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Site selection of a WtE plant in Iceland based on utilization of value streams

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Abstract

In 2021, a feasibility study was carried out on the construction of a so-called waste-to-energy (WtE) plant in Iceland. This thesis is partly based on the findings from this feasibility study. The feasibility study revealed that it was profitable to build one WtE plant in Iceland, which would handle combustible waste from all over the country. It was estimated that if it was decided to continue with the project, it would be possible to build the plant and start operations at the earliest in 2030. The feasibility study states that the plant must have a combustion capacity of up to 130,000 tonnes of combustible waste per year. Such combustion will have a production capacity of 10 MW of electricity and 28 MW of thermal energy. Other possible value streams from a WtE plant of this size are 26000 tons of bottom ash, 22000 tons of scrap metal and approx. 190000 tons of CO_2. The feasibility study also reviewed possible site selections, five locations were identified as possible site selections: Álfsnes, Straumsvík, Helguvík, Þorlákshöfn and Grundartangi. These five locations were compared and evaluated based on the transport efficiency of waste to the plant. Other influencing factors that could affect site selection were discussed at the steering group workshop meeting and an analytical hierarchy process (AHP) was performed to assess the impact of other influencing factors on the plant's site selection. Based on the results of transmission efficiency and AHP analysis of other influencing factors, Álfsnes was assessed as the most efficient site selection. In this thesis, a further analysis of possible value streams from the WtE plant will be performed and each of these same site selections will be evaluated based on the utilization of value streams from the WtE plant of this scale. An AHP was used to compare the site selections based on the utilization of energy and possible value streams from the WtE plant. The site selections were evaluated based on the following criteria: change in thermal demand in the nearby district heating systems, available connections to the national electricity grid, population density of nearby urban areas, distance to the nearest port area and future plans for the development of CO_2 intensive industries in or close to the sites in selection. Results from the AHP analysis based on the aforementioned criteria revealed that Straumsvík would provide the best possible site selection out of the five locations in question. Further research is needed to determine if the utilization of value streams will outweigh the transport efficiency of waste to the WtE plant.

1 Introduction

As the world's population and prosperity increase, so does the demand for raw materials. It involves a huge increase in access to the earth's resources. As we know from the laws of physics, matter can neither be created nor destroyed, just as energy can neither be created nor destroyed. According to these laws, it should be quite obvious that the earth is not expanding, its raw material is not increasing and in that sense the earth's resources are limited. With ever-increasing population growth, technological advances, and the prosperity that results from them, mankind has created enormous problems that we now face, such as climate change, bio-degradation, and pollution. These great transformations have made us think more about the impact and footprint of our activities on the nature and ecosystem of the earth. The nations of the world are now increasingly looking toward sustainable development (SD) in the utilization of resources for the production of goods and products from raw materials and energy. The concept of global SD initially emerged at a United Nations (UN) conference in Stockholm in 1972. Few years later in 1987, the the concept of SD was defined in a report entitled "Our Common Future" published by the World Commission on Environment and Development, led by the Norwegian Gro Harlem Brundtland former prime minister of Norway. In this report, also known as the Brundtland Commission Report, SD is defined as "development that meets the needs of the present without compromising the ability of future generations"[22].

In 1992, five years after the Brundtland report was published, the United Nations Conference on Environment and Development (UNCED), also known as the 'Earth Summit', was held in Rio de Janeiro, Brazil. The Earth Summit was a big event in the history of SD, the summit produced Agenda 21 and led to the creation of the Commission on Sustainable Development. At the summit, UN member countries signed the UN Framework Convention on Climate Change and the Convention on Biological Diversity. UN countries also adopted the Rio Declaration and the Declaration on Forest management principles. Eight years later in 2000, UN member states adopted the Millennium Declaration containing the eight Millennium Development Goals (MDGs). Fifteen years later in 2015, new agenda for SD was adopted, the 2030 Agenda for SD by 2030, containing a new declaration and 17 new global goals called the Sustainable Development Goals (SDGs).

The SDGs were partly based on MDGs and with additional goals to address global challenges such as climate change, biodiversity and consumption to name a few. The Paris Agreement was also adopted in 2015 on the twelfth of December by 196 parties and entered into force fourth of November 2016. The agreement set out a global framework to limit global warming to well below 2°C and pursue efforts to limit it to 1,5°C. The Paris Agreement requires each party of the agreement to outline, communicate and maintain their post-2020 actions in the so-called national determent contributions (NDGs).

One of the key drivers for cities and countries worldwide to achieve the SDGs targets of UN Sustainable 30 Agneda and the NCGs of the Paris Agreement is by reducing global waste generation. According to the World Bank, the generation of solid waste worldwide reached 2,6 billion tonnes in 2016. It was further estimated that these 2,6 billion tonnes of solid waste generated 1,6 billion tonnes of CO_2-equivalent greenhouse gas (GHG) emissions in 2016, equivalent to 5 percent of the total GHG emissions at the time. Waste generation is expected to jump from 2,01 billion tonnes in 2016 to 3.40 tonnes by 2050. Without improvements in the waste sector global GHG emissions from solid waste are expected to reach 2,6 billion tonnes of CO_2-equivalents in 2050 [23]. Implementing a robust waste management system that reduces waste emissions with an increased focus on greenhouse gas capture, can help in achieving NCGs. A waste management system that prioritises actions according to the so-called waste hierarchy promotes economic transformation from a linear economy to a more circular economy. The waste hierarchy is widely known and is usually interpreted as a reversed triangle which is divided into several steps where the top step has the highest priority and then the priority decreases down the triangle. Different interpretations can have different steps with different names, but the priority is generally as shown on figure 1: waste prevention followed by reuse, recycling, recovery and finally disposal last with the lowest priority.

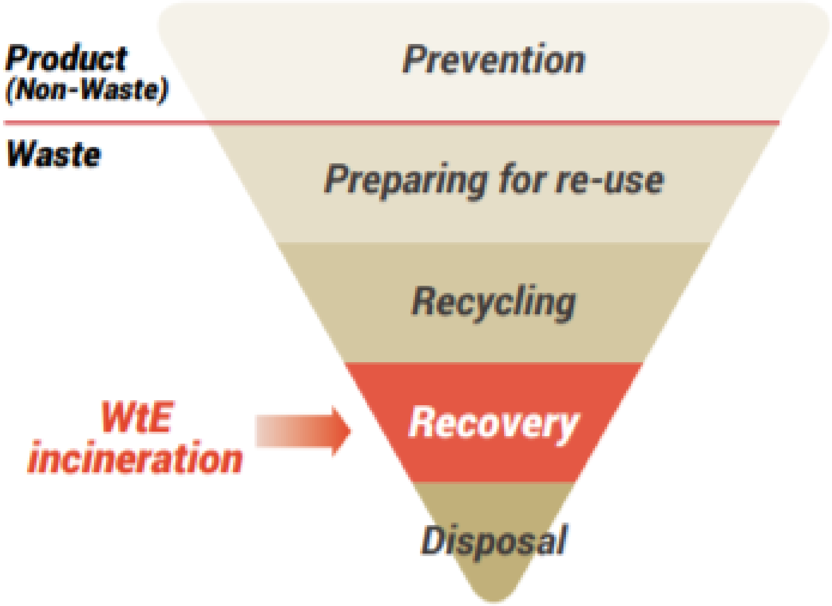


Figure 1: Waste hierarchy [1]

To explain the difference between a linear economy and a circular economy, a linear economy receives material into the economy through the extraction of raw material from natural resources, which goes to the production of goods for consumers and from there after a single use, the material is then discarded as waste through disposal in landfills, which is the lowest level of the waste hierarchy. The circular economy treats waste according to the prioritization of waste hierarchy at all levels of the economy, from the extraction of raw materials from natural resources through production and consumption, and uses a waste system that directs waste back into the economy through recycling and recovery in a semi-closed loop. In this way, the life of materials in the economy is extended and the demand for raw material from natural resources is reduced. The implementation of a circular economy is in line with SDGs, especially SDG target 12.5 which stipulates that countries find a way to reduce waste generation significantly through prevention, reduction, recycling and reuse by 2030. The European Union announced the European Green Deal on December 4, 2019, as a way to achieve the SDGs and its goal of becoming carbon neutral by 2050. One of the building blocks of the EU green deal is the EU circular economy action plan (CEAP) wich was adopted in March 2020. The CEAP announces measures that affect the lifespan of products ranging from design and production to disposal. The plan is intended to extend the life of products in the economy by promoting circular economy processes, encouraging sustainable consumption and keeping the resources entering Europe within the EU economy for as long as possible. Iceland has long been among the top of countries that generate the most waste per capita. In 2019, Iceland was in eighth place among the OECD countries that generated the most municipal solid waste per capita (see figure 2).

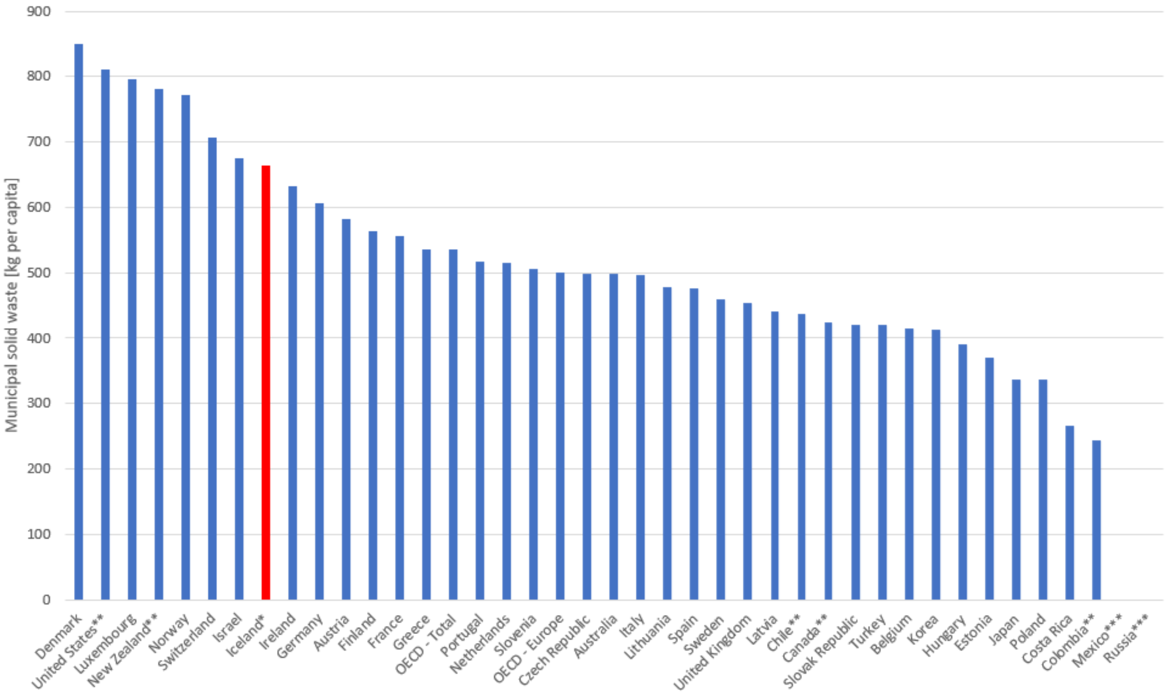


Figure 2: Generation of municipal solid waste in the OECD countries in 2019 [2],
** Data from the Icelandic environmental agency in 2019[3].
*** Data from 2018[2].
**** Missing data.

Although Iceland is not part of the EU, Iceland is a member of the European Free Trade Association (EFTA). EFTA members are obliged to adopt various EU directives through the Agreement of the European Economic Area (EEA) in order to have access to the EU internal market. Iceland is also a part of the UN and adopted the 30 Agenda in 2015, since then, the Icelandic government has integrated the SDGs into government policy in social, economic and environmental affairs. Iceland also signed the Paris Agreement in the fight against climate change and aims to reach carbon neutrality before 2040. In recent years, the Icelandic government has been looking for ways to achieve SDG targets and meet its obligations under these agreements.

In June 2021, the Icelandic Ministry of the Environment and Natural Resources issued a new waste policy called "Í átt að hringrásarhagkerfi" in Icelandic, which can be translated as: Towards circular economy[24]. The policy covers the entire waste hierarchy and is intended to promote the implementation of a circular economy in the country. The policy is divided into two parts, the first part covers waste prevention and introduces goals and measures to reduce waste generation. The second part covers waste treatment and contains measures and goals for recycling and recovery on the other hand. The second part also places more emphasis on the responsibility of municipalities in waste management. The policy has been followed by legislation, when Act No. 103/2021 was passed on 25 June 2021 in the Icelandic Parliament. The enactment of this law implements a new waste management policy while at the same time updating those laws in accordance with new EU directives on waste, most notably Directive 2018/850 on landfill, Directive 2018/851 on waste and Directive 2018/852 on packaging and packaging waste. New legislative changes in Act No. 103/2021, oblige municipalities to sort all waste and ban landfilling and incineration of sorted waste. Furthermore, landfilling of organic waste will be banned from 2023 onwards. These changes can be interpreted as such that the government's goal is to end all landfill as soon as possible. These changes create a great need for the development of infrastructure to process all the waste that otherwise would have been sent to landfill. With respect to these changes, municipalities and waste management companies have begun to look for solutions to recycle and recover energy from waste.

In 2020, the Icelandic Environment Agency commissioned a report to evaluate the generation of combustible waste in the country. The report published in 2021 contained a waste forecast for the generation of combustible waste in Iceland in the period 2025 -2045. The report states that the need for combustion capacity will range from 90,000 to 280,000 tonnes per year based on whether or not the government's recycling target is met. The report also states that it does not seem sensible to export waste for incineration in the further future. On that basis, the Ministry of the Environment and Natural Resources, together with four waste management companies in the southwestern corner of Iceland, launched a feasibility study to determine the feasibility of constructing a so-called waste-to-energy (WtE) plant in Iceland. This feasibility study was published 15 December 2021 stating that it was feasible to build one WtE plant in Iceland that would receive combustible waste from all across the country. However, this would be a moderately small WtE plant on a world scale as it would not receive more than 130,000 tonnes per year[5]. The plant's estimated energy production capacity would be 10 MW of electricity and 28 MW of heat [5]. In addition to electricity and thermal energy, the plant will emit other waste streams that can potentially be utilized and converted into value streams. These value streams are, CO_2 that can be captured from the station's emissions, ash that falls as unburned material from the furnace. There is also a considerable amount of scrap iron that accumulates in the ash, this scrap iron needs to be separated from the ash. Scrap iron removed from the ash can then be used for recycling. The feasibility study, identified five possible site selections for the WtE plant in the south-west corner of Iceland. These five locations were, Álfsnes, Straumsvík, Helguvík, Þorlákshöfn and Grundartangi. The sites were evaluated based on the transportation efficiency of combustible waste to the plant. In this thesis, the aim is to compare the same site selections based on their potential for utilization of value streams from the WtE plant.

Waste treatment such as this could be a powerful way to divert waste from landfills and meet the growing demand for energy in the country. In this context, there has been an increased interest on the part of the government to engage in energy changes in transport and fisheries. The intention is to make the country largely independent in energy production and to phase out fossil fuels in order to reduce greenhouse gas emissions, in accordance with set climate goals. Increased population growth and actions towards energy changes will further increase the demand for energy in the country. It may therefore be interesting to examine how energy production of this kind fits into the Icelandic energy market, which is already powered by 100 % renewable energy sources.

1.1 Research question

This thesis aims to answer the question: Which one of these five locations, Álfsnes, Straumsvík, Helguvík, Þorlákshöfn and Grundartangi, provides the best site selection based on utilization of energy and other value streams from a WtE plant.

1.2 Objectives

To answer the research question, six objectives are presented.

The first objective is to evaluate and make a pair-wise comparison of the site selections based on potential thermal demand in the nearby district heating systems.

The second objective is to evaluate and make a pair-wise comparison of the site selections based on available connections to the national electricity grid.

The third objective is to evaluate and make a pair-wise comparison of the site selections based on the potential for ash utilization.

The forth objective is to evaluate and make a pair-wise comparison of the site selections based on the potential utilization of CO_2 captured from the WtE plant's emission.

The fifth objective is to evaluate and make a pair-wise comparison of the site selections based on access to a port area for the export of scrap metal from the WtE plant.

The sixth objective is to produce a final rating of the five site selections based on the utilization of energy and other value streams from the WtE plant.

2 Background:

Iceland is a large island in the North Atlantic with up to 103.000 square kilometres of land area, making the country the eighteenth largest island in the world. The island is located just south of the Arctic Circle at the junction of two continents that divide the country in two, with the western part of Iceland lying on the North American plate and the eastern part on the European plate. This special location of the country offers a unique potential for energy utilization. Due to Iceland's location in the northern hemisphere, the country is largely covered by glaciers creating the potential for approx. 64 TWh of hydropower [25]. According to the Icelandic Energy Agency, the annual electricity production from hydropower in Iceland was 13,157 TWh in 2020. The location of the country on the Atlantic ridge offers the country enormous possibilities for the utilization of geothermal energy. It is estimated that accessible geothermal energy for power generation in Iceland is approx. 61 TWh [26]. The electric production capacity of the Icelandic geothermal power plants to utilize these 61 TWh was only 6.7 TWh/a in 2020. Thanks to these great energy resources, the country's electricity production comes from 100% renewable energy and is divided into 70% production from hydropower and 30% production from geothermal energy.

Although Iceland is a rather large island on a world scale, the Icelandic nation is rather small on the same scale. According to Statistics Iceland, the nation's population counted no more than 376.248 people 1. January in 2022 [27]. So when looking at the population in terms of land size it is approx. 3,5 person per square kilometer. In this context, the United Kingdom is only 2,4 × larger than Iceland, making it the largest island in Europe with a population density of 281 people per square kilometre [28].

Iceland being a small population on a big island with plenty of renewable energy sources to go around has certainly helped the country to develop in the last century and latest decades. As an indication of Iceland's success, it was ranked as the most developed country in the world by the UN human development index in 2007[29] and is currently ranked as the fourth most developed country in the world [30]. As a developed country, Iceland is a member of the Organization for Economic Co-operation and Development (OECD) along with the most developed countries in the world. When Iceland's success in development is evaluated by various indicators, it is often compared with other OECD countries. One of the main indicators for development is a country's gross domestic product (GDP), which can be used to assess countries prosperity. But GDP itself does not really give a true picture of a country's prosperity. To get a true picture of a country's prosperity, one needs to look at GDP per capita. Being the smallest of the OECD countries and with relatively high income, Iceland usually scores quite high in GDP per capita and has been above the OECD average ever since the 1970s.

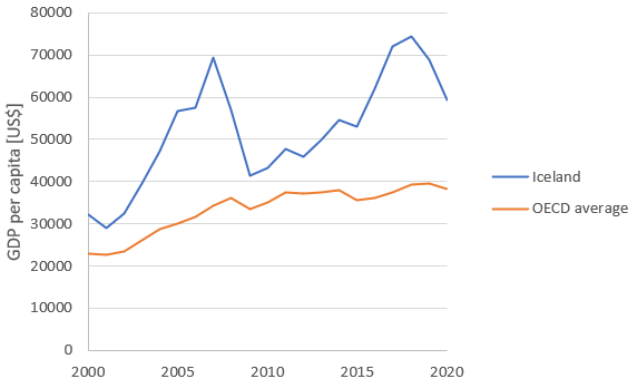


Figure 3: Gross domestic product in Iceland compared to OECD average from 2000-2020[4]

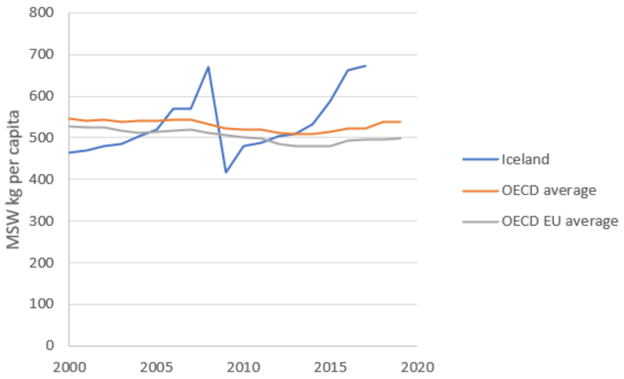


Figure 4: MSW generation in Iceland and OECD countries from 2000-2020[2]

But being a small and rich country also has its downside, as can be seen in figure 3 and 36, MSW generation follows a similar trend as the GDP curve. This indicates a strong correlation between GDP and MSW generation. It has been known for a long time that waste generation is linked to urbanization, economic development and population growth. As a result, many OECD countries have the highest per capita waste generation in the world. Iceland is no exception when it comes to waste generation and has been above and around the OECD average in waste generation per capita since early 2000. Iceland was ranked in fifth place within the OECD in the generation of municipal waste in 2018[2].

In parallel with this high waste generation, Icelandic waste management has undergone major changes in recent decades and has improved considerably since the last century. For most part of the last century waste management had not been very extensive and was mainly carried out with uncontrolled open pit burning. This method obviously had some environmental issues as it had no pollution control and waste could blow away easily. In the 1990s, municipalities started to recognize the disadvantage of having such widespread uncontrolled incineration throughout the country. In response, concrete fire pits were built to prevent waste from blowing away.

At the same time, incineration decreased and landfilling began to increase. In 1995, Iceland joined the EEA and since then Icelandic government has regularly implemented EU directives in recent decades through legislation and regulations, which call for stricter requirements in waste management. In 2000, landfilling had become the main waste treatment in the country and open pit burning was phased out as it could no longer be considered a valid waste treatment. Instead, several small incinerators had been built, some of which were designed with energy recovery equipment. Since 1993, eight waste incinerators have been constructed in Iceland, either with or without energy recovery (ER). This was the beginning of development towards more controlled waste management. In 2003, new legislation (Law no. 55/2003) on waste management came into force. The aim of the legislation was to integrate the Icelandic waste management system with the waste hierarchy's priorities and transposes EU waste targets into Icelandic law. The system was to promote less waste generation through prevention, reuse recycling, recovery and reducing waste sent to landfill. Based on law no. 55/2003 three regulations were issued to implement the EU landfill directive (1999/31/EC) and the incineration directive (2000/76/EC). These regulations were: regulation no. 737/2003 on waste treatment, regulation no. 738/2003 on the landfill of waste and regulation no. 739/2003 on waste incineration[31]. The regulation on waste treatment makes municipalities responsible for the collection, handling and treatment of municipal waste. Regulation on landfill waste was issued to implement the landfill directive. The regulation provided a ban on the landfill of certain waste categories: liquid waste, hazardous waste, contagious and radioactive medical waste, and scrap metal including end-of-life vehicles and tiers. Regulation no. 739/2003 on waste incineration was issued to implement the incineration directive. The regulation entailed stricter operation requirements. These requirements included continuous measurements of certain pollutants in emissions and measurements of dioxin levels every six months. Dioxin refers to a group of chemical compounds also known as persistent organic pollutants (POPs) meaning that they take a long time to break down in the environment. Dioxins are highly toxic and can cause cancer, reproductive and development problems, damage to the immune system and they can interfere with hormones. Dioxin forms in incomplete combustion of organic substances at 200-800 ° C in the presence of chlorine substances. These substances can form in various industrial processes, as well as in waste incinerators that are not operated at a sufficiently high temperature.

