agency 1992) mainly strengthens the concept of waste management hierarchy and focus on the following specific areas:

1. Minimization of waste production and energy consumption through substitution and cleaner technologies.
2. Recycling or utilization: Recycling should be a preferred waste management solution than other treatment options.
3. Incineration: The waste that cannot be recycled should be incinerated to recover energy from it.
4. Controlled Landfill: Lowest priority should be given to landfill due to very scarce land and also for the reason that waste becomes totally useless in case of landfilling.

3.2.4. Waste 21

Waste 21 is referred to the Waste Management Plan 1998- 2004 by the Danish Environment Protection Agency. Waste 21 presented two important challenges to face in the coming years:

1. Improve the quality of Waste treatment
2. Stabilize the total waste amounts

This waste management plan stressed upon reducing the environmental impacts from different contaminants in waste through different treatment technologies as well as the better recovery of resources from waste by recycling and incineration. Waste 21 also shows strong commitment to separate different waste fraction in waste at the source such as organic waste, paper and cardboard, packaging waste, PVC, electronic equipment waste, end of life vehicles and discarded batteries. Moreover this plan also stresses on waste prevention (highest step in waste management hierarchy) by the implementation of cleaner technologies and integrated product policy (IPP)[4] formulation (Danish Environmental Protection Agency 1999).

[4] IPP seeks to minimize the environmental degradation by looking at all the phases of product's life cycle and taking action where it is most effective (European Commission 2010).

3.2.5. Waste Strategy 2005- 2008

Waste strategy 2005 - 2008 also focused on nearly same areas like Waste 21. The main stressed areas in this strategy are also preventing the waste generation at source, efficient resource recovery and improved waste treatment technologies. Along with these aims, this strategy had two more important focus areas which have been stressed upon:

1. Decouple the growth of waste from economic growth
2. Ensure cost effectiveness of environmental policies

These two aims reveal that in this strategy, the economic pillar of sustainable development is also considered along with environmental and social pillars on which the sustainable development is based. This waste strategy was an important element of Danish government strategy for sustainable development called ‘‘A shared future- balanced development’’ in 2002 (The Danish Government 2004).

3.2.6. Waste Strategy 2009- 2012

Danish Waste strategy 2009 – 2012 (Affalds strategi ’10 2010) has three main aspects as resource policy, climate policy and protection of environment and health. This strategy focuses mainly on the following 7 points:

1. We must prevent waste generation
2. We must reduce the loss of resources
3. We must reduce CO_2 emissions from waste treatment
4. We must reduce the overall environmental impacts from waste
5. We must ensure the effectiveness of environmental measures
6. We must increase the quality of waste treatment
7. We must ensure an effective waste sector

The above aims of waste strategy 2009 - 2012 reveal that preventing the waste generation at source is given importance because it not only reduce the pollution burden at the end of pipe but also prevents the loss of valuable resources. This strategy also focuses on reduction of CO_2 from waste management as it leads to global warming and other environmental problems.

3.2.7. Comparative Analysis of above described Waste Plans

All of the above described waste management strategies and plans by Danish Government reveal the evolution of waste management strategies based on enhanced knowledge and up to date technology available. As it is clear from the Waste management plans and policies in 1970s, that the main focus was to establish new sanitary landfills and handle the issue of toxic waste but later in the waste strategy of 1987, the only focus of Government was to repair the environmental damages happened in past and try to prevent these happenings in future. So, the focus was more on end of pipe solutions. But in the later policies, a clear change in mindset is shown when more emphasis is given to minimize the waste generation, recycling, incineration and controlled land fill.

The comparative analysis of focus areas and aims & objectives of Danish government waste management plans from 1970s till now is presented in Table No 3.1, where it clearly shows the evolution of waste management strategies from time to time.

No.	Waste Plan	Focus Areas	Aims & Objectives	Marginal Energy Technologies[1]	Waste Treatment technology in Aalborg[2]
1	Environment Protection Act 1973	• Sanitary Landfills • Environmental permits to operate these landfills	-	Oil	Landfill & Incineration
2	Waste Policy 1987	• Repair the past damages • Prevent pollution from future waste management	-	Coal PP	Incineration with heat recovery
3	Action plan for Waste and Recycling 1993-1997	• Follow waste management hierarchy	Recycling: 54% Incineration: 25% Landfilling: 21%	Coal PP	Incineration with heat & power recovery
4	Waste 21 (1998-2004)	• Improve the waste treatment quality • Stabilize the waste amounts	Recycling: 64% Incineration: 24% Landfilling 12%	Coal CHP	Incineration with heat & power recovery
5	Waste strategy 2005-2008	• Decouple the growth of waste from economic growth • Ensure cost effectiveness of environmental policies	Recycling: 65% Incineration: 26% Land filling: 9%	N gas CHP	Incineration with heat & power recovery
6	Waste Strategy 2009-2012	• Resource policy • Climate policy • Protection of environment & health	Recycling: 65% Incineration: 29% Landfill: 6%	N gas CHP	Incineration with increased heat & power recovery

[1] Source : Mathiesen et al (2009)
[2] Based on Scenarios for LCA (See Chapter 5)

Table No. 3.1: Comparative Analysis of Waste Management Strategies from 1973 up to present

The above described table presents the development of Danish waste management strategies from 1973 upto present based on different focus areas and aims & objectives from time to time depending on the ground facts. As described earlier in this section, the policies that emerged in 1970s and 80s were having a focus on end of pipe solutions for environmental protection. But in 1990s, the important development occurred in terms of policies addressing the pollution prevention problems rather than end of pipe solutions and from 2000 onwards, we see the policies focusing on LCT approach to address all the environmental problems; leading to cleaner products from cleaner production. Remmen & Thrane (2007) have also presented the shift in perception of environmental problems and respective shift in technology to address the problem in the following table:

	Perception of Environmental Problems	Causes mainly addressed	Solution approach	Actors involved	Danish Waste Policy Examples	Focus Areas
1960s ''Out of sight out of mind''	Smoke, noise and waste	Point sources	Dilution	-	-	-
1970/80s ''Environmental Protection''	Emissions	Industry and household	End of Pipe	Government	1. Environment Protection Act 1973 2. Waste Policy 1987	Sanitary Landfills Repair the past damages
1990s ''Pollution Prevention''	Resource use and emissions	Production processes	Cleaner production	Industry, NGOs and Government	1. Action plan for Waste and Recycling 1993- 1997 2. Waste 21 (1998- 2004)	Follow the waste management hierarchy
2000 ''Life Cycle Thinking''	Resource use, emissions and impacts from products	Consumption volume and patterns	Cleaner products	Consumers, Industry, NGOs and Governments	1. Waste strategy 2005 -2008 2. Waste Strategy 2009- 2012	Economic and environment sustainability Policy for resource use, climate, human & environment health (whole life cycle of product)

Originally inspired & modified from Remmen and Thrane (2007)

Table No. 3.2.: Change in Perception of Environmental Problems, Solution Approach & Actors involved (Grey columns show the Example of Waste Management Plans in Denmark)

The perception of environmental problems and the solution approach described in above table supports the comparative analysis of different waste strategies of Danish government from 1970s upto now. As described earlier, the 1973 Environment Protection Act was basically focused on cleaning up the old landfills and establishing the new sanitary landfills whereas in 1987 the waste strategy was addressing the issue of waste, and for both plans the solutions applied were end of pipe. But in the later strategies and waste management action plans in the 1990s, the problems addressed were efficient resource use and prevent the emissions; that's why the Action plan for Waste and Recycling 1993- 1997 and Waste 21 (1998- 2004) were suggesting the solutions like following waste management hierarchy and improve the treatment technologies. Later in the very recent strategy from 2009 – 2012, we can see that the problem addressed is resource use, climate and environmental protection and the respective solution approach suggested is ‘’ Cleaner products rather than cleaner production’’. This solution approach is supported with the help of even more stringent regulations to prevent any wastage of waste (resource) in landfills, increased recycling to avoid raw materials extraction and production and incineration to recover the energy from it to avoid the global warming from fossil fuel burning.

4. Case Study – ‘’Waste to Energy’’ in Aalborg Municipality

The aim of this chapter is to present the case study of Aalborg municipality regarding its history of waste management plans, current waste management situation and energy recovery from waste through incineration. This will lead to the Life cycle Assessment of Waste Management in Aalborg Municipality described in Chapter 5.

4.1. City Profile

Aalborg Municipality is the 3rd largest Danish municipality and lies in North Jutland of Denmark. According to 1st January 2010 statistics, it has a total population of 197,426. Its total area is 1,144 km^2 (City of Aalborg 2010). Aalborg Municipality consist of ten different cities namely Aalborg, Norresundby, Svenstrup, Nibe, Vodskov, Klarup, Gistrup, Storvorde, West Mountain and Frejlev. Out of these 10 cities in Aalborg Municipality, Norresundby is the largest city in North Jutland with a total population of 122, 461 according to 1st January 2009 statistics (Ladefoged 2011).

Aalborg Municipality is taking sustainability initiatives at local level and the current *sustainability plan* is a three years plan from 2008- 2011. This strategy has born through a dialogue process with industry, the agricultural sector, the fish farming sector, nature and outdoor organizations etc., due to the reason that collaboration with these stakeholders is compulsory if any of the strategy’s objectives are to be realized. This strategy has put forward some main objectives for the waste prevention in Aalborg Municipality (City of Aalborg 2008), such as:

1. The amount of industrial waste is to be limited by increasing preventive measures in industrial production.

2. Waste shall be collected, handled and processed in the optimum environmental and economic manner with the greatest possible utilization of resources.

3. It is important that the supply of drinking water can be secured on the basis of clean untreated groundwater of high quality, and vulnerable drinking water areas must be better protected against pollution.

4. All the municipal building construction (conversion and new development) must be carried out as low-energy building with integrated renewable energy supply from 2012 at the latest.

According to City of Aalborg (2010), Aalborg Municipality is connected with the following three municipal corporations for different waste management purposes:

1. Reno-Nord is an incineration company owned by Brønderslev, Jammerbugt, Mariagerfjord, Rebild and Aalborg Municipality. The company runs an incinerator, a landfill and a recycling plant for construction waste (See Section 4.4.1. for more detail).
2. Renovest is owned by Jammerbugt, Rebild, Vesthimmerland and Aalborg Municipality. The company operates a waste disposal center with several activities, including a controlled landfill. Renovest have agreement with Aars Heating Plant on the incineration of waste.
3. Mokana is a hazardous waste receiving station. The owners are a number of municipalities in North and Central Jutland, and furthermore Mokana has an association and cooperation agreement with the Greenland's 18 municipalities.

Aalborg Municipality has also made some commitments in order to achieve sustainable development called ‘’Aalborg Commitments’’. According to City of Aalborg (2005), in these commitments, a Responsible consumption and life style choice is an integral element. Under the heading of this element, some commitments related to waste were also made which are presented as follows:

Selected targets

1. Min. 65% re-use and recycling (R)
2. Max. 26% incineration (I)
3. Max. 9% deposited (D)

Action/results

1. R: 72.4 %
2. I: 17.4 %
3. D: 9.0 % (2003)

So, it is clear that the targets made by Aalborg Municipality regarding waste management are already met.

4.2. History of Waste Management Plans in Aalborg

In this section some of the old waste management plans by Aalborg municipality will be discussed regarding their aims and objectives to be dealt in the coming years. The earliest plan found is from 1989. These plans are given as follows:

4.2.1. Waste Plan 1989

Aalborg Municipality made a waste management plan in 1989 called ‘’ Affaldsplan 1989’’ (Aalborg Municipality 1989). The main objectives of this waste management plan were:

1. All the hazardous waste should be handled, transported and treated in an environmentally safe way.
2. The preferred order of waste treatment should be reuse, recycling and recovery.
3. Organic waste from houses, industry or institutions should be biologically treated to produce biogas.
4. The waste that cannot be recycled should be burned in incinerator (Reno Nord) considering the environmentally favorable options (smoke should be cleaned properly) and the waste is used at best to produce energy
5. The waste that cannot be recycled and incinerated should be landfilled in controlled landfills.

In all of the above described objectives of Waste Plan 1989, stress is given to follow the waste management hierarchy.

4.2.2. Waste Plan for Household 1996 – 2007

The waste management plan for household 1996 – 2007 (Aalborg Municipality 1995) had the following objective:

1. Aalborg Municipality will primarily work for household waste to ensure environmentally sound collection and processing with maximum resource utilization. The priority order for the waste treatment suggested is:
    a) Recycling

b) Incineration with production of electricity and heat
c) Land fill

4.2.3. Waste Plan 2000 – 2012

According to Ladefoged (2011), Waste Plan 2000 – 2012 has the following main objectives:

1. Aalborg Municipality will work towards an environmentally and economically favorable waste collection and processing system with maximum resource utilization.
2. Aalborg Municipality will work as a principle in favor of separation at source to ensure proper waste treatment and maximize recycling.
3. Aalborg Municipality will strive to introduce user friendly and compatible with future requirements waste systems, which can also be integrated architecturally in city's picture.

The preference order of treatment should be as follows:

a) Waste prevention
b) Recycling
c) Energy recovery from waste (Incineration)
d) Landfill

4.2.4. Waste Plan 2005 – 2016

Waste plan 2005 – 2016 has same main objectives to be dealt in the coming years like Waste Plan 2000- 2012. This Waste Plan is following the goals and objectives set by the National legislation regarding waste management such as Waste 21 from 1998- 2004 and Waste Strategy 2005 – 2008 (Aalborg Municipality 2004). In these two national plans, following main aims have been put forward for the year 2000, 2004 and 2008:

Table No. 4.1: Waste Management targets set in Danish Waste Plans

	2000	2004	2008
Recycling	54 %	64 %	65 %
Incineration	25 %	24 %	26 %
Landfilling	21 %	12 %	9 %

4.2.5. Waste Plan 2008 – 2016

Waste management plan in Aalborg Municipality is made for 8 years despite of the fact that waste strategy made by Danish Government is made for only 4 years. The current waste management plan by Aalborg Municipality is from 2008 – 2016 (Forsynings Virksomhederne 2007), focusing on the following general objectives:

1. Aalborg Municipality will work for environmentally and economically optimal collection and processing of waste with maximum resource utilization.
2. Aalborg Municipality as a principle supports source separation to ensure proper waste treatment and most possible reuse.
3. Aalborg Municipality will work to ensure that introduction of user friendly and according to the future demands waste systems suitable with the architecture in City's picture.

Basically, these objectives are incorporated in municipality's multi- sectoral task and thereby affect municipal institutions, citizens and businesses community leading to environment friendly behavior. Especially for this plan, the following objectives were formulated:

1. Aalborg Municipality will work to achieve a consistent level of service
2. Aalborg Municipality will work for more recycling and thereby reduce waste for incineration and Landfill

4.3. Waste situation in Aalborg

According to the waste statistics from Aalborg Municipality, in 2010 the total MSW was 127,377 tons. Out of this waste, 41,893 tons was residual waste (waste that is collected from households including kitchen waste, paper and plastic). The other fraction and their corresponding amounts are such as: glass bottles (2,822 tons), Cardboard and paper (10,688 tons), plastic (1 ton), bulky waste such as furniture (19, 964 tons), yard waste (20,465 tons), iron and metals (2,719 tons), electronic waste (1,379 tons), batteries (32 ton), old clothes (533 tons), PVC (89 ton) etc (waste from construction sites is not included) (Ladefoged 2011).

Following is the graph showing the waste generation pattern in Aalborg municipality from 1993 to 2010.

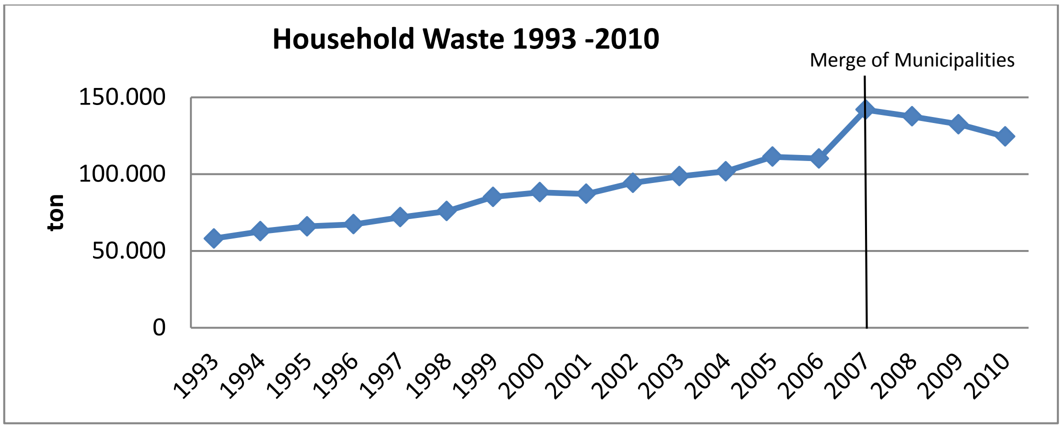


Figure No. 4.1: Waste Generation in Aalborg from 1993 to 2010 (Ladefoged 2011)

According to the above graph it is clear that from 1993 - 2006, there is a continuous and steady increase in waste generation in Aalborg municipality but in 2007, the waste increase is very rapid due to the merge of different municipalities. From 2007, the waste generation rate has decreased due to the worldwide economic crisis but still in 2010 it is higher than the amount of waste generated before the Municipality merge in 2007.

