LAPPEENRANTA UNIVERSITY OF TECHNOLOGY
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Environmental Technology

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OPTIMAL PROCESSING CHAIN FOR WASTE POWER PLANT

Examiners:	Professor Risto Soukka
	Post Doctoral Researcher Virpi Junttila
Supervisor:	Research Director Ari Puurtinen

ABSTRACT

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This study is done to examine waste power plant's optimal processing chain and it is important to consider from several points of view on why one option is better than the other. This is to insure that the right decision is made. Incineration of waste has developed to be one decent option for waste disposal. There are several legislation matters and technical options to consider when starting up a waste power plant. From the techniques pretreatment, burner and flue gas cleaning are the biggest ones to consider. The treatment of incineration residues is important since it can be very harmful for the environment. The actual energy production from waste is not highly efficient and there are several harmful compounds emitted. Recycling of waste before incineration is not very typical and there are not many recycling options for materials that cannot be easily recycled to same product. Life cycle assessment is a good option for studying the environmental effect of the system. It has four phases that are part of the iterative study process. In this study the case environment is a waste power plant. The modeling of the plant is done with GaBi 6 software and the scope is from gate-to-grave. There are three different scenarios, from which the first and second are compared to each other to reach conclusions. Zero scenario is part of the study to demonstrate situation without the power plant. The power plant in this study is recycling some materials in scenario one and in scenario two even more materials and utilize the bottom ash more ways than one. The model has the substitutive processes for the materials when they are not recycled in the plant. The global warming potential results show that scenario one is the best option. The variable costs that have been considered tell the same result. The conclusion is that the waste power plant should not recycle more and utilize bottom ash in a number of ways. The area is not ready for that kind of utilization and production from recycled materials.

TIIVISTELMÄ

Lappeenrannan teknillinen yliopisto
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Soili Nousiainen

Optimaalinen käsittelyketju jätteenpolttolaitokselle

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Hakusanat: yhdyskuntajätteenpoltto, käsittelyketju, jätteenpolttolaitos, elinkaariarviointi, ilmastonlämpenemispotentiaali, muuttuvat kustannukset

Tämän työn tarkoituksena on tutkia jätteenpolttolaitoksen optimaalisinta käsittelyketjua ja on tärkeää pohtia monesta näkökulmasta miksi yksi vaihtoehto on parempi kuin toinen. Näin voidaan varmistaa, että oikea päätös saadaan tehtyä. Jätteen poltosta on tullut yksi mainio tapa hävittää jätteitä. Kun jätteenpolttolaitosta ollaan perustamassa, tulee ottaa huomioon useita lainsäädännöllisiä seikkoja ja teknillisiä vaihtoehtoja. Huomioon otettavista tekniikoista olennaisimmat liittyvät esikäsittelyyn, kattiloihin sekä savukaasujen puhdistamiseen. Myös polton jäännösten käsittely on tärkeää, koska ne voivat olla todella haitallisia ympäristölle. Itse energiantuotanto ei ole erityisen tehokasta ja prosessissa syntyy paljon haitallisia yhdisteitä. Jätteiden kierrätys ennen polttoa ei ole kovin yleistä ja materiaaleille, joita ei voida kierrättää takaisin samoiksi tuotteiksi, ei ole olemassa useaa kierrätysvaihtoehtoa. Elinkaariarviointi on yksi hyvä tapa tutkia tutkitun systeemin vaikutuksia ympäristöön. Siihen kuuluu neljä eri vaihetta, jotka ovat osa iteratiivista tutkimusprosessia. Tässä tutkimuksessa case ympäristönä on jätteenpolttolaitos. Laitoksen mallinnus on tehty GaBi 6 sovelluksella ja työn laajuus on portiltahautaan. Tutkimuksessa on kolme eri skenaarioita, joista ensimmäistä ja toista verrataan toisiinsa johtopäätösten tekemiseksi. Nolla skenaario on osa tutkimusta vertailun vuoksi, osoittamaan mikä tilanne olisi ilman polttolaitosta. Tässä tutkimuksessa polttolaitos aikoo erotella joitain jätejakeita skenaariossa yksi ja skenaariossa kaksi useampia jätejakeita sekä hyödyntää pohjatuhkaa useammalla tavalla. Mallissa on korvaavia prosesseja materiaaleille, kun niitä ei kierrätetä laitokselta. Ilmastonlämpenemispotentiaali tulokset osoittavat, että skenaario yksi on paras vaihtoehto. Huomioon otetut muuttuvat kustannukset osoittavat samaa lopputulosta. Johtopäätös on, ettei jätteenpolttolaitoksen kannattaisi kierrättää enempää ja hyödyntää pohjatuhkaa useammalla tavalla. Alue ei ole valmis tämäntyyppiseen hyötykäyttöön ja kierrätysmateriaaleista valmistettujen tuotteiden tuotantoon.

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ATTACHMENTS

SYMBOLS AND ABBREVIATIONS

Roman

m	mass	[t], [mg]
P	power	[MW]
E	energy	[GWh]
t	time	[a], [h]

Lower indexes

h	heat
e	electricity

Abbreviations

AOX	Absorbable Organic Halogen Compounds
APC	Air Pollution Control Residue
BAT	Best Available Technology
BOD	Biochemical Oxygen Demand
CML	Centre of Environmental Science, University of Leiden, the Netherlands
COD	Chemical Oxygen Demand
EIA	Environmental Impact Assessment
ESP	Electrostatic Precipitators
EU	European Union
GWP	Global Warming Potential
HFO	Heavy Fuel Oil
HSLT	High Speed, Low-Torque
IAWG	International Ash Working Group
ISO	International Standard Organization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LSHT	Low-Speed, High-Torque
MBT	Mechanical-Biological Treatment
MRF	Material Recovery Facility

MSW	Municipal Solid Waste
RDF	Refuse-Derived Fuel
SCR	Selective Catalytic Reduction
SNCR	Selective Non-Catalytic Reduction
SYKE	Finnish Environment Institute
TOX	Total Halogen Content
TOC	Total Organic Carbon
VOC	Volatile Organic Chemicals
ÖWAV	Austrian Water and Waste Management Association

1 INTRODUCTION

Waste amounts have been arising alarmingly and it is clear that something needs to be done (European Commission 2000, 3). Waste is threat to both environment and to humans. Landfills are almost full and there are harmful compounds leaking from them to air, soil and ground water. Waste incineration has been a solution this problem, but it also produces emissions, which are difficult to clean and there is still need for landfilling. The best option would be to decrease the amount of produced waste, but it is not possible to stop producing waste entirely. (Ibid., 5, 8.) In Europe, waste incineration has been used in big cities since the late 1800s when the connection between waste management and epidemic disease was understood. In the beginning the sole purpose for waste power plants was to improve the hygiene in cities, but the utilization of energy and recovery of materials were not that important. When oil prices rise in 1970s, the utilization of energy from waste incineration became more interesting. In the 1980s the flue gas emissions from waste power plants were discovered to be alarmingly high and the emissions limits for waste power plants in Europe were tightened. Also, the incineration and flue gas cleaning techniques started to develop rapidly and the emission amounts started to decrease. In the end of 2000, EU's waste incineration directive became valid and it unified the demands for waste power plants. The guidelines are about reduction of environmental harm from landfills, recycling and recovery of materials and the highest recovery rate of energy from waste's energy content. (Vesanto 2006, 9-10.)

The energy utilization of waste in Finland has been emphasized on co-combustion of waste with conventional fuels. Waste incineration nearly stopped in Finland in the end of 1980s, because there was a cheap option of landfilling and the alarming examples on emission amounts from waste incineration in the 1960s were still remembered. The co-combustion of recycled fuel has been an effective way to utilize energy content of quality waste in electricity production. The emissions have been well controlled since the incinerated waste is highly flammable, but rather harmless waste type. The sorting of waste for utilization has enhanced this type of procedure, despite the lack of utilization possibilities to all the sorted waste particles, besides paper and metals. In 2005 and 2006 waste incineration was in a great turmoil in Finland since the co-incineration of waste became more strictly required. (Ibid., 13-14). Besides the official instructions from the EU and from the Finnish

Government, waste power plants need to work efficiently from environmental, economical and energy points of view. The environmental part comes usually from these given instructions, but the cost effectiveness comes from the processing chain used. Things like structure of costs offering of products, support for the customers and network for distribution are important when competing with rivals but to truly differentiate yourself from them, something else is needed (Junttila 2015), even with waste power plants. These days customers are increasingly conscious and interested in ecological issues that are related to their living and surrounding environment. As an additional thing, the optimum way to operate will vary depending on changes in the environment. (Ibid.)

1.1 Outline

Waste power plants usually work just as an energy production plant and occasionally it seems that it has become the best option for municipal solid waste (MSW) handling, when landfilling is ending. It is easier to burn waste instead of separating materials that could be re-used. But there is a problem on how to give real, monetary or environmental values that can be used to compare on whether it is beneficial to recycle waste before incineration. One way is to use tools that are already known and combine results to optimize the processing chain of a waste power plant. The most widely recognized tool to calculate ecological values is life cycle assessment (LCA) (Klöpffer & Grahl 2014, XI), which is explained later on. It is used as a calculating mechanism in this study since LCA gives results that can be used to calculate or estimate impact on the environment at some, chosen level. Different environmental management tools, besides LCA, can for example help a company to save in costs, to ensure legislative compliance, to minimize environmental risks and to improve company’s image to the public and regulator relationships (Starkley 1998, 15). With some of the tools it is possible to get an effective environmental management system in the company and that system can show to the stakeholders how the company is taking into consideration the environment (Ibid., 34). That is why the emission amounts and for example global warming potential (GWP) that can be calculated from LCA results, are one way to consider the affect directly to the environment. Since the affect is not always the best motivator for the power plant, the savings in costs need to be also considered.

For the power plant it can be important to know or estimate what their global warming potential is so that the can consider how to improve their processes. The legislation can change and the limits can get tighter so when you know what the current situation is, it can be easier to know what needs to be changed when it is necessary. Economical values can be the best motivator for the power plant so the savings in costs are also important to consider. Also, for the users of the produced energy or those who live near the power plant, it can be important to know how the waste incineration affects the environment that they live in. The local affect can be important for these people also so that they do not object the waste power plant. Also it is important to study the possibilities that the recycled materials could have so that they have a purpose of separating them as a material. For example, paper and metals can be recycled but some plastics cannot be recycled to produce the same type of plastic. There are not a lot of LCA studies done on waste incineration, but 2010 in Denmark there was a study that considered the optimal utilization of waste to energy from LCA perspective (Fruergaard & Astrup 2011, 572). This study compared energy production from mixed high calorific waste suitable for solid recovery fuel (SRF) production and organic waste separated at source. The LCA approach of the studied system was a consequential and it focused on the consequences of a made decision. The conclusion from the study was that the co-combustion of SRF has benefits over energy recovery from waste mass burn incineration. This is when considering the non-toxicity impacts. For organic waste incineration with energy recovery is better than anaerobic digestion. (Ibid., 572-573, 581.) Now and then it is possible that the benefits from making RDF come with a higher cost than without it (Klinghoffer & Castaldi 2013, 58).

1.2 Implementation

For this study it has been decided that the best approach methods is to use an example case and LCA. In the second chapter there are information on Finnish legislation on waste incineration and different alternatives for waste burning plants. This means introducing different components of the incineration plant, starting from pretreatment then burner and flue gas cleaning options. The legislation on waste incineration in Finland gives the limits and guidelines for a waste power plant. It is necessary to study and show how the incineration residues are handled. The idea is to give some theoretical background for the next chapter because justification for recycling the waste before incineration is necessary. It is essential to note that recycling can improve the incineration efficiency and lessen the amount of harmful compounds that are emitted or the amount of waste that goes to landfill after incineration. Then the chapter three is about the production opportunities that recycled waste particles have. This means new materials and products from different waste types, which have been separated from the waste stream before incineration. The fourth chapter is the LCA theory in and what kind of tools and components LCA study has. There are two LCA ISO-standards presented because they define the way that LCA should be done. These standards are ISO 14040 and ISO 14044. The first one is “Principles and framework” (ISO 14040:2006, 5) and the second one “Requirements and guidelines” (ISO 14044:2006, 5).

Next on the fifth chapter the case environment is introduced and why it has been chosen in this thesis. The case is a waste power plant and in the study the waste is first sorted at households and then the rest is burned and recycled materials are used for new products. (Puurtinen 2015a.) This case embodies an example of changes in legislation because new guidelines are forbidding the dumbing of organic waste in the future. A way to solve this has been to burn the waste and produce heat and electricity. The question in this case is, whether all the waste should be burned or what could be the optimum operating rate. (Junttila 2015.) The sixth chapter is the modeling chapter. The modeling in practice is done with GaBi 6 software and database and some of the unit processes are done based on information from the case companies or other sources. There are two different scenarios and a zero scenario and the results from them are presented in chapter seven in values of emissions and GWP. Furthermore the variable costs, which are affected by these emissions, are calculated so that the possible savings or costs can be valued. Also, consideration is done on whether it is reasonable to consider producing new materials and products from the waste particles, which are separated in the pretreatment of waste prior to incineration. This means building new business to the area. The end result will be the decision on the optimum processing chain for the waste power plant. Analyzing the results is also a part of the seventh chapter. In this phase, not only the results are taken into consideration but also the legislation, used techniques and other aspect on whether it is reasonable to recycle waste. This also means taking into consideration the options for utilization of the recycled materials. In the eight chapter the conclusion about the whole thesis are made and in the ninth the work is shortly summarized.

2 WASTE POWER PLANT

Waste management has customarily had three alternatives: landfill, composting and incineration. Landfill was appropriate for reclaiming cheap lowlands or restoring affected landscape, composting is still used for organic waste factors and incineration has been used for reduction of waste volume, when the land is priced high and populated densely. Waste incineration is a technique for combusting waste completely and at the same time maintaining, or reducing, emission levels below current standards and also recovering energy and combustion residues. The crucial features of incineration are reduction of waste amount while attaining sterile, compact residues. The cleaning of flue gases is also important part of the power plant. (Bucekens 2013, ix, 1.) Overall waste management practices have developed over the years and nowadays the biggest concerns with waste are the increasing amount and the complexity of different waste particles. To reach this high tech level in waste management, several stages have to be gone through. Today the question on waste incineration, or on any waste-to-energy method, is whether it is needed as waste management method when recycling rates are increasing. (Brunner & Rechberger 2015, 3.)

In the European Union (EU) the approach to waste management is a five-step hierarchy, where prevention of waste is the best option. After that comes preparation for re-use of the waste and recycling of waste. Next the fourth step is other recovery methods and last step is disposal, for example landfilling, which is seen as the last resort. Energy recovery from waste is seen as an option for waste utilization and modern incineration plants can be used for electricity, steam and heat production. This means in practice that the plants need to burn the waste in controlled conditions and at sufficiently high temperatures to make sure that hazardous substances are destroyed completely. When this is not possible, measures for reducing the substance releases into environment need to be done. EU has standard for incineration and co-incineration plants for these reasons and these legislations help to minimize the environmental costs and maximize the benefits of waste incineration. (European Commission 2010, 4-5, 8.) In the next chapters legislation on waste incineration in Finland is first introduced, then different techniques are gone through more accurately and how incineration residues are treated. Then things that affect the incineration are considered and also gone through.

2.1 Legislation in Finland

Legislation for waste power plant begins from the environmental permit. For the permit procedure and clauses there are several international decrees and EU laws. The decrees for giving the permit are told in waste incineration directive (2000/76/EC) and in IPPC-directive (2008/1/EC), in which there is limitations for emission control and for achieving high enough environmental protection level (Saarinen & Leikoski 2009, 6). These two directives have been combined in the new directive on industrial emissions with integrated pollution prevention and control (2010/75/EU). The waste directive (2008/98/EC), waste directive (2006/12/EC) and the Environmental Impact Assessment (EIA) Directive (85/337/EEC) are also important for waste incineration legislation. Finland needs to implement these EU's directives in its' own legislation and they need to be seen as minimum regulations for waste power plants (Saarinen & Leikoski 2009, 6). For these directives there is waste law (17.6.2011/646), environmental protection law (527/2014) and law on environmental impacts' evaluation procedure (10.6.1994/468) and also decrees on landfilling (331/2013) and waste incineration (151/2013). The waste law is meant for prevention of danger and harm to both health and environment from waste and waste management (L 17.6.2011/646). This law is also intended for decreasing the amount of waste and reducing the harmfulness of it, promoting natural resource's sustainable use, ensuring functional waste management and prevention of littering. 18 § prohibits incineration of waste that has not been produced in vessel's usual operations, in Finland's water areas and economical zone. Also in the law, the 110 § states that waste, that is to be incinerated, can be transferred to Finland for incineration if it is based on collaboration between Finland's and Sweden's or Norway's municipalities (Ibid.).

The environmental protection law is meant for preventing deterioration of environment and danger of it, emission control, removal of harm that comes from deterioration and also to preventing environmental damage (L 527/2014). This law's purpose is also to secure healthy, comfortable natural economically sustainable and pleomorphic environment, to support sustainable development and prevention of climate change. Sustainable use of natural resources, decreasing the amount of waste, lessening harmfulness of waste and preventing adverse effects from waste, are also goals of the law. The law is also intended for improving the valuation and consideration of operation that deteriorate the environment and also improve the citizens' possibilities to affect the environmental decision-making. 38 § of the law says that a waste power plant's or parallel-waste power plant's permit affairs jurisdiction cannot be transferred, 107-110 § states what kind of power plants are determined as waste power plants, how the fuel power is calculated as combined and how exceptional situations should be handled. Also 234 § states to what kind of parallel-waste power plants is the law for and in the law there are some regulations for all type of power plants. (Ibid.) Last the law on environmental impacts' evaluation procedure is intended for improving the valuation of environmental effects and to unify the consideration in planning and decision making and also to increase the citizens' access to data and participation possibilities (L 10.6.1994/468).

The government's decree on landfilling is meant for preventing deterioration of surface water, soil and air and to controlling climate change and other collateral wide-ranging harmful environmental effects. The law also helps with landfill planning, foundation, building, use, maintenance, cast-off and aftercare and also waste disposal so that these do not cause any harm or danger to health or to environment, even in the long distance. The 28 § states that fly and bottom ash can be used in waste fill below landfill's cap rock, if there are less than 800 milligram amount of coal in a kilogram of ash and it is in its own pH or 7.5-8 pH level. (D 331/2013.) The other decree on waste incineration is meant for waste power plants and parallel-waste power plants where solid or liquid waste is incinerated (D 151/2013). There are some limitations on what kind of plants this degree does not concern on. For example if the power plant incinerates only agricultural and forestry plant based waste, food industry plant based waste with heat recovery, cork waste, radioactive waste and so on, effect whether the degree concerns them. There are sections on incineration conditions, on energy recovery, on feeding the waste, on emission leading to air and water, on demands for measurements and measurement systems, on how the incineration waste needs to be handled, how to compare measured pollution values to limiting values and how to report if they are crossed, on following the best available technique (BAT) and so on. (Ibid.) This decree basically is the most important to waste power plants and it gives all the limitations and instructions for waste power plants in Finland. If there are changes in legislation that concerns the waste power plants, there may be a great need for changes in used techniques and that can add up to be quite costly since the new laws and degrees need to be followed.

2.2 Technical alternatives

The procedure of choosing the incineration technologies is one of the first important things to consider when building a new waste burning plant. Various options need to be considered and evaluated so that the best option for the situation can be identified. This phase also needs to consider the current requirements. Things to be considered are the market, waste amounts, site, all costs, ownership and finances, but also the risk to environment and community that comes from the operation. Sometimes technologies can conflict with one or more of the goals, even though it seems best suited for another goal. For example, some technique can have the best energy production efficiency, but the costs from building and maintaining it are too high. Sometimes all goals are impossible to achieve and compromises have to be done when selecting the technology. Risks are one of the most important facts and that is why the technique and operations should be chosen so that they are minimized (Rogoff & Screve 2011, 21-22.) Besides reduction of waste amount, hygienisation, costs and environmental protection, waste incineration technique need to consider mineralization and immobilization of hazardous substances, conservation of resources and also public acceptance. Goals for sanitation and volume reduction are becoming more important these days since biological risks are increasing and landfilling is not allowed in close approximation from dense population. The risks from hazardous materials can only be minimized through incineration and it is the only sustainable solution for it. (Brunner & Rechberger 2015, 6.)

Important phase before the actual incineration is the pretreatment of waste. Purpose of pretreatment is to minimize the environmental impact and to remove particles that are not suitable for incineration or are otherwise highly pollutant. Also it is possible to reuse the valuable resources from the waste stream to new purposes. (Klinghoffer & Castaldi 2013, 55-56.) The two main components for the actual incineration of waste are burners and scrubbers. Besides these, there usually are storage, crane, hopper, valve, shaft, furnace and grate that are stages before the actual burning and flue gas cleaning (Buekens 2013, xiii). Storage is the place where the waste is delivered for the incineration. Storage chamber is usually a deep pit that is made from concrete. Crane moves the waste from storage to the hopper, where it goes to the valve that closes the furnace when necessary. Crane can also mix the waste in the storage. Shaft is just a junction with the combustion chamber, which is also known as the furnace. The type of the furnace depends on characteristics of the waste and also on the waste feeding strategies. Grate supports, conveys and pokes the waste before it goes to the burner that starts the combustion. Boiler then recovers the heat from the burning. Lastly the flue gas goes to dust collection where the bulk is removed and then to scrubber which does acid gas neutralization. (Ibid., xi-xiii) The pretreatment of waste takes usually part between storage and hopper. The idea of pretreatment in waste power plants is quite new (Klinghoffer & Castaldi 2013, 55) so there can be different kind of placements for the actual pretreatment machine, depending on whether the plant is old or new. Next figure one shows an example on how these stages can be connected. In the next chapters' pretreatment processes, commonly used burner and flue gas cleaning options are introduced more precisely.

