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the Built Environment**

Technical Development of Waste Sector in Sweden: Survey and Life Cycle Environmental Assessment of Emerging Technologies

Atiq Uz Zaman

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KTH, Department of Urban Planning and Environment
Division of Environmental Strategies Research - fms

Kungliga Tekniska högskolan

ABSTRACT

Waste can be considered as an urban burden or as a valuable resource depending on how it is managed. Different waste treatment technologies are available at present to manage municipal solid waste (MSW). Various actors are involved to develop waste treatment technology for certain area. The aim of this study is to analyze the driving forces in technical development in waste sector in Sweden. The study is also done to identify emerging waste management technology in Sweden. Moreover, a comparative study of existing and emerging technologies is done by Life Cycle Assessment (LCA) model. An extensive literature review and pilot questionnaire survey among the waste management professionals' is done for the study. LCA model is developed by SimaPro software CML2 baseline method is used for identifying environmental burden from the waste technologies.

Dry composting, Pyrolysis-Gasification (P-G), Plasma-Arc are identified as potential emerging technologies for waste management system in Sweden. Technical developments of these technologies are influenced by indigenous people's behavior, waste characteristics, regulations, health or environmental impact and global climate change. Comparative LCA model of P-G and Incineration shows that, P-G is a favorable waste treatment technology than Incineration for MSW, especially in acidification, global warming and aquatic eco-toxicity impact categories.

Keywords: *Municipal Solid Waste (MSW), Integrated Waste Management System (IWMS), Life Cycle Assessment (LCA), Waste-to-Energy (WTE), Emerging Technology, Pyrolysis-Gasification, Incineration.*

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LIST OF ACRONYMS AND ABBREVIATIONS

ACRONYMS	ABBREVIATIONS
AD	Anaerobic Digestion
AP	Acidification Potential
APC	Air Particulate Cleaning residues
CBA	Cost Benefit Analysis
COD	Chemical Oxygen Demand
EEP	Electrical and Electronics Product
ELV	End of Life Vehicles
EP	Eutro-phication Potential
ETP	Eco-toxicity Potential
EU	European Union
GDP	Gross Domestic Product
GWP	Global Warming Potential
HTP	Human Toxicity Potential
ISO	International Organization for Standardization
ISWM	Integrated Solid Waste Management
IWMS	Integrated Waste Management System
IWMS	Integrated Waste Management System
kWh	Kilo-Watt-hour
LCA	Life Cycle Analysis
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
MSW	Municipal Solid Waste
NGO's	Non Government Organizations
ODP	Ozone Depletion Potential
POCP	Photochemical Ozone Creation Potential
RoHS	Restriction of Hazardous Substances
SEPA	Swedish Environmental Protection Agency
SETAC	Society of Environmental Toxicology and Chemistry
SWOT	Strength, Weakness, Opportunity and Cost
VOC	Volatile Organic Carbon
WEEE	Waste Electrical & Electronic Equipment
WMS	Waste Management System
WM	Waste Management

1 INTRODUCTION

1.1 Background

Waste can be considered as an urban burden or as a valuable resource depending on how it is managed. Therefore, management of municipal solid waste (MSW) is becoming more resource oriented and environmentally sustainable now. Sweden has set up explicit goals to manage municipal waste in a sustainable manner. Life cycle thinking is important for waste management system to assist the EU waste framework directive (EUROPEN, 2006). However, LCA of waste is dealing with one phase of the life cycle.

Sweden has tried to manage municipal solid waste in an environmentally sound manner. However, this initiative is facing different social, economical and environmental problems in the present waste management sector. Colossal amounts (4,717,380 tonnes) of household waste in Sweden are managed by the four treatment methods: material recycling, biological treatment, waste-to-energy and landfill (Avfall Sverige, 2008). Undeniably, the an increase of 23.8 percent in household waste generation during the last decade has propelled to treat waste with newest and incinerating technologies. This by far, has gained much importance while on the other hand; land filling has reduced by 81.7 per cent in the past decade (Avfall Sverige, 2008). A complex composition of MSW consisting of paper, glass, chemical, metal, organic and other waste fractions, makes it difficult to treat solid waste by the waste treatment technologies. Moreover, global climate change has shifted the thinking of waste management problems traditional way to the sustainable way of solving the problems.

A mega project called “Tools for Sustainable Waste Management” financed by Swedish Environmental Protection Agency is being carried out with cooperation from different institutes to find out a sustainable and future oriented solution for waste management system in Sweden (KTH, 2009). The project aims to foresee the emerging technology in long time perspective in the context of life cycle assessment (LCA). This master’s thesis is a part of the project and the study aims to contribute in the project through analyzing background study of the waste management system in Sweden. As a part of the project, the study also examined the possible ways of analyzing emerging technologies development trends based on past development and though LCA decision support tool.

Different waste management decision support tools like cost benefit analysis, multi-criteria analysis are available now. Life Cycle Assessment tool is one of the effective tools to assess the flow dynamics of the resources and can give us the idea on potential environmental burdens per kg or tonne of waste generated (Ekvall et. al., 2007). Moreover, it would be easier to assess the environmental suitability of a new and emerging technology through LCA model. Therefore, a strategic planning for sustainable waste management system is necessary for the future development. The success of waste management planning and policy relies on the forecasting and design of the technical development of waste treatment technologies in the future. Sweden has thus taken up the challenge to find out potential future solutions for waste management problems and hence draw

closer to the sustainable waste management strategy. The research tries to understand the technical development trends of the waste management sector in Sweden so that, future forecast could be made on the basis of knowledge gained from the past.

1.2 Aim of the Study

This thesis aims to contribute to the field of sustainable waste management by conducting a survey to identify the waste management development trends in Sweden. The study also aims to analyze emerging waste treatment technology by a LCA model.

1.3 Research Objectives

- To analyze the current waste management trends and identifies the driving forces in technical development of waste sector in Sweden.
- To examine existing and potential emerging waste treatment technologies in Sweden.
- To develop an LCA model and assess the potential environmental impacts of the emerging technology.
- To compare the existing waste treatment technology with the emerging waste treatment technology using an LCA model.

1.4 Research Questions

- What are the challenges in sustainable waste management system in Sweden?
- What are the drivers that are playing a role in technical development of waste sector in Sweden?
- What are the available and emerging technologies for municipal solid waste treatment?
- How environmentally sound the proposed emerging technologies are?

1.5 Scope and Limitation of the Study

The study primarily focuses on the treatment facilities of municipal solid waste in Sweden. Generally, MSW includes waste generated from private households collected by or on behalf of the local authorities from any sources (Hester and Harrison, 2002). Therefore, non hazardous common garbage from household or commercial areas is considered in the study for the waste management system in Sweden. The study has two different aspects: (a) analysis of Swedish waste management system and (b) assessment of environmental performance of an emerging waste treatment technology by using an LCA model.

In the first part of the study, municipal waste management system in Sweden where wastes generally collected from the residential, commercial centers like market, shops, restaurants etc are analyzed. Industrial waste, hazardous waste, mining waste and the waste for which producers are responsible for their generation are not included in the study. Moreover, the study has identified the existing and potential emerging waste treatment technologies in Sweden. In the second part of the study, an LCA model has been developed based on the emerging waste treatment technology for Sweden to analyze potential environmental burden from the system. Additionally, a study has been done to compare the existing waste treatment technology to the emerging waste treatment technology by LCA model.

However, the study has some limitations. The study analyzed waste treatment technology on the basis of municipal solid waste. Different waste fractions like electronics or hazardous waste are not considered for the study. Municipal solid waste (MSW) defined by EU waste directive is considered for the analysis. A questionnaire survey is conducted among the waste management experts (consultants, engineer, researchers, scientists etc.) who do not represent the whole community of a society. However, the reason for choosing particular expert group is to get feedback on waste treatment technologies within short scope of time. Waste management system is interlinked with multi-sector collaboration, however, the study do not consider the social or economical issues for the assessment of the emerging technology.

1.6 Delimitations

Delimitations of the study are:

- Only Municipal solid waste define by EU waste directive is considered in the study.
- Environmental performances of the technologies are considered as the prime analyzing criteria for the study, therefore socio-economic issues are not discussed deeply in the study.
- The study focused only on technology based waste management system but not on physical processes like avoiding, recycling or reusing methods.

1.7 Significance of the Study

Different policies and programmes have been adopted in Sweden to manage waste in a sustainable manner. However, significant problems still exist in the waste sector, especially regarding environmental sustainability. One example is the introduction of Swedish waste incineration tax that increased recycling of waste, but only in small environmental improvements (Björklund and Finnveden, 2007).

It is important to understand the development trends while planning for future waste management system and hence the reason behind carrying out this study. The study aims to understand the technical development trends of the waste sector in Sweden and also aims to identify the driving forces that actually lead to future development. It is not only the technology that influences waste management system for a region, but also other parameters like waste regulations, policy or socio-economical matters that influence the overall waste management system.

Future technology is difficult to model, as compared to the existing technology. However, the study has aimed to contribute knowledge in waste management sector by developing an LCA model of the emerging waste treatment technology so that, it can be included in the future oriented LCA of waste management.

2 METHODOLOGY

The research has followed a qualitative and quantitative analysis, through three different phases

1. Analysis of driving forces in technical development of waste sector in Sweden
2. Identification of emerging waste treatment technologies for Sweden and
3. Analysis of environmental performance of the emerging technology by using an LCA model.

The first two phases are carried out by qualitative analysis like literature review and questionnaire survey; and the third phase is done by quantitative analysis through LCA model.

2.1. Analyzing the Driving Forces

In the first phase, key driving forces or the leading actors in the development of waste technology in Sweden are analyzed through literature review and a questionnaire survey. Literature review has been conducted with following materials;

- Books
- Research papers from publications
- KTH research database
- International Journals (peer reviewed)
- Waste management and treatment reports
- Questionnaire survey for professionals' opinion.
- Field visit of Swedish waste management facilities.
- Information from the open source (internet).

A questionnaire survey has also been done among waste management organizations working in Sweden. Survey was done in person as well as forwarding the questionnaire by email to the professionals' in different waste management organizations companies like, TPS, AF, SWECO, Swedish EPA, Avfall Sverige, and Stockholm Municipality etc in Sweden. 16 waste management experts from Sweden are participate in the questionnaire survey and gave their valuable feedback.

Moreover, twenty-three PhD students were interviewed at DTU Campus, Denmark, between 11th and 17th June 2009 who worked in waste management systems for different countries during an LCA course on waste management. Sample questions (Box 1) of the questionnaire survey are given bellow.

Box 1: Questionnaire for the survey

Question 1: In your opinion, what are the key factors (driving forces) for developing waste treatment technologies in Sweden?

Question 2: What are the most challenging factors in sustainable waste management system in Sweden?

Question 3: Do you recommend any emerging (new or developing) technology for Sweden which can be implemented in future for sustainable waste management system?

2.2. Identification of Emerging Technologies

Through the literature review and questionnaire survey, emerging technologies are identified first, and then SWOT analysis has been done to analyze strength, weakness, opportunity and threats of the technologies. A qualitative evaluation of the overall performance of the technologies has been done on the basis of some criteria's which are described below.

2.2.1 Survey of emerging technology

In second phase, emerging technologies are identified from the literature review and from the professionals' feedback. Emerging technology is referred as a developing technology or a technology that will be developed in near future. Emerging technology is a cutting edge technology and it need not be a new technology. In this study, emerging technologies are considered as those technologies which are not available now in Sweden. Emerging technology may be implemented for different problem solving context but this study was done by considering the treatment of municipal solid waste technology in Sweden.

Emerging technologies in waste treatment sector are analyzed by some selected criteria's and a catalogue of all emerging technologies is prepared for different waste treatment process system. Five criteria's are selected for analyzing the emerging technologies, those are; process type, waste categories, contaminated medium, development stage, data availability. In the process type, waste treatment technologies are categorized base on the process like mechanical, biological, chemical or thermal process. Emerging technologies are analyzed based on treatment of waste fraction, i.e. whether technologies can manage single waste fraction (paper, glass, plastic) or the different waste fractions at a time. Contaminated medium shows the probable way of contamination from the emerging technologies, therefore for different waste treatment technology it can be air, water or soil. Development stage is very important criteria because while planning for future waste management system development of technology and applicability in the real scenario is the key issue. Therefore, emerging technologies are also analyzed based on their development stage i.e. laboratory stage to

advanced mature stage. For research work, data availability is undeniable criteria. It is not easy to get real and reliable data for emerging technologies most of the time. Therefore, data availability is also considered as key criteria's while analyzing the emerging technologies. Figure 1 shows the key criteria's of emerging technologies.

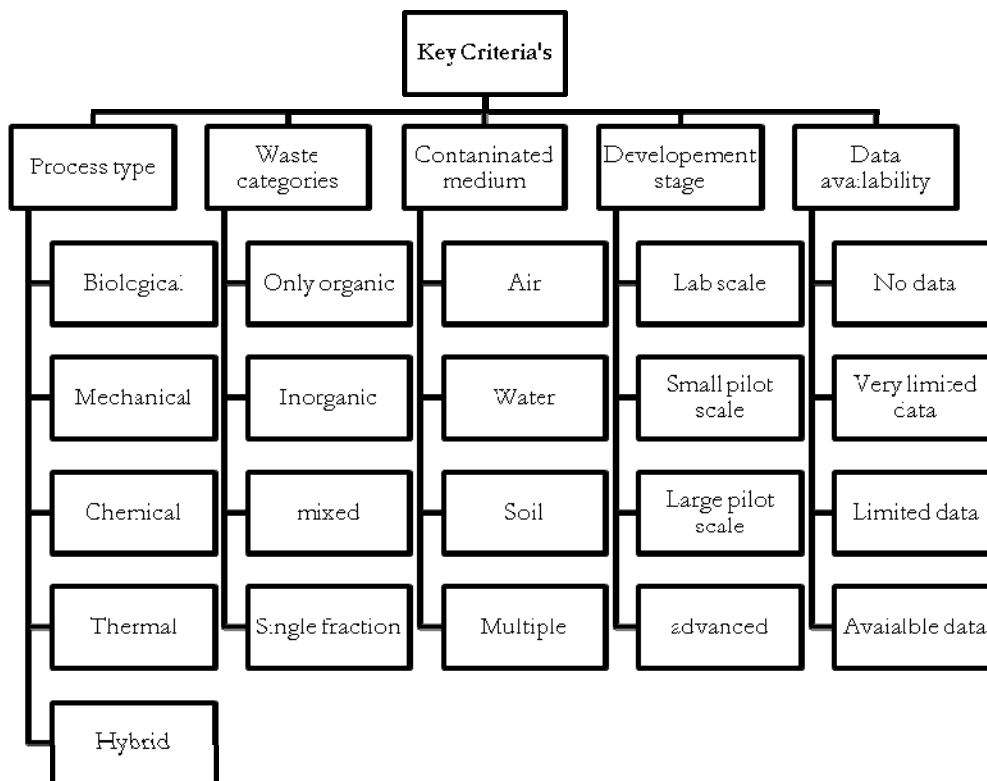


Figure 1: Key criteria's for analyzing emerging technologies

2.2.2 SWOT analysis

Emerging technologies are analyzed by SWOT analysis. SWOT analysis is a planning tool used to understand the Strengths, Weaknesses, Opportunities, and Threats involved in a project or in a business. However, the tool is very useful to analyze particular process or technology. SWOT analysis is useful to understand the technology in order to analyze probable strength, weakness, benefit and probable threats. In the next step, emerging technologies are evaluated by a qualitative evaluation.

2.2.3 Qualitative evaluation of the emerging technologies

Based on SWOT analysis technologies are analyzed in the context of potential strength, weakness, opportunity and threats. Technologies are assigned higher or lower values giving importance to its criteria and its qualitative data. Different technologies have different waste handling capacity, while most of the thermal waste treatment technologies can treat all type of waste fractions, biodegradable

waste fractions are handled by biological waste treatment technology. Therefore, while, some technologies require higher sorting efficiency for better performance, others can manage in lower sorting system..

Emerging technology can be new or under the process of getting developed and it can also be a technology with retro fittings. Therefore, development stage of the technology is one of the vital factors for emerging technology selection process and based on its efficiency and adaptability, development of technology has moved from the lab scale to the large project scale. Criteria problem solving capacity is not only the focus in sustainable waste management system but also the enabling factor. Economical as well as environmental performance must be considered in the overall waste management system. Environmental performance of the technology gives the high priority in the problem solving capacity.

Table 1 shows the criteria for evaluating emerging technology while the qualitative valuation is used based on the level of significance.

Table 1: Evaluation criteria's of selecting the emerging waste technology

Criteria's	Range/ ranking	Symbol used
Waste handling capacity	Limited type of waste,	*
	Sorted waste	***
	All type of waste	*****
Development stage	Lab scale	*
	Pilot scale	**
	Large pilot scale	***
	Advanced/ mature level	*****
Problem solving capacity	Very poor	*
	Poor	**
	Good	***
	Very good	*****

Selection of emerging technology for further study (LCA study) is done based on the waste management problem solving capacity, development stage and data availability. Since, existing technology is compared with the emerging technology; selection of emerging technology is done by considering the process type, waste handling capacity and similar like multi-output or single output from the system.

2.3. LCA Methodology

Society of Environmental Toxicology and Chemistry (SETAC) defines LCA as

“an objective process to evaluate the environmental burdens associated with a product, process or activity, by identifying and quantifying energy and materials used and waste released to the environment, and to evaluate and implement opportunities to effect environmental improvements” (Barton et al., 1996). Simply

by ISO 14040, LCA is “*compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle*”.

According to ISO 14040, LCA has four principle phases described as;

1. Goal & scope definition,
2. Inventory analysis,
3. Impact assessment and
4. Interpretation.

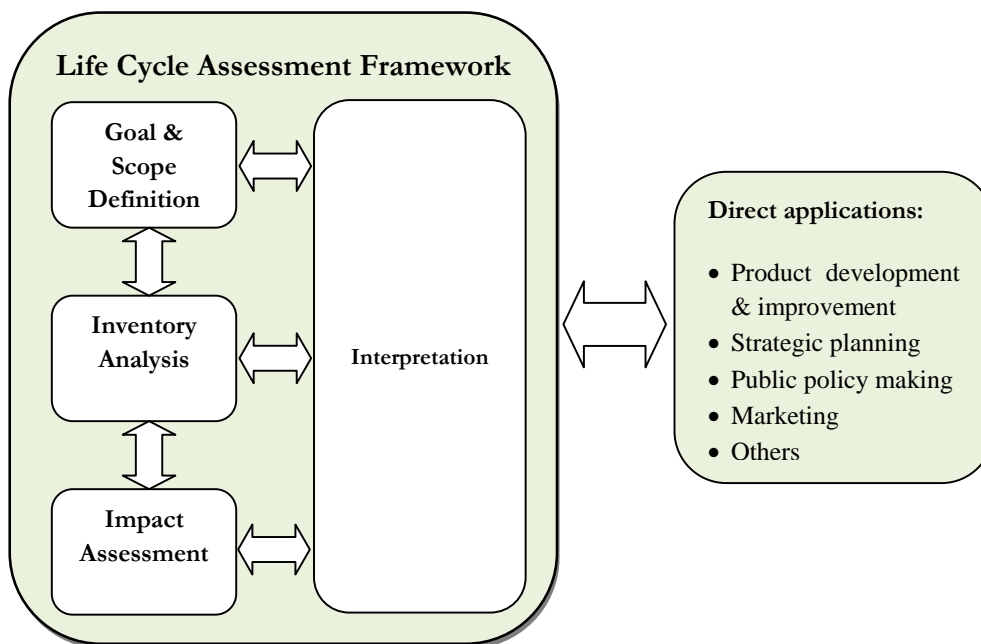


Figure 2: Life Cycle Assessment Framework (ISO, 1997)

Goal and scope definition: Goal and scope definition stands important in LCA because it clarifies the reason of conducting an LCA study and intended application of the findings. In the goal and scope definition, functional unit (reference unit for analysis or comparison) and system boundaries are defined precisely. Scope of LCA also provides information to the reader whether the model is accounting or change oriented. In accounting LCA, model represents the contribution of potential environmental impacts by a product or service, whereas, consequential LCA represents the consequence of the alternatives course of actions. Additionally, in accounting or stand alone LCA, average data are preferred and in consequential LCA marginal data are preferred to develop models.

Inventory analysis: Inventory analysis is the construction of flow models, where inflow and outflow of the materials, energy, emissions data etc. are collected for the LCA model by considering the product life cycle. Flow chart of the model is developed in the inventory stage and data is then collected based on the quality of the data and the relevance of the model. Allocation of the different functions

in the inventory analysis phase is one of the most important parts in LCA. Allocation can be done by the partitioning or system expansion (Baumann and Tillman, 2004) depending on multi-input or multi-output processes.

Impact Assessment: In the impact assessment phase, environmental burdens which are identified in the inventory stage are translated into different impact categories like resource use, human health and ecological consequences. Then these impact categories may be further normalized based on regional or global impact value. Impact assessment is done by characterization of impact categories, which represents the contribution of the impact in the environment. Normalization of impact categories represents the contribution of impact on their significance (i.e. impact is much or less significant compare to baseline normalize value).

Interpretation: Interpretation is the valuation process of the finding from the LCI and impact assessment phases. The results are presented in the interpretation phase in different quantitative ways. Interpretation is done when comparing two different functions in order to identify which one has higher or less environmental impact.

Direct application of LCA: there are different ways of applying LCA in practical world. Primarily, LCA is used in product design and improvement; however, it's hard to limit that at current situation because LCA is now being applying for different products and services at different levels. Strategic planning for waste management system is also very widely applicable area for LCA tool.

In this study, the LCA model has been developed using the software SimaPro (7.0 version). There are four ISO standards (ISO 14040 to ISO14043) specifically designed for LCA applications, which would be replaced by the upcoming draft standard (ISO/DIS 14040 and ISO/DIS 14044) (PRé Consultants, 2006). Environmental assessment of the emerging technology (Pyrolysis-Gasification) has been done by using CML 2 baseline method. Ten different impact categories are shown in CML method while analyze environment burdens. Figure 3 shows the conceptual framework of CML 2000 method.

