Simon Challet
s101545

Optimization of heat utilization from the waste incinerator in Sisimiut

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Supervisors:
Pernille Erland Jensen (DTU ARTEK)
Masoud Rokni (DTU MEK)

ARCTIC TECHNOLOGY CENTRE

Technical University of Denmark

Preface

This project took place from summer to autumn 2011, as part of the course “11 427: Arctic Technology” organized by the Arctic Technology Center (ARTEK), and was worth 15 ECTS. The ARTEK Center is a collaboration between the Building and Construction school of Sisimiut (Sanaartornermik Ilinniarfik) and the Technical University of Denmark (DTU), in Lyngby. The Center is funded by the Government of Greenland and private donators, and belongs officially to the Department of Civil Engineering of DTU.

The Arctic technology course included a preliminary semester of evening classes, during which a broad overview of Greenland was given to the students by a group of specialists from ARTEK, each teaching about his own field. The purpose of the present project was originally defined as a technical and economic analysis looking at analysing, modelling and optimizing the extension and potential merging of district heating networks in Sisimiut, using linear programming software. Optimization of heat utilization from the incinerator was included in the topic.

Three weeks of fieldwork were then carried out in Sisimiut in the month of August 2011, during which contact was established with interlocutors from the municipal waste incinerator, the municipality, the Nukissiorfiit office and private consultants. Knowledge and understanding of the local context was acquired, as well as the various opinions of my contacts on the waste incinerator and district heating management and operation in the city. This has been a very enriching phase.

Most of the work presented in this report took place during the autumn semester. It was realised then that the primary goal of the project could not be achieved due to a lack of accurate data regarding the district heating systems in Sisimiut. Therefore the secondary subject of optimization of heat utilization from the waste incinerator was prioritized to become the main subject for the project.

This course was taken as part of my education on the Master program in Sustainable Energy Engineering, study line in Thermal Energy, at the Technical University of Denmark.

Simon P.F. Challet
DTU, Kgs. Lyngby, 5 December 2011

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- Henrik Steffensen, district heating engineer at Rambøll Copenhagen.
- Jørn Hansen, consultant engineer at Rambøll Sisimiut.
- John Thomsen, engineer at Nukissiorfiit Sisimiut.
- Lone Kristensen, environmental engineer for the municipality of Sisimiut.

I greatly appreciate their patience and kindness.

Finally, I express my gratitude to my supervisors Pernille Jensen and Masoud Rokni, who have been available for me more than I have requested.

I. Introduction

Sisimiut is a small town located on the west coast of Greenland, just north of the Arctic Circle. With roughly 5 500 inhabitants it is the second largest locality in a country which is on the same scale as Europe, and which interior transportation's is mainly based on aviation and maritime ways. The remoteness and clustered infrastructure of Greenlandic communities makes appropriate waste management challenging at the local and national scales. In Sisimiut significant efforts are made to ensure that the environmental and sanitary impact of generated waste remains as low as possible, given the local constraints. A high priority is given to the disposal of household and commercial waste, containing high fractions of organic materials and therefore a non-negligible threat to the health of the town's residents. Since landfilling organic waste would only result in poor sanitary conditions and high methane emissions to the atmosphere, residential waste is collected every week day and incinerated in the purpose-built municipal waste incinerator.

In total roughly 3 000 tons of waste are incinerated every year, and hot water is produced from the process in order to supply district heating to a neighboring part of the city. District heat is also provided in this network by two dedicated heat plants in which electric boilers and oil boilers are operated. These two plants and the district heat system are owned by Nukissiorfiit, a Greenlandic government-owned utility in charge of public electricity and heat supply in the country, and which buys heat from the incinerator plant. Priority is given to the utilization of heat generated by the waste incinerator over the boilers located in the plants, since this recovered heat is considered as a 'free' by-product from a necessary process. Utilizing waste heat from the incineration plant therefore reduces the consumption of oil in the district heat system, and lowers the carbon emissions of the city.

Operation records from the incinerator however show that at times only a fraction of the recovered heat is being sold to the district heat grid, and that large amounts of this heat are rather dissipated to the ambient air in a back-up cooling station. One suggested reason for this major system inefficiency is that the district heating grid is undersized compared to the heat capacity of the waste incinerator.

The work presented in this report aims at evaluating the different causes behind the problem of low heat utilization from the waste incinerator, at identifying and quantifying the major parameters influencing the issue, and at suggesting methods to improve the situation.

A description of the energy and waste contexts in Greenland and Sisimiut are given in the two first parts of the report, including a portrayal of the waste management site and incinerator in Sisimiut. The problematic of the project is then introduced in more details, and an analysis of the incinerator parameters identified as being the most relevant is carried out. The results of this analysis are used as an input to a conceived Excel spreadsheet model, which allows its user to simulate the incinerator operation in varying functional conditions. The created model is at that point used to evaluate the maximal heat utilization factor achievable by the incinerator in the present conditions. The expected influence of future changing systemic parameters on the maximal heat utilization factor is similarly assessed. Finally recommendations for physical implementations leading to further improved heat utilization are given, involving the examination of a heat storage tank.