This waste is treated in three different ways i.e. recycling, incineration and land filling. According to the waste statistics 2010 of Aalborg, 39.45 % of this waste is recycled, 53.33% is incinerated and the rest 4.88% is land filled (See chapter 6 for the waste treatment technology for every MSW fraction). Following is the graph showing the waste treatment options for MSW from 1993 to 2009:

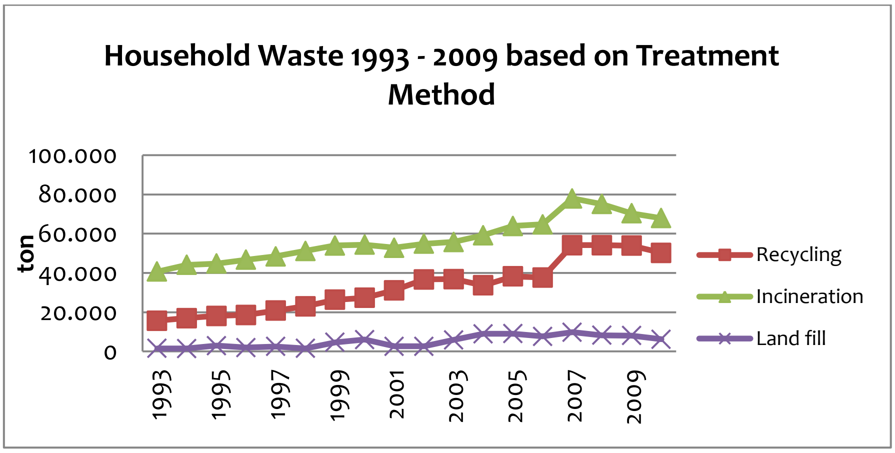


Figure No. 4.2: Household Waste Management from 1993 to 2009 (Ladefoged 2011)

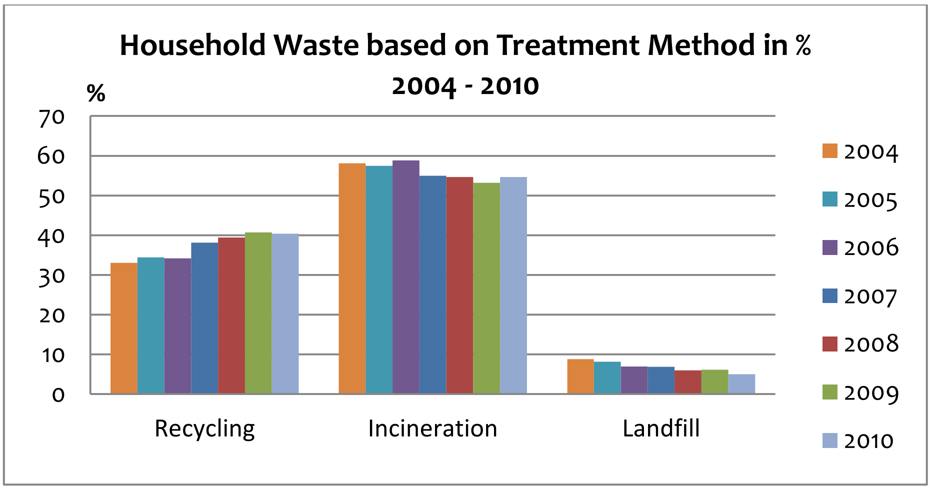


Figure No. 4.3: Household waste based on Treatment Method in % from 2004 – 2010 (Ladefoged 2011)

In the above two figures, it is clear that amount of household waste being land filled has decreased from 1993 up to 2010. On the other hand we see a continuous trend of increase in recycling from 1993 up to 2007 and from that time it seems to be nearly constant. In case of incineration, there is an increase tend from 1993 to 2007 and later it is showing a decrease trend because in Aalborg Commitments, there is more focus on recycling the waste then incinerating it (See Section 4.1). Figure No. 4.3 is showing a more detailed overview of change in handling of household waste on the basis of their amount.

4.4. ''Waste to Energy'' in Aalborg

Aalborg Municipality is the perfect example of '' Waste to Energy'' as heat and electricity supplied at homes and offices is provided by the burning of waste at Reno Nord (the incineration facility in Aalborg), a cement production company (Aalborg Portland) and also from a CHP plant (Nordjyllands vaerket). Some other companies also provide energy based on natural gas boilers to the city and mainly work only in the peak demand hours. Reno Nord is the primary supplier of heat in Aalborg but in case of excess demand, Aalborg Portland and Nordjyllands vaerket also make their contributions to the grid. But in case if the demand grows even higher than the gas boilers start work to provide extra heat (Hill 2010).

4.4.1. Reno Nord

Reno Nord is the incineration facility situated in Aalborg east. It has also a landfill facility in Rærup. The company profile of Reno Nord in this section is described because of its major role in ''Waste to energy'' in Aalborg Municipality. The information regarding Reno Nord presented in this section is derived from the conversation with Thomas Lyngholm, the Environmental Manager at Reno Nord during a visit to the facility (referred as Lyngholm 2011).

Reno Nord facility was built in 1978 in Aalborg Municipality. Before Reno Nord, there was an old incineration facility that stopped working when Reno Nord was built. Reno Nord was built with the cooperation of seven municipalities in Northern Jutland named Aalborg, Aabybro, Dronninglund, Hals, Sejlford, Skørping and Arden. But later in 2007, according to the reorganization of municipalities, these municipalities turned into five as Aalborg, Brønderslev, Jammerbrugt, Rebild and Mariagerfjord. The amount of waste received from all these five municipalities is as follows:

Table No. 4.2: Waste Received from different Municipalities at Reno Nord

No.	Municipality	Waste Generation (tons)
1	Aalborg (gl. Hals, Sejlflod og Aalborg Municipality)	185.161
2	Brønderslev (gl. Dronninglund Municipality)	15.209
3	Jammerbrugt (gl. Aabybro Municipality)	11.390
4	Mariagerfjord (gl. Arden Municipality)	8.534
5	Rebild (gl. Skørping Municipality)	9.799
	Total	**230.093**

At Reno Nord currently there are two boiler lines in operation. The latest oven 4 was built in 2003 and started working in 2005. There is one older oven 3 as well and is used as a reserve oven from 1991. Oven 4 is one of the most modern incineration plants in Europe and it is complying with new incineration standards set by EU. This incineration facility is having an advanced emission control system, which use an electrostatic filter to remove solid particles from the flue gas. The water used in this treatment process is released to Limfjord after the quality treatment at the facility.

The capacity of Oven 4 is 20t/h. According to the capacity, if there is 160,000 tons of waste then 12 MJ/kg of energy is produced per year that leads to the respective electricity production of 18 MW. This electricity is enough for 35, 000 homes. At this capacity, the heat production is 48MJ/s at the incineration facility, which is sufficient for 16.000 homes. The efficiency ratio of Oven 4 is 98 – 100%. The lifetime of Oven 4 is 20 years. Approximately, 65% of the waste coming at Reno Nord is household waste and the remaining is coming from industries and hospitals. The incineration facility is provided with a *Monitoring Bay* with an overhead camera, which allows the Municipality officials to check the waste composition from different industries. If they find that the amount of recyclables such as paper and plastic is more from a company, then they try to discuss the different recycling opportunities with that company to avoid any resource waste in future.

The waste from hospitals is directly put into the Oven due to its infectious nature. On the other hand, the waste coming from homes and industry is first loaded at a storing place and then it is moved to the Oven. After the incineration process, 20% of the waste is left at the base as ash. This ash is 99% used in building and construction industry after the separation of some metals; hence total recycling of this ash is performed. The metals are sold in the market again.

5. Life Cycle Assessment

The main objective of this chapter is to quantify the GWP_{100} from different ways of handling the municipal solid waste in Aalborg Municipality from 1970 - 2020.

5.1. Phase 1- Goal and Scope Definition

In this phase goal of study, definition of functional unit and the relevant processes such as system boundary are described. This phase tells why this LCA is made and for whom. It also explains the scenarios, which are dealt with in LCA.

5.1.1. Goal

The goal of this LCA is '*'to quantify the GWP_{100} of different waste management options such as Recycling, Incineration and landfill from 1970 s upto 2020 in Aalborg Municipality taking the energy value of waste and technological development in account''*. The waste considered in this LCA is MSW in Aalborg municipality including food waste, yard waste and plastic, paper, cardboard etc. A total of six scenarios have been made representing every single decade from 1970-2020. In these scenarios, there is a technological development regarding incineration process, energy recovery and use from it; and the basic idea for this is taken from (Poulsen and Hansen 2009; Damgaard et al. 2009). The data about the marginal energy sources in all the scenarios is obtained from Mathiesen et al (2009). The data regarding historical development of air pollution control in incineration systems in all the scenarios is obtained from Damgaard et al (2009). The scenarios are described as below:

5.1.1.1. Scenario 1: 1970

In this scenario, it is assumed that all the municipal solid waste was going to landfill and the landfill was unlined hence leading to leaching of pollutants in ground water. In this landfill, no methane collection system was available. The electricity used was produced from Oil as in 1970 Denmark was totally dependent on oil as energy source (Lund 2007).

5.1.1.2. Scenario 2: 1980

In this scenario, all the waste was incinerated at a rotary oven incinerator without any energy recovery and the bottom ash was land filled. In this scenario, the energy used is electricity produced from coal because due to 1973 oil crisis, electricity generation started from coal. Mathiesen et al (2009) also describes coal as the marginal energy source in 1980.

5.1.1.3. Scenario 3: 1990

In this scenario, the residual waste was incinerated in a rotary oven incinerator with energy recovery in the form of district heating. Bottom ash resulting from this process was utilized in many purposes such as road and building construction. Food and yard waste was composted and paper, glass and iron waste was recycled. In 1990, the energy produced as a result of heat generation during incineration process substituted the energy produced from coal as coal was the marginal energy source (Mathiesen et al. 2009).

5.1.1.4. Scenario 4: 2000

In 2000, the residual waste was incinerated with both heat and electricity generation by installation of a steam turbine generator system at the incinerator. Food and yard waste was composted and paper, glass and iron was recycled. In 2000, the electricity and heat produced as a result of incineration process substituted the electricity and heat produced by coal CHP (Mathiesen et al. 2009). On the other hand, incineration plant operated on its own produced power.

5.1.1.5. Scenario 5: 2010

In this scenario, the incinerator is operating with condensation of the water vapor present in the flue gases to increase the heat recovery. In 2010, as the heat recovery has increased due to condensation of water vapor in flue gas, this recovered heat substitutes the heat produced by natural gas CHP. Likewise, the electricity produced by the incineration process substitutes the electricity produced by natural gas CHP. Food and yard waste was composted and paper, glass, plastic, PVC and iron waste was recycled.

5.1.1.6. Scenario 6: 2020

In this scenario, it is assumed that the incineration technology, amount and composition of MSW remain the same as in 2010. But, the marginal energy source is assumed to be wind power for electricity and marginal heat source is assumed to be the heat produced from waste incineration. This scenario is imagined on the basis of total renewable marginal energy sources.

The ***rationale behind the choice of these scenarios*** is explained as follows:

1. These scenarios have been selected on the basis of available technologies for municipal solid waste management ways used in Aalborg municipality during the history from 1970 onwards that makes the application of these scenarios more realistic. The technology development here means the development in efficiency and energy recovery from incineration process.

2. Moreover, the historical development of air pollution control regarding the incineration process in all the scenarios is also a rationale behind the choice of scenarios.

3. These scenarios offer more real picture of solid waste management in Aalborg municipality for using the marginal energy source according to the respective scenario time period. This means that the energy recovered during the incineration process in different time periods is substituted with the marginal energy source such as coal, oil, natural gas or wind energy according to those time periods.

4. Also, there is one very detailed study about the global warming impact from both solid and liquid waste in Aalborg Municipality by Poulsen and Hansen (2009), but the current study aims to fill the gap in the sense that in research by Poulsen and Hansen (2009), same waste amount and composition is assumed in all the time periods. Whereas the current study will use a representative solid waste composition from every time period.

5.1.2. Functional Unit (FU)

The functional unit describes the amount of MSW analyzed in the LCA. In all the three scenarios, the functional unit is same to make it possible to compare all the scenarios on the same basis and identify the environmentally best solution. This study focuses on the MSW in Aalborg municipality in different time periods. The functional unit in the current study is ***one ton of MSW treated per year in Aalborg Municipality***.

The validity of this Functional Unit is dependent on different scenarios as the waste composition has changed in every scenario from 1970 upto 2010. Also, the waste treatment technology is not same for all the fractions in MSW stream. So, it means that FU in 1970 is the combination of different waste fractions such as residual waste, plastic, paper and glass all going to be land filled but in case of 2010, the FU comprise of again different MSW fractions such as residual waste, food and yard waste, paper & cardboard, plastic, PVC, glass and iron etc with different treatment technologies for every fraction (the detail of these MSW composition and their treatment technology is described in Section 5.2).

5.1.3. System Boundary

In the system boundary, processes relevant for LCA are included and the rest processes are excluded.

Thrane and Schmidt (2007) explain two different approaches for system delimitation called *Consequential modelling* and *Attributional modelling*. These are described as follows:

1. Consequential modelling – uses a market oriented approach to identify the affected process.
2. Attributional modelling – identifies processes to be included by analyzing the bio- physical flows in the current supply chain.

In the current project, consequential modeling is used. Thus the system boundaries are set. So, only the processes affected are included. The system boundaries related to every scenario are shown in the sub sections below:

5.1.3.1. Scenario – 1 (1970)

Scenario 1 corresponds to the year 1970, in which all the waste was going to an unlined landfill with no landfill gas recovery. The corresponding system boundary for this scenario is as follows:

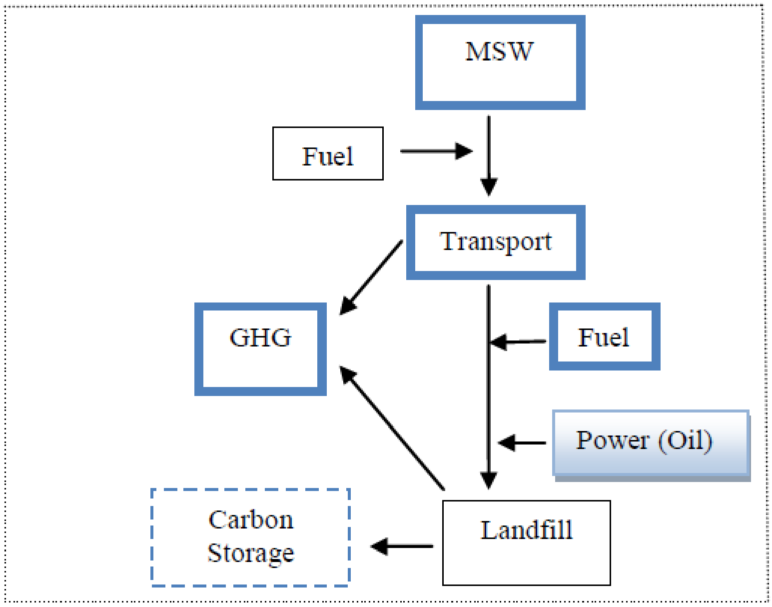


Figure No. 5.1: System Boundary for Scenario 1 showing the material and energy flows (The Blue line boxes show the unit processes used in SimaPro 7.2 whereas the dashed box shows that it is not accounted. The Blue colored box shows the marginal energy source)

5.1.3.2. Scenario – 2 (1980)

Scenario 2 corresponds to the year 1980 where waste was incinerated in a rotary oven incinerator. At this stage the energy recovered was not utilized at all and the bottom ash was landfilled. The system Boundary for this scenario is as follows:

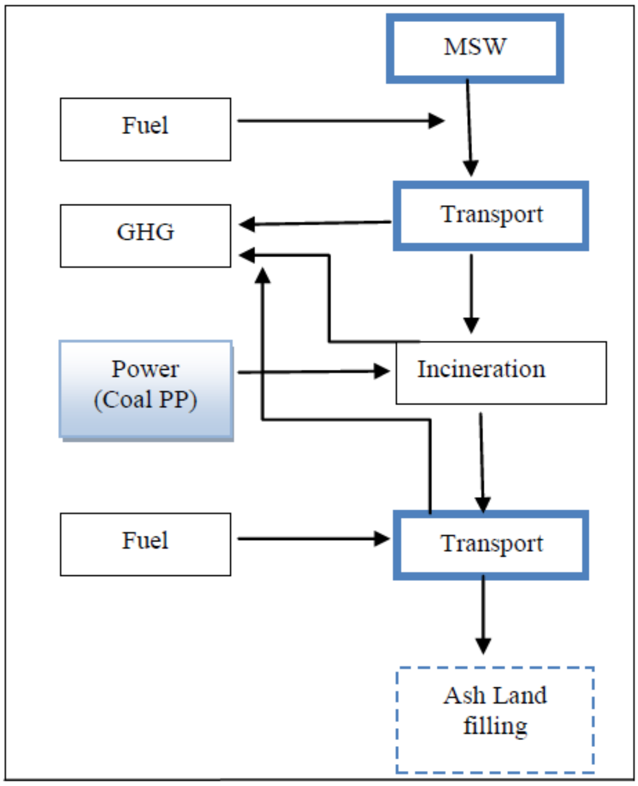


Figure No. 5.2: System Boundary for Scenario 2 showing the material and energy flows (The Blue line boxes show the unit processes used in SimaPro 7.2 whereas the dashed box shows that it is not accounted. The Blue colored box shows the marginal energy source)

5.1.3.3. Scenario – 3 (1990)

This scenario corresponds to 1990 where the solid waste was incinerated in a rotary oven incinerator with energy recovery in the form of district heating. Bottom ash resulting from this process was utilized in many purposes such as road and building construction. The system Boundary for this scenario is shown in Figure No. 5.3.

5.1.3.4. Scenario – 4 (2000)

This scenario corresponds to year 2000 where the waste was incinerated with both heat and electricity generation by installation of a steam turbine generator system at the incinerator. The system boundary for this scenario is shown in Figure No. 5.4.