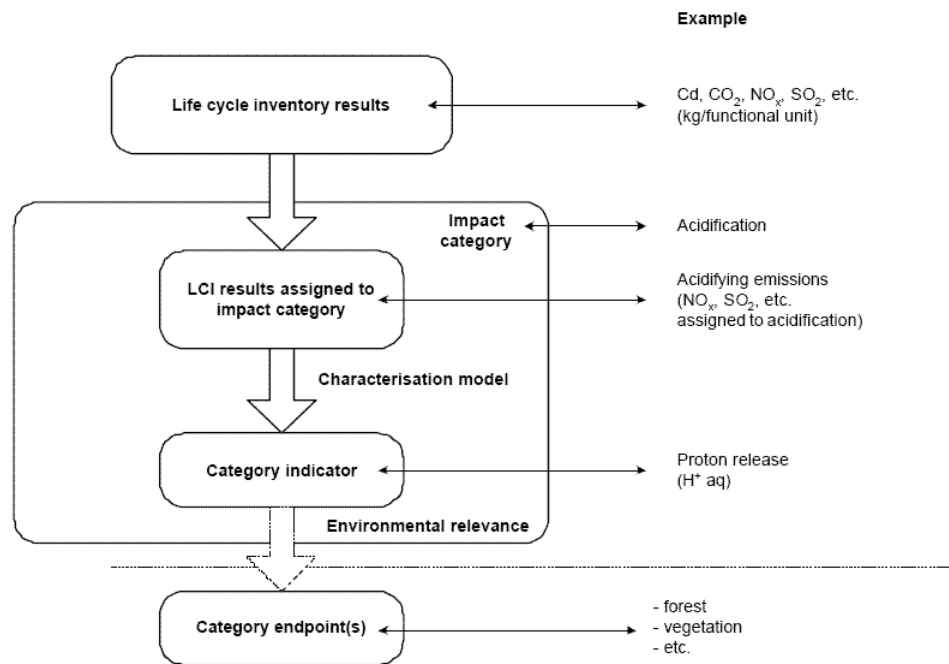


Figure 3: Conceptual frame work of defining categories indicator (CML, 2001)

Life cycle inventory results are analyzed based on impact categories. Characterization model and environmental impacts are considered for the model as the midpoint analysis in the CML method. In SimaPro software, CML model analyzes potential environmental impact using the following different impact categories:

- Abiotic Depletion
- Acidification
- Eutrophication
- Global Warming
- Ozone Layer Depletion
- Human Toxicity
- Fresh Water Ecotoxicity
- Marine Ecotoxicity
- Terrestrial Ecotoxicity
- Photochemical Oxidation

Characterization in LCA model gives the idea on how much environmental burden, the process or product contributes to the environment. Normalization value implies the level of significance based on reference normalization values. In CML method, different normalization values like West Europe (1995), Netherlands (1997) or World (1995) can be considered. In this study, West Europe (1995) values are considered for the model. Table 2 shows the different reference normalization value.

Table 2: Normalization value in different impact categories in CML method

Adopted LCA themes	Unit	West Europe, 1995	The Netherlands, 1997	World, 1995
Abiotic depletion	kg Sb eq	6.76E-11	5.85E-10	6.39E-12
Acidification	kg SO2 eq	3.66E-11	1.49E-9	3.11E-12
Eutrophication	kg PO4 ⁻⁻⁻ eq	8.02E-11	1.99E-9	7.56E-12
Global warming (GWP100)	kg CO2 eq	2.08 E-13	3.96E-12	2.41E-14
Ozone layer depletion (ODP)	kg CFC-11 eq	1.20E-8	1.02E-6	1.94E-9
Human toxicity	kg 1,4-DB eq	1.32E-13	5.32E-12	1.75E-14
Fresh water aquatic ecotox.	kg 1,4-DB eq	1.98E-12	1.33E-10	4.90E-13
Marine aquatic ecotoxicity	kg 1,4-DB eq	8.81E-15	3.14E-13	1.95E-15
Terrestrial ecotoxicity	kg 1,4-DB eq	2.12E-11	1.09E-9	3.72E-12
Photochemical oxidation	kg C2H4	1.21E-10	5.49E-9	1.04E-11
SimaPro, 2007				

For this study, west Europe 1995 normalized data was considered as the baseline normalization data for the LCA model. Therefore, the normalization values showed in the LCA results, meaning that, significant of the different impact categories were compared with West Europe per person emission unit.

3 STAKEHOLDERS IN WMS

Waste management system in Sweden involves with diverse actors from multi disciplinary sectors. Therefore, identification of stakeholders is important for tracking down the development trends of waste sector in Sweden. Different administrative bodies who involve in nation and international strategic development project from the planning to the implementation level are important to understand their role. Local authority involves local people during the development plan and people have the right to discuss and deliver their opinion. Public participation is one of the important factor that tries to ensure in project planning phase in Sweden. Waste management system involves local people; producers and consumers group and also involve regional, national and international actors in different way. People's value's and practices are important in waste management system, therefore, stakeholders identification is an important issues while planning or analyzing waste technology development. From the literature review of the administrative structures of Sweden and analyzing waste sector in Sweden; primarily two types of stakeholders are identified and those are,

1. National level stakeholders

- ✓ Local people (producers and consumers)
- ✓ Local administrative authority (i.e. Church of Sweden, Parishes or församlingar, Municipalities or kommuner)
- ✓ Local environmental regulatory body (Swedish EPA, Avfall Sverige)
- ✓ Local business and monitoring firms (collection, transportation, sorting, recovery and treatment organization)
- ✓ Regional administrative authority (County Council or landsting, County Administrative Board or länsstyrelse,)
- ✓ Finance authority
- ✓ Tax department (Skatteverket)
- ✓ Non Governmental Organizations
- ✓ Research and development organizations/ Institutes, and

2. International level stakeholders

- ✓ Organizations from Nordic region
- ✓ Organizations from Baltic Sea region
- ✓ European Union
- ✓ Organization for Economic Co-operation and Development (OECD)
- ✓ United Nations

Administrative structure in Sweden is very important while playing role in the development from the regional level to the very local level. For example, church has significant influence to motivate local people. Therefore, church is also a part of the administrative body. While, conducting a local or

regional development plan, people's participations are performed from the different level of the development from the planning to the implementation and local citizen to the regional planning division.

Waste management authority (Avfall Sverige) is responsible for taking care of the waste. With the incorporation with different regulatory and development organizations like Swedish EPA, Avfall Sverige is developing environmental strategies for waste. Consulting and business firms, regulatory bodies like EU, Tax and finance department are also incorporated with the strategic development process while aiming to achieve national environmental goals and objectives.

Therefore, it is important to identify different stakeholders in waste management system in Sweden. Each stakeholder has significant importance in the promotion of sustainability and development of waste management technology in Sweden.

The study tried to understand the role of the different stakeholders in the overall development processes. However, detail analysis has not been done, while only technical development of waste sector is considered. Therefore, the role of stakeholders in technical development of waste sector in Sweden is analyzed for the study.

4. LITERATURE REVIEW

4.1 Waste Management Development Drivers

In this section of the chapter, trends of waste generation are analyzed with different factors such as population, GDP, consumption rate, rules and regulations, innovative technology and management practices (recycle, reuse, and recover). From the literature review, a direct relationship between the population growths, gross domestic product-GDP with waste generation has been found (Mazzanti, M. & Zoboli, R., 2008). Population index and their consumption behavior affect very much on the amount of waste volume.

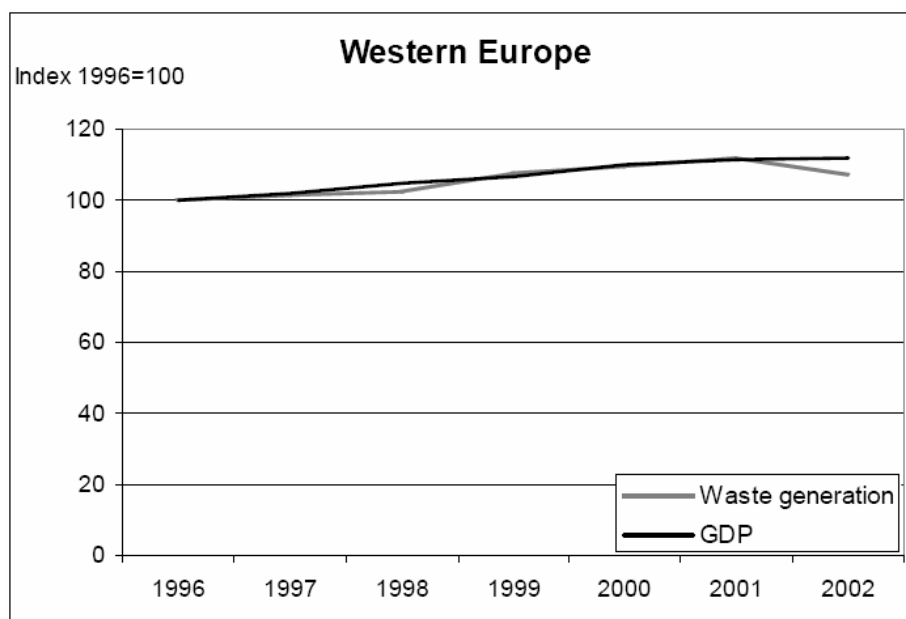


Figure 4: Relationship of waste generation and GDP growth (EEA, 2008)

European Union Environmental Agency's indicator fact sheet 2008 (EEA, 2008) mentions the relationship between total generation of waste and GDP for the period between 1996 and 2002 in Western Europe. Figure 4 highlights the relationship between GDP and waste generation. Capital formation with the relation of GDP of Sweden is given in Appendix Figure A4. Comparison of waste treatment volume over time, as shown in figure A1 of Appendix, with the GDP of Sweden, gives similar findings that GDP and waste generation have a linear relationship. As the GDP of Sweden is increasing over time and the consumption rate of the people is also increasing according to the economical stability, higher volumes of waste are generated every year.

Different global, national or regional level actors have significant influence on technical development in waste management sector. Wilson, D. (2007) has categorized the following waste management development drivers for the waste sector:

1. Public health,

2. Environmental protection,
3. Resource value of waste closing the loop,
4. Institutional development
5. Responsible issues and
6. Public awareness over the time.

Environmental rules and regulations are also the key drivers in technical development in the waste sector of Sweden. To achieve sustainability goal, Sweden has started to take measure of sustainability indicator and put restriction on waste management system like on landfilling. Producer's responsibility in production and landfill tax has dramatic influence in reducing the volume of landfill waste in the waste management system of Sweden. Moreover, after inaugurating the producers' responsibility, landfill tax and banning the landfill for certain waste streams, recycling of materials and energy is recovered in double from 1994 to 2004 (SEPA, 2005).

4.2 What does Waste Mean?

According to European Union waste directive (EU Directive 2008/98/EC), “*waste means any substance or object which the holder discards or intends or is required to discard*”. The transformation of a useful product into waste strongly depends on the function it has for the owner and its economic value and as per Ludwing et al., (2003) waste is the material with 'no economic value'. However, the definition of classical economic of waste may not be applicable for the traditional MSW because waste has significant resource value (Wilson, 2007) today. In traditional classification, waste is divided into three different categories as domestic, industrial and hazardous waste (Hartln, 1996). The physical composition of municipal solid waste (MSW) includes organic and inorganic waste and combined with paper products, plastics, food, yard waste, textile, rubber, glass, metal, dirt, bulky waste and also different other types of waste fractions (Pichtel, 2005, p6). However, the composition of waste changes over time due to changes in the consumption pattern of the products. The categories of waste have been increasing over time based on the sources of generation.

Table 3 shows the typical waste composition in municipal solid waste in Sweden and this composition might be varied for household or other waste depending on sorting facilities.

Table 3: Composition of MSW in Sweden

Waste Categories	MSW after source separation (wet wt. %)
Newspapers/newsprint	7,8%
Corrugated cardboard	0,8%
Soft plastic packaging materials	7,2%
Styrofoam	0,3%
Rigid plastic packaging	7,7%
Glass packaging	2,3%
Metal packaging	1,7%
Food waste	42,8%
Diapers	5,5%
Garden waste	6,7%

other Glass	0,2%
other plastics	0,9%
other metal	0,9%
Textiles	2,3%
Wood	0,5%
other combustible	4,2%
other	4,6%
Hazardous waste	3.6%
<i>RVF (2005)</i>	

4.3 Integrated Waste Management System (IWMS)

Ever since urbanization process, waste has been of enormous concern (Ludwing et al., 2003, p6) although during the same period, the management practices have been established. Solid waste management is considered on its generation, on-site storage, collection, transfer, transportation, processing and recovery, and ultimate disposal of wastes (Pichtel, 2005, p12) and is inextricably linked with economical, ecological and social issues (Ludwing et al., 2003, p2). Thus involving a diverse stakeholder from different levels of society taking part in waste management programme for a particular area, such as government, local authority, NGO's, producers, consumers, technical experts etc. Ideally waste management system is to reduce or avoid waste generation by developing or changing production systems and least preferable to manage by disposing waste in landfill. As waste reduction or recycling has lower environmental impact (Björklund and Finnveden, 2005) and Landfill or disposal has higher environmental potential impacts, comparison of waste recycling (Figure 5), with waste management hierarchy shows the least and most preferable conditions.

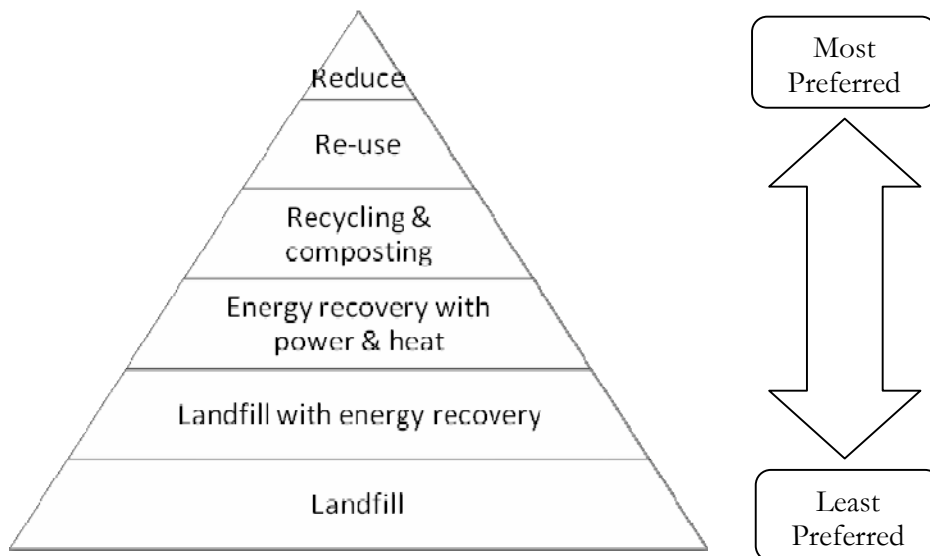


Figure 5: Waste Management Hierarchy (Jaspers, 2003)

EU waste policy is based on the waste hierarchy concept (European Commission, 2005) preference. Therefore, the primary focus of waste management system is to prevent or reduce waste. The waste that cannot be prevented or reduced should be recycled, re-used or recovered as much as possible. The waste that cannot be recycled or re-used should be treated by advanced waste treatment technologies and the rest of the waste should be managed by Landfill. Efficient product design initiative is trying to reduce harmful substance for the manufacture process. The more that waste can be recycled or reused, its position will move to the top of the hierarchy.

Integrated Waste Management Systems strategy (IWMS) is more applied across the world because IWMS promotes sustainable waste management by applying different techniques and at the same time, provide an option to recover resource and energy from the waste stream. IWMS has been considered extensively due to the higher resource recovery rate and potential least environmental impacts from the waste management system. IWMS includes waste sorting, resource recovery, recycling, advance treatment for energy recovery from the waste and disposal of the final residues (Feo et al., 2003).

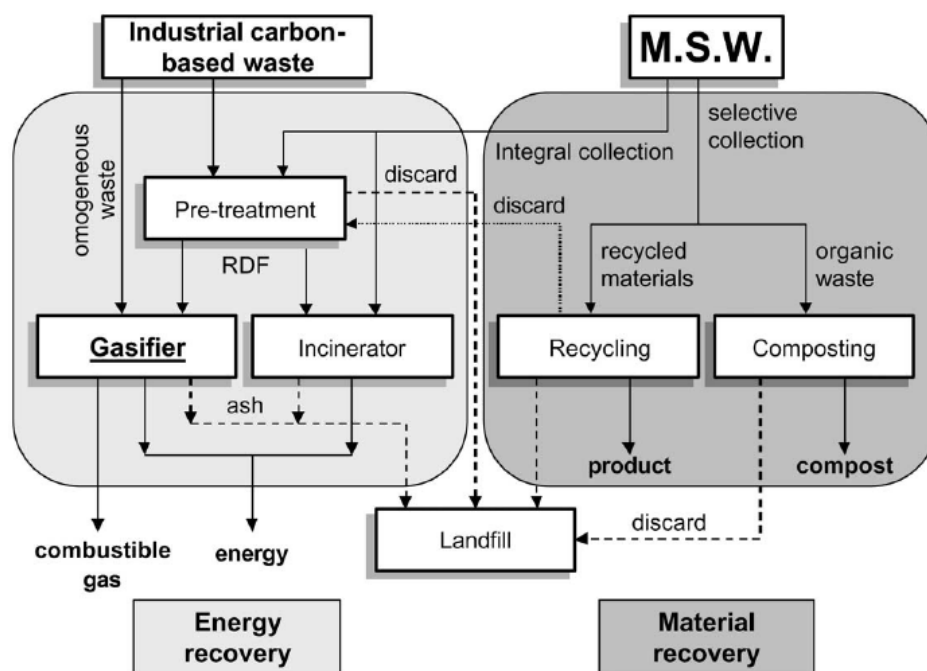


Figure 6: Integrated waste management system (Feo et al., 2003)

Figure 6 shows the integrated waste management system where electricity is produced from gasification or incineration processes and recycling of the waste has been done early of the waste treatment to maximize the resource recovery and final disposal goes to the landfill site.

4.4 Sustainable Waste Management

Waste is related with economical, environmental and social aspects and the definition of 'sustainable development' given by World Commission for Environment and Development is, "*sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" (WCED, 1987). Therefore, sustainable development also depends on the efficient management system of the waste. New ways of thinking and modern technology give us the opportunity to make less valued waste to valuable energy generation and resource recovery option. Even though, waste management system was adopted due to the health and hygienic point of view but over the time the context has changed into positive ways. High consumption of the resources and irresponsible waste generation lead current generation to an uncertain and adverse future. As a result, current global climate change forces us to think about more sustainable ways of using resources and managing the waste pouncing people to develop new technology for sustainable solution. Efficient way of development with least natural resources is important to ensure future generations' well being.

Sustainable waste management concept first came out in Earth Summit; also known as Agenda 21, in 1992. Minimizing waste generation, maximizing waste recycling, reusing and sound disposal of waste are the key criteria's in sustainable waste management. Later, Department of the Environment and Welsh Office in 1995 proposed '3R' principle of waste (reduction, re-use and recovery), known as the waste hierarchy, which is considered as the principles of sustainable waste management system.

4.5 Waste Management System in Sweden

Sweden is one of the economically developed and technologically advanced countries in the world with 9.25 million populations (Statistics Sweden, 2008) in 450,000 km² of land area. Waste management system in Sweden started from the beginning of its urbanization and historically speaking, waste handling regulations were first laid in 1869 mainly fearing epidemic (Björklund, 2000).

Despite the ambition of prevention or minimization of waste, Sweden produces high volume of waste every year. A total of 4,717,380 tonnes of household waste, 514 kg per person waste was treated in 2007 with an increasing rate of 4.8 per cent per year (Avfall Sverige, 2008). Primarily, recycling, resource and energy recovery from incineration, biological treatment and landfill technologies are used for household waste management in Sweden. As a global leading environmental concern country, Sweden has taken strategic planning for waste management with minimum environmental hazard. According to Avfall Sverige (2008), material and energy recovery from waste in the form of biogas or biofuel by biological treatment process and district heating and electricity from the incineration process has increased as each every year progresses.

However, significant problems from the waste management system prevail and one of them is emissions from the waste treatment facilities. The environmental problems caused by the waste management (WM) in Sweden need more attention at the current time. In addition, using LCA for

WM is a clever way to look into the different WM system or within the system to find out the new way of managing MSW.

There are many strategic planning and policy works accelerating the sustainability issues. However, a very small part of the total academic research works has been conducted in the waste sector in Sweden in the last decade and significant lack of collaboration is observed between industry and academic institutes (Lagerkvist, 2005). In developed countries like Denmark (Kirkeby et al., 2006), USA (Eighmy and Kosson, 1996), Canada, Germany, Netherlands (Sakai et al., 1996), UK (Ackroyd et al., 2008) and in developing countries in Asia (Terazono et al., 2006) and Africa (Widmer, 2005), research in waste sector has been conducted to identify potential environmental impact from the waste and trying to develop waste management technology.

After becoming a member state of EU, Swedish waste management system has been influenced by the EU regulations, because the key policy decisions and regulations are now decided by the European Union. However, Sweden has its own sustainable waste management strategy based on the Government's sustainable development goal (SEPA, 2005). Four principle guidelines (SEPA, 2005) are followed to achieve sustainable waste management goal and those are

1. Preventive action to reduce the quantity of waste and the hazards it poses
2. Detoxification of natural cycles
3. Using the resource that waste represents as efficiently as possible
4. Safe treatment.

Integrated waste management system is used for Swedish waste management system. Local authority like municipality is responsible for the taking care of the household waste. However, different product producers are responsible for the higher volume of waste that produces from the production system (Avfall Sverige, 2008). Waste is a complex composition of various chemical and biological components and due to the lack of information, there are many environmental impacts associated from MSW still unknown. Therefore, for a sustainable waste management system it is important to quantify and track on the waste flow, effective waste treatment methods and direct and indirect environmental effects.