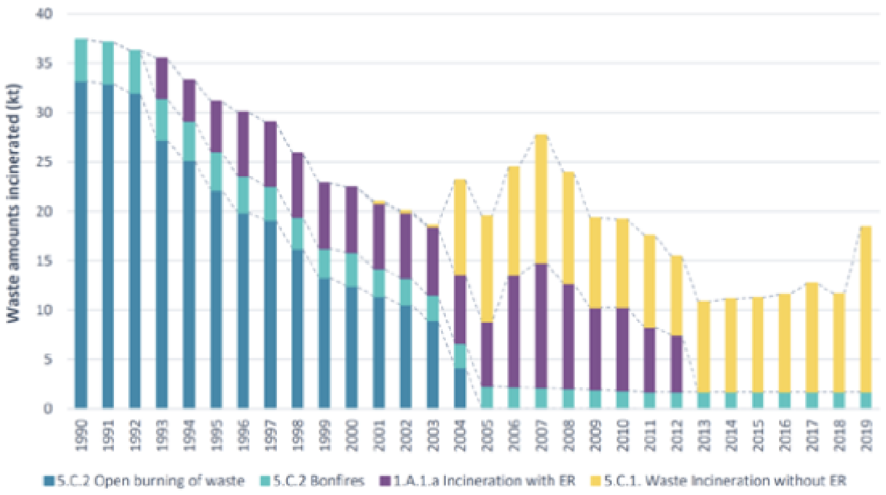


Figure 5: Waste incineration in Iceland from 1990 to 2019 [5]

Seven of the eight incinerators in Iceland could not maintain a sufficiently high temperature to discard of POPs. Only one of these incineration plants was equipped with sufficient equipment to meet the requirements of the regulation, and that was the waste facility Kalka which is located in the municipality of Reykjanesbær in the southwest corner of Iceland. Unlike the other incinerators, Kalka operates a pyrolysis process which does not form these substances at as high rates. The seven incinerators that could not comply with the directive goals, requested an exemption from the regulation in order to continue operating on the grounds that they were so small and therefore would not generate too much pollution. These incinerators were granted an exemption, provided that they complied with regulations from previous directives and that at least one dioxin test would be carried out by 2008. Only four of these seven incinerators were still operating in 2008. When dioxin measurements were carried out in 2007 and 2011, they showed that dioxin was measured far above the desired level. This indicated that the incineration plants could not in any way be operated under the established regulation. One by one the incineration plants ceased operations and the last plant was closed in 2011. Kalka is therefore the only thermal treatment plant still in operation in Iceland today, with a processing capacity of 12.300 tons per year. Kalka contributes most of the yellow bar in figure 5. Bonfires, which are shown in grey in figure 5, can mostly be traced to the Icelandic tradition to hold large bonfires at the end of Christmas every year to celebrate the end of Christmas and the new year. These bonfires are mostly made from waste wood such as construction waste, wooden pallets and Christmas trees. As can be seen in figure 5, waste incineration has declined in recent decades. It had dropped down to 12600 tonnes in 2014 and amounted to 2% of total waste treatment [32]. In 2019, Kalka received 10550 tonnes of waste for incineration. At the same time, the total waste generation in Iceland amounted to 1114 thousand tonnes, of which 218605 tons went to landfill. The ratio of landfilled waste has therefore decreased from 80% in 1995 to 20% in 2019. This reduction in landfill can be attributed to a stricter requirement for what waste can be landfilled according to the landfill regulation that came into force in 2003. In 2021, new EU directives were implemented with new legislation, when Act No 103/2021 came into force. It can be expected that landfilling will continue to decrease in the coming years with a ban on landfilled sorted waste and organic waste. These bans will also increase the need for infrastructure development in both the processing of organic waste and sorted non-recyclable waste. In 2019, landfilling of organic household waste in the country amounted to 83000 tonnes. In that context, there is only one composting plant in the country which started operations in 2020. This station can receive about 40 thousand tons/year of organic waste and would therefore only be able to process about half of the generation of organic household waste generated in the country today. This development in decreasing landfill will also create a need for new ways to treat non-recyclable waste as well as recyclable waste that cannot be recycled for various reasons.

2.1 Incineration plants in Europe

Along with the increase in population growth within the European Union, waste generation is increasing. Nevertheless, despite this increase in waste generation, municipal waste sent to landfill has decreased at the same time, see Figure 6. In 1995, landfilling of municipal waste within the EU amounted to 121 million tonnes, equivalent to 286 kg per capita. From 1995 to 2018, the amount of municipal waste sent to landfills ín EU has decreased by 57

%, which is equivalent to 69 million tonnes, corresponding to an average annual decline of 3.5%. As a result, only 52 million tonnes of municipal waste were landfilled with in EU in 2018, or 117 kg per capita. The data show that the share of landfill waste of waste generated in the EU decreased from 61 % in 1995 to 24 % in 2018[6]. This development in waste management can be attributed to the long-term goal of the EU transiting from a linear economy into a circular economy based on the prioritization of the waste hierarchy. This transition aims to divert waste from landfills by waste prevention, reuse, recycling and recovery. This has been done through a number of EU directives, most notably the WFD (Directive 2018/851 and the European Parliament and the Council on amending Directive 2008/98 / EC on waste) and the Landfill Directive (Directive 2018/850 of the European Parliament and of the Council amending Directive 1999/31/EC on the landfill of waste) which aims to prevent or reduce the harmful effects of landfills on the environment. In accordance with the EU Landfill Directive, member states are required to reduce the amount of municipal waste sent to landfill to 10% or less of the total amount of municipal waste produced by 2035.

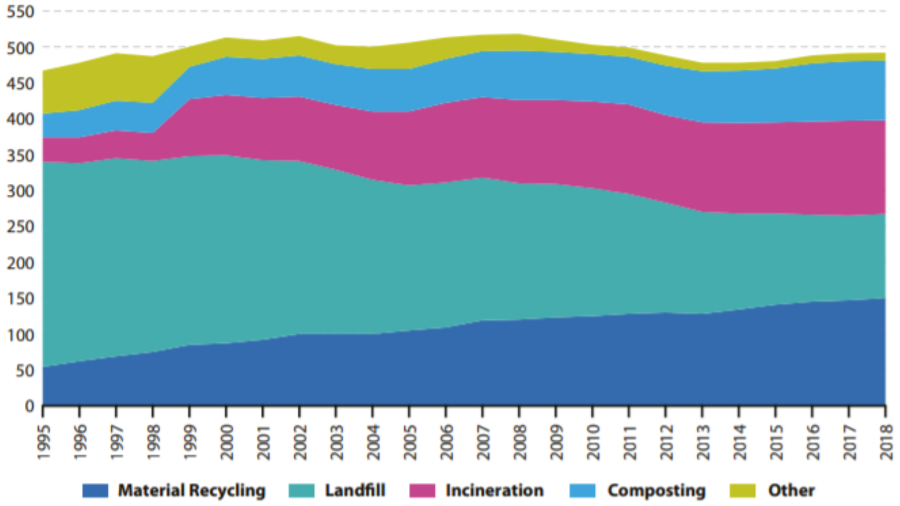


Figure 6: Municipal waste treatment by sector in kg of waste per capita in EU-27 from 1995-2018[6]

The EU's goal of diverting waste from landfills has forced member states to implement new technologies to treat waste in a more environmentally friendly way than landfills, such as, composting, material recovery and energy recovery. Unlike Iceland, development in waste management in the EU has led to increased incineration capacity within Europe. This increase in waste incineration can be attributed to the development of the WtE technology. Unlike the small waste incinerator operated in Iceland in the past decades, modern WtE plants are equipped with much more advanced flue gas treatment for pollution control, they are also designed to operate 24 hours a day all year round with 2-3 week maintenance stop each year. Development has also led to better designs in regard to higher energy efficiency, making WtE more economically attractive.

Figure 7: Copenhill WtE plant at Amager bakke in Copenhagen [7]

A good example of high energy efficiency is in the newly built Copenhill WtE plant on Amager Bakke in Copenhagen. The Copenhill plant started operation in 2017 and is one of the most advanced WtE plant in the world with a net thermal efficiency of 107%. This high efficiency is due to the plant's design to utilize waste heat from flue gas condensation. Apart from high efficiency, the plant is also quite large and has a permit to treat at maximum of 560 thousand tonnes per year, although in 2020 the plant treated 599 thousand tonnes. The plant is owned by five municipalities in Copenhagen and receives waste from 645 thousand citizens and 68 thousand businesses located in the 5 owner municipalities. The waste is composed of approximately 23% residual waste generated by households, and the rest is commercial and industrial waste. The plant's capacity is actually higher than the demand for waste treatment. Therefore the plant imports about 10% of the waste or receives waste from other municipalities over the winter time when there is a higher demand for energy. The Copenhill plant is designed with two incineration lines with two grate-fired boilers, 112 MW each for combined heat and power (CHP) production. In 2020 the plant generated 1.363 GWh of heat supplied to 90 thousand apartments and 244 GWh of electricity for 80 thousand households [33]. Despite its high efficiency and perfect equipment, the Copenhill plant is even better known for its strange architecture (see figure7). The plant is designed with a ski slope on the roof which is accessible to people for skiing all year round. It also has a tree-lined hiking and running trail all the way to the top where one can enjoy the view from the viewing platform.

The Copenhill plant is not the only WtE plant in Europe, in fact, there were 492 WtE plants operating in

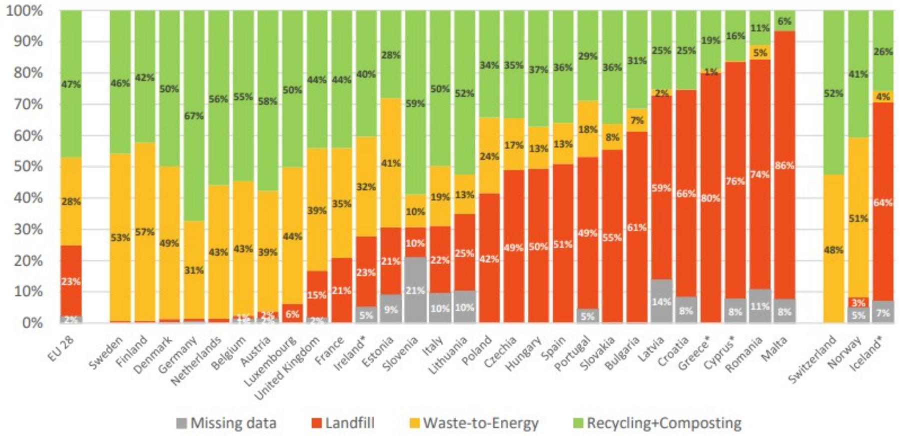


Figure 8: Waste treatment in Europe in 2020[8]

Europe in 2017 treating 96 million tonnes of waste. In 2018, the ratio of waste sent to landfill is down to 23% in EU28 countries. It is notable that the countries that have made the most progress in achieving the goal of reducing landfills are also the countries that have built up the most waste incineration capacity (see figure 8). This suggests that waste incineration is at least an effective way to reduce landfill. Still, 12 of the EU28 countries landfill around 50% or more of their waste. WtE has many advantages and environmental benefits such as diverting waste from landfill, substituting for fossil fuels in energy production, providing baseload power for the generation of electricity and supplying thermal energy for district heating. The energy content of waste treated in Europe today could substitute 10-54 million tonnes of fossil fuels on annual bases which would emit 24 - 49 million tonnes of CO_2 [34]. Using WtE can also be an effective way for countries to divert waste from landfill in order to meet the requirements of the Landfill Directive to reduce landfill waste below 10 % of total waste. Diverting waste from landfill is also known to have environmental benefits, as landfills release large amounts of methane gas. This is mainly due to the decomposition of organic waste in landfills and it is well known that methane gas has 28× more Global Warming Potential (GWP) than CO_2. Unlike landfills, the WtE plants built today burn gases such as methane and emit almost exclusively CO_2 gas and H_2O in the form of water vapour in its emissions. Incineration also produces a significant amount of ash, composed of inert, non-combustible material left over from the combustion process. The ash can also contain some amount of scrap metal like metal hardware, aluminium cans or copper from electrical cable material and so on. This metal can be recovered from the ash and recycled. In 2018, 19 million tonnes of bottom ash was recovered from the 96 million tonnes incinerated or approximately 20% of the recovered ash is metal. Recycling metal saves 2000 kg of CO_2 eq. per tonne of metal recycled and about 3,8 million tonnes were saved by recycling metal from waste incineration in the EU in 2018[8]. It is interesting to see from figure 8 that the countries with the highest incineration capacity also have higher recycling and composting ratio. This could indicate that WtE encourages recycling in parallel with recovery. Although WtE technology has shown good results in metal recovery and CO_2 savings from waste, the environmental benefits of the method are by no means indisputable. On the contrary, WtE technology has been heavily criticized within the EU, mainly due to CO $_2$ emissions. One of the most vocalists against WtE technology in the EU is the organization Zero Waste Europe (ZWE), which is an organization created in 2014. ZWE was founded as the European regional branch of the Global Alliance for Incinerator Alternatives (GAIA), which is a worldwide alliance of organizations that promote a zero-waste ideology. Broadly speaking, the ideology is about strengthening actions at the top of the waste hierarchy and avoiding the generation of waste altogether. Their goal is to pave the way for a completely closed-loop economy where all materials and products are ultimately reconverted through reused or recycling. Furthermore the organization's campaign against all WtE incineration and development in energy recovery from waste. ZWE states that WtE incineration undermines the efforts of the EU to transition towards a circular and net-zero emissions economy, as incineration destroys vast amounts of resources, increases exploitation of raw material and in that way perpetuates a linear economy. In its campaign, ZWE has actively raised awareness of the negative climate and environmental impact of waste incineration and repelled the advantages of incinerating waste as a substitute for fossil fuels in energy production. ZWE points out that power production in WtE plants is in fact more carbon intensive than producing power from fossil fuels [35].

Because power production with fossil fuels has a higher energy efficiency than power production from MSW in WtE facility. This would undermine the EU's goal to a net-zero emission economy. In this context, there has been some development in carbon capture and storage (CCS) technology from WtE incineration plants in recent years. CCS from waste incineration would make a big difference in WtE technology, such technology could eliminate almost all greenhouse gas emissions from the process. Several WtE plants in the EU have already started to develop techniques for carbon capture from their emissions. The Fortum Oslo Varme WtE facility in Klemetstrud, Norway shown on figure 9 is the most advanced WtE plant in the development of CCS from waste incineration and aims to be the first WtE plant worldwide with a full-scale carbon capture technology. In 2019 a carbon capture pilot was conducted on real flue gas at the Klemetstrud WtE facility. The pilot demonstrated a possibility to capture more than 90% of all CO_2 in the flue gas. WtE facility with such carbon capture technology combined with approved pollution control equipment would therefore almost exclusively emit H_2O in the form of water vapour. Another WtE facility the Twence WtE plant in Hengelo in the Netherlands has also started a carbon capture project. The Twence plant has been operating since 1986 and processes over 830000 tonnes of waste annually, generating 405000 MWh of electricity and 1,5 million GJ of thermal energy for district heating. Unlike the Klemetstrud plant in Norway, the Twence facility only captures about 100 thousand tonnes (12%) of CO_2 per year and intends to sell liquefied captured CO_2 for use in horticulture and industrial processes. The advantage of using CO_2 from WtE in greenhouses to grow vegetables is that it both returns carbon into the natural carbon cycle and it substitutes for the burning of fossil fuels to generate CO_2 for greenhouses. The Copenhill plant has also started a pilot project for the capture of CO_2 from the plant's flue gas. It is estimated that the demonstration plant will be able to capture 12 tonnes of CO_2 per day in 2022. It has been decided to scale up this carbon capture in the coming years and estimates suggest that carbon capture from the plant could amount to a total of 500 thousand tonnes per year if successful. These development projects show promising results for carbon capture from emissions and could make these WtE plants carbon-neutral in the coming years.

Despite this promising development in CCS from WtE incineration, ZWE refutes litigation on benefits from coupling CCS technology with WtE plants and points out several flaws regarding CCS. One of the flaws ZWE points out is that development in CCS from WtE can slow down the development of renewable energy infrastructure. ZWE also states that CCS is a distraction from resource efficiency and undermines the transition to a circular economy. Furthermore, ZWE state that CCS could accelerate the build-up in incineration capacity in Europe and in that way increase the risk of a so-called lock-in effect of incinerators [36]. The term lock-in effect is used to describe over capacity of waste incinerators leading to a decline in recycling rates, as incinerators are forced to burn recyclable waste to keep in operation. The Confederation of European Waste-to-Energy Plants (CEWEP) disagrees with this dispute and states that these assumptions are not based on real-life evidence. On the contrary, recycling rates are actually higher in countries with higher incineration capacity (see figure 8). Even if overcapacity does not cause lower recycling rates there is still a risk in building a high WtE capacity. When recycling rates in countries with high incineration capacities increase, it forces countries to import waste rather than burn recyclables. Around 70 million tonnes of waste is shipped between EU countries yearly. Importing waste for incineration can be rather unreliable, as countries that export waste may also be looking for ways to treat their own waste through recycling and WtE rather than exporting the waste to other countries. As can be seen in figure 8, the incineration capacity is somewhat unequal between countries within Europe. CEWEP has estimated

Figure 9: Fortum Oslo Varme WtE plant in Klemetstrud [7]

Figure 10: Twence WtE facility in Hengelo, Netherlands [9]

that incineration capacity will need to increase from a capacity of 90 million tonnes in 2017 to 142 million tonnes in 2035 [37]. Judging from the evolution of WtE in the EU and promising results in recent development in capturing CO_2 from flue gas, WtE might seem like an optimal option to improve the waste management system in Iceland. However, there are differing views on the role of WtE in the circular economy that need to be taken into account and then there is also the risk of installing overcapacity. There are many things to consider when deciding on the design and construction of WtE plants in Iceland. One of the most important things to do before designing such a plant is to make a thorough assessment of the quality and quantity of the waste that is to be treated in such a plant.

3 Resource

Waste can be vary heterogeneous resource, according to the EU WFD, waste means any substance or object which the holder discards or intends or is required to discard. In 2019, waste generation in Iceland amounted to 1100 thousand tonnes. The total amount of waste is divided into 237 thousand tonnes (22%) of household waste, 327 thousand tons (30%) of industrial and operational waste and 550 thousand tons (50%) from construction. However, it is necessary to understand that 382.138 tons or about 70 % of these 550 thousand tons of construction waste are gravel and soil from construction excavations that can be reused in landscaping. As this is a significant part of the construction waste and the total waste, it is necessary to keep in mind that this could for example distort the image of the treatment of recyclables in construction waste. The generation of household waste in Iceland was 664 kg per capita in 2019, compared to 502 kg per capita in the EU at the same time. This ranked Iceland in fifth place in the generation of household waste per capita in Europe [32]. A detailed analysis of the amount and composition of the waste is necessary to assess the size of the plant and determine which technical solutions are best fitted for the WtE plant to treat the waste. But before such an assessment can be made, the waste must first be collected.

3.1 Waste collection

Sorting and collecting waste is one of the critical steps in a circular economy. The waste collection scheme acts as an interface between the waste producer and the general waste management system. Quality of waste depends a lot on the composition of the waste and the composition of waste varies depending on the source. The quantity and generation of waste also varies according to origin. It is necessary to be aware of the different origins of waste in the area collected for incineration to better understand fluctuations in the quality and quantity of the waste collected. **Residential or Domestic waste** is waste collected from households, this can of course be everything existing in and produced by normal household activities. To name some common objects this could be, food waste, food packaging, packaging, electrical equipment like computers and televisions, and bulky waste like washing machines, furniture, and mattresses. The composition of household waste may vary between higher-income and lower-income households.**Commercial waste** is waste from commercial establishments such as shops, restaurants, hotels, offices and similar operations. This waste can be similar in composition to domestic waste but should be more uniform as it is usually collected in bigger containers and each of these operations in most cases handle fever product categories than households in general. This is for example expired or defective food products or other products, in or without packages, from supermarkets or guarantors. **Institutional waste** is waste collected from all kinds of institutions like schools, hospitals, clinics, government offices and so on. This waste can be composed of food waste from canteens and cafeterias. This could be health care, biological and chemical waste from hospitals, clinics and laboratories. Institutional waste could also be office waste and waste similar to other commercial waste. **Industrial waste (IW)** is waste from all kinds of industries such as machine shops and manufacturing companies. This could be composed of production residues like metal-, paper- or plastic clippings, some sort of industrial sludge or some other raw material leftovers. This type of waste is often relatively clean and should be recycled rather than incinerated. **Construction and Demolition (C&D) waste** This source is composed of all kinds of building material, both a construction material and packaging and old building materials from demolition, maintenance and reconstruction in the construction industry. This category also contains grinds from excavations from houses foundations, which is a massive proportion of the waste generated in Iceland and should be borne in mind when looking at waste figures. **Waste from food production**, like agricultural waste collected from farms, such as plastic packaging from hey bailing or waste from aquaculture, horticulture, forestry, bakeries, fishing like fishing gear from ships, pre-consumer organic waste from slaughterhouses and fish processing and bakeries and so on. **Vehicle waste** is waste from damaged and discarded vehicles that end up in scrap yards. Most of this waste is recyclable metallic waste, both ferrous and non-ferrous metals, windscreens and tires. This waste is also composed of tread from cars which is a combination of lining, car interiors and seats.

Different origins of waste calls for different waste collection systems both in terms of volume and frequency of waste disposal and characteristics of waste. To connect the waste management system to the circular economy, waste streams need to be separated according to in which step of the waste hierarchy the waste is to be treated i.e. whether it is sent for recycling, biological treatment, composting, thermal treatment or disposal in a landfill. Furthermore, the collection scheme may need to consider the collection of different types of recycling material, because recycling materials need to be separated according to the recycling process they are subjected to. When it comes to the collection of recycling materials, it is first and foremost important to separate them from organic waste (food waste) at the source. Because when organic waste comes in contact with the recycling material it pollutes the recycling materials and reduces their quality for recycling. Then the recyclables can either be collected in separate categories in a separate collection or collected all together in a single stream. When recyclables are collected in a single stream they need to be separated in a Material Recovery Facility (MRF). In a MRF the recyclables are separated manually and mechanically into different recycling streams. How extensive sorting takes place in MRF varies between facilities. Generally speaking, the more thoroughly the waste is separated, the more valuable the recyclable material will be. But at the same time, more advanced separation is more expensive for the waste management system. It should therefore be more beneficial to maintain a separate collection scheme and sort waste closer to the source so that consumers can sort their waste as thoroughly as possible as soon they dispose of the waste. This keeps the waste streams separate at the source and requires less expensive pre-treatment of the waste for recycling.

In the current policy of the Icelandic government, the administrative role of municipalities in waste management is divided in two: household waste and operational waste. According to EU Landfill Directive, municipal solid waste is defined as 'waste from households, as well as other waste which, because of its nature or composition, is similar to waste from households, household waste mostly originated from domestic, commercial and institutional waste. Operational waste includes waste from food production and C&D waste, Vehicle waste industrial waste and waste from heavy industries such as aluminium smelters. The collection of household waste usually takes place in a door-to-door collection, where waste is collected in a waste container outside of institutions, businesses or the residents' houses. Municipalities are obliged to ensure that the waste collection of household waste is carried out on their site. The municipality does, however, have the choice to outsource waste collection to a private party, but the responsibility always lies with the municipality. The collection of operational waste, on the other hand, is the responsibility of the operator that disposes of the waste. The municipality is, however, responsible for ensuring that collection points for operational waste are available to the inhabitants of the municipality. According to Act 103/2021, on the first of January 2023 municipalities will be required to carry out separate collections of at least the following categories of waste: paper, cardboard, plastic, textiles, organic waste, glass, metals and hazardous waste. Furthermore, the collection of paper, cardboard, plastic and organic waste should be collected in a door-to-door collection within the site of a household, institution or business[38].