II. The Greenlandic context: Generalities, Energy and Waste

1. Short introduction to Greenland

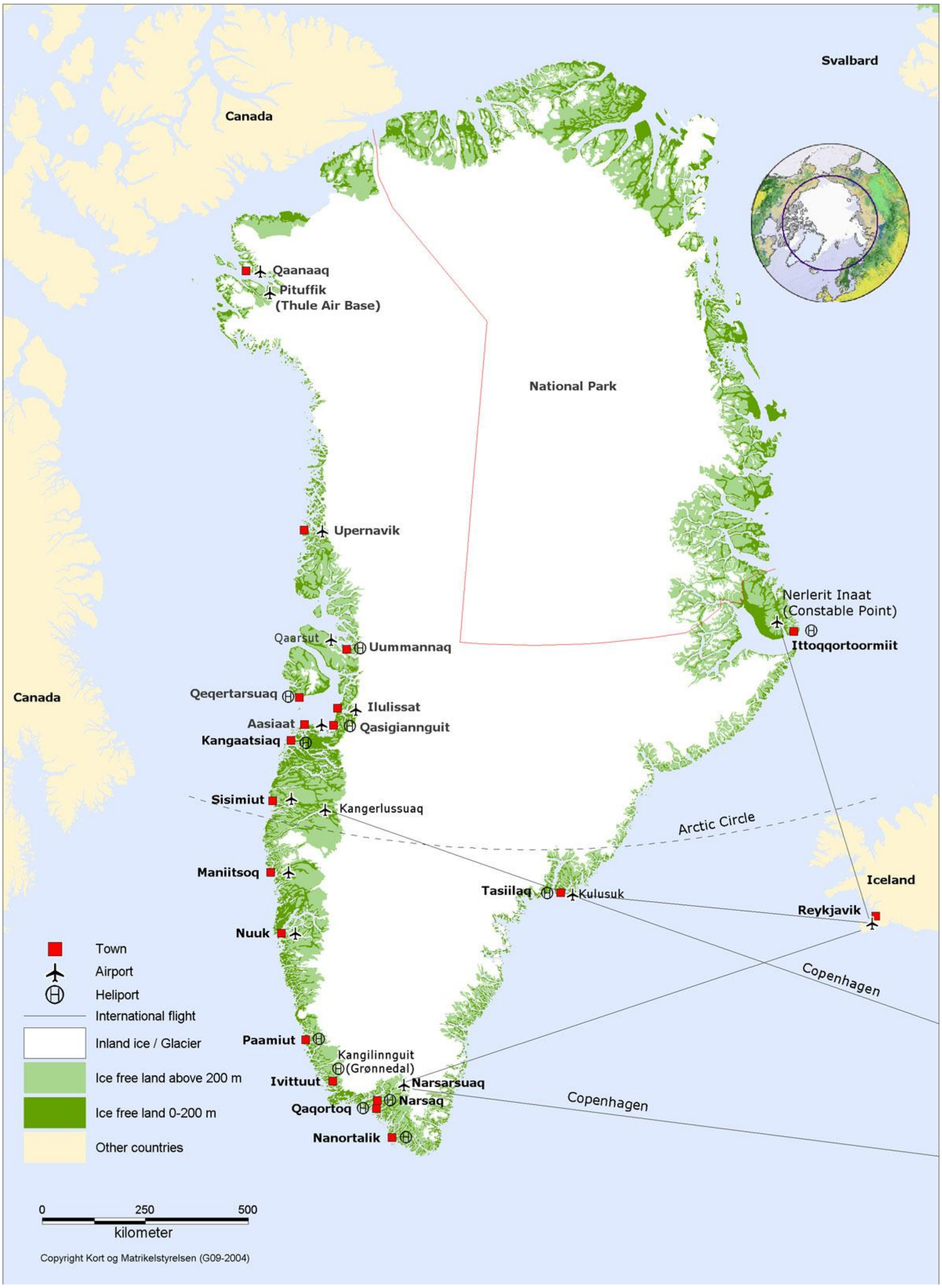

FIGURE 1: MAP OF GREENLAND (2)

Located north of the Atlantic Ocean, between north Canada and Iceland, Greenland is the largest island on Earth with an area of 2.4 million kilometers. Two thirds of its landmass lies north of the Arctic Circle, and the climate varies from arctic in the Southern tip (60°N) to subarctic in the North (83°N). The regions north of the Arctic Circle are exposed to "Midnight sun" in summer and uninterrupted periods of darkness during winter. Greenland is widely known for the 3 kilometer thick ice cap that covers about 80% of its surface area, and with a volume of 2.8 million cubic kilometers holds 10% of the world's total fresh water reserves (3). It is estimated that ice from the polar cap is in some parts as ancient as 110 000 years old, and that if it melted completely due to climate change the global sea level could rise by 7.2 meters within a few hundred years (4). Ice-free landscapes are found along the coastline of Greenland and are characterized by eroded mountains and deep fjords. The vegetation is very limited due to the long arctic winters, and local wildlife consists of a small variety of fishes, birds, reindeers, muskoxen, polar bears, seals and whales.

FIGURE 2 : TYPICAL GREENLANDIC COASTAL LANDSCAPE DURING SUMMERTIME, BETWEEN SISIMIUT AND KANGERLUSSUAQ.

The earliest traces of human presence in Greenland have been dated to 2500 BC and since then different tribes and cultures have slowly expanded, evolving in the now prevailing Inuit ethnicity. Icelanders and Norwegians founded the first colonizing settlements in Greenland from 1000 AD, but Denmark easily obtained sovereignty over the island in the early 17th century. The air and maritime transport infrastructure of Greenland were intensely developed by the United States during World War II, as Greenland was one of the necessary stops in the aerial bridge linking America to Europe over the North-Atlantic. Greenland gained some autonomy in 1979 with the ratification of the Home rule, while remaining part of the Kingdom of Denmark. The Greenlandic parliament was further granted more power in 2009, with foreign affairs, security and financial policies remaining in hand of Denmark. Greenland is also still economically dependent from Denmark, at a level of 3.4 billion Kroners per year, equivalent to half of the public spending (5).