Even though Sweden is experienced in waste incineration and has been doing it over hundred years, significant pollutants are still emitted from the incineration while uncertain long term risk remain in the landfill system. Without overcoming these problems sustainable waste management goal cannot be achieved. EU waste directive, national environmental goal and agreement to Agenda 21 are the guiding tools for the Swedish waste management system to direct a sustainable waste management system in future.

a) Present WM Situation

Waste management system is very much dependent on socio-economic and political decisions. Different waste management regulations act as the leading potentials for developing waste management system for a country. Sweden is very prominent in adopting and applying environmental rules and regulations of both EU's and its own as these regulations will change the

face of the nation. Since early 1960s, the landfilling project started in Sweden but this led to several environmental risks as technology then was not advanced. As a result, environmental protection act (Miljöskyddslag, 1969:387) was introduced in the late 60s. Recyclable cans were introduced in 80s and new production design of beverage was getting importance at that time. In the middle of 90s, for better waste management and recycling system, EU packaging directive (94/62/EC) was introduced in Sweden. These regulations and innovative packaging system increased the recycling rate of waste and beverage cans.

Incineration is the leading waste treatment technology in Sweden. Air emissions primarily, CO₂, SO_x, NO_x and Dioxin emission were the leading pollutants before 21st century in Sweden. CO₂ contributing global climate change; SO_x or NO_x contributing Ozone depletion and dioxin has great impact on human health. Emissions from the incineration were very high compare to the current emissions level and standard emission level is also modified after alternative time differences. Later in the 20th century, global climate change came under the light. That is one of the prime reasons of developing EU waste incineration directive (2000/76/EC) for standard emission in atmosphere from the incineration processes. Later, landfill directive (2001:512) was introduced for certain categories of waste that cannot be land filled, so those wastes are managed by other waste treatment technologies like biological treatment, combustible waste by Incineration and so on.

According to the analysis of Avfall Sverige in 2007 reveals that a total of 4,717,380 tons of household waste has been treated in 2007 while the generation of waste volume is on the increasing note, with the resource recovery facilities. However, the volume of waste managed by landfill has decreased tremendously in the last decade. Anaerobic digestion and incineration processes are used for the higher portion of MSW in Sweden. The primary waste treatment technologies that are used in Sweden are as follows (Avfall Sverige, 2008):

- Material recycling
- Biological treatment
- Waste-to-energy
- Landfill

In 2007, about 48.7 per cent of material recycling, including biological treatment have been taken place and a total of 13.6 TWh of energy was recovered through incineration during 2007 (Avfall Sverige, 2008).

From Figure 7 below, it can be said that material recovery (37% of the total waste) and incineration (46% of the total waste) are the predominant techniques for managing solid waste in Sweden while landfill technique has lower percentage. Figures Figure A1, Figure A2 and Figure A3 in appendix show the treatment process and emission from the Incineration of MSW in Sweden.

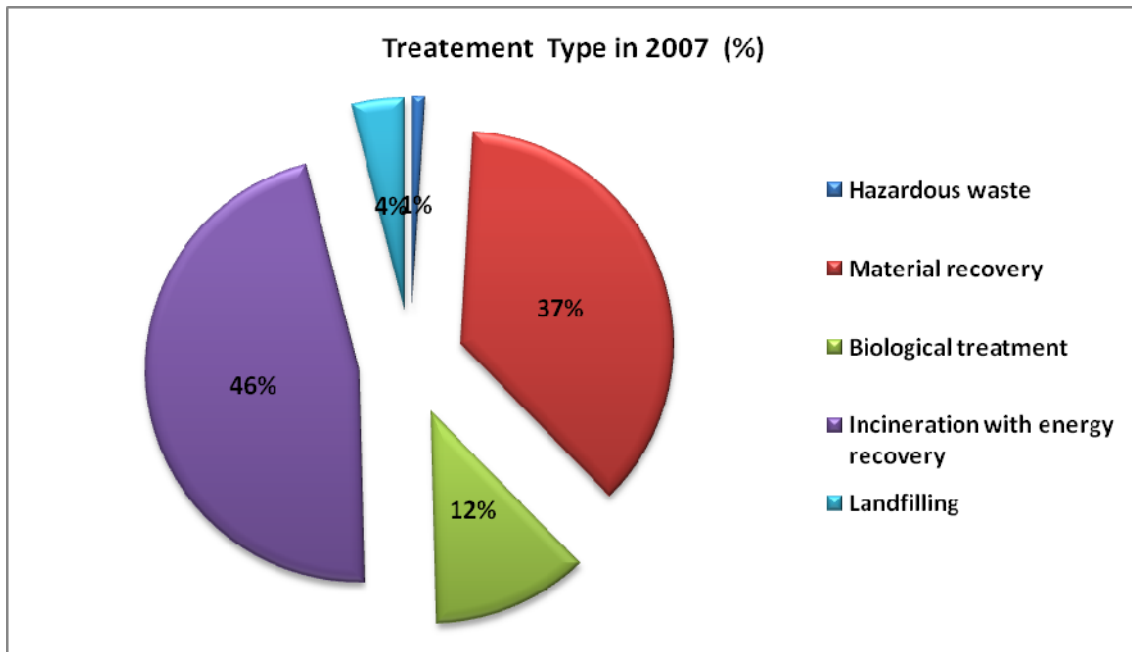


Figure 7: Percentages of treatment type and process (Avfall Sverige, 2008)

b) Common waste treatment technologies in Sweden

There are different waste management techniques available in Sweden, from the very old natural waste management system like composting to the advanced waste to energy system like incineration. Incineration and land-filling were the leading waste treatment technologies before 1990s (Hartln, 1996) in Sweden. However, in the last decade anaerobic digestion and recycling of waste techniques have increased significantly.

The great ‘3R’ concept refers to reduce, reuse and recycle (DoE, 1995) is very popular in Sweden. Sweden has tremendous achievement in waste sorting and recycling of household waste. Therefore, resource recovery and recycling is very common options for waste management technologies in Sweden. There are other physical processes like mechanical and thermo-chemical processes, biological treatment (aerobic/anaerobic), waste to energy processes to manage wastes.

General principle and limitations of the common applied technologies in waste management system in Sweden are briefly explained below:

(i) Biological Treatment

Composting and anaerobic digestion are commonly applied in organic waste management system in Sweden.

Composting:

“Composting is the biological decomposition of the biodegradable organic fraction of MSW under controlled conditions to a state sufficiently stable for nuisance-free storage

and handling and for safe use in land applications” (Golueke et al., 1955; Golueke, 1972; Diaz et al., 1993).

Composting is one element of an integrated solid waste management strategy that can be applied to mixed municipal solid waste (MSW) or to separately collected leaves, yard wastes, and food wastes. The four basic functions (Tchobanoglous & Kreith, 2002) of composting are (1) preparation, (2) decomposition, (3) post-processing, and (4) marketing. Composting is a common waste treatment technology for garden waste or organic waste fraction. Composting has some limitations like; composting is suitable for organic or biodegradable waste, so that during the biological process it can degrade waste as fertilizers. Huge land area is need for composting process and emission control is hard to control in the process.

Anaerobic Digestion:

Anaerobic digestion (AD) is a biological process and achieved with the help of microbes in the absence of oxygen. Anaerobic digestion usually takes place in an enclosed reactor with controlled and favorable environment maintaining temperature, moisture content, pH value etc. In the chamber biogas and compost residue are produced as a final product, while biogas can be used as fuel for electricity, compost can be used as organic fertilizer based on nutrient content. Biogas; consists of methane (ranging 55% to 70%) and carbon dioxide (CO₂) is produced from the process after 2-3 weeks. Anaerobic digestion is more preferred, as it has lower environmental impacts however, AD needs special type of waste feed (organic waste) for the treatment process, which might be problematic pre-sorting or recycling has not been done at household level. Only organic waste is managed by anaerobic digestion process. AD with energy recovery facilities requires more waste preprocess for better efficiency.

(ii) Thermal Waste Treatment Technology (Incineration)

Incineration is an advanced thermal process. Combustion process takes place at the presence of oxygen at temperature of about 850°C. Waste is then converted to flue gas carbon dioxide, water and non-combustible materials called bottom ash. Flue gas is used to generate heat and electricity through boiler and after cleaning the flue gas, gas is emitted to the atmosphere. Figure 8 shows the schematic diagram of incineration process. The process produces heat and electricity, however in the study total electricity conversion value is considered as the energy potential of the incineration process. Therefore, total heat value of the process is converted as the energy value and due to similar data output for two different treatment processes (P-G & Incineration) only electricity potentials is considered for the study.

Depending on the thermal treatment process, volume pollutants are exposed to the environment. Incineration primarily takes place at the presence of air which produces huge volume of CO₂. Incineration of MSW has two process stages, i.e. a) burning of MSW and b) cleaning of flue gas. In the first stage, wastes are collected and stored in the refuse bunker. Wastes are then feed to the refuse hopper through the crane and combustion takes place at the furnace. Flue gas and bottom ash are produces from the combustion of MSW. The burnt-out grate slag (bottom ash) is discharged

through a slag chute at the end of the grate into an ash discharger. For modern plants, the ash discharger is often a pusher type with a water bath in which the 500-600°C hot slag is cooled to 40-70°C. In addition to ensuring cooling of the ash, the purpose of the water bath is to form a safe air seal to the furnace. Water boilers are generally used for the heat exchange and heat and electricity is produced from the incineration of MSW process. In the modern process computerized fluid dynamic (CFD) controls the heat exchange system.

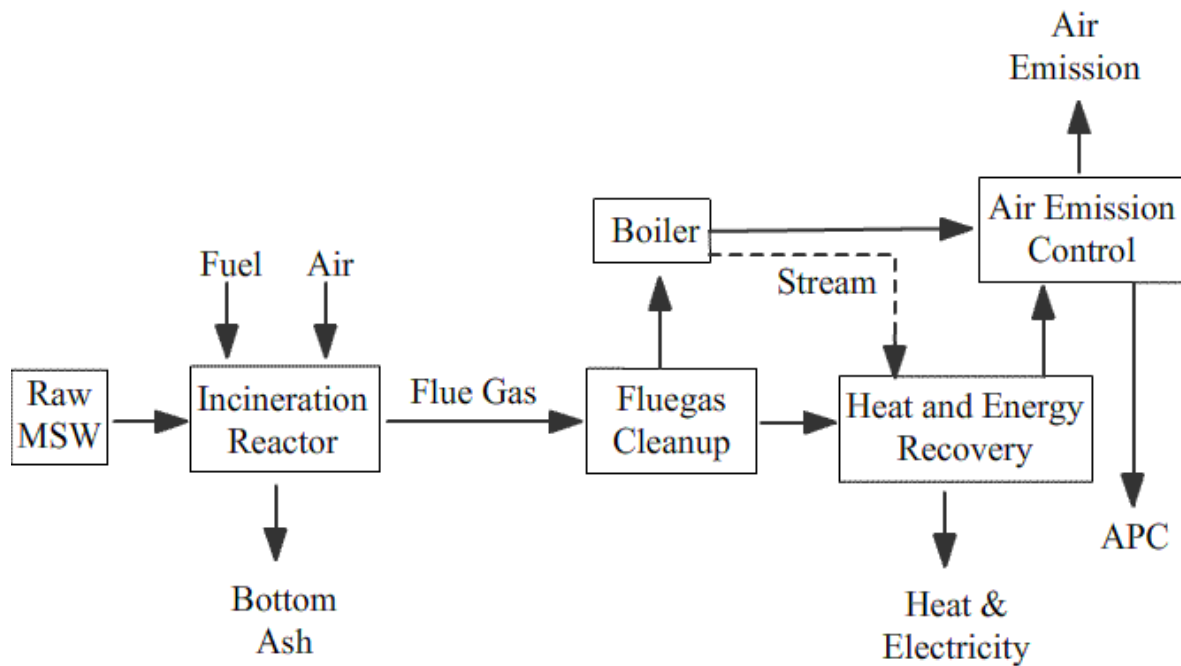


Figure 8: Schematic diagram of MSW Incineration

In the second stage, advance flue gas treatment (FGT) is done. The waste combustion process produces flue gas that contains a broad spectrum of air pollutants (e.g., dust, acidic compounds, heavy metals, and dioxins). Therefore, flue gas cleaning is the primary environmental concern of MSW treatment by Incineration process.

Wastes are delivered in combustion plant as feed stock to the pre-combustion (grate). In the first phase, gas and slug or ashes are produced due to combustion of MSW. In the second phase, flue gas is cleaned by water absorber or different filtering methods (Ludwing et al., 2002). Finally, the clean gas is emitted through the chimney to the air.

Incineration is the leading waste treatment technology in Sweden that produces electricity and heat as final product. Incineration can manage different type of waste fractions however; significant environmental impact can be contemplated from Incineration process. In the early phase of waste management system, significant emission to the air had occurred from the Incineration process. According to Avfall Sverige (2008) report, emission rate has decreased for Dust, HCl, NO_x, Dioxin and heavy metal, from 2003 to 2007. However, higher volume of waste has been incinerated in 2007

than in 2003. Fly ash emission is still a concerned environmental problem in Sweden leading to constant research on new waste technologies for Sweden.

(iii) Land-filling

Landfill is the most used global technology for waste management system. Due to the low management cost; however, landfill has higher environmental impact. Landfill is the term used to describe the physical facilities for the disposal of solid wastes and solid waste residuals in the surface soils of the earth (Tchobanoglous and Kreith, 2002, p669). Landfills for the disposal of hazardous wastes are called secure landfills (Tchobanoglous & Kreith, 2002, p669) and in secure landfill, advanced methods are applied to make safe the environment from the landfill site. While wastes are deposited in the landfill, biogas is generated from the landfill facility containing primarily of methane and carbon dioxide. Sweden has stringent regulations regarding landfill as a technique to treat waste. CO₂ and Methane contributing extensively in global warming problem are generated during landfill technique. Although one may see this technique as a sound practice for treating waste but it damages the environment slowly. Large amounts of land are required to hold the waste for a longer duration and moreover, it can contaminate groundwater due to the leaching of pollutants in the water. However, to overcome this problem, advanced and controlled landfill technology known as 'sanitary landfill' has developed. In this technology landfill gas is collected for the energy recovery. The principles and analysis clearly indicates that limitations of older technology to treat waste drive the younger generation to develop new technologies to overcome the current environmental problems. However, not only environmental problems solving capabilities of the waste treatment technology are the prime concern but different socio-economic factors are also important in developing waste management technology.

4.6 Emerging Waste Treatment Technology (P-G)

Pyrolysis-Gasification is a hybrid thermo-chemical conversion process (combination of pyrolysis and gasification process) where solid materials are converted to the gaseous products. The gaseous product contains CO₂, CO, H₂, CH₄, H₂O, traces of hydrocarbons in high amounts, inert gases present in the gasification agent, various contaminants such as small char particles, ash and tars (Bridgwater, 1994). Pyrolysis generally takes place in high temperatures of around 400°C-1000°C. Thermal degradation of waste occurs in the absence of air to produce syngas, oil or char and slug; however, in reality it is quite impossible to degrade waste to zero air environments. Compared to pyrolysis, gasification takes place at higher temperatures, at around 1,000°C -1,400°C in controlled amount of oxygen. The majority of the carbon content in the waste is converted into gaseous form (syngas). For most waste feedstock, the gas produced will contain highly toxic and corrosive reduced species the gas may therefore require cleaning before combustion (NSCA, 2002).

Pyrolysis-gasification is a hybrid process and therefore, it is referred to as an emerging and advanced thermal treatment (NSCA, 2002) for MSW treatment. MSW pyrolysis and in particular gasification is obviously very efficient in reducing and avoid corrosion and emissions by retaining alkali and heavy metals (Malkow, 2004). There would be a net reduction in the emission of the sulphur di-oxide and

particulates from the pyrolysis/gasification processes. However, the emission of oxides of nitrogen, VOCs and dioxins might be similar with the other thermal waste treatment technology (DEFRA, 2004).

There are different types of gasification processes based on different waste treatment process systems and processes flow (Feo et al., 2003). By considering the oxygen present in the processes, gasification is divided into two categories; direct gasification (oxygen controlled atmosphere) and indirect gasification (oxygen free atmosphere). Fixed bed gasification processes are further categorized by updraft or downdraft of gas outlet. Fluidized bed system can be further subdivided as bubbling or circulating, depending on circulation options of the inert and char. Figure 9 and Figure 10 shows the processes flow and flow diagram of Pyrolysis-Gasification of MSW.

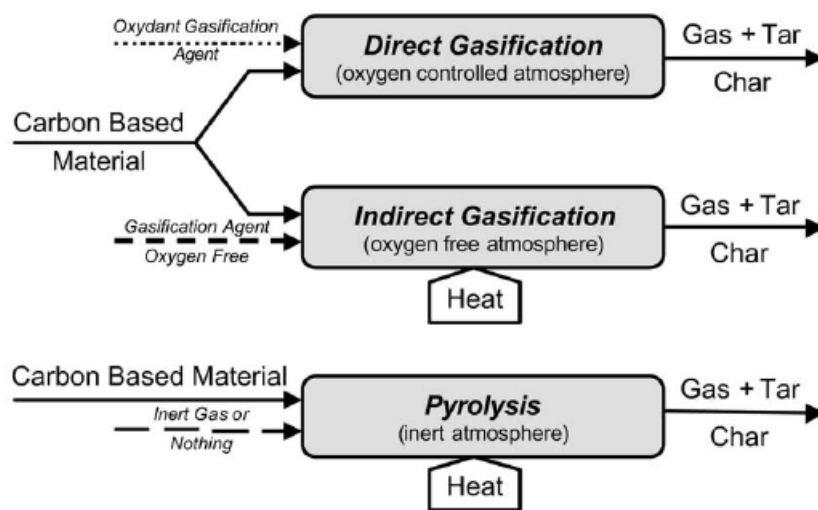
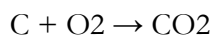
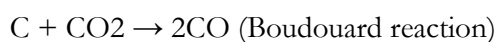
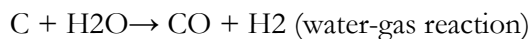


Figure 9: Gasification and pyrolysis processes (Feo et al., 2003)

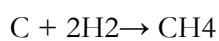
In Pyrolysis process carbon-based materials are “cooked” in an oven without oxygen, and hence, no direct burning takes place. In the gasifier, the addition of air or oxygen for gasification of the feedstock leads to a small amount of combustion, forming some CO₂ and release of heat:



Depending on the gasifier design, 10-30% of the heating value of the feedstock is used in this reaction. Utilizing that heat, the organic compounds in the feedstock begin to thermally degrade, forming pyrolysis gases, oils, liquids and char. Therefore, gasifier reaction can be



Some of the carbon may react with the hydrogen, forming additional methane gas:



Carbon monoxide, hydrogen, and methane form the primary components of syngas.

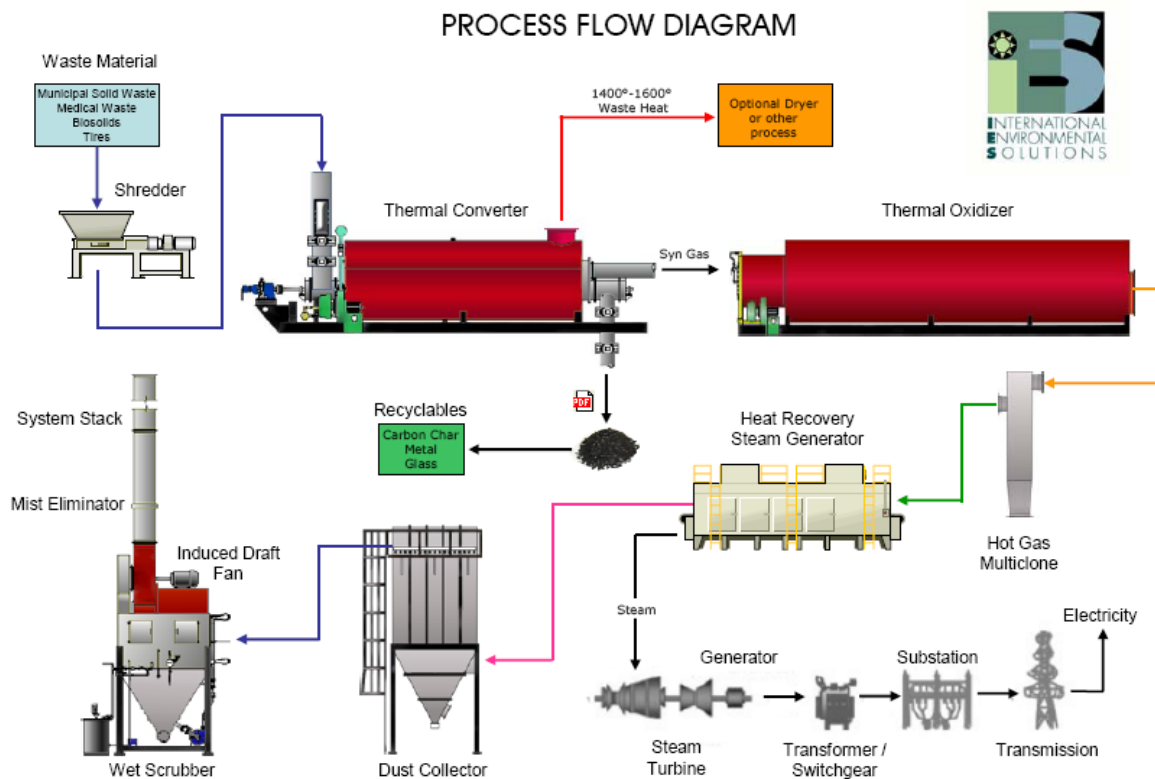


Figure 10: Flow diagram of P-G of MSW (Alternative Resources Inc., 2007)

Pyrolysis-Gasification is not a new technology, however, the process has been used for MSW very recently (Saft, 2007), (McKay, 2004), (Malkow, 2004). Coal gasification was used since the early 1800s to produce town gas and the first four-stroke engine was run on producer gas in 1876 (Wheeler & Rome, 2002). Gasification technology is by no means a new technology, in 1850s, most of the city of London was illuminated by “town gas” produced from the gasification of coal (Feo et al., 2003).