5.1.3.5. Scenario – 5 (2010)

This scenario corresponds to the year 2010 where the incinerator is operating with condensation of the water vapor present in the flue gases to increase the heat recovery. The system boundary for this scenario is shown in Figure No. 5.5.

5.1.3.6. Scenario - 6 (2020)

Scenario 6 is about year 2020 where assumption is made that the marginal energy source will be wind power for electricity and energy produced from waste incineration for heat. Whereas the MSW amount, composition and the regarding treatment technology are assumed to be the same as they are in 2010. The system boundary for this scenario is shown in Figure No. 5.6.

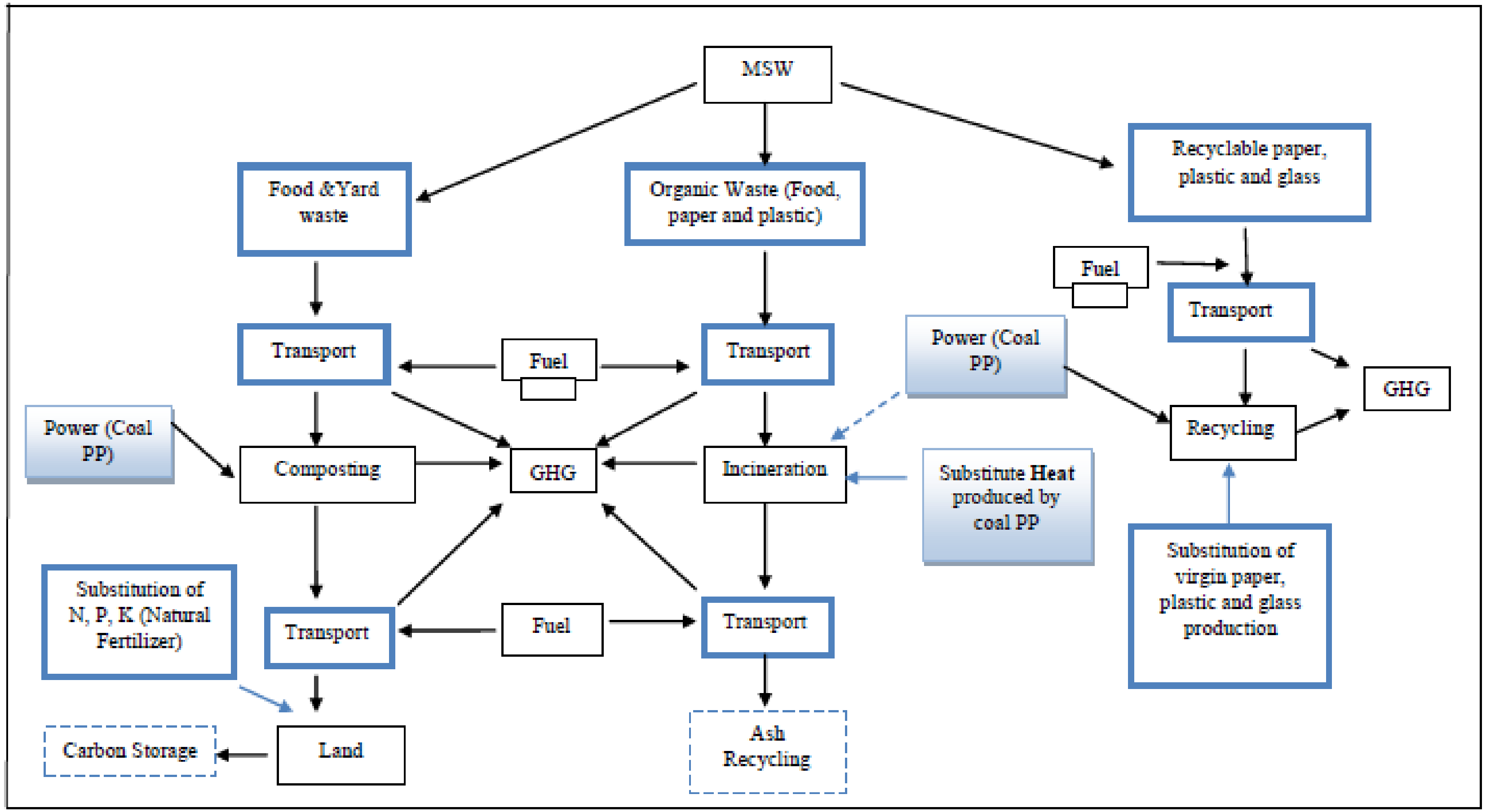


Figure No. 5.3: System Boundary for Scenario 3: 1990 (Blue solid arrows show the substitutions and blue dashed arrow shows that energy used is part of energy produced. Blue colored boxes show the marginal energy source and blue line boxes show the unit processes used in SimaPro 7.2)

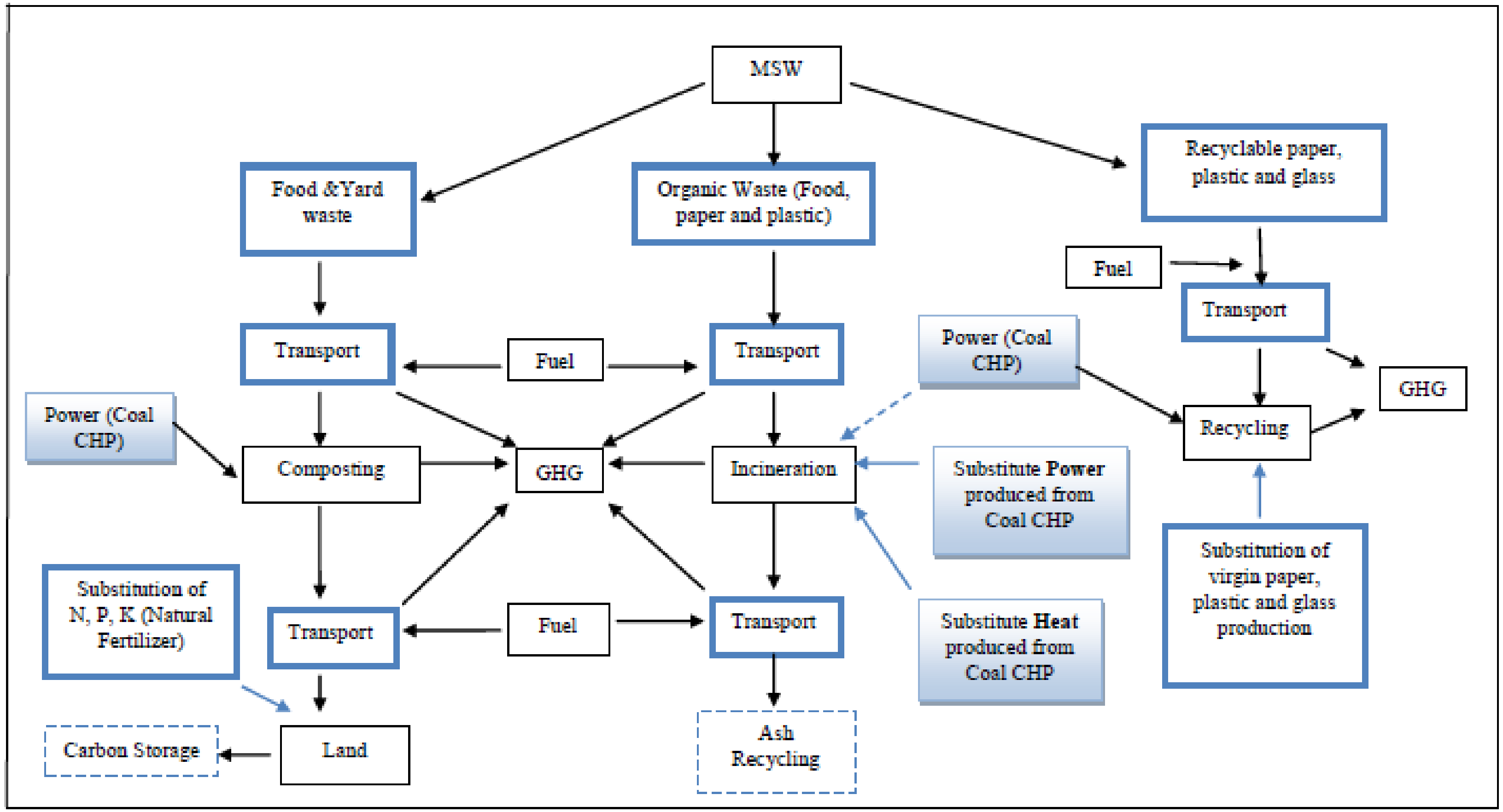


Figure No. 5.4: System Boundary for Scenario 4: 2000 (Blue solid arrows show the substitutions and blue dashed arrow shows that energy used is part of energy produced. Blue colored boxes show the marginal energy source and blue line boxes show the unit processes used in SimaPro 7.2)

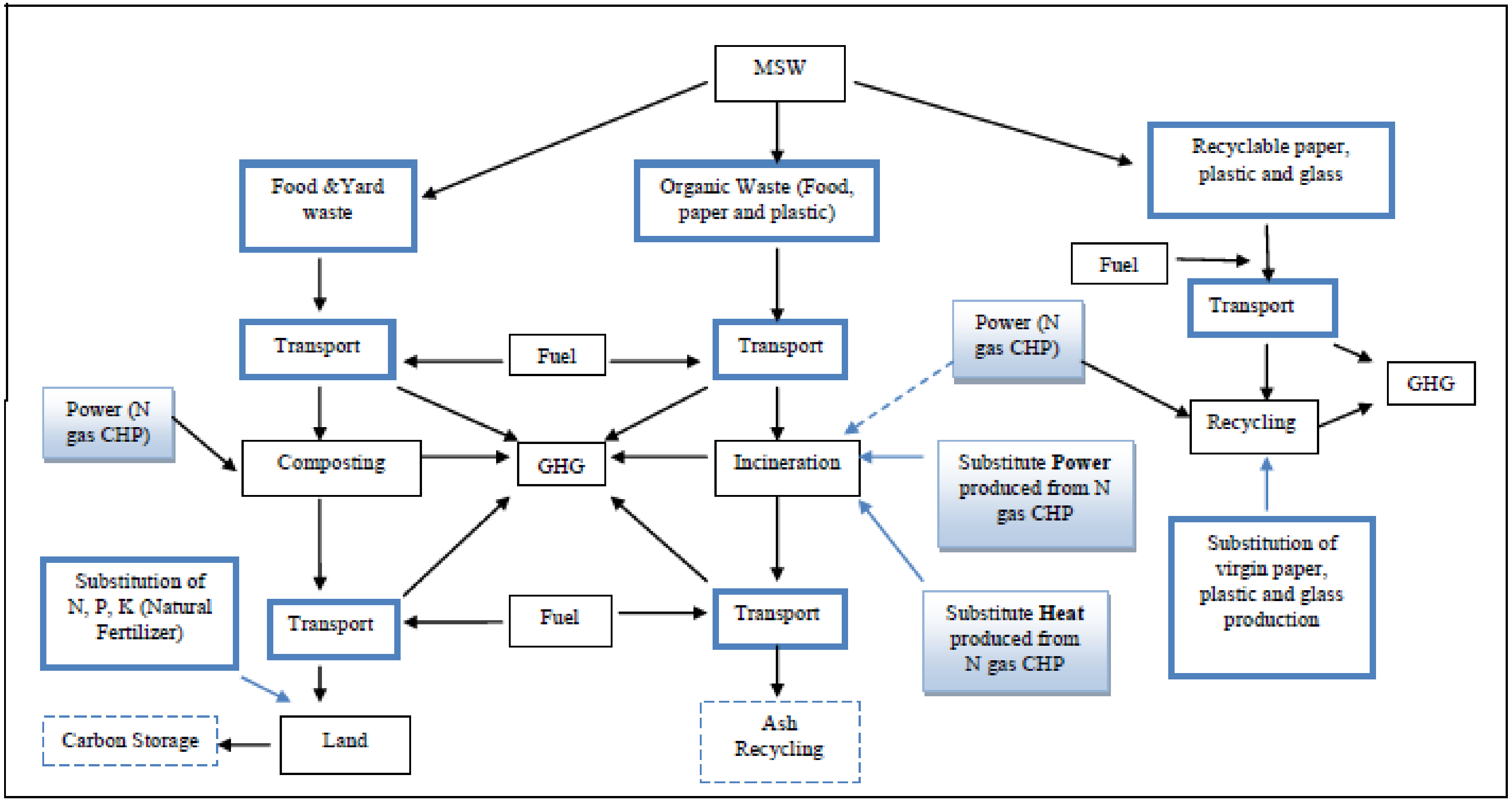


Figure No. 5.5: System Boundary for Scenario 5: 2010 (Blue solid arrows show the substitutions and blue dashed arrow shows that energy used is part of energy produced. Blue colored boxes show the marginal energy source and blue line boxes show the unit processes used in SimaPro 7.2)

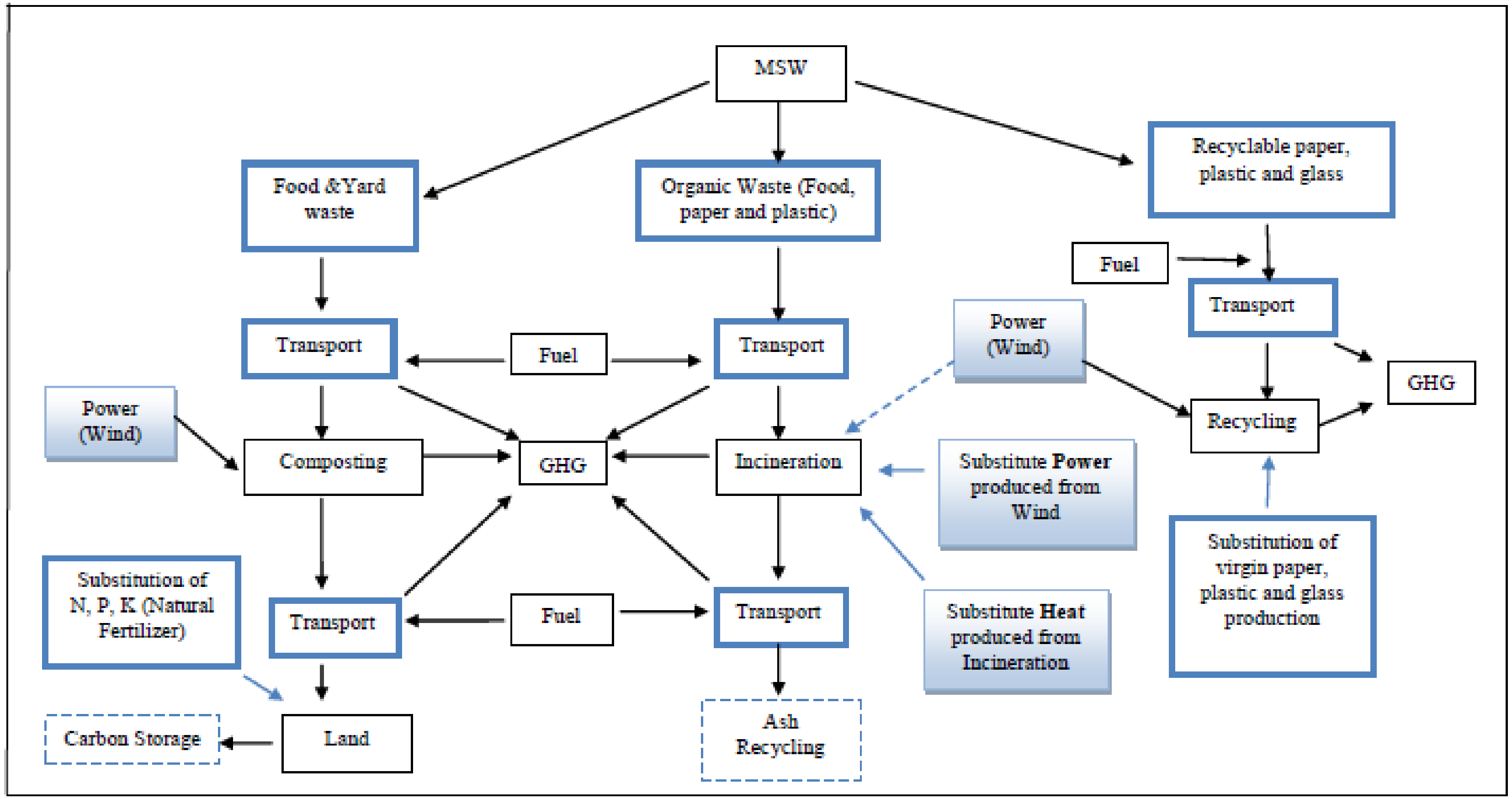


Figure No. 5.6: System Boundary for Scenario 6: 2020 (Blue solid arrows show the substitutions and blue dashed arrow shows that energy used is part of energy produced. Blue colored boxes show the marginal energy source and blue line boxes show the unit processes used in SimaPro 7.2)

5.1.3. Cut – off Criteria

Cut – off criteria is mainly used for delimitation of processes and materials in the LCA process to avoid indefinite growth of system. In the current LCA study, no cut of criteria is used due to the fact that consequential modeling is used which avoids cut off criteria by applying system expansion.

5.1.4. Method used

To find out the GWP_{100} from all the above described scenarios, it is compulsory to choose an assessment method in SimaPro 7.2 (Pre 2008). For the current project, EDIP (Environmental design of Industrial Products) 2003 is used as this method is developed for Danish conditions and all the scenarios in this study take place in Denmark.

5.1.4. Temporal Scope

For the current project, data from 1970 upto now will be used to calculate the global warming impact from different waste management scenarios.