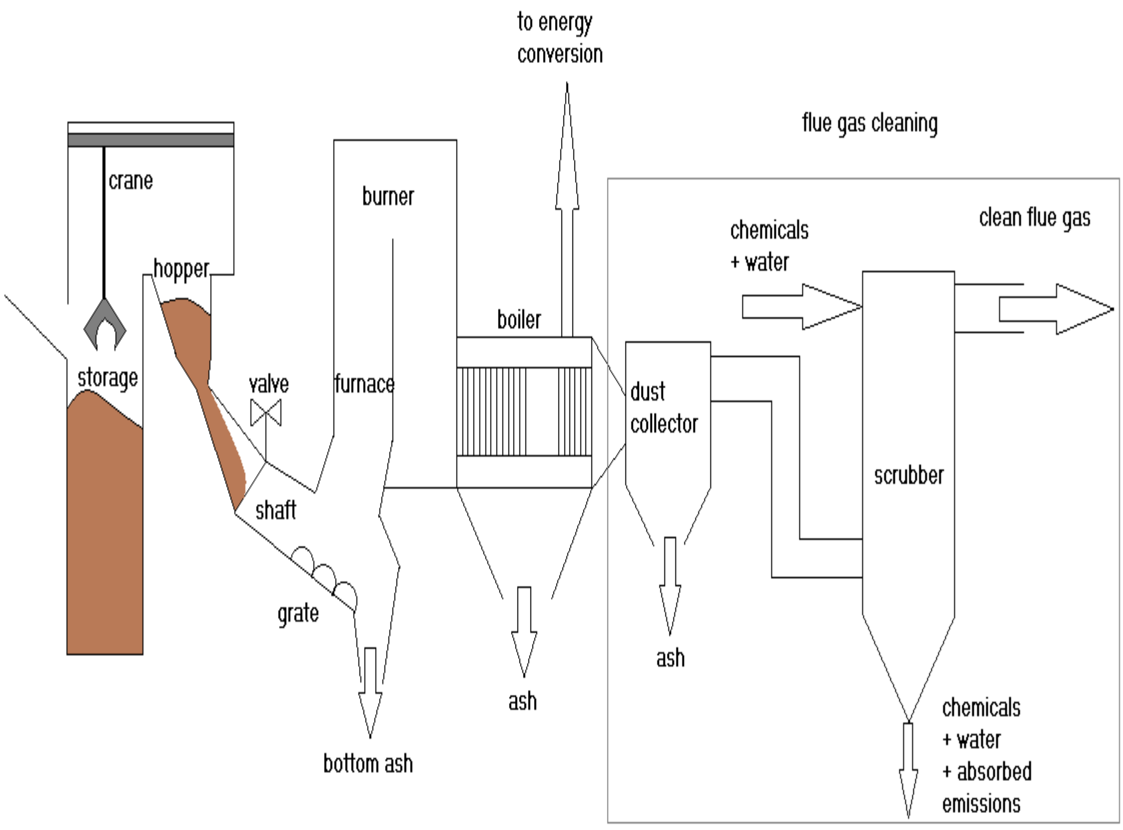


Figure 1. Waste incineration plant flowchart example (Buekens 2013, xiii, Rogoff & Screve 2011, 29, Global Environment Centre Foundation 2011, Engineering Timelines 2015 & SICK Sensor Intelligence 2015).

2.2.1 Pretreatment

There are several options for pretreatment of waste, from which some fill the same purpose, but there are also different options for different purposes. Mass burn of waste does not usually require pretreatment of waste, but combustion chambers need a consistent waste stream that is homogenous in particle size and has a constant heating value to operate efficiently. The most primitive processing method in pretreatment is screening, which is also the most commonly used method. Since waste that comes to incineration is quite heterogeneous and there may be some bulky and hazardous materials, which are better remove before incineration. Basically this removal is done with the crane or on the pitting floor where the trucks empty their contents. The unwanted material is then removed from the waste flow by hand. Also the crane is used for fluffing the waste, which means that waste is mixed and redistributed evenly to the pit, but the crane also breaks the plastics and homogenizes the waste. Screening with fluffing are commonly the only pretreatment operations in waste incineration plants. Also the waste can be treated more precisely with mechanical, biological or thermal processing to improve heating value, material recovery and reduction of pollutants. This type of fuel that is produced from waste is called refused-derived fuel (RDF) and it is done by trommeling, shredding, sorting and dehydrating the waste. The purpose for these processes is to produce homogenous fuel that has better incineration features besides higher heating value. RDF can occasionally help to reduce amounts of ash and residual carbon production in waste incineration. Also higher energy recovery and lower heavy-metal pollution are possible with RDF, but it is good to note that waste and RDF compositions can vary quite much, so it is possible that these improvements also differ. There are similarly waste power plants that use only shredding of waste before it goes to burning and sometimes there is also some sort of separation and recovery techniques. These plants remove ferrous and non-ferrous materials before the waste flow goes to incineration. (Klinghoffer & Castaldi 2013, 56-59.)

For advanced screening, separation and processing, the idea is to remove materials that can be recycled from the waste flow. Usually in these kinds of processes there are several stages for sorting and separation of material, which are based on different features of the waste. This type of separation facility is usually called material recovery facility (MRF) and they are either called dirty or clean facilities, depending on whether the waste is recycled before it comes to the facility. First type of screening and separation technique is called trommel, which basically is just a rotating tubular screen. This method is based on balance between angular momentum and gravitational forces to separate the waste by size. The efficiency of a trommel depends on the declination angle, size of the screen openings and also on the rotation speed. The rotational moment, combined with the angle, defines the rate for particle collision with the surface of the trommel, which is why the moment can be used for adjusting the separation. (Ibid., 59-60.) This type of separation is quite versatile and it can also be used to protect shredders by sorting the waste before shredding (Tchobanoglous et al. 1993, 552-553).

Other method for separation is air classification and it uses the different densities of waste particles to separate them. The waste is fed to an upward moving air stream and in the stream the heavy materials fall to the bottom and light fractions are lifted up. The light factures are collected from the air stream with a cyclone system. Other air separation method is called knifing where the air is led to the waste stream horizontally when the waste is falling vertically. In this method the lighter particles are blown to the side to a collection area. This method allows the waste to be sorted into more than two components. (Klinghoffer & Castaldi 2013, 60.) Also, it is possible to led air from the bottom and waste from the up of a vertical chute. This is the simplest type of air classifier. There can also be zigzagging in the chute or some sorts of angles, which can help break the waste into smaller parts. It is likewise possible to use pulsing air current instead of constant stream and this helps with separation of particles that have same terminal velocity. (Tchobanoglous et al.1993, 559-560.)

Next separation technique option is magnetic and it is used for removing ferrous materials from the waste flow. This method simply uses magnetic fields separating the ferrous materials from the flow and there are two main options. First one is rotating drum magnets in a suspended drum where the system uses permanent electromagnet to attract the ferrous materials. There is a conveyor belt that travels the unsorted material forward and before it drops, next to it is the rotating magnet drum that picks the ferrous parts and collects them to another conveyor. The other magnetic separation method is top feed configuration with overhead belt magnets. In this method the unsorted waste comes over the magnetic collector and the magnetic drum collects the ferrous metal to a separate conveyor, when the non-ferrous material continues to another conveyor. (Klinghoffer & Castaldi 2013, 60-62.) Sometimes it is necessary to use two or three magnets to help the transfer and collection of the ferrous-materials in the system (Tchobanoglous et al.1993, 565-566). Next technique for separation is eddy current, which helps separation of aluminum, brass and copper from the waste flow. This method is an advanced technique that is used to remove non-ferrous, valuable materials from the waste and it uses induced current in electrically conductive materials to create an eddy current. These currents create their own magnetic fields, which can then separate the non-ferrous materials away from the eddy current to a drum or collection bin. (Klinghoffer & Castaldi 2013, 62.) This method is based on Faraday's law on electromagnetic induction and since they are so complicated to use, it is questioned whether they are financially viable to use (Tchobanoglous et al.1993, 567-568).

There is also mechanical-biological treatment (MBT), which is meant for waste flows that have biologically degradable components. This technique is not usually used for incineration. MBT plants are combination of material recovery and aerobic or anaerobic treatment. The purpose is to recover the recyclable material and stabilize the organic particles before it goes to landfill. The biological part of this treatment is done with either aerobic digestion, which is microbiological process where microorganisms break down biodegradable material with oxygen, or with anaerobic degradation, which converts the organic fraction using aerobic microorganisms without oxygen. Torrefaction is other method to pretreat waste. It is a thermal pretreatment technique for waste and it is used to increase the fuel value of organic materials and it also condenses the fuel, decreases the amount of moisture and increases the calorific value. Torrefaction is a process where oxygen and water are removed from the biomass. This typically means drying the fuel in high-temperature. Torrefied fuel is adaptable and can be used in several different co-fuel plants. It also has values that make the transportation easier. (Klinghoffer & Castaldi 2013, 62-65.)

Shredding is one of the mechanical methods for waste pretreatment. There are two types of shredder options and first one of them is the hammermill shredder. This type is high speed, low-torque (HSLT) shredder and it utilizes high-speed rotating shafts that have fixed or pinned hammers that crush the waste. The hammers do the size reduction of the waste and they need to be in right conditions and they require maintenance to work at optimum rate. This method depends on impact and abrasive forces to crash the material into smaller size.

It controls the size of the waste with sizing bars or sieves that are below the hammers in the machine. Moisture is sometimes a big problem with this sort of technique because it can lower the efficiency of the machine. The other option is low-speed, high-torque (LSHT) shear cutter which uses only shear force for cutting and tearing of the waste. There are knives or hooks in the LSHT machine that do the actual shredding. The capacity depends on the rotor speed and the available volume between the knives. It is normal for both types of shredders to operate in harsh conditions and undergo wear and tear, which is why it is vital to maintain the hammers and cutters very well. Sometimes the size can get too small and be problematic in the incineration process. These very fine particles can lead to entrainment problems and lead to higher pollution rates. These introduced techniques are only the most commonly used processes and cover the basic systems. The economical value of pretreatment is not yet proofed to be profitable for the power plant but it is most definitely better for the environment. (Klinghoffer & Castaldi 2013, 65-70.)

2.2.2 Burner

According to Finnish Environment Institute (SYKE) study in 2006 about best available techniques (BAT) on waste incineration in Finland, fixed bed incineration has been long used as a basic technique for solid waste incineration. Depending on the manufacturer, there can be differences in the movement mechanisms, in the shape of the furnaces and types of boiler. In this technique the waste is fed to a feed hopper with a grab, where the waste then goes to the grate with hydraulic pushers. In the furnace there are three different stages for wet fuel burning. These stages are drying, pyrolysis and gasification. After these stages there is the burning stage for the charring residues. The newest plants have slanting grate where the mixing is done during the burning stage. Also it is possible to control the burning in different places of the grate with adjusting the amount of added air. The furnaces are designed so that the different gases are mixed as good as possible and they burn in very high temperature above the grate. Coarse ash and materials that do not burn, are removed through the bottom of the grate. Usually the flue gases are then led to pre-cooling chamber and then to the boiler that recovers the heat. This gas contains high amounts of fine ash and evaporated inorganic compounds that are striven to be solidified for easier removal. Part of the material that solidifies, is removed through the bottom of the boiler and it is called boiler slag. After this the flue gases are led to the cleaning process. This technique is well suited for many type of waste incineration and there is no need for pre-treatment of waste before the incineration. The process can handle the changes in moisture, caloric value and ash content of waste well, when the actual incineration is regulated right. (Vesanto 2006, 30.) Next figure two illustrates the functional diagram of fixed bed incineration.

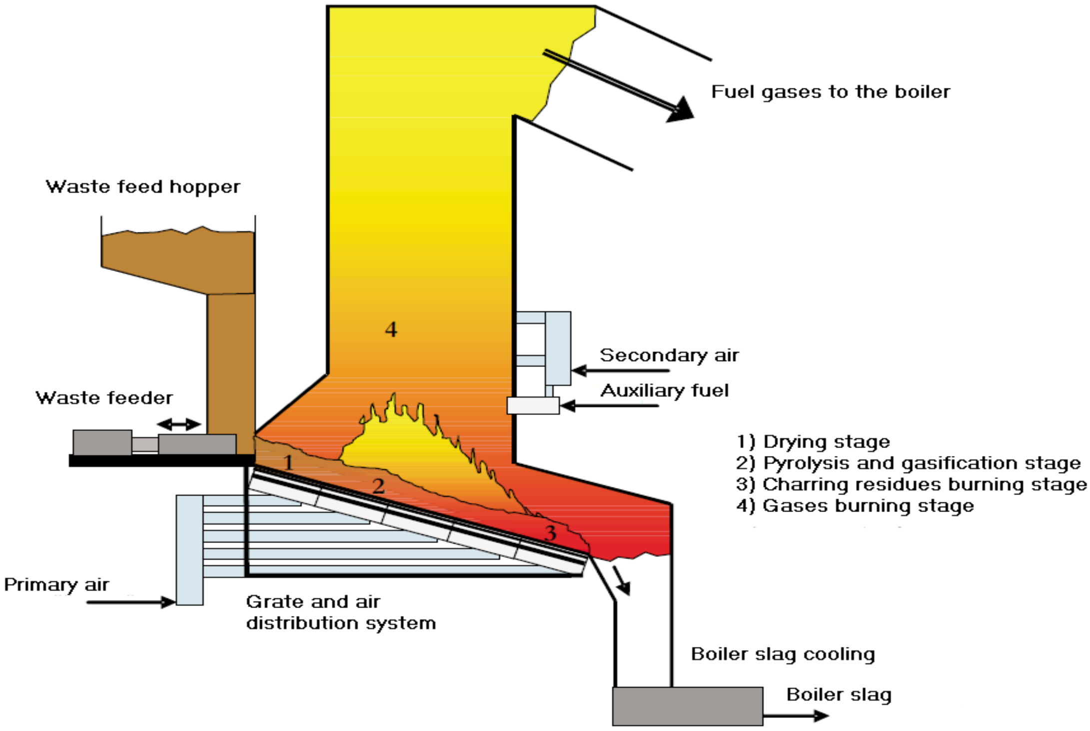


Figure 2. Fixed bed incineration functional diagram (Vesanto 2006, 31).

The second option, according to the same study, is fluidized bed incineration, where the waste is burned in incandescent sand and ash layer that is airborne with air currents. This layer is also known as bed and the amount of ash in it can be quite high in waste incineration use. This method is newer than the fixed bed incineration method. The fuel constantly moves and mixes in the bed layer, and the transition of gases and heat are highly efficient. There are two different main ways to execute fluidized bed incineration. The first one is bubbling fluidized bed technique, where the shape and measurements of the furnace are chosen so that flue gas flow speed is low and the bed material particles do not leave with the flue gas. The second one is circulating fluidized bed technique, where the flow speed is bigger and the gas stream that leaves the bed, carries also the bed material with it. In this technique the fuel mixing is stronger, which is why the burning is effective and the needed furnace volume is smaller. That is a big reason why circulating fluidized bed technique is used in larger power plants. Also, because the mixing is so strong, this technique is better suited for slowly oxidizing fuels and waste, than bubbling fluidized bed technique. In this technique the energy consumption can be bigger, because there are bigger pressure differences. There is also several different combinations and versions besides these two main technique option. (Ibid., 31-33.)

The waste is fed to the furnaces either through drop horn or screw feeder and there should not be any air led to the feeding system, because it would mess up the gas flows. The waste needs to be crushed to proper sized pieces and this, plus removal of metal pieces, are key elements in maintaining a constant operation. Big pieces of waste, and especially metal objects, can easily block the feeding and ash removal equipment. The size today is about 100 mm for the piece size. Most of the combustion air is fed from the bottom of the furnace and rest above the bed as secondary air when necessary. Coarse ash and unburned materials are removed from the bottom of the furnace, when fine ash and pulverized bed material drift with flue gases out of the furnace and separate from the flue gas later in the progress. This material is separated in circulating fluidized bed technic from the flue gas with a cyclone and then brought back to the furnace. In bubbling fluidized bed waste incineration, the flue gas is lead to pre cooling chamber from the furnace and the walls of it work as a heat exchanger surface. The flue gas is also led to a precooling chamber in the bubbling fluidized bed technique after it gets out from the cyclone. The purpose of this cooling chamber is to cool down the gases so that part of the evaporated metals and inorganic compounds solidify and separate. The temperature in these techniques is kept below the melting temperature of ash and bed material so that there does not shape any sintered pieces in the bed. In principle the temperatures are around 800 – 1 000 °C and when the ash is easily melted, the controlling of temperatures is important. (Ibid., 32-33.) Next in figures three and four functional diagrams of these fluidized bed incinerator and circulating fluidized bed incinerator techniques are shown.

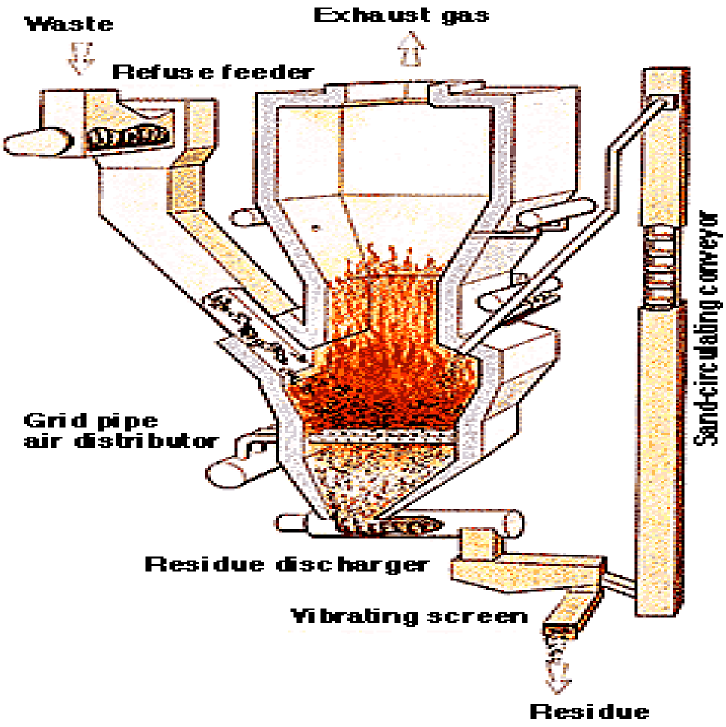


Figure 3. IHI Fluidized bed incinerator functional diagram (Global Environment Centre Foundation 2014).

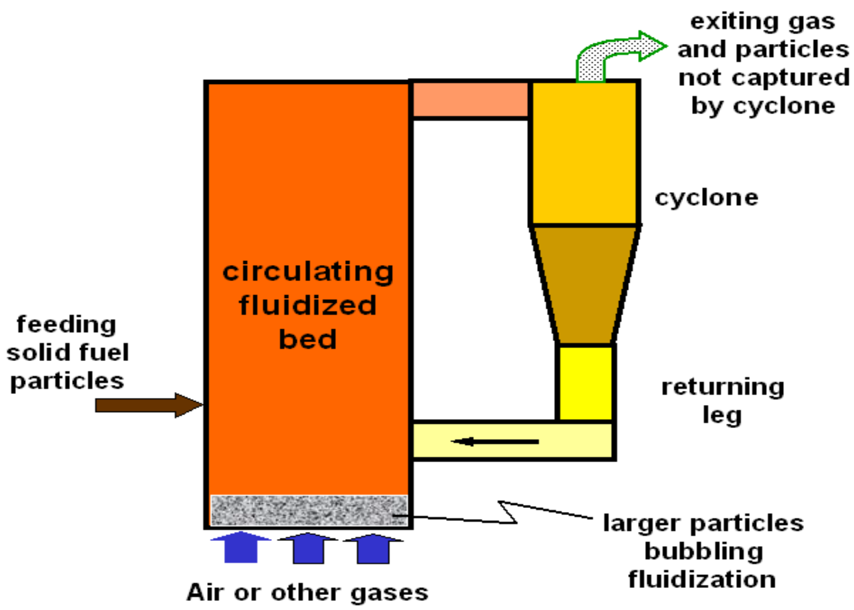


Figure 4. Circulating fluidized bed incinerator functional diagram (CSFMB©/CeSFaMBTM 2015).

The third option for burner, according to SYKE's study is reel oven, which is normally used for incineration of hazardous waste. The reel ovens are well suited to incineration of solid, liquid, pasty and gaseous materials. The dwell time in the reel can be very long, if necessary, and the temperature is quite high. The reel oven can also be dimensioned to melt the ash. The oven itself is a 10 to 15 meters long and in a slight slant. The waste and combustion air is inserted from the top of the oven. There can also be a crushing feeder, screw or hopper and feeders for gases or liquids and pneumatic feeder for powdery waste, when necessary. The oven rotates slowly and depending on the quality of the waste, the speed can vary from 5 to 40 rounds per hour. Waste moves forward and mixes in the oven because of the slant and rotation. The outside of the furnace is cooled with either air or water, depending on the caloric value of the waste. When the calorific value is high, water cooling is more commonly use. The temperature in these ovens can is 850 – 1 400 °C, depending on the purpose and structure of the oven. Normally there is an after-flame space attached to the oven, where rest of the gas is burned and in waste incineration, the necessary support burners for clean fuel are also installed to this space. Gases and liquids are usually fed straight in this phase. The high enough temperature is assured with these support burners. When the space works well, there should be hardly any incombustible inorganic compounds in the ash and flue gases. The flue gases are then led to a pre cooling chamber and to a heat recovery boiler and then to flue gas cleaning. (Vesanto 2006, 34.) Figure five illustrates a functional diagram of the reel oven.