With a surface area 56 times bigger than Denmark, Greenland has one of the scarcest population densities in the world. The majority of the 56 000 Greenlanders is found in towns and settlements on the west, mostly ice-free shore of the island, and 15 000 alone live in the capital city Nuuk. Although elements of Danish and international culture have diffused in Greenland, the Inuit culture still holds a special importance in the local lifestyle. The official language remains Greenlandic before Danish, and traditions such as hunting, whaling, kayaking and dog sledging are well maintained. The Greenlandic economy is mostly based on fishing (90% of exports), with a continued growth of tourism, and prospects suggest that mineral mining and oil production are likely to take a significant place in the coming years. Overall, Greenland is very dependent on imports of goods from Denmark and Europe, which are for the most part conveyed by boat (5). Due to the large distances involved, inter-city road infrastructure is inexistent in Greenland. Transportation between towns and settlements is done either by helicopter, plane, boat, or dog-sledge and snowmobile during winter. Road transportation is found in the largest towns in Greenland, and the country reportedly has only four operational traffic lights (6).

Despite hosting some of the most pristine environments on Earth, Greenland is presently faced with strong environmental issues. These problems partly have global sources, with for example the threat of global warming on the stability of the ice cap, but also many indigenous sources. Environmental awareness has remained marginal for a long period in Greenland and air, water and ground have already paid a heavy toll to local pollution in many inhabited places. Moreover, despite the now more ambitious Governmental plans to improve sustainability in Greenland, the country ranked in 2006 as having the third largest ecological footprint per person in the world, behind the USA and ex aequo with the Bahamas (7).

2. *Energy context in Greenland*

Electricity production in Greenland is managed by a government-owned utility called Nukissiorfiit. Since the towns and settlements are located far from each other, no national or regional electricity grids are operated. Electricity production and consumption are therefore matched locally, in closed systems. From the 1950s, electricity generation in Greenland has been based mostly on diesel engines, due to the technology’s availability, relatively low investment costs and scalable generation features. The fuel used in such engines (and in Greenlandic diesel vehicles) is Arctic Grade Oil (AGO). This oil is characterized by a low paraffin content, which lowers the cloud point (the temperature at which crystallization starts in the fuel) and is suited for storage and use in cold temperature environments.

Diesel engines commonly have a thermal efficiency close to 35%, which means that 65% of their fuel consumption is rejected as heat. In order to utilize this ‘waste’ heat, most of the Diesel generators in Greenland have progressively been converted to Combined Heat and Power (CHP) technology, making the waste heat from the engines available for heating purposes (5). The efficiency of the process can be very high in well-designed systems, with up to 90% of the fuel heat content being utilized.

With a willingness to reduce dependency on imported oil and use more local renewable energy, preliminary studies on Greenlandic hydropower plants started in the 1970s. The real development of the technology started only in the 1990s, and in 2010 five towns were equipped with medium-to-large scale hydropower, together representing 40% of the total Greenlandic electricity demand (5). A new 22 MW hydropower plant is currently under construction in Ilulissat and is expected to begin production in 2012-2013, and micro hydropower projects for remote settlements are under development. Wind power is also seen as a possibility to produce renewable energy in southern Greenland, where the wind is the strongest, and small scale wind turbines have already been implemented in a handful of settlements. Tidal and wave power as well as geothermal energy are considered as potential renewable sources for the future electricity supply in Greenland (8).

FIGURE 3: BUKSEFJORD HYDROPOWER PLANT, SUPPLYING NUUK WITH A CAPACITY OF 45 MW (8).

Space heating for buildings is required all year long due to the arctic climate prevailing in Greenland. Heat is supplied in two different ways: either through individual oil boilers (mostly in individual houses and small settlements) or by connection to a district heat network. District heating is mostly developed in the largest Greenlandic towns, where building density is high and good infrastructure is available. A number of dedicated heat plants then supplies heat to the connected buildings through a series of insulated pipes, which can be either buried underground or laid overground, and in which hot water is pumped. In large district heat systems the heat is transferred from the pipe network to the heating and domestic hot water systems of the customer buildings through heat exchangers called substations. In this way water from the district heat network is not directly circulated inside the buildings. The basic layout of a district heating network is sketched in Figure 4. District heating is usually regarded as being more efficient and cost-effective compared to individual heating, and allows utilization from waste heat originating from CHP plants or waste incinerators.

Recently solar heating has also been introduced in Greenland on a testing scale, as a renewable complement to individual heating.

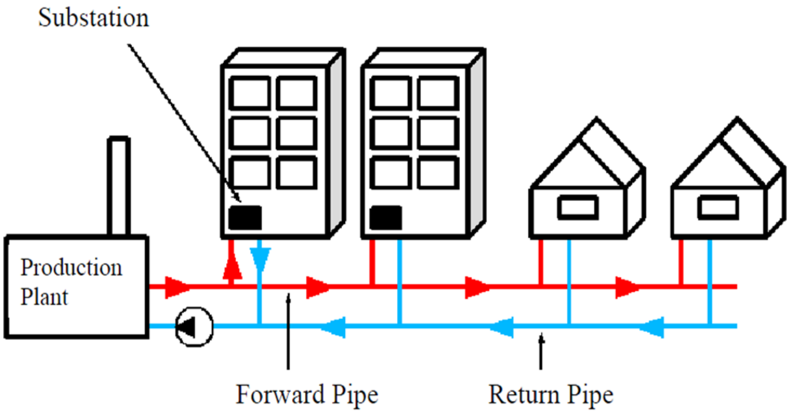

FIGURE 4: BASIC LAYOUT OF A DISTRICT HEATING SYSTEM (9).

A good example of energy-efficient CHP power production and heat utilization can be found in the northern settlement of Qaanaaq, near the American air force base of Thule, where carefully designed modernizations of the district heating and the heat generation system have been implemented for the last 21 years. During this period, the electricity consumption rose by 50% while the surface area covered by district heating increased by more than 100%. Still, the accomplished renovations allowed the total energy consumption for heat and power production to remain constant, with a global CHP efficiency now superior to 90% (10). This proves that high energy savings and CO_2 emissions reductions can be obtained in Greenland by simple design modifications, even in locations where no renewables are available at the moment and where the winter climate is very harsh.