Many studies have been conducted to analyze the environmental performance and some studies on the processes have been done by Malkow (2004), Feo et al. (2003), Khoo (2009), Horst et al., (2008), Saft (2007), Choi et al. (2006), Morris and Waldheim (1998), Cherubini et al., (2008). Potential environmental impact from the Pyrolysis-Gasification of MSW has been analyzed by the LCA model, while a comparative study of Pyrolysis-Gasification process with incineration have also been done to analyze overall performance of the emerging technology.

4.7 Life Cycle Assessment of Municipal Solid Waste

Over the time in waste management sector, various models (Morrissey & Browne, 2004) have been developed to be considered as prime decision support tools. In the end of the 1960's waste management model had started its journey with computerized waste planning model (Björklund,

2000) with the other cost analysis, multi-criteria optimization (MCO) or multiple criteria analysis (MCA) tools. There are different environmental system analysis tools (Finnveden and Moberg, 2004) that are available currently. However, Life Cycle Assessment (LCA) (also known as 'cradle-to-grave' analysis) is becoming as a prime tool to assess the potential environmental impact in waste management systems.

In Life Cycle Analysis, environmental assessment of a certain product or service has been done from the raw material extraction/manufacture phase (cradle) to the end of life/disposal phase (grave). A waste management system can be considered as a service, which plays different functions in the society. However, it is complex to define 'cradle' and 'grave' in LCA for waste management system because, waste consists of different kind of products so the 'cradle' of the waste will be the same as the product. However, in LCA of waste management, upstream processes are excluded from the analysis (Björklund, A. 2000) and wastes are treated as 'zero burden' inputs and 'cradle' phase is started from the collection of waste. Life cycle stages for waste are shown in the below Figure 11 based on White (1999) model.

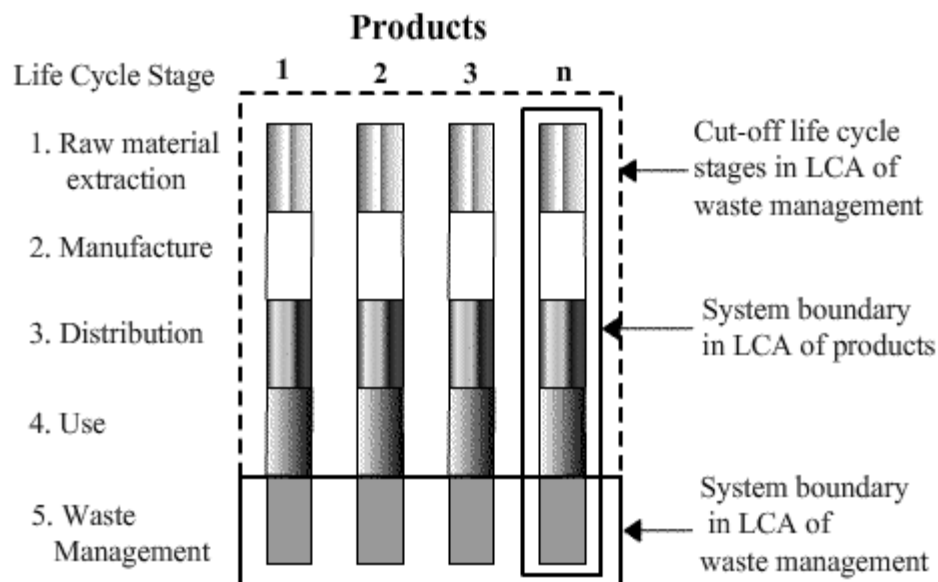


Figure 11: Up-stream life cycle stages cut-off in LCA of waste management based on White (1999)

Many research work has already been done to examine the scope, limitations and potentiality of LCA model as waste management decision support tool and among them few have been done by Barton and Patel (1996), Björklund A. (2000), Ekvall and Finnveden (2000), Matsuto (2002), Rebitzer et al., (2004), Pennington et al., (2004), Björklund and Finnveden (2007), Bilitewski and Winkler (2007), Ekvall et al., (2007), Gheewala and Liamsangun (2008), Pennington and Koneczny (2007), Cherubini et al. (2008), Cherubini et al. (2008¹), Manfredi and Christensen (2009). Therefore, LCA is quite a strong analytical tool to assess emerging technology for future perspective of waste management.

Though, life-cycle assessment (LCA) model is the principal decision support tool, LCA has limitations (Christensen et al., 2007) and restriction on developing certain comparative model (Ekvall et al., 2007). Different LCA methods (Finnveden et al., 2007) and models like MSW: DST, IWM, THE IFEU PROJECT, ORWARE, or EASEWASTE (Christensen et al., 2006) have been used to assess environmental impacts associated with the waste. However, all of these models have different analytical perspectives and applicability in identifying the environmental burdens by solid waste. Moreover, LCA has scope for economical valuation of the waste known as life cycle cost analysis (LCCA). In this research, only environmental assessment has been considered.

5. RESULTS & DISCUSSIONS

The study has covered three different aspects consisting of analysis of the key drivers responsible for waste technology development, identification of emerging waste treatment technologies for Sweden and analysis of environmental burdens of emerging technology through LCA model. The results of the study are presented in three different sections below:

1. Waste management development drivers
2. Emerging waste treatment technologies for Sweden
3. LCA of emerging technology

5.1 Waste Management Development Drivers

Waste management sector involves multidisciplinary issues and development of waste technologies includes different social, economical, environmental and technological aspects. There are two type of drivers that acting technical development of waste sector in Sweden: a) local drivers and 2) global drivers. Some of the drivers are working from the local level whereas the other is acting in the global level. Brief descriptions of the driving actors, based on the Swedish context are given below

5.1.1 Socio-economic drivers

Indigenous or local people's practices have significant influence in waste management system. Historically, people adopt with the time and depending on the local culture, they are habituated with different practices. For example, people sorted out things from early of the history depending on the value (monetary or nonmonetary value) that the things might posses. Generation of waste is depending on the consumption of the resources and result shows that, generation of waste is influenced by the economical growth of a country. Waste management system is always related with public health. Therefore, from the public health safety perspective, development of waste management has influenced significantly.

5.1.2 Environmental drivers

Global climate change is one of the leading environmental problems, which is kept in mind forevery development strategies in the recent years. Emission of hazardous gases in the atmosphere like Carbon dioxide, SO_x, NO_x, heavy metal or dioxins emission from the waste management facilities are the leading environmental cancers of technical development in waste sector. In the early of the waste management system in Sweden, dioxin emission as well as other air emissions has significant impact on environment compared to the present technological development. Environmental awareness and regulation of standard emission limits to air or water lead the improvement of technology of waste management system in Sweden. Carbon emissions to atmosphere and leachate pollution to the ground water from landfill are still the major sources of environmental pollution in Sweden. Therefore, environmental awareness and safety lead to the development of emerging technologies in waste sector.

5.1.3 Technological drivers

Technological development in waste sector depends on the significance or importance of the problems that needed to be solved by the technology like volume of waste or environmental problems from waste management system. Socio-political decision has encouraged more resource recovery from the waste management system. Therefore, incineration got importance due to resource recovery option after 1970s in Sweden. Availability and efficiency of waste management technology leads faster development of certain technology. For waste management technology, development of certain technology depends on the waste handling capacity (single waste fraction or multi waste fractions), type of management system (simple single sorting or complex various sorting), resource recovery capacity, economical consideration and on environmental performance (emissions).

5.1.4 Sustainability Drivers in Technical Development in Sweden

Since 1990s, waste management system has gained significant importance for betterment of social structure in Sweden. Consumption of resources is inevitable, in parallel generating equal amount of waste. Waste volume has deep relations with economical growth, gross domestic product (GDP) as well as the consumption rate of the resources in line of observation that the waste generation rate is higher in developed country than in developing country.

In early phase of the urbanization process when sorting was not done very efficiently, landfill was used as the primary waste management technique in Sweden. After being shackled by the adverse environmental impact of the landfill, Sweden started focusing more on the Incineration process. Incineration of MSW produces electricity and heat, which are among the leading factors to promote Incineration in Sweden. After 1975 world oil crisis, waste management system in Sweden started to maximize the resource recovery from the waste. Emission from the waste treatment facilities led to develop new strategy for waste management system in Sweden. Therefore, different regulations have been introduced in different context to promote new ideas and technology. Three different questions were delivered to the waste management professionals to get their feedback. Policy, regulations, waste characteristics, resource value and environmental awareness have identified as the leading factors in the development of waste technology. Reduction of volume of waste, complex waste composition, cradle to cradle production systems are the most challenging areas for sustainable waste management in Sweden.

Figure 12, shows the drivers for sustainable development and their relation with the different actors in waste technology development. Market or economical drivers were the primary actors in technical development few decades ago. However, social driver later come into the focus; at present, environmental issues are also set as prime drivers for sustainable development. Some of the drivers are inter related with different sectors such as consumption of resources (can be economical or socials drivers), regulations and policy (can be social, environmental or even economical drivers) and technical availability (can be both economical and environmentally applicable).

Some of the driving forces act as foreground actor and others act as background actors. Some of the drivers directly influence in the development process. For example, depending on waste fraction (organic/inorganic/combustible waste), different waste treatment technologies (AD/Landfill/Incineration) are developed. Economical benefit or market driven factors promote more energy or resource recovery technologies. Volume of waste, regulations or environmental awareness acts as background actors. Depending on the necessity, all these drivers are act combined or indocently to develop certain waste management technology.

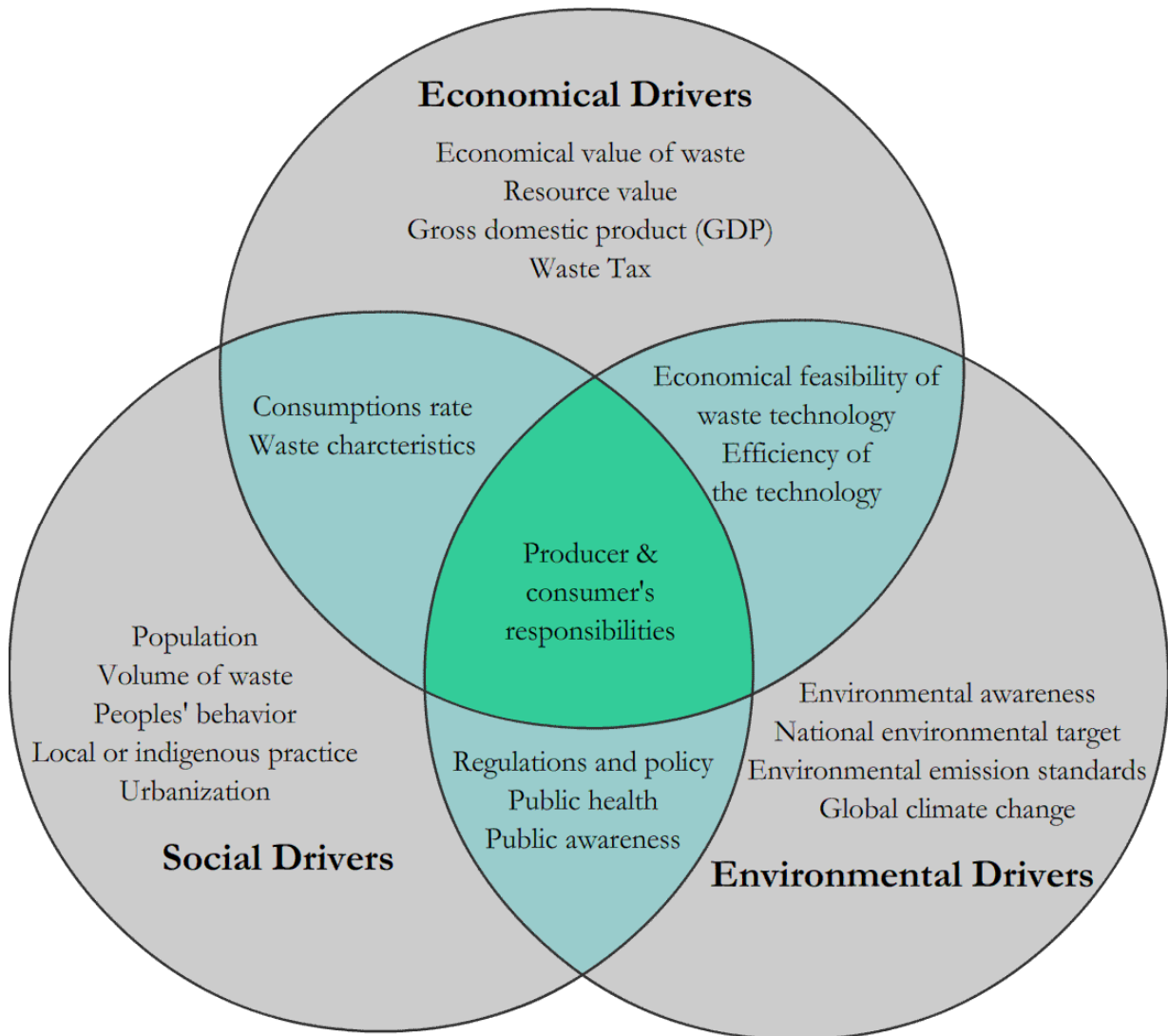


Figure 12: Drivers in sustainable waste treatment technology development in Sweden

Indigenous practice and people’s behavior are important in technical development because public participation in sorting and recycling of waste is vital for sound waste management system. Consumption of resource influences the volume of waste, which also depends on the number of population and urbanization process. Recycling or sorting of waste give the higher resource recovery

benefit to the technology. Now in Sweden, paper, glass, aluminum can and hazardous materials like batteries are collected separately which lead different treatment technology for the society. Waste characteristics are also dependent on the local practice. Composition of waste fraction is very much important for selecting waste treatment technology. Moreover, single waste fraction can be treated with different waste treatment technology for example; previously biodegradable wastes were treated by composting technology, now more favorably it is treated by anaerobic digestion, the method is more environmental friendly and more economical.

Extended producers and consumers responsibilities can influence sustainable waste management system significantly. In every step of resource consumptions, innovative product design, waste generation, collection and treatment of waste individuals can make a difference by their personal responsibilities through choosing the right thing to our environment.

National and international rules or regulations have tremendous influence in the development of waste treatment technology. Regulations are very much depending on the awareness and urgency of the need for functioning society in a better way. Regulation is acting as the supporting tool for promoting a system. Landfill of waste technique was used profoundly until mid 90s where later rules and regulation made the Landfill technique less favorable. Moreover, regulation imposed in Sweden for Landfilling of biodegradable waste prompted to extend the technology in treating the waste biologically. Regulation of combustible waste ban to the landfill ensures higher waste volume for continuous treatment of the Incineration process. Producers' responsibilities encourage more recycling and resource recovery option for the producer in the society. Landfill and incineration tax shift people to go for more recycling and reuse methods. Regulations acts as supporting tool for the integrated waste management system in Sweden. Diverse waste treatment technology like landfill, anaerobic digestion, incineration and resource recovery technology are promoting the local and international regulations.

The study identified a list of important milestone in MSW generation and management in Sweden (table 4) which also explains how regulations are adopted due to economical reasons and how these regulations promote certain waste management technologies in Sweden. This milestone gives the major waste generation sources and management resources for Sweden from twentieth century. Mile stone also help to describe roles of regulation in waste technology development. Some milestones have direct influence on waste technologies like landfill tax, banning of organic waste to landfill and incineration directive and other have indirect influence like package design or environmental code.

Table 4: Significant Milestones in MSW Generation and Management in Sweden (1900-2009)

Year	Milestone	Reference
2009	Incorporating EU Battery Directive to the Swedish legislation	El-Kretsen (2009)
2006	EU Battery Directive (2006/66/EC)	EU (2009)
2005	Ban on organic waste to landfill	Avfall Sverige (2008)
2005	Ordinance (2005:209) on producer responsibility for EEPs	SCS (2005)
2005	Regulation (2005:220) on the return system for bottles & cans	SCS ¹ (2005)
2003	Regulation on Incineration of Waste (2002:1060)	Eionet (2007)
2002	EU RoHS & WEEE directive (Directive 2002/95-96/EC)	EU (2002)
2002	Ban on putting combustible waste to landfill	Avfall Sverige (2008)
2001	The Landfill Ordinance (2001:512)	Eionet (2007)
2000	EU End-of Life Vehicles (ELV)/ Tyres (2000/53/EC)	EU (2000)
2000	EU Waste Incineration Directive, 2000/76/EC	EU Directive (2000)
2000	Introduction of landfill tax	Avfall Sverige (2008)
1998	The Swedish Environmental Code (16 EQOs)	Regeringen (2000)
1997	Regulation for batteries (1997:645)	SFS (1997)
1997	Packaging (1997:185), Producer responsibility for packaging	SFS ¹ (1997)
1994	EU Packaging Directive 94/62/EC	EU Directive (1994)
1993	The Eco-cycle bill (Government Bill 2002/03:117)	SGO (2004)
1991	The Act (1991:336) on certain beverage containers (PET)	SFS (1991)
1982	The Act (1982:349) on recycling of Al drinking containers	SJV (2005)
1969	Miljöskyddslag (1969:387)-Environmental Protection Act	EU directive (1988)
1960s	Landfill started for MSW disposal	Miliute & Plepys (2009)
1951	Tetra Pak founded	Tetra Pak (2009)
1927	Volvo founded	Volvo (2009)
1901	The first waste incineration plant in Sweden in Lövsta	RVF (1999)

First waste incineration plant was established in 1901 in Lövsta without any energy recovery facilities. Technology for heat and energy recovery was not available at that time. Moreover, waste had no economical value until 70s. Due to high volume of waste and urbanization process in 1960s, wastes were landfilled in Sweden without any recycling. After the global economical crisis, technology developed in incineration to recover energy and heat from the process, which eventually lead to the further development of incineration in Sweden. Meanwhile, zero monetary value waste started being treated as a resource in 21st century and environmental awareness grew very rapidly due to the consequences of the climate change. Therefore, 40 years later, Sweden introduced landfill tax which significantly influences recycling and incineration process. Ban of combustible waste to landfill secure incineration to get continuous feedstock for the combustion. Due to environmental concerns, Landfilling of organic waste is also banned for promoting anaerobic digestion (AD) in Sweden. Recent hazardous waste directives (2006, 2009) might be promoting emerging technologies like pyrolysis of waste technology.

5.2 Emerging Waste Treatment Technologies for Sweden

As an emerging technology, the study identified those technology that are not present at the current time in Sweden and are not yet developed significantly for waste management system in Sweden. For example, conventional technologies like composting, landfill, anaerobic digestion and incineration are already established for waste treatment technologies in Sweden. Hence, these technologies are not analyzed in the study.

Key feature of the emerging technologies are presented in Table 5 Emerging technologies are analyzed by SWOT analysis on the basis of strength, weakness, opportunity and threat of the certain technology. Results of the SWOT analysis are shown in Table 6.

Different emerging technologies are identified as the potential waste treatment technologies for Sweden. Some of the technologies are tested at the research level at the laboratory and some of the technologies are applied as the pilot scale. For example, waste to protein is tested at the laboratory level with very limited data availability. On the other hand, pyrolysis-gasification is now applying mostly in small to large scale pilot project. Therefore, the development pace of emerging technologies is quite faster comparing to mature waste treatment technologies.

Dry composting is one of the potential organic waste treatment options for Sweden. Dry composting is still on small scale pilot project level but very promising due to organic waste preservative options. Waste can be dried up and stored for the further energy recovery facilities like AD.

Thermal waste treatment technology can manage different waste fractions at the same time, which is the primary benefit of thermal waste technologies. Resource recovery is also another reason for development of thermal technologies.

Table 5 shows the key features of emerging technologies. Key features are given in the key points with other criteria's.