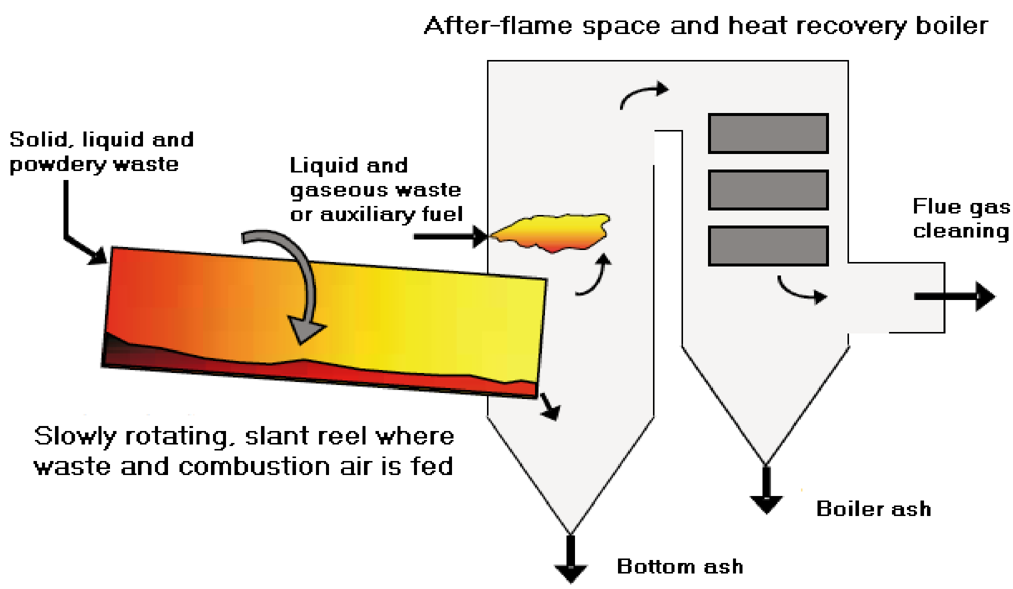


Figure 5. Reel oven functional diagram (Vesanto 2006, 35).

2.2.3 Flue gas cleaning

The type of the waste has an impact on the emitted flue gas amounts. When the waste type changes, there may be also need for changes in the flue gas cleaning system. For example, removal of bio waste, rubber and plastics would affect the amount of carbon dioxide since they are mostly made out of carbon (Tchobanoglous et al. 1993, 81). According to the directive on industrial emissions by European Parliament and the Council, the air emissions that need to be limited in waste power plants are gaseous and vaporous organic substances, expressed as total organic carbon (TOC), hydrogen chloride (HCl), hydrogen fluoride (HF), sulfur dioxide (SO_2), nitrogen oxides (NO_2 & NO), cadmium (Cd), thallium (Tl), mercury (Hg), antimony (Sb), arsenic (As), lead (Pb), chromium (Cr), cobalt (Co), copper (Cu), manganese (Mn), nickel (Ni), vanadium (V), dioxins and furans (D 2010/75/EU). The values for the power plants emission limits are determined more precisely in the environmental permits. This means that these emissions need to be controlled, either with burning techniques, with flue gas cleaning or with both. First, some of the most typical emission control technologies in waste incineration are electrostatic precipitators (ESP) and fabric filters, which help remove particles from the flue gases (Rogoff & Screve 2011, 97).

ESP has very high removal efficiency, up to 99%, and it can work quite well in high temperatures, compared to other methods. Also the energy consumption is quite low and the fire hazard potential is minimal. It uses positive and negative electrical charges to collect particles when the flue gas is led to the electrical field in the ESP system. This field first charges the particles and they are then collected to oppositely charged plates. There usually are several of these plates and the higher amount of plates usually helps to get higher removal efficiency. The plates have to be cleaned from time to time by shaking them so that the collected particles fall off. This removal typically affects the removal efficiency of the device so it is important to do the cleaning frequently. Besides the amount and cleaning of plates, the collection area of plates, gas velocity, gas passages’ width, length and amount, strength of electrical fields, particle in field residence time and their size distribution and fly ash resistivity also affect the removal efficiency. The potential problems with ESPs are corrosive condensation, variation in particulate concentration, reduced efficiency for small particles’ removal and decreased removal efficiency when particle resistivity increases, moisture content decreases and flue gas flow gas increases. (Ibid., 97-98.)

Fabric filters are a simpler technique and the flue gas passes the filters and they simply capture the particles. Multiple modular units, which have tubular fabric bags, are used to filter the flue gases. The initial collection forms a thick, porous cake of particles on the filtering fabric. The efficiency of removal improves when the cake thickens and eventually the pressure drop in the fabric makes it necessary to remove the cake. The advantages in fabric filters are high control efficiency for smaller particles, independent collection efficiency and lastly insensitivity to electrical resistivity of fly ash. The disadvantages are possible corrosion, vulnerability to fires, loss of structural integrity of bags in some temperatures, filter fabric cementation, binding or clogging in certain circumstances and little experiences in waste incineration use. There are new types of fabrics in development that can minimize some of these unwanted effects and the life expectancy of the bags can be improved by selecting the fabric and cleaning method properly. Also gas velocity can affect the potential problems. There are three categories in fabric filters and the method for categorizing is how the cake is removed from the bags. First one is the shaker method, which is not suitable for mass burning without acid gas control. The other two are reverse gas and pulse jet methods which both remove the cake by reversing the gas flow. (Rogoff & Screve 2011, 98-99.)

According to the previously mentioned SYKE study, the options for removal of different acid and alkali compounds from flue gas are wet, half dry and dry methods. In the wet cleaning process, the flue gases are washed with water or with solutions that react with the impurities. The removal efficiency of impurities is good and the capacity is high enough for temporarily arisen impurity contents when the quality of waste varies. The disadvantages in this method are its complicatedness, energy consumption and production of wastewater that is challenging to purify. In new plants the wastewater is handled in the process by evaporating it, so that the impurities can be disposed or further treated. The removal of particles, is done before this process and in the end there is a phase where mercury and dioxins are removed and also possibly the amount of nitrogen oxides is reduced. After that the flue gas is washed with water in a washing tower, which is chosen so that the contact area between water and flue gas is as large as possible and the contact time is long enough. This method is also known as acid washer because in the washer, hydrochloric acid dissolves in water from the gases, which is why the cyclic water is intensively acid. Next the flue gas is washed with alkaline wash where the washing liquid is usually lime wash or sodium hydroxide aqueous solution. When choosing the washing liquid, it is important to take into consideration the flue gas features and the handling of washing products and water. This wet method removes sulfur oxides and if catalytic nitrogen oxide reduction is needed, it usually is after alkaline wash and ammoniac is used in this wash. In this method the flue gases need to be heated before they go to the catalytic unit and after that the heat can be recovered and flue gas cooled down again. The last phase is the removal of metallic mercury and dioxins and they both are removed with active carbon filter. (Vesanto 2006, 36-38.)

Next method is the half-dry method where the acid and sulfur compounds are fixed to calcium hydroxide-water-sludge, which is also known as lime wash, in a spray scrubber. Particles are usually removed before this half-dry method. This method is an option in plants where the emission amounts do not change much. The process is dimensioned so that the sludge dries in the flue gas flow and the reacted products are removed as dust mixed into the flue gas. This dust is then removed with a fabric filter, which acts also as chemically active cleaner, when the flue gas goes through the inert calcium hydroxide that is in the dust. Fine activated carbon is blown to the flue gas many times before the filter to fix mercury and dioxins, but active carbon also can be mixed to the lime wash. Nitrogen oxides are usually controlled in the process with technical options before this cleaning method. There is no wastewater in this method, but the amount of solid cleaning waste is significantly high. The last option of these, is the dry cleaning method. The principle is quite same then in half-dry method but the anchoring agent is mixed to the flue gas dry. This sorbent is basically blown to the flue gas channel before the fabric filter and in the blowing part the anchoring agent is damped because the binding reactions happen in sorbent particles' soluble state surface. The agent is either calcium hydroxide or sodium carbonate and it is possible to mix activated carbon to it to capture mercury and dioxins. This method is simple and fits into a small space and the emission limit values can be achieved with it when the quality of the waste is homogeneous. The consumption of calcium oxide is usually higher than in half-dry method and sodium carbonate is only used in certain temperature of flue gas, because calcium hydroxide does not react effectively after certain temperature. Sodium carbonate is more expensive then calcium oxide but its consumption is usually bit slighter and the amount of cleaning waste smaller. (Ibid., 38-39.)

Sometimes it is also necessary to use additional methods to clean enough nitrogen oxides from the flue gas (Ibid., 36). Selective non-catalytic reduction (SNCR) and selective catalytic reduction (SCR) are both methods meant for nitrogen oxides removal and they use ammonia in some form. In SNCR the ammonia solution is inserted to the flue gases in 900 °C temperature when in SCR temperature is usually 300-400 °C. SNCR requires oxygen because the ammonia degrades and reduces the nitrogen oxides to bare nitrogen and the process produces water. SCR method works basically the same way, but it also requires some catalyst for high enough rate of reaction. SCR usually has higher reduction rate than SNCR, but similarly higher costs. Overall SNCR can be a better method, when it is used with incineration techniques, which reduce the amount of nitrogen oxides in burning stage. On the other hand, that is why SCR can be a better option, because it does not require this sort of techniques that can also be expensive. (Jalovaara et al. 2003, 68.)

2.3 Treatment of incineration residues

According to the Finnish Government Decree on waste incineration's 16 §, the amount of waste from incineration needs to be decreased and prevent its harmfulness as much as possible. Also when possible, the waste needs to be recycled immediately in the plant or other ways, as said in the environmental permit. The dry, pulverulent waste and dry incineration waste from flue gas cleaning has to be transported and put to an intermediate storage in a way that it does not get in contact with the environment. Furthermore, before defining the treatment method, it is necessary to find out physical and chemical properties and harmfulness to the environment, of different incineration wastes. (D 151/2013.) According to a study done by VTT, the essential wastes from incineration are bottom ash, boiler ash, fly ash and air pollution control residue (APC). Bottom ash and cinder include different materials, such as glass, earth minerals, metal, different minerals and also organic material. Fly and boiler ash and APS waste are from flue gas cleaning and they include, besides ash, lime surplus, reaction products from gas cleaning, handling sludge from washer solution and also gypsum. (Laine-Ylijoki et al. 2005, 23-24, 32.) Sometimes the ashes from incineration need to be handled as hazardous waste and this will mean costs from the treatment or landfill of the hazardous waste.

Both of these wastes include a lot of heavy metals, salts and also micro-pollutants. Metal can be recycled from the waste and the separation from the incineration waste has become an important method. If this is not possible, disposable of the waste in environmentally and economically acceptable manner is necessary. Also it is important that the waste does not cause any harm to environment or to people and fulfillment of these aims requires an understanding on how the waste behaves in landfill. Big issue with this is that it is vital to ensure that the contamination from the waste remains environmentally acceptable. (Sabbas et al. 2003, 63-64.) It is also possible to utilize the bottom ashes in earth construction, but it requires knowledge-based -studies on laboratory and field, and also experimental building. This is necessary so that the special characteristics of the bottom ash from natural stones can be taken into consideration when the ash is used. Also the ash content varies quite much between different incinerators and even in the same incinerator. Processing the ash with simple separators, it is possible to improve the ash quality quite remarkably and the processed ash is actually from its' characteristics quite close to a natural material. That is why it can be used to replace sand, gravel and chippings and it is possible to use it in superstructure that replaces or divides the filter bed layer. (Laine-Ylijoki et al. 2005, 50-53.)

2.4 Energy production and harmful compounds

Energy production from waste in modern countries is about 5 % of the total demand of energy. Municipal solid waste (MSW), that is the most commonly incinerated waste type, is quite heterogeneous and has complex composition and that's why it can be difficult to process. Sometimes there can be high amounts of chlorine and sulfur that lead to great concentrations of acids in the gas, which can lead to corrosion of boilers. To minimize this, the temperature and pressure are limited and the values are quite low, so these types of plants have quite low energy efficiency in comparison to for example power plants using fossil fuels. According to one study done by Austrian Water and Waste Management Association (ÖWAV), when the only purpose of MSW incineration is to produce electricity in maximum level, the efficiency is around 21 %. When the production of energy in MSW incineration is used both for heat and electricity production, the electricity production efficiency is only about 5-6 %, but the heat production efficiency is about 68 %. These two cases are typical energy balances of waste-to-energy facilities and they take into consideration possible losses and internal electricity consumption at the plant. The losses are bigger when only electricity is produced compared to the co-generation. Both cases the used techniques for energy recovery are boiler in the same pressure and temperature and turbine plus generator. The products that come from incineration can be both seen as hazardous materials and resources, depending on the perspective. Incinerators can sometimes be a type of concentrators for many substances that occur during the burning. If some additional treatments are done to these products, they can become valuables, when the harmful compounds are separated. This depends much on the potential market for the products, but also on the available technologies and their competitiveness. For the ash from the incineration, there have already been use purposes for example in construction. The problem with using ash for instance in road construction, is that it includes some heavy metals that can lead to contamination in soil and groundwater. On the other hand, the ash is recycled and it replaces some other material consumption instead of going to landfill. For instance, iron, stainless steel, aluminum, copper and brass can be found from concentrated bottom ash and some of them are potentially recovered from it to recycling. (Brunner & Rechberger 2015, 8-10.)

The recovery of metals from bottom ash has increased since the recovery has become financially beneficial and improves the quality of the ash-recovered aggregate. Also a study done in the United Kingdom shows, how the metal recovery can reduce for example the climate change burden, eutrophication, resource depletion, human toxicity, acidification and aquatic ecotoxicity. The biggest effect to these reductions comes when ash, ferrous metals and non-ferrous metals are all recovered from the bottom ash. Also an increase in the energy efficiency is important for lowering these burdens, because they replace usually some fossil fuel use. The study shows also, that at least in the United Kingdom, waste incineration is a better option as a MSW management method than landfilling, but also that the environmental impacts from the incineration are very dependent on which fuel it replaces. (Burnley et al. 2015, 296, 301-303.) Besides variation of materials in waste, also the size of the waste particles affects the incineration time and with that the energy efficiency. Because there are so many things affecting the efficiency, it does not come as a surprise, that the efficiencies are lower when compared to fossil fuel power plants. Of course, besides the waste as fuel itself, the plant structure affects the efficiency. It has also been seen that from energy recovery point, the pretreatment of waste before incineration does not seem to be beneficial. When the purpose of the pretreatment is to improve the fuel quality, so that it can partially substitute fossil fuels, it can be more beneficial to use some pretreatment. (Lombardi et al. 2015, 28, 30, 34.)

According to a study done by the international ash working group (IAWG) the major elements (more than 10 000 mg/kg) found in bottom ash are oxygen, silicon, iron, calcium, aluminum, sodium, potassium and carbon. The minor elements (1 000 to 10 000 mg/kg) instead are magnesium, titanium, chlorine, manganese, barium, zinc, copper, lead and chromium. These are the more significant residues but there are also some smaller amounts of different elements, such as bromine, cobalt and mercury. The values are from MSW combustors in Canada, United States, Germany, Demark, Netherlands and Sweden. (Chandler et al. 1997, 339, 379, 383, 385, 388, 391, 396.) In a Danish study they found in the bottom ash even more different elements, for example arsenic, beryllium, cadmium, molybdenum, nickel, sulfur, selenium, tin, strontium and vanadium (Allegrini et al. 2015, 130). These elements are found as usually harmful compounds from the ash and the amount is dependent on the waste. That is why it is important to recycle the residues and also because waste is burned more and more. Landfilling is also a possible option, but not the best solution since these harmful compounds can spoil the soil and groundwater. There are techniques in development to help with this recycling process. One of these techniques is sintering, which is temperature-induced densification and other is concrescence of solid, porous particles below their melting point. Other one is vitrification where the residue is melted with glass forming additives to form a homogenous liquid phase. Next option is melting which is quite similar to vitrification, but it does not use usually any additives and the product is heterogeneous mixture. Another option is separation of volatile metals, which means vaporizing them from the ash with high temperatures. (Lindberg et al. 2014, 82, 84-89, 91.) These metals and other harmful compounds can be dangerous and ruin not only to the environment but also to human health through air and used ground water.

3 UTILIZATION OF RECYCLED WASTE

When waste is recycled, whether it is done by the producer or by the waste management actor, the waste should have some sort of use besides incineration or landfilling. Sometimes the materials can be recycled to same use but sometimes it is necessary to find new use purposes for the materials. Also the degree of separation and quality of the material effects on how it can be re-used (Tchobanoglous & Kreith 2002, 9.4). Glass, plastics, metals, wood and paper for example, are materials that have different kind of re-use potentials. Glass can be used for asphalt and aggregate blends, insulation, various fills, sandblasting besides new bottles and water insulation. There are three different colors of glass on which it can be categorized during separation. Plastics instead are grated to seven different labels and the categorization happens by grade and color. Recycled plastics can be used for example to lumber, different type of containers, carpet, bags, pallets and film. The most popular recyclable plastics are high-density polyethylene and polyethylene terephthalate because they have more demand. Metals are quite valuable recycled and they can be recycled back to containers and other metal products. Recycled wood instead is good for fiberboard, mulch and paper as recycled material. Lastly, paper can be recycled to new paper, insulation, mulch, wallboard, packing and fill material. (Ibid., 9.5-9.6.) In Finland glass, metal, paper, cardboard and bio waste and also hazardous waste are meant to be separated by the consumer from mixed waste that goes to either landfill or incineration. Mixed waste usually contains mainly plastics and waste that cannot be sorted or recycled.

Plastics are probably the hardest material to recycle. There are several different types of plastics and besides oil there are different types of additives in the plastics (Myllymaa et al. 2008, 33). Also, there are several different use purposes for plastics and it can be a porous material, depending on the type of plastic. This makes it hard to trace and predict the quality of the plastics. The handling methods sometimes require absolute cleanness without any contaminants. This is a big reason why in Finland only PET plastic bottles are recycled from households. (Ibid., 34.) Ekokem in Finland is manufacturing Muovix profiles that are produced from recycled plastics. They can be used basically everywhere to replace wood and they are very durable. (Ekokem 2015, 2.) Wellman Plastics Recycling manufactures environmentally friendly and also cost effective products that are also high quality. The products are for automotive, garden and lawn. (Wellman Plastics Recycling LLC, 2015.)

That is another way to use plastics but there is also new type of use purposes for glass, recycled paper and multi material carton. Saint-Gobain Building Products Ltd. is the biggest user of recycled glass in Finland (Isover Saint-Gobain 2015). The company produces glass wool from it and about 80 % of the used materials are recycled glass. Glass wool is then used for insulation and it can be also recycled to new glass wool if necessary. (Ibid.) Other insulation material can be made from recycled wood fiber that is from recycled paper. Ekovilla produces insulation from these types of fiber and the material can also be re-recycled. This type of insulation also binds the carbon from the wood fiber to itself for its' entire working life and reduces the carbon footprint. (Ekovilla 2015.) Corenso uses recycled beverage cartons, laminated coverings and corrugated containers from Finnish households and paper mills. They produce coreboard from these materials and over 90 % of the used materials are recycled materials. (Corenso 2015.)

From the 1990s designers have started to take environmental values into account and use recycled materials in their designs. When this type of idealism is used in designing, it is called eco-design. The idea is to produce environmentally friendly products, but recycling is not usually the only purpose. All the stages of production need to take environmental values into account. The material that is recycled needs to be possible to be sorted by companies that do recycling and also sustains its mechanical and chemical material goods. (Worrel & Reuter 2014, 421-422.) There is definitely need and market for using recycled materials to replace virgin materials. Since the European Union (EU) wants recycling to be done when prevention and re-use are not possible (European Commission 2010, 5), recycling techniques and use purposes for recycled materials are necessary. According to EU, most of the waste that people cast away can be recycled and by recycling the need for landfilling is decreased. The purpose of the EU waste policy is to make sure that waste is used for production when possible. (Ibid., 9.) Sometimes it is necessary to invent new methods and products for recycling to get more profit and benefit from the recycling and manufacturing. It is sometimes easy to recycle materials that have been collected separately but the most difficult is to recycle materials that are in the municipal solid waste (MSW) mix that comes from example typical households. This is because it needs to be separated from the waste flow and also probably cleaned too.

4 LIFE CYCLE ASSESSMENT

LCA as a concept has been developing from the 1970s and 80s and in time it has developed to be the only ecological product valuation method that has been standardized. The ISO standards began to take form in 1997 and the latest version came in 2006. ISO is an abbreviation from 'International Standard Organization' and when it developed the LCA ISO standards, there were 40 countries involved. The standards are written so that no misuse of any method should be impossible, especially in marketing or advertisement purposes. The most significant application of LCA seems to be to better learn and understand the environmental problems that product system causes. With the help of LCA, ecologically correct decision-making in product progression will lead to better products in the future. (Klöpffer & Grahl 2014, XI-XII.) According to the LCA standard ISO 14040 (2006, 9): "LCA addresses the environmental aspects and potential environmental impacts (e.g. use of resources and the environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e. cradle-to-grave)". This means that LCA can help in environmental performance improvement identification, in notifying several different decision-makers, with the selecting of relevant indicators of environmental fulfillment and last of all, with marketing. The information that has been developed in the LCA inquiry can and is used as a part of the comprehensive policy making process. Because the comparison of results from different LCAs depends on the made assumptions and perspective of each study, there are numerous requirements and recommendations in the ISO standard to guarantee transparency on these matters. LCA is only one of many methods for environmental management and it may not be suitable to every situation. LCA does not usually address the economic or social sides of the product, but it is possible to apply some of these sides to it with the ISO standard. (ISO 14040 2006, 9, 11.)

There are four different steps in LCA. The first step is when the goal and scope of the study are defined. The scope is determined by the subject and intended use of the LCA. This includes the system boundaries and level of detail. Depending on the goal of the LCA, the complexity and the extent can vary noticeably. In the second step the inventory analysis is made. The life cycle inventory analysis phase (LCI phase) is an inventory of input or output statistics of the studied system. In practice this means collecting the required data to meet the defend goals. Next the third step is the impact assessment phase. It is also known as the life cycle impact assessment phase (LCIA) and its purpose is to provide supplementary data to help evaluate the LCI results as to better comprehend their environmental importance. Finally the fourth step is the interpretation phase. (Ibid., 9.) This is different from SETAC's fourth step, which was called Improvement Analysis or later on Improvement Assessment, when they defined LCA in 1990/1991 (Klöpffer & Grahl 2014, 10-11). This life cycle interpretation step is the concluding step and in which the results from previous LCI or LCIA, or both, are summarized and basis for conclusions are made. Also testimonials and decision-making in unity with the definition of the goal and the scope are made. Every so often there are cases that can satisfy the LCA study with only doing and inventory analysis and interpretation, that are usually known together as a LCI study. These are quite similar to LCA studies but they are missing the LCIA phase. LCI studies should not be confused with the LCI phase. (ISO 14040 2006, 9.) The steps of LCA are presented in figure six.