3. Waste context in Greenland

With the opening of Greenland on the world throughout the 20th and 21st centuries, the traditional and sober Inuit way of life has gradually been replaced by a more modern and intensive lifestyle, very similar to the European and North American standards. About 80% of the goods consumed in Greenland now originate from Denmark and Sweden, due to the low autonomous production capacity of the island. All the consumed products eventually end up as waste and the climatic and demographic specificities of Greenland make the management of this waste a particular issue (11). Waste management is in Greenland the prerogative of municipalities, and depending on the towns and settlements a combination of municipality-owned and private-company owned vehicles are in charge of waste collection.

Different types of waste are generated from different activities, each with different specificities and different treatments:

- **Residential waste** includes mixed waste from households and residential buildings. Fractions of it are sometimes sorted by the inhabitants, especially bulky or dangerous chemical items (bikes, fridges, pieces of furniture, batteries,…) which are in theory deposited separately at designated drop-off locations or disposed of by municipal vehicles. Regular residential waste contains a high share of organic materials, which natural decomposition can be hazardous for human health and therefore necessitates its disposal by incineration. A distinction is consequently made between combustible waste and non-combustible waste, for which disposal solutions other than incineration (recycling or landfilling) must be used.

- **Commercial waste** mostly consists of expired food items from supermarkets and packaging items (cardboard, wood). The volume of commercial waste is non-negligible in the total amounts of waste handled, and a majority of it is suitable for waste incineration.

- **Industrial waste** is on the other hand very limited in Greenland, being given that the local industry is predominantly based on fishing. The vast majority of waste from fisheries and shrimp factories is organic and rejected directly to the sea through sewage.

- **Construction and demolition waste** is for the most part construction waste and includes wood, cardboard and various plastics. This type of waste is also considered combustible, as long as no paint or other highly toxic materials are blended in.

Overall little is known on the quantities and exact compositions of waste in Greenland, especially in the smallest settlements, and the general data presented in this report originates from on-going research work focused on the area (11). It is estimated that the largest fraction of all waste generated in Greenland derives from packaging from imported goods and post-consumer waste, and that the total waste resource is expected to be around 50 000 tons per year for the whole country. The waste which is not suitable for incineration and is visually identified as such by waste management operators is either landfilled locally (mixed waste) or exported to Denmark once in a while (mostly metals, with a benefit due to scrap value). The layout of Greenlandic landfills is very basic, without any kind of ground liner or leachate control, and results in the direct contamination of local soil and water by wash off from toxic products contained in the waste.

FIGURE 5: GARBAGE DUMP IN ILULISSAT, WITH ICEBERGS OF THE DISKO BAY (UNESCO WORLD HERITAGE SITE) IN THE BACKGROUND

Waste incineration is presently carried out at different scales in Greenland. Converted straw incinerators are in use in about 30 small settlements whereas larger, more efficient and less polluting incineration units with heat recovery are operated in the six largest towns. At the moment no waste is being transferred from small settlements to larger towns on a regular basis; this option is however considered as a possibility to help small settlements deal with their waste management in a better way in the future. The same logics could see recyclable waste from Greenland shipped to Denmark, where the waste would be sorted and handled in appropriate facilities.

It is estimated that currently only 25% of the hazardous waste from residential dwellings is disposed of appropriately, with the remaining 75% ending up mixed with burnable waste (12). Results from waste analysis in Greenland suggest that waste management could be greatly improved if the waste was sorted more thoroughly before being disposed of, thus ensuring that different types of homogenous waste would each receive appropriate treatment. For incinerated waste, the problem of glass, metals and toxic products (such as medication, electronics, batteries, solvents,…) being introduced in the furnace would be greatly reduced; this would in turn lead to better heat utilization (increased Lower Heating Value of the waste; the quantity of heat producible from the waste) and increased lifetime for the large waste incinerators, as well as less harmful atmospheric emissions from the toxic products. This point is of significant importance since the waste incinerators are located in the direct vicinity of local households, and the consequences of harmful flue gas emissions are directly impacting Greenlandic inhabitants. Related health disorders include damage to eye sight, headaches, allergies, and even in the long term asthma, lung cancer and heart decease (12).

III. Energy and waste context in Sisimiut

1. *Electricity supply*

A new hydropower plant was inaugurated in 2010 and supplies electricity from the lake Tasersuaq to Sisimiut, through a 27 kilometer long high voltage line. The plant has a capacity of 15 MW but is in normal operation conditions delivering between 5 and 10 MW, covering the total electricity demand in the town. The limit on yearly electricity production is dictated by the water resources at the lake, and is currently at a level of 56-58 GWh per year (13). Nukissiorfiit (who is in charge of electricity and public heating in Sisimiut) maintains the old generation plant located on the harbor operational, as a back-up in case the hydropower plant knows a breakdown. The back-up generation plant includes large CHP Diesel engines which are kept ready to start instantly at any required time.

FIGURE 6: COMBINED HEAT AND POWER DIESEL ENGINE IN SISIMIUT, NOW BACK-UP ELECTRICITY GENERATOR (13)

FIGURE 7: THE ELECTRICITY SUPPLY LINE LINKING THE HYDROPOWER PLANT TO SISIMIUT (14)

2. *Heat supply*

Heat supply in Sisimiut is currently provided in two forms: Most small households and a number of large buildings are equipped with individual oil burners whereas areas with more concentrated, larger dwellings are supplied with district heating. Figure 8 pictures an example of individual familial household in Sisimiut, with a heating and domestic hot water system based on an individual oil boiler. The flue gas chimney and the oil tank (at the right of the picture) can be visualized.

FIGURE 8: A TYPICAL DESIGN FOR A FAMILIAL GREENLANDIC HOUSE, EQUIPPED WITH AN INDIVIDUAL OIL BOILER.