3.2 Sorting and selection

The heterogeneous nature of waste means that sorting and selection of waste is vital to direct the waste into the most convenient waste treatment. After the waste has been collected in a separate collection in a curbside collection and at collection points, the waste is transported to collection centres or MRFs where the waste can be treated for further transportation or export to recycling or recovery facilities. In these collection stations or MRF, the waste can be shredded and pressed to reduce transportation costs. Some further segregation of the waste streams may also be carried out at this point to increase the quality of certain waste streams. According to the waste hierarchy, energy recovery from waste is less desirable option than recycling. Recyclable material should therefore be diverted from incineration as much as possible. Residual waste from collection stations and MRF that is not considered suitable for recycling can then instead be separated and sent to recovery or landfill. In order to have a good overview of the size of these different waste streams, it is important to record their quantities systematically. According to Regulation 2150/2002/EC on waste statistics, EU and EEA member states are required to report statistical data on waste generation and waste treatment to Eurostat. Data transmitted to Eurostat must be recorded according to the EU statistical waste nomenclature EWC-Stat. Member States then have a free choice as to how to categorise waste as long as statistical data is submitted in accordance with EWC-stat. Waste classification in EWC-Stat is mainly based on substance-oriented categories defined in the European List of Wastes (LoW). As a result, many countries also use the LoW classification to simplify their data reports to Eurostat. EWC-Stat classifies waste into 33 categories, which then are further classified into hazardous and non-hazardous waste. Since LoW is a substance-based classification, it is easy to define which categories are suitable for incineration and which are not based on their material characteristics. Residual waste meant for incineration in a WtE facility must be meet certain requirements, first of the waste must be combustible in order to extract energy from the waste. Secondly, the waste should be non-recyclable according to the prioritisation of the waste hierarchy. Thirdly the waste should be non-hazardous, because hazardous waste could cause corrosion problems and damage equipment, resulting in higher maintenance costs. Hazardous waste can also contaminate the ash produced in the incineration process and in that way spoiled possible usage of the ash. The waste should also be in a solid state or at least low in moisture, for higher energy recovery potential. On that basis waste selected for incineration in a WtE facility should ideally be combustible, non-recyclable, non-hazardous, solid waste.

3.3 Waste characteristic

When assessing the suitability of waste for incineration in the WtE facility, it can be considered from two perspectives. One way is to look at the potential damage to equipment or the environment from the combustion of materials. Waste containing inorganic salts, high levels of sulfur or halogen and other hazardous waste is known to have a detrimental effect on equipment in WtE plants. Inorganic salts that dissolve during combustion, accumulate on the inside walls of the furnace and thus reduce the efficiency of the plant. High sulfur or halogen content of waste has severe corrosive effects on equipment and increases maintenance costs. Other hazardous waste can have a negative effect on equipment and ash is a possible value stream. Hazardous waste can also have a toxic or negative effect on the surrounding environment and employees of the facility and should be treated in a special facility. Another perspective is to look at the energy content and combustibility of the waste.

3.3.1 Combustible waste

When considering the use of combustible material for energy recovery, it is important to consider the ability of that material to maintain its own combustion. If the combustibility of the material is too low, the combustion must be maintained with auxiliary fuels. The self-sustained combustibility of material is often assessed through proximate analysis of the waste material. The proximate analysis divides material down to three fractions based on the moisture, ash, and combustible content of the material. These fractions are measured according to international standards. The moisture fraction is simply the water content (W) of the matter and can by determined using equation 1.

$$Moisture\ content\ (W\%) = \frac{wetweight - dryweight}{wet\ weight} \times 100\% \tag{1}$$

Wet weight is the initial weight of the sample, dry weight is the weight of the sample after it has been dried sufficiently to remove all moisture from the sample. The energy that goes into the evaporation of moisture from waste is not recovered from the incineration process. Assessing the moisture content of waste is therefore essential for estimations of the energy potential of waste. Material with high moisture content is less suitable for incineration in a WtE facility. A combustible fraction of waste is the organic part of the material and can be divided into volatile matter (VM) and fixed carbon (FC). Volatile matter is the portion of the waste that converts to gas before and during the incineration process. The volatile fraction of material can be found by measuring the dry-weight difference of a material before and after the volatilization of the material.

$$Volatile\ matter\ (VM\%) = \frac{dry\ weight - weight\ after\ volatilization}{wet\ weight} \times 100\% \tag{2}$$

Most of the energy obtained from the incineration process is released from oxidation of volatile gases in the furnace, which means that a higher ratio of volatile matter in the waste results in higher energy efficiency. Fixed carbon is the solid combustible residue that remains after the volatilisation of the waste material. The fraction of fixed carbon can be measured as the weight difference of material after volatilization and ash after complete combustion.

$$\textit{Fixed carbon (FC\%)} = \frac{\textit{weight after volatilization} - \textit{ash weight}}{\textit{wet weight}} \times 100\% \tag{3}$$

The fixed carbon does not burn as easily as the volatiles and converts to char in the combustion chamber and requires more time to burn up in a complete combustion. Therefore waste with a higher ratio of fixed carbon may require longer residence time in the combustion chamber to achieve acceptable combustion of the waste. The ash content (A) of the material is the remaining non-combustible residues which are left after all moisture, volatile matter and fixed carbon have been burned away.

$$\textit{Ash content (A\%)} = \frac{\textit{wet weigth} - W - VM - FC}{\textit{wet weight}} \times 100\% \tag{4}$$

Assessing the ash content is essential for the estimation of the energy potential of waste, as the non-combustible material only adds to the weight of the waste and does not contribute to energy recovery from the waste incinerated. The ash content can also be used to assess the amount of ash produced in the process. Results from the proximate analysis can also be used to define criteria for the self-sustained combustibility of material. In order for a material to have self-sustained combustibility, the combustible fraction must be at least 25% of the material, the moisture content of the material must not exceed 50% and the ash fraction must not exceed 60%. The common way of displaying these criteria is through the Tanner diagram shown on figure 11. The Tanner diagram is a triangle where each fraction is an axis on the sides of the triangle. The grey area within the diagram is limited by the aforementioned criteria for the combustibility of material, so the material that falls within the grey area is considered to have self-sustained combustibility, without extra fuel.

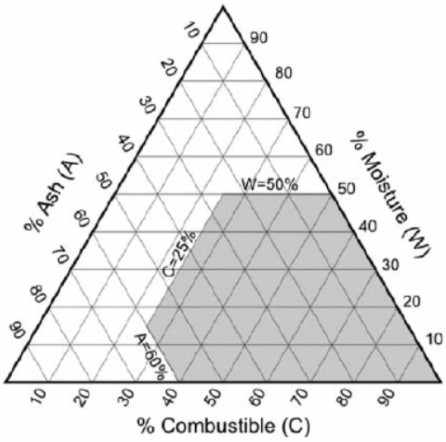


Figure 11: Tanner diagram for assessment of combustibility of MSW[10]

Another necessary measure of the quality of the waste stream is the calorific value. The calorific value can then be used to assess the combustibility and energy content of waste. Calorific value is usually divided into two heat values, higher heat value (HHV) and lower heat value (LHV). The difference between HHV and LHV is that

HHV includes the energy needed to evaporate moisture content from the material once incinerated. HHV can be calculated by using measurements from a calorimeter. Experimental measurements of energy content is usually done with a bomb calorimeter also known as a constant volume calorimeter. In a constant volume calorimeter, a sample of a material is burned in excess of oxygen at a constant volume. This is done to ensure that the sample burns in complete combustion where the material is completely oxidized into its most stable oxides. The calorimeter detects the energy released from the combustion, but since the combustion takes place at a fixed volume, the moisture formed by the combustion condenses back into liquid. Therefore the bomb calorimeter also detects the latent heat of vaporization of the moisture content within the sample. The calorimeter therefore measures the total energy of the sample which is used to obtain the HHV also known as the gross calorific value. As opposed to the HHV the LHV is the energy released from the combustion excluding the latent heat of vaporization of the moisture content of the combusted material. The LHV can be obtained from proximate analysis by subtracting the moisture content times the latent heat of vaporisation from the HHV as shown in equation 5, h_{vapour} is the latent heat of vaporization of water and W% is the moisture content obtained from the proximate analysis shown in equation1.

$$LHV = HHV - h_{vapour} \cdot W\% \tag{5}$$

The calorific value can be used to assess the combustibility of waste, When assessing the energy content of waste for energy recovery from waste, LHV is more relevant than HHV as the moisture content does not contribute to the energy recovery. LHV is a critical parameter in both the design and operation of a WtE plant. The LHV value of different waste materials is used to calculate the total average LHV of the waste stream and is therefore a vital parameter in calculations of the energy balance of a WtE plant. Because WtE plants are designed to maintain a certain temperature value in and above the combustion chamber in the plant furnace during operations, the LHV is also essential in determining the size of the combustion chamber in the plant's furnace. Heating values have been measured for most if not all raw materials and consumables produced in the world. The LHV of certain material streams can therefore be obtained by simply multiplying the quantity of material by its previously known LHV. The overall LHV of the waste stream can then be obtained by simply taking the average LHV of each individual material stream of the total waste stream. This underlines the need to carefully determine the composition of the combustible waste stream intended for incineration in WtE. According to the waste hierarchy, WtE is considered an inferior alternative to recycling. The size of the combustible waste stream therefore depends a lot on the set recycling goals or rather how well those goals are achieved. Consequently, when trying to anticipate the need for combustion capacity, it is quite important to be well aware of the difference between non-recyclable vs recyclable materials and moreover, what determines their ability to be recycled.

3.3.2 Recyclable vs Non-recyclable waste

Recycling is a process of converting waste into valuable resources for new products. Iceland has set timed and numerical targets for reuse, recycling and landfilling. Most of these targets originate from the EU and are therefore similar in other European countries. Targets have been set for the recycling of the categories collected in separate collections, and there are also special targets for recycling packaging waste. According to the European Packaging and Packaging Waste Directive (PPWD) 94/62 / EC, member states are required to recycle 65 % by weight of all packaging waste by December 21, 2025. Packaging waste is rather homogeneous where a single packaging is usually made from a single material, whereas e-waste is heterogeneous and composed of many different materials like different plastics, metal and glass fibres. Heterogeneous waste requires more extensive pre-treatment than waste from a single material. Packaging waste however can be less desirable for recycling due to contamination like food packaging for instance is often contaminated with leftover food products. It could therefore also be helpful to distinguish between pre-consumer waste and post-consumer waste. Waste collected from a door-to-door collection is typical post-consumer waste like food packaging, whereas pre-consumer waste is rather originated from commercial or industrial operations like clippings or defective products from production. Municipalities are required to conduct a separate door-to-door collection of, paper, plastic, glass, metal and organic waste. These homogeneous waste streams should ideally be recycled, but as they are mostly composed of post-consumer waste they may be less desirable for recycling. To understand the ability of materials for recycling one needs to understand how the material is produced in the first place. Some necessary physical and/or chemical properties of the raw material may be lost in production, which makes the recycling of waste into secondary raw-material more expensive and sometimes impossible for economic reasons. In that case, incineration with energy recovery may be the best resort.

3.3.3 Hazardous vs Non-hazardous waste

Compared to non-hazardous waste, hazardous waste is more dangerous for the environment and those who handle it, and therefore stricter requirements generally apply for the treatment of hazardous waste than for non-hazardous waste. EU waste management legislation stipulates that hazardous waste may only be treated in specially designed facilities that have the required permits for the disposal of such waste in accordance with Articles 23 and 25 of the Waste Framework Directive (WFD). The EU WFD defines hazardous waste as waste which displays one or more of the fifteen hazardous properties listed below[39].

- **Explosive:** *"Waste which is capable by chemical reaction of producing gas at such a temperature and pressure and at such a speed as to cause damage to the surroundings. Pyrotechnic waste, explosive organic peroxide waste and explosive self-reactive waste are included"[39].*
- **Oxidising:** *"Waste which may, generally by providing oxygen, cause or contribute to the combustion of other materials"[39]*
- **Flammable:**

  -"Flammable liquid waste: liquid waste having a flash point below 60 °C or waste gas oil, diesel and light heating oils having a flash point > 55 °C and 75 °C"

  -"Flammable pyrophoric liquid and solid waste: solid or liquid waste which, even in small quantities, is liable to ignite within five minutes after coming into contact with air"

- *"Flammable solid waste: solid waste which is readily combustible or may cause or contribute to fire through friction"*

  - *"Flammable gaseous waste: gaseous waste which is flammable in air at 20 °C and a standard pressure of 101,3 kPa"*

  - *"Water reactive waste: waste which, in contact with water, emits flammable gases in dangerous quantities"*

  - *"Other flammable waste: flammable aerosols, flammable self-heating waste, flammable organic peroxides and flammable self-reactive waste"*

- **Irritant - Skin irritation and eye damage:** *"waste which on application can cause skin irritation or damage to the eye"[39]*

- **Specific Target Organ Toxicity (STOT)/Aspiration Toxicity:** *"Waste which can cause specific target organ toxicity either from a single or repeated exposure or which cause acute toxic effects following aspiration"[39]*

- **Acute Toxicity:** *"Waste which can cause acute toxic effects following oral or dermal administration, or inhalation exposure"[39]*

- **Carcinogenic:** *"Waste which induces cancer or increases its incidence"[39]*

- **Corrosive:** *"Waste which on application can cause skin corrosion"[39]*

- **Infectious** *"Waste containing viable micro-organisms or their toxins which are known or reliably believed to cause disease in man or other living organisms"[39]*

- **Toxic for reproduction:** *"Waste which has adverse effects on sexual function and fertility in adult males and females, as well as developmental toxicity in the offspring"[39]*

- **Mutagenic:** *"Waste which may cause a mutation, that is a permanent change in the amount or structure of the genetic material in a cell"[39]*

- **Release of an acute toxic gas:** *"Waste which releases acute toxic gases (Acute Tox. 1, 2 or 3) in contact with water or an acid"[39]*

- **Sensitizing :** *"Waste which contains one or more substances known to cause sensitizing effects to the skin or the respiratory organs"[39]*

- **Ecotoxic:** *"Waste which presents or may present immediate or delayed risks for one or more sectors of the environment"[39]*

- **Waste capable of exhibiting a hazardous property listed above not directly displayed by the original waste:** *"Waste which presents or may present immediate or delayed risks for one or more sectors of the environment"[39]*

Common hazardous waste sources are institutional waste types like clinical waste, bio-hazardous waste, medical waste, industrial sludge, spent solvents, used oils, and acid-alkaline or salt wastes. Hazardous waste can have damaging effects on incinerator equipment and toxic effects on employees and the surrounding environment as well.

3.3.4 Solid vs Liquid waste

Solid waste is a waste that is neither water nor airborne. It may therefore be concluded that solid waste is composed of a material in a solid state, but the term solid waste can still cover material in liquid forms such as sludge from wastewater treatment and liquid chemical waste[10]. Sludge, however, is generally not considered suitable for incineration in mass burning without more severe treatment (drying) due to its high moisture content.

3.3.5 Biogenic vs Non-biogenic

Organic matter can be divided into two types according to the source of carbon in the substance. Biogenic material is a material made from natural carbon, i.e. carbon that originates from the natural cycle of carbon in nature. Non-biogenic material is made from carbon derived from fossil fuels such as coal, natural gas or crude oil. It is therefore necessary to distinguish between biogenic waste and non-biogenic when assessing the carbon footprint of WtE plants. CO_2 emissions from biogenic carbon combustion can be viewed as carbon neutral, as a part of the natural carbon cycle. Bio-genic carbon can therefore be neglected in the calculation of the carbon footprint. However, when CO_2 is captured from WtE emissions using CCS technology, it may be more advantageous to take bio-genic carbon into account. In that case, carbon is in fact being removed from the natural cycle, so WtE's activity could become carbon neutral if biogenic carbon is on a par with non-biogenic carbon in emissions. Even further if biogenic carbon is found to be higher in CCS, the WtE plant can be considered as carbon negative. In that case CCS becomes, bio-CCS or BECCS. The most visible non-biogenic material is a plastic derived from the distillation of crude oil, common biogenic materials are paper, wood and bio-plastic. The proportion of biogenic carbon in MSW is usually between 33% to 50% and burning 1 Mg of MSW produces 0.7 - 1.2 Mg of CO_2.

3.4 Waste forecast

In 2020, the Icelandic Environment Agency commissioned a study on the need for waste incineration in Iceland. The study was conducted by the company Resource International e.h.f., the results of this study will be used as a basis in this thesis. In the waste forecast that Resurce International e.h.f. performed, three scenarios were set up forecasting evolution in the quantity of non-recyclable waste in Iceland over 20 year period, ie. from 2025 to 2045. The first scenario (SM1) assumes an unchanged situation in waste matters and Iceland does not improve the ratio of recycling and reuse against non-recyclable waste. The second scenario (SM2) assumes that the EU's targets of waste management will be achieved and that Iceland will increase the proportion of recycling and reuse by 2045. The third scenario (SM3) assumes maximum results in the opinion of Resource International e.h.f. in the recycling of all major recycling categories in Iceland by 2050.

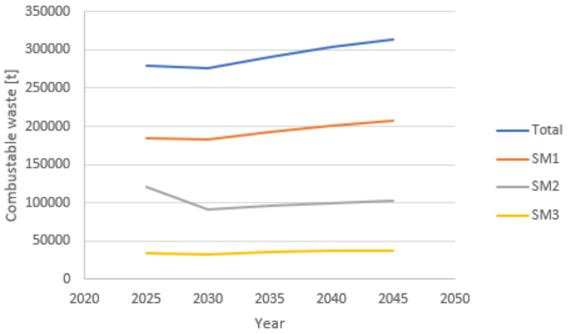


Figure 12: Forecast for quantity of combustable waste in Iceland from 2025 to 2045 [11]

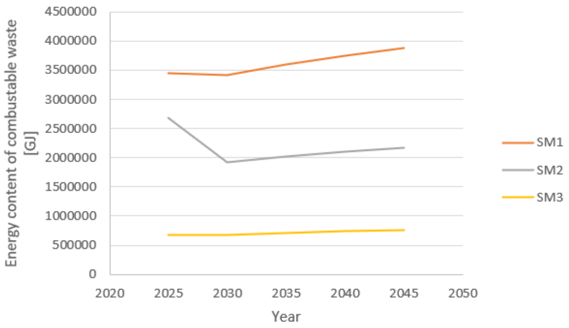


Figure 13: Energy content of combustable waste in Iceland from 2025 to 2045 [11]

The solid line (Total) at the top of the graph shows the total amount of combustible waste that is expected to be generated in the period from 2025 to 2045. The difference between the total waste generated and the three scenarios is the amount of waste that is expected to be recycled. According to SM1, non-recyclable, combustible waste will amount to 143000 tonnes in 2030. SM1 shows a much higher ratio of mixed household waste than SM2, that because SM1 assumes that waste collection does not change to higher source separation. SM2 and SM3 however show the same composition and assume source separation takes place leading to higher recycling ratios and less combustible waste for incineration. According to SM2, combustible non-recyclable waste for disposal will amount to 93011 tonnes in 2030.

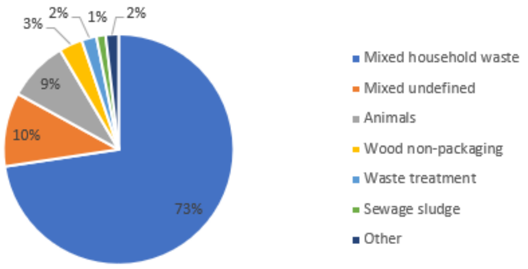


Figure 14: Combustible waste for disposal 2030-2045 according to SM1 [11]

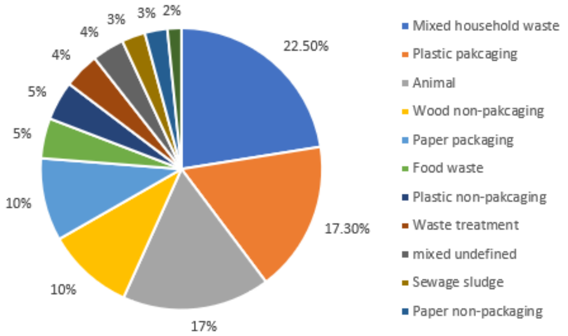


Figure 15: Combustible waste for disposal 2030-2045 according to SM2 [11]

SM3 was not considered a realistic outcome in the given time frame 2030-2045 and was not considered in the feasibility study for the WtE plant [11]. The feasibility study contained another forecast on potential incineration capacity, conducted by the Icelandic environmental consultant company Environice. Environice estimated that the incineration capacity would have to be somewhere between SM1 and SM2. Results from further estimations revealed that the WtE plant would need incineration capacity to treat about 130000 tonnes of non-recyclable combustible waste in 2030. The Danish engineering consultant company COWI took part in the feasibility study and wrote a report on technical solutions for the WtE plant. Based on the results from Environice, COWI concluded that the plant could have a power capacity for the generation of 10 MW of electricity and 28 MW of thermal power for district heating service or steam generation for industrial processes[5]. These conclusions were made based on the 10 kJ/kg average calorific value of the waste, this value was derived from the EU BREF document. However, this value can be assumed to be underestimated as combustible waste in EU is usually composed of much more organic waste. Recent laws in Iceland stipulate that organic waste shall be sorted from combustible waste, and it can therefore be assumed that the ratio of organic waste will be much less in combustible waste in Iceland. Less organic waste in the combustible waste mixture will increase the average calorific value of the waste. Therefore it may be assumed that COWI's estimation of the WtE plant's production capacity, both in electric and thermal power are minimum estimations.

4 Thermal Conversion

Thermal conversion is a process which breaks down material via a thermochemical reaction and converts the material into heat energy. Thermal conversion can be roughly divided into combustion or pyrolysis with different yield and residues in either gas, liquid or solid state depending on the technology used and the composition of the material treated. Combustion and pyrolysis are both thermochemical reactions which are different in the way that combustion occurs under the presence of oxygen whereas pyrolysis is done in the absence or near absence of oxygen. Combustion is an exothermic chemical reaction where substances react with oxygen and produce heat and light energy. Combustion reactions can be further divided into complete combustion and incomplete combustion. Whereas complete combustion also known as burning or incineration occurs in the presence of excess oxygen. In complete combustion, a chemical element is burned and completely oxidized into the most stable oxide of that element and yields a limited amount of products. For example, when an organic substance like fuel or waste is burned (incinerated) it is converted into CO_2 and H_2O. Incomplete combustion on the other hand occurs in the presence of a limited amount of oxygen and yields a wider range of products than complete combustion. The thermal conversion process which uses incomplete combustion is called gasification as it produces more gas products than incineration. Pyrolysis on the other hand is a decomposition reaction in which organic material decomposes when provided with heat in the absence of oxygen. Thermal treatment of waste is often divided into these three types thermal conversion incineration, gasification and pyrolysis.

4.1 Pyrolysis

Pyrolysis is a thermal process in which a substance is maintained at a very high temperature in oxygen-depleted conditions. The word pyrolysis is composed of the Greek words Pyro "fire" and lysis "separation". Pyrolysis has various applications, depending on the feedstock, resident time and reaction temperature of the process. Different applications yield different products, pyrolysis products can be in solid, liquid and gas phases. Solid products from pyrolysis is called char and is mainly composed of carbon, like charcoal. Liquid products from pyrolysis is called tar or pyrolysis oil. The process is generally divided into three main types conducted in different temperature ranges: Slow pyrolysis, Fast pyrolysis and Flash pyrolysis. **Slow pyrolysis** also known as carbonisation, like the name implies is slow heating of the feedstock where the volatiles from the organic material evaporates partly and the main product is char consisting mainly of carbon. This process is conducted at a temperature range from 300 to 400°C and a residence time of up to one hour. **Fast pyrolysis** is a rapid heating of the feedstock at a temperature range from 400 to 600°C at a short residence time of only few seconds. This process yields tar and is used for the production of pyrolysis oil from plastics and plant biomass for example. **Flash pyrolysis** is extremely rapid and is conducted at a high-temperature range >1000°C/s. Flach pyrolysis yields a high ratio of pyrolysis oil and gas.[40]

4.2 Gasification

Gasification is a thermal treatment which converts carbonous material such as MSW into a gaseous product in an oxygen-starved environment. The process is generally used for the production of syngas comprising mostly of carbon monoxide (CO), hydrogen (H) and methane(CH_4), steam is injected into the process to promote CO and H_2 production. Syngas can be used for the production of fuels for energy production and many chemical products via bio-chemical- or chemical synthesis routes, such as the production of ammonia (NH_3), hydrogen (H_2), methanol, synthetic natural gas (SNG) and production of gas to liquids [41].

4.3 Incineration (Mass Burning)

Incineration or mass-burning is a process of burning waste as received with low or no pre-treatment in a complete combustion with excess oxygen. This is the most common thermal treatment of MSW. The biggest advantage of mass-burning is high volume and mass reduction of the waste material.