Table 5: The Key Features of Emerging Waste Management Technologies

Process categories	Processes Type	Key Features	Waste Type	Contamination Medium (Emission)	Development Stage	Data Availability	References
Biological Conversion	Dry Composting	<ul style="list-style-type: none"> ✓ Natural decomposition process. ✓ Produces methane & carbon di-oxide (CH₄ & CO₂). ✓ In dry composting, organic waste or food wastes are preserved in dry mechanism. ✓ It reduces waste weight and volume by about 75%. ✓ Dried material can extract biogas via anaerobic digestion. ✓ Easy to preserve waste for future energy production. 	Organic waste, garden waste, biodegradable waste	Multiple, (air, water and soil)	Pilot scale	Limited emission data	SWM Manuals (2000), Walker, L., et al.(2009) Prabha et al. (2007) Demirci et al., (2005), Richard Tom L., (2000), Avfall Sverige (2009)
	Sanitary Landfilling	<ul style="list-style-type: none"> ✓ Biological waste treatment in control landfill area. ✓ Artificial liner is used for preventing leachate pollution ✓ Landfill gas contents primarily of methane and carbon dioxide are generated from the degradation of waste. ✓ More environmental friendly compare to traditional landfill due to controlled operation area. 	MSW	Multiple (air, water)	Large Pilot scale	Available	Ludwing et al., (2003), Tchobanoglos and George, (2002), Federation of Canadian Municipalities (2004)
Thermal Conversion	Gasification	<ul style="list-style-type: none"> ✓ Thermal waste treatment technology. ✓ Gasification can be fermentation, briquetting, Fluidized bed or thermal cracking. ✓ Gasification is done in an controlled environment with limited access of air in 400-600°C. ✓ Gasification can be possible for both wet and dry biomass for the production of synthesis gas, hydrogen- and methane-rich gas. <p>Water gas reaction can be, $C + H_2O = CO + H_2$</p>	MSW	Multiple (air/water)	Pilot Scale	Limited	Rossum et al., (2008), Kruse, A. (2008), LEE, Andrew, O. (2001) Wilen et al., (2004), Alternative Resources, Inc (2006)

		Water gas shift, $CO+H_2O=CO_2+H_2$					
	Pyrolysis Thermal processes	<ul style="list-style-type: none"> ✓ Pyrolysis is a thermal process of MSW treatment technology. ✓ Unsorted MSW can be treated by pyrolysis process at 600-650°C in absence of oxygen. ✓ Waste converted to the syngas and char from the process and combustion can be done sequentially. ✓ Reaction is taken as, $C+H_2O=CO+H_2$ 	MSW	Air	Pilot Scale	Limited	Halton EFW Business Case (2007), Khoo Hsien H.(2009), Niessen W.R. (2002)
	Plasma Arc	<ul style="list-style-type: none"> ✓ The system basically uses a plasma reactor which houses one or more. ✓ Plasma Arc Torches which generate, by application of high voltage between two electrodes. a high voltage discharge and consequently ✓ In an extremely high temperature environment (between 5000-14,000°C) wastes are oxidized. . ✓ Gas output after scrubbing comprise mainly of CO and H₂. ✓ The liquefied product is mainly methanol. ✓ High efficiency in energy recovery from waste. 	MSW	Air	Lab Scale	Very Limited	SWM Manuals (2000), Circeo, Circeo, Louis J. (2009)
Hybrid Technology	Bio-chemical conversion, anaerobic process	<ul style="list-style-type: none"> ✓ In MBT shredding followed by trammel separation, material recovery and biological (drying) treatment, and subsequent fuel preparation. ✓ Pre-digestion stage of heating to 70°C for one hour followed by mesophilic digestion at 35°C, or a thermophilic digestion process, operating the whole digester at 57°C. 	MSW	Multiple	Pilot scale	Limited	Greater London Authority (2003)
	Pyrolysis-Gasification	<ul style="list-style-type: none"> ✓ Pyrolysis-gasification is a hybrid waste treatment technology. ✓ Pre-drying of the waste and capture of the thermal energy uses a heat recovery steam generator (HRSG). ✓ The process converts MSW to useful energy in the form of electricity. ✓ P-G has the higher efficiency in waste-to-energy conversion process. 	MSW	Air	Pilot level	Limited	Alternative Resources, Inc (2007), Feo et al., (2003), Khoo Hsien H.(2009), (NSCA, 2002), (Malkow, 2004), (DEFRA, 2004)

		<ul style="list-style-type: none"> ✓ Normal combustion, as in conventional incineration requires the presence of sufficient amount of oxygen which will ensure complete oxidation of organic matter. ✓ Using cellulose (C₆ H₁₀ O₅) to represent organic matter, the reaction is C₆ H₁₀ O₅ + 6O₂ = 6CO₂ + 5H₂ O + heat (H₂ O : Water) (CH₄ + 2O₂ = CO₂ + 2H₂ O + heat) 					
	Plasma arc-Gasification	<ul style="list-style-type: none"> ✓ Reactor temperatures range from approximately 800°F for a cracking technology to as high as 8,000°F for a plasma gasification technology. ✓ The organic fraction of the MSW is converted to a gas typically composed of hydrogen, carbon monoxide and carbon dioxide gases. 	MSW	Air	Pilot Scale	Limited	Alternative Resources, Inc (2006), Circeo, Louis J. (2009)
Other processes	Bioreactor technology	<ul style="list-style-type: none"> ✓ Waste is pre-processed for the landfill. ✓ Anoxic stage followed by the oxidation phase, methane formation, nitrogen concentrations increase along with carbon dioxide concentration originating from methane oxidation. ✓ MBT is combination of mechanical with biological processes, aiming, mainly at the stabilization of the biologically degradable components. ✓ Anaerobic or aerobic processes then can continue to generate biogas from landfill 	Organic waste	Multiple	Pilot Scale	Limited	Muntoni et al., (2009), Ludwing et al., (2003)
	Hydrolysis	<ul style="list-style-type: none"> ✓ Oxynol hydrolysis is not yet in commercial operation for MSW. ✓ The four major processes are: (1) waste preparation; (2) acid hydrolysis; (3) fermentation, and (4) distillation. 	MSW, Sewage sludge	Water	Lab Scale	Very Limited	Alternative Resources, Inc. (2006), Biffa (2003)
	Conversion of solid wastes to protein	<ul style="list-style-type: none"> ✓ Laboratory investigations conducted at Louisiana State University, USA. ✓ In aerobic conditions, it is possible to convert the insoluble cellulose contained in municipal waste by a cellulite bacteria. ✓ The bacteria are then harvested from the media for use as protein. 	Cellulose Waste	No data	Lab Scale	Very Limited	SWM Manuals (2000)

	<ul style="list-style-type: none"> ✓ Studies were conducted using waste bagasse as the sole carbon source. ✓ The process involves size reduction followed by a mild alkaline oxidation treatment before aerobic oxidation. ✓ The bagasse is slurried in water, mixed with simple nutrient salts mixture and then fed to the reactor from where it is harvested. ✓ The single cell protein produced has a crude protein content of 50 to 60%. 						
Hydro-pulping	<ul style="list-style-type: none"> ✓ hydropulp the waste and recovers paper fiber from refuse. ✓ The method is being used in a full scale plant of 150 tpd capacity operating at Franklin, Ohio, USA. ✓ The method is suitable for processing of paper waste. 	Paper waste	Multiple	Pilot scale	Very limited	SWM Manuals (2000)	

Table 6: SWOT Analysis of the Emerging Waste Treatment Technologies

Methods	Strength	Weakness	Opportunity	Threats
Dry Composting	Biological process in a confined or open area. Possibility to get nutrient-rich organic fertilizer and soil conditioner from the waste. Dried material can be extracted biogas via anaerobic digestion.	Only biodegradable waste can be managed by this process. Emission control from the system is difficult.	Opportunity of resource recovery and making bio-fertilizer. Biogas can be generated from the dry waste.	Potential threat to water and soil contamination for poor management. Emissions to the atmosphere are a great threat for environmental degradation.
Sanitary Landfilling	Natural decomposition process in confine area and can handle different types of waste with larger volume. Waste can be managed in controlled environment with low environmental impact.	Huge land area is needed and emission control is difficult and costly. Long time is required to reclaim the landfill land restoration.	Opportunity to recover biogas from the landfill. Opportunity to manage waste more environmental friendly way if sanitary landfill fully functioned.	Threat to global warming potential, soil and water pollution due to poor maintenances.
Gasification	Almost all types of waste fractions can be treated with gasification process. Low final residue is generated from the processes.	High investment cost and still developing technology for MSW.	Energy and heat can be recovered from the gasification of MSW.	Environmental impact through emission to the atmosphere and final residue
Pyrolysis	Different waste categories can be treated by Pyrolysis process with lower volume of final residue.	Higher investment cost and technology not yet matured enough for MSW.	Opportunity of resource and energy recovery.	Potential environmental threat from emissions.
Plasma Arc	Almost all types of waste categories can be treated with lower disposable residue.	New technology for MSW management and high investment cost.	Opportunity of higher energy and heat recovery option.	Threat to environmental impact from the emission.
Bio-chemical conversion of MSW	Integrated waste treatment process with MBT with anaerobic digestion.	Limited waste treatment capacity; organic waste can be treated by this technology.	Energy and resource recovery can be possible.	Potential environmental threat from emissions to the atmosphere and water.
Pyrolysis-Gasification	Hybrid thermal process with large volume of different waste treatment capabilities.	Emerging technology with higher investment cost.	Opportunity of energy and resource recovery.	Potential environmental threat from air and water emissions.
Bio-reactor	Landfill with MBT facilities. Higher waste volume can be managed by this process compare to traditional landfill.	Pre-processing of waste is required.	Higher volume of biogas can be recovered from the bio-reactor.	Environmental threats due to emissions from the technology.
Hydrolysis process	Chemical processes of food/fruit waste to ethanol production.	Very new technology with limited problem solving capacity.	Opportunity of ethanol production.	Water contamination.
Conversion of solid wastes to protein	Conversion of waste to nutrient.	Experimental stage with lower problem solving potentials.	Opportunity of having nutrient recovery from waste.	Unknown
Hydro-pulping	Resource recovery and reuse in paper and pulp industry.	Only paper waste can be managed by this process.	Resource recovery.	Threat of environmental pollution from chemicals and waste water.

Qualitative evaluations of the emerging technologies are done by three criteria with certain evaluation value. Readers are requested to go the methodology section Table 1 for details of the evaluation criteria. Table 7 shows that, thermal waste treatment technologies have higher potentials in waste handling, development stage and problem solving capacity. Bioreactor and sanitary landfill has also potential as emerging technology. Solid waste to protein, slurry curb process and dry composting are still experimenting in lab scale, which might be developed in the near future.

Table 7: Qualitative evaluation of the selected emerging technologies

Methods	Process type	Waste handling capacity	Development stage	Problem solving capacity
Dry Composting	Biological process	***	**	***
Sanitary Landfilling	Biological process	*****	***	****
Gasification	Thermal process	*****	***	*****
Pyrolysis	Thermal process	*****	**	*****
Plasma Arc	Thermal process	*****	**	*****
Pyrolysis-gasification	Thermal process	*****	***	*****
MBT and aerobic fermentation	MB processes	***	**	****
Hydrolysis	Biological process	***	**	**
Bioreactor	Biological process	*****	****	***
Solid wastes to protein	Biological process	**	*	*
Hydro-pulping	Thermo-chemical	**	**	**
Slurry curb process	Thermo-chemical	***	*	**

Pyrolysis-Gasification is selected as an emerging technology for LCA Model. The main reasons for choosing P-G for LCA model are:

- It is an advanced thermal treatment process which can manage different type of waste fractions
- It produces energy which is the leading economical benefit from it.
- Moreover, the emissions data required for the LCA model are available for the P-G process rather than other emerging waste treatment technologies.
- Potential waste management problem solving capacity of P-G.

5.3 LCA of Emerging Technology

5.3.1 Goal and Scope

As a part of master's thesis goal, an LCA model for emerging technology (Pyrolysis-Gasification) is developed. A comparative study of the emerging and existing technology is further analyzed by LCA model. As an existing technology, Incineration is considered for the model since Incineration and PG are similar technology managing same type of waste fractions. Therefore, for a fair comparison, incineration is compared with the P-G process. Life Cycle Impact Assessment (LCIA) has been done by the CML 2 baseline 2000 method considering 10 different impact categories. For this study two different scenarios are considered stated below,

- Case 1: Stand alone or attributional LCA model for Pyrolysis-Gasification Process and
- Case 2: Attributional comparative model to compare Pyrolysis-Gasification and Incineration Process.

5.3.2 Functional Unit

The functional unit of the LCA study is 1 ton of MSW mass. Therefore, both scenarios have been modeled based on 1 ton of MSW treatment facilities. All input-output data are considered for 1 ton of waste mass.

5.3.3 System Boundaries

Case 1: 1 ton of MSW is considered for the treatment and transportation of MSW is not considered for the P-G process. It is assumed that, the distance for transporting waste is same for both P-G and Incineration processes. Therefore, common features can be omitted from the LCA model. During the thermal process, syngas is produced that can be used for energy generation. After cleaning process, gas is released in the atmosphere and solid waste that is produced as final residue from the process is assumed to be landfilled for the further treatment. As resource, inflow-outflow is 1 ton of MSW waste, emission of gases to air and water, final residue treatment and energy generation from the process are considered within the system boundary. Figure 13 shows the system boundary for the P-G process.

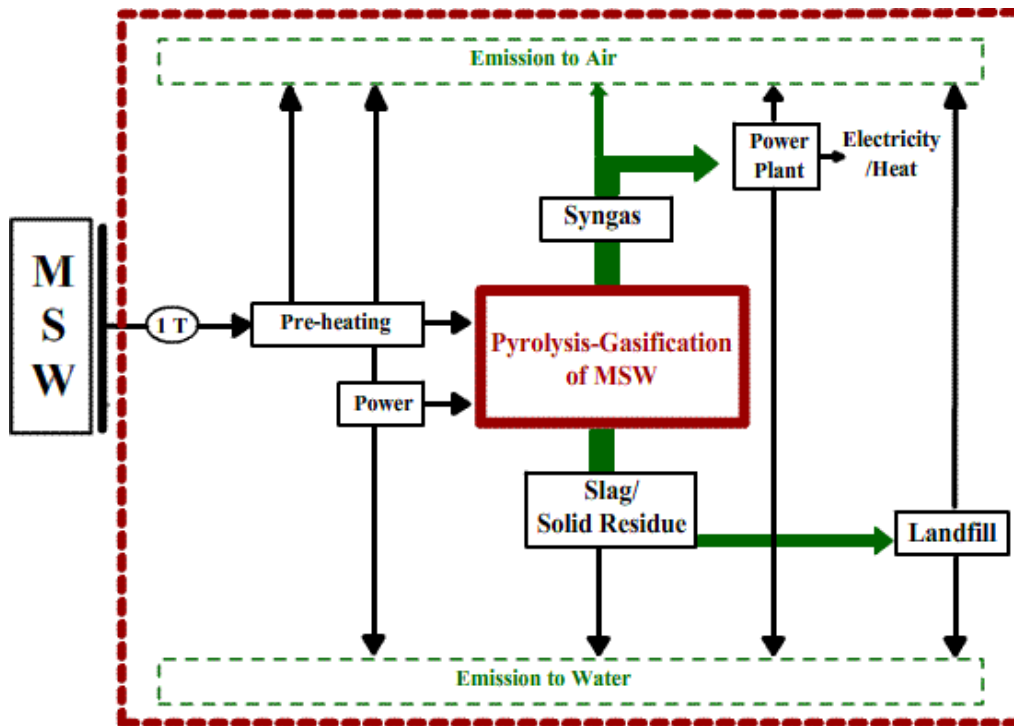


Figure 13: Case 1- System boundary for Pyrolysis-Gasification of MSW

Case 2: A comparative study of Pyrolysis-Gasification and Incineration process of LCA model is done in case 2 where both the processes handle 1 ton of MSW for the model. Transportation of waste is not considered and all emissions from the process are considered as the outflow from the system. Energy and final residue from the system are also accounted for the model. A simplified comparative LCA model is shown in the Figure 14.

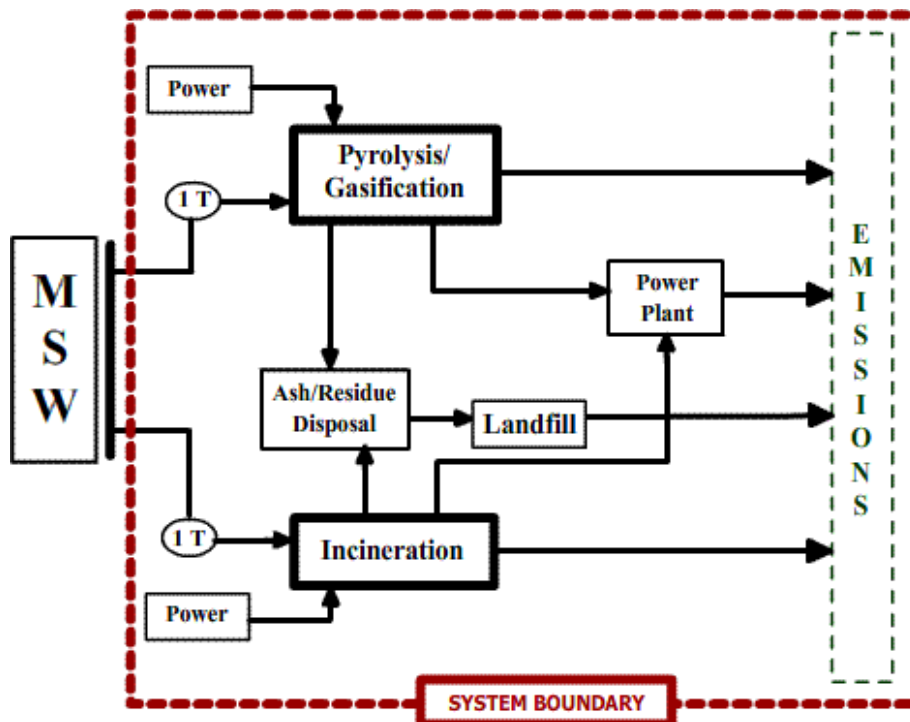


Figure 14: Case 2- System boundary for three different MSW treatment processes

5.3.4 Assumptions and Limitations

The following assumptions have been made during the LCA model development:

- For both scenarios, transportation of waste has been ignored by assuming that transportation distance for waste is same for both treatment plants.
- Average energy data is considered for the model assuming the similar impact on the model for the two processes. Average data are taken for Sweden context.
- Data is based on UK's waste treatment facilities. However, we assume that electricity that is consumed by the systems will be quite similar with the Swedish perspective, so electricity consumed by system is assumed to come from the Swedish national grid (medium voltage).
- CO₂ data for P-G is assumed to be same as incineration of MSW because same waste type with same carbon content would be combusted in the two different processes. This assumption is made due to the lack of carbon data for P-G process.

5.3.5 Life Cycle Inventory Analysis

Life cycle inventory of the LCA model is made based primarily on the literature, report and publications and some of the important papers are DEFRA (2004), Feo et al., (2003), Bridgwater (1994), NSCA (2002), Halton EFW Business Case (2007), Cherubini et al., (2008), Finnveden et al., (2000), Circeo (2009), Khoo (2009). LCA Model has been developed based on the inflow-outflow material data that are available from the reference sources. It is important to understand and decipher the data quality and reliability of the data while developing a comparative model. It should be asserted that, the mountable data for P-G process is not available in Sweden since, there are no P-G plants in large projects in Sweden. However, the data gathered for the LCA model is quite effective for developing LCA model since data for LCA is not adversely available for emerging technologies.

Data Analysis

In the LCA model of Pyrolysis-Gasification, the input data is taken as waste resource (1 ton MSW), energy (electricity kWh/ton of MSW), emission (gm/T) in air, soil or water, Energy generation (kWh/ton of MSW) and residue (kg/ton) produced by the facilities. Most of the data that is used for the LCA model is based on the waste composition in UK. Typical waste composition is shown in the appendix Table A1. Both technologies require startup energy and both generate energy from the waste treatment facilities and final residues are generated from the processes. Table 8 shows the Inflow-outflow energy and solid waste from the processes.

Table 8: Input-output (energy and residue) in different MSW treatment processes

Input/output	Pyrolysis-Gasification	Incineration
Start-up energy (kWh/T)	339.3 (3)	77.8 (1)
Energy generated(kWh/T)	685 (4)	544 (4)
Solid residue (kg/T)	19.6 (3)	180 (2)
(1) Finnveden et al., (2000), (2) DEFRA (2004) , (3) Khoo(2009), (4) Circeo (2009)		

Start up energy required for the system is taken from the average country electricity grid and Sweden's average energy mix is considered using the data from the SimaPro (2007) LCA. Both processes produce electricity from the system. As a result, avoided electricity production is also considered for the system as average country (Sweden) mix from the database. The LCA model is developed based on emission data, assuming waste as zero burden materials. The model is thus process specific LCA. No transportation emission is considered for the model. All the emissions data that are taken into account for the LCA model are the average emission data; which means this is not a plant specific emission data. Therefore, average emission data from P-G and Incineration of MSW are used for the LCA model. Table 9 shows the emission data for two waste treatment facilities.

Table 9: Emissions to air from waste management facilities (grams per ton of MSW)

Substances	Emissions of MWS treatment processes (g/T)	
	Pyrolysis-Gasification	Incineration
Nitrogen oxides	780	1600
Particulates	12	38
Sulphur dioxide	52	42
Hydrogen chloride	32	58
Hydrogen fluoride	0.34	1
VOCs	11	8
Cadmium	0.0069	0.005
Nickel	0.040	0.05
Arsenic	0.060	0.005
Mercury	0.069	0.05
Dioxins and furans	$4,8 \times 10^{-8}$	$4,0 \times 10^{-7}$
Polychlorinated biphenyls	No data	0.0001
Carbon Dioxide	10,00,000*	10,00,000
Carbon Monoxide	100	No data
DEFRA (2004) * CO2 emission assumed similar in both combustion technologies.		

There is data gap for P-G process. Carbon emission is not given in the Defra report because the process did not consider the post treatment emission after electricity generation by the syngas. Therefore, to minimize data gap, carbon emission is assumed to be same as incineration of MSW. This assumptions might have an impact on the results; mainly in global warming potentials but it could still be useful while comparing the two different technologies. Since the carbon dioxide is the content of biogenic and fossil carbon, therefore, to identify environmental burdens only carbon dioxide is considered in the model. From the eco-invent data base, municipal solid waste contributes 39.5% of fossil carbon, therefore, 39.5% of total carbon emission is considered for both processes in the LCA model. Calculation of fossil carbon is shown in the appendix.

The LCA model is an attributional LCA model therefore; average country mix is used for electricity generation as avoided product. Difference between the average data and the marginal one is average data represents the average situation for certain process, and marginal data represent the last number unit that produce in the system. For example, in extreme winter, during high heat demand, Sweden generates heat from coal or diesel power plant. Usually, Sweden does

not produce heat from coal. Therefore, marginal data would replace heat from coal whereas average data would replace average heat source.

5.3.6 Life Cycle Impact Assessment

Life cycle impact assessment is done with the CML 2 baseline (2000) method. CML 2 baseline is developed by Centre of Environmental Studies (CML), University of Leiden, Netherlands. CML 2 baseline is a midpoint analytical method having the option of three different groups of impact categories; Group A: baseline impact categories, Group B: study specific impact categories, Group C: other impact categories (CML, 2001).