The map provided in Appendix 1 (page 56) shows an overview of the location and layouts of the three distinct district heat networks found in the town at the moment. These grids are labeled in this report as 'DH1', 'DH2' and 'DH3' and their main characteristics are given here:

- **DH1**: The largest district heat grid of Sisimiut supplies two high density residential areas, one over the harbor, and the other south of the Kangerluarsunnguaq Bay (Ulkebugten), both mainly composed of communal apartment blocks, but also a school, the town's hospital, a post office and various shops. Two dedicated plants supply heat to DH1: The main one is located at the back-up generator site of Nukissiorfiit on the harbor, whereas the second one is located in the residential blocks area to the east.

- **DH2**: The second district heat grid supplies a series of apartment blocks around the old people's home, in the west of the city. Only one dedicated plant produces heat for this network.

- **DH3** (detailed in Figure 11): This district heat area is found south of Sisimiut, and is actually constituted of two smaller networks that have subsequently been connected together. Almost exclusively residential buildings are supplied by this network, and one heat production plant is located in each of the two sub-networks. These Nukissiorfiit heat plants are respectively referred to as 'VV3' and 'VV4' on the map in Figure 11 and in this report. Buried district heating pipes are represented as purple dotted lines in Figure 11, overground district heating pipes are represented as crossed purple lines, and the substations transferring heat from the district heat network to the secondary heating systems of buildings are shown as crossed purple squares. The 'DN***' mentions placed along the pipes refer to their interior diameters, normalized in millimeters. Further, overground pipes (corresponding to reference points 129 to 130 in Figure 11) linking the two sub-networks are pictured in Figure 9, along with some typical Greenlandic residential blocks. Figure 10 shows heating plant VV4 and pipes corresponding to reference points 121 to 123 in Figure 11.


FIGURE 9: OVERGROUND DISTRICT HEATING PIPES BETWEEN VV3 AND VV4, IN AUGUST 2011.


FIGURE 10: DISTRICT HEAT PLANT VV4, WITH OVERGROUND DISTRICT HEATING PIPES IN THE FOREGROUND.

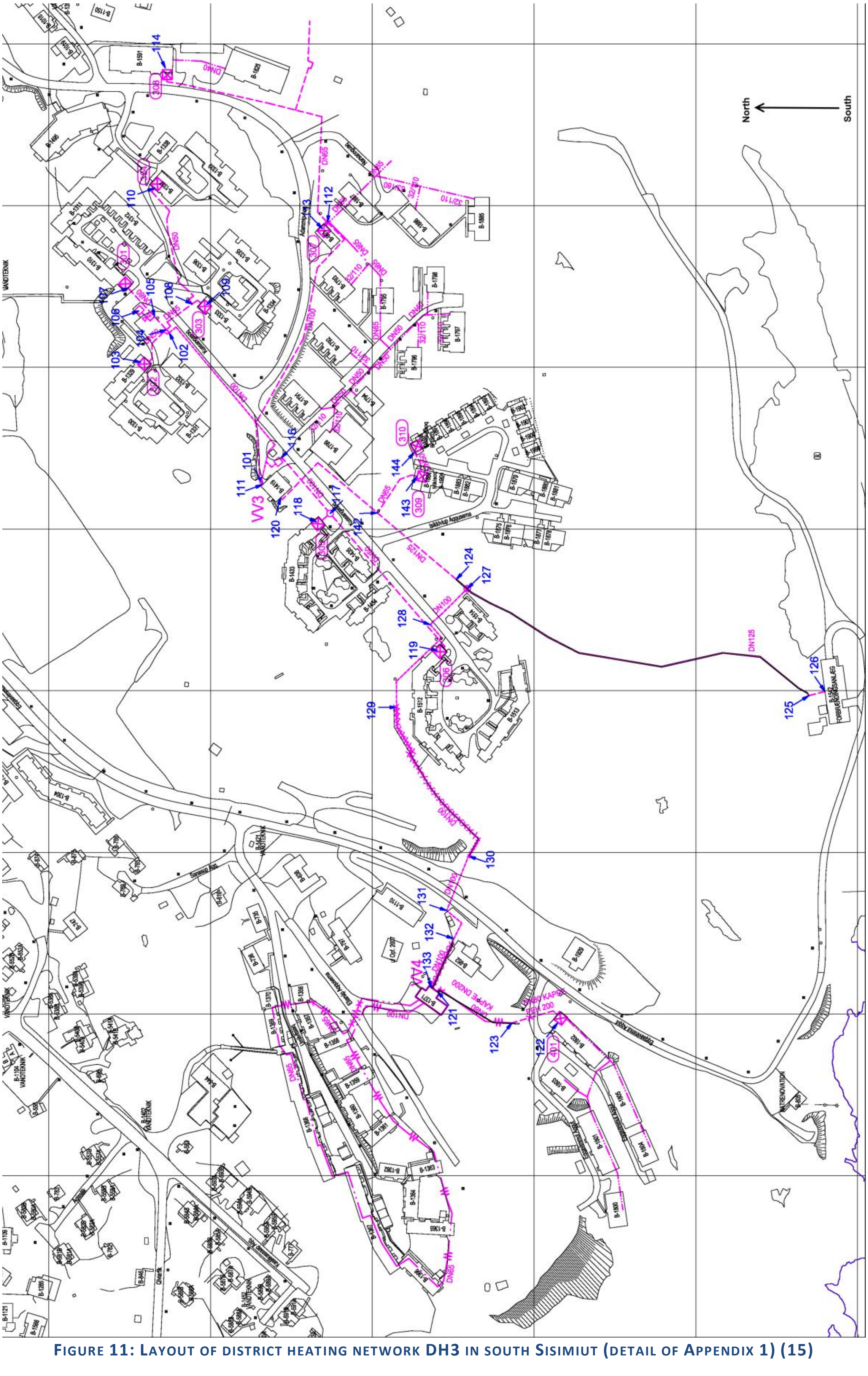

FIGURE 11: LAYOUT OF DISTRICT HEATING NETWORK DH3 IN SOUTH SISIMIUT (DETAIL OF APPENDIX 1) (15)

Before the introduction of hydropower in Sisimiut the district heat networks were supplied solely by large oil boilers located in the above-mentioned dedicated heat plants and, in the case of DH1, by heat recovered from the Diesel generators. The annual consumption of oil for district heating alone was then close to 25 000 liters (13). A picture of the oil boilers equipping the heating plant VV3 is shown in Figure 12 below.