4.4 Thermal Units

Thermal units are often selected according to the thermal treatment they are designed for or by the waste pre-treatment required for their use. The thermal units are either designed to burn the waste as received in the mass-burning process or the waste is turned into what is known as refuse-derived fuel (RDF). The definition of RDF also known as solid recovered fuels (SRF) can vary. A short definition of RDF/SRF is turning a heterogeneous waste mixture into a more homogeneous mixture through extensive pre-treatment. The pre-treatment can involve many different process steps like magnetic separation for removal of metals, density separation with air, screening to remove glass or recover other recyclables, size screening, shredding to obtain uniform grain size, and drying to increase the energy content. Finally, the end product is sometimes pelletized into pellets to reduce transportation costs and homogenize the end product. Quality of the RDF/SRF of course varies greatly depending both on the composition of the waste and how extensive pre-treatment is used in the production. SRF can be distinguished from RDF in that waste must meet certain quality standards to be considered SRF. Applications of RDF/SRF also vary depending on the quality. RDF/SRF is often used in the cement industry as a substitute fuel for coal in cement kilns.

The choice between RFD/SRF or mass-burning depends on the purpose of the combustion process, if the process is intended to deal large quantities at a time with low cost, mass-burning is a more suitable option. RDF, on the other hand, generally has a higher LHV than MSW intended for mass burning. The selection of thermal units for mass burning is therefore largely determined by the possible throughput. Many different thermal units have been designed and developed for thermal treatment of waste material such as moving grate furnaces (multiple

Table 1: Typical throughput of different thermal treatment technologies[15]

Technology	Througput tons/day
Moving grate furnace	120-720
Fluidised bed	36-200
Rotary kiln	10-350
Pyrolysis	10-100
Gasification	250-500

chambers), rotary kilns, fluidized bed, hearth incinerators, liquid injection furnaces, and plasma arc gasifiers to name a few. The most common thermal units for incineration are, the moving grate furnace, rotary kiln and fluidized bed.

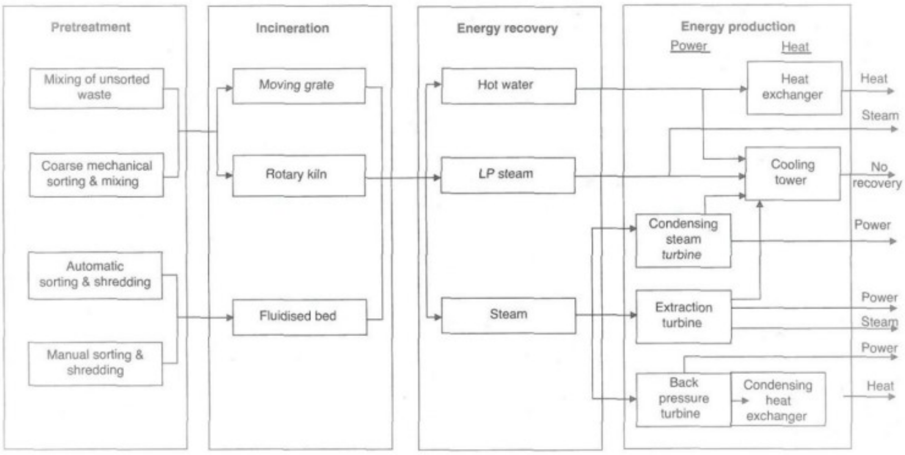


Figure 16: Different incineration methods[12]

4.4.1 Fluidized bed

Fluidized bed incinerators are generally made of vertical cylindrical vessels, with a bed of solid particles such as sand or a sand-like material in the lower section of the vessel. The sand bed is fluidized by blowing pre-heated air into the sand from the bottom of the vessel, suspending the bed particles in air. The hot air heats the fluidized bed up to around 650°C, while the air above the bed heats up to 850-950°C [15]. Input material is fed into the process through the top of the vessel and from there, drying volatilisation, ignition and combustion can take place all the way into the fluidized bed. For acceptable this process requires input material of a certain particle size, so there is a need for selection or pre-treatment of input material for this process. The particle size required is rather small, often with a maximum diameter of 50mm, which makes this process rather inapplicable for the incineration of MSW. Instead, it is more suitable for the thermal treatment of more homogeneous and fine-sized wastes such as RDF, sewage or industrial sludge. Although certain types of fluidized bed incinerators may accept material with diameters up to 200-300, in that case, pre-treatment of MSW is still needed. Common applications of fluidized bed reactors are, stationary or bubbling fluidized bed, rotating fluidized bed and circulating fluidized bed.

4.4.2 Rotary kiln

Rotary kilns consist of horizontally orientated cylindrical vessels, slightly inclined with the feed intake at the higher end. The vessel rotates and the waste is conveyed through the furnace by gravity and disposed through the lower end of the vessel. The residence time of waste inside the kiln is determined by the rotation speed and the horizontal angle of the vessel, normal residence time is 30 to 90 minutes. The kiln can operate in a wide temperature range from 500°C up to 1450°C depending on its application. Conventional waste incineration takes place around 850°C, but a higher temperature range of 900°C to 1200°C is required for the combustion of hazardous waste. The advantage of rotary kiln reactors is the high acceptability of different types of waste. Rotary kilns can be used to incinerate both solid and liquid waste and have been used to incinerate MSW, industrial waste, sewage and industrial sludge. Although rotary kiln is most commonly used for the thermal treatment of hazardous waste and most hazardous clinical waste is incinerated in a high-temperature rotary kiln incinerator in the temperature range 900°C to 1200°C[15].

4.4.3 Moving grate furnace

Moving grate furnaces is the most common technology for mass burning of MSW. Moving grate furnaces consist of moving grates which convey the waste through a combustion chamber where the waste is incinerated in complete combustion. Volatile gases released from the waste on the grates is incinerated in and above the combustion chamber in the furnace. Moving grate incinerators for MSW are designed to operate at a temperature of 850°C to 1100°C and are usually combined with a multiple pass furnace which leads the gases from the combustion chamber through two to three passes so the gas is completely oxidized in the process. The flue gas from the oxidation is very hot and needs to be cooled down before it enters a flue gas cleaning system. The furnace is equipped with a steam boiler which recovers heat from the process and cools the flue gas. Heat recovered from the process can be utilized for power generation in a steam turbine. Moving grate mass burning is the most robust thermal treatment for MSW compared to other thermal treatment technologies, with a typical throughput of 120-720 tonnes per day (see table 1). The process requires low or no pre-treatment, mostly limited to shredding of bulky objects. Low pre-treatment requirements and high throughput make the moving grate technology the most common technique for the mass-burning of MSW. There are many different technical solutions for the mass-burning of MSW in a moving grate furnace. Developments in moving grate technology have led to more choices between a different embodiment of equipment such as grate systems, furnace designs, cooling systems and boilers[15].

5 The process

The thermal treatment process under the scope of this thesis is a mass-burning process in a moving grate incinerator (MGI) with energy recovery. This will be a high-tech WtE facility designed with an incineration capacity of 130 thousand tonnes per year, processing 16.3 tonnes per hour. High-tech WtE plants are designed to operate 24 hours a day and 8000 hours a year, with a 2-week maintenance stop each year. WtE plants offer baseload power and based on the waste forecast the potential power output of the plant is 10 MW of electric power and 28 MW of thermal energy. Many different technical solutions exist for moving grate incinerators (MGI), but they all work in a similar way.

To explain the process, it is helpful to divide the process into four parts.

- Pre-treatment
- Incineration
- Energy recovery
- Flue gas treatment

Each part can then be divided into many smaller steps. Even though the main focus of this thesis is on energy recovery, it is good to get a brief overview of the entire process to understand better where the energy comes from and what residues come out of the process.

5.1 Pre-treatment

Thermal treatment of waste may require some kind of pre-treatment before the waste is loaded into the combustion chamber. Mass burning incineration requires little or no pre-treatment. Pre-treatment for mass burning is usually limited to metal recovery, shredding of bulky objects to avoid blockage in the feeding system and mixing of waste to gain homogenization which is usually done by overhead cranes in the bunker.

5.1.1 Bunker

When waste has been delivered to the process sight and undergone appropriate selection and pre-treatment available for the mass burning process, the waste is dumped into the waste bunker, a large concrete waste pit. The bunker is usually designed with a storage capacity of 3 to 5 days of the plant's average throughput. Inside the bunker, the waste gets mixed by an overhead crane to form a homogeneous mixture. This is done to obtain an even CV for stable combustion and even energy production. The waste bunker is equipped with two overhead cranes. One to mix the waste and the other to load the waste mixture into the feed hopper. Air duct system sucks air for the combustion process from the bunker, this creates under-pressure inside the bunker which prevents odors from escaping the bunker and polluting any nearby industrial or residential areas.

5.2 Incineration

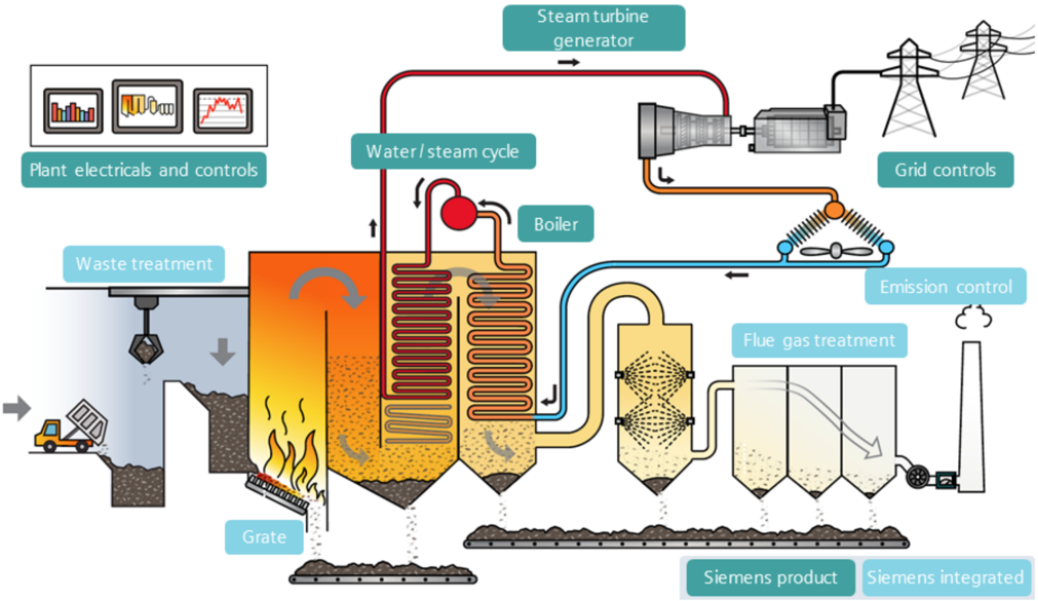


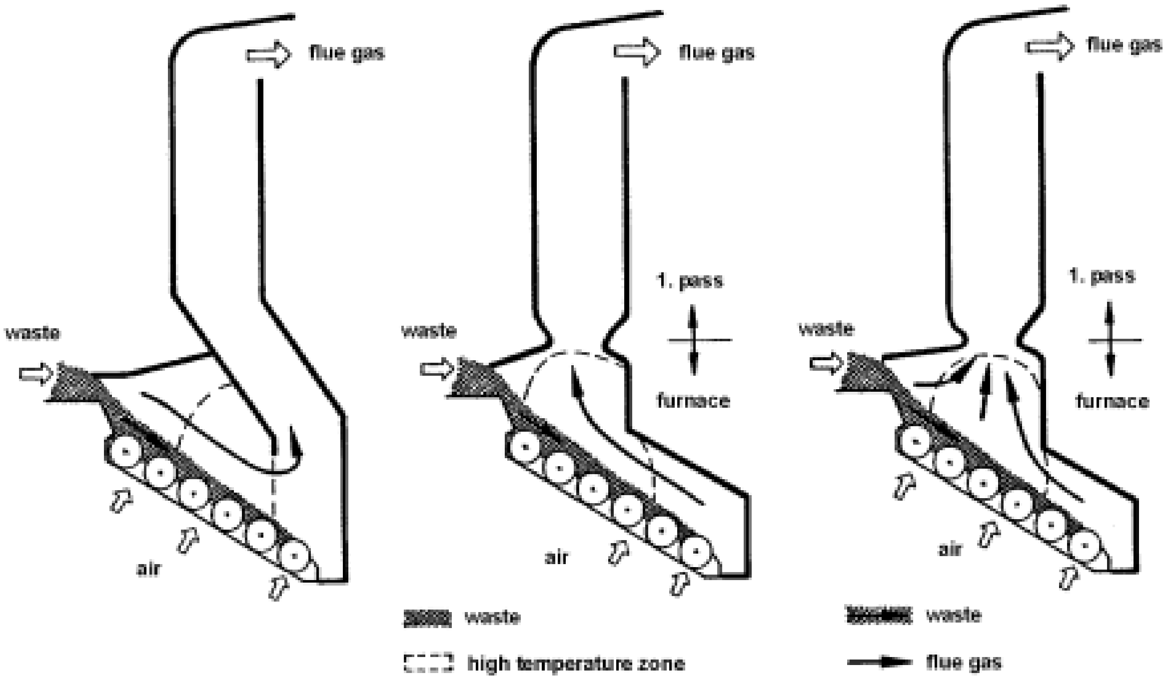
Figure 17: General setup of a multiple pass moving grate incinerator with energy recovery[13]

5.2.1 Waste Feeder

When the waste has been mixed appropriately, the overhead crane feeds a homogeneous waste mixture from the bunker into a filling hopper, which then works as a continuous fuel supplier for the furnace. When designing the feeding system, it is important to have a good idea of the composition and nature of the waste. The feeding system must be designed in such a way that there is little risk of it becoming clogged. The choice of material can be very important here, it is convenient that the material chosen has low frictional resistance and that the opening down from the chute is large enough. It is also important that the material connected to the oven is fireproof so that it can withstand flashbacks from the oven. The lower end of the chute is sometimes equipped with a stop valve that closes the furnace of from the chute to avoided these back flashes. At the lower end of the chute is connected to a dosing system that connects the chute to the furnace. This dosing system can be either mechanically or hydraulically driven.

5.2.2 Furnace

WtE furnaces are designed around three operation parameters, temperature, turbulence and time. A furnace in a moving grate incinerator consists of a combustion chamber where the combustion itself occurs and radiation passes where heat radiation from the combustion is absorbed to the water walls in the furnace. The furnace can either be a single-pass furnace with only one radiation pass, or a multi-pass furnace with two or more radiation passes. The process in the combustion chamber separates the waste input into two flow paths, gas flow from the waste pile and flow of solid residue from the combustion. The combustion chamber is split into specific conversion zones, describing the combustion process. When the waste is fed into the combustion chamber it first enters the drying zone, where moisture is dried out of the waste. Next, there is the devolitisation or de-gassing zone where volatile gases are most real from the waste. Then the waste goes into the ignition zone where the waste catches on fire and following the ignition zone is the main combustion zone. Then last there is the post-combustion zone where ash and other leftover residues accumulate at the back of the combustion chamber. Above the combustion zone is the high-temperature zone or burnout zone where most of the volatile gases are oxidised (burned out) and form flue gas. The high-temperature zone should always be positioned where all volatile gases are forced to pass through it when leaving the combustion chamber. Positioning the high-temperature zone can affect the waste of residence time in the furnace. There are two time parameters to keep track of each flow path, one is the residence time of waste which determines the throughput through the combustion chamber. The residence time of waste on the grates is usually between 45 minutes to 1 hour. The other time parameter is the residence time of gases in the combustion chamber. According to EU incineration directive 2000/76/EC, the furnace needs to maintain the combustion gases at a minimum of 850°C and oxygen level of at least 6% for at least 2 seconds to achieve good burnout of the gases and quality combustion[15]. Some furnaces are designed with special features to create extra turbulence in the burn-out zone to better mix the volatile gases in and above the high-temperature zone. Higher turbulence achieves better burnout of the volatile gases. A furnace designed for waste incineration is of three standard geometries, defined by the flow of gas and combustion residues through the combustion chamber of the furnace. These three types are as shown on figure 18, Parallel flow, Counterflow and Center flow.



(a.) Parallel Flow (b.) Counter Flow (c.) Centre Flow

Figure 18: Furnace geometries (schematic) for municipal waste incineration plants [14]

Parallel flow furnace also known as uniderection flow furnace meaning that both the waste pile and the flue gases flow in the same direction. The advantage of this design is that the gases released from the drying zone and the gasification zone must pass through the high temperature zone before escaping from the combustion chamber. This design is more suitable for lower LHV. In a **counter flow** furnace the gas outlet is located above the front end of the grates. This means that the gas flow is in opposition to the waste flow down the grate system. This causes the gas to overflow the first stages of the combustion chamber namely the drying and gasification zone before escaping from the combustion chamber, thus increasing the heat transfer from the ignition zone to the drying and gasification zone in the combustion chamber. The disadvantage of this design, however, is that gas is more likely to bypass the high temperature area and thus avoid satisfactory burnout of gases. This design is considered more suitable for higher LHV. **Central flow** is a kind of level between parallel and counter flow designs. This design is therefore suitable for a much wider range at LHV and is therefore better equipped to deal with fluctuations in the inflow into the process[14].

5.2.3 Moving grate systems

The grate system serves a multifaceted role and it is the key component to control the incineration process. First of the grates hold up the waste pile and close off the bottom of the combustion chamber. Movement of the grates helps in stoking and loosening up the waste pile, distributing the waste pile in the combustion chamber. Through the grate system, the operator controls the conveying speed of the waste pile through the furnace and in that way he also controls the position of the high temperature zone. The operator controls air feed into the combustion chamber partly through the grates. Air feed into the combustion chamber is divided into primary and secondary air supply as shown in figure 17. The air duct system is connected underneath the grate system and blows primary air through grate spacings. Primary air is blown into the waste pile to dry the material and provide oxygen for oxidation and enhance combustion. Primary air can also be used to cool the grates. Since the combustion takes place under such extreme temperatures the grates need to be implemented with a cooling system to withstand the heat load. These cooling systems may vary depending on the coolant used. In Europe, air is most commonly used as a cooling medium, but water or other liquids can also be suitable. Water is especially suitable if the LHV of the waste is 12 MJ/kg or higher. The advantage of heaving water cooled great system is that it can be used directly in other steps of the process. It can be used partly as a evaporator for the boiler or to reheat flue gas later in the flue gas cleaning process. It can also be used to pre-heat the primary air, in this way primary air can be used more explicitly to dry the material before it is ignited and continues through the combustion chamber. As a result, more energy would be released from the incineration, resulting in higher energy recovery. Essentially there are five main types of grates, distinguished by the way they move the waste through the furnace. **Rocking grate** system is composed of alternating grate rows that rock back and forth generating upward and forward motion on the waste pile. **Travelling grate** system is simply an embodiment of metal conveyor belts that extend across the furnace either in a single layer or interconnected belts, which move the waste pile through the furnace. **Roller grates** are composed of a series of roller which rolls the waste pile forward.**Reciprocating grates** are the most common type used today. There are both forward feed grate and backward feed grate as shown in Figure 19

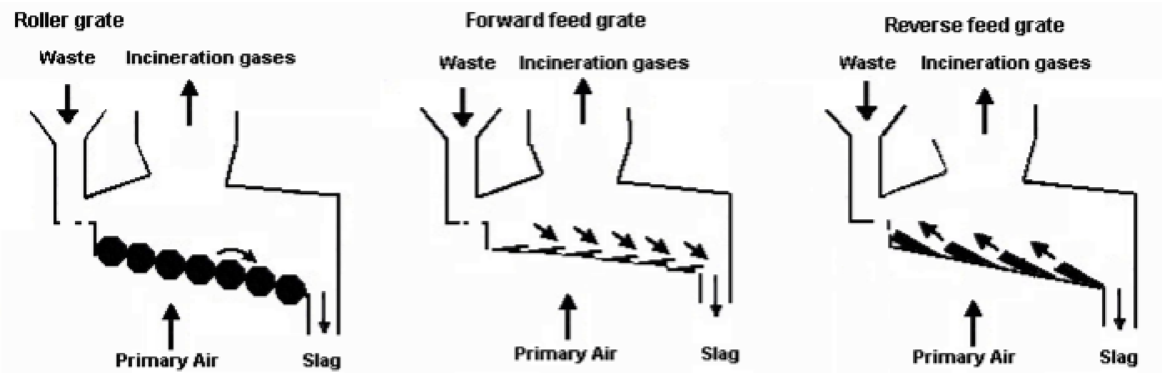


Figure 19: Different types of grate systems [15]

5.2.4 Bottom ash discharger

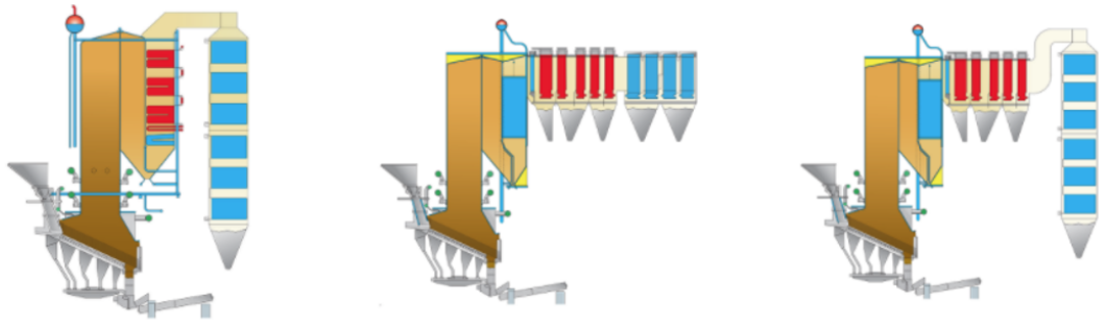
Solid residues of fixed carbon and ash accumulate at the end of the grate as bottom ash/slag. The bottom ash falls off the end of the grates and is discharged through a special discharge mechanism called bottom ash discharger. This discharge mechanism seals the end of the combustion chamber and is usually designed to cool the ash at the same time as it is unloaded from the furnace. The ash is submerged in water in the discharger to cool the ash. In that case, the water level also functions as a seal to prevent smoke and gases from escaping from the combustion chamber. If there is no water cooling the ash is used to seal of the combustion chamber. Metals and other non-combustible materials usually accumulate in the ash. As the ash is conveyed from the discharger it passes through magnetic separators that remove ferrous metals and eddy current separators to remove non-ferrous metals from the ash stream. The ash is either collected in a pile at the end of the conveyor belt which is then removed by a payloader or collected directly in an ash bunker for longer storage.

5.3 Energy recovery

Volatile gases released from the combustion chamber burn on their way through the furnace and produce hot flue gas which passes through a series of water tube bundles in a steam boiler. Heat is also recovered through water-cooled membrane walls on the inside walls of the furnace and combustion chamber. The water walls absorb heat through radiation in the combustion chamber and in the empty passes in the furnace. The heat radiation evaporates water in the water walls to steam, the steam then continues to the superheater which heats the steam to a superheated state.

5.3.1 Boilers

The boiler is essential equipment to recover energy from the process. The boiler is part of the furnace that acts as a link between the incineration process and energy production. A boiler that is generally used to recover energy in mass-burning incineration is the so-called water tube boiler, which is a specific type of boiler ideal for high-pressure applications. The heat transfer that takes place in the boiler serves a dual role, on the one hand, to capture heat from the flue gas which also cools the flue gas down to the required exit gas temperature from the boiler before it continues into the FGC system. The boiler is composed of three main heat absorption units, economizer, evaporator and superheater. **The economizer** is the rear part of the boiler and is the last part that the flue gas passes before it continues to the FGC system. At the same time, the economizer is the first heat absorption unit in the boiler as it pre-heats the feedwater before it is evaporated in the next step. Pre-heated water may also be retrieved from the grate water cooling system. The next step is the **evaporator**, which is part of the boiler where water is evaporated to form saturated steam. Most of the evaporation happens in the water walls in the empty passes of the furnace. **The superheater** is part of the boiler where the saturated steam is heated up to form superheated steam. There are three major types of furnaces that are most common for the combustion of residue waste, they are shown in figure 20they are defined by how the flue gas flows through them.[16].