5.1.5. Geographical Scope

The geographical scope of current project is limited to Aalborg Municipality.

5.1.6. Technological Scope

The MSW stream in Aalborg Municipality is having different fractions of waste in it such as yard waste, food waste, paper, plastic and cardboard etc. During different time periods from 1970s onwards this waste has been treated in different ways such as: land filling, incineration without energy recovery, incineration with only heat and later both heat and electricity recovery and the latest (Scenario 5 - 2010) with increased heat recovery. All these technologies will be described in detail in next phase of LCA named LCI (See Section 5.2). For the incineration process from 1980 upto 2010, the historical development of air pollution control system is given in the following table (the data regarding APC system is assumed to be the same in 2020 as it is in 2010):

Table No. 5.1: Historical Development of APC in MSW incineration system

Flue Gas Cleaning	1980	1990	2000	2010	2020
Technical Configuration • Particle removal	Yes	Yes	Yes	Yes	Yes
• Scrubbing	No	Dry	Wet	Semi Dry	Semi Dry
• Dioxin filter	No	No	Yes	Yes	Yes
• Flue gas Condensation	No	No	No	Yes	Yes
• De NOx technology	No	No	SNCR	SCR	SCR
Energy Use (kWh / ton MSW) • Electricity Consumption	30	40	70	75	75
Material Use (kg/ton MSW) • Activated carbon			0.5		
• Ammonia water			2.4	3.3	3.3
• $CaCO_3$			7.1		
• $FeCl_3$			0.06		
• Hydrated lime $Ca(OH)_2$		6.7		10	10
• NaOH			0.4	1.5	1.5
• Polymer			0.01		
• TMT- 15			0.04		
• Water (m^3/ tone)		0.1	0.20		

Continued….

Flu Gas Cleaning	**1980**	**1990**	**2000**	**2010**	**2020**
Air Emissions (g/ tone MSW) • SO_2	1100	270	109	55	55
• HCl	3800	110	11	5	5
• NOx	2200	2200	900	55	55
• NH_3	3	3	1	16	16
• Particles	400	55	11	5	5
• Hg	0.82	0.11	0.05	0.003	0.003
• Pb	5	1.1	0.5	0.11	0.11
• Cd	1.1	0.16	0.05	0.01	0.01
• As	0.5	0.16	0.05	0.01	0.01
• CO_2 fossil (kg/ tonne)	300	300	300	300	300
• Dioxin (µg/ tone)	16	3	0.3	0.11	0.11
Solid Outputs (kg / tonne MSW)[1] • Fly Ash	7.8		8.2		
• Mixed solid APC residue		19.8		23.6	23.6
Wastewater (m^3/ tone)			0.1	0.04	0.04
• Gypsum (90% dry solids)				2.9	
Sludge with heavy metals				2.0	

[1] Solid outputs are described for information but they are not modelled in LCA.

Source: Damgaard et al (2009)

Besides taking the technological development in the air pollution control system of incinerators, the technological development regarding controlling the vehicular emissions from transport of MSW is also analyzed in the current report as transportation is also the integral unit process in the whole system boundary of every scenario. So, following is the table describing the air emissions and fuel consumption in different time periods during the history from 1970 up to 2000:

Table No. 5.2: Estimated Vehicle emissions and fuel consumption, European Vehicles, Urban driving (g/km) for more than 2000cc vehicle

Year	Carbon Monoxide (CO)	Nitrogen Oxides (NOx)	Methane (CH_4)	Nitrous Oxide (N_2O)	Ammonia	Non Methane VOC	Fuel Consumption (l/100 km)
1970	56.8	1.7	0.224	0.005	0.002	4.2	19.23
1980	22.3	2.5	0.224	0.005	0.002	3.3	15.87
1990	21.4	2.3	0.224	0.005	0.002	2.6	18.29
2000	4.1	0.4	0.062	0.050	0.070	0.4	12.99

Source: Faiz et al (1996)

In the above table only data upto 2000 is described as for *Scenario 5 – 2010* and *Scenario 6 - 2020*, the unit process for transport is selected from Ecoinvent Unit Processes in SimaPro 7.2 ‘’Transport, municipal waste collection, lorry 21t/CH U’’.

5.1.7. Data Quality

For the assessment of most accurate global warming impact results related to different waste management scenarios, reliable data has been used from Aalborg municipality, Reno Nord and scientific reports.

5.1.8. Key Assumptions

1. As the exact composition of MSW in *Scenario 1 – 1970* and *Scenario 2 – 1980* is not available, so to get the total amount of MSW, the population of Aalborg municipality in 1970 (100,587) is multiplied with 0.46 ton of waste / person / year according to an assumption made by Poulsen (2011). Likewise is the case with

Scenario 2 – 1980, where the population of Aalborg municipality in 1980 (114, 302) is multiplied with 0.54 ton of waste / person / year (Poulsen 2011). Later the composition ratio of this waste has been adopted from Affald (1988) and modified to fill up the total percentage of waste.

2. The data for *Scenario 3 - 1990* is from year 1993 obtained from Aalborg Municipality as the data before does not exist due to the first record keeping of MSW data started in 1993.

3. For getting the further detailed composition of residual waste *in Scenario 3- 1990*, data has been obtained and modified from Nissen et al (1994) and Tonning et al (1997).

4. To overcome the problem of further detailed data regarding the composition of residual waste in 2000 and 2010, the data obtained and modified from Nissen et al (1994) and Tonning et al (1997) has been developed considering the observation that the plastic waste generation has increased due to change in living patterns and so the food waste has decreased as it is going more to composting as well. The amount of paper is also decreasing with time due to the fact that it is also going to recycling. Plastic waste is a problem fraction also due to the fact that there is an ongoing debate whether to recycle plastic or incinerate it as it takes a lot of energy for recycling of plastic (Ladefoged 2011). See the following table for the data developed:

Table No. 5.3: Composition of Residual waste in 1990, 2000 and 2010

Fractions in Residual Waste	**% of total Residual Waste**		
	1990	**2000**	**2010**
Food Waste	44.44	38.89	33.34
Paper	44.44	38.89	33.34
Plastic	11.11	22.22	33.33
Total	100	100	100

Source: Modified from Nissen et al (1994) and Tonning et al (1997)

5. In the current LCA, only food waste, yard waste, paper, plastic, PVC, glass and metals have been considered due to the very different composition of MSW stream. The compositions avoided in this study are bulky waste, electronic waste, wood waste and construction waste. Waste clothes are also avoided in the current LCA study as according to Ladefoged (2011), they are given to some charities to reuse them.

6. The distance for transporting waste is assumed to be 20 km in every scenario despite of the fact that some waste treatment facilities can be at more distance.

7. As the current study focus only on MSW, so no waste water from Aalborg municipality is analyzed in the current study.

5.2. Phase II- Life Cycle Inventory

In the second phase of LCA named Life Cycle Inventory, material flows which are going to be analyzed in LCA are explained such as transport, energy, any kind of materials and emissions to environment etc. This phase also tells about data collection, calculation, handling of co product allocation and also handling of avoided products. Finally a Life Cycle Inventory is made with a complete overview of elementary flows, later used as an input to the 3rd phase named Life Cycle Impact Assessment. Following is given the Life Cycle Inventory of every scenario based on the changing waste composition, technology development for waste treatment and energy recovery (substituted non- renewable energy source).

5.2.1. Scenario 1 – 1970

Table No. 5.4: Composition of MSW in 1970 and the treatment technology

Fractions in MSW	% of total MSW	Amount of Waste (ton)	Waste Management Option
1. Food waste	35	16,194	Landfill without the CH_4 recovery
2. Paper	35	16,194	
3. Plastic	8	3,702	
4. Glass	10	4,627	
5. Iron	6	2,776	
6. Yard Waste	6	2,776	
Total	100	46,269	

Source: Modified from Affald (1988)

5.2.2. Scenario 2 – 1980

Table No. 5.5: Composition of MSW in 1980 and the treatment technology

Fractions in MSW	% of total Waste	Amount of Waste (tons)	Waste Management Option
1. Food waste	35	21,603	Incineration without energy utilization
2. Paper	35	21,603	
3. Plastic	8	4,9378	
4. Glass	10	6,1723	
5. Iron	6	3,7034	
6. Yard Waste	6	3,7034	
Total	100	61,723	

Source: Modified from Affald (1988)

5.2.3. Scenario 3 – 1990

Table No. 5.6: Composition of MSW in 1990 and the treatment technology

Fractions in MSW	**Amount of Waste (tons)**	**Waste Management Option**
Residual waste 1. Food waste 2. Paper 3. Plastic	31, 688 14,082 14,082 3,520	Incineration with heat recovery
Food Waste	296	Composting
Yard Waste	7, 203	Composting
Paper and Card board	3, 683	Recycling
Glass	2, 631	Recycling
Iron	1, 631	Recycling
Total	56,038	

Source: Ladefoged 2011

5.2.4. Scenario 4 – 2000

Table No. 5.7: Composition of MSW in 2000 and treatment technologies

Fractions in MSW	**Amount of Waste (tons)**	**Waste Management Option**
Residual waste	36, 232	Incineration with heat and power recovery
1. Food waste	14,091	
2. Paper	14,091	
3. Plastic	8,051	
Food Waste	318	Composting
Yard Waste	20, 465	Composting
Paper and Card board	5, 188	Recycling
Glass	2, 466	Recycling
Iron	2,570	Recycling
Total	85,100	

Source: Ladefoged 2011

5.2.5. Scenario 5 – 2010

Table No. 5.8: Composition of MSW in 2010 and the treatment technologies

Fractions in MSW	**Amount of Waste (tons)**	**Waste Management Option**
Residual waste 1. Food waste 2. Paper 3. Plastic	41, 893 13,967 13,967 13,963	Incineration with increased heat and power recovery
Food Waste	500	Composting
Yard Waste	20, 465	Composting
Paper and Card board	10,688	Recycling
Glass	2,822	Recycling
Plastic	1	Recycling
PVC	89	Recycling
Iron	2,719	Recycling
Total	99,141	

Source: Ladefoged 2011

5.2.6. Scenario 6 – 2020

For this scenario, all the waste composition, amount and the treatment technology is same. The only difference is the use of marginal energy source as it shifts from non- renewable energy source to renewable energy source. So, Table No. 5.8 is also valid for this scenario.

5.2.7. Unit Processes Used in Waste Management Scenarios

In this section, different unit processes used in SimaPro 7.2 regarding the recycling, composting and incineration of different MSW streams are given.

5.2.7.1. Recycling

The LCI with unit processes used in SimaPro 7.2 for recycling of paper, plastic, glass, PVC, Iron and metals can be seen in Appendix I.

5.2.7.2. Composting

The LCI with unit processes used in SimaPro 7.2 for composting of food and yard waste can be seen in Appendix II.

5.2.7.3. Incineration

In the years 1990, 2000 and 2010, energy produced from the incineration process of residual waste has been utilized in different purposes such as district heating etc. But in year 1980, it has been assumed that energy produced from the incineration plant was not utilized at all. Hence the inventory for Incineration of Residual Waste for the year 1990, 2000 and 2010 is as follows:

Table No. 5.9: % of Energy Production by incineration of different waste fractions in 1990, 2000 and 2010

Waste Fraction	Lower Heat Value (LHV) (GJ/ ton)[5]	Combustion Efficiency (%)			Power Production (% of LHV)			Heat Production (% of LHV)		
		1990	2000	2010	1990	2000	2010	1990	2000	2010
Paper	13	99	99	99	-	23.5	28	85	69.5	83
Plastic	32	99	99	99	-	23.5	28	85	69.5	83
Organic (Food)	4	99	99	99	-	23.5	28	85	69.5	83

Source: Poulsen & Hansen (2009)

Based on above data related to the combustion efficiency, power production and heat production, following calculations have been made in order to feed in SimaPro 7.2.

Table No. 5.10: Energy Production by incineration of different waste fractions in 1990, 2000 and 2010

Waste Fraction	Power Production / ton (GJ/ton)			Heat Production / ton (GJ/ton)		
	1990	2000	2010	1990	2000	2010
Paper	-	3.055	3.64	11.05	9.035	10.79
Plastic	-	7.52	8.96	27.2	22.24	26.56
Organic (food)	-	0.94	1.12	3.4	2.78	3.32

Source: Poulsen & Hansen (2009)

The above described two tables show only the production of energy from incineration process of residual waste in different scenarios. But following is the table showing the energy use by this incineration process in different scenarios based on the figures presented in the above two tables.

[5] Astrup et al (2009a)

Table No. 5.11: Power use for the incineration of different waste fractions in 1990, 2000 and 2010

Waste Fraction	Power Use (% of power production)			Power Use / ton (GJ/ton)		
	1990[6]	2000	2010	1990	2000	2010
Paper	5	13	13	0.5525	0.39715	0.4732
Plastic	5	13	13	1.36	0.9776	1.1648
Organic (food)	5	13	13	0.17	0.1222	0.1456

Poulsen & Hansen (2009)

For the year 1980, the inventory of incineration process is as follows:

Table No. 5.12: Energy use by incineration process in 1980

Fractions in MSW	Lower Heating Value (LHV) / ton[7]	Electricity use (% of LHV)	Electricity use GJ / ton
Food waste	4	3	0.12
Paper	13	3	0.39
Plastic	32	3	0.96
Glass	0	3	0
Iron	0	3	0
Yard Waste	7	3	0.21

Source: Poulsen & Hansen (2009)

The detailed LCI for incineration process including the unit processes used in SimaPro 7.2 can be seen in Appendix III.

[6] For 1990, power use is the % of heat produced as at that time only heat was recovered.

[7] LHV for Yard waste is taken from Poulsen & Hansen (2009), but the LHV for rest of compositions is taken from Astrup et al (2009a)

5.2.7.4. Landfill

The LCI for Scenario 1 – 1970, where all the waste was going to landfill is given as follows:

Table No. 5.13. LCI for land filling in 1970

Inputs & Emissions	**Amount & Units / ton of MSW**
Food and Yard waste	410 kg
Paper waste	350 kg
Iron waste	60 kg
Glass waste	100 kg
Plastic waste	80 kg
Fuel	3 L
Electricity	8 kWh
Transport	20 tkm
CH_4	13.5 kg
CO_2	228 kg

The data in above table for fuel use, electricity use, methane and carbon dioxide emissions are taken from Manfredi (2009). The detailed LCI for landfill of MSW including the unit processes used in SimaPro 7.2 can be seen in Appendix IV.

5.2.7.5. Air Pollution Control (APC) System

The APC system used in different scenarios (See Table No. 5.1) regarding the incineration process of residual waste can be seen in Appendix V, describing in detail the unit processes used in SimaPro 7.2 (Pre 2008).

5.3. Phase III- Life Cycle Impact Assessment

In this phase, the elements of Life Cycle Inventory from the second phase are converted into environmental impacts. These environmental impacts can be of various kinds such as global warming, ozone depletion, acidification, eutrophication, human and eco toxicity etc. In the phase III of LCA, three steps are used for impact assessment named as characterization, normalization and weighing. These are described as follows:

- **Characterization-** In this step, impact potentials from each scenario are calculated based on Life Cycle Inventory results and the results are presented as impact indicators.

- **Normalization-** Normalization is the calculation of the magnitude of the category indicator results relative to some reference information. The aim of the normalization is to understand better the relative magnitude for each indicator result of the product system under study. It is an optional element (ISO 14044 2006).

- **Weighting**-Weighting is the process of converting indicator results of different impact categories by using numerical factors based on value-choices. It may include aggregation of the weighted indicator results (ISO 14044 2006).

In the current study, normalization and weighting are not used as only one impact category ‘’global warming’’ is studied.

5.4. Phase IV- Interpretation

The last phase of LCA is Interpretation where the significant results of study are presented. In this phase, results are critically reflected in order to check their consistency by doing the sensitivity analysis. The results of current LCA study are presented in detail in next chapter named *‘’Global Warming from MSWM in Aalborg Municipality’’.*

6. Global Warming from MSWM in Aalborg Municipality

The aim of this chapter is to present the results of LCIA presented in chapter 5 in the form of Global Warming impacts from MSW management in Aalborg Municipality from 1970 up to now as well as for the assumed scenario of 2020. At the end this chapter will present the sensitivity analysis and evaluation of results followed by a brief discussion on results.

6.1. Global Warming

Global warming is defined as absorption of energy emitted from earth by the atmosphere resulting in increased earth temperature (Guinee et al. 2001). Global warming occurs due to the presence of GHG in the atmosphere which trigger the energy emitted by earth by not letting it escape out of atmosphere and heat up the earth. These gases are CO_2, CH_4, N_2O, HFCs, PFCs but the major responsible GHG are CO_2, CH_4 and N_2O. In the 4th Assessment report by IPCC in 2007, the GWP_{100} of CO_2 is 1, for CH_4 it is 25 and for N_2O it is 298. These values are valid until 2012 because by that time Kyoto Protocol is active (Gentil and Christensen 2009).