FIGURE 12: OIL BOILERS IN DISTRICT HEAT PLANT VV3 (16)

Since 2010 and the opening of the hydroelectric plant, large electric boilers have been fitted in all heating plants to replace the oil boilers, except in the heating plant VV3. About 55% of the annual electricity production from the hydropower plant is now used in these electric boilers and in dedicated electric boilers heating the Building and Construction school and the old people's home (which are not connected to district heat grids). The 'old' oil boilers have been kept in place in all cases and serve as back-up heat producers.

The district heat network DH3 is of special interest in this work as it is connected to the municipal waste incinerator of Sisimiut (at the reference point 126 in Figure 11). The incinerator's furnace is equipped with a boiler which recovers the majority of the heat contained in the waste, as detailed further in the report. The recovered heat is transferred to Nukissiorfiit's heating plants VV3 and VV4 through a series of pipes, and water is then heated further if necessary, ensuring that the district heat supply temperature remains above an acceptable limit. The incinerator is used as a base heat producer since the heat it generates is recovered from a 'free' local fuel and would otherwise be wasted. The heating plants only produce heat as a complement of the incinerator if the heat demand in DH3 exceeds heat production from the incinerator, or cover the totality of the heat demand if the incinerator is out of operation. It can be noted that the heat produced at the incineration plant is sold to Nukissiorfiit, according to a nationwide tariff for heat production from waste incinerators. This price was in August 2011 set at 476 DKK/MWh.

After the transition to electric boilers for district heating in most of the heat plants, the annual oil consumption is now estimated to 5 000 liters (13). This represents 20% of the oil consumption before the inauguration of the hydroelectric plant.

3. *Waste management*

Categories of handled waste and applied treatment

All the waste generated in Sisimiut is collected and brought to the waste management site located at the south of the city, close to the sea. The satellite view provided in Figure 13 gives an overview of the waste management site and of its distinctive areas.

FIGURE 13: SATELLITE VIEW OF THE WASTE MANAGEMENT SITE IN 2011 (17).

Bulky and problematic waste (furniture, concrete blocks, construction materials, tires,…) which cannot be incinerated due to their size, structure or materials are laid out in an open air landfill and remain there since no appropriate solution for their disposal has been found yet (Figure 14). Some quantities of this 'mixed waste' are periodically buried underground. Large metallic waste (cars and snowmobile wrecks for example) is collected by a private company in a specific area of the waste management site and shipped out to be sold as scrap metals when the accumulated volume makes the operation profitable. Toxic and sensitive waste that is sorted by the population of Sisimiut and disposed of in dedicated collection points is assembled by category (batteries, computer components, electric cables,…) and then shipped to Denmark to be properly treated.

FIGURE 14: MIXED WASTE IN THE LANDFILL IN SISIMIUT, AUGUST 2011.

But the largest quantities of waste are from residential and commercial origins. This waste contains a high fraction of organic materials combined with plastics, papers and cardboard and is for the largest part incinerated. A household waste analysis campaign was led in summer 2009 in Sisimiut as part of the PhD research activity of Rasmus Eisted, from DTU ARTEK. The measurements results showed that the investigated waste contained about 43% of biowaste (food scraps, hunting waste, flower bouquets, used coffee filters,…) which is perfectly suitable for incineration, as long as the humidity content remains low enough. The measured amounts of metal and glass in the waste were respectively 2% and 7% (18). These fractions can usually be processed through the incineration process but do not burn or produce any energy. They rather absorb energy, especially if they melt partially or totally, and can cause technical problems by getting stuck in the mechanisms of the incinerator, which is why it is important to filter them out of the incinerated waste as much as possible. Furthermore, it was found that hazardous waste such as medication and batteries were found at a low fraction of about 1%, which shows that the inhabitants are already making efforts to sort their waste in Sisimiut.

Drums of used oil from local trawlers and mechanics workshops are also deposited at the waste management site in relatively large quantities every year. This ‘dirty’ fuel is mixed with the incinerated waste in small proportions to increase the overall heating value of the waste when it is humid, typically in winter. The same effect can be achieved by mixing some dry wood waste obtained from the stock of mixed waste. This is done to ensure that the combustion temperature in the furnace is maintained high enough: if the combustion temperature is too low the combustion process is less complete and the emissions of hazardous pollutants in the atmosphere increase.

Figure 15: Drums of used oil in Sisimiut (12).

Description of the waste incineration facility

Figure 16: Waste incinerator viewed from the entrance of the waste management site, in August 2011.

The waste incineration facility can be described in three main parts: the receiving area, the treatment area and the residual area (11). The main components of each of these parts are described here.

The receiving area includes the ramp used by the collection trucks to deliver household and commercial waste to the incinerator, a waste pit in which the waste is stored before being fed to the furnace (pictured in Figure 17), as well as a waste shredder used to reduce the size of voluminous waste. A temporary waste disposal area is also formed along the ramp when the pit is full; this situation typically occurs when the incinerator is out of operation for a prolonged period.

FIGURE 17: WASTE PIT AND GRAB SEEN FROM THE RAMP AREA IN SISIMIUT. THE WASTE FUNNEL IS BEHIND THE BACK WALL (12).