Multiple pass furnace with vertical convection pass

Multiple pass furnace with horizontal convection pass

Multiple pass furnace with horizontal convection pass and a vertical economizer

Figure 20: Different types of steam-boiler furnaces[16]

In a multiple-pass furnace with a vertical convection pass, the superheater is located in the third vertical radiation pass and the economizer is in the fourth vertical pass. The advantage of this type of furnace is that he takes up less floor space in the facility, The disadvantage on the other hand is that the superheater in the vertical pass is less accessible which makes maintenance work more difficult. In the furnace with a horizontal convection pass, the economizer is located in the third vertical pass. The economizer cools the flue gas to the required temperature before entering the horizontal pass where the superheater and a second part of the economizer are located. This layout has the advantage of having easier access to the boiler equipment, resulting in lower maintenance costs. The disadvantage in contrast two the other layout is the larger footprint which takes up more space, resulting in higher CAPEX. The third furnace configuration is kind of intermediate between the other two designs, with an economizer in the third vertical pass, a superheater in the horizontal pass and then an economizer again in the fourth vertical pass. The boiler equipment is very sensitive to corrosion and erosion, due to the extreme temperature conditions. Higher temperature and pressure allow for higher energy transfer to the steam which provides higher energy recovery and higher efficiency in the steam turbine. Higher temperature and pressure, however, require higher grade steel in the boiler equipment to resist corrosion, especially on the superheater. These corrosion problems set certain constraints on the boiler efficiency and generally the steam parameters in the boiler are not allowed to exceed the temperature of 400°C and 40 bara pressure entering the turbine [15].

5.4 Turbines

Energy recovery from waste is very similar to energy recovery in conventional fossil fuel power plants. Both fields recover heat from flue gas in a water steam boiler to turn a steam turbine for power generation in a Rankin cycle. There are essentially three different ways to utilize the energy recovered from the WtE plant, only electric power generation, a co-generation of heat and power (CHP) for district heating or power generation with co-generation of steam for industrial processes. After the heat has been recovered in the boiler, the superheated steam at 400°C and 40 bara enters a turbine which harnesses the heat from the steam back pressure. There are three main types of steam turbines to utilize steam from a WtE plant: condensing turbine, non-condensing turbine or extraction condensing turbine. The selection of a turbine depends on the specific utilization of heat from the turbine, a condensing turbine is meant for power generation only, but non-condensing and extraction condensing turbines can be used in CHP production.

5.4.1 Condensing turbine

In the case of only producing electrical power from the plant a condensing turbine is an ideal option. In a condensing turbine, all the steam outlet from the turbine is condensed below atmospheric pressure to extract the maximum amount of energy from the steam in the steam turbine. The condensation can be done through an air-cooled condenser, seawater-cooled condenser or water-cooled condenser. In this case, it is possible to convert 35% of the available energy from the waste to power. Power production only is not considered a viable option unless the WtE plant is situated in such a remote location where a connection to a district heating system or a steam-demanding industry is not an option.

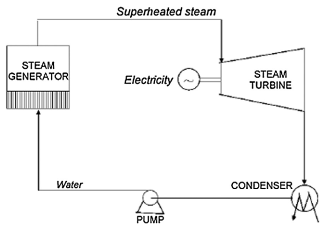


Figure 21: Rankine cycle [17]

5.4.2 Non-condensing turbine

Non-condensing turbines also known as back-pressure turbines can be used for CHP production. In a non-condensing, the steam is exhausted out of the turbine without condensation at or above atmospheric pressure. The discharge pressure from a back-pressure turbine can be established by the specific CHP applications. The outlet steam can led in a pipe to industrial users or through a heat exchanger to heat up water for district heating. If the heat is intended for district heating, the outlet pressure does not really matter and can be as low as atmospheric pressure. If the steam is intended for use in an industrial process, the discharge pressure may need to be higher. Back pressure turbines however are usually used when heat is to be supplied to a district heat network, where a significant amount of heat needs to be supplied to customers.

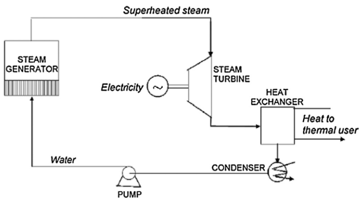


Figure 22: Rankine cycle [17]

5.4.3 Extraction condensing turbine

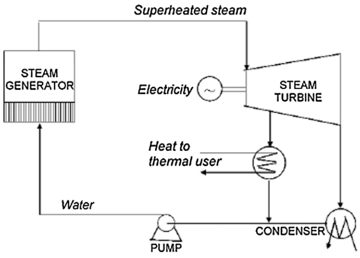


Figure 23: Rankine cycle [17]

Extraction turbines can be used for CHP production for district heating or industrial processes. In an extraction turbine, steam is extracted from the turbine at some intermediate pressure between the inlet and outlet pressure before the last stage of the turbine, the outlet steam is then condensed to maximise the power output. The extracted steam is then cooled down with district heating water or transported in a pipe to industrial users. Extraction turbine allows for more flexible power generation as the ratio between power and heat generation can be changed depending on the demand. When heat demand increases more steam can be extracted from the turbine to provide heat for a district heating network, at the same time power generation is reduced. If heat demand is extremely high the operator can close of the last stage of the turbine and extract all the steam from the turbine, in that case, the turbine works as a back-pressure turbine. The operator can the same way shut off the steam extraction and use all the steam for power generation instead, in that case, the turbine works as a condensing turbine. The extraction turbine can therefore be considered as a kind of intermediate between the condensing and the non-condensing turbine. Extraction turbines are usually used when steam from the turbine is to be used for industrial processes.

5.4.4 Energy efficiency

Energy efficiency is a major factor in the economic and environmental feasibility of a WtE plant and any power plant for that matter. The efficiency of WtE plants varies greatly depending on whether heat is co-generated or only power produced. If the case of power production only with a condensing turbine, the gross electric efficiency is expressed as in equation 6.

$$\eta_e = \frac{W_e}{Q_{th}} \times \left(\frac{Q_b}{Q_b - Q_i} \right) \tag{6}$$

Where:

- W$_e$ is the electric power generated, MW.
- Q$_t h$ is thermal input to the furnace, including the waste and auxiliary fuels that are used continuously (excluding short use in start-up), in MW$_{th}$ expressed as the lower heating value.
- Q$_b$ is thermal power produced by the boiler, in MW.
- Q$_i$ is thermal power that is used internally, in MW.

If the WtE plant produces CHP with a back-pressure or extraction condensing turbine the gross thermal efficiency is expressed with equation 7

$$\eta_h = \frac{W_e + Q_{he} + Q_{de} + Q_i}{Q_{th}} \tag{7}$$

Where:

- Q_{he} is thermal power supplied to the heat exchangers on the primary side, in MW.
- Q_{de} is the directly exported thermal power less the power of the return flow, in MW.

In order for the WtE facility to be considered as energy recovery in the EU, the facility needs to achieve a minimum gross efficiency. These criteria for energy recovery are described in EU WFD as the R1 rule shown here in equation8.

$$R1 = \frac{E_p - (E_f + E_i)}{0,97(E_W + E_f)} \tag{8}$$

E_p equals the gross electric or thermal energy generated by the plant in GJ/year, the electric energy is weight by a factor of 2,6 and thermal energy is weight by a factor of 1,1. E_f is energy in fuels contributing to steam production in GJ/year. E_W is energy in the waste in GJ/year. E_i is energy imported other than E_W and E_f in GJ/year. According to the WFD, a WtE plant must reach R1 higher than 0,65 to be considered an energy recovery facility in the waste management system. It is easier to meet the R1 criteria when using CHP than only power production. CHP WtE plants can reach up to 90% or higher efficiency, in that contrast the Copenhill plant has a net thermal efficiency of 107%. It is much harder to achieve an efficiency of 0,65 or higher with when producing power only, it is thought possible with extremely efficient steam turbines. These kinds of turbines however are much more expensive and therefore not an economically viable option. WtE plant should therefore always be designed with CHP where it is possible. Power only should only be considered where connection to the district heating network or industrial processes is not an option.

5.5 Flue gas treatment

WtE plants in the EU and EEA are required to conduct efficient cleansing of flue gas from the process in line with the EU industrial emission directive (IED) 2010/75/EU, to keep pollution from stack emission under certain IED limits (see table 2). Technical solutions for flue gas treatment and IED limits are defined in the latest update of the best available technique reference document (BREF) 2019. According to the industrial emission directive and the BREF, the pollutants that are needed to be removed from the flue gas are: particulate matter (dust), acid gases, acid hydrogen chloride (HCl), acid sulphur dioxide (SO_2), hydrogen fluoride (HF), nitrogen oxides (NO_X), carbon monoxide, ammonia and ammonium (NH_3), heavy metals (including mercury (Hg)), dioxins/furans (PCDD/F) and total organic compounds (TOC). When the flue gas passes through the boiler it cools down before it enters the flue gas cleaning (FGC) system. Particulate matter is removed in electrostatic precipitators, baghouse filters or cyclones. Acid gases such as HCl, HF and SO_X are removed from the flue gas with alkaline reagents like caustic soda or lime. Heavy metals such as: cadmium (Cd), thallium (Tl), mercury (Hg), Antimony (Sb), arsenic (As), lead (Pb), chromium (Cr), cobalt (Co), copper (Cu), manganese (Mn), nickel (Ni) and vanadium (V)[42]. Much of the heavy metals are removed in the scrubbing process but the remaining heavy metals are removed with active carbon injection. NO_X compounds are removed with an injection of ammonia, either directly into the furnace in a selective non-catalytic reduction (SNCR) process or through a special catalyst unit in a selective catalytic reduction (SCR) process. Dioxins and other organic compounds are removed with active carbon injection. Three different types of FGC processes, wet process, semi-wet process and dry process. The main difference be-

Table 2: Operational flue gas emission levels for releses to air. Data is standardized at 11% oxygen, dry gas, 273 K and 101,3 kPa[21]

Directive 2010/75/EU ; BREF 2019	
Substance	**24-hour average [mg/Nm^3]**
Total dust	5
HCl	6
HF	1
SO_2	30
NO_x	120
TOC	10
CO	50
	Measured average [mg/Nm^3]
Hg	0,02
Cd-Tl	0,02
Other heavy metals	0,3
PDCC/F	0,06
NH_3	10

tween these three processes is the use of alkaline reagents to remove acids from the flue gas in a scrubbing process.

5.5.1 Wet process

Before the wet process, the flue gas is usually lead through an electrostatic precipitator which removes most dust particles and heavy metals from the flue gas. Sometimes active carbon is also injected to the flue gas to remove heavy metals prior to the scrubbing process. From the precipitator or bag filter, the flue gas enters the scrubber unit where the wet process takes place. The wet scrubbing process take place in two stages, the first stage removes HCL and HF from the flue gas, the second stage removes SO_2. Dust particles, heavy metals, organic compounds and other pollutants are also partly removed in the scrubbing process. In the first stage flue gas enters a scrubber were the flue gas comes in contact with water, hydrogen peroxide, and/or a washing solution which partly contains the alkaline absorption reagent. The scrubber solution removes HCl and HF and a low amount of SO_2 from the flue gas. HCl and HF form strong acids in the scrubber solution, therefore the first stage is strongly acidic with a pH value between 0-1. The second stage is carried out under controlled pH values in close to neutral conditions, generally between 6-7 pH. In the second stage the alkaline reagent either caustic soda or milk of lime is added to the process. The scrubbing process produces solid residues and waste water which requires special treatment. The solid residues vary depending on the alkaline reagent used in the process. If milk of lime or limestone is used, gypsum, carbonates and fluorides will accumulate in the solid residues. The solid residues from the scrubber are highly polluted by chemicals from the flue gas and need to be disposed of as hazardous waste. Less solid residues are formed when caustic soda is used and the process produces mostly water-soluble products, solid residues of $CaCO_3$ can form if NaOH is used. Solid residues that accumulate inside the scrubber can form deposits on some of the hardware and inside walls of the scrubber. These deposits need to be removed from the scrubber periodically by acidification to prevent clogging in the scrubber. The disadvantage of wet scrubbing is that liquid solutions from the scrubber are removed from the circuit as wastewater that requires extensive wastewater treatment to remove pollutants accumulating in the scrubber liquid before the water is either discharged or used in other parts of the process.

5.5.2 Dry process

In a dry process, unlike the wet process, a dry absorption reagent is fed into the process as powder. Only solid residues are produced and need to be removed from the process as dust with bag filters in a subsequent stage. The feed rate of the reagent depends on the composition and temperature of the flue gas and which type of reagent is used. Common reagents for a dry process are calcium hydroxide or sodium bicarbonate and active carbon. In the case of overdosing on a reagent, the dust can be recirculated to avoid overuse of the absorption agent. The solid residues just like in the wet process are highly contaminated with pollutants and need to be disposed of as hazardous waste.

5.5.3 Semi-wet process

Semi-wet or semi-dry process works in a similar way as the dry process. The big difference is that in a semi-dry process, the reagent is injected into the process as a lime-water solution. As the reagent solution is sprayed into the hot flue gas flow, the solvent evaporates and solid reaction products are formed as dust from the reaction of the reagent with the pollutant in the flue gas. The solid residue dust is then removed from the process with a bag filter much like in the dry process.

5.5.4 Carbon injection

Powdered activated carbon (PAC) is injected into the flue gas flow to absorb heavy metals and is used to capture heavy metals and any traces of PDCC and furans gases. The PAC is injected after the wet scrubbing process but during the semi-wet and dry processes.

5.5.5 Bag filter

Bag filters also known as baghouse filters are widely used in various industrial processes to remove dust and particle matter $< 5\text{mg}/m^3$ from flue gas emissions. The baghouse filters consist of a series of long fabric bag filters The fabric bags screen out dust and particles as the flue gas is sucked through the filter bags, only the smallest particles escape through the filter depending on the mesh size of the bags. A balance needs to be found between the mesh size and the efficiency of the filter bags. Smaller mesh size leads to better cleaning but also slows the flow through the filter bag. The filter housing is usually divided into several compartments so that part of the filter housing can be isolated from the process during maintenance. The choice of filter bag material can also be important, the filter bags must withstand both thermal and mechanical stresses generated in the FGC process. Common fibre types for FGC systems in waste incineration plants are polyimide, PTFE and fibreglass. Special bag fabrics also have catalyst elements for extra reduction of NO_X compounds and destruction of dioxin/furans compounds.

5.5.6 SCR vs SNCR

In the combustion process, quite an amount of NO_X ($NO + NO_2$) is formed when combustion air burns in the furnace. These NO_X compounds are removed from the flue gas with an injection of a reducing agent into the flue gas. Either ammonia (NH_3) or urea ($CO(NH_2)_2$) are used as reduction agents for NO_X. Injection of the reducing agent is either conducted through SCR or SNCR process. In an SNCR process, the reduction agent is injected directly into the furnace above the combustion chamber, where the reduction agent reacts with the NO_X gases and produces nitrogen gas and water vapour.

$$NH_3 + NO_X \rightarrow N_2 + H_2O \tag{9}$$

The reaction between the NH_3 and the NO_X compounds (see equation 9) occurs in the temperature range of 850 - 1000°C. Urea has a bit wider effective temperature range between 750-1000°C but has a bit lower peak NO_X reduction potential in return. The feed rate of the reducing agent needs to be carefully controlled in contrast with NO_X formation and temperature. A too high feed rate of reducing agent results in ammonia slip as there is not enough NO_x present to react with all the reducing agents. The ammonia can though be captured in the FGC system in case of a slip, when using a wet scrubber the ammonia may even be recovered from the FGC process through ammonia stripping and re-injected to the process. A too-low feed of reducing agent simply results in lower reduction efficiency which leads to higher NO_X emissions. The SNCR process generally achieves reduction efficiency between 60 - 80%, tempts of achieving higher efficiency require higher addition of reducing agent which increases the risk of ammonia slip. Urea may be preferred over ammonia for cost reasons as urea is cheaper than ammonia.

In an SCR process, the flue gas flows through an SCR unit where the NO_X compound reacts with a reducing agent (usually ammonia in the case of SCR) in a catalyst reaction. The SCR unit is packed with a catalyst material, usually a mesh made from platinum, rhodium, TiO_2 or zeolites catalysts. A mixture of ammonia and air is injected into the flue gas in the SCR unit. As the mixture of flue gas and ammonia flows on the catalytic mesh surface, the catalyst speeds up the reaction between ammonia and NO_X which produces clean N_2 gas and H_2O vapour. The SCR process achieves up to 90% reduction rate of NO_X and is more efficient than the SNCR process. Due to the presence of a catalyst in the reaction, the SCR process can also be conducted at a much lower temperature range between 150-400°C. However, as the SCR process is conducted after other stages in the FGC system the flue gas needs to be reheated for the SCR process, which reduces the overall efficiency of the plant.

5.5.7 Stack

At the end of the FGC system, there is an induced draft (ID) fan which draws the flue gas from the furnace through the boiler and FGC system to the stack. The suction power of ID fan needs to be balanced with the airflow into the combustion chamber to ensure that the negative pressure is maintained in the furnace within certain limits. The clean flue gas from the FGC system gets sucked through the ID fan and into the stack, from there the clean flue gas flows up through the stack and is released into the atmosphere. Modern FGC systems are able to deliver great performance with very low levels of pollutants in emissions. Typical air emission values from new WtE plants in the EU show great results in FGC, where the concentration of pollutants in emissions is far below the IED limits.

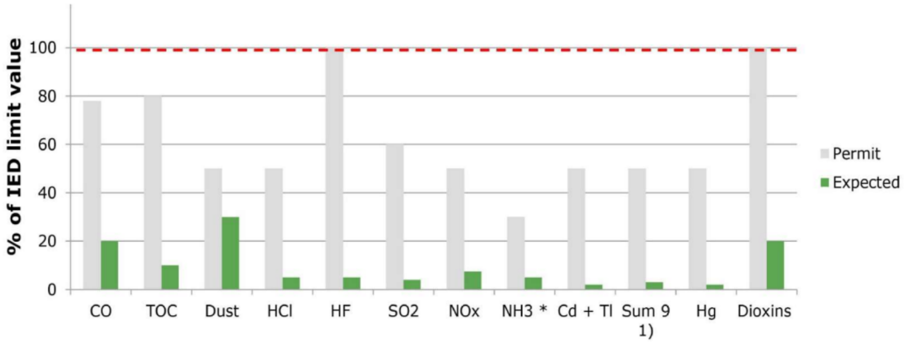


Figure 24: Typical stack emission of IED values from WtE plants in the EU [18]

6 Possible value streams

The main value stream from a WtE plant is heat and power output, but those are not the only outputs from the plants. WtE plants also generate a considerable amount of residues, some of which may become possible value streams. Residues from WtE plants are incinerator bottom ash (IBA), ferrous and non-ferrous metals, boiler ash, fly ash and air pollution control residues (APCR). Some recent development in carbon capture may produce CO_2 as a possible by-product from WtE plants, but these development projects are still in the pilot phase and have not been fully scaled yet.

6.1 Ash

The main by-product of moving the grate incinerator is IBA. Waste incineration reduces waste by 70 - 80% mass and 80%-90% volume, the remaining residues are inert, non-combustible (ash content) material from the combusted waste. These remaining residues are discharged from the process, either as IBA discharged from the bottom ash discharger or as fly ash from the boilers and bag filters in the FGC system. Fly ash which accumulates in the boiler is usually called boiler ash.

6.1.1 Bottom ash

The IBA ratio depends on the ash content of the waste incinerated, although there may also be some amount of unburned material and fixed carbon. The bottom ash is generally composed of 80%-85% minerals, 10-12% non-ferrous scrap metal and 2-5% ferrous metal. Around 60% of the non-ferrous metals recovered are aluminium, 15% residue and 25% are other metals, mainly copper, zinc, brass and stainless steel. The ash is collected in the ash bunker or similar storage on site. IBA can be put to use in road constructions as a road base or sub-base, it is also common to use IBA in sound barriers along streets in residential areas or for other landscaping. Before the ash is put to use it needs some pre-treatment to prepare it for use. First the ash needs to age for 6 to 20 weeks, as the ash ages it dries and the pH decreases. When the ash has aged enough it is degraded, stable and is ready for pre-treatment. Before the ash is put to use it goes through further metal recovery and screening two separate the ash into different particle sizes.

IBA has been used in the EU for a long time, as almost all the IBA can be put to use. Some EU countries have even set special targets for the utilization of IBA. For instance, all WtE operators in the Netherlands have signed a deal which stipulates that the minimum recovery of metals from the IBA shall be 75 % and that 100 % of the IBA produced shall be processed so that it is safe to use. Denmark has already achieved high success in IBA utilization and around 99% of IBA produced in the country is already utilized for construction[43]. If the ash is not put to use it can be sent to a landfill, however, the ash still needs to be dried and stabilised to prevent leaching to the groundwater. It is estimated that 1 kg of waste incinerated produces around 0,2 - 0,15 kg of IBA. If this statistic is applied to the proposed WtE plant in Iceland, the ash produced would be somewhere between 19600 to 26200 tonnes per year or 2,5 to 3,3 tonnes per hour.

6.1.2 Metal recovery

Metals are valuable recyclables that accumulate in the IBA and can be recovered through magnet and eddy current separation. The rate of metals recovered from the ash may vary, but in state-of-the-art cases up to 80% of metal embedded in the bottom ash can be recovered. Recycling metal also saves a lot of energy as it is less energy-intensive to produce new products from scrap metal than through the extraction of raw material from natural resources. Likewise recycling metal also reduces CO_2 emissions, it is estimated that metal recycling saves approx. 2000 kg of CO_2 per tonne recycled. If these same statistics are used in Iceland, it can be estimated that about 15720 tonnes of ferrous metal and 6550 tonnes of non-ferrous metal will accumulate in ash from a WtE plant that would be built in Iceland. If 80 % of that metal were recovered from the ash and recycled, it would save >35 kt of CO_2 annually.

6.1.3 Fly ash

Fly ash is typically about 2,5% of the waste incinerated, in this case, it would amount to 3.250 tonnes per year based on 130.000-ton input of combustible waste. The fly ash is lighter than the IBA and rises up from the combustion chamber with the combustion gases and flows with the flue gas through the multiple passes in the furnace and accumulates in the dust filters of the FGC system. Some of the fly ash falls out on the way in the vertical passes and accumulates in the furnace and boiler. The ash settles on the equipment and inside walls of the furnace and falls off eventually and gets collected in funnels under the boiler and vertical passes. The fly ash is then either conveyed to the bottom ash bunker or collected in a separate silo. The fly as is usually polluted with heavy metals, specially fly ash collected in the FGC system which is combined with APCR. The fly ash must therefore be treated as hazardous waste and can neither be utilized nor sent to a landfill like the IBA. Fly ash and APCR are usually sent to special storage sites where they can be permanently storage. One of these storage sites is an old abandoned limestone quarry on the island Langøya in southern Norway, it is currently the only storage site for fly ash in Scandinavia. However, this storage site is heading for closure in the coming years. Norwegian companies are looking for new storage sites, and salt mines in Germany have been considered as an alternative.

6.2 Carbon dioxide

Climate change is one of the biggest challenges that mankind faces today and needs to be addressed immediately. It is a widespread belief that climate change is a man-made issue caused by global warming due to greenhouse gas emissions. Climate change, however, is not a newly discovered problem and has been well known since the second half of the last century, in 1988 the UN established the Intergovernmental Panel on Climate Change (IPCC) and the UNFCCC in 1992. But since then, emissions have only increased and climate change has continued to escalate, scientists believe that, above all, global warming must be kept below 2°C to prevent irreversible climate changes. In 2015, there was a breakthrough in the battle against climate change, with the signing of the Paris Agreement and the adoption of the UN 2030 Agenda containing the 17 SDGs. With these agreements, nations set common goals to reduce GHG emissions in an effort to keep global warming below 2°C, many nations have committed to becoming carbon neutral by 2050 or earlier. Similarly, the EU has set goals of a 55% reduction in GHG emissions before 2030 and climate neutrality by 2050. This development has led to increased emphasis on capturing CO_2 from flue gas emissions in power plants and industrial processes. Iceland has made a commitment to reach carbon neutrality by 2040 and 40% reduction of greenhouse gas emissions by 2030, under the Paris Agreement.