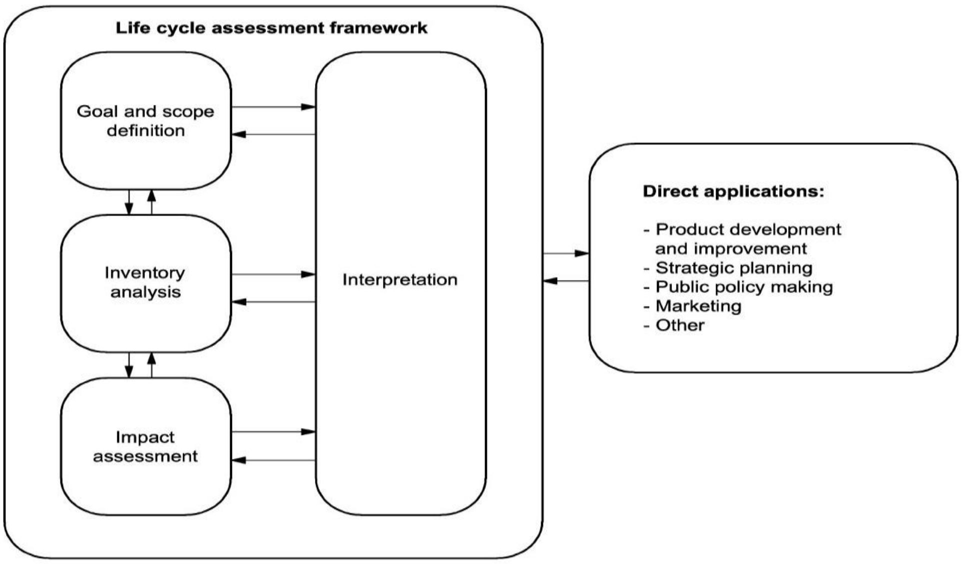


Figure 6. Stages of LCA (ISO 14040 2006, 25).

4.1 Goal and scope definition

In this phase the goal of the LCA states the application that is intended, the reason behind the study, the viewers of the study and of the results from the study is envisioned to be used in comparative assertions. Also the scope of the study should be defined sufficiently so that the extent, detail and depth of the study are compatible and adequate to address the goal of the study. The scope of the study contains the studied product system, functions of the system, the functional unit, the system boundaries and allocation measures. (Ibid., 31.) All the functions in the studied system need to be clearly and quite shortly described so that it gives a basis for the definition of the functional unit (Klöpffer & Grahl 2014, 28). Also the selected impact categories and impact assessment methodology of impact and subsequent interpretation to be used, need to be described. The data requirements, assumptions, limitations, initial data quality requirements, the type of the critical review, if necessary, and the type and format of the report should also be defined here in the beginning. Since LCA is an iterative technique, the scope of the study may require modification to meet the goal of the study, when more information is collected and the study changes. The studied system can have several functions and the one for the study depends on the goal and scope. The functional unit instead defines the quantification of the recognized functions of the product. Its primary purpose is to offer reference to the related inputs and outputs. This is necessary of the comparability of the LCA results and it is especially critical when two different systems are being assessed. That is why it is also important to define the reference flows in the system so that the intended function is fulfilled. This means that the amount of products needed is satisfied. (ISO 14040 2006 31.)

It is essential to define the boundaries of the system because they outline the included unit processes. This means that it contours what unit processes are going to be in the studied LCA. Ideally this would be done so that the input and output flows, that are inside the boundaries, should be elementary flows, but resources should not be consumed on flows that does not change the conclusions meaningfully. When deciding the boundaries for the studied system, it is important to take a number of life cycle stages, flows and unit processes into deliberation. Often the boundaries may need to be redefined when the study proceeds. Elimination of certain stages, processes and flows is allowed when it doesn't change the conclusions. It is useful to use a process flow diagram that shows the unit processes and their relations. Each one of the unit processes should be labeled as where it begins and ends and what is the nature of the operations that take place in it. The selection of the systems depends on the goal and scope, envisioned application and audience, the presumptions, data and cost constrains and criteria for cut-offs. The criteria why some things are left outside of the study should be described clearly and understandably. The used models need to be described and the made assumptions recognized. The most commonly used cut-off criteria in LCA are mass, energy and environmental importance. When mass is used as the criteria, it would require insertion of inputs that cumulatively add to the life cycle more than a defined percentage to of the systems' mass input. Energy as criteria requires same then mass criteria. Instead environmental significance requires inclusion of inputs that contribute more than an extra specified amount of system's estimated quantity of data that are especially selected because of significance to environment. This kind of criteria can also be used for the inputs of the study. (ISO 14040 2006, 33 & ISO 14044 2006, 25, 27.)

The used data should have quality requirements that specify the needed data. That is why it is important to describe the quality so that the reliability of the results is understood and properly interpreted. (ISO 14040 2006, 33.) The requirements for the data should include time-related, geographical and technology coverage, completeness, precision, representativeness, reproducibility, consistency, sources of the data and uncertainty of the information. Also when data is missing, it should be documented. Sometimes inputs can include mineral resources, but this is not a limitation. This means that they can be, for example metals from ores or from recycling. Emissions too can be separately identified in data collection. All emissions to air, water and soil are usually some sort of releases from the diffuse sources, after they have come through pollution control devices. This kind of emission data should also include fugitive emissions and the indicator parameters can include for example biochemical and chemical oxygen demand (BOD & COD), total halogen content (TOX), absorbable organic halogen compounds (AOX) and volatile organic chemicals (VOC). If the studied system is interpreted to use in a comparison to another study, this should be stated in the beginning. All the measures in this first phase should be done so that the comparison is possible. Also the need for critical review should be determined in this phase, what type it should be and who will do it. (ISO 14044 2006, 29, 31.)

4.2 Inventory analysis (LCI)

This phase involves data collection and calculation for relevant inputs and outputs of the system. The process, as well as LCA as a whole, is an iterative study. When the data is from public sources, they need to be referenced and also the data that is significant to the conclusions, all the relevant information from the collection will have to be told in detail. Even when the collected data does not meet the defined qualities, it is essential to state that. The data collection should include data for each used unit processes, which are inside the system boundaries. It is also important to record a description of these unit processes so that the risk for misunderstanding is minimized. The data for the unit processes can be categorized to energy, raw material, ancillary and other physical inputs, products and co-products, waste, emissions and discharges and to other environmental aspects. The energy flows should take into consideration all the flows with the generation and use of the energy. This means that the used fuels and electricity sources are taken into account, but also the conversion efficiency and distribution of energy. Since the collection can go over numerous reporting locations and references, it is significant to take actions so that the study is uniform and understanding of its consistent. This should include drawing of unspecific flow diagrams that outline all the unit processes, detail description of every unit process, listing of flows and operating conditions relevant data, list of the used units, description on the collection of data and needed calculation techniques and instructions for documentation of any special cases and irregularities. This collection can be resource-intensive process and that is why some constraints should be considered. In this phase it is also necessary to check validation of the found data so that it meets the requirements. In this is possible to involve balances of mass or energy. Also a sensitivity check to the scope of the study is necessary so that need for exclusion of stages, unit processes or inputs and outputs or inclusion of new unit processes is identified. (ISO 14040 2006, 33, 35 & ISO 14044 2006, 33, 37.)

The data calculation should include validation, relating the data to unit processes and to the reference flow of the functional unit. These are necessary to generation of results of the LCI and for each unit process and functional unit that are to be modeled in the studied system. (ISO 14040 2006, 35.) All of the calculation processes need to be documented clearly and the made assumptions stated distinctly. Throughout the study the same calculations need to be used consistently. As often as possible, the actual production mix should be used, when defining the elementary flows, so that all the various types of resources consumed are shown. When calculating energy flows, it is important to report, which heating value is used, but it is possible to transform combustible material to energy with this kind of calculation. For the unit processes, every suitable flow will be defined and the input and output data will be calculated in relation to the flow. This means that system input and output data that is referenced to the functional unit, should result from the calculations. It is necessary to make sure that care is taken when the inputs and outputs are aggregated to the system. This aggregation needs to be in consistent with the study goal. This means that the aggregation should only happen if the data is related to similar environmental impacts and to equal substances. (ISO 14044 2006, 35, 37.)

Allocation of flows and discharges is also a part of this process and it means according to the ISO 14040 (2006, 17): “partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems”. Because only some industrial processes are based on a linearity of raw material flows or have only a single output, allocation is important. (ISO 14040 2006, 35.) In practice, allocation means apportioning every input and output to the different products of the system. The sum from these should be same as before the allocation. If it’s possible to allocate the system in several different ways, a sensitivity analysis about the consequences from the selected approach is necessary. Allocation as a procedure has three steps after the need for allocation is identified. The first step is to avoid allocation, if possible. This can be done dividing the unit processes that need the allocation to two or more sub-processes or by increasing the product system to take in the functions that are related to the co-products from the system. The second step is to partition the inputs and outputs of the system between the different products or functions. The third step is to allocate inputs between the products and functions in a way that shows the relationships of them. In practice this means that when you cannot do the first step, try the second and if that does not work either, try the third step. (ISO 14044 2006, 37, 39.)

When the outputs from the system are partly waste and partly co-products, it is necessary to identify the ratio between them, since it affects the allocation of the inputs. Allocation for reuse or recycling has its own recommendations, but it is possible to use the normal procedure. Because reuse and recycling can imply that the inputs and outputs are shared between several product systems, it also may change the essential properties of materials and the definition of system boundary needs specific care, there are own instructions for this kind of allocation. One of these options is called a closed-loop allocation where need for allocation is avoided because the recycling of material replaces the use of virgin material. The other option is an open-loop allocation where the material is recycled into other product systems and the material goes through a change in its characteristic properties. These options need to be allocated first on physical properties, then in economic value and at last in the number of subsequent uses of the material that is recycled. (Ibid., 39, 41.) Allocation rules are important to know and they have been done bot on process and system level so that the study is credible and understood easily (Klöpffer & Grahl 2014, 153). Simplified version of a whole LCI is presented in figure seven.

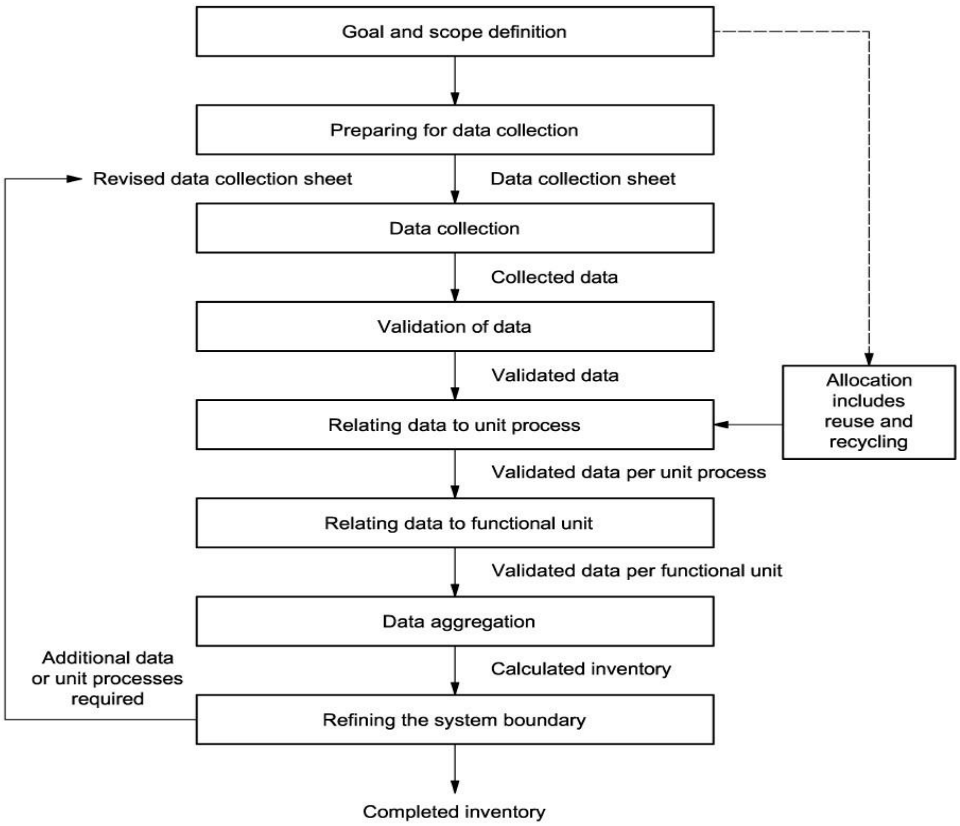


Figure 7. Simplified procedures for LCI (ISO 14044 2006, 35).

4.3 Impact assessment (LCIA)

This phase evaluates the importance of possible environmental impacts by using the results from the LCI. In practice this means connecting the inventory data with different environmental impact categories and trying to understand the impacts of the studied system. This phase is also important for the interpretation of the LCA study. It is necessary to check that the quality of the LCI is sufficient for the LCIA phase. It can also be iterative if necessary and the modification of goal and scope may also be essential. This means that the system boundaries and cut-off criteria for the data need to be sufficiently reviewed. The environmental relevance of the results from the LCIA should not be decreased from the LCI functions. Some issues, like choice, evaluation and modeling of the impact categories can give some subjectivity into this phase. That is why transparency to the LCIA is critical so that assumptions are reported clearly. LCIA has three mandatory and three optional elements. The mandatory elements are selection of impact categories, category indicators and characterization models, assignment of LCI results (classification) and calculation of category indicator results (characterization). (ISO 14040 2006, 35 & ISO 14044 2006, 41, 43.)

When choosing the impact categories, category indicators and characterization models, all the information and sources need to be referenced and they have to be justified and in consistent with scope and goal. Sometimes it is necessary to define new categories, indicators and models when there are not enough sufficient ones in existence. These should also be accurately named and they have all in all several requirements so that reliability is confirmed. The impact categories should reflect environmental issues of the study when the characterization model reflects the environmental mechanism by showing the relationship between the LCI and category indicators. For the chosen impact categories it is important to identify the endpoints, define the category indicator, identify the appropriate results from the LCI and identify the characterization model and factors. In the classification stage, the idea is to consider assignment of LCI results that are only in one impact category and identify LCI results that relate to more than one category. Then the characterization stage involves the conversion of LCI results to commonly known units and combination of the results within the same impact category. The result from this calculation is a numerical indicator and the method for this need to be identified and documented. The methods and assumptions that are used in this can vary between different impact categories and in different areas. If there is some variation in the quality of the category indicators, it can affect accuracy of the LCA and that is not good. With these elements it is possible to get LCIA results already, but optional elements that can be included are normalization, grouping and weighting. (ISO 14044 2006, 43, 45, 47, 49.)

According to the ISO 14044 (2006, 51) normalization means: “calculating the magnitude of category indicator results relative to reference information”, grouping: “sorting and possibly ranking of the impact categories” and weighting: “converting and possibly aggregating indicator results across impact categories using numerical factors based on value-choices; data prior to weighting should remain available”. There is also a fourth optional element that is data quality analysis and it can be used to better understand the reliability of the indicator results collection. Normalization is the calculation of the extent of the results of category indicator, which are relative to chosen reference information. This means that it changes the indicator by dividing it with a selected reference value and it can change the made conclusions. (Ibid., 51). It is also important to describe the bases for the normalization (Klöpffer & Grahl 2014, 305). Grouping instead means sorting the impact categories on nominal basis or ranking them in a given hierarchy. This means that grouping is based purely on value choices. (ISO 14044 2006, 53). Also in this phase, the value-based elements are incorporated to the study (Klöpffer & Grahl 2014, 310). Then the next optional element is weighting and it means converting results with selected weighting factors or aggregating them across different impact categories. Weighting is also a value based method and that is why different results are possible when weighting is not done on same principles. The last optional element is data quality analysis where there are three different techniques. The first one is gravity analysis where the most contributing data for the indicator results is recognized. The second one is uncertainty analysis and in it the determination of uncertainties in data and assumptions and how they affect the reliability of the results from the LCIA. The third and last option is sensitivity analysis, where changes in data and methodological choices affecting the results are determined. (ISO 14044 2006 53, 55.)

There are some limitations for the LCIA because it only addresses the environmental issues that have been selected and that are why LCIA is not a comprehensive valuation of all environmental issues of the studied system. Lack of spatial and temporal dimensions in the results from LCI shows uncertainty also in the LCIA results. This varies in every impact category depending on the characteristics. LCIA cannot always show differences between the related indicator results of alternative product systems and impact categories. This can have several different reasons, for example limited development of some things, limitations of the LCI phase and limitations in the collection of inventory data. (ISO 14040 2006, 39.) When the LCIA study is intended for public comparative affirmation use, the study needs to have sufficiently comprehensive category indicators. These need to be at least scientifically and technically valid and also environmentally relevant. Also they should be internationally accepted and weighting should not have been done. Instead sensitivity and uncertainty are needed. (ISO 14044 2006, 55.)

4.4 Interpretation

Interpretation is the phase where all the findings from the LCI and LCIA are considered together. The results should be in consistent with the goal and scope that have been defined earlier. Also the results should reach conclusions, explain the limitations of the study and provide recommendations for the future. The phase should also reflect that the LCIA results are based on a relative approach, they indicate potential effects and they do not predict actual impacts. Interpretation of a LCA study is also envisioned to offer an understandable, complete and consistent presentation of the results. In this phase there might also be need for some iterative processing of the scope, collected data and goal. (ISO 14040 2006, 39.) It is also important to consider the appropriateness of the definitions of the system functions, functional units and system boundaries, limitations that have been identified in the data quality assessment and sensitive analysis. Results from the LCI need to be interpreted cautiously because they are about the input and output data, not about the environmental impacts. In practice there are three elements in the interpretation stage of the LCA study. (ISO 14044 2006, 55, 57.)

The first element is to recognize the significant issues based on the LCI and LCIA results. There are four different information types that are needed from the previous phases. These are findings from the LCI and LCIA, the used methodological choices, the used value-choices and the responsibilities and role of the different parties. When these are found to match the goal and scope demands, the significant issues can be defined. The second element is a completeness, sensitivity and consistency checks evaluation. This element is intended to establish and enhance the confidence in and reliability of the results. The completeness check is done to make sure that all the related information needed for the interpretation is accessible and complete. The sensitivity check is done to assess the reliability of the results and conclusions by defining how they are affected by uncertainties. The consistency check can be done to define if the assumptions, methods and data are consistent with the goal and scope of the study. The third element is about making conclusions, identify limitations and giving recommendations. Conclusions should be done based on the study, recommendations base on the conclusions and specific recommendations done related to the intended application. Identification of significant issues, evaluation of methodology and results for completeness, sensitivity and consistency are part of this phase. Drawing of preliminary conclusions and checking whether they are on line with previous phases and then reporting them as final conclusions, if they are in consistent are also done in this phase. The interpretation should also include the appropriateness of the definitions of functions, functional unit and boundaries and also the identified limitations to the data quality assessment and sensitivity analysis. (Ibid., 55, 59, 61, 63.) The relationships between the three elements within the interpretation phase and with the other phases of LCA are presented in figure eight.

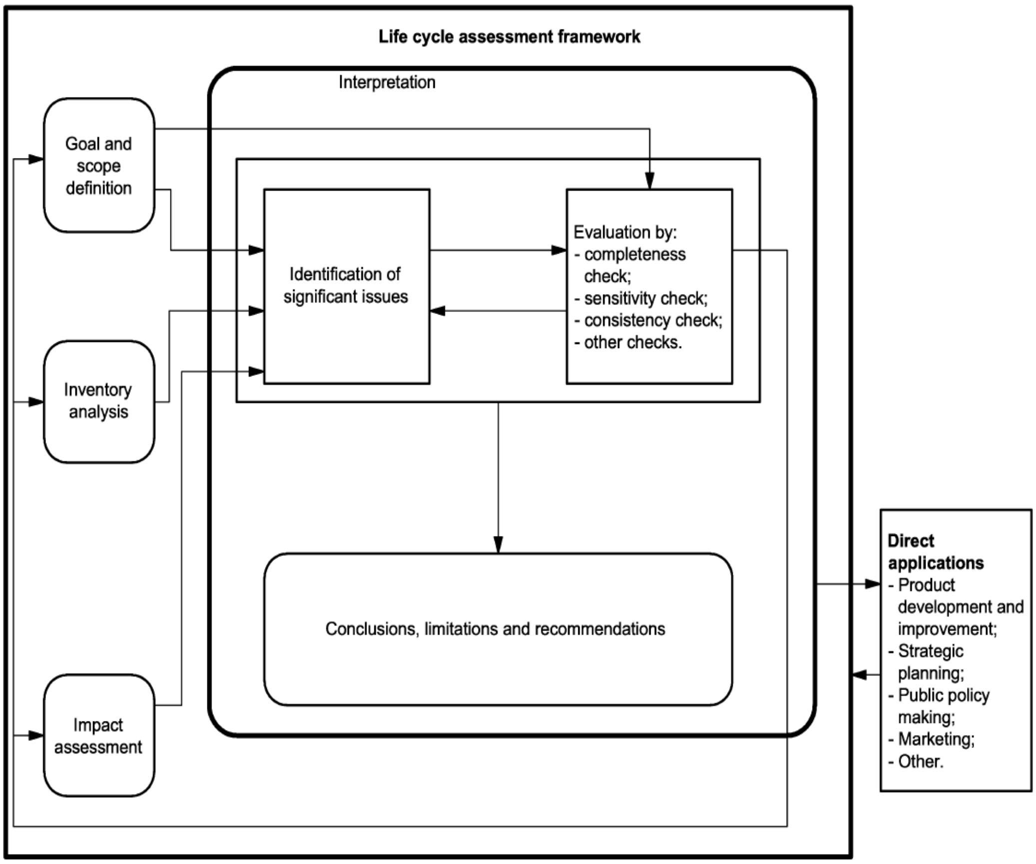


Figure 8. Relationships between interpretation phase and other phases of LCA (ISO 14044 2006, 57).