The treatment area is the most important and voluminous part of the incineration facility. To begin, a technician remotely operates a grab located above the pit with two purposes: firstly, to mix the received waste and therefore ensure that it is as homogenous as possible. Secondly, to grab loads of waste and introduce them in the inlet funnel that leads to the entrance of the furnace. There the waste is automatically conveyed into the furnace, and the air inlet and rate of waste incineration are controlled so as to obtain an optimal combustion temperature of about 1000°C (19). The remains from the combusted waste are called 'bottom ashes' and are collected from the furnace after roughly two hours of incineration time. The flue gases from the combustion are led through a heat exchanger (the boiler) which heats up water in a closed pumped loop. The water from the boiler circuit is led through a counter-flow heat exchanger in which the recovered heat is transferred to the district heating circuit leading to Nukissiorfiit's heating plants. If the heat demand in the district heating network DH3 is lower than the heat production from the waste incinerator, a secondary cooling system is used to ventilate the recovered heat into ambient air through two fan stations. This cooling effect is necessary to ensure that the boiler and the electro-filter do not overheat and suffer from heavy corrosion. The fan stations are pictured in Figure 18.

Finally, before being expelled into the exhaust stack, the flue gases are passed through an electro-filter, which extracts the heaviest pollution particles by inducing a rotational gas movement, and then collects these particles (fly ashes) by gravity. The residual area therefore comprises a bottom ash recovery container (Figure 19) and a fly ash container bag. The bottom ashes typically represent 10% to 25% of the volume of incinerated waste (19), and also include remains from non-combustible waste such as metals and glass. All these ashes are deposited in the ground in Sisimiut, whereas the fly ashes are exported for treatment in Denmark (20).

FIGURE 18: THE TWO COOLING STATIONS BESIDE THE INCINERATOR, IN AUGUST 2011.

FIGURE 19: BOTTOM ASH CONTAINER, IN THE RESIDUAL AREA OF THE WASTE INCINERATOR.

The municipal incinerator of Sisimiut was built in 1999 and was manufactured by the Danish constructor REKA. The specific model is GRAF and has according to the operation manual (19) a nominal heat output of 2.3 MW, for a waste input of 0.8 ton per hour and a Lower Heating Value[1] of the waste of 2.9 MWh/ton. This corresponds to a thermal recovery efficiency of 85%. The main elements of the REKA incinerator as such can be visualized on a technical drawing presented in Appendix 2 (page 57).

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[1] LHV, the heat content contained in the flue gases, without considering condensation of the water vapor.

A comment can be made here on a specific environmental impact issue from the waste management site. Indeed, a characterization of the flue gases from the incinerator remains to be carried out, especially with respects to health impacts. The incinerator is at the moment not equipped with any sort of flue gas composition measurement equipment and real pollutant emissions are only a matter of guesswork. The incinerator is bordered by residential buildings which are located on hills on its north side, roughly at the same height as the top of the plant's flue gas stack. It is very common for the sea breeze to blow flue gases directly in the direction of these households, which is likely to incur a serious health hazard for the residents. It is globally feared that heavy pollutants emitted in the flue gases are deposited in the surroundings of the incinerator and Sisimiut, and then absorbed by plants which are consumed locally, with inhabitants being eventually contaminated (21).

IV. Problematic and aim of the project

To a certain extent, heat recovery from waste incineration is considered as a sustainable process. In Sisimiut, it is therefore desired to utilize heat from the municipal incinerator as much as possible, so as to replace the developed use of oil for heating purposes in the town. The only way allowing heat produced at the incinerator site to be fully utilized seems at the moment to be district heating, being given the isolation of the waste management site from industrial activities (concentrated on the harbor), and the preliminary existence of the district heat grid DH3. Despite being connected to this public heat network since its construction, it has been shown that the heat produced by the incinerator is being cooled, and therefore wasted, in large proportions throughout the years.