Carbon capture is mainly comprised of three processes, pre-combustion, post-combustion and oxyfuel combustion. After the carbon has been captured there are essential options available, utilization or sequestration. Carbon capture and utilization (CCU) offers the opportunity to keep carbon in a closed loop where the carbon is used to produce new products for consumption. This option is a bit harder to regulate as the carbon stream could be put to use in many different ways and it could prove to be hard to keep track of the carbon and monitor how much of it actually stays in the loop and how much escapes in various applications. Carbon capture and sequestration (CCS) however, is easier to regulate as there is only a need to keep track of the amount of carbon that is captured and transported for storage. Then the storage site assumable needs to be monitored to make sure that no carbon escapes from storage.

6.2.1 Carbon capture

The most conventional way to capture carbon from industrial processes is through post-combustion, monoethanolamine (MEA) stripping. The capture process takes place in three unit steps, absorber unit, heat exchanger and stripper unit. In the first step, CO_2 in flue gas enters at the bottom of the absorber unit and flows up to the top. Cold MEA solvent enters at the top of the absorber unit and rains down, so the two streams pass each other. When the flue gas passes the MEA solvent, the CO_2 in the flue gas reacts with the solvent and falls in a solution to the bottom of the absorber unit. Cold CO_2 rich MEA solution is pumped from the bottom of the absorber through a heat exchanger which heats the CO_2 rich MEA solution to 95°C. The hot-rich MEA solution then flows to the

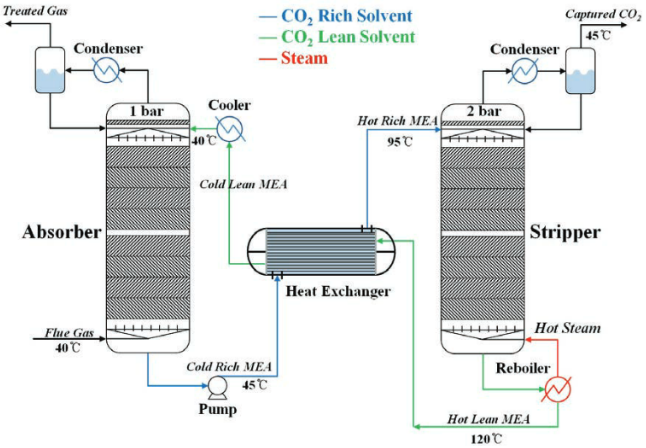


Figure 25: Carbon capture via MEA stripping[19]

top of a stripper unit where the solvent is desorbed at a high temperature. When the CO_2 is released from the solvent it flows up through the top of the stripper and enters a condenser which cools the CO_2 gas, the CO_2 is compressed to liquid for more economic transport (see figure 25)[19].

6.2.2 CCS

Sequestration of CO_2 in sediments deep in the earth's crust is now being considered as safe long-term storage of CO_2. In 2020 the Norwegian government launched a full-scale CCS project called Longship. The aim of the project is to build the first-ever cross-border, open-source CO_2 transport and storage infrastructure network. The project will offer companies all across Europe the opportunity to store their CO_2 safely and permanently underground. The CO_2 will be pumped offshore to injection wells in the north see where the CO_2 will be trapped in cavities in sediments deep beneath the seabed. Two companies are in collaboration with the Longship project, Norcem Brevik cement factory and Fortum Oslo Varme a WtE plant in Klemetstrud, Oslo. The Fortum plant processes over 400.000 tonnes of non-recyclable MSW and has a generation capacity of 55MW of heat energy for 40.000 homes and 10,5 MW of electricity. The plant emits about 400.000 tonnes of CO_2 per year, there of about 50% is from biogenic carbon. Fortum conducted a 5.500-hour carbon capture pilot project in 2019, the project demonstrated up to 90% capture efficiency. Fortum now intends to start a full-scale carbon capture facility, which would be able to remove about 90% of all its CO_2 emissions. In Iceland, there is an ongoing carbon capture project called Carbfix in collaboration with ON, the largest geothermal power producer in Iceland. In the Carbfix project, CO_2 is dissolved in geothermal brine and pumped down injection wells deep into the geothermal reservoir. The rock formations in the reservoir are mainly made from basalt rock, special chemical properties of the basalt rock make the formation reactive to the CO_2 in the brine. As a result, the CO_2 reacts with the rock formation in the reservoir and forms solid carbonate minerals. This is a great advantage over the Longship project as there is no risk of carbon escaping the reservoir once it has reacted with the rock formation. This quality of the Icelandic rock formation makes the country an ideal place for CCS facilities.

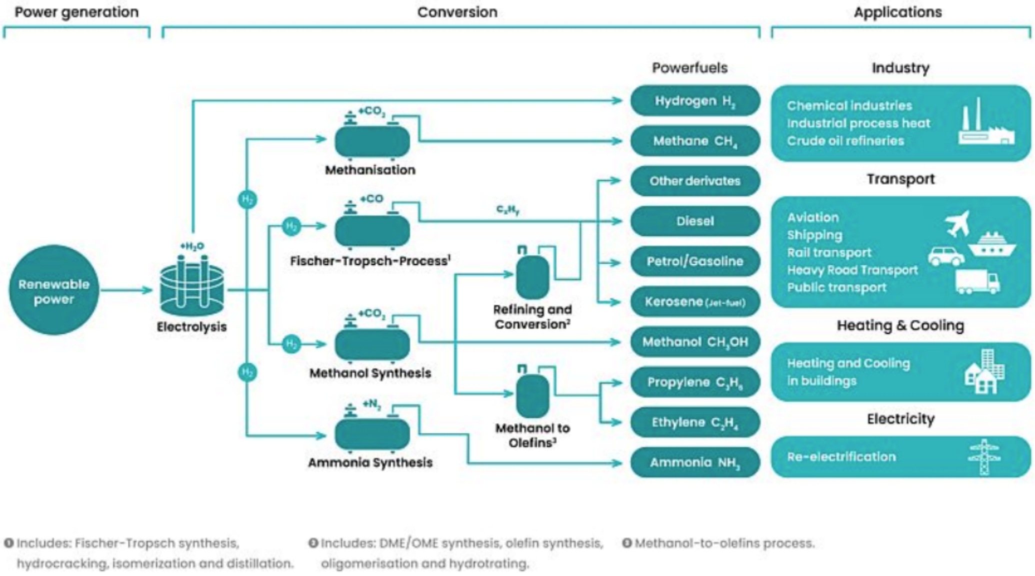
6.2.3 BECCS

When assessing CO_2 emissions from a WtE plant it is important to distinguish between biogenic and non-biogenic carbon. Biogenic carbon is considered to emit net-zero emissions of CO_2 to the atmosphere as it is originated from the natural circulation of carbon. Therefore only the non-biogenic carbon fraction is taken into account in calculations of the carbon footprint of a WtE plant. But this can be misleading as biogenic carbon certainly has just the same effect on the atmosphere as non-biogenic carbon. In light of the over-exploitation of the earth's resources, it can be argued that too much biogenic carbon is emitted from industrial combustion processes, ie. more than is bound in a natural cycle. Thus, CO_2 from biogenic carbon combustion actually has the same harmful environmental impact as $CO\ _2$ from other carbon sources. However, this could be changed through developments in carbon capture from WtE plants emissions. Carbon capture from WtE has revolutionary implications for the waste incineration sector. By removing biogenic carbon from its natural circulation, WtE plants have the possibility of becoming carbon negative. When biogenic carbon is removed with CCS it is known as bio-CCS or BECCS. The environmental consultancy Evironice analyzed a possible CO_2 emission from a WtE plant in Iceland. The results showed that about 210 kt of CO_2 would be emitted from a WtE plant. An estimate of the ratio of non-biogenic vs biogenic carbon revealed that 132 kt of CO_2 were of biogenic origin and the remaining 78 kt of CO_2 were of non-biogenic origin. The plant could potentially be carbon negative with sequestration of CO_2 from the atmosphere[5]. If the WtE plant would be combined with a full-scale CCS equipment like the Klementstrud in Norway with 90% capture efficiency, the plant could capture 189 kt from the plant's emissions, there of 118971 tonnes from the natural circulation of CO_2 in the atmosphere.

6.2.4 CCU

Instead of sequestrating the CO_2 in deep reservoirs, the CO_2 can be used in the production of goods and kept in a closed consumption loop or returned back to natural circulation. There are many applications for CO_2 in various industries such as in the food industry where CO_2 is used in the production of food and beverages. CO_2 is most notably used as a preservative in the production of drinks, where CO_2 gas is used to carbonate soft drinks, beers and vines to prevent bacterial growth and fungal. CO_2 is also used to de-caffeinate coffee. CO_2 is used in the petroleum industry where CO_2 is pumped down oil wells to maintain pressure within the formation of the oil reservoir to increase oil extraction. In the metal industry, CO_2 is used to enhance the hardness of casting moulds. In welding with MIG/MAG, CO_2 is used on a large scale as shield gas to protect the weld puddle from oxidation as it cools. CO_2 in a mixture with argon is also commonly used in welding to achieve higher welding rate. In horticulture, CO_2 is commonly known to enhance crop growth and increase quality. CO_2 is used in the Chemical industry for the production of methanol and urea.

In recent years, there has been increasing discussion in Iceland about the production of alternative fuels by electrolysis of hydrogen. This discussion can easily be traced to Iceland's commitment to reducing carbon dioxide emissions from burning fossil fuels. As previously stated, the Icelandic government have set ambitious goals for Iceland's carbon neutrality by 2040. One key action to achieve these goals is to phase out the use of fossil fuels in the marine industry and domestic aviation. As Iceland's electricity production comes 100% from renewable energy sources, the country offers a unique opportunity for the production of green hydrogen (ie environmentally friendly hydrogen). Hydrogen is an extremely valuable raw material that is used in a variety of chemical processes, hydrogen can also be used directly as an energy source or for the production of other fuels. Power to gas (PtG) technology is a synonym for the production processes that use electric power for the production of gaseous fuels, such as hydrogen, methane, methanol, ammonia and so on (see figure 26). Electric power can be used to separate H_2O into H_2 and O_2 via electrolysis as shown in equation 10.



❶ Includes: Fischer-Tropsch synthesis, hydrocracking, isomerization and distillation. ❷ Includes: DME/OME synthesis, olefin synthesis, oligomerisation and hydrotrating. ❸ Methanol-to-olefins process.

Figure 26: Different chemical processes for the production of alternative fuels from the electrolysis of water to hydrogen and oxygen[20]

$$2H_2O \rightarrow 2H_2 + O_2 \tag{10}$$

The hydrogen can then be reacted with CO_2 to produce methane via methanisation or methanol via methanol synthesis. Carbon Recycling International (CRI) is an Icelandic company which has operated a full-scale methanol synthesis process since 2012. CRI is located at the Svartsengi power plant owned by HS Orka power company on the Reykjanes peninsula. The process uses green hydrogen produced via electrolysis and reacts it with CO_2 captured from the Svartsengi geothermal power plant. Methanol ($[CH_3OH]$) is produced by reacting hydrogen ($[H_2]$) with carbondioxide ($[CO_2]$) (see equation 11).

$$CO_2 + 3H_2 \rightleftharpoons CH_3OH + H_2O \tag{11}$$

At least two other companies intend to build similar PtG plants in the coming years. The company Hydrogen Ventures intends to build a 30 MW PtG methanol plant in Reykjanes, close to either one of HS orka's two power plants in the Reykjanes peninsula.

The company Nordur Renewables Iceland intends to construct a 25 MW PtG methane plant in Hellisheiði, close to the ON geothermal power plant. Methane ($[CH_4]$) is produced by reacting $[H_2]$ with $[CO_2]$ (see equation

12).

$$CO_2 + 4H_2 \rightleftharpoons CH_4 + 2H_2O \tag{12}$$

The PtG plant will produce 6.000 tonnes of e-methane per year from the value streams provided by Hellisheiði ECO park.

7 Methodology

As previously stated in the introduction, the Icelandic Ministry of the Environment and Natural Resources, together with the four largest waste management companies in collaboration with the Association of Icelandic Municipalities in Iceland, commissioned a feasibility study on a future solution in the treatment of combustible waste instead of landfill. The results of the study showed that it is considered a feasible option to build one WtE plant in Iceland, that will handle combustible waste from all over the country. The results further indicated that the demand for waste incineration will amount to approximately 100-130 thousand tons of combustible waste per year. The study also involved examining the technical requirements for pollution control, flue gas treatment and energy efficiency that the plant must meet in order to comply with regulations on waste incineration and waste treatment. Furthermore, the study provides suggestions on technical solutions suited for the project and a rough cost estimate was made. The WtE plant will be installed with 10 MW of electric power capacity and 28 MW of thermal power capacity. If the WtE plant operates for about 8000 hours per year, the power capacity amounts to the production of 80 GWh of electric power and 224 GWh of thermal energy. It was estimated that if all went according to plan, the WtE plant could start operations at the earliest in eight years or around 2030. In this thesis, it is therefore assumed that the WtE plant will start operations in 2030 and the operation period is 30 years, i.e. 2030-2060.

Possible site selections for the plant were also investigated in terms of the transport efficiency of combustible waste to the plant. Five sites were identified in the feasibility study, Álfsnes, Straumsvík, Helguvík, Þorlákshöfn and Grundartangi. Of these five sites, Álfsnes was found to have the highest transportation efficiency based on the transport of combustible waste to the WtE plant. Grundartangi scored lowest of the other four compared to Álfsnes.

7.1 Objective

In this thesis the aim is to evaluate the same five site selections based on the utilization of possible value streams from the WtE plant described in Chapter 5 (the process) and 6 (possible value streams). The value streams from the WtE plant are, thermal energy, electricity, CO_2, scrap metal, IBA and fly ash. However, it was decided to leave the fly ash out of the evaluation, as fly ash is generally considered hazardous waste due to heavy metal concentration and needs to be shipped abroad for permanent storage in designated storage areas for hazardous waste.

Utilization of thermal demand will be evaluated based on changes in thermal demand in the five locations. The more that change in thermal demand succeeds the WtE plants production capacity the higher the site scores in the evaluation. The utilization of electric power from the plant will be evaluated based on the available connections to the national electric grid, better connection scores are higher. Utilization of CO_2 will be evaluated based on future construction plans of CO_2 intensive industries in or close to the sites in question. The site with the most promising plans in the development of a CO_2 intensive industrial environment will be ranked highest and so on. Utilization of IBA will be evaluated in close proximity to the dens population area. Utilization of scrap metal is evaluated based on close proximity to a port area.

7.2 Analytical hierarchy process

To compare these five different site selections based on the utilization of five of the possible value streams, it was decided to use the so-called analytical hierarchy process (AHP). AHP is a method used in multi-criteria decision-making. In an AHP, different criteria are weighed and alternatives are prioritised based on a ranking, usually from 1-9 (see table 3).

Table 3: AHP ranking system

Ranking system	
No difference	1
Small difference	3
Quite a difference	5
Big difference	7
Decisive difference	9

First step in the AHP is to define the decision problem and goal. In this case, the goal is to answer the thesis question, to determine which one of the sites in selection offers the best location based on the utilization of possible value streams from the WtE plant.

The second step is to identify and structure the decision criteria and alternatives, in this case the decision criteria are the different value streams, thermal energy, electric power, CO_2, IBA and scrap metal. The alternatives are the five different site selections in question, Álfsnes, Straumsvík, Helguvík, Þorlákshöfn and Grundartangi.

Third step: Evaluate and judge the relative importance of the decision criteria. Make a pairwise comparison of each decision criteria based on the ranking system shown in table 3. Rank the decision criteria based on which value stream is most important for the WtE plant to succeed. Create a criteria comparison matrix ([C]).

Table 4: Example of a pairwise comparison matrix for the decision criteria

Criteria comparison matrix $[C_C]$					
	Thermal Demand	Grid Connection	CO_2 utilization	IBA utilization	Scrap metal export
Thermal Demand	1	2	7	5	9
Grid Connection	0,50	1	6	3	8
CO2 utilization	0,14	0,17	1	0,33	3
IBA utilization	0,20	0,33	3,00	1	1
Scrap Metal export	0,11	0,13	0,33	1,00	1
Sum	1,95	3,63	17,33	10,33	22,00

Now each element in the matrix [C] is divided be the sum of its column, this creates the normalisation matrix. The sum of each column in the normalization matrix should be equal to 1.

Table 5: Example of a normalization matrix of matrix [C] in table 4

Normalization matrix [N$_C$]					
	Thermal Demand	Grid Connection	CO2 utilization	IBA utilization	Scrap Metal export
Thermal Demand	0,51	0,55	0,40	0,48	0,41
Grid Connection	0,26	0,28	0,35	0,29	0,36
CO2 utilization	0,07	0,05	0,06	0,03	0,14
IBA utilization	0,10	0,09	0,17	0,10	0,05
Scrap Metal export	0,06	0,03	0,02	0,10	0,05
Sum	1	1	1	1	1

Fourth step: After the normalisation matrix has been obtained, the normalized principal Eigenvector also known as the criteria weight vector [W], can be obtained be taking the average across each row in the normalization matrix [N$_C$]. The criteria weight vector [W] contains the relative weight of each criteria.

$$[W] = \begin{bmatrix} 0,24 \\ 0,35 \\ 0,13 \\ 0,13 \\ 0,15 \end{bmatrix} \tag{13}$$

Fifth step: Evaluate and judge the relative value of the alternatives on each decision criteria. That is, create a pairwise comparison matrix of the alternative site selections for each criteria.

Table 6: Example of pairwise comparison matrix for alternative site selections based on thermal demand

Comparison matrix for Thermal Demand [C$_{TD}$]					
	Álfsnes	Straumsvík	Helguvík	Þorlákshöfn	Grundartangi
Álfsnes	1	1	5	9	9
Straumsvík	1	1	5	9	9
Helguvík	0,2	0,2	1	5	5
Þorlákshöfn	0,11	0,11	0,20	1	3
Grundartangi	0,11	0,11	0,20	0,33	1
Sum	2,4	2,4	11	24	27

Sixth step: Create a normalization matrix of each pairwise comparison matrix and obtain a priority vector from each normalization matrix.The priority vector is obtained the same way as the criteria weight vector, by taking the average across each row in the normalized comparison matrix.

Seventh step: Repeat steps five and six for all the other criteria and combine all priority vectors to gather in one matrix, called the final rating matrix [F]. Each priority vector represents one row in [F]. Then the final rating is obtained by taking the dot product of the transposed final rating matrix [F] and the criteria weights vector

Table 7: Example of normalization of comparison matrix and site selection priority vector based on thermal demand

	Normalization matrix for thermal demand [N_{TD}]				
	Álfsnes	Straumsvík	Helguvík	Þorlákshöfn	Grundartangi
Álfsnes	0,41	0,41	0,44	0,37	0,33
Straumsvík	0,41	0,41	0,44	0,37	0,33
Helguvík	0,08	0,08	0,09	0,21	0,19
Þorlákshöfn	0,05	0,05	0,02	0,04	0,11
Grundartangi	0,05	0,05	0,02	0,01	0,04

Site selection priority vector [P_{TD}]
0,39
0,39
0,13
0,05
0,03

Sum	1	1	1	1	1

Table 8: Example of a final rating matrix

Final rating matrix					
	Álfsnes	Straumsvík	Helguvík	Þorlákshöfn	Grundartangi
Thermal demand	0,40	0,40	0,10	0,06	0,04
Grid connection	0,03	0,37	0,06	0,17	0,37
CO2 utilization	0,08	0,10	0,05	0,27	0,51
IBA utilization	0,34	0,34	0,13	0,06	0,13
Scrap metal export	0,32	0,49	0,05	0,04	0,10

Sum	1	1	1	1	1

[W] (see equation 14).

$$Finalrating = [F]^T \cdot [W] \tag{14}$$

8 Alternative site selections

Figure 27: Alternative site selections for WtE plant in the southwest corner of Iceland

In the aforementioned feasibility study, there were given certain constraints to the site selection. These constraints were that the WtE plant has to be located in the southwest corner of the country and preferably as close to the capital area, where about 75% of the combustible waste is generated. It was also considered desirable to position the plant in the vicinity of the port area for the possibility of marine transportation of waste from places further out in the country to the plant. It may also be necessary to transfer waste/value streams from the plant's process abroad for storage or further processing, so proximity to the port is considered important. The feasibility study identified five alternative site selections: Álfsnes, Straumsvík, Helguvík, Þorlákshöfn and Grundartangi (see figure 27).

8.1 Álfsnes

Álfsnes is a small headland on the northern side of the capital area. The Álfsnes area contains the largest and most developed landfill site in the country and the GAJA compost plant. Álfsnes scored highest in terms of transport efficiency of waste to the WtE plant, Straumsvík had the second highest score as both sites are within the capital area where most of the country's combustible waste is produced or 75%. The capital area has population density of 240.882 inhabitants (1 jan. 2022). Although Álfsnes has scored higher than Straumsvík in comparison to the transport efficiency of waste to the plant, Álfsnes is a somewhat more remote location than Straumsvík. From Álfsnes, for example, it is about 18 km to the nearest port area. However, this could change in the near future, as there are plans to build a new highway (Sundabraut) that connects the northern route into the capital area through the Álfsnes headland. Construction could possibly begin in 2025 and be completed by 2030[44]. This new highway would shorten the connection of Álfsnes to the capital area considerably, for example, the distance to the port area would be shortened by approx. 10 km. There are also plans for the construction of a small port area in Álfsnes close to the GAJA compost plant, in relation to the transfer of the mineral processing company Björgun to the area. Björgun intends to build a small port area for its mineral processing. This port area could potentially be used for unloading waste which could be transported by sea to Álfsnes[45].

8.2 Straumsvík

Straumsvík is an industrial port area in the southern limits of the capital area in the municipality Hafnafjörður. Straumsvík industrial area houses Ísal aluminium smelter owned be Rio Tinto Alcan. Next to the smelter is a freeway that runs from the capital area to the municipalities on the Reykjanes peninsula. On the other side of the freeway opposite the aluminium smelter is a large industrial area. This area also shares boundaries with residential area on the outskirts of the town Hafnarfjörður. This industrial area would be a possible site selection in relation to connection with the Straumsvík port area and will be referred to as the Straumsvík area in this thesis. The Straumsvík area is at the southern end of the capital area and hoses various industries like manufacturing companies, machine shops and service companies for the smelter in Straumsvík. This industrial area also houses waste management companies, such as Terra and Fura as well as concrete manufacturers and an asphalt plant.

8.3 Helguvík

Helguvík is an industrial area located on the outskirts of the town of Reykjanesbær in the southwest corner of the country. Reykjanesbær is a town of 20.298 inhabitants (1.jan 2022) which is fairly big town on the Icelandic scale. Reykjanesbær is the fourth biggest municipality in Iceland[46]. The industrial area of Helguvík houses the Kalka waste incineration plant. As previously stated, Kalka is the only operating waste incinerator in Iceland with an incineration capacity of approximately 12.000 tonnes per year. Kalka accepts hazardous waste for incineration, so it is important that such a station is operated so that hazardous waste has a safe disposal route in the country. It is not considered desirable to accept hazardous waste into the WtE plant, as hazardous waste would pollute the IBA coming from the plant so that it could not be utilized. However, it could be of great benefit to build the WtE plant next to Kalka, where there is already a lot of experience and knowledge in waste incineration. There would also be streamlining of maintenance as the same maintenance team could take care of maintenance at both stations. There would also be the possibility of using heat from the Kalka furnace to increase the plant's production capacity.

8.4 Þorlákshöfn

Þorlákshöfn is a town in the municipality Ölfus on the south coast of Reykjanes peninsula in the southwest corner of Iceland. Þorlákshöfn is a relatively small town with a population of 1927 inhabitants (1.jan 2022)[46]. Ölfus Cluster (ÖC) is an alliance of companies and public bodies, established to promote employment and industry development in the municipality of Ölfus, including the town Þorlákshöfn. The main industry developments in the Þorlákshöfn area in recent years have been around aquaculture, i.e. salmon and trout farming.