5 CASE ENVIRONMENT

An environmental permit of one waste power plant has been used for this study as a source of information on a real waste power plant. In this studied power plant, the MSW is first crushed into a suitable fragment size, which is then burned in modern circulating fluidized bed boiler. The waste is burned efficiently and environmentally friendly with high efficiency. The flue gases are cleaned with cleaning equipment to make sure that the emissions are below regulations and standards. The flue gas emission amounts are observed regularly. Bottom ash from the process is utilized when possible and the end products from flue gas cleaning are treated and then disposed correctly. According to the environmental impact evaluation statement the building of this power plant has a positive impact to the waste handling companies' environment because the waste amount that goes to landfilling decreases. There should not be any effect to the soil and surface- and groundwater and only little effect on the quality of air from the plant, but there is also small effect to the quality of air because heavy traffic increases and in building stage there is also some noise emissions. (ISAVI/17/04.08/2013, 3-4.) Table one shows the main technical information about the studied power plant.

Table 1. Technical information about a waste power plant (ISAVI/17/04.08/2013, 6, 47).

	Symbol	Value	Unit
Maximum fuel capacity (MSW)	m	170 000	t/a
Maximum fuel power	P	65	MW
District heat production	E_h	210	GWh/a
Electricity production	E_e	130	GWh/a
Operating time	t	8 000	h/a

When the waste goes to the power plant, it is first stored in a bunker, which can hold up to 5 100 tons of waste. The waste is mixed in the bunker and big components are removed from MSW mixture. The big components than cannot be burned are delivered to landfill or to other suitable processing. Also there is a crusher in the bunker that crushes big wood waste components. In the pretreatment, metals and other inert materials are going to be removed and the waste is going to be handled to a suitable size. The metals are delivered to re-use. There is going to be crushing either in one or two stages, and the ferrous metals are removed with a belt magnet. Non-ferrous metals are then removed with an eddy current. After that air classifier separates particles with different densities. There originates reject from the pretreatment that is mainly not suitable for burning, which is why it is delivered to landfill. After pretreatment, the waste goes to storage to be stored in bales. Most of the waste is MSW, sorted at birth place, but it is also possible to incinerate waste from business life and industries, building and wood waste, impregnated wood and other waste types that have been classified hazardous. Besides waste, there is a need for a start-up and auxiliary fuel, which is light fuel oil. (Ibid., 10-11, 18, 28.)

The power plant is using fluidized bed incinerator for the actual burning and the incinerated waste is mainly municipal solid waste, as stated before. There is also start up and auxiliary torches that are oil powered. After the incineration the flue gases are then cleaned with SNCR method for nitrogen removal in the burning process and half-dry method for removal of sulfurs, chlorines, fluorine and other acid components after incineration. The reagent in half-dry method is either calcium hydroxide or calcium oxide. Also active carbon is added to the cleaning process for separation of heavy metals, dioxins and furans. Before the half-dry cleaning, there is removal of particles with a fabric filter or ESP. The flue gases can be cooled before cleaning and for all the cooling processes, closed cooling water circuits that use a mixture of water and glycol, are used. When the incineration uses dangerous waste particles, a condenser or washer needs to be attached to the half-dry cleaning. The chemical used is sodium hydroxide and it helps to boost the separation of sulfurs, chlorines and fluorine. The bottom slag or ash, which includes ash from incineration and also bed sand, can be utilized as a material or delivered to landfill after metals are removed from it. The boiler ash is combined with the end product from flue gas cleaning and it is classified as dangerous waste. This type of waste is stored and then delivered to an adequate handling. (Ibid., 6-8, 26, 28-29.)

6 MODELING THE WASTE POWER PLANT

To be able to find the optimal processing chain, GaBi 6 software is used for the modeling of the life cycle, which in this case is limited from gate-to-grave. GaBi software is the leading LCA software in the world and it helps business to achieve best product sustainability performance with powerful LCA tools and the most accurate database available (thinkstep GaBi 2015a). The purpose of this study is to model how waste is pre-treated and then incinerated in the case waste power plant. There are few different scenarios about the studied waste power plant. There is a zero scenario where waste is not incinerated and instead goes to landfill and the energy is produced other ways and the recycled materials are produced from other sources. The process of landfilling describes all relevant steps and technologies for the treatment of waste to landfill (GaBi 6 2015). First scenario is a situation where the waste is mostly incinerated, only metals are separated as a valuable material in pretreatment and bottom ash is utilized only in excavation. The second and last scenario is a situation where plastics and glass are also separated as valuables and the bottom ash is utilized more ways than as an excavation material and also metals are separated from the bottom ash (Puurtinen 2015b).

The actual modeling starts from the collection of waste. The transportations of waste from the different cities are not taken into consideration since the emissions from them are hard to divide and take into the calculations. Also the study viewpoint is from the power plant’s view so the emissions from transportations are not that important, because there is no way to avoid the transportations, and the actual amounts of waste from the birthplaces are not known. The next step is the pretreatment of waste, were different waste flows are separated from the waste flow. After that the waste goes to incineration process, where the energy in form of heat and electricity is produced. Also the bottom ash utilization and hazardous waste collection are part of this process. The scenario zero is that there is no incineration of waste and the electricity is produced with typical Finnish electricity mix and heat with heavy fuel oil (HFO) since it is used in the Varkaus area (Energiateollisuus 2014, 24), which has been chosen as an example city for this study. Finnish grid mix composition is 32 % nuclear, 17 % coal gases, 15, biomass, 13 % hard coal, 13 % wind, 7 % peat and the rest are from hydro, HFO, lignite, biogas and waste (GaBi 6 2015). The thermal energy from HFO process describes process from production to thermal energy production (Ibid.).

With the scenarios the purpose is to compare how the separation of certain waste streams could affect the emissions and global warming potential (GWP). Some assumptions needs to be done on how much the emissions are. The environmental permit gives most of the information for the assumptions so that the modeling is possible to do. Besides the permit, other studies and textbooks are used. For the modeling, it is necessary to calculate values for inputs and outputs. Table two shows what happens to the waste in the different scenarios.

Table 2. Scenario description.

<table>
<tr><th></th><th>Scenario 0</th><th>Scenario 1</th><th>Scenario 2</th></tr>
<tr><td rowspan="2">Landfill</td><td rowspan="2">Total MSW</td><td>Reject</td><td>Reject</td></tr>
<tr><td>Big particles</td><td>Big particles</td></tr>
<tr><td rowspan="3">Separation in pretreatment</td><td rowspan="3">-</td><td rowspan="3">Metals</td><td>Metals</td></tr>
<tr><td>Glass</td></tr>
<tr><td>Plastics</td></tr>
<tr><td rowspan="4">Utilization of bottom ash</td><td rowspan="4">-</td><td rowspan="4">Excavation material</td><td>Excavation material</td></tr>
<tr><td>Minerals</td></tr>
<tr><td>Filler material</td></tr>
<tr><td>Metals</td></tr>
<tr><td rowspan="4">Energy production</td><td rowspan="2">Electricity grid mix</td><td rowspan="2">Electricity from waste incineration</td><td>Electricity from waste incineration</td></tr>
<tr><td>Heat from waste incineration</td></tr>
<tr><td rowspan="2">Thermal energy from HFO</td><td rowspan="2">Heat from waste incineration</td><td>Electricity grid mix</td></tr>
<tr><td>Thermal energy from HFO</td></tr>
<tr><td rowspan="2">Consumption</td><td rowspan="2">-</td><td>Electricity in pretreatment</td><td>Electricity in pretreatment</td></tr>
<tr><td>Light fuel oil</td><td>Light fuel oil</td></tr>
</table>

The inputs and outputs need to be unit per kilogram of waste because the waste amount is the variable. It is assumed that in this study only municipal solid waste, that has been sorted in its' birthplace, goes to incineration, even though the power plant can incinerate also other waste particles, such as wood and building waste (ISAVI/17/04.08/2013, 11). These amounts vary from zero to thirty thousand tons, when the amount of MSW varies from hundred thousand to 170 000 t/a (Ibid.). This 170 000 tons of MSW is the functional unit of this study since there is a need to handle the waste in some way. This waste is MSW and it can come from several cities and it is estimated to be the amount of waste that comes to incineration and sorting in one year. The variation is why it is easier to estimate in this particular study that only MSW is incinerated, when there is a possibility that there are no other waste particles to be incinerated. First the separation rates need to be calculated. Since it is estimated that from the 170 000 t/a of municipal solid waste, big parts removed are 1 700 t/a, removed metal is 4 300 t/a and reject is 9 500 t/a it is possible to calculate the removal rates (Ibid., 8). The rates are calculated by dividing the removal amount with the inserted waste amount. This means that for big parts, the removal is 1 %, for metal, it is 2.5 % and for reject, 5.6 %. This also means that the maximum waste amount that goes to incineration is 154 500 t/a in the first scenario. For the second scenario, the amount of waste to incineration is counted to be about 124 000 t/a.

There have been several studies on waste composition in Finland from which it is possible to estimate how much there is plastics and glass in MSW (Honkanen 2014, Teirasvuo 2011, Kähkönen 2012, Päijät-Hämeen Jätehuolto Oy 2006, Karvonen & Voutilainen 2007, HSY 2012, Hynynen 2008, Teirasvuo 2010, Koskela & Elfving 2014, Pöyry 2013 & Mikkonen 2013). The estimated amount of plastics is about 15.6 % and 2.4 % of glass which are around 26 500 t/a of plastics and 4 000 t/a of glass. Attachment I shows what the studies have found the waste composition to be in the studied places. Since the amount of recyclable plastics is close to a zero percent (Honkanen 2014, 26-27 & Teirasvuo 2011, 89-90), it is not necessary to consider separating only that part of plastics from the MSW. Also, the amount of aluminum, copper and iron in municipal solid waste's metals has been studied in one waste sorting center and the average amounts for iron and steel is 81.5 %, for aluminum 7.6 % and for copper 0.215 % (Kuitunen 2012, 30). When the electricity and heat production values from table one is first converted to MJ/a from GWh/a, by multiplying them with 3 600 000 MJ/GWh the new values are 468 000 000 MJ/a for electricity and 756

000 000 MJ/a for heat. These values represent the amount of energy that needs to be produced in all the scenarios. For the second scenario, there is need to calculate coefficients so that the energy amount from outside sources is correct. These coefficients are calculated by dividing the amount of energy needed from outside sources with the amount of energy calculated to come from incineration. If the amount of waste or the amount of energy needed changes, these values need to be re-calculated and changed as well.

The actual energy from waste incineration is calculated with caloric value of 12.12 MJ/kg, which has been calculated by dividing the amount of incinerated waste in scenario one, with the maximum fuel efficiency of the plant, which is 65 MW (ISAVI/17/04.08/2013, 6). This is then multiplied with the efficiency rates, which are also calculated by dividing the needed electricity or heat amount with caloric value. These are then yet multiplied with incinerated waste amount, to get the produced energy amounts. The efficiency rates are calculated to be for electricity 25 % and for heat 40 %. The caloric value in scenario two is about 8.48 MJ/kg since the plastics are removed and their caloric value is quite high, about 31.80 % (Al-Salem et al. 2009, 2640). Separation of glass does not affect the actual incineration efficiency, but it affects the amount of ash generated since it comes mostly out with incineration ash (Tchobanoglous et al. 1993, 80), which is taken into consideration when the incinerated waste amount is smaller, also the ash amounts get smaller. Same thing concerns the separation of metal (Ibid.). It is estimated that the plants own electricity consumption is about 20 % from the total electricity need, with the pretreatment of waste (ISAVI/17/04.08/2013, 22). Also for this study, it is assumed that from the total energy need, the consumption of energy is 25 % in scenario two. This increase is due to the separation of plastics and glass in pretreatment and the broader utilization of bottom ash. It is also estimated that the use of light fuel oil is 200-400 t/a (Ibid., 8) and in this case the average value of 300 t/a is used for the calculations. In GaBi 6 the process of light fuel oil includes all the necessary flows to produce light fuel oil (GaBi 6 2015).

The actual emissions from incineration are assumed to be in scenario one, the maximum emission amounts from the environmental permit, which can be seen from attachment II. The smallest amounts of emissions (Cd & Tl, Hg, Sb, As, Pb, Cr, Co, Cu, Mn, Ni & V, dioxins & furans) are basically so minor that they have been left out from the actual modeling. They are too close to a zero when the amounts are calculated for the different substances by dividing the total amounts with the number of substances. These values work as input and output parameters in the actual modeling with what the calculations in the unit processes are done. There is no chemical use for cleaning up these emissions in the modeling, since the use of the chemicals is not clearly estimated and they do not seem to be so important for this comparison. This is because it is not clear that what type of cleaning system they are actually having for the flue gas cleaning. Besides, the actual incineration and emitted amounts are more important for this part of the study. Also, since there are no amounts for emissions to water, the wastewaters are not taken into consideration. The amount of bottom ash is estimated to be 2 200 t/a, with bed sand, and hazardous waste to be 26 200 t/a, which includes boiler ash, flue gas cleaning end products and fly ash (ISA-VI/17/04.08/2013, 29-30). Bottom ash composition has been estimated to be in this study about 20.6 % of metals, 19.4 % of filler material, 30 % of minerals and 30 % of excavation materials (Kaartinen et al. 2007, 15). From the metals in bottom ash it is calculated that about 22.9 % is aluminum, 2 % is copper and 37.3 % is iron (Ibid.). Table three illustrates how much different materials are possible to get out from the processing. There are also percentages to these amounts, except for hazardous waste since it is not a part of some waste amount.

Table 3. Percentages and amounts of waste that are possible to separate from the waste incineration stream (ISAVI/17/04.08/2013, 8 & 29-30, Honkanen 2014, 27, Teirasvuo 2011, 96, Kähkönen 2012, 26,35 & 38, Päijät-Hämeen Jätehuolto Oy 2006, 8, Karvonen & Voutilainen 2007, 12, HSY 2012, 17 Hynynen 2008, 51 Teirasvuo 2010, 40, Koskela & Elfving 2014, 15-16, Pöyry 2013, 20, Mikkonen 2013, 5 & Kaartinen et al. 2007, 15).

		Scenario 1		**Scenario 2**	
Material:		**[%]**	**[t/a]**	**[%]**	**[t/a]**
Total MSW		100	170 000	100	170 000
Pretreatment	**Big particles**	1.0	1 700	1	1 700
	Reject	5.6	9 500	5.6	9 500
	Metals	2.5	4 300	2.5	4 300
	-aluminum	7.6	327	7.6	327
	-iron	81.5	3 505	81.5	3 505
	-copper	0.22	9	0.2	9
	Plastics	0	0	15.6	26 520
	Glass	0	0	2.4	4 080
Waste to incineration		90.9	154 500	72.9	123 900
Incineration	**Bottom ash**	1.4	2 200	1.4	1 764
	-excavation material	10	2 200	30.0	529
	-metals	0	0	21.0	370
	-aluminum	0	0	23.0	85
	-iron	0	0	37.0	137
	-copper	0	0	0.02	0.07
	-minerals	0	0	30	529
	-filler material	0	0	19	426
	Hazardous waste	-	26 200	-	21 011

The treatment of hazardous waste has been left out from this modeling because it can be either utilized or landfilled so the actual handling does no concern the waste power plant. There is a demand for several calculations in the unit processes concerning the collection and utilization of bottom ash, because the substitutive processes need to have calculations on the amounts for the needed materials are. There are clauses on several of the unit processes that calculate values, based on what the values on certain parameters are. These parameters are used for clauses that determine whether the waste is incinerated or not, whether the plastics and glass are separated in pretreatment or not and whether the bottom ash is utilized more widely than just for excavation material, or not. Basically the value of the parameter is either zero or one, and the clauses in the unit processes have different values based on which one the parameter value is. The waste incineration parameters are used in collection and energy consumption unit processes. It defines that all of the electricity and heat comes from outside sources. The plastic and glass separation parameter is used in their consumption unit processes and the bottom ash utilization parameter in bottom ash collection process. Also, the plastic and glass separation is used in electricity consumption in the pretreatment, to define the needed electricity amount. It is also used in electricity and heat consumption unit processes to help define, when the need from outside sources is something else than a zero or the full amount of needed electricity or heat. In attachment III, all of the calculated inputs and outputs and the values are presented.

The substitutive processes for the different materials are based on the closest surrogate that GaBi 6 database has to offer for the material production. It is simpler to get the emissions and global warming potential (GWP) directly from GaBi 6 since it can give the emission amounts of the processes and calculate the GWP based on the chosen method from the database. Also, it is assumed that the substitution is for the same amount, so when a certain amount of, for example aluminum is separated, the substitutive process produces the exact amount of aluminum, when there's no recycling for it. For iron consumption, it has chosen to be hot rolled coil of steel, because iron is usually used for steel production, for aluminum consumption sheets of aluminum, since it was the most suitable option from all the aluminum production unit processes, and for copper consumption, copper from Sweden, since there was no unit process for copper production in Finland or Europe. The process mostly includes raw material extraction and processing, energy consumption (GaBi 6 2015).

For glass consumption the substitutive process is container glass, since most of the glass in MSW is usually container glass, but for plastic is particle board since it assumed that all the plastics would be separated and then turned into profiles that replace different wood and construction materials, like Ekokem's Muovix. The particle board process includes raw material processing, energy and material consumption and also waste handling to a certain degree (Ibid.) Container glass production includes all the processing operations from raw material and all the needed energy and materials for it (Ibid.). Since the percentage amounts from MSW for glass and plastic are only estimations, there are no separation rates for them. Usually the separation percentages for different waste separation machines are not 100 %, depending on the machine and the material separated from the waste stream. For filler material consumption, the substitutive process is talcum powder since it is the only filler material in the database, and for mineral consumption, it is mineralic render, since it seems to be the closest option in the database. Mineralic render and talcum powder both considers from cradle to gate perspective, which means material to product process (Ibid.). The substitutive processes may not exactly be the accurate ones but they do give a type of idea on how much the emissions and GWP could be in the accurate processes.

Lastly, the model can be broadened to take into consideration other things that have been left out. Transportations from different places can be easily attached to the collection unit process, if the amount of waste and also the distances from places to the power plant are known. Also, there are now only three types of scenarios, but it is possible to study more detailed scenarios. By changing a few clauses and changing the amount of energy needed in pretreatment, it is possible to consider different separations and utilizations separately. For example, it is possible to consider unconnectedly the separation of plastic and glass from the bottom ash utilization. If there's need for the separate study on all the separations in pretreatment or the different utilization options for bottom ash, there is need for new calculated inputs and outputs and for new calculations. But since the basic process is done, it is not difficult to calculate more values and add new clauses to the unit processes. The model is easily adapted, when more valid information is available or when there's need for other un-major changes. Even when there is need for bigger changes, it is not too difficult to add new flows and unit process to the model. Most of the actual limitations for the modeling come from GaBi 6 itself or from the lack of information, since GaBi 6's database is limited and sometimes not all the necessary information is available. Simplified versions of the actual modeling is shown in figures nine, ten and eleven with the substitutive processes to illustrate what type of processes and flows there is in the GaBi model.

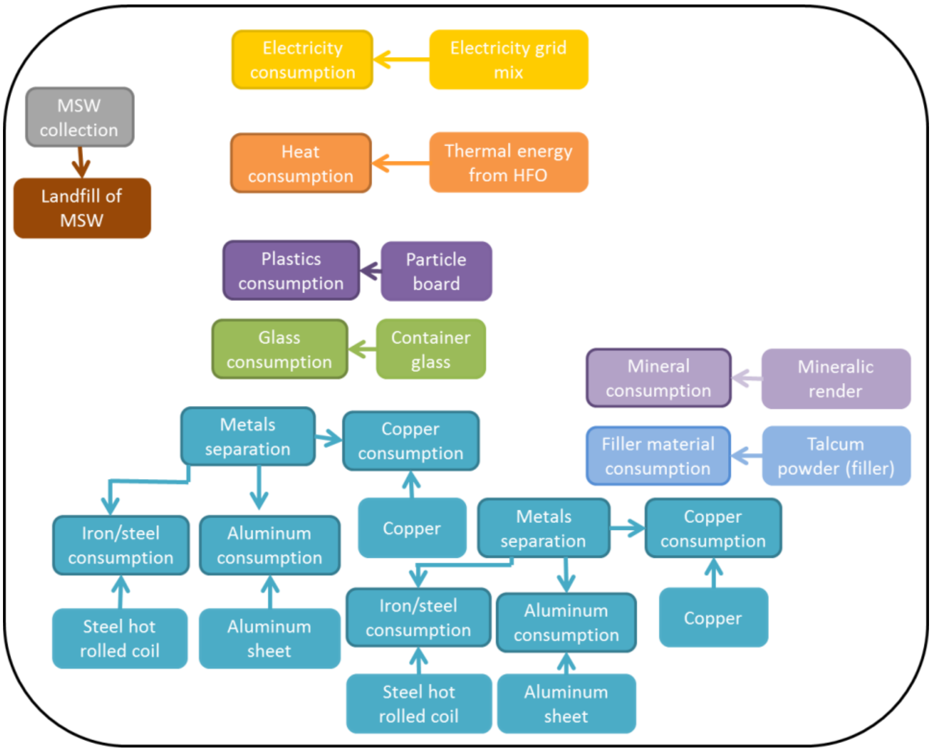


Figure 9. Simplified flow chart of the scenario zero GaBi model with process boundary.