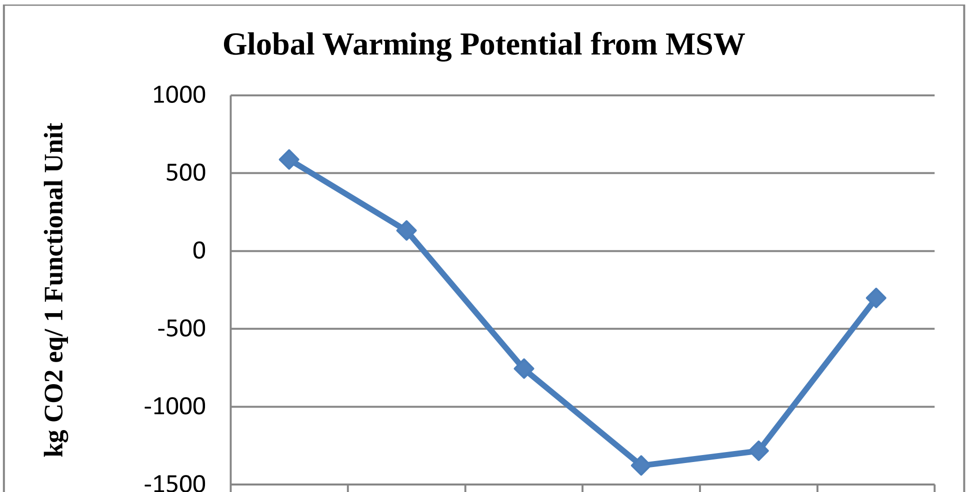
6.2. Global Warming Results from the current LCIA

In the previous chapter, all the methodological procedure, data entry and unit processes used in SimaPro 7.2 (Pre 2008) have been described in detail. The GWP_{100} is calculated using the PC tool SimaPro 7.2 (Pre 2008). The method used for impact assessment is EDIP 2003 V1.02. Here are the results of this LCIA of MSW stream in Aalborg Municipality from 1970 up to now.

Table No. 6.1: GWP_{100} / 1 Functional Unit

Impact Category	Unit	1970	1980	1990	2000	2010	2020
Global Warming 100a	kg CO_2 eq	586	130	-758	-1379	-1284	-304

The trends of GWP_{100} are shown in the following graphical representation:



	1970	1980	1990	2000	2010	2020
kg CO2 eq	586	130	-758	-1379	-1284	-304

Figure No. 6.1: Global Warming from MSW in Aalborg Municipality from 1970 up to 2020

In the above figure it is clear that in 1970, the GWP_{100} of MSW was highest because all the waste was going to landfill without landfill gas recovery. Also, at that time any power use for landfill operations was based on fossil fuels such as oil. In 1980, although the GWP_{100} has reduced because all the waste was going to incineration operating on power source based on coal, but still it is the 2nd highest value in the Figure No.6.1 because the energy produced from this process was not utilized but wasted. In 1990, the GHG emissions leading to global warming have been saved because the heat produced from this process has substituted the heat produced from coal. In the year 2000, again the rapid decrease in GWP_{100} is clear. This is due to heat and electricity recovery from incineration process as both of them replace the heat and electricity produced by coal CHP. In this scenario, materials such as paper, glass and metals like iron are also recovered from the waste stream by recycling process and that ultimately saves the avoided production of these materials. In 2010, the emissions leading to global warming are still saved but less than in year 2000. The reason for this might be the recycling of plastic and PVC fraction as well which consumes a lot of energy. For the year 2020, the emissions leading to global warming have been saved but less than 2010 because in year 2010 the substituted heat and electricity sources are natural gas CHP but in 2020, it is assumed that the power produced by the incineration process substitutes the energy produced from renewable energy sources such as wind mills. The detailed analysis of every scenario is given in the following sections. The trend of GWP_{100} from MSWM in Aalborg municipality from 1970 to 2020 can be more elaborated in terms of analyzing it per person rather than per 1 ton of MSW. This is shown in the following graph (See Appendix VI for background calculations):

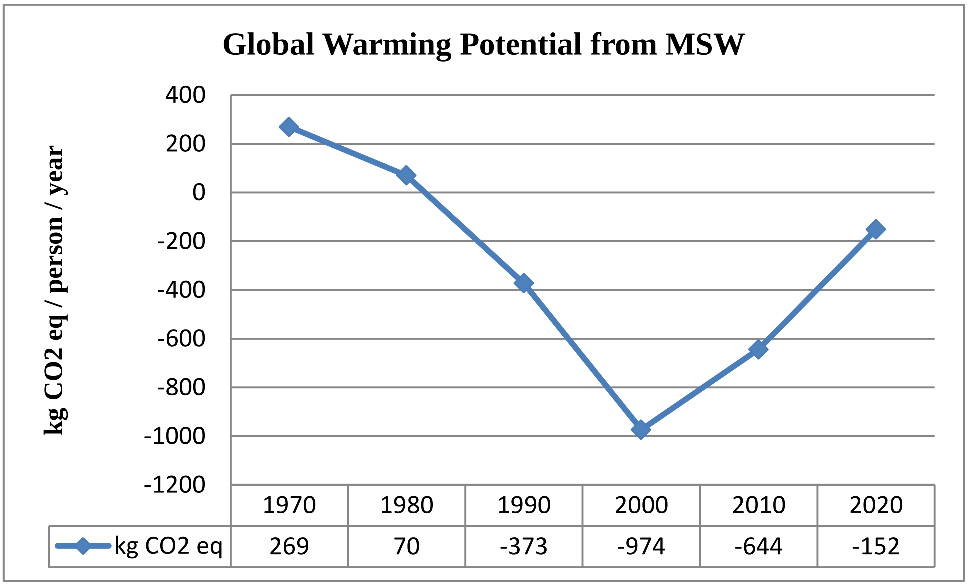


Figure No. 6.2: Global Warming from MSW per person in Aalborg Municipality

The above described figure of GWP_{100} from MSWM / person shows the same trend as GWP_{100} from MSWM / 1 ton of MSW (See Figure No. 6.1 for comparison). The reason behind this is the upward growth of MSW generation and population growth at the same rate (See Appendix VI). According to the above figure, in 1970 every person was responsible for 269 kg CO_2 eq. But later in 1980 it reduced to 70 kg CO_2 eq, in 1990 it declined upto -373 kg CO_2 eq and in 2000 the GWP_{100} per person is lowest at -974 kg CO_2 eq. In 2010, every single person in Aalborg Municipality is saving -644 kg CO_2 eq / year. In 2020, in the assumed conditions of same MSW composition and amount and same population as 2010, every person in Aalborg will be saving -152 kg CO_2 eq.

6.2.1. Global Warming from MSW in 1970

As described earlier, in 1970 MSW was land filled without the recovery of landfill gas. Figure No. 6.1 also reveals that this was the time when the global warming emissions were at the highest level as per ton of MSW, the GWP_{100} was 586 kg CO_2 eq. Out of this 586 kg CO_2

eq, 581.6 kg CO_2 eq is arising from the landfill process of different waste fractions and the rest 4.34 kg CO_2 eq is coming from transporting this waste to landfill site. There is no energy recovery from landfill in the form of landfill gas and on the other hand diesel and electricity are used for onsite operations (remember the energy source was oil in 1970) adding to GWP_{100} from landfill. But it should be considered that in this scenario carbon storage or carbon bonding in soil is not analyzed and that may have an overall effect to lower the GWP_{100}.

6.2.2. Global Warming from MSW in 1980

In 1980, all the MSW was going to incinerator but the energy produced from incineration process was not utilized, and so it was wasted. As shown in Figure No. 6.1, the emissions leading to global warming have decreased upto 130 kg CO_2 eq compared to 586 kg CO_2 eq in 1970 only due to the fact that waste was incinerated rather than land filling it as in the landfilling process no material or energy is recovered from waste ultimately leading to increased GHG emissions. The contribution of different unit processes leading to global warming from MSW in 1980 is as follows:

Table No. 6.2: Process contribution to Global warming from MSW in 1980 (kg CO_2 eq/ 1 FU)

Incineration of Food waste	Incineration of Paper waste	Incineration of plastic waste	Incineration of glass waste	Incineration of iron waste	Incineration of yard waste	APC
16.8	53.6	20.79	3.1	2.68	4.32	29.03

From the above table it is clear that most of the emissions leading to global warming are coming from the incineration of paper waste as compared to other waste fractions. The reason behind this is the high amount of paper waste (35%) compared to other fractions and also high amount of energy use for incineration (0.39 GJ/ ton). Although the energy use for plastic incineration is highest (0.96 GJ/ ton) but in this scenario the GWP_{100} from plastic waste incineration is not higher because its volume is not high as paper waste. The amount of food waste and paper waste going to incineration in this scenario is same but the GWP_{100} from food waste is much less than paper waste because the energy use for this purpose is very less (0.2 GJ/ ton) compared to paper waste. One interesting result in this scenario is from APC as the materials used in order to control the air emissions from incineration process result in almost 22% of the total greenhouse gas emissions from the treatment of total waste stream in 1980.

6.2.3. Global Warming from MSW in 1990

In 1990, the emissions leading to global warming from MSW have been saved due to the heat recovery from incineration process as it substitutes the heat produced by hard coal in 1990. GWP_{100} from MSW in Aalborg Municipality has decreased from 130 kg CO_2 eq in 1980 to −758 kg CO_2 eq in 1990. In 1990, different waste fractions were going to different kind of waste treatment options such as residual waste (food waste, paper, plastic) go to incineration, food waste and yard waste collected from households was composted and paper and cardboard, glass and metals were going to recycling. The GWP_{100} from these different waste treatment technologies in 1990 is shown in the following table:

Table No. 6.3. Process contribution to Global warming from MSW in 1990 (kg CO_2 eq/ 1 FU)

Incineration of Food waste	Incineration of Paper	Incineration of Plastic	Composting of Food waste	Composting of Yard waste
-129.7	-116.5	-268.5	-0.54	-23.67
Recycling of Paper	**Recycling of Glass**	**Recycling of Metals**	**APC**	-
-94.58	-40.32	-109	24.74	

From the above table it is clear that incineration of plastic is the process saving most of emissions although the amount of food waste and plastic waste going to incineration is same but due to high LHV of plastic compared to food, the heat recovered from plastic incineration is more than food waste incineration which substitutes the heat produced from coal ultimately saving the emissions leading to global warming. On the other hand this scenario gives an opportunity to compare the interesting results regarding recycling of paper and incineration of paper as it shows that recycling of paper is environmentally favorable waste management option but saving less GHG emissions then incineration of paper waste.

6.2.4. Global Warming from MSW in 2000

As shown in Figure 6.1, the GWP_{100} from MSW in Aalborg Municipality is lowest in 2000 where it has decreased from – 758 kg CO_2 eq/ ton in 1990 to – 1379 kg CO_2 eq/ ton. The main reason behind this increased saving of GHG emissions is due to the both heat and power recovery from incineration process. The process contribution towards global warming is given as follows:

Table No. 6.4: Process contribution to Global warming from MSW in 2000 (kg CO_2 eq/ 1 FU)

Incineration of Food waste	**Incineration of Paper**	**Incineration of Plastic**	**Composting of Food waste**	**Composting of Yard waste**
-110	-358.3	-671.2	-0.38	-44.6
Recycling of Paper	**Recycling of Glass**	**Recycling of Metals**	**APC**	-
-88	-25	-113	32	

From above table, it is clear that incineration of plastic waste is the most environment friendly treatment technology as it is saving maximum GHG emissions leading to global warming. In this scenario, the strange result comes from the comparison of recycling of paper waste and incineration of paper waste where it shows that incineration of paper is more favorable option in terms of global warming because the amount of paper going to incineration (14091 tons) is much more than the paper being recycled (5188 tons) and also due to the reason that in incineration process heat and power both are produced but in recycling raw material production is avoided with the loss of 30% material input.

6.2.5. Global Warming from MSW in 2010

In 2010, the GHG emissions leading to global warming have been saved but as compared to - 1379 kg CO_2 eq/ ton in 2000, the GWP_{100} has grew up to - 1284 kg CO_2 eq/ ton. The reason behind this is the recycling of two more waste fractions as plastic and PVC and increased MSW generation. In this scenario the emissions have been saved due to increased heat recovery and power production from incineration. The process contribution leading to global warming from MSW in 2010 is shown in the following table:

Table No. 6.5. Process contribution to Global warming from MSW in 2010 (kg CO_2 eq/ 1 FU)

Incineration of Food Waste	**Incineration of Paper waste**	**Incineration of plastic waste**	**Composting of food waste**	**Composting of Yard waste**
-51.67	-189.25	-750.3	-0.51	-38
Recycling of plastic waste	**Recycling of paper waste**	**Recycling of PVC waste**	**Recycling of metals waste**	**Recycling of Glass**
0.008	-153.8	0.20	-102	-23.8
APC	-			
25.9				

The above table is giving a detailed overview of the GWP_{100} from different unit processes from MSW treatment technologies in 2010. This scenario shows the negative GWP_{100} due to heat and power production in incineration process which ultimately substitutes the heat and electricity produced by fossil fuels such as natural gas. Also, the incineration plants use the energy produced by them, so they are not dependent on the external source of energy. From the numbers given in this table, it is clear that only two processes are responsible for global warming in 2010 i.e. recycling of plastic and recycling of PVC (although the GWP_{100} is very low) as all the other processes are saving the GHG emissions leading to global warming. As discussed earlier that decision between recycling and incinerating the plastic, is the topic of discussion now a days as in recycling of plastic huge amount of energy is required and on the other hand in incinerating this plastic provides heat and electricity. So, the results based on scientific evidence can be a source to develop policy regarding selection of one of these options for plastic waste management.

6.2.6. Global Warming from MSW in 2020

This last scenario is primarily based on the assumption that the marginal energy source in 2020 will be renewable such as wind power. But the remaining inputs (waste composition, amount and transport) are assumed to be the same as year 2010. As a result of LCIA, it is clear that the GWP_{100} from this scenario is -304 kg CO_2 eq. If we compare this value to the GWP_{100} in year 2010, then it shows a decline from -1284 kg CO_2 eq in year 2010 to -304 kg CO_2 eq in year 2020. Hence, it becomes clear that the emissions leading to global warming are still saved but not as much as in year 2010. The main reason behind this can be that the power produced by the incineration process substitutes the power produced by wind mills instead of coal or natural gas. As the wind power is already a renewable energy source, so the emissions saved for GWP_{100} are also less as compared to the situation where non- renewable energy source is substituted.

Table No. 6.6: Process contribution to Global warming from MSW in 2020 (kg CO_2 eq/ 1 FU)

Incineration of Food Waste	**Incineration of Paper waste**	**Incineration of plastic waste**	**Composting of food waste**	**Composting of Yard waste**
6.06	11.75	0.035	-0.7	-45.83
Recycling of plastic waste	**Recycling of paper waste**	**Recycling of PVC waste**	**Recycling of metals waste**	**Recycling of Glass**
0.006	-155.6	0.03	-103	-24.3
APC				
7.33	-			

In the above table it is clear that the processes such as Incineration of food, paper and plastic waste are adding to the global warming emissions in year 2020 as compared to the year 2010 where all these unit processes are saving emissions. This is primarily due the reason of using wind power as the marginal electricity source in 2020 rather than using the natural gas. So, the energy produced by the incineration process substitutes the energy produced by wind power which is already environment friendly in terms of global warming. As a result, the emissions leading to global warming are not saved as much as they are saved in year 2010.

6.2.7. Global Warming from APC system of Incinerator

Apart from the global warming impact from the MSW in Aalborg municipality from 1970 onwards, there are some other interesting results as well to be noticed. These results are related to the unit processes such as APC system and transport as both have technologically evolved from 1970 up to now in order to reduce more and more air emissions. Following is the table describing the global warming impacts from APC in all the scenarios:

Table No. 6.7: GWP_{100} (kg CO_2 eq / 1 FU) from the APC system in the Incineration process

1980	1990	2000	2010	2020
29.03	24.74	32	25.9	7.33

In the above table it is shown that with the technological development of APC in the incineration process, the emissions leading to global warming have been reduced with time. For example, in 1980, the GHG emissions were higher but in 1990 they became lower. In 2000, an increasing trend has been noticed due to the use of some other chemicals to reduce the air emissions from incinerators to the best extent (See Table No. 5.1). But in year 2010, the emissions have been reduced once again compared to year 2000 due to the more efficient technology and reduced amount of chemicals used to improve the air emissions quality. In the year 2020, the emissions are shown to be the lowest because of the use of wind power as energy source rather than coal or natural gas.

6.2.8. Global Warming from Transport Sector

Another interesting result has been found regarding the transport sector in all the scenarios analyzed in this report. Following is the table showing the emissions from transport sector in different time periods:

Table No. 6.8: GWP_{100} (kg CO_2 eq / 1 tkm) from the Transport system in different scenarios

1970	1980	1990	2000	2010
0.217	0.131	0.142	0.0763	1.32

In the above table, it is clear that the GWP_{100} (kg CO_2 eq / tkm) from transport sector during different time periods has decreased from 1970 to 2000 due to the better control over the vehicular emissions and less fuel consumption with every passing decade. But in year 2010, an increase is seen in the GHG emissions. This is because that for the year 2010, the unit process already present in SimaPro 7.2 and Ecoinvent database called ‘’ Transport, municipal waste collection, lorry 21t/CH U’’ is used. In this unit process the emissions regarding the maintenance operations have been also included but for the previous years the emissions from maintenance operation have not been included.

6.3. Other Impact Categories

Apart from Global Warming impact from MSWM, there are several other impact categories coming as a result of different treatment options of MSW. These impact categories are ozone depletion, eutrophication, acidification, human and eco system toxicity etc. Figure No. 6.3 is showing all the other environmental impact categories arising from MSWM in Aalborg Municipality from 1970 upto 2020. The figure reveals that regarding the MSWM, global warming is not the only indicator category and in fact it is less important compared to Aquatic Eutrophication (P) and Human Toxicity impacts. The results shown are obtained after *normalization* and *weighting* (See Section 5.3) to get the actual relevance and importance of each impact category.