8.5 Grundartangi

Grundartangi is an industrial area that houses heavy industries such as Norðurál aluminium smelter, Elkem ferroalloy plant, as well as smaller metal processing companies and service companies that serve the industry in the area. There is a harbour in the area that stands by the fjord Hvalfjörður. The Grundartangi industrial area does not stand close to any town or district areas and does therefore not have high thermal demand for district heating. However, the idea is to build a so-called green industrial park in the area, which would utilize waste streams from the heavy industry in the area. Most notably there has been talk about capturing carbon dioxide and waste heat from Elkem's ferroalloy plant. The waste heat will be used for CHP production, where heat could be utilized in the industry park for various thermal-demanding industries. The plan is also to lay a hot water pipeline from the industrial park and connect it to a district heating system that supplies the municipalities of

Akranes and Hvalfjarðarsveit with hot water. In that way, heat production in the industrial park could be used for district heating in nearby municipalities. The current district heating system in Akranes and Hvalfjarðarsveit is operated by the utility company Veitur.

In 2021, the Minister of Tourism, Industry and Innovation along with other stakeholders in the industrial park signed a statement of intent on starting the first phase of the industrial park project. The first phase of the project includes[47]:

- CCS from Elkem's ferroalloy production, the CO_2 will then be sequestrated in Grundartangi.
- Power production from waste heat produced in Elkem's ferroalloy production.
- Connection to the district heating network for Akranes and Hvalfjarðarsveit.

Connection to the district heating system in the nearby municipalities strengthens the possibility of utilizing thermal energy from the industrial park and ensures stable thermal demand from the area. However, this heat demand is not necessarily high enough to utilize all the heat energy that will be produced in the area. The excess heat energy generated can therefore be used to build up the heat-demanding industry in the industrial park.

9 Criteria

Energy production from the WtE plant producing CHP can easily be compared to the energy production of geothermal power plants producing both electricity and hot water into the district heating network. The main difference is the heat resource, whereas geothermal power plants extract heat from geothermal reservoirs deep in the earth's crust, but WtE plants create their own heat from the incineration of combustible waste. In that sense, the WtE plant of the scale in question can be regarded as a small geothermal power plant in Iceland, producing electric power and hot water for district heating. In addition to the power production the WtE plant also produces quite a lot amount of ash and CO_2 which has some potential value.

9.1 Thermal power

In regard to the utilization of thermal power, the five site locations in question can be divided into four district heating areas, ie. the capital area, Fitjar, Þorlákshöfn and Akranes/Hvalfjarðarsveit. Two of the five site selections Álfsnes and Straumsvík, coincide under the same district heating system in the capital area. When thermal demand was investigated in the four district heating areas, it was assumed that the change in thermal demand over the operation time of the WtE plant (2030-2060) would follow the population growth in the areas. Population forecast from the Icelandic Institute of Regional Development (Byggðastofnun) was used to determine the change in thermal demand in four district heating systems in question, a more detailed explanation of the population forecast can be found on the Regional Development Institute's website[**?**]. This was done by multiplying the proportional change in population with the thermal demand from 2020 in each area. The population forecast shows the average population growth rate with 5% and 95% percentage limits. The percentage limits are displayed in figure 29 through 32 as high (95%) and low (5%) changes in thermal demand.

Figure 28 shows the change in thermal demand in accordance with the average population growth rate over the WtE plant's operation period in the four areas in question. From figure 28 it is clear how much higher thermal demand is in the capital area than in the other district heating systems. However, the thermal demand itself is perhaps not good enough to decide which location is more suitable than others, as the existing thermal demand is already met. It may therefore be more suitable to look at the change in thermal demand over the plant operation period and evaluate how thermal energy from waste incineration can be used to meet the increase in thermal demand.

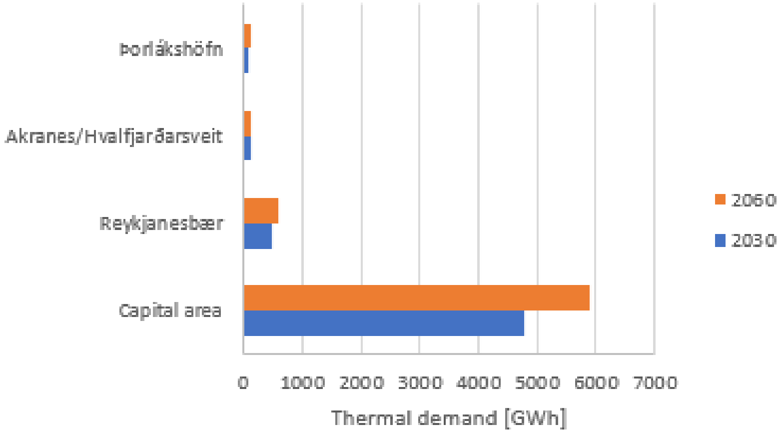


Figure 28: Change in thermal demand in four district heating areas over the plant's operation period

9.1.1 Capital area

The district heating system in the capital area is operated by the utility company Veitur. District heating water supplied to the capital area is extracted from four low-temperature geothermal fields in the capital area and freshwater heated by geothermal fluid from geothermal power plants in Hellisheiði and Nesjavellir. In 2021, about 39% of the hot water came from low-temperature geothermal fields in the capital area and 61% was supplied from the power plants in Hellisheiði and Nesjavellir. Total production of district heating water in the capital area amounted to 4187 GWh in 2021, in comparison the production capacity of the WtE plant will only be around 7% of that.

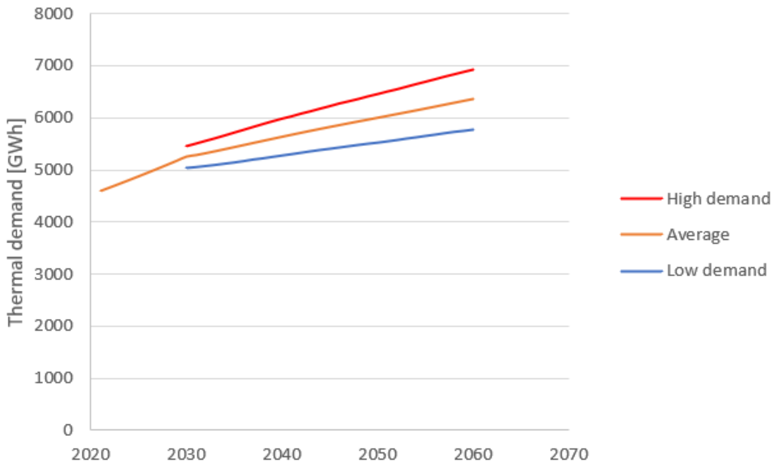


Figure 29: Thermal demand in the capital area in correlation with population growth forecast

According to Veitur, it is estimated that the thermal demand of the capital area will increase by 1,5% /year in the next 8-10 years and then follow population growth in the area over the WtE plants operation period. The graph in figure 29 shows the evolution in thermal demand in the capital area in accordance with the average population forecast with 5% and 95% percentage limits over the next 40 years. The low demand curve displays the 5% percentage limit and the high demand curve displays the 95% percentage limit. This additional supply of district heating water to the capital area would reduce the production load on the geothermal fields in and around the capital area. In that way the WtE plant could delay the necessary exploitation of the geothermal fields in Hellisheiði for some years. According to the graph in figure 29 the WtE plant capacity could cover the increase in thermal demand in the capital area for 4-10 years. If the demand follows the average curve the WtE thermal capacity would cover the increase in thermal demand for 6 years.

Table 9: Change in thermal demand in the capital area compared to WtE plants thermal capacity

Th. demand [GWh]	**Low**	**Average**	**High**
2030	5033	5248	5456
2060	5765	6350	6937
Change	15%	21%	27%
WtE plants capacity over change	31%	20%	15%

9.1.2 Helguvík

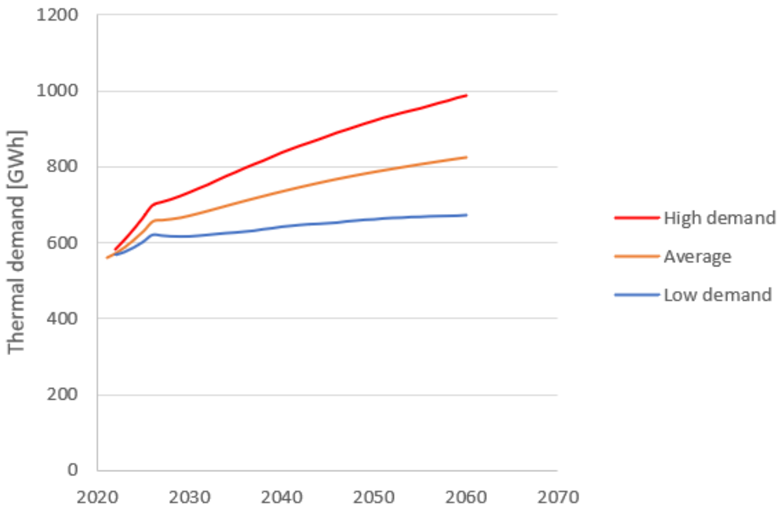


Figure 30: Thermal demand in Reykjanesbær in correlation with population forecast

Helguvík industrial area is located in the municipality Reykjanesbær on the Reykjanes peninsula in the south corner of Iceland. Reykjanesbær is supplied with district heating water from the geothermal power plant in Svartsengi owned by the HS Orka power company. The utility company HS Veitur operates the district heating system connected to the HS Orka power plant in Svartsengi. HS Veitur receives hot water from Svartsengi in two locations. One is at Selháls which supplies district heating to the town Grindavík close to the Svartsengi power plant and the other is Fitjar which supplies district heating to three municipalities on the Reykjanes peninsula, Vogar, Reykjanesbær and Suðurnesjabær. If the WtE plant would be constructed in Helguvík, it could be connected to the Fitjar district heating system. The graph on figure 30 shows the thermal demand

Table 10: Change in thermal demand in Fitjar system compared to WtE plants thermal capacity

Th. demand [GWh]	**Low**	**Average**	**High**
2030	615	672	731
2060	672	825	987
Change	9%	23%	35%
WtE plant capacity over change	399%	147%	88%

forecast for the Fitjar system in relation to population growth in the three municipalities connected to the Fitjar system. The graph shows three possible outcomes, high, average and low increase in thermal demand. According to figure 30 the average thermal demand in the Fitjar system is estimated to increase by 23% over the operation period. This is a similar increase as in the capital area. However, as shown in figure 28 the overall thermal demand in the Fitjar system is significantly lower than in the capital area. In the same sense, the quantitative increase in thermal demand in the Fitja system is much lower than in the capital area. The change in thermal demand is in fact so small that the WtE plant's thermal capacity would cover the entire average increase over the whole period. The increase in the high demand curve is however a bit higher than the WtE plant's capacity. It is estimated that the WtE plants capacity could cover at least 17 years of increase in thermal demand in the Fitjar district heating system in the period between 2030 to 2060.

9.1.3 Þorlákshöfn

Þorlákshöfn is supplied with district heating water from two geothermal wells approximately 11 km from the town limits. District heat demand in 2020 amounted to 95,8 GWh. The graph in figure 31 shows a prediction of thermal demand in correspondence with the population forecast in the municipality of Ölfus from 2022 to 2060. The graph shows three possible outcomes based on high, average and low population growth. In 2020, thermal demand in Þorlákshöfn amounted to only 95,6 GWh according to the Icelandic energy agency. If the thermal demand evolves in correspondence with population growth in the area the total thermal demand will amount to approximately 115 GWh in 2030. That is only 51% of the WtE plant's thermal production capacity. Figure 31 shows a very low average increase in demand of 7% or only 8 GWh over the WtE plants operation period.

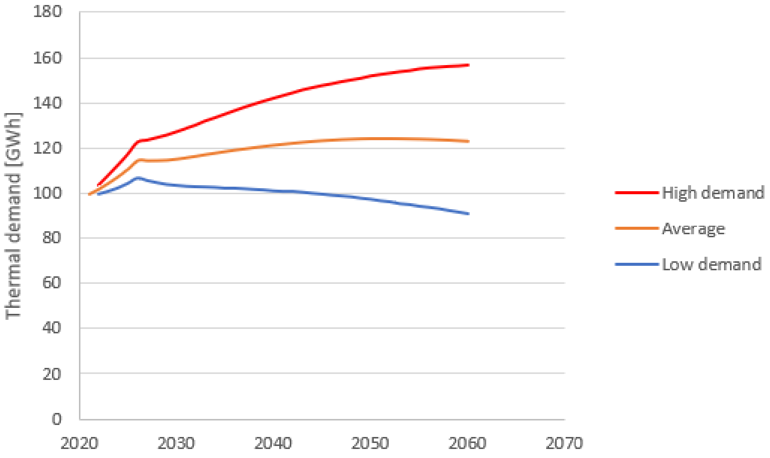


Figure 31: Thermal demand in Þorlákshöfn in correlation with population forecast

The low demand curve even shows a decrease of 12% over the period. The high demand curve shows an increase of 23%, which seems good but only amounts to 29,5 GWh or 13% of the plant's thermal production capacity. From this, it can be deduced that even if thermal demand would increase in line with high population growth, the total thermal demand at the end of the operation period would only be enough to utilize about 70% of the thermal energy supplied by the WtE plant. There would therefore need to be some build-up of a heat-demanding industry in the area that could utilize the excess thermal energy from the WtE plant. In that case, the WtE plant would be highly dependent on the success of this industry.

Table 11: Change in thermal demand in Þorlákshöfn compared to WtE plants thermal capacity

Th. demand [GWh]	**Low**	**Average**	**High**
2030	104	115	127
2060	91	123	157
Change	-12%	7%	23%
Change over WtE plants th. capacity	-	4%	13%

9.1.4 Grundartangi

Thermal demand in the Grundartangi industrial area comes from few service buildings and is estimated to be around 30 GWh. Utilization of thermal energy production from the WtE plant would therefore be completely dependent on the development of the industrial park in the area and connection to the district heating network in the nearby municipalities, Akranes and Hvalfjarðarsveit.

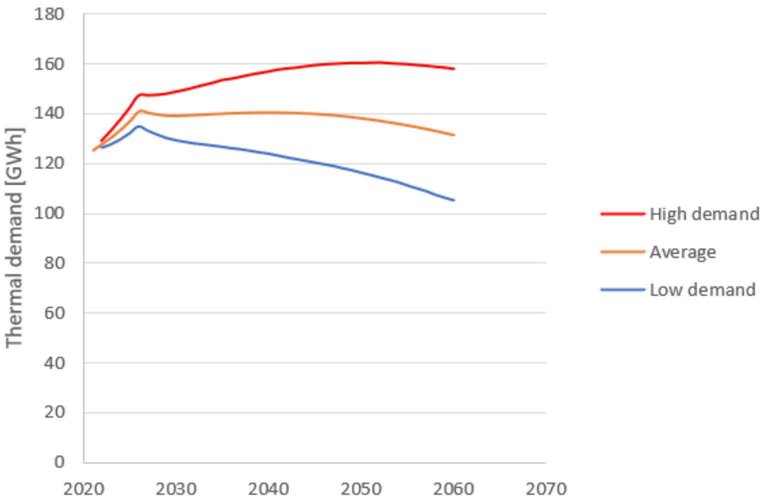


Figure 32: Thermal demand in Akranes in correlation with population forecast

The graph in figure 32 shows the thermal demand forecast in correspondence with population growth in the municipalities of Akranes and Hvalfjarðarsveit, from the year 2022 over the WtE plant's operation period from 2030 to 2060. In 2020, the total thermal demand in Akranes amounted to 122 GWh, which is only 55% of the WtE plant's thermal production capacity. The average change in thermal demand is estimated to decrease by 6% over the WtE plant's operation period. The higher demand curve displays an increase of 9 GWh over the period from 149 GWh to 158 GWh or 6%, which is only about 4% of the WtE plant capacity. However, even if the thermal demand would increase by 6%, the total thermal demand in Akranes would only amount to 70% of the WtE plant's thermal production capacity at the end of the period.

Table 12: Change in thermal demand in Akranes compared to WtE plants thermal capacity

Th. Demand [GWh]	**Low**	**Average**	**High**
2030	129	139	149
2060	105	131	158
Change	-19%	-6%	6%
Change over WtE plants capacity	-	-	4%

It should also be borne in mind that there are plans to utilize waste heat from Elkems ferroalloy factory, for CHP production in the industrial park. It is therefore safe to say that the WtE plant's site selection in the area is highly dependent on the development and construction of infrastructure of the planned industrial park in the Grundartangi area.

9.2 Connections to the power grid

When evaluating the different site selections it is important to consider the existing electricity connections and viability for connection to the national electric power grid in the five areas in question. The national electric power grid in Iceland is operated by the utility company Landsnet. According to Landsnet's terms, an energy producer with a 10MW production capacity or more needs a minimum power grid connection of 66kV.

9.2.1 Álfsnes

There is no power transmission or distribution substation in the Álfsnes area. Korpa power distribution substation is the closest one about 5 km away in the straight airline from the supposed site selection in Álfsnes [48].

9.2.2 Straumsvík

The Hamranes distribution substation is located at the boundaries of the industrial area in Hafnarfjörður at the south limits of the capital area [48]. Hamranes distribution station connects to five, 220 kV high voltage lines and two 132 kV lines. Two of the 220 kV lines lie from Hamranes to the aluminium smelter in Straumsvík. One 132 kV line lies between Hamranes and Fitjar in Reykjanesbær, and the other 132 kV line is an underground cable that lies to the Hnoðraholt distribution substation in the capital area.

9.2.3 Helguvík

The power distribution station in Fitjar provides Reykjanesbær with electricity. Two 132 kV high voltage lines transfer electricity to Fitjar, Fitjalína 1 and Suðurnesjalína. There are plans to lay a 220 kV high voltage line (Suðurnesjalína 2) from the Hamranes substation in Hafnarfjörður to Fitjar and thus increase the transmission capacity of electricity to Reykjanesbær. Reykjanesbær's general plan is to provide five underground cables from the Fitjar substation to the Helguvík industrial area. If the transmission capacity of electricity to Reykjanesbær were increased by 220 kV, the underground power cables between Fitjar and Helguvík could also be up to 220 kV. Currently, there is one 132 kV underground cable laying from the Fitjar substation to the industrial area in Helguvík [48].

9.2.4 Þorlákshöfn

One 66 kV high voltage line runs to Þorlákshöfn from the power transmission station in Hveragerði [48]. The distribution substation for Þorlákshöfn is located just outside the town's limit, so the WtE plant could be stationed fairly close to the grid connection.

9.2.5 Grundartangi

Three 220 kV high voltage lines lay from the transmission substation Brennimelur to the Grundartangi industrial area [48]. The power lines are connected to heavy industry and a distribution substation in the industrial area.

9.3 Incineration bottom ash (IBA)

IBA from the WtE plant is estimated to be between 19600 to 26200 tonnes on a yearly basis or about 2,5 to 3,3 tonnes per hour. The most conventional utilization of IBA is as a base or sub-base for road construction. IBA is also common in the construction of sound barriers along side streets in residential areas or other similar landscaping. IBA can also be used as an aggregate in concrete or asphalt, in which case close proximity to concrete and/or asphalt production plants would be beneficial for the WtE plant. Based on these utilization possibilities it was decided to evaluate the site selection on proximity to densely populated areas and concrete or asphalt plants, for short transportation to potential IBA users.

Table 13: Population density in the residential areas relative to the site selections

	Population	**Population forecast**	
Year	**2022**	**2030**	**2060**
Capital area	**242.259**	**274.247**	**332.195**
Reykjanesbær	**20.105**	**23.579**	**29.070**
Þorlákshöfn	**2.423**	**2.744**	**2.935**
Akranes	**8.518**	**9.269**	**8.752**

Three concrete- and two asphalt production companies were identified as possible buyers. The three concrete companies are Steinsteypan, Steipustöðin and BM Vallá. The two asphalt companies are Hlaðbær Colas and Malbikunarstöðin. Driving distances were measured using the google maps application (see table 14).

Table 14: Shortest distance to the nearest concrete plant and asphalt plant

	Concrete	**Asphalt**
Álfsnes	**16 km**	**3 km**
Straumsvík	**On site**	**On site**
Helguvík	**On site**	**40 km**
Grundartangi	**16 km**	**30 km**
Þorlákshöfn	**30 km**	**47 km**

The nearest concrete plant to Álfsnes is at Breiðhöfði in Reykjavík, owned by the company BM Vallá. According to the google maps application, BM Vallá concrete plant at Breiðhöfði is 16 km driving distance away from the Álfsnes site selection. The closest asphalt plant to the Álfsnes site selection was identified in the industrial area Esjumelur 3 km driving distance away from the site selection in Álfsnes. There are two concrete production plants in the Straumsvík area, one is owned by Steypustöðin and the other is owned by Steinsteypan. One asphalt plant is located in the Straumsvík are owned by Hlaðbær Colas. One concrete production plant owned by Steipustöðin was identified in the Helguvík industrial area. The closest asphalt production plant is located in the Straumsvík area a 40 km driving distance from Helguvík industrial area. The closest concrete production plant to Þorlákshöfn is located in the town of Selfoss, in 30 km driving distance away from Þorlákshöfn. The closest asphalt production plant is Malbikunarstöðin Höfði, located at Sævarhöfði in Reykjavík. The closest concrete production plant to the Grundartangi industrial area is owned by BM Vallá, located on the outskirts of the town of Akranes within 16 km driving distance from the Grundartangi industrial area. The closest asphalt production plant is located at Esjumelur industrial area 16 km driving distance from the Grundartangi industrial area.

9.4 Scrap metal

It is estimated that the recovery of metals from the WtE plant can be approx. 16000 tons of ferrous metal and 6500 tons of non-ferrous metals. There are no actual metal recycling facilities in Iceland, so all scrap metal recovered from the WtE plant would ultimately need to be exported abroad for recycling. In that case, close proximity to the port area is most beneficial regarding the site selection. From that perspective, it was decided to compare distances to the nearest port area, when assessing the possible utilization of scrap metal. Approximated driving distance to the nearest port area can be seen in table 15, distance was measured using the google maps application.

Table 15: Driving distance to the nearest port area

Álfsnes	19,5 km
Straumsvík	4,5 km
Helguvík	<1 km
Grundartangi	<1km
Þorlákshöfn	<1,5 km

9.5 Carbon dioxide

It can be estimated that approx. 189.000 tonnes of carbon dioxide could be captured from the waste incineration emission if 90% capture efficiency is achieved. In the feasibility study made for the WtE plant, it is stated that the WtE plant will not be profitable with additional equipment to capture CO_2 unless the CO_2 captured can be sold for utilization. When the utilization possibilities of carbon dioxide are explored in Iceland, there is no single production that could utilize all that amount today. In fact, the total CO_2 demand in Iceland is only about 6.000 tonnes per year, around 4.000 tonnes are produced in Iceland and the rest is imported from Sweden. It is therefore difficult to estimate the potential use of CO_2 in the site selections based on the current infrastructure. Instead, it was decided to evaluate the potential use of CO_2 based on future plans for the infrastructure development of

CO_2 intensive industry on and around the sites in selection. In this way, the sites that are more advanced in the development of such an industrial environment could be valued higher than other site selections based on utilization of CO_2. The most promising development in CO_2 intensive industry in Iceland in the coming years involves the production of alternative fuels.

9.5.1 Carbon Recycling International (CRI)

CRI is an Icelandic company founded in 2006, the company was founded around the idea of utilizing CO_2 from geothermal gas emissions for the production of valuable products. The company designed its own PtG technology and started the operation of a full-scale PtG plant in 2012. This was the first industrial-scale production plant to utilize CO_2 from waste gas for methanol production. The PtG plant is located close to HS Orka's geothermal power plant in Svartsengi and utilizes CO_2 from the geothermal gas to produce e-methanol. The plant's production capacity is around 4.000 tonnes per year, which translates into recycling of 5.500 tonnes of CO_2 per year[49].

9.5.2 Hydrogen Venture Limited (H2V)

H2V is a venture capital firm that focuses on investments in green hydrogen production projects. The firm is based in the UK and is a collaboration between Climate Change Ventures and Wellington Street Partners. H2V intends to produce a significant amount of hydrogen in collaboration with HS Orka Resource Park on the Reykjanes peninsula. The hydrogen produced will the be used for production of e-methanol. In the first phase of the project, H2V intends to build 30 MW of hydrogen production in the vicinity of one of HS Orka's two geothermal power plants on the Reykjanes peninsula in Iceland. In the project's second phase the production of hydrogen and e-methanol will then be increased to much larger scale[50].