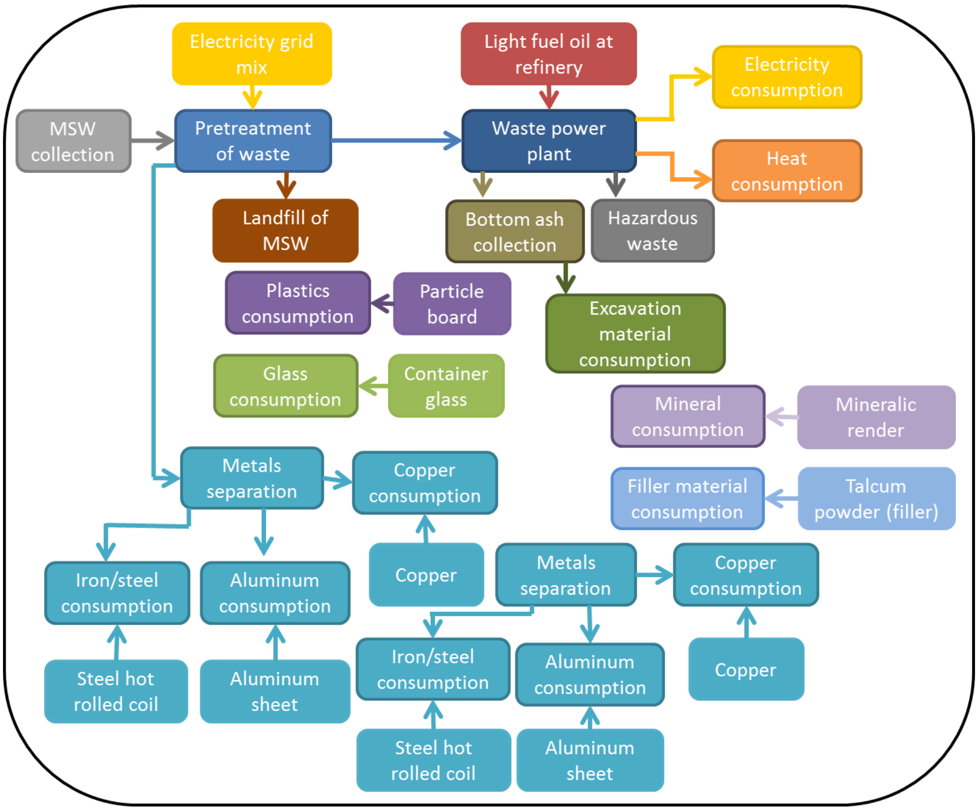


Figure 10. Simplified flow chart of the scenario one GaBi model with process boundary.

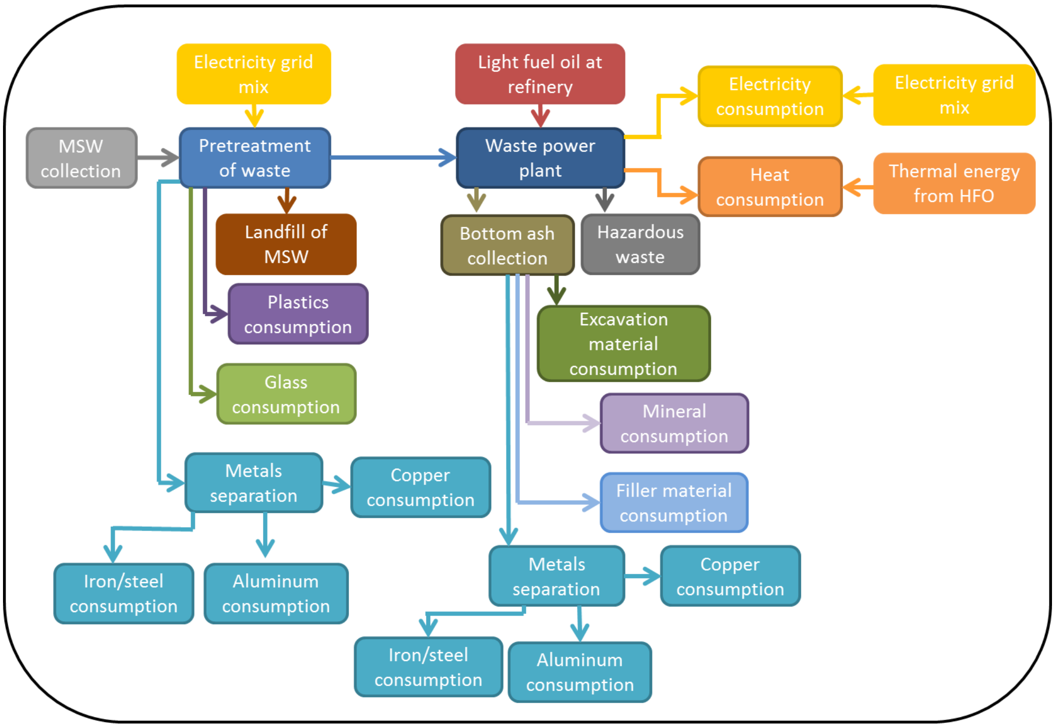


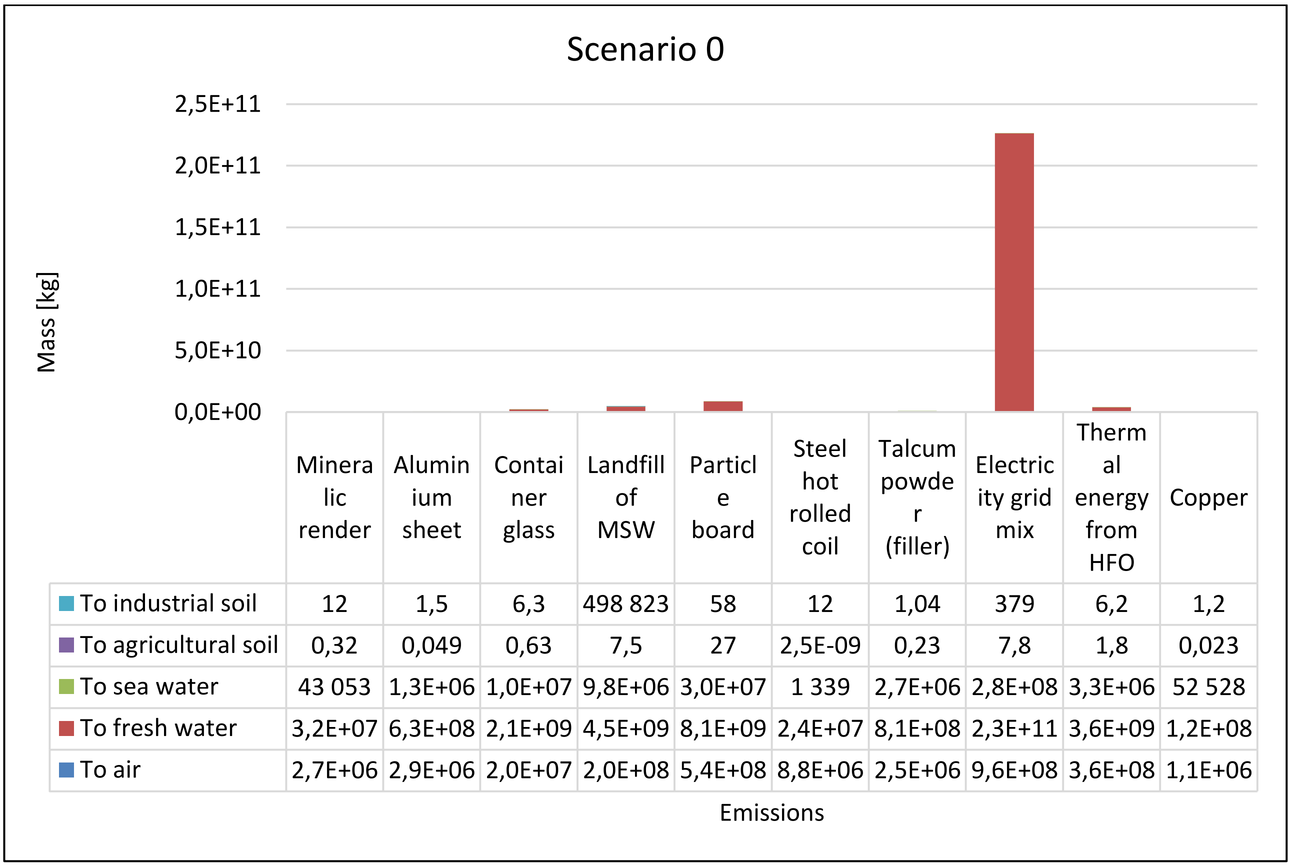
Figure 11. Simplified flow chart of the scenario two GaBi model with process boundary.

7 RESULTS AND ANALYSIS

To be able to decide on which type of processing chain is the most optimal, different perspectives need to be taken into consideration. From the LCA modeling with GaBi 6, emissions and GWP are taken out and considered from different viewpoints. For this study, other things need to be considered, such as the variable costs, utilization possibilities for the separated waste particles and also the techniques and machines used in the waste power plant. The idea is to consider the scenarios and some detailed information. For example, what type of separation from waste or which bottom ash utilization option saves the most emissions or GWP. The emission amounts are shown, but because GWP is more known and used value, it is used for the analyzing. GWP basically means the influence of a gas emission to global warming from one unit of that gas relative to the unit of reference gas. (GreenFacts 2015). GWP has been calculated with CML2001 - Apr. 2013, Global Warming Potential (GWP 100 years) -impact assessment method (thinkstep GaBi 2015b). CML is short for Centre of Environmental Science, University of Leiden, which is in the Netherlands and it includes classification, characterization and also normalization (PE International 2011, 6). This helps to transfer the GaBi database’s unit processes from emissions to GWP in the GaBi 6. CML 2001 is only used to transform the emission and resources to GWP.

7.1 Emissions and global warming potential

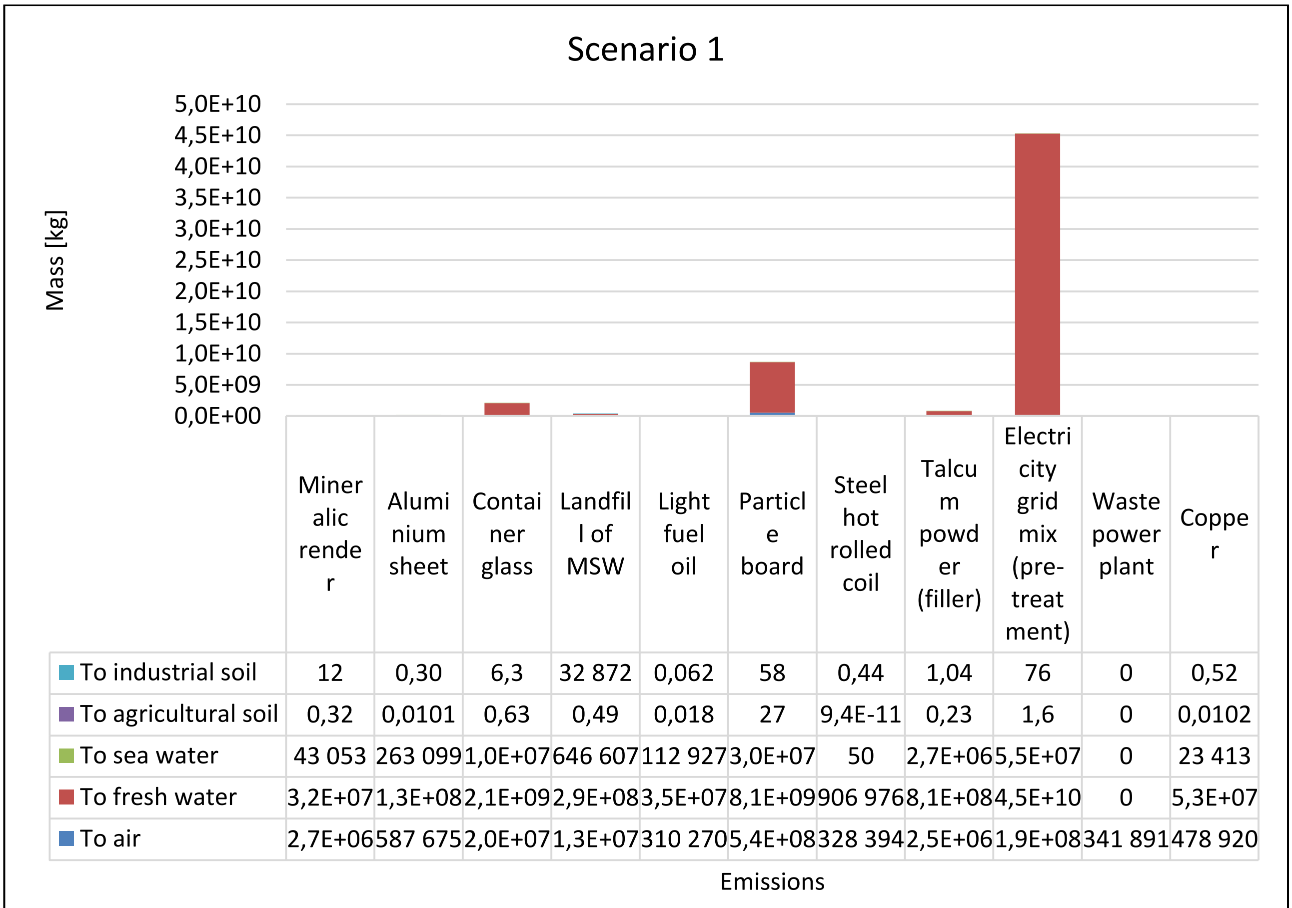
The emissions from the different scenarios are presented in kilograms per unit process. Same way the GWPs are presented in kg CO_2-Equivalent, which is usually used as the value. This means that the emissions are transformed to responding amounts of carbon dioxide emissions. These first figures tell how much different emissions are emitted from the different unit processes in the different scenarios. The emission amounts are a starter point for the GWPs. Figure twelve presents the amount of emissions produced in scenario zero, when the waste goes to landfill and energy is produced from other sources.



	Mineralic render	Aluminium sheet	Container glass	Landfill of MSW	Particle board	Steel hot rolled coil	Talcum powder (filler)	Electricity grid mix	Thermal energy from HFO	Copper
To industrial soil	12	1,5	6,3	498 823	58	12	1,04	379	6,2	1,2
To agricultural soil	0,32	0,049	0,63	7,5	27	2,5E-09	0,23	7,8	1,8	0,023
To sea water	43 053	1,3E+06	1,0E+07	9,8E+06	3,0E+07	1 339	2,7E+06	2,8E+08	3,3E+06	52 528
To fresh water	3,2E+07	6,3E+08	2,1E+09	4,5E+09	8,1E+09	2,4E+07	8,1E+08	2,3E+11	3,6E+09	1,2E+08
To air	2,7E+06	2,9E+06	2,0E+07	2,0E+08	5,4E+08	8,8E+06	2,5E+06	9,6E+08	3,6E+08	1,1E+06

Figure 12. Emission amounts in scenario zero.

The emissions from both metal separation processes (pretreatment and bottom ash collection) are combined in this case, to help illustrate the emissions. As can be seen from the figure twelve, the biggest amount of emissions comes from the produced electricity, which is about 92 % of total emissions. This production mix is an average mix of different energy sources used in Finland to produce electricity. The second biggest amount of emissions comes from particle board production. The total emission amount of particle board production is less than 4 % from the total emissions. The comparison is a bit difficult, because of the differences from the electricity production emissions are so big. That is why GWP also has important role in the analyzing phase. Most of the emissions seem to be going to fresh water and least to agricultural soil. The total emission amount from scenario zero is approximately $246*10^6$ t/a. Next the emission amounts from scenario one are presented in figure thirteen.



	Mineralic render	Aluminium sheet	Container glass	Landfill of MSW	Light fuel oil	Particle board	Steel hot rolled coil	Talcum powder (filler)	Electricity grid mix (pre-treatment)	Waste power plant	Copper
To industrial soil	12	0,30	6,3	32 872	0,062	58	0,44	1,04	76	0	0,52
To agricultural soil	0,32	0,0101	0,63	0,49	0,018	27	9,4E-11	0,23	1,6	0	0,0102
To sea water	43 053	263 099	1,0E+07	646 607	112 927	3,0E+07	50	2,7E+06	5,5E+07	0	23 413
To fresh water	3,2E+07	1,3E+08	2,1E+09	2,9E+08	3,5E+07	8,1E+09	906 976	8,1E+08	4,5E+10	0	5,3E+07
To air	2,7E+06	587 675	2,0E+07	1,3E+07	310 270	5,4E+08	328 394	2,5E+06	1,9E+08	341 891	478 920

Figure 13. Emission amounts in scenario one.

In scenario one, the emissions from electricity grid mix are again the highest, almost 79 % from total emissions, and this time it is used for the pretreatment's electricity consumption. The emissions are lower though, since the electricity need is only 20 % from the previous scenario. The particle board is again the second biggest emitter and now it is over 15 % from the total emissions. This time the lowest emitter is the waste power plant. This is because there virtually are no emissions from the plant, because they are not all estimated. The used emission calculations from the environmental permit and from other used sources, do not give a totally realistic value, but it is better to use the values that are estimated and not make too many assumptions. The total emission amount from scenario one is around $58*10^6$ t/a. Next the emission amounts from scenario two are presented in figure fourteen.

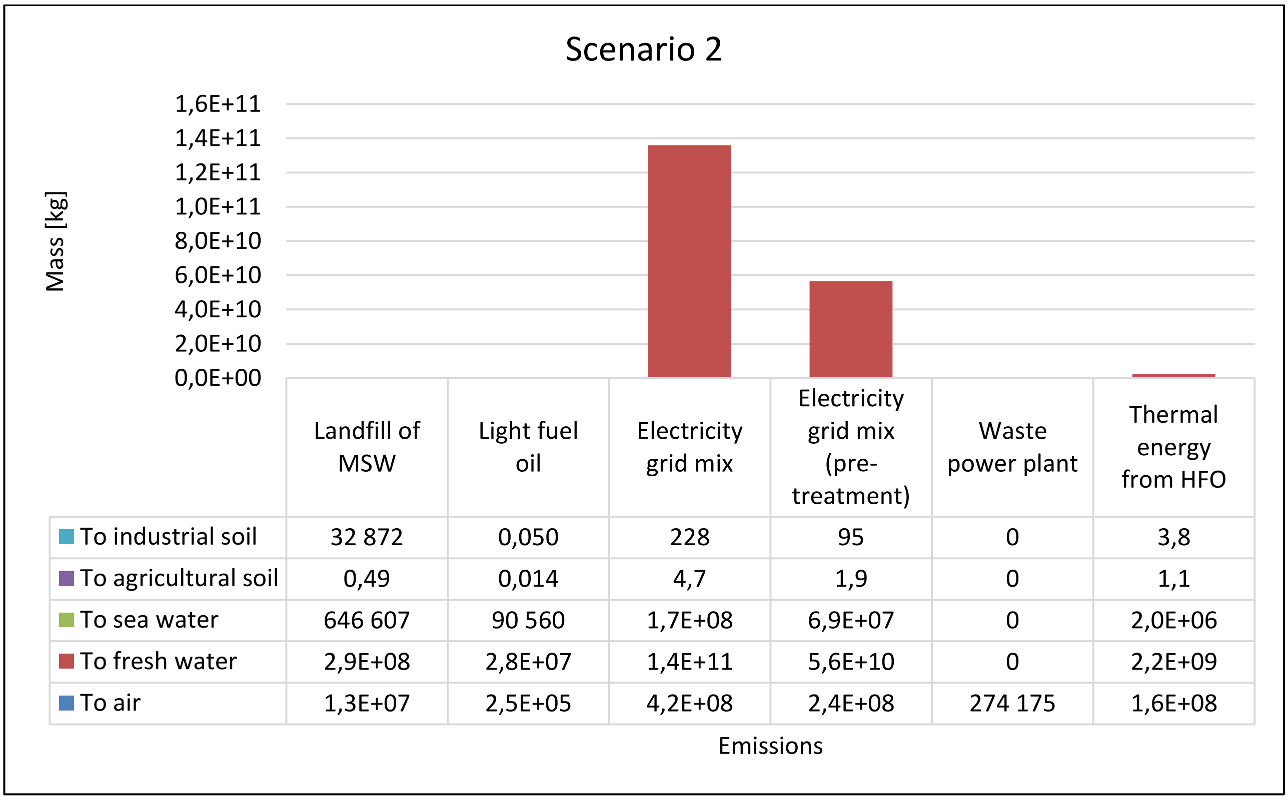


Figure 14. Emission amounts in scenario two.

Scenario two emissions are roughly $195*10^6$ t/a, and they are more than in scenario one. This is because there is need for electricity production from the grid mix, because the electricity produced in the waste power plant does not cover the total need of electricity. Again the most of the emissions come from the electricity grid mix that is used both for the fulfillment of the electricity need and pretreatment of waste. Together they are nearly 99 % from the total emissions. This time the second highest emitter, when electricity is considered as the highest, is the heavy fuel oil used for thermal energy production to fulfill the need for heat. Again the lowest emitter is the actual power plant since the emission amounts for it are so low and limited. The evaluation of emissions amounts show that scenario one would be the best option for the power plant since it has the least emissions. There is still need for more comparison than only emissions and that is why GWP results are presented and assimilated next. First the figure fifteen illustrates the GWP in scenario zero.