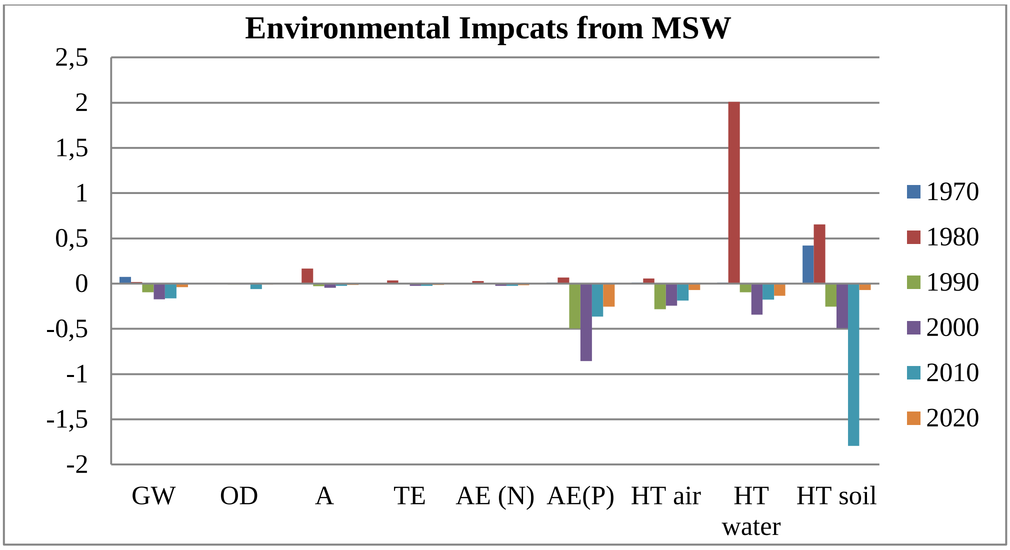


Figure No. 6.3: Environmental Impacts from MSWM in Aalborg from 1970 – 2020

GW: Global Warming, OD: Ozone Depletion, A: Acidification, TE: Terrestrial Eutrophication, AE (N): Aquatic Eutrophication (Nitrogen), AE (P): Aquatic Eutrophication (Phosphorus), HT: Human Toxicity

6.4. Sensitivity Analysis

Sensitivity analysis (sensitivity check) is performed to check the reliability and sensitivity of results by doing variations in assumptions, methods and data. Mainly, the sensitivity of the most significant issues identified is checked. In the sensitivity analysis, a comparison of the results is made, obtained by using the given assumptions, methods or data with the results obtained using altered assumptions, methods or data (ISO 14044 2006). In this section, two sensitivity analyses are made to check the reliability and sensitivity of results. These analyses are as follows:

6.4.1. Sensitivity Analysis 1

Sensitivity analysis 1 related to the change of method used for LCIA to check the sensitivity of results. In the current study, EDIP 2003 vi.02 has been used, but for sensitivity analysis, another method called ReCiPe Midpoint (H) V1. 04 version for European countries (Europe ReCiPe H) is used. This method is available in the new version of SimaPro 7.2.4. The results of sensitivity analysis 1 and actual results are as follows:

Table No. 6.6. A comparison of Actual LCIA results and Sensitivity Analysis 1

	Unit	1970	1980	1990	2000	2010	2020
Actual Results	kg CO_2 eq	586	130	-758	-1379	-1284	-304
Sensitivity Analysis 1	kg CO_2 eq	610	130	-688	-1333	-1290	-310

From the above table, it is clear that the results are not changed with a great variation but they lie in the same range with close similarity. Even for the year 1980, the results are exactly same. This confirms the reliability of data and method used for this LCA study.

6.4.2. Sensitivity Analysis 2

In this analysis the results of *Scenario 1 – 1970* will be analyzed by changing the assumption made that the total distance travelled by waste is 20 km. But now if we change this assumption with the perception that landfills are generally in the outskirts of city and this travel is 100 km instead of 20 km, then our results are changed like this:

Table No. 6.6. Comparison of actual LCA results and Sensitivity Analysis 2

	Unit	1970	Landfill operations	Transport
Actual Results	kg CO_2 eq	586	582	4
Sensitivity Analysis 1	kg CO_2 eq	603	582	21

From the above table, it is clear that transport sector has a major impact as when the distance travelled per ton of waste is increased from 20 tkm to 100 tkm then the share of global warming from transporting the waste increases but it still does not grows higher than landfill operation emissions which confirms the reliability of our results.

6.4.3. Sensitivity Analysis 3

The 3rd Sensitivity analysis is performed to check the assumption regarding the wind power as marginal electricity source in 2020. In order to check the sensitivity of this assumption, the considered marginal electricity source in 2020 is Biomass. Sensitivity analysis results show −317 kg CO_2 eq/ 1 FU whereas the actual study results are -304 kg CO_2 eq / 1FU. So, the detailed results of this sensitivity analysis and actual study results are compared in Table No. 6.7 (the numbers in black are actual study results whereas the numbers in blue are sensitivity analysis 3 results).

Table No. 6.7: Comparison of Actual LCA Results for Scenario 6 -2020 and Sensitivity Analysis 3

Incineration of Food Waste	**Incineration of Paper waste**	**Incineration of plastic waste**	**Composting of food waste**	**Composting of Yard waste**
6.06	11.75	0.035	-0.7	-45.83
5.07	7.91	-9.42	-0.693	-45.5
Recycling of plastic waste	**Recycling of paper waste**	**Recycling of PVC waste**	**Recycling of metals waste**	**Recycling of Glass**
0.006	-155.6	0.03	-103	-24.3
0.006	-156	0.04	-103	-24.3
APC	-			
7.33				
8.19				

Although the comparison reveals that sensitivity analysis result and actual study result remain in the same range with very little variation as the sensitivity analysis is saving more GHG emissions leading to global warming then the actual results. The reason behind this is the use of biomass as a marginal source of electricity in sensitivity analysis rather than the wind energy. The GWP_{100} / kWh of electricity produced from biomass is 0.04 whereas the GWP_{100} / kWh of electricity produced from wind power is 0.01. This shows that electricity produced from wind power is preferred to electricity produced from biomass regarding the GWP_{100} / kWh, revealing that more GHG emissions will be saved if substituted energy is from biomass rather than wind power.

6.4.4. Conclusion of Sensitivity Analysis

At the end of sensitivity analysis it can be concluded that no significant changes in results happened after the performance of all the three sensitivity analysis which supports the reliability of our results.

6.5. Evaluation of Results

According to the guidelines given in ISO 14044, the aim of evaluation of results is to build up and enhance the confidence in the reliability and accuracy of the results obtained from the LCA study. During the evaluation of results in current study, following three techniques are considered:

6.5.1. Completeness Check

The aim of the completeness check is to confirm that all the relevant information and data needed for the *Phase III - LCIA* of LCA are available and complete. For the current study, chapter 5 presents a detailed overview of all the data and information necessary for LCA. Most of the data regarding composition of MSW is primary and taken from Aalborg Municipality (Ladefoged, 2011), and the rest is secondary taken from literature studies.

6.5.2. Sensitivity Check

The purpose of sensitivity check is to check the reliability and sensitivity of results by changing the method used for LCA, change of assumptions made or data change. The section 6.4 of current chapter presents a comprehensive overview of sensitivity analysis performed for the current LCA study. Sensitivity analysis 1 was performed by changing the impact assessment method to see the effect on results. Sensitivity analysis 2 was done with the change in assumption made regarding distance travelled. Sensitivity analysis 3 was performed to check the sensitivity of marginal energy source for Scenario 6 – 2020.

6.5.3. Consistency Check

The purpose of the consistency check is to see if the assumptions, methods and data used are consistent with the goal and scope of study (ISO 14044 2006). The consistency check deals with the issues such as regional and/or temporal differences, allocation rules and system boundary and the consistently application of impact assessment elements.

For the current study, chapter 5 described in detail the goal and scope of study and addressed the issues of geographical and temporal scope. It was clearly stated that the study is limited to geographic boundaries of Aalborg Municipality, Denmark and data from year 1970, 1980, 1990, 2000 and 2010 will be used for LCA. The data source was mainly Aalborg Municipality, incineration plant named ''Reno Nord'' and literature studies. There were some assumptions made which were checked by the sensitivity analysis. There was no allocation applied to the modeling system due to system expansion in consequential modeling. The system boundary of all the scenarios is also consistent with the goal and scope of study. LCIA results were obtained using the software tool SimaPro 7.2 (Pre 2008). The software is very much consistent to the scenarios made in the study and also makes the necessary calculations after considering the functional unit of study.

6.6. Limitations of LCA Study

The limitations of current LCA study are as follows:

1. The Global Warming from MSWM in Aalborg Municipality is still not presenting the full picture as liquid waste, bulky waste (furniture etc), electronics waste, out of use automobiles waste and waste clothes are not analyzed in this study.
2. The recycling and composting processes are same without any technology change from 1990 to 2010, which is not realistic as there is always efficiency development regarding a certain technology.
3. Recycling and land filling of ash produced as a result of incineration process is not analyzed.
4. Transport data for every unit process and scenario is set same as 20 tkm, which is not according to the ground reality.

6.7. Discussion

From the LCA results, it is clear that GWP_{100} from MSWM in Aalborg Municipality very much depends on the respective treatment technology. In the current study, four different treatment technologies were analysed i.e. landfill, incineration, recycling and composting. These treatment options were different for different waste fractions in different time periods. Such as in 1970 only landfill option is analysed whereas in 1980 only incineration option is used. But from 1990 onwards, along with the incineration option, composting for food and yard waste and recycling for paper, glass, plastic, PVC and metals out of MSW stream are also included in analysis. The study has shown that in 1970 the GWP_{100} was highest as 586 kg CO_2 eq / ton of MSW and in 1980 it reduced upto 130 kg CO_2 eq/ ton of MSW. But from 1990 onwards the emissions leading to global warming are saved and in 2010 the emissions of -1284 kg CO_2 eq / ton of MSW were saved.

The main saver for global warming emissions from 1990 – 2020 have been the incineration process due to the heat and electricity production, recycling for the avoided production of raw materials and composting due to their fertilizer value. If the results of this case study are compared with the Poulsen & Hansen (2009), then the global warming impact shows the same trend as in the current study. Although Poulsen & Hansen (2009) have excluded the recycling for various waste fractions such as paper, plastic, glass, metals and PVC and have included waste water with its corresponding treatment technology (anaerobic digestion) in their analysis. But still in both of studies, incineration is the common unit process which proved to be the major terminator regarding the energy recovery and GHG emission's saving. If the results are compared per person, then both studies show the similarity such as in 1970 the GWP_{100} per capita was 269 kg CO_2 eq and in 2010 it has reduced upto -644 kg CO_2 eq / person/ year. In the study by Poulsen & Hansen (2009), every person was responsible for about 200 kg CO_2 eq / person / year in 1970 to -170 kg CO_2 eq / person / year in 2005. Hence, both of studies show a shift from net emitter in 1970 to net saver now a days.

Furthermore, in the current study only GWP_{100} was used as the representative indicator category for MSWM but in Figure No. 6.3, it is clear that the chosen category did not seemed to be an appropriate impact category in terms of MSWM as other impact categories such as acidification, aquatic eutrophication and human toxicity revealed to be more significant impact categories compared to GWP_{100}. So, assessing the waste management systems on the basis of only global warming may not be appropriate for researchers and decision makers both (Merrild 2009). On the other hand, GWP_{100} and acidification are two mostly used impact categories to assess the environmental impacts from waste management systems (Cleary 2009). Human and ecosystem toxicology categories are less used compared to GWP_{100} because there are large uncertainties attached to these categories compared to the popular category of GWP_{100} (Moberg et al. 2005). Moreover, according to Reap et al (2008), the models to assess the toxicological impacts have not been fully established by now and they are still under development process to handle the problem of associated uncertainties.

Lastly, *Scenario 6 – 2020* is completely based on assumptions and there may be several uncertainties as future is always uncertain and unexpected. So, if there is this assumption tested in current study that in 2020, the marginal energy source will be wind power then according to Mathiesen et al (2009), ‘’Wind power operation cannot respond to changes in demand, and it has natural constraints as its potential is limited from one region to another; thus, wind cannot be considered the marginal technology neither in short-term nor in long-term LCA studies’’. In this situation, biomass can prove to be the future marginal energy source which is tested in Sensitivity Analysis 3. But if the long run, renewable energy is going to be the main energy source, then the energy phased out will be Coal and gas CHP. And if the lifetime of coal power plants is considered, then there might be some old coal power plants near to end of life which can be the marginal source of energy in future as they will be subject to be affected by change in demand. Hence, it is clear that the decision about the marginal energy source for future is having some uncertainties in it.

7. Conclusion

7.1. General Conclusion

Historical analysis and comparison of different waste streams regarding their GWP_{100} has always been an interesting field as many researchers have been working on it. Going back into history and look for the waste composition and amounts, their respective treatment technologies is very useful to learn the experiences from the past and not to repeat the same mistakes in future. This practice not only supports to identify the loopholes in the previous decades regarding the development of waste management plans but also it give a clue to economic wellbeing of the social system in different time periods e.g. more economic development leads to the ‘’use and throw societies’’ which has been seen in 1970s in Denmark as well. It helps to fill up the knowledge gap regarding the data limitations in different time periods as well.

Waste is not waste until and unless it can be used to recover materials and energy from it. The phenomenon of ‘’Waste to Energy’’ is not new in Denmark as the first incinerator was built in 1903 in Frederiksberg and the energy produced from this incinerator was sold to a nearby hospital. This first incinerator had a motive of no more landfill space availability issue behind its construction. But as the time passed away, the awareness regarding the environmental impacts arising from handling and treatment of MSW increased and Government put its focus on developing the waste strategies considering the material and fuel value of this waste. Secondly, the oil crisis in 1973 also pushed the Government to focus more on renewable energy sources and cut the use of fossil fuels slowly as at that time Denmark’s total economy was dependent on oil. So, the previous motive of Landfill place availability had been shifted to environmental safety and energy security from 1970 onwards.

With the change of background motive for Incineration, the need of hour was to develop the waste management strategies and plans based on the scientific evidence to prefer and support one treatment option on the other regarding their environmental pros and cons. LCA is the appropriate tool to provide this scientific evidence for the development of respective waste management plans and strategies.

7.2. Conclusion on Waste Management Plans and Strategies

Waste management plans and strategies in Denmark have been evolved from a very common perspective of ‘’dilution’’ in 1970s and ‘’end of pipe solutions’’ in 1980s to ‘’cleaner production’’ in 1990s and ‘’ cleaner products’’ in 2000 and onwards in terms of environmental solutions. The *1973 Environmental Protection Act* focused on making the sanitary landfills because upto that time the landfills were unlined causing the ground water pollution. During the same time period, environmentally safe transport, handling and treatment of toxic waste was also a topic of discussion and very much focused in Government waste management plans. The *Waste Policy of 1987* stressed on repairing the environmental damages happened in past and put an effort to avoid these damages in future, hence encouraging the ‘’end of pipe solutions’’. Later in the *Action Plan for Waste and Recycling 1993 – 1997*, the stress was given to follow the Waste Management Hierarchy by giving the preference order of recycling, incineration and landfill by setting a target of recycling the 54% of total waste, incinerating 25% and landfilling 21%. In the next plan *‘’ Waste 21 1998 – 2004’’* , again the focus was to follow the waste management hierarchy by setting even more stringent targets such as 64% Recycling, 24% incineration and 12% land filling along with a focus to improve these waste management technologies. In the *‘’Waste Strategy 2005 – 2008’’*, the focus had been given to decouple the waste generation from economic growth as it has been seen that as a result of economic growth, the waste generation rate also accelerates. This strategy came with stricter targets of 65% recycling, 26% incineration and 9% landfilling. The latest plan *‘’Waste Strategy 2009 – 2012’’* set the target of 65% recycling, 29% incineration and 6% landfilling. So, it is concluded that the focus of Government polices has been to increase the recycling of waste and decrease the amount of waste going to incineration and landfilling but in last two policies the target for recycling is same but the target for landfilling has been decreased and the load from landfill has been shifted towards incineration.

The case study of Aalborg Municipality gave the writer a chance to compare the waste management plans at local level as well. The earliest plan found in Aalborg is *‘’Waste Plan 1989’’* stressing to follow the waste management hierarchy. The next plan found is *‘’ Waste Plan for Households 1996 – 2007’’* again stressing on following the waste management hierarchy by preferring the recycling over incineration and the least preferred option as landfill. Later in *‘’ Waste plan 2000 – 2012’’*, along with following the waste management hierarchy, focus is given to encourage the waste prevention at the source rather than end of pipe solutions. *''Waste Plan 2005- 2016''* sets the same target to be followed as in National Waste management plans of '' Waste 21 1998- 2004'' and ''Waste Strategy 2005- 2008''. The latest waste management plan is *'' Waste Plan 2008 – 2016''* and it is actually the same plan as the previous one but the Municipality required to re-launch it due to the merge of municipalities in 2007. At the end, it reveals that the national and local waste management plans go hand in hand regarding the main aims and objectives and also the set targets.

7.3. Conclusion on LCA Results

In relation to the LCA of MSW in Aalborg Municipality from 1970 up to 2020, GWP_{100} has been used as the representative impact category. The LCA results show that in 1970 when all the MSW was land filled had the highest GWP_{100} as 586 kg CO_2 eq / 1 FU. In 1980, the situation became little better when MSW was incinerated rather than land filling and this practice lowered the GWP_{100} up to 130 kg CO_2 eq / 1 FU. In 1990, the emissions leading to global warming shown a downward trend and became lower than ''0'' revealing the saving of emissions. So, the GWP_{100} at that time was -758 kg CO_2 eq/ 1 FU. The emissions were saved because the heat produced from incineration processes substituted the heat produced from coal and also paper, glass and metals were recycled which led to the avoided virgin material production of these waste fractions. In 2000, the global warming emissions were even more saved and in fact at this time, the emissions were at its lowest point (See Figure No. 6.1) as −1379 kg CO_2 eq/ 1FU. This happened due to the heat and electricity production from the incineration process as both of these energy forms substituted the heat and electricity produced from coal. Moreover, paper, glass and metals were recycled at that time as well. In 2010, the GWP_{100} is – 1284 kg CO_2 eq/ 1FU and it is clear that emissions leading to global warming are saved because the heat and electricity produced from incineration of waste substitutes the heat and electricity produced from natural gas. In 2020, the GWP_{100} is -304 kg CO_2 eq/ 1FU which means that global warming emissions from MSWM will be saved in 2020 as well but not as much as they are saved in 2010 because in 2010 the substituted energy source is natural gas (fossil fuel) but in 2020 the substituted energy source is assumed to be wind power.