LCA model is developed for P-G of MSW and for comparative study with Incineration of MSW. Two different scenarios are developed for LCA model:

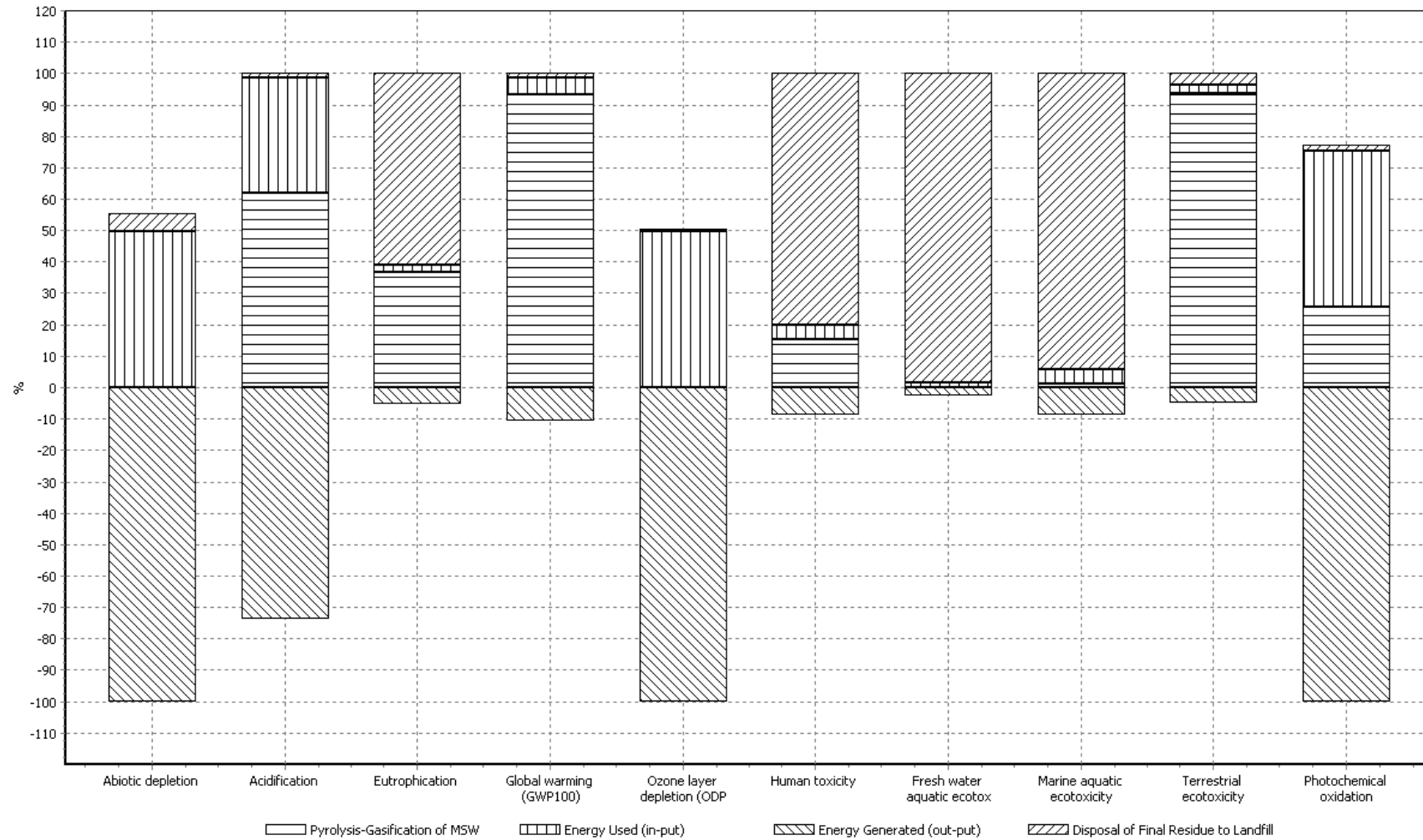
- Case 1: Pyrolysis-Gasification (P-G) (Attributional LCA model)
- Case 2: Comparative Study of P-G and Incineration of MSW (Attributional LCA model)

Results from the LCA software are given below.

Case 1: Pyrolysis-Gasification (P-G)

Results of the LCA model are presented in characterization of impact and normalization of impact methods. Characterization represents the contribution of emission to the environment by different impact categories. Inventory of the characterization gives the idea on the polluting substances and process phases for the environmental burden. Results are presented in ten different impact categories in the both characterization and normalization of LCA model. Figure 15 shows the characterization graph of the LCA model and characterization values are presented in the Table A4. Negative value of the model represents the savings of environmental burdens. Therefore, negative value does not mean that it improves certain impact categories; rather it means that impact can be avoided or saved by the technology. Positive values show the environmental burden imposed by the technology.

Figure 15: Characterization graph showing different impacts from Pyrolysis-Gasification

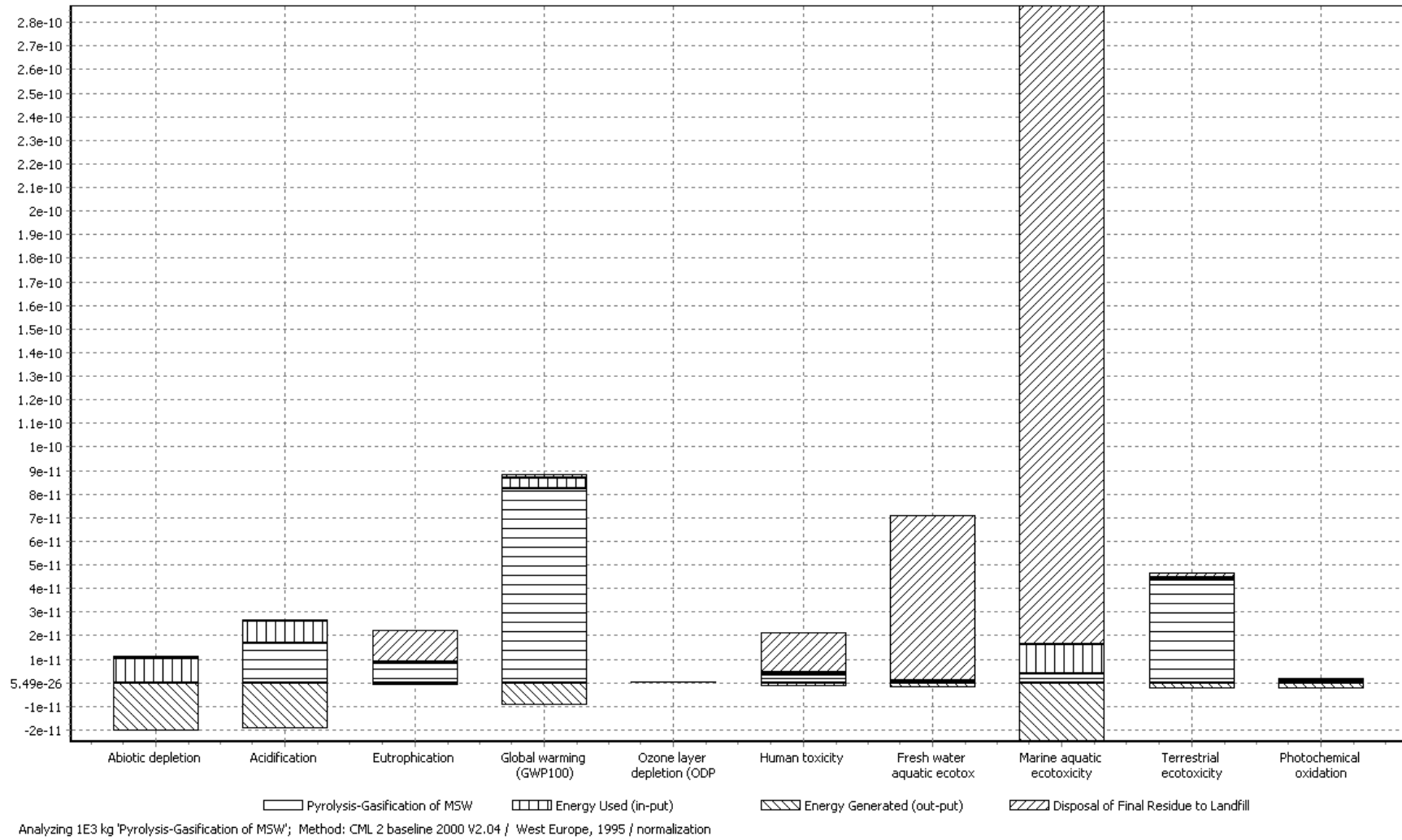


Analyzing 1E3 kg 'Pyrolysis-Gasification of MSW'; Method: CML 2 baseline 2000 V2.04 / West Europe, 1995 / characterization

Characterization graph shows that disposal of final residue and energy recoveries from the waste treatment processes are the most environmentally friendly and significant part of the P-G processes. Environmental burden is less from the process emission compare to the disposal of final residue. For P-G process, volume of final residue is important in considering the environmental burdens and is responsible for each and every impact categories. Since, it is assumed that final residue will be disposed to the landfill, higher volume of inert residue will impose higher burden on environment. However, different research shows the possibilities of secondary use of inert residue as construction material. If the final residue can be used as construction materials then the environmental burden will reduce tremendously on the P-G processes.

Electricity generation is one of the most environmental beneficial factors for P-G process. Model shows the environmental saving for the energy generation in different impact categories, especially, Acidification and Photochemical oxidation. In the model, energy output is considered as the avoided product and average country mix has been considered for the model. If, the avoided value is taken as the marginal of country electricity production then the model would show more environmental favorable output for the process. Because marginal value is taken from the most possible substitution energy option, i.e. if Sweden has coal power plant for electricity production, then assumption made for marginal value is that electricity produced from the P-G will replace the coal power plant.

Figure 16: Normalization Graph of the Pyrolysis-Gasification



P-G process is responsible for acidification, global warming, eutrophication, human toxicity, marine ecotoxicity and terrestrial ecotoxicity impact categories. Emission from the process is responsible for the environmental burdens since the P-G process occurs in the limited amount of air; the volume of syngas is less, which is one of the key benefits of P-G process. If more air is used in the process, higher volume of syngas is produced and more environmental burden would be imposed.

Figure 16 shows the normalization graph of the model representing the level of significance for different impact categories. From the figure, P-G of MSW has significantly high environmental impact on marine aquatic ecotoxicity, fresh aquatic ecotoxicity, global warming, human toxicity, eutrophication, terrestrial eco-toxicity and acidification. Normalization graph shows that, environmental burden of the P-G of MSW is primarily caused by the disposal of final residue. Therefore, volume of final residue and the treatment of the residue in one of the key concern to promote P-G as waste treatment technology as future of sustainable waste management system in Sweden. Significant environmental impact categories are analyzed for P-G of MSW in the following section.

Aquatic Depletion: P-G has significant impacts on marine and fresh aquatic categories. Disposal of final residue is the primary cause for aquatic quality depletion. Vanadium Copper (ion) and Selenium is the main disposal degrading aquatic environment and Nickel, Zinc and Antimony are the primary pollutants for the aquatic depletion.

Global Warming Potential: Carbon dioxide, carbon monoxide emission is mainly causing global warming impact. Disposal of final residue is also responsible for global warming impact. The process of MSW treatment has lower GWP however, significant impact occurs during the conversion of syngas to electricity from the process.

Human Toxicity: Pyrolysis-Gasification has significant environmental impact on human toxicity and the impact is primarily associated with the process stage and for the disposal of final residue. Arsenic, Cadmium, Mercury, Nickel, Nitrogen oxide and Hydrogen fluoride are the primary pollutants for the Human toxicity which are emitted in the atmosphere and water by the P-G process.

Terrestrial Ecotoxicity: P-G has a significant terrestrial ecotoxicity impacts. Mercury, Arsenic and Nickel that are emitted from the process in the atmosphere are the primary cause for terrestrial ecotoxicity.

Acidification: Disposal of final residue in thin environment causes acidification burden. However, acidification can be avoided by the P-G process due to energy generation. Nitrogen oxide and sulphur dioxide are the primary reason for the acidification impact and these gases are emitted in the atmosphere during the process stages.

From the inventory analysis, major pollutants that cause environmental impacts due to the MSW Pyrolysis-Gasification have been identified and the data are shown in [Table 10](#).

Table 10: Major pollutants and mode of pollution from Pyrolysis-Gasification of MSW

Name of the Pollutants	Pollution medium	Impact categories			Processes stage
Vanadium, ion	Water	Aquatic Toxicity	Depletion,	Human	disposal of residue
Selenium	Water	Aquatic Toxicity	Depletion,	Human	disposal of residue
Nickel, ion	Water	Aquatic Toxicity	Depletion,	Human	disposal of residue
Copper, ion	Water	Aquatic Toxicity	Depletion,	Human	disposal of residue
Molybdenum	Water	Aquatic Toxicity	Depletion,	Human	disposal of residue
Antimony	Water	Aquatic Toxicity	Depletion,	Human	disposal of residue
Cobalt	Water	Aquatic Toxicity	Depletion,	Human	disposal of residue
Zinc, ion	Water	Aquatic Toxicity	Depletion,	Human	disposal of residue
Mercury	Air	Terrestrial Ecotoxicity			process, disposal of residue
Arsenic	Air	Terrestrial Ecotoxicity			Process
Nickel	Air	Terrestrial Ecotoxicity			Process
Cadmium	Air	Terrestrial Ecotoxicity			Process
Hydrogen fluoride	Air	Terrestrial Ecotoxicity			Process
Benzene	Air	Photochemical Oxidation,			process, disposal of residue
Carbondioxide	Air	Global Warming, Photochemical Oxidation			process, disposal of residue
Carbon mono-oxide	Air	Photochemical Oxidation			process, disposal of residue
Methane	Air	Photochemical Oxidation			disposal of residue
Sulphur dioxide	Air	Photo, Acidification			Process
Phosphate	Water	Eutrophication			disposal of residue
COD	Water	Eutrophication			disposal of residue
Nitrogen oxide	Air	Eutrophication, Acidification			Process

Primarily, water and air medium pollutants have the significant environmental impact from the Pyrolysis-Gasification process. Emission control of the P-G process and the volume of the final residue are the key source of environmental impact by the system. For sustainable waste management system these problem should be corrected in near future. Since, P-G is an emerging technology there is scope for improvement in these areas to promote the technology as a proven technology. Appendix (A-5) shows the 0.01% cutoff of inventory results for the polluter identification in different impact categories.

Case 2: Comparative LCA model

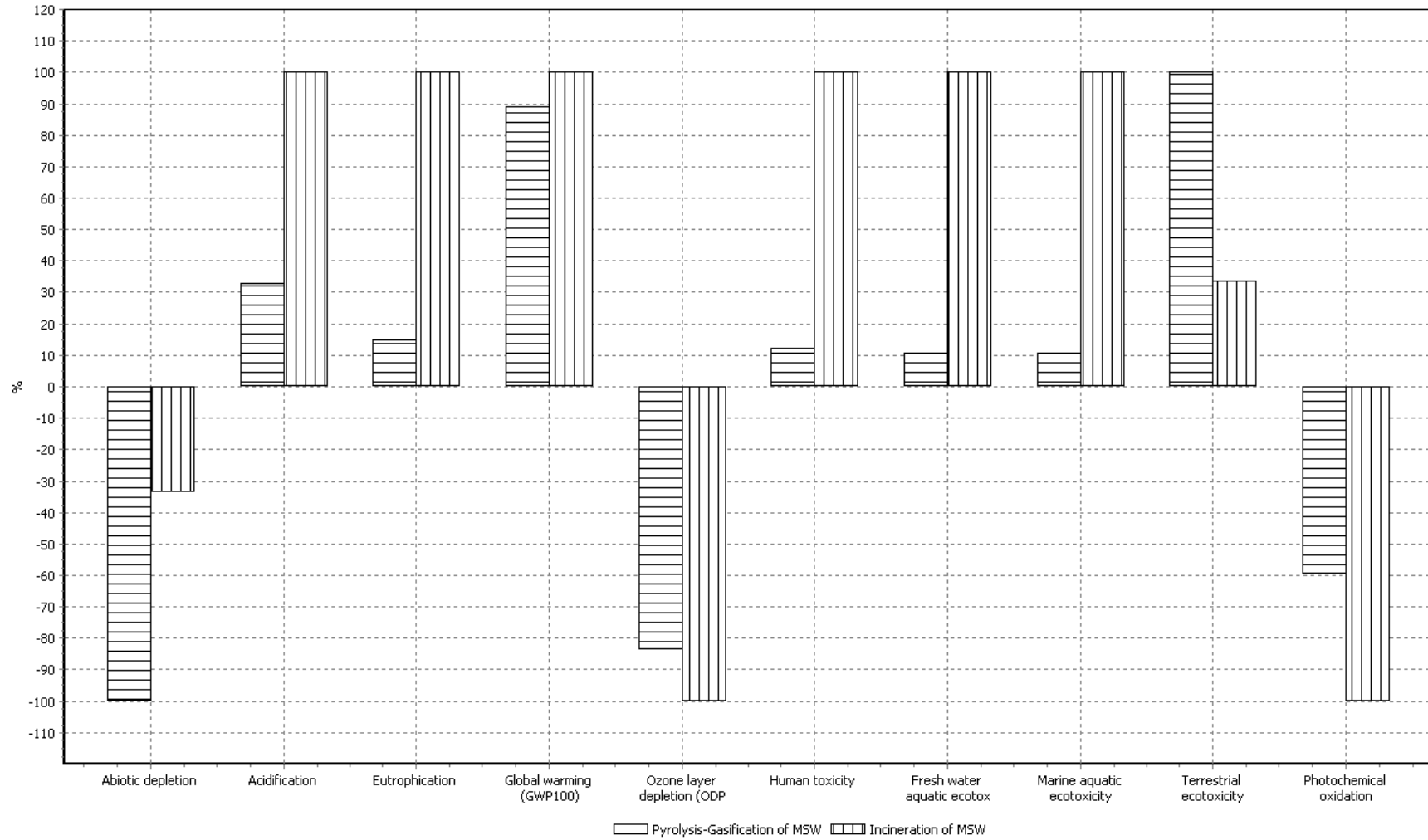
In case 2, comparative study between Pyrolysis-Gasification and Incineration is conducted. In this case, transportation impact is not considered for any of the processes. Table A4 shows the characterization value of different impact categories. All of the MSW treatment facility has the positive environmental impact on abiotic and ozone layer depletion due to the electricity

generation by the processes. Incineration has the higher value in ozone layer depletion category than the Pyrolysis-Gasification process.

Figure 17 shows the characterization graph of the comparative LCA model. Characterization graph shows the contribution of emission or environmental savings in different impact categories. Characterization value does not show the significance of the impact. Rather it highlights the contribution of emission by the processes. Thus, higher contribution value does not mean most adverse environmental impact.

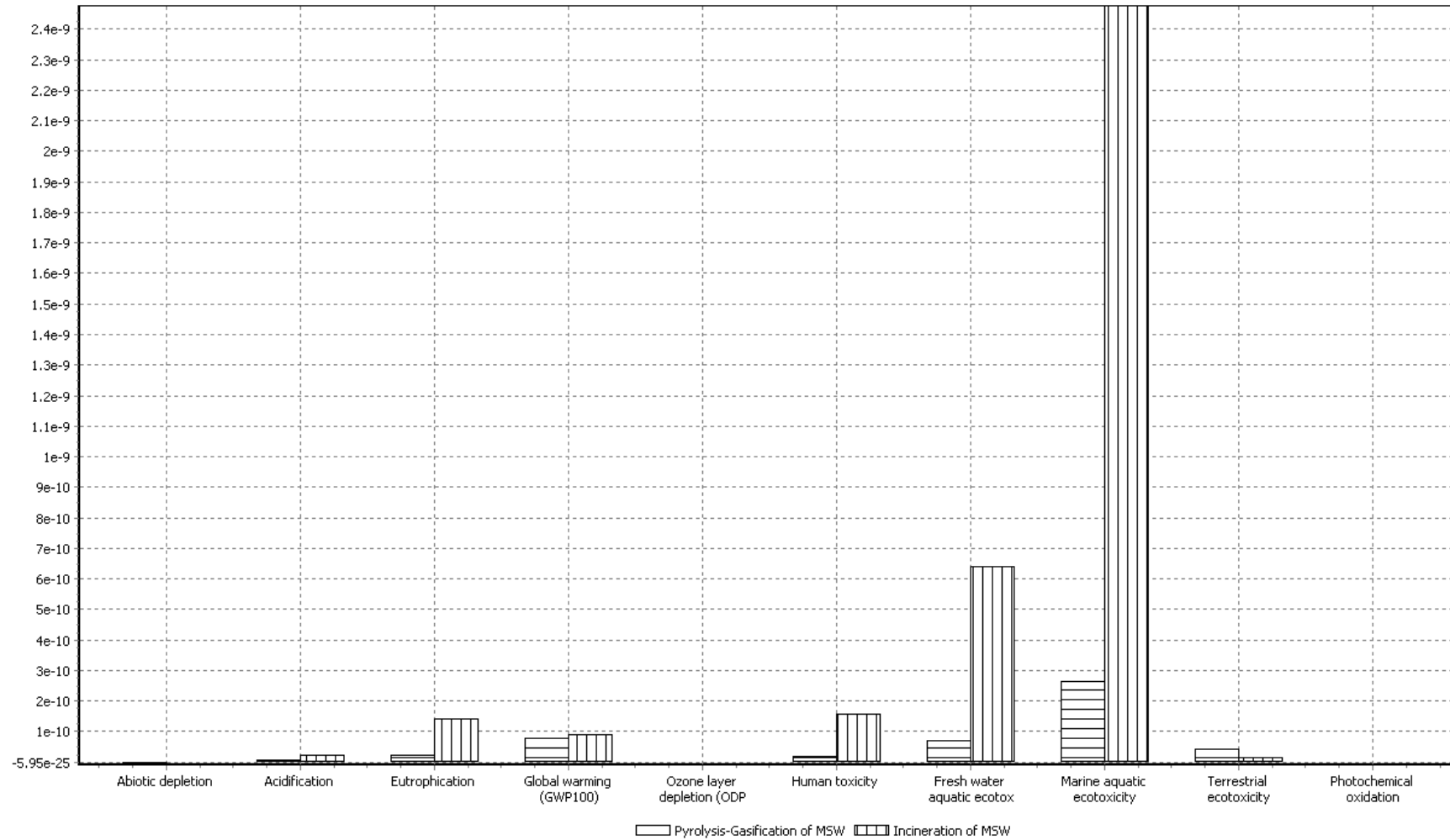
From the characterization graph, incineration has the higher environmental impact as compared to the Pyrolysis-Gasification in the acidification, eutrophication, global warming, human toxicity, aquatic toxicity categories. However; Gasification has the higher potential environmental impact in terrestrial ecotoxicity and photochemical oxidation categories. Incineration has the highest global warming impact among the two facilities and Pyrolysis-Gasification has the least GWP.