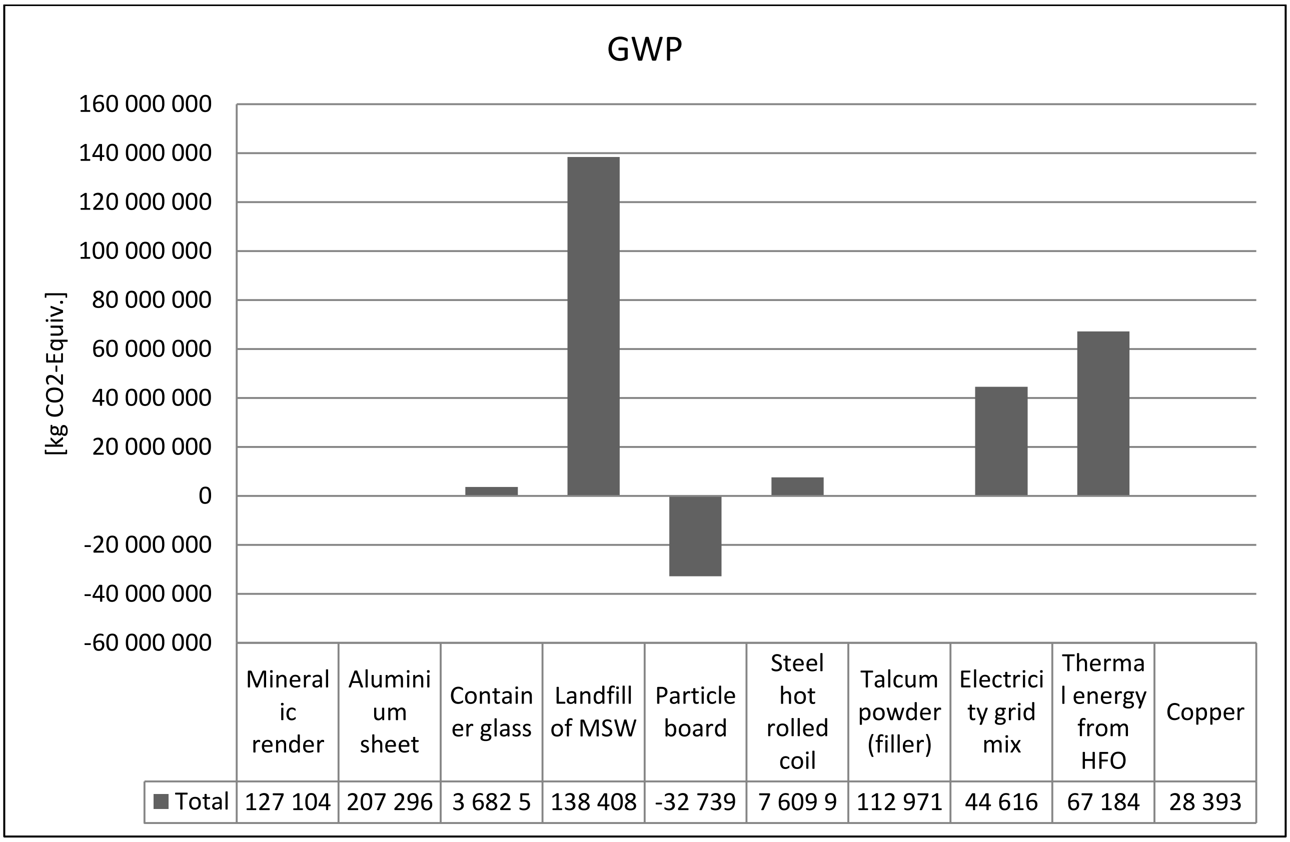


Figure 15. Global warming potential in scenario zero.

When compared to the emission amounts from scenario zero in picture eleven, there is a noticeable difference on which processes have the highest impact. The biggest impacts to global warming come from landfilling the municipal solid waste and even thermal energy from HFO has a bigger impact than the electricity grid mix. The GWP of landfilling is over 60 % from the total GWP of scenario zero. The biggest influence in this is that the GWP is calculated from emission to air gases and from used resources, and they have different factors based on how much the values are, when transformed to carbon dioxide equivalents. Landfilling usually emits a high amount of methane (CH_4) and if it is not captured and used, it has a quite high global warming factor that can be around 28 to 36 in the hundred year's inspection (United States Environmental Protection Agency 2015). This time the lowest influencer is copper production, which actually has the lowest amount of emissions to air in scenario zero. The total GWP from scenario zero is $229*10^6$ kg CO_2-Equiv. The particle board GWP is negative since it acts as a carbon sink. Carbon sink basically means a reservoir of carbon which size is growing (Science Daily 2015). Carbon sinks is fundamentally the contrary of carbon source (Ibid.). This is because it is produced from wood based products (GaBi 6 2015) and wood binds carbon dioxide into it when growing in the forest. Next in the figure sixteen, the GWP of the scenario one is presented. The effect of the particle board carbon sink can be seen more clearly in this scenario.

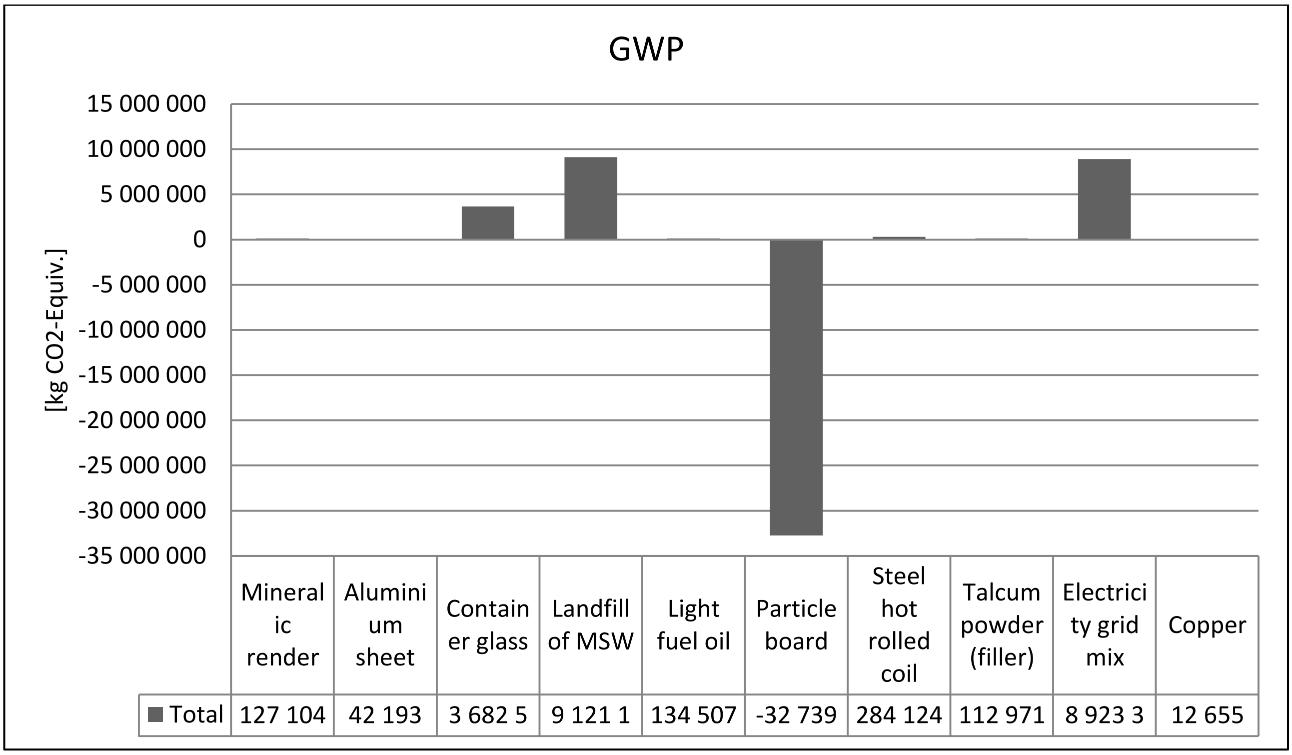


Figure 16. Global warming potential in scenario one.

In scenario one, the highest influence to the total GWP comes from particle board production and then from the electricity grid mix needed for the pretreatment of waste. Since the GWP of the particle board is negative, electricity grid mix need is much smaller and there is a lower need for landfilling of waste, the total GWP is $-10*10^6$ kg CO_2-Equiv. Only from this difference, it is possible to consider that it is better to incinerate the waste than put it to landfill. Again the problem with the comparison is that there is no GWP for the waste power plant because CML 2001 – Apr. 2013, Global Warming Potential (GWP 100 years) does not consider the used emissions to have any affect to global warming (GaBi 6 2015). This makes it more difficult to compare GWPs between scenarios. The GWP from scenario two is presented in figure seventeen.

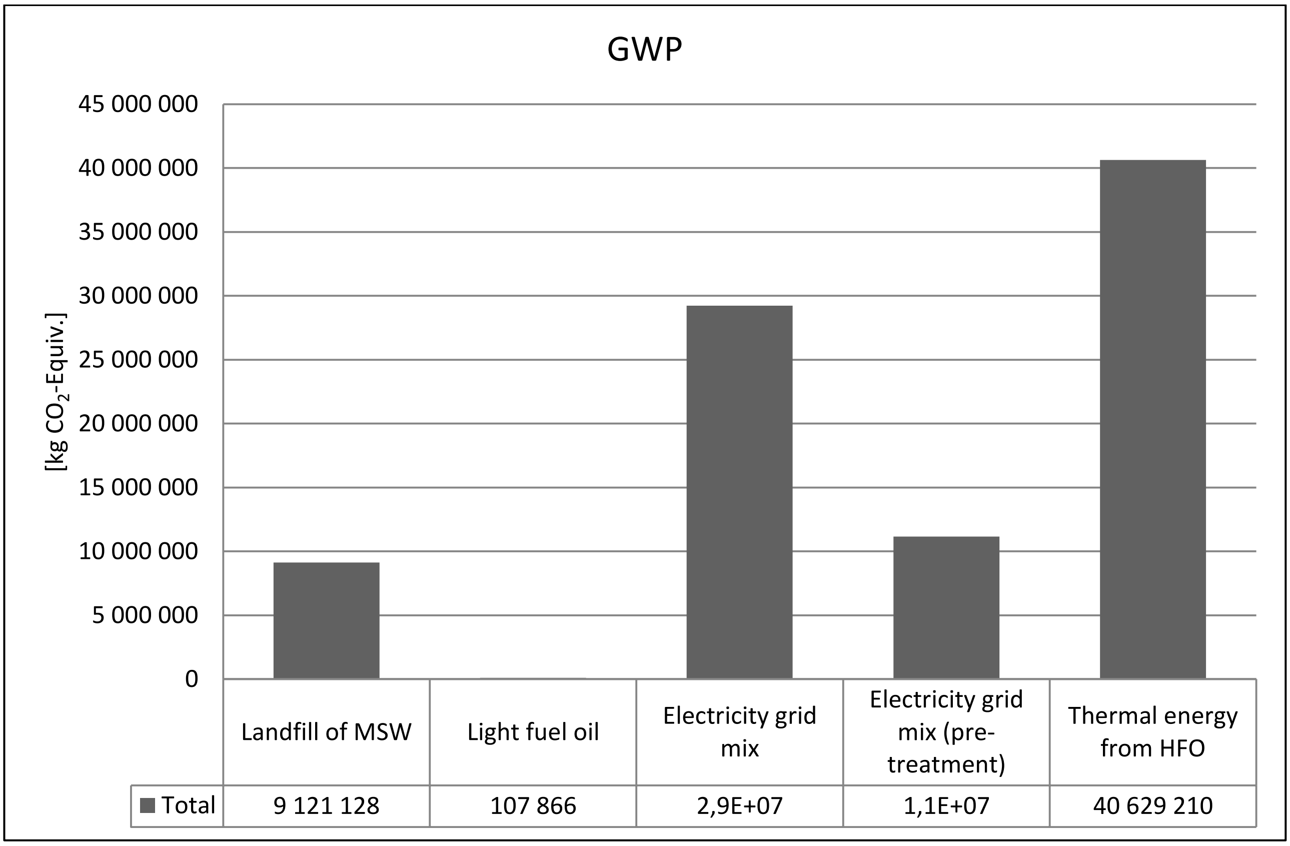


Figure 17. Global warming potential in scenario two.

The GWP for the scenario two is over $90*10^6$ kg CO_2-Equiv. This is more than two and a half times the amount from scenario one. The biggest influencers are thermal energy from HFO and the electricity grid mix production. In total the electricity grid mix processes and thermal energy from HFO are both about 45 % from the total GWP. If the energy aspect is left out, because of the lack of information on how much the GWP of the studied power plant is, scenario two would have much lower GWP than scenario one. This is because the substitutive processes are taken out of the calculations. The biggest challenge for the comparison is going to be, whether energy production or reuse of separated materials is seen more important than the other. There are several things to be taken into consideration besides the emissions and GWP, such as the possibilities for production of new products from the recycled materials. Lastly figure eighteen illustrates the comparison of GWPs from the different scenarios.

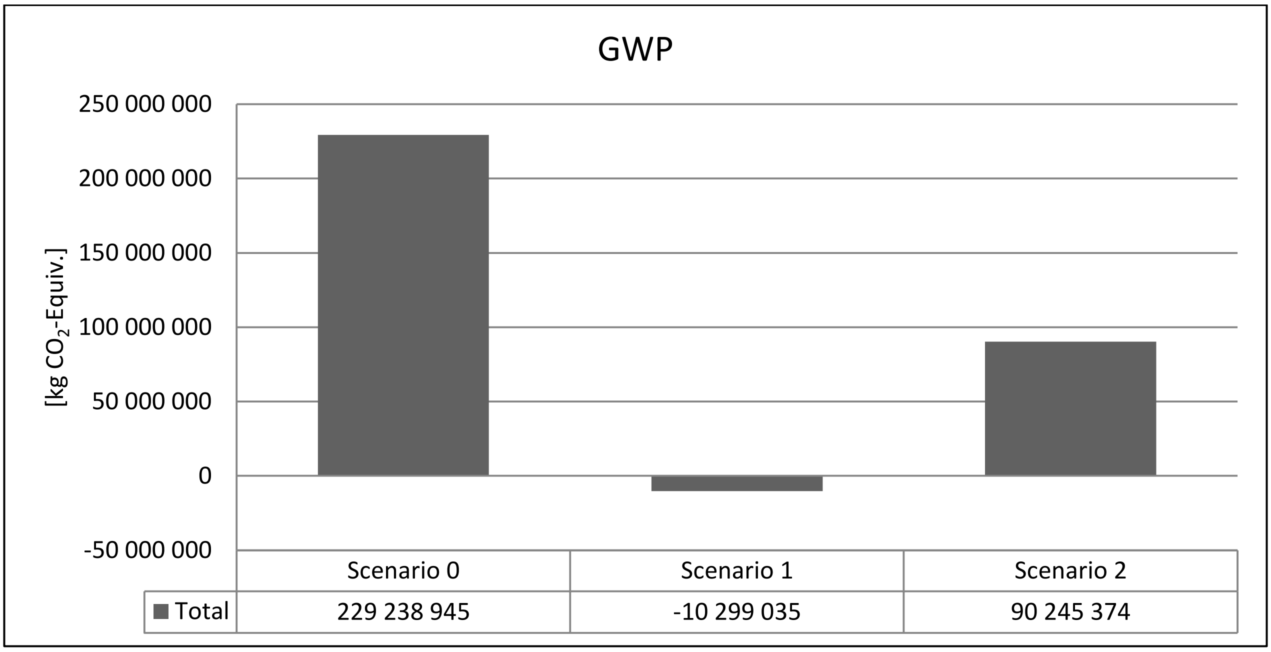


Figure 18. Total global warming potential from all the scenarios.

From the figure eighteen it is possible to really notice the difference from scenario zero to scenarios one and two. The reason why scenario one is better than scenario two, can be found from the particle board and energy production. But if again the unit processes that replace the bottom ash utilization and material use from separated waste particles are compared, the most savings to GWP come from steel hot coil production when iron is both separated from municipal solid waste and bottom ash, and also from the container glass production. This is again different result then from the emission amounts. The particle board replacement with plastics is the biggest influencer on both accounts, when considering the material placement and also the energy production. Also plastic seems to have the most difficult process to be produced to replace products like particle boards. But as said before, there is need for more viewpoints for the analyzing, since there are some accurate values missing and other issues that will affect the end result. In figures nineteen and twenty, the different substitutive systems are compared from emission and GWP point of view. These figures show the contradiction in particle board production since the emissions are highest, but the GWP is still negative since the production absorbs carbon emissions.

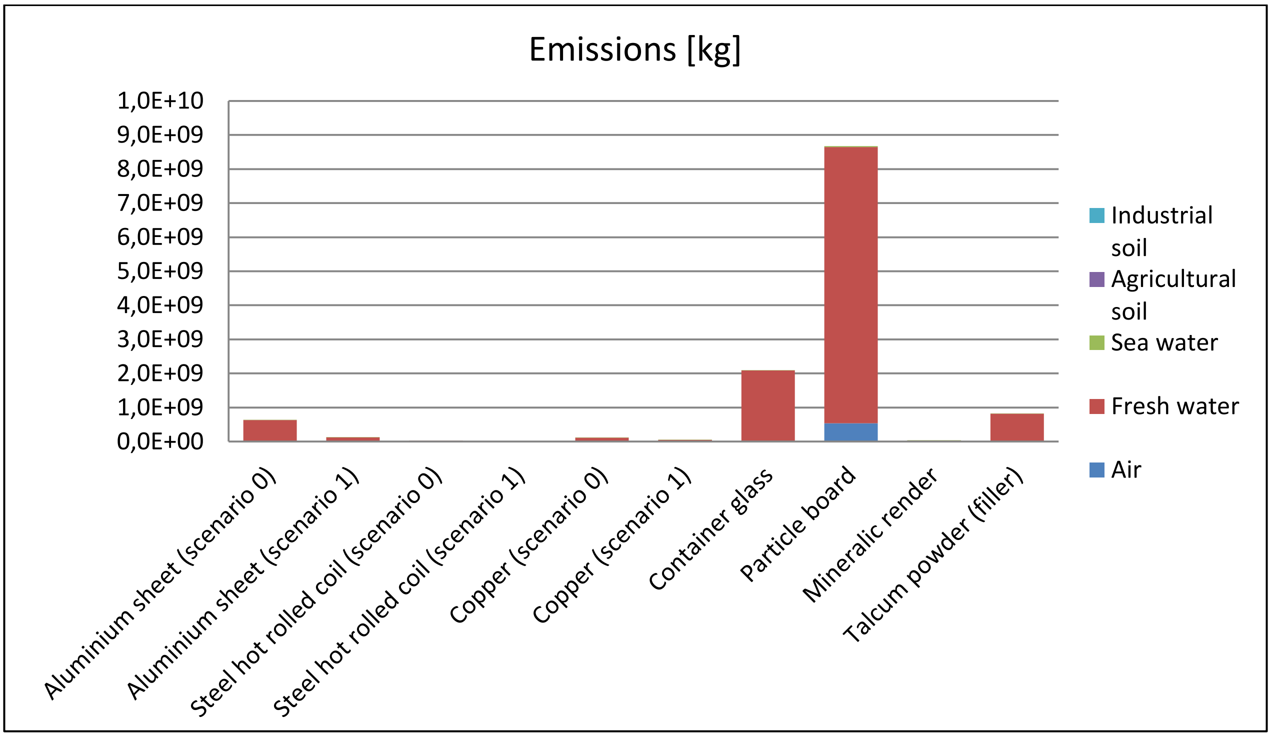


Figure 19. Emissions from different substitutive processes.

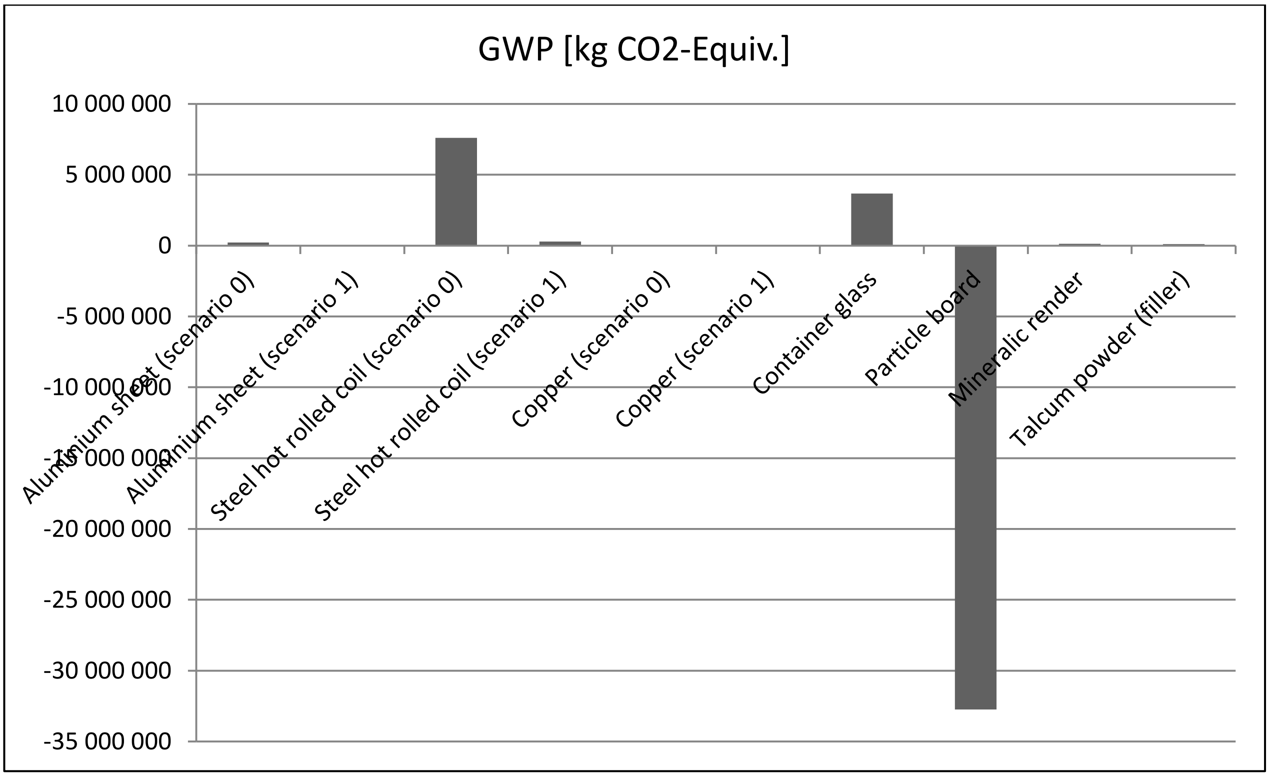


Figure 20. GWPs from different substitutive processes.

7.2 Variable costs

In this study the variable costs concern only the costs from chemicals used for flue gas cleaning and handling of hazardous waste. All these costs are based on estimations so they only give some sort of idea on how much the costs could be and what the possible savings would be with these costs. Also, the costs per energy unit are considered so that the difference in costs can be seen contemplated on how much produced energy amounts change. The emission amounts decrease from scenario one to two because the incinerated waste amount decreases. The calculated inputs and outputs can be seen from attachment III and the actual emissions and the differences between scenarios in the next table four.

Table 4. Emission amounts and differences.