Regarding the GWP_{100} from MSW per person, the trend is again same as per ton of MSW treated per year in Aalborg (See Figure No. 6.2). In 1970, every single person in Aalborg municipality was responsible for 269 kg CO_2 eq arising from MSW per year but the GWP_{100}

reduced per person with time and in 2010, every single person is saving -644 kg CO_2 eq from MSW per year.

At the end it is concluded that although there are several issues to be considered when performing LCA such as efficiency of the waste treatment system and marginal energy source etc, but still LCA has proved to be a very useful tool for the environmental assessment of different waste management options in different time periods. So, it can be used for developing the waste management policies based on the proper scientific evidence to support and prefer one treatment technology over the other. But the results of this LCA study are only valid for the case study of Aalborg Municipality and decision makers should always develop the waste management policies based on LCA studies only after checking the geographical boundaries of study.

8. Perspective

The aim of current study was to present a historical overview of GWP_{100} coming from MSWM in Aalborg Municipality and for this purpose the time period selected was from 1970 up to 2020, out of which only 2020 scenario was a total assumption based scenario and the rest years present the actual picture. As reliable and precise data has a significant importance in LCA studies and in current study there had been difficulties in collecting the data from especially 1970 and 1980, so some assumptions have been made in order to fill up the knowledge gap regarding the historical comparison of Global Warming from MSW in Aalborg. Hence, to be able to use the results of current study at policy making level, there are certain limitations of the current study primarily due to lack of data which should be cared about. These data limitations are related to treatment technology, different waste fractions in different time periods, energy and transport sector.

First of all, the current study still not present the complete picture of global warming impact from MSW in Aalborg as some of the waste fractions have not been analyzed such as bulky waste (furniture), electronic waste and construction waste. These fractions are also handled in different ways. Regarding the treatment technologies, this study did not considered the anaerobic decomposition which leads to the biogas production, ultimately leading to the substitution of fossil fuel resources. Including this waste treatment option in the current study could also change the overall results of LCA study. So, in future to fill up all the gaps, it is recommended to include all the waste fractions of MSW and all the available and currently used waste treatment technologies in Aalborg.

Regarding the transport sector as described earlier in Section 6.5, the distance travelled for MSW to different treatment options is assumed to be the same which is not realistic as the distance is different for different treatment options. For example, the distance to the incineration plant and landfill can be smaller because they mostly lie in the vicinities of urban areas but for the recycling plants, mainly they are not available in every city and maybe there are only a few recycling stations across the country. So, now if the global warming impact from recycling of paper and plastic is less than incinerating these fractions according to the pre-determined same distance travel, and if as a result of increasing the distance for recycling process the global warming impact becomes higher from recycling than incineration then recycling will no more be a green option. So, in order to make some policy decision about choosing between recycling and incineration, the ground realities of transporting the waste to different facilities should also be considered as for transport sector still Gasoline (the fossil fuel) is the common fuel rather than developing some renewable transport fuel.

The current study was mainly focused on ‘’Energy from Waste’’ and it has been tried to look the change in GWP_{100} from especially incineration process from 1980 onwards. Also the development in efficiency of these incineration plants and their APC system has been analyzed. It looks very strange when a system to clean the air emissions itself contributes to the GWP_{100} due to the use of several chemicals and energy as a lot of gaseous emissions come out of this APC system. So, in future it is needed to carefully analyze the APC system in incineration process by making a detailed comparison of the environmental benefits obtained from incineration process and the environmental loss from APC system to clear all the confusions.

To get the complete picture of Sustainable Development, only environmental sustainability is not enough. Social and economic perspectives as well have their own importance and significance. So, for the future research it is highly recommended to include the social LCA and LCC to reach the actual sustainable waste management solution.

References

Aalborg Municipality. 1989. Affaldsplan, Aalborg Kommune, May 1989.

Aalborg Municipality. 1995. Affaldsplan for Husholdninger 1996- 2007, April 1995.

Aalborg Municipality. 2004. Affaldsplan 2005 – 2016, June 2004.

Affald. 1988. Danmarks Naturfredningsforening, Denmark.

Affaldsstrategi ’10. 2010. Ministry of Environment, Copenhagen, Denmark. Accessed April 8, 2011. http://www.mst.dk/NR/rdonlyres/5944D6BF-C455-4A94-A7D1-9062ED0173A0/0/Affaldsstrategi10.pdf.

Astrup, T., Møller, J., and Fruergaard, T. 2009a. ‘’Incineration and co – combustion of waste: accounting of greenhouse gases and global warming contributions’’. *Waste Management and Research* 27: 789 – 799.

Astrup, T., Fruergaard, T., and Christensen, T.H. 2009b. ‘’Recycling of plastic: accounting of greenhouse gases and global warming contributions’’. *Waste Management & Research* 27: 763 – 772.

Barlaz, M. 1998. ‘’Carbon Storage during biodegradation of municipal solid waste components in laboratory- scale landfills’’. *Global Biogeochemical Cycles* 12: 373- 380

Bogner, J., and Matthews, E. 2003. ‘’Global methane emissions from landfills: New methodology and annual estimates 1980- 1996’’. *Global Biogeochemical Cycles* 17: 1-18

Bogner, J., Pipatti, R., Hashimoto, S., Diaz, C., Mereckova, K., Diaz, L, Kjeldsen, P., Monni, S., Faaij, A., Gao, Q., Zhang, T., Ahmed, M.A., Sutamihardja, R.T.M., and Gregory, R. 2008. ‘’Mitigation of Global Greenhouse gas Emissions from waste: conclusions and strategies from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report; Working Group III (Mitigation)’’. *Waste Management and Research* 26: 11- 32.

Boldrin, A., Andersen, J.K., Møller, J., and Christensen, T.H. 2009. ‘’Composting and compost utilization: accounting of greenhouse gases and global warming contributions’’. *Waste Management and Research* 27: 800 – 812.

Bryman, A. 2008. *Social Research Methods*. Oxford University Press, Oxford.

Christensen, P. 2011. Personal Conversation with Prof. Per Christensen at Department of Development and Planning, University of Aalborg on May 31, 2011.

City of Aalborg. 2010. ''Aalborg in figures''. Department of Finance. Accessed March 27, 2011. http://www.aalborgMunicipality.dk/Om_Municipalityn/fakta-om-Municipalityn/Aalborg-i-tal/Documents/Aalborg-in-figures-2010.pdf.

City of Aalborg, 2005. ''Aalborg Commitments: A baseline Review''. Department of Sustainability and Health. Accessed March 28, 2011. http://www.aalborgplus10.dk/media/pdf2005/aalborg_commitments_engelsk.pdf.

City of Aalborg, 2008. ''Local Initiatives for Sustainable Development: Sustainability Strategy 2008-11''. Department of Sustainability and Health. Accessed April 8, 2011. http://www.aalborgMunicipality.dk/english-version/Documents/baeredygtighedstrategi_engelsk_version.pdf.

Cleary, J. 2009. ''Life Cycle Assessment of Municipal Solid Waste Management Systems, A comparative analysis of selected peer reviewed literature''. *Environment International* 35:1256–1266

Consonni, S., Giugliano, M., and Grosso, M. 2005. ''Alternative strategies for energy recovery from municipal solid waste. Part B- Emission and cost estimates''. *Waste Management* 25: 137-148.

Dalager, S. 2006. ''Waste Incineration in Denmark.Ramboll, Denmark''. Accessed March 23, 2011. www.ramboll.dk/wte.

Dalager, S. 2011. Personal conversation with Søren Dalager from Ramboll, Denmark on April 18, 2011.

Damgaard, A., Larsen, A.W., and Christensen, T.H. 2009. ''Recycling of metals: accounting of greenhouse gases and global warming contributions''. *Waste Management and Research* 27: 773 – 780

Danish Energy Agency. 2009. ''Energy Statistics 2009''. Accessed March 9, 2011. http://www.ens.dk/en-US/Info/FactsAndFigures/Energy_statistics_and_indicators/Annual%20Statistics/Documents/Energi%20Statistics%202009.pdf

Danish Environmental Protection Agency. 1992. ''Action Plan on Waste and Recycling 1993 – 1997''. Ministry of the Environment, Copenhagen, Denmark.

Danish Environmental Protection Agency. 1999. ‘’Waste 21: Waste Management Plan 1998 – 2004’’. Danish Ministry of Environment and Energy, Denmark. Accessed April 3, 2011. http://www2.mst.dk/udgiv/Publications/1999/87-7909-571-2/pdf/87-7909-570-4.pdf.

Deuber, O., Cames, M., Poetzsch, S., and Repenning, J. 2005. ‘’Analysis of Greenhouse Gas Emissions of European Countries with Regards to the Impact of Policies and Measures’’. Report by Oko- Institute to the German Umweltbundesamt, Berlin.

EEA. 2004. ‘’Greenhouse Gas Emission Trends and Projections in Europe 2004’’. European Environment Agency (EEA) Report no 5/2004, Progress EU and its member states towards achieving their Kyoto targets. EEA, Luxembourg.

EIPPC Bureau. 2006. ‘’Reference Document on the Best Available Techniques for Waste Incineration (BREF), Integrated Pollution Prevention and Control’’. European IPPC, Seville, Spain.

Eriksson, O., Finnveden, G., Ekvall, T., and Bjorklund, A. 2007. ‘’Life cycle assessment of fuels for district heating: A comparison of waste incineration, biomass- and natural gas combustion’’. *Energy Policy* 35: 1346–1362.

European Commission. 2005. ‘’Story behind the Strategy; EU Waste Policy’’. Accessed February 21, 2011. http://ec.europa.eu/environment/waste/pdf/story_book.pdf.

European Commission. 2008. ‘’Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives’’. *Official Journal of the European Union*, L 312: 3-30.

European Commission. 2010. "What is integrated product policy". European Commission homepage. Accessed May 23, 2011. http://ec.europa.eu/environment/ipp/integratedpp.htm.

European Environment Agency. 2010a. ‘’The European Environment State and Outlook 2010; Synthesis’’. Accessed February 22, 2011. http://www.eea.europa.eu/soer/synthesis/synthesis/natural-resources-and-waste-2014.

European Environment Agency. 2010b. ‘’The European Environment State and Outlook 2010; Waste (Denmark)’’. Accessed February, 2011. http://www.eea.europa.eu/soer/countries/dk/soertopic_view?topic=waste.

Faiz, A., Weaver, C.S & Walsh, M.P. 1996. *Air Pollution from Motor Vehicles: Standards and Technologies for controlling emissions*. The World Bank, Washington, D.C. Accessed on May 23, 2011. http://www.google.com/books?hl=da&lr=&id=Hqsyv_KD0lgC&oi=fnd&pg=PR13&dq=air+pollution+from+road+transport+in+1970&ots=Dd1DjtON1k&sig=iPeBEeqvzdKj1LX_RsB7GBIXt9E#v=onepage&q&f=true.

Finneveden, G., Hauschild, M.Z., Ekvall, T., Guine’ e, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., and Suh, S. 2009. ‘’Recent Developments in Life Cycle Assessment’’. *Journal of Environmental Management* 91: 1 – 21.

Finnveden, G., Johansson, J., Lind, P., and Moberg, A. 2005. ‘’Life cycle assessment of energy from solid waste—part 1: general methodology and results’’. *Journal of Cleaner Production* 13: 213–229.

Finnveden, G., and Ekvall, T. 1998. ‘’Life-cycle assessment as a decision-support tool—the case of recycling versus incineration of paper’’. *Resources, Conservation and Recycling* 24: 235–256.

Flugsrud, K., Hoem, B., Kvingedal, E., and Rypdal, K. 2001. ’’Estimating net Emissions of CO_2 from Harvested Wood Products’’. SFT Report 1831/200, Norwegian Pollution Control Authority, Oslo.

Forsynings Virksomhederne. 2007. ‘’Affaldsplan 2008 – 2016’’. December 2007.

Gentil, E., and Christensen, T.H. 2009. ‘’Greenhouse gas accounting and Waste management’’. *Waste Management and Research* 27: 696- 706.

Guinee, J.B., Gorree,M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., van Ores, L., Weneger, A., Suh, S., Udo de Haes, H.A., DE Bruijn, H., van Duin, R., and Huijbregts, M. 2001. *Life Cycle Assessment: an operational guide to the ISO standards; Part 2a*. Leiden, The Netherlands.

Hashimoto, S., and Moriguchi, Y. 2004. *Data book: Material and Carbon Flow of Harvested Wood in Japan*. CGER Report D034, National Institute for Environmental Studies, Japan, Tsukuba.

Hill, A.L. 2010. *Life Cycle Assessment of Municipal Waste Management: Improving on the Waste Hierarchy*. Master’s thesis at Department of Development and Planning, Aalborg University, Denmark.

IPCC. 2007a. Bogner, J., M. Abdelrafie Ahmed, C. Diaz, A. Faaij, Q. Gao, S. Hashimoto, K. Mareckova, R. Pipatti., and T. Zhang. 2007, Chapter 10. *Waste Management, in Climate Change*, 2007: Mitigation, Contribution of Working Group III to the 4th Assessment Report of IPCC.

IPCC. 2007b. *Climate Change. Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Core Writing Team, Pachauri, R. K., and Reisinger, A. IPPC, Geneva, Switzerland.

ISO 14040. 2006. *Environmental Management – Life Cycle Assessment - Principles and Framework.* International Standard Organization (ISO), Geneve.

ISWA. 2009. ''Waste and Climate Change; ISWA White Paper''. Accessed March 21, 2011. http://www.iswa.org/fileadmin/user_upload/_temp_/WEB_ISWA_White_paper.pdf.

Jolliet, O., R. Müller-Wenk, J. Bare, A. Brent, M. Goedkopp, R. Heijungs, N. Itsubo, C. Peña, D. Pennington, J. Potting, G. Rebitzer, M. Stewart, H. Udo de Haes., and B. Weidema, 2004. ''The LCIA Midpoint-damage Framework of the UNEP/SETAC Life Cycle Initiative''. *International Journal of Life Cycle Assessment* 9: 394-404.

Kleis, H., Babcock., Vølund, W., and Dalager, S. 2003. ''100 Years of Waste Incineration in Denmark''. Babcock & Wilcox Vølund A/S & Ramboll, Denmark. Accessed March 21, 2011. http://www.ramboll.com/services/energy%20and%20climate/~/media/Files/RGR/Documents/waste%20to%20energy/100YearsLowRes.ashx.

Ladefoged, D. 2011. Personal conversation with Dorte Ladefoged, Civil Engineer at Aalborg Municipality on May 5, 2011.

Larsen, A.W., Merrild, H., and Christensen, T.H. 2009. ''Recycling of glass: accounting of greenhouse gases and global warming contributions''. *Waste Management and Research* 27: 754 – 762

Lund, H. 2007. ''Renewable energy strategies for Sustainable Development''. *Energy* 32: 912 – 919.

Lyngholm, T. 2011. Persoanl conversation with Thomas Lyungholm, the Environmental Manager at Reno Nord, Aalborg on April, 15, 2011.

Manfredi, S., Tonini, D., and Christensen, T.H. 2009. ''Landfilling of waste: accounting of greenhouse gases and global warming contributions''. *Waste Management and Research* 27: 825 – 836

Mathiesen, B.V., Munster, M., and Fruesrgaard, T. 2009. ''Uncertainties related to the identification of the marginal energy technology in Consequential Life Cycle Assessments''. *Journal of Cleaner Production* 17: 1331 – 1338.

Merrild, H. 2009. ''Indicators for waste management: How representative is global warming as an indicator for environmental performance of waste management?''. PhD Thesis, Department of Environmental Engineering. DTU, Denmark.

Merrild, H., Damgaard, A., and Christensen, T.H. 2009. ''Recycling of Paper: accounting of greenhouse gases and global warming contributions''. *Waste Management and Research* 27: 746 – 753.

Ministry of Environment. 1987. ''Danish Waste Policy: Existing problems and proposed measures. National Agency of Environment Protection, Denmark''. Accessed April 5, 2011. http://www2.blst.dk/download/aar/aaa/www/pdf/87-503-6449-9.pdf.

Moberg, A., Finnveden, G., Johansson, J., and Lind, P. 2005. ''Life cycle assessment of energy from solid waste - part 2: landfilling compared to other treatment methods''. *J Clean Prod* 13: 231–40.

Monni, S., Pipatti, R., Lehtila, A., Savolainen, I., and Syri, S. 2006. ''Global Climate Change Mitigation Scenarios for Solid Waste Management''. Technical Research Centre of Finland. VTT Publications, Espoo.

Nissen, B., Hansen, G., Høeg, P., Nielsen, A., and Pommer, K. 1994. ''Dagrenovation fro private husholdninger''. Miljøprojekt nr. 264, Miljøstyrelsen, København.