Figure 17: Comparative LCA model for Pyrolysis-Gasification and Incineration



Comparing 1E3 kg 'Pyrolysis-Gasification of MSW' with 1E3 kg 'Incineration of MSW'; Method: CML 2 baseline 2000 V2.04 / West Europe, 1995 / characterization

Figure 18: Comparative normalization model for Pyrolysis-Gasification and Incineration



Comparing 1E3 kg 'Pyrolysis-Gasification of MSW' with 1E3 kg 'Incineration of MSW'; Method: CML 2 baseline 2000 V2.04 / West Europe, 1995 / normalization

Normalization graph (Figure 18) shows the significance of impact & comparative impact level in different impact categories. Normalization graph shows that, aquatic life can get significantly vulnerable by both processes.

Now, from the inventory of the both waste treatment technologies, important impact categories are analyzed below:

Aquatic Depletion: Incineration has significantly higher contribution in aquatic depletion both marine and fresh water than P-G of MSW. Emissions from the leachate of the final residue disposal to landfill are the main reason for aquatic depletion both for fresh and marine system. Since, incineration process produce higher volume of residual waste, therefore, aquatic emissions from the final residue is also higher for incineration of MSW. Heavy metal pollution like vanadium, nickel, zinc, copper and the emission of selenium, antimony and molybdenum to air are the main polluters for the aquatic depletion.

Human Toxicity: Pyrolysis-Gasification has lower contribution in Human toxicity impact compare to Incineration. Impact mainly contributes from the disposal of final residue. Arsenic, Cadmium, Mercury, Nickel, Nitrogen oxide and Hydrogen fluoride are the primary pollutants for the Human toxicity which are emitted to atmosphere and water by the P-G process. Antimony and Selenium mainly causes human toxicity by the incineration process through groundwater pollution.

Global Warming Potential: Incineration has slightly higher contribution in global warming however, the carbon emission is assumed same for the both technologies. The reason for the difference is that, the volumes of final residue produced by the two technologies are different. Therefore, the global warming potentials are also different as a whole impact.

Terrestrial Ecotoxicity: In terrestrial ecotoxicity, P-G has higher contribution that incineration process. Heavy metals, like mercury, cadmium emission to the atmosphere are the main reason for terrestrial ecotoxicity. It is important for both global as well as trans-boundary issues while taking decision for waste facilities in certain technology.

5.3.7 Sensitivity Analysis

Avfall Sverige 2008 report shows that, a significant improvement in emission of Incineration process has been made from 2003 to 2007. Per ton waste treatment emission of HCl, SO_x, NO_x, and Dioxin have been reduced to 66%, 73%, 15% and 87% respectively from 2003 to 2007. For the sensitivity analysis, it is assumed that 30% of emission can be improved for P-G process for the next 5 years. Electricity generation and its use can be more efficient during that duration and can achieve 5% more efficiency. Comparative analysis is shown in the following Figure 19 and Table A5 (Appendix).

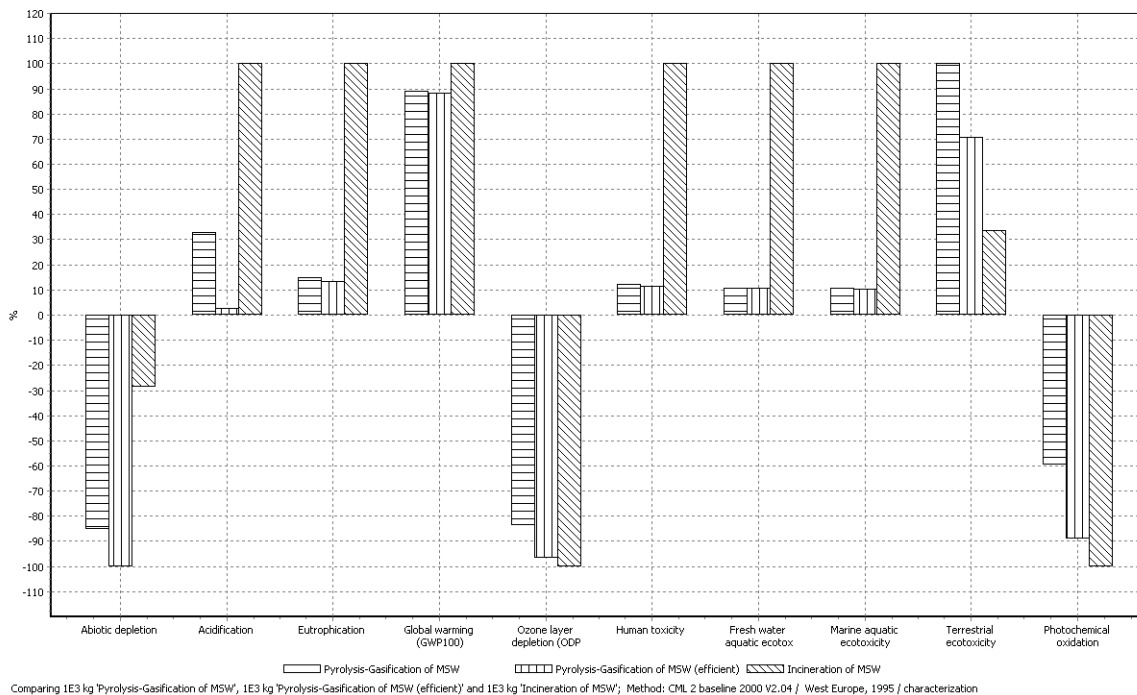


Figure 19: Characterization of efficient P-G with the previous study.

From the sensitivity graph, most of the impact categories have shown the expected result trends except acidification and abiotic depletions. Since, assumption has been made of 30% efficiency in emission reduction; the impact of environmental burden has also been reduced to a similar ratio. Acidification has higher environmental savings compared to other impact categories. SO_x and NO_x emission are the primary pollutants for acidification, which are reduced from both emission efficiency, as well as from the improvement of electricity generation. Hence, total acidification has gotten a higher positive value than other impact categories. Therefore, these two impact categories are very sensitive with the improvement of the technology.

5.3.8 Uncertainty and Limitations of the Results

Different waste management system analysis tools have different context of analytical capabilities. Even LCA model used in different countries has different baseline assessment methods such as per person impact equivalent or per year impact equivalent and so on. Moreover, un-harmonized analysis tools of LCA in different socioeconomic and environmental context make it complex in decision making process for waste management. Research work has been done by considering only air emission and final disposal from Pyrolysis-Gasification and Incineration processes. However, there are other emissions which might have significant environmental impacts and those emissions have not been considered in the study. In addition, there are significant uncertainties being observed in reality because of lack of information and knowledge on cause effect chain of environmental impact (Finnveden et al., 1992).

6. CONCLUSION & RECOMMENDATION

The study identified that, the development of waste technologies are influenced by different drivers; socio-economic or environmental drivers in Sweden. Among all drivers, increased volume of waste is one of the prime concerns in waste management system in Sweden. Number of population and their consumption rate of resources influence the generation of waste volume which lead to the management of waste technologies based on the waste fractions. The fraction which is more economical to recover is taking care by advanced treatment facilities due to market driven development system. Economical value or market value of the resources accelerates the pace of technical development trends more faster and easier way. Waste policy on the other hand has significant influences to promote certain waste treatment facilities. Incentives from the government for certain technology or waste tax act as a promoter for certain technology development. As a part of market driven factor, energy recovery and efficiency of waste treatment technologies are getting importance in selecting and developing waste treatment technologies. Sustainable waste management is not only managing the waste but also increasing the recovery rate in every stages of the management. Therefore, responsibility from producers and consumers are identified as the vital drivers in waste treatment technology development in Sweden. The study identified that, not only technology can solve the whole waste problem; but, a combination of physical process (recycling, reusing, innovative product design) and efficient technology development can lead us to the right direction to achieve sustainability goal. In one hand, producer's responsibilities decrease the gap of loop and increase the possibilities of higher resources recovery options by innovative product design. Personal behavioral change, reduce the resource use and awareness of environmental consequence have the impact on reducing the waste burden on the other. Therefore, extended producers and consumers responsibilities have the significant impact on the development of emerging technologies in Sweden. To forecast the development of emerging technologies in Sweden the role of driving forces are important to understand profoundly.

The study identifies different technologies as a potential emerging waste treatment technologies for Sweden; among them, P-G, Plasma arc, dry composting seems very promising for waste management in future. Resource recovery efficiency is the vital issue in the development of certain emerging technologies in Sweden. Thermal technologies are more efficient in energy recovery and at the same time can manage different waste fractions. Biological treatment options are more favorable in biodegradable waste fractions. However, not a single technology is available that can solve the waste management problem as a whole. Decision support tool helps decision maker to come up with the right choice while plan for future. The study analyzed emerging technology by LCA as a decision support tool to compare environmental performance of the waste treatment technologies.

LCA model analyzed that, Pyrolysis-Gasification has lower environmental impact in certain impact categories than the incineration of waste. Due to the lack of information, it is difficult to say which technology is best or has the lowest environmental impacts. Moreover, it is not fair comparison to compare between emerging and very mature technology on the basis of same criteria. However, analysis is done to measure the potential of the emerging technology in near

future. LCA study concludes that, P-G is important emerging technology for Sweden. One of the main reason for lower environmental burden from P-G process is the controlled use of air during the combustion. Another reason is that P-G produces higher amount of heat and electricity compared to incineration. Nevertheless, P-G has some limitations which should be considered while planning for waste management plan in future. Air Particulate Cleaning residues (APC) that is trapped in the syngas cleaning process, the solid residue from the combustion and the emission are needed to be improved further for sustainable waste management.

In the study, LCA is used as a tool to identify environmental burden from emerging technology. However, socio-economic issues can be analyzed by other tools like cost benefit analysis (CBA) or multi-criteria decision analysis. Life cycle costing, though not considered in this study, is one of the vital tools for decision making processes while selecting any particular technology in future. A comparative analysis of different waste management technology by LCC or other decision support tools is thus recommended.

Key points from the research findings are listed below:

- Sweden needs to focus more in innovative production and consumption to reduce the volume of waste in future.
- Waste management sector is a multi-sectored; influence by multi-shareholders' decision support. Therefore, for sustainable waste management and future technical development, the roles of the key actors are needed to be understood clearly.
- It is important to promote emerging technology for future development. Continuous research and development work is needed to find sustainable waste management technology.
- The study identified P-G process as a potential emerging waste treatment technology. Sweden can take in consideration while planning for future waste treatment technology.
- For better understanding of waste treatment technology, the implementation of different system support tool like LCC, CBA are important. Therefore, implementation of decision support tool should be made mandatory by law for waste management system in future.

It can thus be concluded that, single solution by a single technology is not possible for solving all waste management problems. Integrated waste management system is considered as the appropriate strategy for the waste management facilities at this moment. It is important to integrate different socio-economic, environmental perspectives through multi-stakeholders activities in the overall IWM strategy. Institutional development is important for driving the sustainability activity in waste sector. Public participation in overall waste management system is also one of the important key factors to accelerate sustainable waste management programme in Sweden.

Scope of Future Study

- This study has only considered Pyrolysis-Gasification process as an emerging technology. However, other emerging technologies such as Plasma Arc Gasification, Hydrolysis, Solid

wastes to protein, Hydro-pulping etc. identified in this research work, could be analyzed in future.

- The study is done by considering environmental perspective. However, socioeconomic issues are also important for decision making process. Therefore, there is a scope for future study by life cycle costing or other decision support tool.
- Study has been done by considering technology based waste management solution. However, other physical processes like recycling, reusing or innovative production design are also important and could be analyzed in future.

Advanced thermal waste treatment technologies such as Pyrolysis-Gasification seems very promising when considering waste volume reduction and emission compared to incineration. High resource recovery is possible from these technologies. However, these technologies are not sustainable for long time perspectives. Resources are not recycled by the processes in the thermal waste treatment technologies, which is more sustainable, compared to burning the resource to get limited benefit from it. Therefore, sustainable waste management reduction of waste generation and recycling and reusing the materials are essential.

Since, the study is a part of the project "Tools for Sustainable Waste Management", one of the aims of the project is to forecast waste management technology in future and develop LCA for waste management system in futuristic point of view. The waste management development trends shows that, waste management system would be focused more on recycling and reusing methodology because of sustainability issues. Innovative production, packaging, extended producer's responsibility and personal behaviors would be significantly playing key roles in the development of waste treatment technology in future. It is hard to predict which technologies are going to take place in waste management sector in future. Nevertheless, it can be assumed that a technology supportive to 'waste hierarchy' will get priority for sustainable waste management in future.

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APPENDICES

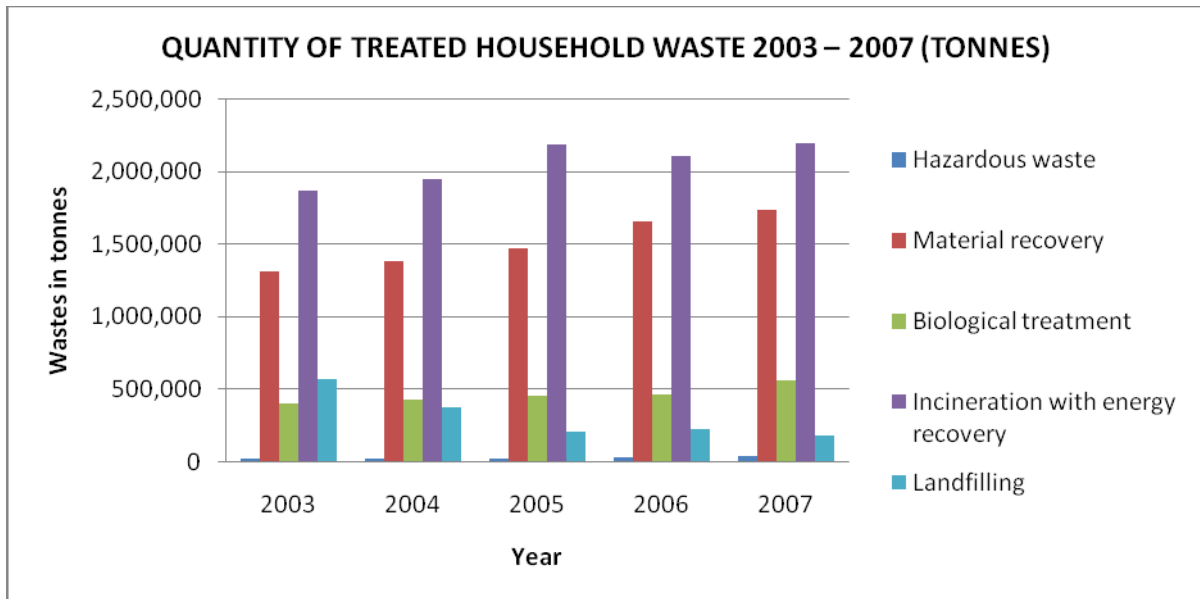


Figure A 1: Quantity of Treated household waste in 2003-2007 (Avfall Sverige, 2008)

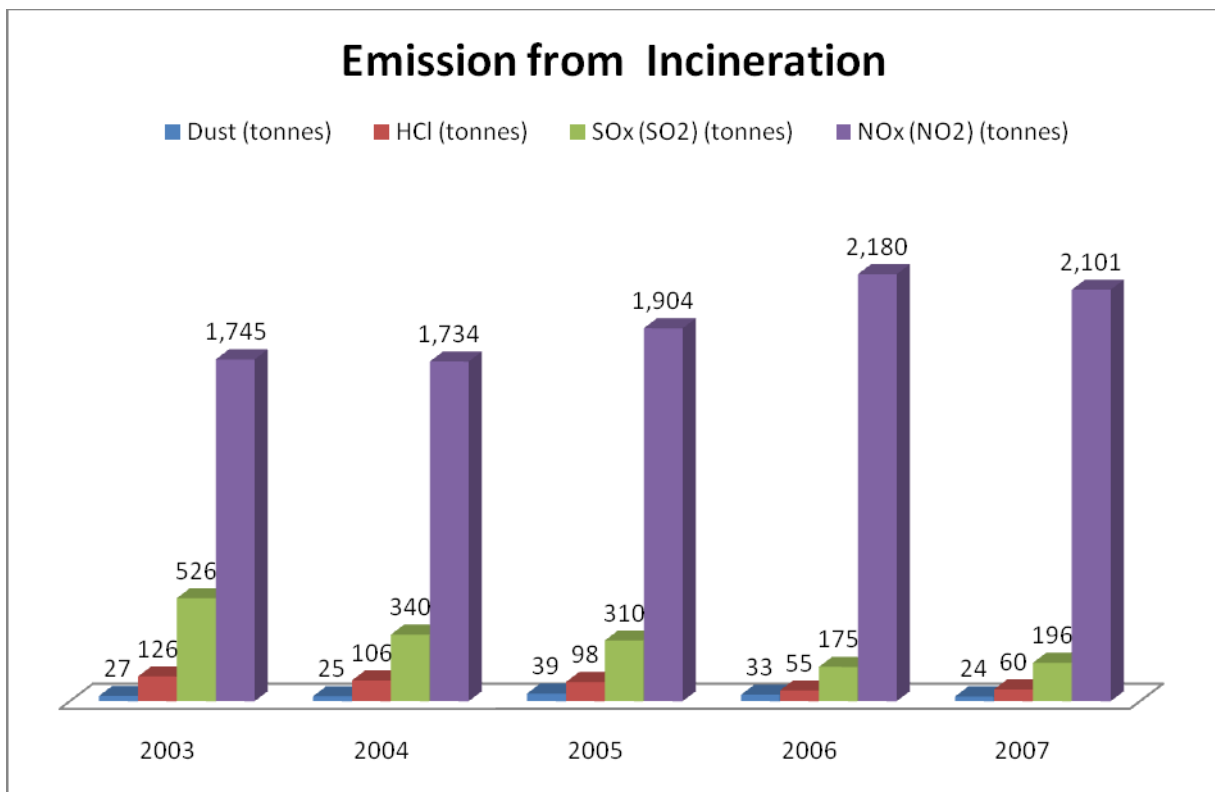


Figure A 2: Emission (tonnes) to the air from the incineration process (Avfall Sverige, 2008)

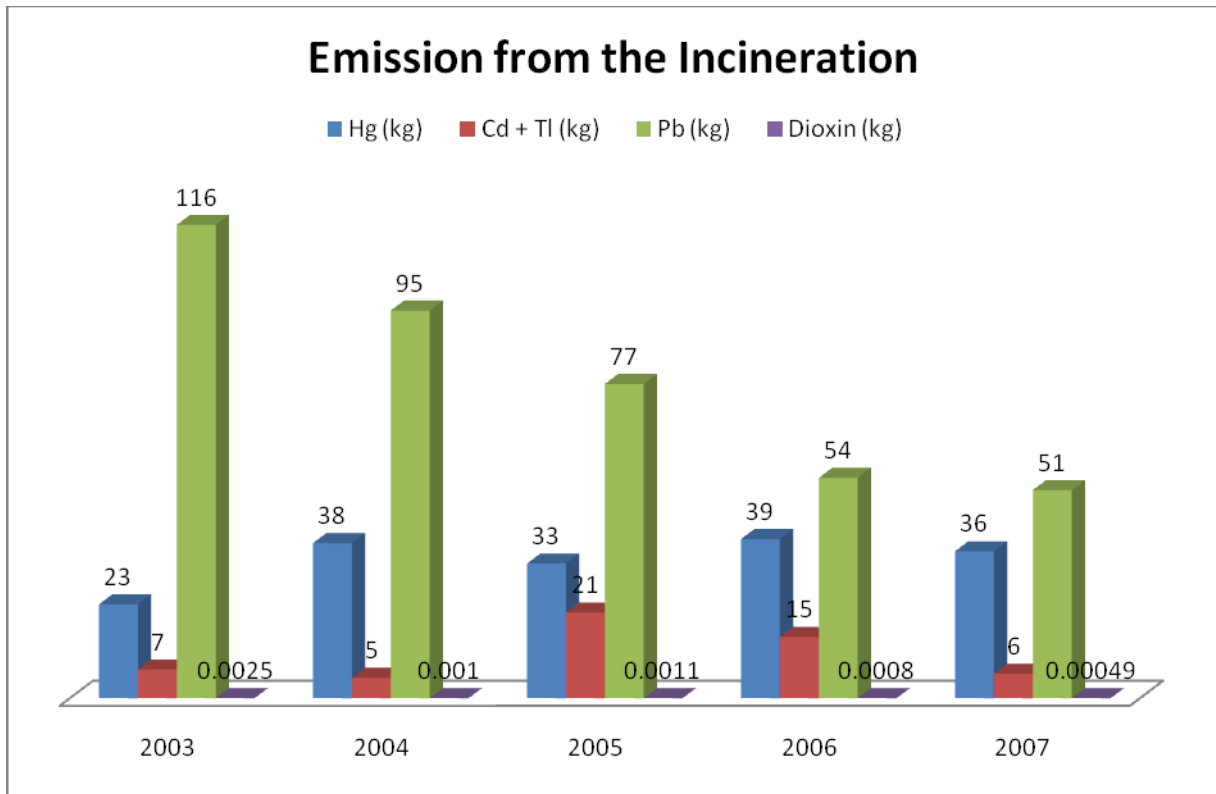


Figure A 3: Emission (kg) to the air from the incineration process (Avfall Sverige, 2008)

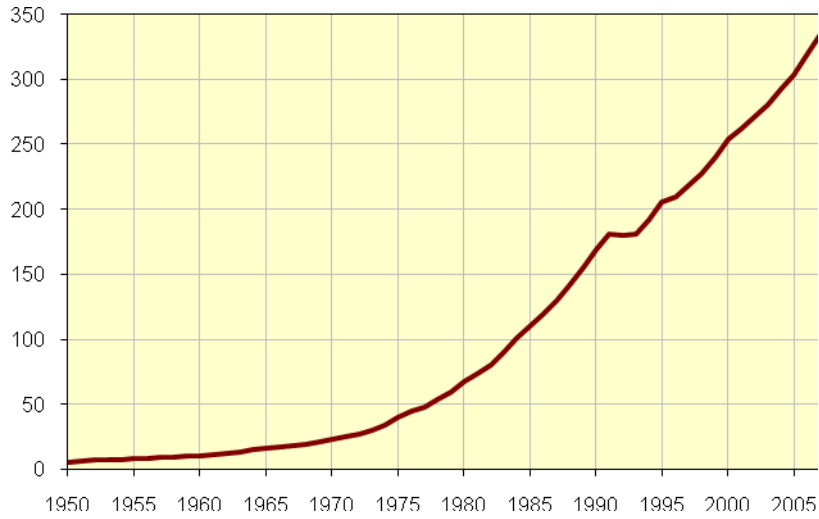


Figure A 4:: Gross domestic product (GDP) per capita 1950- 2009 (Statistics Sweden, 2009)

Table A 1: Composition of waste in UK

Waste Types		Waste fraction in %
Categories	Sub-categories	
Compostable Organic Waste (24.9%)	Compostable food waste	10.5
	Garden waste	14.4
Recyclable Waste (33.4%)	Recyclable paper	22.4
	Plastic Bottles	1.9
	Aluminum	0.7
	Steel Cans	2.5
	Glass Bottle/Glass	4.0
	Metals	1.9
Others (41.7%)	Card paper/packaging	6.4
	Non-compostable organic waste	5.4
	Wood	1
	Nappies	2.6
	Textile and Shoes	5.2
	Other Plastics	10.9
	Other paper/Card	3.7
Unclassified fines	6.5	

DEFRA (2004), Department for Environment, Food and Rural Affairs Review of Environmental and Health Effects of Waste Management: Municipal Solid Waste and Similar Wastes, accomplished by Enviro Consulting Ltd and University of Birmingham with Risk and Policy Analysts Ltd, Open University and Maggie Thurgood.