	Scenario 1		**Scenario 2**		**Decrease**	
SO_2	52	t/a	42	t/a	19.8	%
NO_2	206	t/a	165	t/a	19.8	%
Particles	10.3	t/a	8.3	t/a	19.8	%
HCl	10.3	t/a	8.3	t/a	19.8	%
HF	1	t/a	0.8	t/a	19.8	%
CO	52	t/a	42	t/a	19.8	%
TOC	10.3	t/a	8.3	t/a	19.8	%

As can be seen from table four, the emissions decrease is 19.8 % between scenarios. This same amount is estimated to be the decrease in the chemical consumption. The case power plant is using aqueous ammonia 800 t/a for the selective non-catalytic reduction (SNCR) flue gas cleaning technique to remove nitrogen oxides, calcium hydroxide 2 500 – 3 500 t/a or calcium oxide 2 000 – 2 800 t/a for the half dry technique to remove acid components and activated carbon 100 t/a to remove heavy metals, dioxins and furans (ISA-VI/17/04.08/2013, 7, 19, 20). For calcium oxide and calcium hydroxide, average values are used in this case. The hazardous waste is boiler ash, flue gas cleaning end products and fly ash and about 26 200 t/a (Ibid., 30) and in GaBi 6 the calculated amount of hazardous waste in scenario two is 21 010 t/a. These values represent the amounts used in scenario one and the calculated values calculate the amounts used in scenario two. Table five presents the amounts of used chemicals.

Table 5. Amount of chemicals needed for the flue gas cleaning.

	Scenario 1		Scenario 2	
NH_4OH (<25%)	800	t/a	642	t/a
$Ca(OH)_2$	3 000	t/a	2 406	t/a
CaO	2 400	t/a	1 925	t/a
Activated carbon	100	t/a	80	t/a
Hazardous waste	26 200	t/a	21 010	t/a

For the cost estimation of chemical consumption, prices from Alibaba.com were used. Price of aqueous ammonia is estimated to be 180 – 400 $/t (Alibaba.com 2015a), calcium hydroxide 80 - 320 $/t (Alibaba.com 2015b), calcium oxide 120 – 200 $/t (Alibaba.com 2015c) and for activated carbon 300 - 2 500 $/t (Alibaba.com 2015d). The prices were first translated to euros and then the average values used for the calculations. These probably are not the most reliable prices for Finland, but they give an idea on how much the cost can vary globally. For the price of hazardous waste handling, Keski-Savon Jätehuolto prices for acid and alkali waste was used and it is 2 085 €/t (Keski-Savon Jätehuolto 2013). Since most of the waste in this study's hazardous waste is acid or alkali waste, only this value is used. Table six illustrates the costs and difference from scenarios.

Table 6. Costs from chemical use (Keski-Savon Jätehuolto 2013, Alibaba.com 2015a, 2015b, 2015c & 2015d).

	Cost		Scenario 1		Scenario 2		Difference	
NH_4OH (<25%)	252	€/t	201 200	€/a	161 351	€/a	-39 849	€/a
$Ca(OH)_2$	174	€/t	52 200	€/a	41 861	€/a	-10 339	€/a
CaO	139	€/t	333 600	€/a	267 528	€/a	-66 072	€/a
Activated carbon	1 215	€/t	121 500	€/a	97 436	€/a	-24 064	€/a
Hazardous waste	1 085	€/t	28 427 000	€/a	22 795 850	€/a	-5 631 150	€/a
TOTAL ($Ca(OH)_2$)	2 726	€/t	28 801 900	€/t	23 096 498	€/t	-5 705 402	€/t
TOTAL (CaO)	2 691	€/t	29 083 300	€/t	23 322 164	€/t	-5 761 136	€/t

The savings from scenario two, when compared to scenario one, are nearly 6 million euros per year with both calcium hydroxide and calcium oxide. Since this only tells how much the variable costs change between scenarios, it is also necessary to calculate how much the costs per megawatt hour are. This tells really how the costs change when plastic and glass are separated and the amount of waste and heating value decreases. The costs for this are important since the amount of electricity and heat produced, are the vital income. The price for electricity and heat do not vary based on the amount on how much the power plant can produce energy, so the variable costs for production are important. If the energy amounts are smaller and costs per energy unit are also smaller, it can be profitable to produce less with slighter costs. Next on table seven the amount of energy produced in scenarios are shown and in table eight the costs per megawatt hour are presented.

Table 7. Electricity and heat production in the waste power plant.

	Scenario 1		**Scenario 2**	
Electricity	130 000	MWh/a	73 000	MWh/a
Heat	210 000	MWh/a	118 000	MWh/a
TOTAL	340 000	MWh/a	191 000	MWh/a

Table 8. Variable costs per energy.

	Scenario 1		**Scenario 2**		**Difference**	
Costs/energy	85.13	€/MWh	121.51	€/MWh	+36.39	€/MWh

Both the produced amount of electricity and heat reduce from scenario one to two, which is not a surprise since the incinerated amount reduces. The costs per megawatt hour arise, even though the variable costs get smaller. The costs are calculated with average total between the different calcium solutions. The variable costs decrease around 19.8 % when the amount of energy produced decreases 43.8 % so since the costs decrease less, the variable costs per megawatt hour increase. From this is seems that it is not profitable to separate plastics from the MSW, before incinerating the waste. When the prices for the produced energy and recycled materials are known, they can affect the results so that it is better to separate plastics since the profits are higher. The analyzing of these costs and the previously presented GWP amounts are done next, so that the results are combined to evaluate if the separation is profitable idea.

7.3 Analyzing the scenarios

Solely based on emissions, the scenario two seems better than scenario one. Based on GWPs the scenario one is better than scenario two. GWP tells more on how much the production and emissions do affect the environment, so it has more value to the results than the emission amounts. The particle board production is the biggest influencer in these results and if the plastic separation would be used to replace some other product, which is not produced from materials that absorb carbon, the results could be quite different. But the chosen processes in this study show that scenario one is better than scenario two, based on the LCA modeling. A sensitivity check could help on seeing how much the change in amount of waste and separation rates change the results, but the problem is that the modeling is vulnerable to little changes and would require more calculation. Especially when changes in the separation rates are done, the vulnerability is visible, so it does not seem useful to do the check in this case. The calculated variable costs tell also which is more profitable for the waste power plant solely based on the regarded costs. Based on the variable costs only, the scenario two is cheaper than scenario one. When the costs are divided by the produced energy, the comparison changes again and the scenario one seems to be the best option. The overall results demonstrate that scenario one is to better than scenario two but it is good to consider the recycling of materials from other perspectives.

The city of Varkaus, where the recycled materials are assumed to be used, is a city of over 20 000 citizens and land area of nearly 390 square kilometers (Varkaus 2015, 2). There have been different industries in the city since 1815 and the industries vary from wood processing industry to manufacturing of power plant and industry boilers (Ibid., 4). It seems that there’s no big industry that could utilize the metals, glass, plastics and bottom ash materials in their production. The minerals, filler and excavation materials could probably be used in different projects in the area, but this depends highly on how much processing the bottom ash needs before it can be used as these kinds of resources. There are different types of business utilities in the city (Ibid., 7), so it could be possible to establish new industries that could utilize these recycled materials. These new industries need to get the recycled, secondary materials also from other places besides the studied waste power plant. It is most likely too expensive for the waste power plant to use the materials by themselves to produce new products. They would have to require new investments on machinery and work force to do that. If there comes up new inventions and interest on producing some products from the materials, the possibilities can be higher when the production is more possible. That is why it seems more reasonable to sell the materials to another company. The separation itself needs to be first decided, but there needs to be some sort of demand for the materials so that there is enough profit from the separation.

8 CONCLUSIONS

The modelled waste power plant is using techniques that are well suited for waste incineration. Since the power plant is operating in Finland, the plant needs to follow the legislations concerning incineration of waste. The actual pretreatment in the plant is done with one or two stage crushing, a belt magnet, eddy current and air classifier (ISAVI/17/04.08/2013, 10), which are suitable for the removal of the recycled materials in scenario one. Air classifier could be used to separate the plastics and glass since it is used to separate waste's with different densities (Klinghoffer & Castaldi 2013, 60), which are separated in scenario two, so the scenario one systems could be suitable for the second scenario system too, but it would probably need upgrading. The actual incineration is done with circulating fluidized bed boiler (ISAVI/17/04.08/2013, 8) which is not very common to use in waste incineration in Finland (Puurtinen 2015b). Circulating fluidized bed boiler is very suitable for waste incineration. The cleaning of flue gases is done with SNCR method, fabric filter and possibly with ESP, half-dry method and as well active carbon (ISAVI/17/04.08/2013, 7, 26) which should work together well so that the emission targets are met, even when the composition of the incinerated waste varies. The actual bottom ash utilization possibilities need to have new equipment for the power plant in scenario two. There is probably a need for some sort of magnet, and possibly to eddy current too, for the metal separation and for example and air classifier to separate the mineralic and filler material.

The goal of the study has been to find solutions on which one of the scenarios is better for the studied waste power plant. The scope was on the waste incineration at the plant and on the utilization of the recycled materials. Also the substitutive processes were part of the LCA model. The functional unit was the waste amount and the reference flows were the different handling options for it. The impact category was chosen to be the GWP of the different scenarios and the amount of effect they have on the environment. The actual modeling done, based on these outlines tells only the situation that has been assumed to be close to the real situation. The emphasis of the GWPs from the LCA modeling is in the substitutive processes since they seem to have the biggest effect on the GWP totals. The biggest influencing substitutive process is the particle board production. It has negative GWP since it is a sort of carbon sink due to the fact that it is produced from wood based products. It has the biggest impact in the scenario one GWP since the total is negative because of it. These results show that it would be probably better to consider some other process for the substitution of plastic consumption. This also means that there should be other production option the mixed plastic waste. The other substitutive processes instead, seem to have good arguments to be replaced by the recycled materials from the waste power plant, especially when all of the iron and glass is separated and recycled. Their substitutive processes have the second and third highest GWPs from all the substitutive options.

Solely based on the GWP results, the scenario one is better than scenario two. Without the particle board substitutive process, scenario one is still better since the GWPs from the electricity and thermal energy production from outside sources are high. The variable costs give the same result since the costs per produced megawatt hour are higher in scenario two than in scenario two. So the results tell that it is better to stay in the scenario one situation and consider the scenario two option when it is more profitable and it can be indicated that the GWP is smaller then. Also, it is important to consider the profits from both sold electricity and heat and also from the recycled materials. Sometimes it can be worth the extra cost to earn more money and preserve the environment. The area, where the recycled materials are assumed to be used for production, does not currently have any big industry that could utilize the materials. So basically the results show that it is not purposeful to invest in separation of plastics and glass and the broader utilization of bottom ash. There needs to be a change in the utilization possibilities and bigger market for the materials and products from these materials. This requires new investments on new inventions that can reduce GWP from a more harmful production and be more profitable that the bigger costs do not matter. There also may be need for new techniques for the separation of materials and valuables, from both the main waste stream and from bottom ash, so that the utilization of them is easier. New ideas need money and for that, there needs to be more demand on the utilization of the recycled materials instead of using them in energy production. The possible impacts are to be understood in this phase and this is essential for interpretation.

Waste incineration could be useful in other cities and areas too, since it is quite easy way to get rid of MSW when the landfilling needs to end. Also sometimes it is possible to update old power plants to do co-combustion of waste or even just change the techniques in a way to change the fuel to waste. Usually it seems to be more efficient to produce thermal energy or heat but price of electricity can make the co-production of both the most profitable option. The waste amounts need to be high enough so that it is a reasonable investment on building a power plant, so it would probably be better to build a waste power plant for a bigger area than just for one city. Also the composition of waste that comes to incineration is important to know, since it effects on what sort of technologies are best suited for the pretreatment, actual incineration and flue gas cleaning. The idea of separating valuable materials, such as metals, may prove to be a good add on to the pre-treatment. The removal of glass can be profitable, since it does not really affect the heating value, but the amounts are quite low so it has to be profitable and otherwise justified. The utilization of bottom ash in other ways, than just for excavation, seems reasonable since there are so many potential use purposes for it. The separation of plastics is the only complicated process, because it can reduce the heating value a lot and it does not have so many ways to utilize all the plastics mixed together.

For the future, it would be wise to study more on how the plastics affect the incineration and what kind of utilization possibilities there are for it as a secondary material. A more accurate LCA of a waste power plant could be very useful to study, but it would require more information about the emissions when operating and also from the building and end phases. It is similarly important to consider doing more studies so that there could be found justification on why plastics should be recycled from the waste stream. There is a need for more studies on justification of waste incineration, especially why and what type of recycled materials should be taken out of the MSW before it is incinerated. This study only justifies why the modelled waste power plant should not recycle other waste particles then metal. The utilization of bottom ash does not seem to be reasonable, since there are no big enough utilization possibilities for it in the assumed operating area. The return rate of the materials back to incineration is also a subject that could use some more researching. Glass and metal most likely turn back to incineration at some rate, but if plastics are used to produce Muovix type of profiles, it is not clear whether it would return to incineration and with what rate. Also, there would be a big need for investment on the equipment sorting the bottom ash. The bottom ash utilization seems still to be more reasonable to execute than the larger scale separation in pretreatment.

9 SUMMARY

Incineration of waste has become to be a solution for the increasing waste amounts. Landfills are quite full and they are harming the environment, so it is important to find suitable options for landfilling, since it is not likely that produced waste amounts would decrease. Waste incineration history starts from the 1800s and it has developed from a way to get rid of waste to an energy production method. In Finland the waste incineration has been co-combustion with other fuels, but it nearly ended in the 1980 s, because of the emitted harmful compounds in the 1960s. Still waste power plants have started to come up Finland and the plants thrive to work more efficiently. There is a need for studies on how recycling can be beneficial before incineration in waste power plants. It is possible to use tools already in use to get an efficient environmental management system to waste incineration. It is important to study the situations so that when legislation changes, it is easier to do changes, or to find ways to save money in the production, when necessary. According to the EU fives steps hierarchy says that energy recovery from waste is the fourth step and it is an option for utilization of the waste. It is important to do the incineration efficiently. This is also a part of the Finnish legislation that covers waste power plants. There is a need for environmental permit, for which there is EU laws and decrees. In Finland there are three different laws and two decrees that define how these EU laws and decrees are executed in Finnish legislation. The objective of the study is to consider which option is better for the studied power plant from GWP and variable costs perspective. There are different things to consider on the technical side when starting a waste power plant. The first thing to consider is pretreatment of waste and for that there are several options. It is important to get a consistent and homogenous waste stream to incineration so pretreatment is important.

The options for waste pretreatment are screening for unwanted objects, for size conversion trammeling, shredding and sorting, dehydration to remove water, air classification for separation of particles with different density, for metal removal magnets and eddy current and for biologically degradable components the MBT and torrefaction. For the incineration the burner options are fixed bed incineration, fluidized bed incineration, either bubbling or circulating bed, and reel oven. Fixed bed incineration is the most used one of these. The flue gas cleaning is needed but the incineration technique also has a role on the emitted flue gas amounts. For the particle removal either ESP or fabric filters are used. After that there is wet, half dry and dry washing methods that wash the glue gases with different types of solutions. These methods remove sulfur oxides, nitrogen oxides, mercury and dioxins. Sometimes SNCR or SCR method is needed to remove more nitrogen oxides. The residues from waste incineration need to be reduced in amount and harmfulness. The residues are treated as hazardous waste, but it is also possible to use them in earth construction. Incineration of waste covers a small segment of total energy production and the amount of harmful compounds produced is significant. There are still problems with the utilization, since the harmful compounds can leak to environment when used in construction. The recycling of metals from the residues has improved since the benefits from it have been found to be noteworthy. The utilization of these ashes and other materials is being studied. The different materials in the mix have different re-use purposes, for example glass is good for asphalt and aggregate blends, insulations and so on. Recycled wood is good for fiberboard and paper production. Plastics are hard to recycle because of the wide variety, but they can be used for containers, carpets and film. Recycled plastics are also used for profiles production and automotive, garden and lawn products. There is a market and demand for products that are produced from recycled materials.

To study environmental values from products, whether they are produced from virgin or recycled material, LCA is a great tool. LCA is a tool that is mostly based on two ISO standards. There are four main steps in an LCA study which are goal and scope definition, LCI, LCIA and interpretation of results. The first phase determines the goal and for what the study is intended, what are the reasons on why the study is done. Also the product system that includes the processes, boundaries, functional unit and possible allocation needs to be presented. The impact categories and assessment should also be part of this phase. The LCI phase is about the collection of needed data and calculation of the system flows. Also the possible allocation flows and actual allocation needs to be calculated in this phase. The found data is connected to the processes in the LCI. The next LCIA phase is about evaluation of impacts to the environment. This is done based on the data from LCI study and it essentially is connection of inventory data with the chosen impact categories concerning the environment. The impact categories, category indicators and characterization models all need to be referenced with the information and sources and sometimes there is need for changes. LCIA has three optional elements that can be used when necessary. These elements are normalization, grouping and weighting. The last phase of an LCA study is the interpretation which fundamentally considers all the findings from the LCI and LCIA to an LCA. Results need to be consistent with the previously defined goal and scope and since LCA study is iterative, there may been need for changes to previous stages when the study progresses from goal and scope to interpretation. In this phase, there are three elements, which are recognition of noteworthy issues, evaluation of completeness, sensitivity and consistency checks and lastly conclusions, limitations and recommendations.

The studied waste power plant is going to produce electricity and thermal energy, from MSW. The pretreatment includes crushing, magnets, eddy current and air classifier, the incineration happens in modern fluidized bed incinerator, the flue gases are cleaned with SNCR, half-dry method, fabric filter and possibly even ESP and the bottom ash is utilized when possible. The actual modeling of the plant with GaBi 6 software starts from the MSW, and then goes to pretreatment stage, incineration and lastly consumption. There are three scenarios considered and the scenario zero is the one where the MSW goes to landfill and all the consumptions are fulfilled from outside sources. In scenario one is the waste is incinerated, metals are recycled and bottom ash is utilized in one way only. In the second scenario, plastics and glass are also separated from the MSW and the bottom ash is utilized in several ways. The energy consumption also needs outside sources in this scenario. The substitutive processes are directly from GaBi 6 database but most of the other unit processes are done by hand and with calculations. From the emission amounts it can be seen that scenario zero has the biggest, scenario one second biggest and scenario two the lowest emission amounts. The actual GWPs, calculated by GaBi 6, show that scenario zero has the biggest, scenario two the second biggest and scenario one the lowest GWP. Since also some of the costs can affect the decision making, variable costs from chemical consumption on flue gas cleaning and handling of hazardous waste, are considered. Scenario two has lower variable costs than scenario one, but when they are divided with the produced energy amounts, the costs per megawatt hour are higher in scenario two. These showcase that scenario two is not an option at the moment. There needs to be big industries so that the recycled materials can be utilized. That is why there should be more studies done on these subjects.

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ATTACHMENT I: Studies on MSW composition in Finland

[%]	Biowaste	Metals	Glass	Paper and cardboard	Combustible waste	Non-compustible waste	Hazardous waste and electric and electronic devices	Plastics	Source:
South Karelia	16.2/24	4.8/4	1.8/3	15.7/15	48.2/43	13/10	0.3/2	24.8/-	Honkanen 2014, 27 & Teirasvuo 2011, 96
Turku	31	1.8	1.4	13	49	3.2	0.6	7	Kähkönen 2012, 26, 35 & 38
Päijät-Häme	23	5	3	12	32	21.1	6	10	Päijät-Hämeen Jätehuolto Oy 2006, 8
Savonlinna	9	4	2	12	33	38	3	12	Karvonen & Voutilainen 2007, 12
Helsinki area	38,8	3	2.4	17.3	36.2	1	1.2	-	HSY 2012, 17
Kuopio	35	3	2	11	23	26	2	9	Hynynen 2008, 51
Mikkeli	30.4	3	2.5	15.2	30	26.6	1.5	-	Teirasvuo 2010, 40
Kainuu	33.6	2.7	3.7	11.5	45.4	-	3.1	15	Koskela & Elfving 2014, 15-16
Varsinais-Suomi	31.9	2.2	1.5	2.6	57.4	3.6	0.8	27	Pöyry 2013, 20
Joensuu	24	3	3	14	39	12	5	20	Mikkonen 2013, 5
AVERAGE:	**27,0**	**3,4**	**2,4**	**12,7**	**39,7**	**14,0**	**2,3**	**15,6**	

ATTACHMENT II: Yearly emission amounts

Source: ISAVI/17/04.08/2013, 27	
Emission Component	**Amount [t/a]**
Sulfur dioxide (SO_2)	52
Nitrogen oxides (transformed to NO_2)	206
Particles	10.3
Hydrogen chloride (HCL)	10.3
Hydrogen fluoride (HF)	1
Carbon monoxide (CO)	52
Organic matter as total organic carbon amount (TOC)	10.3
Cadmium and thallium (Cd, Tl)	0.05
Mercury (Hg)	0.05
Antimony (Sb), arsenic (As), lead (Pb), chromium (Cr), cobalt (Co), copper (Cu), manganese (Mn), nickel (Ni), vanadium (V)	0.5
Dioxins and furans	$0.10*10^{-6}$

ATTACHMENT III: Calculated values for the inputs and outputs in the modeling.

	Flow	Inputs/outputs
MSW	**Waste amount**	170 000 000
Pretreatment of waste	**Reject**	0.0559
	Big particles	0.0100
	Metal	0.0253
	-aluminum	0.0760
	-iron	0.8150
	-copper	0.00215
	Plastics	0.156
	Glass	0.024
Incineration	**Light fuel oil**	0.00194
	Electricity efficiency	0.250
	Heat efficiency	0.404
	Electricity consumption (scenario 1)	0.551
	Electricity consumption (scenario 2)	0.688
	Caloric value (scenario 1)	12.2
	Caloric value (scenario 2)	8.48
Emissions	**SO2**	0.000337
	NO2	0.00133
	Particles	0.0000667
	HCl	0.0000667
	HF	0.00000647
	CO	0.000336
	TOC	0.0000667
Bottom ash	**Bottom ash**	0.0142
	-metal	0.206
	-aluminum	0.230
	-iron	0.0204
	-copper	0.373
	-excavation	0.300
	-filler	0.194
	-minerals	0.300
Hazardous waste	**Hazardous waste**	0.170