Pichtel, J. 2005. *Waste Management Practices: Municipal, Hazardous, and Industrial*. eBook ISBN: 978-1-4200-3751-7. Taylor & Francis Goup LLC. Accessed March 12, 2011. http://www.crcnetbase.com.zorac.aub.aau.dk/isbn/9781420037517

Pre. 2008. ''SimaPro 7.2 Pre Consultants B.V''. Amersfoort, The Netherlands. www.pre.nl

Poulsen, T.G., and Hansen, J.A. 2009. ''Assessing the impacts of changes in treatment technology on energy and greenhouse gas balances for organic waste and waste water treatment using historical data''. *Waste Management & Research* 27: 861 – 870.

Poulsen, T.G. 2011. Personal conversation with Tjalfe G Poulsen, Associate Professor at Aalborg University in April and May 2011.

Reap, J., Roman, F., Duncan, S., and Bras, B. 2008. ''A survey of unresolved problems in life cycle assessment. Part 2: Impact assessment and interpretation''. *International Journal of Life Cycle Assessment* 13: 374- 388.

Remmen, A., and Thrane, M. 2007. ''Pollution Prevention''. In Kørnøve, L., Thrane, M., Remmen, A and Lund, H. 2007. *Tools for Sustainable Development*. Aalborg Universitetsforlag, 9220 Aalborg, Denmark.

Schmidt, J. H. 2007. *Life cycle assessment of rapeseed oil and palm oil*. Ph.D. thesis, Part 3: Life cycle inventory of rapeseed oil and palm oil. Department of Development and Planning, Aalborg University, Aalborg.

Thrane, M., and Schmidt, J.A. 2007. ''Life Cycle Assessment''. In Kørnøv, L., Thrane, M., Remmen, A & Lund, H: *Tools for Sustainable Development*, Aalborg Universitetsforlag, 9220 Aalborg, Denmark.

The Danish Government. 2004. *Waste Strategy 2005 – 2008*. Accessed April 12, 2011. http://www2.mst.dk/udgiv/publications/2004/87-7614-249-3/pdf/87-7614-250-7.pdf

Tønning, K., Ottosen, L.M., Malmgren-Hansen, B., Petersen, C., and Skøvgaard, M. 1997. ''Genanvendelse af dagrenovation – miljømæssig og økonomisk vurdering''. Arbejdsrapport nr. 86. Miljøstyrelsen, København.

UN HABITAT. 2010. *Solid Waste Management in the World's Cities; Water and Sanitation in the World's Cities 2010*. Accessed January 1, 2011. http://www.unhabitat.org/pmss/getPage.asp?page=bookView&book=2918.

UNEP. 2003. *Evaluation of Environmental Impacts in Life Cycle Assessment.* United Nations Environment Program, Division of Technology, Industry and Economics Production and Consumption Branch. United Nations Publication. ISBN: 92-807-2144-5. Accessed April 4, 2011. http://lcinitiative.unep.fr/default.asp?site=lcinit&page_id=F511DC47-8407-41E9-AB5D-6493413088FB.

UNEP. 2007. ''Life Cycle Management: A Business Guide to Sustainability''. ISBN: 978-92-807-2772-2 DTI/0889/PA.

US EPA. 2006. ''Global Anthropogenic Non- CO_2 Greenhouse Gas Emissions: 1990- 2020''. Office of Atmospheric Programs, Climate Change Division.

Weidema, B. 2003. ''Market Information in life cycle assessment''. Environmental Project No. 863. Danish Environmental Protection Agency, Copenhagen

Weidema, B.P. 2001. ''Avoiding co- product allocation in life cycle assessment''. *Journal of Industrial Ecology* 4: 11 – 33.

Willumsen, H.C. 2003. ''Landfill gas plants: number and type worldwide''. In Proc. of the Sardinia 05, International Solid and Hazardous Waste Symposium, October 2005. CISA, University of Cagliari, Sardinia.

Appendix I

1. Recycling of Plastic

All the data used for this LCI is from Astrup et al (2009b) and it is assessed with a rate of 30% loss of material[8].

LCI for Recycling of Plastic

Inputs and Outputs of ''Recycling of Plastic''	Amounts & Units	Unit Process Used in SimaPro 7.2
Input		
• Polyethylene High Density	1 ton	Polyethylene, HDPE, granulate, at plant/RER U
• Fuel Oil	0.6 L	Heavy fuel oil, at regional storage/RER U
• Electricity 2010	330 kWh	Electricity, natural gas, at power plant/NORDEL U
• Electricity 2020		Electricity, at wind power plant/RER U
• Natural gas	264 kWh	Natural gas, high pressure, at consumer/DK U
Output / Avoided Product		
• Polyethylene High Density	720 kg	Polyethylene, HDPE, granulate, at plant/RER U

Source: Astrup et al (2009)

[8] Astrup *et al* (2009b)

2. Recycling of Paper

All the data for this LCI is used from Merrild et al (2009) with a rate of 2.4% loss of material[9].

LCI for Paper Recycling

Inputs and Outputs of ''Recycling of Paper''	**Amounts & Units**	**Unit Process Used in SimaPro 7.2**
Input		
• Waste Paper	1 ton	Waste paper, mixed, from public collection, for further treatment/CH S
• Fuel Diesel	1 L	Diesel, at regional storage/RER U
• Electricity 1990 & 2000 • Electricity 2010 • Electricity 2020	30 kWh	Electricity, hard coal, at power plant/NORDEL U Electricity, natural gas, at power plant/NORDEL U Electricity, at wind power plant/RER U
• Natural gas	87 MJ	Natural gas, high pressure, at consumer/DK U
Output / Avoided Product		
• Recycled Paper	976 kg	Paper, recycling, with deinking, at plant/RER U

Source: Merrild et al (2009)

[9] Merrild et al (2009)

3. Recycling of PVC

LCI for PVC Recycling

Inputs and Outputs of ''Recycling of PVC''	**Amounts & Units**	**Unit Process Used in SimaPro 7.2**
Input		
• Polyvinylchloride	1 ton	Polyvinylchloride, at regional storage/RER U
• Fuel Oil	0.6 L	Heavy fuel oil, at regional storage/RER U
• Electricity 2010	330 kWh	Electricity, natural gas, at power plant/NORDEL U
• Electricity 2020		Electricity, at wind power plant/RER U
• Natural gas	264 kWh	Natural gas, high pressure, at consumer/DK U
Output / Avoided Product		
• Polyvinylchloride	1 ton	Polyvinylchloride, at regional storage/RER U

Source: Modified from Astrup et al (2009b)

4. Recycling of Glass

All the data for this LCI is used from Larsen et al (2009) with a rate of 7% loss[10].

LCI for Glass Recycling

Inputs and Outputs of ''Recycling of Glass''	**Amounts & Units**	**Unit Process Used in SimaPro 7.2**
Input		
• Waste Glass	1 ton	Glass, from public collection, unsorted/RER U
• Electricity 1990 & 2000 Electricity 2010 Electricity 2020	20 kWh	Electricity, hard coal, at power plant/NORDEL U Electricity, natural gas, at power plant/NORDEL U Electricity, at wind power plant/RER U
• Natural gas	47.3 kWh	Natural gas, high pressure, at consumer/DK U
Output / Avoided Product		
• Recycled Glass	730 kg	Flat glass, uncoated, at plant/RER U

Source: Larsen et al (2009)

[10] Larsen et al (2009)

5. Recycling of Metals

LCI for Metals Recycling

Inputs and Outputs of ''Recycling of Metals''	**Amounts & Units**	**Unit Process Used in SimaPro 7.2**
Input		
• Waste Iron	500 kg	Iron scrap, at plant/RER U
• Waste Aluminium	500 kg	Aluminium scrap, old, at plant/RER U
• Electricity 1990 & 2000	50 kWh	Electricity, hard coal, at power plant/NORDEL U
• Electricity 2010		Electricity, natural gas, at power plant/NORDEL U
• Electricity 2020		Electricity, at wind power plant/RER U
• Fuel Oil	6.8 L	Heavy fuel oil, at regional storage/RER U
Output / Avoided Product		
• Recycled Iron	475 kg	Pellets, iron, at plant/GLO U
• Recycled Aluminium	465 kg	Aluminium, production mix, at plant/RER U

Source: Damgaard et al (2009)

Appendix II

1. Composting of Food Waste

LCI for Food Waste Composting

Inputs and Outputs of ''Composting of Food Waste''	**Amounts & Units**	**Unit Process Used in SimaPro 7.2**
Input		
• Food Waste	1 ton	Biowaste, at collection point/CH U
• Electricity 1990 & 2000 Electricity 2010 Electricity 2020	65 kWh	Electricity, hard coal, at power plant/NORDEL U Electricity, natural gas, at power plant/NORDEL U Electricity, at wind power plant/RER U
• Fuel Oil	3 L	Heavy fuel oil, at regional storage/RER U
Output / Avoided Product		
• Compost	400 kg	Compost, at plant/CH U
• N fertilizer	5.2 kg	Fertiliser (N)
• P fertilizer	1.9 kg	Fertiliser (P)
• K fertilizer	5.4 kg	Fertiliser (K)

Source: Boldrin et al (2009)

2. Composting of Yard Waste

LCI for Yard Waste Composting

Inputs and Outputs of ''Composting of Yard Waste''	Amounts & Units	Unit Process Used in SimaPro 7.2
Input		
• Yard Waste	1 ton	Biowaste, at collection point/CH U
• Electricity 1990 & 2000	65 kWh	Electricity, hard coal, at power plant/NORDEL U
Electricity 2010		Electricity, natural gas, at power plant/NORDEL U
Electricity 2020		Electricity, at wind power plant/RER U
• Fuel Oil	3 L	Heavy fuel oil, at regional storage/RER U
Output / Avoided Product		
• Compost	700 kg	Compost, at plant/CH U
• N fertilizer	3.4 kg	Fertiliser (N)
• P fertilizer	2.8 kg	Fertiliser (P)
• K fertilizer	9.7 kg	Fertiliser (K)

Source: Boldrin et al (2009)

Appendix III

1. LCI for Incineration of Food waste

Year	Incineration of Food Waste	Amount and Units	Unit process used in SimaPro 7.2
2010 & 2020	**Inputs** 1. Biowaste	1 ton	Biowaste, at collection point/CH U
	2. Power	0.1456 GJ	Electricity, biowaste, at waste incineration plant, allocation price/CH U
	Outputs / Avoided Products 1. Electricity	3.32 GJ	2010: Electricity, natural gas, at power plant/NORDEL U 2020: Electricity, at wind power plant/RER U
	2. Heat	0.94 GJ	2010: Heat, natural gas, at industrial furnace low-NOx >100kW/RER U 2020: Heat from waste, at municipal waste incineration plant/CH U
2000	**Inputs** 1. Biowaste	1 ton	Biowaste, at collection point/CH U
	2. Power	0.1222 GJ	Electricity, biowaste, at waste incineration plant, allocation price/CH U
	Outputs / Avoided Products 1. Electricity	3.32 GJ	Electricity, hard coal, at power plant/NORDEL U
	2. Heat	0.94 GJ	Heat, anthracite, at stove 5-15kW/RER U
	Inputs 1. Biowaste	1 ton	Biowaste, at collection point/CH U
	2. Power	0.17 GJ	Heat, biowaste, at waste incineration plant,

1990			allocation price/CH U
	Outputs / Avoided Products 1. Heat	3.4 GJ	Heat, anthracite, at stove 5-15kW/RER U

Following is the inventory for incineration of paper waste out of residual waste fraction according to different scenarios:

2. LCI for Incineration of Paper waste

Year	Incineration of Paper Waste	Amount and Units	Unit process used in SimaPro 7.2
2010 & 2020	**Inputs** 1. Waste Paper	1 ton	Waste paper, mixed, from public collection, for further treatment/RER U
	2. Power	0.4732 GJ	Electricity from waste, at municipal waste incineration plant/CH U
	Outputs / Avoided Products 1. Electricity	3.64 GJ	2010: Electricity, natural gas, at power plant/NORDEL U 2020: Electricity, at wind power plant/RER U
	2. Heat	10.79 GJ	2010: Heat, natural gas, at industrial furnace low-NOx >100kW/RER U 2020: Heat from waste, at municipal waste incineration plant/CH U
2000	**Inputs** 1. Waste Paper	1 ton	Waste paper, mixed, from public collection, for further treatment/RER U
	2. Power	0.39715	Electricity from waste, at municipal waste incineration plant/CH U

	Outputs / Avoided Products 1. Electricity	3.055 GJ	Electricity, hard coal, at power plant/NORDEL U
	2. Heat	9.035 GJ	Heat, anthracite, at stove 5-15kW/RER U
1990	**Inputs** 1. Waste Paper	1 ton	Waste paper, mixed, from public collection, for further treatment/RER U
	2. Power	0.17 GJ	Heat from waste, at municipal waste incineration plant/CH U
	Outputs / Avoided Products 1. Heat	3.4 GJ	Heat, anthracite, at stove 5-15kW/RER U

Following is the LCI for incineration of plastic out of total Residual waste fraction of MSW:

3. LCI for incineration of Plastic waste

Year	Incineration of Plastic Waste	Amount and Units	Unit process used in SimaPro 7.2
2010 & 2020	**Inputs** 1. Waste Plastic	1 ton	Polystyrene scrap, old, at plant/CH U
	2. Power	1.1648 GJ	Electricity from waste, at municipal waste incineration plant/CH U
	Outputs / Avoided Products 1. Electricity	8.96 GJ	2010: Electricity, natural gas, at power plant/NORDEL U 2020: Electricity, at wind power plant/RER U
	2. Heat	26.56 GJ	2010: Heat, natural gas, at industrial furnace low-NOx >100kW/RER U 2020: Heat from waste, at municipal waste

			incineration plant/CH U
2000	**Inputs** 1. Waste Plastic	1 ton	Polystyrene scrap, old, at plant/CH U
	2. Power	0.9776 GJ	Electricity from waste, at municipal waste incineration plant/CH U
	Outputs / Avoided Products 1. Electricity	7.52 GJ	Electricity, hard coal, at power plant/NORDEL U
	2. Heat	22.24 GJ	Heat, anthracite, at stove 5-15kW/RER U
1990	**Inputs** 1. Waste Plastic	1 ton	Polystyrene scrap, old, at plant/CH U
	2. Power	1.36 GJ	Heat from waste, at municipal waste incineration plant/CH U
	Outputs / Avoided Products 1. Heat	27.2 GJ	Heat, anthracite, at stove 5-15kW/RER U

4. LCI for incineration of waste in 1980

MSW fraction	Inputs for the incineration process	Amount & Units	Unit Process used in SimaPro 7.2
Food	Food Waste Power	1 ton 0.12 GJ	Biowaste, at collection point/CH U Electricity, hard coal, at power plant/NORDEL U
Paper	Paper waste	1 ton	Waste paper, mixed, from public collection, for further treatment/CH U

	Power	0.39 GJ	Electricity, hard coal, at power plant/NORDEL U
Plastic	Plastic waste Power	1 ton 0.96	Polystyrene scrap, old, at plant/CH U Electricity, hard coal, at power plant/NORDEL U
Yard Waste	Garden waste Power	1 ton 0.21GJ	Biowaste, at collection point/CH U Electricity, hard coal, at power plant/NORDEL U
Iron	Iron waste	1 ton	Iron scrap, at plant/RER U
Glass	Glass waste	1 ton	Glass, from public collection, unsorted/RER U

Appendix IV

1. Land filling of MSW in 1970

The LCI for Scenario 1 – 1970, where all the waste was going to landfill is given as follows:

LCI for land filling in 1970

Inputs & Emissions	**Amount & Units / ton of MSW**	**Unit process in SimaPro 7.2**
Food and Yard waste	410 kg	Biowaste, at collection point/CH U
Paper waste	350 kg	Waste paper, mixed, from public collection, for further treatment/RER U
Iron waste	60 kg	Iron scrap, at plant/RER U
Glass waste	100 kg	Glass, from public collection, unsorted/RER U
Plastic waste	80 kg	Polystyrene scrap, old, at plant/CH U
Fuel	3 L	Diesel, low-sulphur, at regional storage/RER U
Electricity	8 kWh	Electricity, oil, at power plant/DK U
CH_4	13.5 kg	Methane
CO_2	228 kg	Carbon dioxide, fossil

The data is above table for fuel use, electricity use, methane and carbon dioxide emissions are taken from Manfredi (2009).

Appendix V

For the Air Pollution Control System, following unit processes are used in SimaPro 7.2.

1. Water (tap)
2. Lime, hydrated, packed, at plant/CH U
3. Carbon black, at plant/GLO U
4. Ammonia, liquid, at regional storehouse/RER U
5. Limestone, crushed, washed/CH U
6. Iron (III) chloride, 40% in H2O, at plant/CH U
7. Sodium hydroxide, 50% in H2O, production mix, at plant/RER U
8. Sulfur dioxide
9. Hydrogen chloride
10. Nitrogen oxides
11. Ammonia
12. Mercury
13. Lead
14. Cadmium
15. Arsenic
16. Carbon dioxide, fossil
17. Dioxin, 1,2,3,7,8,9-hexachlorodibenzo-

Note: The chemical's amounts and units can be seen in Table No. 5.1.

Appendix VI

Year	Population	MSW	Global warming per ton	Global Warming from total MSW	Global Warming per person
1970	100,587	46,270	585	46,270* 585 = 27067950	27067950 / 100, 587 = 269
1980	114,302	61,723	130	61,723 * 130= 8023990	8023990/114,302= 70
1990	113,599	56,083	-757	56,083*-757= -42454831	-42454831/113,599 = -373
2000	120.359	85,100	-1378	85,100 * -1378 = -117267800	-117267800 /120,359= -974
2010	197,426	99,141	-1283	99,141* -1283= -127197903	-127197903/ 197,426 = -644
2020	197,426	99,141	-304	99,141*-304 = -30138864	-30138864/ 197,426 = -152.7