Table A 2: Major findings from the questionnaire survey

Questions	Professionals feedback
In your opinion, what are the key factors (driving forces) for developing waste treatment technologies in Sweden?	Laws (national & international), national policy, environmental code, waste tax, producers responsibility, volume of waste, exporting waste technology, (proposed bio-waste directive), resource recovery, environmental values, economical benefit, business or policy lobby, geographical factors (location), consumption patterns, environmental awareness,
What are the most challenging factors in sustainable waste management system in Sweden?	Increasing volume of waste, waste composition, hazardous content, emissions, economical viability, and 'cradle-to-cradle' production system.
Do you recommend any emerging (new or developing) technology for Sweden which can be implemented in future for sustainable waste management system?	Dry composting, Anaerobic digestion, personal behavior (!), Gasification, extended producers responsibilities (EPR), Pyrolysis, 'cradle-to-cradle' concept, Bio-covers to the landfill, Home composting,

Table A 3: Characterization value of P-G

Impact category	Unit	Total	Pyrolysis-Gasification of MSW	Energy Used (in-put)	Energy Generated (out-put)	Disposal of Final Residue to Landfill
Abiotic depletion	kg Sb eq	-0.13644	0	0.151243	-0.30534	0.01766
Acidification	kg SO2 eq	0.191525	0.4524	0.266826	-0.53868	0.010984
Eutrophication	kg PO4---eq	0.2632	0.1014	0.007164	-0.01446	0.169099
Global warming (GWP100)	kg CO2 eq	378.6286	395.153	22.63846	-45.7039	6.541048
Ozone layer depletion (ODP)	kg CFC-11 eq	-1.6E-05	0	1.6E-05	-3.2E-05	3.18E-07
Human toxicity	kg 1,4-DB eq	146.3751	24.69638	6.879374	-13.8885	128.6879
Fresh water aquatic ecotox.	kg 1,4-DB eq	34.80127	0.053575	0.492722	-0.99474	35.24971
Marine aquatic ecotoxicity	kg 1,4-DB eq	29741.86	431.519	1404.988	-2836.48	30741.83
Terrestrial ecotoxicity	kg 1,4-DB eq	2.080998	2.054501	0.055803	-0.11266	0.083352
Photochemical oxidation	kg C2H4	-0.00463	0.005196	0.010058	-0.02031	0.000426

Table A 4: Normalization value of P-G

Impact category	Unit	Total	Pyrolysis-Gasification of MSW	Energy Used (in-put)	Energy Generated (out-put)	Disposal of Final Residue to Landfill
Abiotic depletion		-9.2E-12	0	1.02E-11	-2.1E-11	1.19E-12
Acidification		7.01E-12	1.66E-11	9.77E-12	-2E-11	4.02E-13
Eutrophication		2.11E-11	8.13E-12	5.75E-13	-1.2E-12	1.36E-11
Global warming (GWP100)		7.88E-11	8.22E-11	4.71E-12	-9.5E-12	1.36E-12
Ozone layer depletion (ODP)		-1.9E-13	0	1.93E-13	-3.9E-13	3.82E-15
Human toxicity		1.93E-11	3.26E-12	9.08E-13	-1.8E-12	1.7E-11
Fresh water aquatic		6.89E-12	1.06E-13	9.76E-13	-2E-12	6.98E-12

ecotox.		11		13		11
Marine aquatic ecotoxicity		2.62E-10	3.8E-12	1.24E-11	-2.5E-11	2.71E-10
Terrestrial ecotoxicity		4.41E-11	4.36E-11	1.18E-12	-2.4E-12	1.77E-12
Photochemical oxidation		-5.6E-13	6.29E-13	1.22E-12	-2.5E-12	5.15E-14

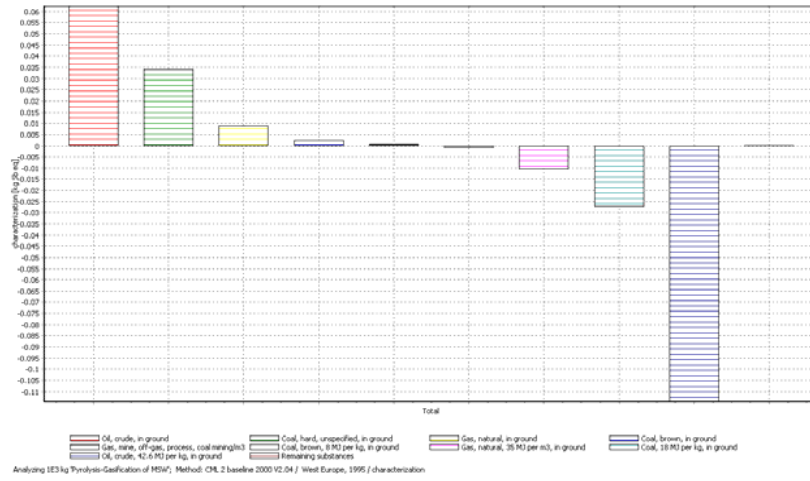
Table A 5: Comparative characterization table of P-G and Incineration of MSW

Impact category	Unit	Pyrolysis-Gasification of MSW	Incineration of MSW
Abiotic depletion	kg Sb eq	-0.13644	-0.04563
Acidification	kg SO ₂ eq	0.191525	0.584653
Eutrophication	kg PO ₄ --- eq	0.2632	1.751102
Global warming (GWP100)	kg CO ₂ eq	378.6286	424.4022
Ozone layer depletion (ODP)	kg CFC-11 eq	-1.6E-05	-1.9E-05
Human toxicity	kg 1,4-DB eq	146.3751	1178.666
Fresh water aquatic ecotox.	kg 1,4-DB eq	34.80127	323.0821
Marine aquatic ecotoxicity	kg 1,4-DB eq	29741.86	281106.3
Terrestrial ecotoxicity	kg 1,4-DB eq	2.080998	0.703079
Photochemical oxidation	kg C ₂ H ₄	-0.00463	-0.00778

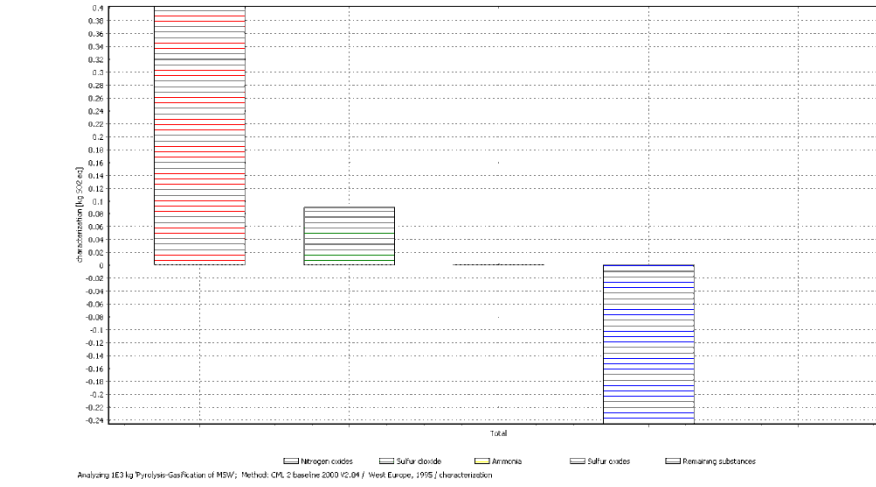
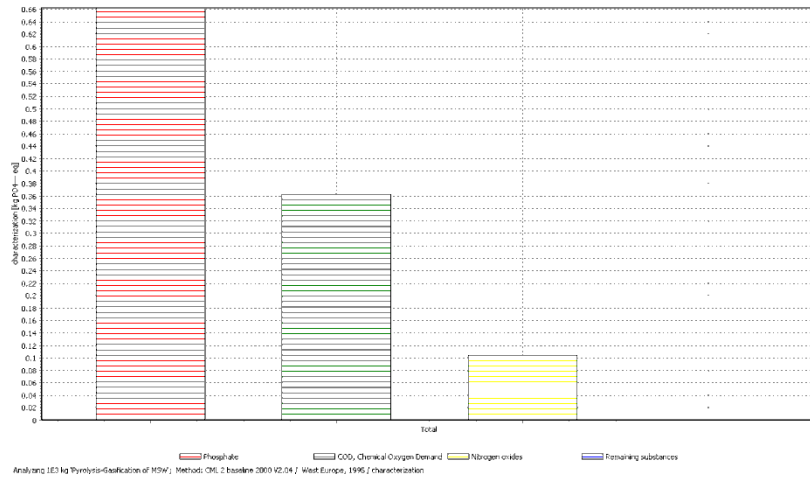
Table A 6: Comparative normalization value

Impact category	Unit	Pyrolysis-Gasification of MSW	Incineration of MSW
Abiotic depletion		-9.2E-12	-3.1E-12
Acidification		7.01E-12	2.14E-11
Eutrophication		2.11E-11	1.4E-10
Global warming (GWP100)		7.88E-11	8.83E-11
Ozone layer depletion (ODP)		-1.9E-13	-2.3E-13
Human toxicity		1.93E-11	1.56E-10
Fresh water aquatic ecotox.		6.89E-11	6.4E-10
Marine aquatic ecotoxicity		2.62E-10	2.48E-09
Terrestrial ecotoxicity		4.41E-11	1.49E-11
Photochemical oxidation		-5.6E-13	-9.4E-13

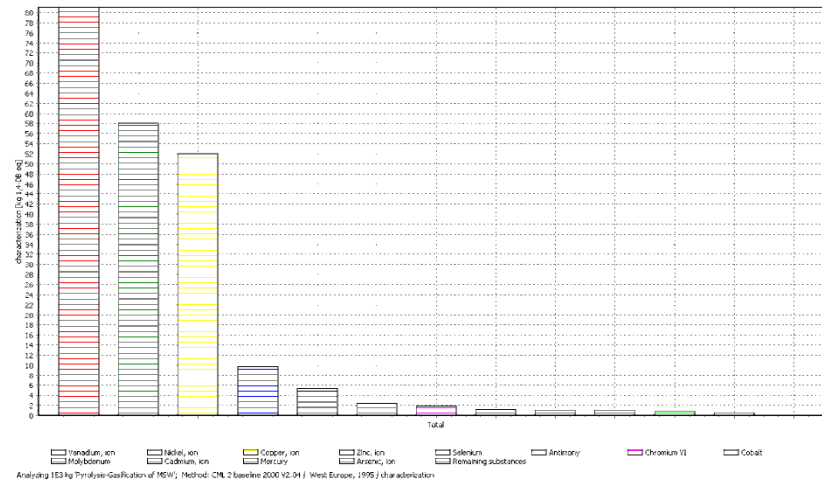
Appendix A5: Inventory of the 0.01% cutoff of impact categories for polluters



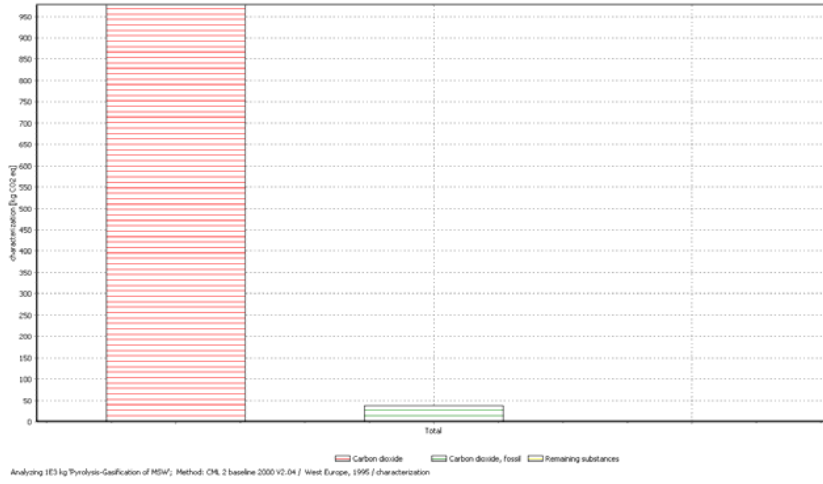
a) Abiotic



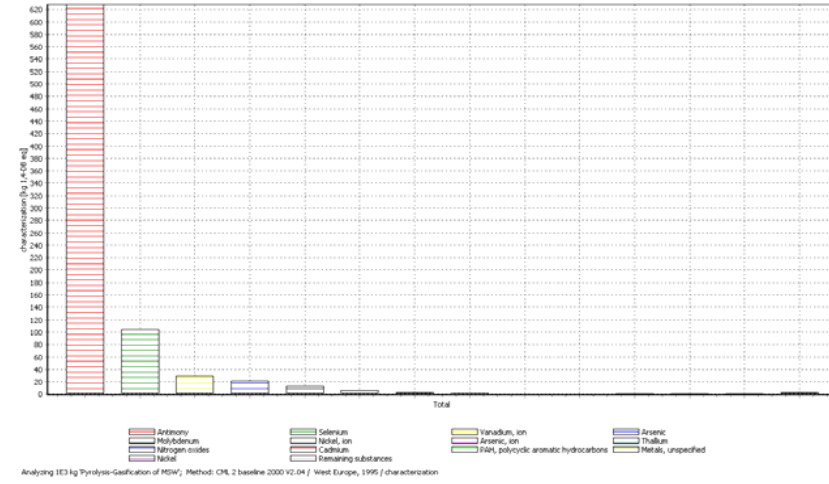
b) Acidification



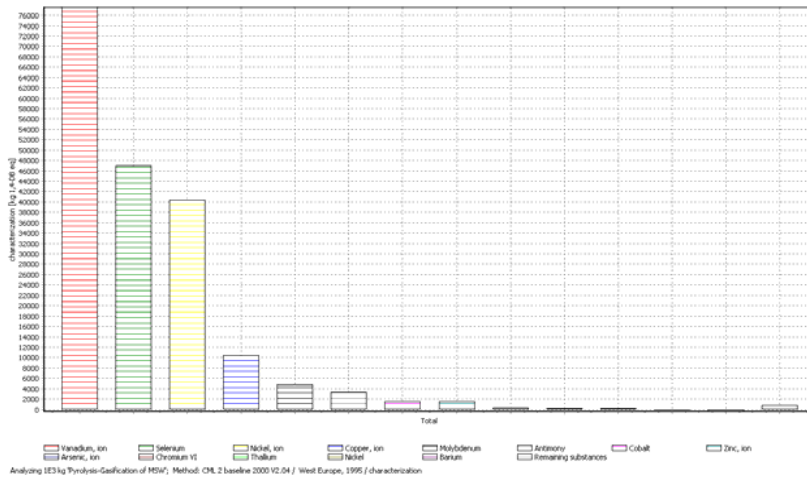
c) Eutro-phication



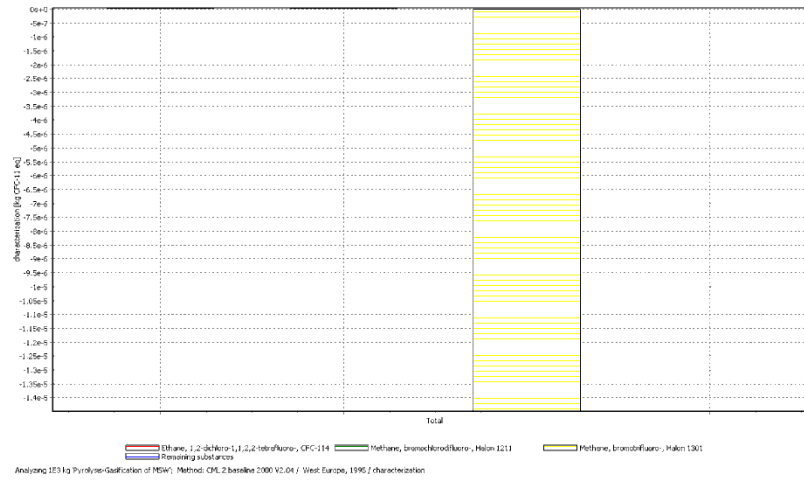
d) Fresh water ecotoxicity



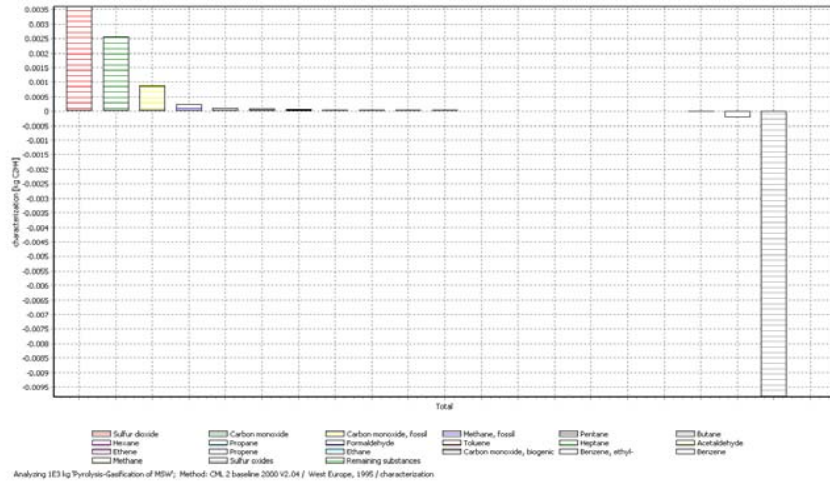
e) Global warming



f) Human toxicity

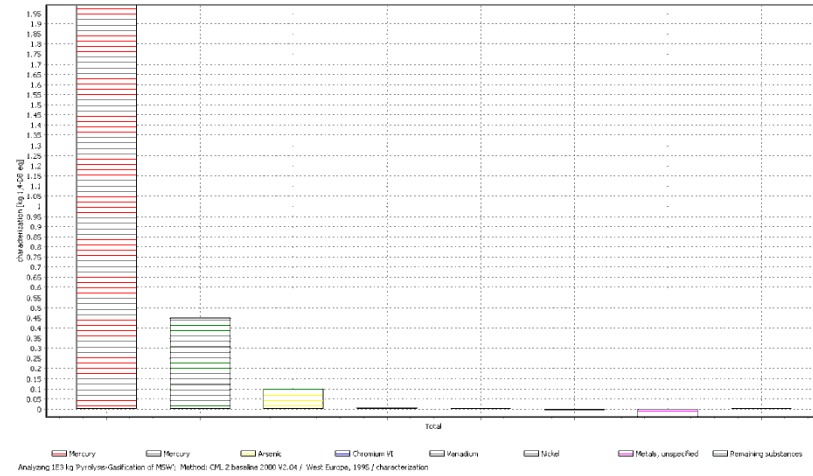


g) Marine aquatic ecotoxicity



i) photo chemical oxidation

h) Ozone depletion



j) terrestrial ecotoxicity

Calculation of fossil carbon in MSW

According to eco-invent data base,

Carbon dioxide emissions from 1 kg of MSW is

Biogenic carbon = 0.723kg

Fossil carbon= 0.474 kg

So, the total fossil CO₂ emissions is $(0.474/(0.723 + 0.474) = 39.5\%)$

Therefore, 39.5% fossil emissions come from both P-G and Incineration processes.

List of acknowledged participants

1. Catarina Ostlund,
Swedish EPA
catarina.ostlund@naturvardsverket.se,
2. Karin Jönsson
Avfall Sverige
karin.jonsson@avfallsverige.se
3. Eva Larsson,
TPS
Eva.larsson@tps.se
4. Martijn van Praagh
Sweco Environment AB
martijn.van.praagh@sweco.se,
5. kundservice-avfall@tk.stockholm.se,
6. anna.nordin@naturvardsverket.se,
7. Ingrid.Nohlgren@afconsult.com
8. List of anonymous participants are not attached in the report.