9.5.3 Þorlákshöfn

There are ideas for the development of hydrogen production in Þorlákshöfn for the production of hydrogen and/or alternative fuels. On March 25, 2021, the board of the municipality of Ölfus agreed to start a collaboration with Efla engineering consultant agency and Summa investment company, to undertake a feasibility study on hydrogen production in Þorlákshöfn and other hydrogen-derived products such as e-methanol or other alternative fuels.

9.5.4 Nordur Renewables Iceland

The company Nordur Renewables Iceland intends to construct and operate a PtG plant in ON ECO park at Hellisheiði, which produces hydrogen and SNG from hydrogen and CO_2. The geothermal power plant in Hellisheiði is in the municipality of Ölfus, but provides thermal power to the capital area. The ON ECO park is an industrial park which utilizes value streams from the geothermal power plant in Hellisheiði. The geothermal power plant provides value streams such as electricity, thermal energy, cold water and CO_2 to companies connected to the ECO park. The PtG plant will produce 3.300 tonnes of $[H_2]$ per year and use about 18.200 tonnes of CO_2 from ON geothermal power plant, for production of 6.000 tonnes of e-methane [51]. In relation to the site selections, the ECO park is in similar proximity to both Straumsvík and Álfsnes areas, or about 38 km driving distance. However, the shortest distance is to the Þorlákshöfn area or approx. 28 km driving distance.

9.5.5 Grundartangi

Þróunarfélag Grundartangi is an association of companies, municipalities and other stakeholders in the Grundartangi area who work together to develop a green industrial park in the Grundatangi area. Development on the construction of a green industrial park or ECO park in the Grundartangi area has already begun. As previously stated, the government has signed a statement of intent with municipalities and stakeholders in the Grundartangi area, to start cooperation in building up infrastructure for the green industrial park. The first phase of the project will be to build infrastructure such as a connection to the district heating system from the area to the surrounding municipalities, preparation for CHP utilization of waste heat and CCS from Elkem's ferroalloy plant in the area. The second phase of the project will look at the production of alternative fuels by electrolysis of hydrogen. Cooperation has already begun between CRI, Landsvirkjun (National Power Company of Iceland), Þróunarfélag Grundartangi and Elkem Iceland, to examine the possibility of producing e-methanol with CO_2 captured from Elkem's ferroalloy plant in the Grundartangi area [52].

10 Results

AHP analysis was used to compare site selections based on potential value streams from the WtE plant. AHP is a decision-making process for organizing and analysing complex decisions, where alternatives are compared based on multiple criteria. In this case, the site selections are the alternatives and the value streams are the different criteria.

Table 16: Criteria weights of the WtE plants value streams

	Weights [%]
Thermal demand	**47%**
Grid connection	**31%**
CO2 utilization	**7%**
IBA utilization	**10%**
Scrap metal	**5%**

The value streams are thermal energy, electric power, CO_2, IBA and scrap metal. In making the AHP analysis the criteria are compared through pair-wise comparison, two at a time and weighted based on importance. To make the pair-wise comparison the criteria has to be evaluated and evaluations of the criteria are then converted into numbers based on a ranking system. Thermal demand is considered the most important criteria due to the need to comply with the R1 rule on energy efficiency. Connection to the electric grid is second most important, for the possibility of selling electricity. The third most important value stream is the IBA, as it is relatively easy to put IBA to use instead of sending it to a landfill. CO_2 was ranked less important value stream than IBA, as it is not sufficiently certain that it will be possible to utilize that value stream domestically, at least not in the amount expected. It depends a lot on infrastructure development in hydrogen production for making alternative fuels such as methane, methanol, SNG or other CO_2 demanding industries. Scrap metal is considered the least relevant value stream with respect to site selection, based on how much less amount scrap metal is estimated to accumulate from the process compared to the other value streams. When the criteria has been weighed, the alternatives are evaluated and compared based on the different criteria. Results from the pair-wise comparison of the site selections can be seen in figures 33 to 37.

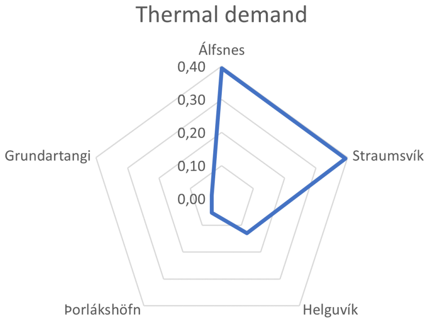


Figure 33: Comparison of sites based on change in thermal demand in the corresponding district heating systems

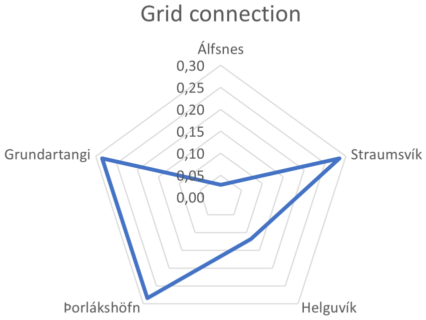


Figure 34: Pairwise comparison of sites based on available connections to the national electirc grid

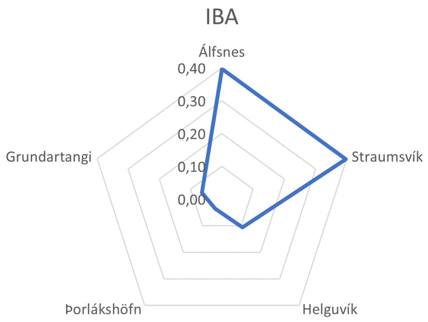


Figure 35: Pairwise comparison of sites based on IBA utilization

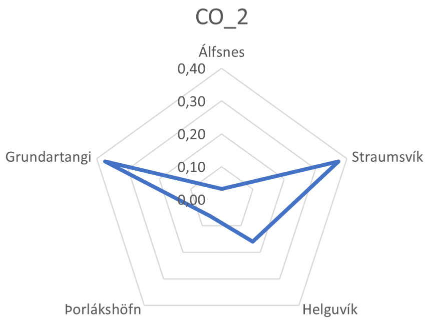


Figure 36: Pairwise comparison of sites based on CO_2 utilization

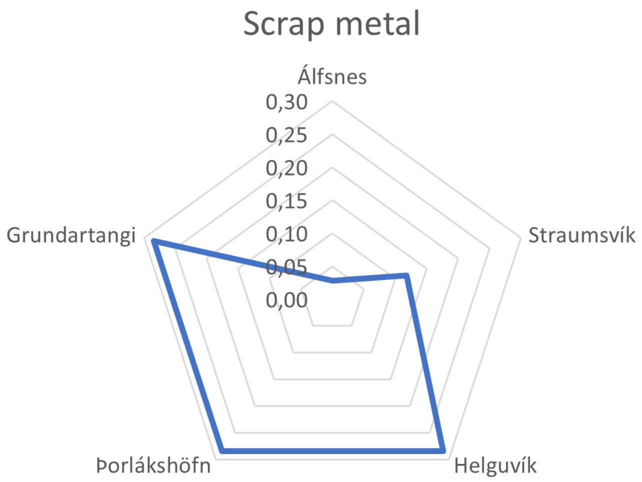


Figure 37: Pairwise comparison of sites based on proximity to port area

The site selections were prioritized based on the potential utilization of the value streams and there importance. The final rating of the site selections can be seen in table 17. These results show the superiority of Straumsvík and Álfsnes over the other alternatives for utilizing value streams from the WtE plant, based on the data that were used as a basis and for comparison.

Table 17: Site selections final rating based on utilization of value streams

	Rating [%]
Álfsnes	**24%**
Straumsvík	**35%**
Helguvík	**13%**
Þorlákshöfn	**13%**
Grundartangi	**15%**

11 Discussion

When a change in thermal demand was compared between the four district heating systems that were considered, the capital area scored the highest, as by far the largest change in thermal demand can occur. Álfsnes and Straumsvík are both locations within the capital area and were equated in this analysis. Next came Helguvík with the possibility of connecting to the Fitjar district heating system. The thermal demand in the Fitjar system is relatively small compared to the thermal demand in the capital area, in fact, it is so small that the thermal supply from the WtE plant could potentially cover the entire change in thermal demand in the Fitjar system over the period 2030-2060. However, the total thermal demand in the Fitjar district heating system is so low that the additional thermal supply from the WtE plant would cover most of the total thermal demand at the beginning of the period. This would therefore create hard competition for heat supply with the current heat producer in the area, which is HS Orka power company. The district heating systems applicable for Grundartangi and Þorlákshöfn are both too small to utilize the thermal supply from the WtE plant. In that case, the WtE plant would be highly dependent on thermal demanding industries in the areas, which would not be optimal for the operational security of the plant.

When connections to the national electricity grid were considered, it turned out that only three of the five sites had adequate connection possibilities to the grid ready on site. These sites were Þorlákshöfn, Straumsvík and Grundartangi, and were equated in the pair-wise comparison (see Appendix 3). It shall be noted, that Þorlákshöfn only has a 66kV grid connection available but both Straumsvík and Grundartangi have 220 kV grid connections. However, since a 66kV grid connection is enough for 10 MW power connection they were considered equal in the analysis. Helguvík has one 132 kW power cable which is connected to a silicon production plant in the area, however, the future of the heavy industry in the Helguvík area is still a bit uncertain. It is therefore not considered reliable to use the electrical connection that is already present or whether a new cable will need to be installed if electricity production is established in the area. In that context, it shall be noted that laying of additional 132-220 kV power cables into the Helguvík area is already part of the municipal plan in Reykjanesbær. Álfsnes is therefore the only site that does not have sufficient electrical connection to the national grid for electricity production and therefore scored the lowest in that category.

Utilization of CO_2 was evaluated based on the development of CO_2 demanding industries in or in close proximity to the sites in selection. However, this could be a bad approach as the location of the CO_2 derived fuel production would probably depend on the location of the CO_2 source rather than the other way around. Thus, it would actually be better to estimate locations based on the electrical connection for hydrogen production via electrolysis purified water. It was therefore decided to include an electrical connection in the assessment of the utilization of CO_2 from the plant. This led to Straumsvík and Grundartangi scoring equally in the comparison of CO_2 utilization, as both locations have the advantage of a 220 kV electrical connection on site. The second highest score went to Helguvík as the area has the possibility of 132 kV electric grid connection and H2V has already shown interest in collaboration with HS Orka's Resource Park for the production of methanol close to the Helguvík area. Although Þorlákshöfn was considered to have an adequate grid connection to transmit electricity from the WtE plant, it is not considered sufficient enough for the production of hydrogen via water electrolysis of the scale in question. Álfsnes scored lowest in the comparison of CO_2 utilization. The area does not present any special properties for the production of electric fuel as there is no electricity transmission or distribution station in the area and the nearest electricity transmission station is at a considerable distance from the site.

Utilization of IBA was evaluated based on population density and proximity to concrete or asphalt production plants. Straumsvík and Álfsnes scored equal and highest in the pair-wise comparison of IBA utilization, as both sites are located within the capital area which has by far the highest population density. Though it shall be noted, that the mineral processing company Björgun, intends to move its mineral processing plant over to the Álfsnes industrial area. This may create significant potential for the utilization of IBA in the area. Helguvík has the second highest score as Reykjanesbær is the fourth largest municipality in Iceland. There is one concrete production plant located in the Helguvík area. However, the demand for IBA in the Helguvík area is not expected to be high enough to fully utilise the IBA produced. In that case, the excess IBA would have to be transported a long way (min 40 km) to the capital area for utilization. Grundartangi and Þorlákshöfn scored lowest in the pair-wise comparison for IBA, as both areas have very low utilization possibilities in relation to population density. Grundartangi scored a bit higher as it has closer proximity to a concrete production plant.

Utilization of scrap metal was evaluated based on close proximity to a port area, three sites scored equal in the pair-wise comparison, Þorlákshöfn, Helguvík and Grundartangi. All these three sites have possible access to a port area within a 1 km driving distance. Straumsvík scored a bit lower as the port area in Straumsvík is not quite as accessible as in the other three sites. Álfsnes provides by far the worst access to a port area of all the sites in the selection, as the shortest driving distance from Álfsnes to the nearest port area is about 20 km. However, this distance will decrease significantly if future plans for a new highway that connects the north route into the capital area, through the Álfsnes industrial area become a reality.

12 Conclusion

Based on the results presented, Straumsvík industrial area provides the best site selection for utilization of energy and other value streams from the WtE plant on the scale in question. In a previous study, three sites: Álfsnes, Straumsvík and Helguvík were considered similar options for site selection in terms of transport efficiency to the plant and other important criteria. Grundartangi and Þorlákshöfn were deemed non-competitive to the other locations in that same comparison. In terms of transport efficiency of combustible waste to the WtE plant, Álfsnes was assessed to be the best site selection. The other four locations were then compared in terms of additional transportation costs compared to Álfsnes. Straumsvík was found to have the second lowest transportation cost, with 23 million ISK/year. Grundartangi came in third place with 47 million ISK/year additional cost and then Helguvík and Þorlákshöfn came last with 74 million additional transportation cost of combustible waste to the WtE plant.

From the results of this thesis it is further concluded, that in terms of combined transportation cost and utilization of energy and other value streams from the WtE plant, Helguvík can be deemed noncompetitive to Álfsnes and Straumsvík. Therefore the final choice stands between Álfsnes and Straumsvík. However, it is still uncertain whether the cost of transporting waste to the plant will outweigh the utilization of value streams from the plant. Further research is needed to determine which place stands out in that comparison. It should also be noted that there is still a lot of uncertainty regarding the Álfsnes area. For example, new highway connection through the Álfsnes area into the capital area could decrease transportation costs considerably and increase the gap in transportation costs between Álfsnes and Straumsvík even further. The two locations scored equal in pair-wise comparison of IBA utilization, although Álfsnes is a bit more remote to the capital area than Straumsvík. The main difference, however, that makes Straumsvík a more desirable alternative than Álfsnes, can be attributed to the connection potential with the national electricity grid. Álfsnes scored lowest in the pair-wise comparison of electric grid connection while Straumsvík scored highest. The electric grid connection is the second most important criteria, but the grid connection also attributes to the potential CO_2 utilization as it provides the possibility of large-scale CO_2 demanding production of valuable products such as methane, methanol and SNG.

In light of the rapid technological development that is currently taking place in the capture of $CO\ _2$ from the emissions of WtE plants, both in Norway and Denmark, this technology might be commercialized by 2030. It is therefore likely that CO_2 will weigh even more heavily in comparison value streams from a WtE plant in the near future. Iceland's special position in the production of green energy and the government's optimistic goals in energy change in the fisheries sector and air transport in the coming years create unique opportunities for the utilization of CO_2. High utilization of CO_2 would also be in line with climate goals as well as SDGs for higher resource efficiency and better utilization of raw material, which is also in line with the government's policy towards a circular economy. It is highly suggested for further research be undertaken on potential CO_2 utilization from the WtE plant's emission. To ensure that the plant supports the economic, environmental and social pillars of sustainable development in the best possible way.

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14 Appendix

.1 Criteria comparison

Table 18: Pair-wise comparison of energy and value streams from the WtE plant

Criteria comparison matrix [C_C]					
	Thermal Demand	Grid Connection	CO_2 utilization	IBA utilization	Scrap metal export
Thermal Demand	1	2	7	5	9
Grid Connection	0,50	1	6	3	8
CO2 utilization	0,14	0,17	1	0,33	3
IBA utilization	0,20	0,33	3,00	1	1
Scrap Metal export	0,11	0,13	0,33	1,00	1
Sum	1,95	3,63	17,33	10,33	22,00

Table 19: Normalization of the criteria comparison matrix [C_C]

Normalization matrix [N_C]					
	Thermal Demand	Grid Connection	CO2 utilization	IBA utilization	Scrap Metal export
Thermal Demand	0,51	0,55	0,40	0,48	0,41
Grid Connection	0,26	0,28	0,35	0,29	0,36
CO2 utilization	0,07	0,05	0,06	0,03	0,14
IBA utilization	0,10	0,09	0,17	0,10	0,05
Scrap Metal export	0,06	0,03	0,02	0,10	0,05
Sum	1	1	1	1	1

.2 Pair-wise comparison of site selections based on thermal demand

Table 20: Comparison matrix shows pair-wise comparison of site selections based on change in thermal demand

Comparison matrix for Thermal Demand [C_{TD}]					
	Álfsnes	Straumsvík	Helguvík	Þorlákshöfn	Grundartangi
Álfsnes	1	1	5	9	9
Straumsvík	1	1	5	9	9
Helguvík	0,2	0,2	1	5	5
Þorlákshöfn	0,11	0,11	0,20	1	3
Grundartangi	0,11	0,11	0,20	0,33	1
Sum	2,4	2,4	11	24	27

Table 21: Normalization of [C_{TD}] and priority vector for site selections based on thermal demand

Normalization matrix for thermal demand [N_{TD}]						Site selection priority vector [P_{TD}]
	Álfsnes	Straumsvík	Helguvík	Þorlákshöfn	Grundartangi	
Álfsnes	0,41	0,41	0,44	0,37	0,33	0,39
Straumsvík	0,41	0,41	0,44	0,37	0,33	0,39
Helguvík	0,08	0,08	0,09	0,21	0,19	0,13
Þorlákshöfn	0,05	0,05	0,02	0,04	0,11	0,05
Grundartangi	0,05	0,05	0,02	0,01	0,04	0,03

Sum	1	1	1	1	1

.3 Pair-wise comparison of site selections based on electric grid connection

Table 22: Comparison matrix shows pair-wise comparison of site selections based on electric grid connection

Comparison matrix for Grid Connection C[$_{GC}$]					
	Álfsnes	Straumsvík	Helguvík	Þorlákshöfn	Grundartangi
Álfsnes	1	0,11	0,14	0,11	0,11
Straumsvík	9	1	3	1	1
Helguvík	7	0,3	1	0,33	0,33
Þorlákshöfn	9	1	3	1	1
Grundartangi	9	1	3	1	1

Sum	35	3,4	10	3,4	3,4

Table 23: Normalization of [C_{GC}] and priority vector for site selections based on electric grid connection

Normalization matrix for Grid Connection [N_{GC}]						Site selection priority vector [P_{GC}]
	Álfsnes	Straumsvík	Helguvík	Þorlákshöfn	Grundartangi	
Álfsnes	0,03	0,03	0,01	0,03	0,03	0,03
Straumsvík	0,26	0,29	0,30	0,29	0,29	0,28
Helguvík	0,20	0,10	0,10	0,10	0,10	0,12
Þorlákshöfn	0,26	0,29	0,30	0,29	0,29	0,28
Grundartangi	0,26	0,29	0,30	0,29	0,29	0,28

Sum	1	1	1	1	1

.4 Pair-wise comparison of site selections based on CO_2 utilization

Table 24: Comparison matrix shows pair-wise comparison of site selections based on CO_2 utilization

Comparison matrix for CO2 use [C_{CO_2}]					
	Álfsnes	Straumsvík	Helguvík	Þorlákshöfn	Grundartangi
Álfsnes	1	0,11	0,14	0,33	0,11
Straumsvík	9	1	3	7	1
Helguvík	7	0,33	1	3	0,33
Þorlákshöfn	3	0,14	0,33	1	0,14
Grundartangi	9	1	3	7	1

Sum	29,0	2,6	7,5	18,3	2,6

Table 25: Normalization of [C_{CO_2}] and priority vector for site selections based on CO_2 utilization

Normalization matrix for CO2 use [N_{CO_2}]					
	Álfsnes	Straumsvík	Helguvík	Þorlákshöfn	Grundartangi
Álfsnes	0,03	0,04	0,02	0,02	0,04
Straumsvík	0,31	0,39	0,40	0,38	0,39
Helguvík	0,24	0,13	0,13	0,16	0,13
Þorlákshöfn	0,10	0,06	0,04	0,05	0,06
Grundartangi	0,31	0,39	0,40	0,38	0,39
Sum	1	1	1	1	1

Site selection priority vector [P_{CO_2}]
0,03
0,37
0,16
0,06
0,37

.5 Pair-wise comparison of site selections based on IBA utilization

Table 26: Comparison matrix shows pair-wise comparison of site selections based on IBA utilization

Comparison matrix for IBA use [C_{IBA}]					
	Álfsnes	Straumsvík	Helguvík	Þorlákshöfn	Grundartangi
Álfsnes	1	1	5	9	7
Straumsvík	1	1	5	9	7
Helguvík	0,20	0,20	1	3	3
Þorlákshöfn	0,11	0,11	0,33	1	0,33
Grundartangi	0,14	0,14	0,33	3	1
Sum	2,5	2,5	12	25	18

Table 27: Normalization of [C_{IBA}] and priority vector for site selections based on IBA utilization

Normalization matrix for IBA use [N_{IBA}]					
	Álfsnes	Straumsvík	Helguvík	Þorlákshöfn	Grundartangi
Álfsnes	0,41	0,41	0,43	0,36	0,38
Straumsvík	0,41	0,41	0,43	0,36	0,38
Helguvík	0,08	0,08	0,09	0,12	0,16
Þorlákshöfn	0,05	0,05	0,03	0,04	0,02
Grundartangi	0,06	0,06	0,03	0,12	0,05
Sum	1	1	1	1	1

Site selection priority vector [P_{IBA}]
0,40
0,40
0,11
0,04
0,06

.6 Pair-wise comparison of site selections based on scrap metal export

Table 28: Comparison matrix shows pair-wise comparison of site selections based on scrap metal export

Comparison matrix for scrap metal export [C_{SM}]					
	Álfsnes	Straumsvík	Helguvík	Þorlákshöfn	Grundartangi
Álfsnes	1	0,14	0,11	0,11	0,11
Straumsvík	7	1	0,33	0,33	0,33
Helguvík	9	3	1	1	1
Þorlákshöfn	9	3	1	1	1
Grundartangi	9	3	1	1	1
Sum	35	10	3,4	3,4	3,4

Table 29: Normalization of [C$_{SM}$] and priority vector for site selections based on scrap metal export

Normalization matrix for scrap metal export [N$_{SM}$]						Site selection priority vector [P$_{SM}$]
	Álfsnes	Straumsvík	Helguvík	Þorlákshöfn	Grundartangi	
Álfsnes	0,03	0,01	0,03	0,03	0,03	0,03
Straumsvík	0,20	0,10	0,10	0,10	0,10	0,12
Helguvík	0,26	0,30	0,29	0,29	0,29	0,28
Þorlákshöfn	0,26	0,30	0,29	0,29	0,29	0,28
Grundartangi	0,26	0,30	0,29	0,29	0,29	0,28
Sum	1	1	1	1	1	

.7 Final rating matrix from site selection priority vectors

Table 30: Final raing matrix containing all site selection priority vectors

Final rating matrix [F]					
	Álfsnes	Straumsvík	Helguvík	Þorlákshöfn	Grundartangi
[P$_{TD}$]	0,39	0,39	0,13	0,05	0,03
[P$_{GC}$]	0,03	0,28	0,12	0,28	0,28
[P$_{CO_2}$]	0,03	0,37	0,16	0,06	0,37
[P$_{IBA}$]	0,40	0,40	0,11	0,04	0,06
[P$_{SM}$]	0,03	0,12	0,28	0,28	0,28

.8 Transposed final rating matrix from site selection priority vectors

Table 31: Transposed final rating matrix for calculations of final rating

Final rating matrix transposed [F]^T					
	[P$_{TD}$]	[P$_{GC}$]	[P$_{CO_2}$]	[P$_{IBA}$]	[P$_{SM}$]
Álfsnes	0,39	0,03	0,03	0,40	0,03
Straumsvík	0,39	0,28	0,37	0,40	0,12
Helguvík	0,13	0,12	0,16	0,11	0,28
Þorlákshöfn	0,05	0,28	0,06	0,04	0,28
Grundartangi	0,03	0,28	0,37	0,06	0,28