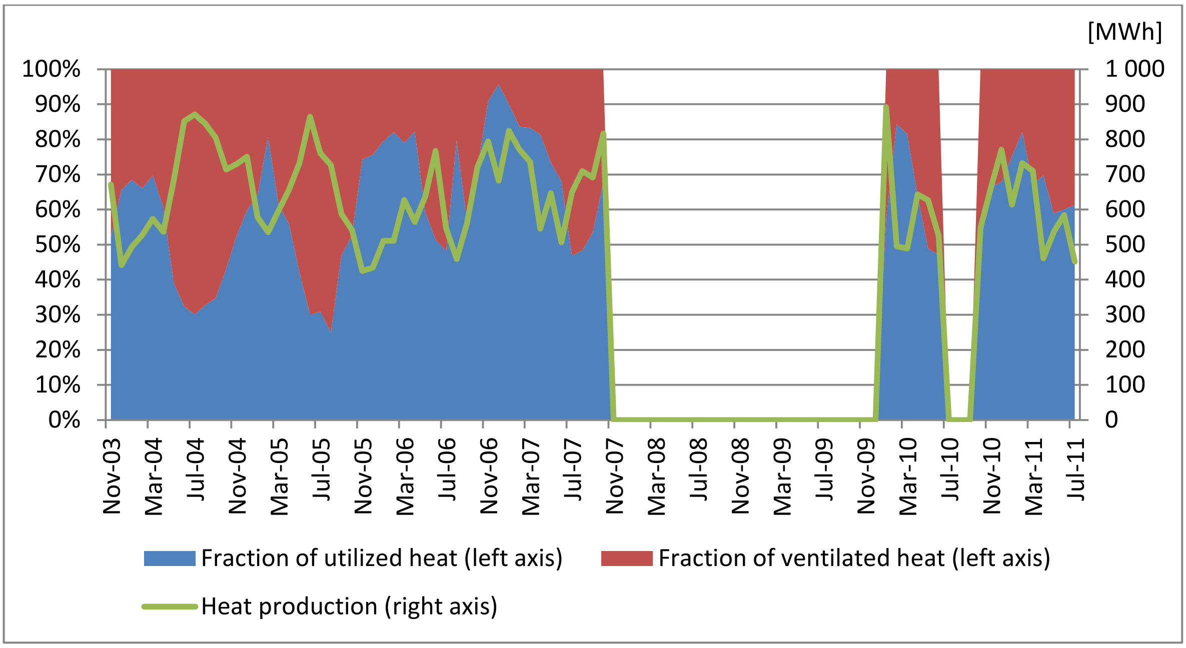


FIGURE 20: MONTHLY HEAT PRODUCTION AND UTILIZATION RECORDS FROM THE WASTE INCINERATOR, 2003-2011 (20).

Heat production and utilization records from the waste incinerator are presented in Figure 20. The data is based on monthly values and covers the period 2003-2011 with intermittence. Large variations in both the amounts of heat produced and the heat utilization are observed; generally heat production spikes coincide with low heat utilization periods, especially in the years 2003-2007. Low heat utilization periods correspond to summer periods in all cases. This is due to a mismatch between the heat production capacity of the waste incinerator and the heat demand in the supplied district heat network. Two main reasons are responsible for this unbalance:

- Firstly and simply, the demand in district heat network DH3 is too small compared to the heat recovery ability of the incinerator. This is particularly verified during summer, when the space heating load in buildings is reduced compared to winter.

- Secondly, it can be seen that the heat production has been significantly higher during the summer compared to winter throughout the period 2003-2007. This pattern might be due to difficulties in operating the incinerator smoothly all year-round at the time, with the harsh winter season decreasing the capacity of the plant.

The combination of these two issues is responsible for the very low heat utilization from the incinerator achieved for example in August 2005, with a lowest registered value of 25%. The maximal heat utilization was on the other hand recorded in December 2006, with 96% of the heat produced being sold to Nukissiorfiit. But overall an average of 38% of the produced heat has been cooled in the ventilation stations on the whole records period, which represents a significant waste of heat (16 000 MWh). The analysis presented further in this report indicates that the annual district heat consumption in DH3 can be approximated to 8000 MWh. Therefore about two years worth of district heating have been ventilated away in five (discontinuous) recorded years of operation.

It is also worth noticing that the total annually recorded heat production from the incinerator varied between 7 400 and 8 400 MWh in the analyzed period. All in all, the annual heat production from the incinerator and the annual heat consumption in DH3 are at equivalent levels. Still, in the current state of things, it is not possible to utilize all heat from the waste incinerator due to its intrinsic prime function, which is to incinerate waste on a daily basis to prevent health and vermin development issues, as well as uncontrolled landfilling in the surroundings of Sisimiut. Waste incineration is a lean production process which cannot or should ideally not be used as a flexible heat production capability. Hence in an optimal system the waste incineration rate only knows small variations throughout the year, and the focus is more on optimizing waste disposal on a daily or monthly basis than heat production on an hourly basis.

The purpose of the work presented in this report is then:

- To collect and model the present main parameters characterizing the district heating demand, the waste resource and the heat production from the waste incinerator.

- To understand how the heat demand in DH3, the operation of the incineration plant and the resulting heat utilization parameter are linked;

- To propose and assess procedures to optimize heat utilization from the incinerator, simply looking at availability and quality of the waste resource, as well as operation patterns; therefore impacting the management system;

- To assess the effects of changes in the district heat and waste incinerator infrastructures to optimize heat utilization; therefore impacting the physical system;

- To make some recommendations regarding cost-effective and energy-efficient solutions to improve heat utilization from the waste incineration plant, taking into account the forecast evolution of some key parameters which may impact the known situation in the years to come; therefore reducing the consumption of oil for heating in south Sisimiut.

V. Analysis and modeling of waste incinerator operation

1. *Simulation model design*

An excel spreadsheet is created in order to model the operation of the waste incinerator and the consumption in the district heating network. Since the district heating demand is very sensitive to both the outdoor temperature and the time of day (due to spikes of demand in the morning and the evening), the base time unit chosen for the model is the hour. The model simulates one full year of operation, therefore 8760 time steps are used in the calculations. For each time step, a number of imbricated “if” and “or” functions are used to compare values (district heat demand and heat production from the incinerator, for example) and take into account hourly or monthly modification factors, the result being a rather convincing model replicating real phenomenon and patterns (with of course complexity limits inherent to simulation models).

The spreadsheet is designed so that only a few inputs are necessary to simulate changes in the most important operation parameters, thus making it very accessible to neophyte users. Most of the model inputs and parameters are detailed in the following chapters. In order to make the control of the chosen inputs and the reading of the model outputs as accessible as possible, a series of graphs is also updated automatically in the spreadsheet in function of the parameters entered in the model; some of them are illustrated in this report.

One of the most important points about the model is that the key inputs are directly and easily modifiable by the user. In case errors or approximations made in the course of this work are spotted by the simulation model user, on the Lower Heating Value of waste in Sisimiut for example, more precise and realistic results can then be obtained after very few changes, in very few seconds.

A screen capture of the main inputs and results window from the developed model is proposed in Appendix 3. The simulation parameters correspond to the further defined Scenario 9, which is presented in page Table 3.

2. *Waste resource*

Records from the waste incinerator are first analyzed to estimate the annual waste resource in terms of weight, as well as the potential monthly variations observed in waste generation. It must be noted that only monthly values for incinerated waste are available, which can be different from the amount of waste generated, in the case of an incinerator breakdown or if some waste is voluntarily stored for later use, from one month to the other. Moreover the weighting of the waste is very sensitive and only approximate, according to the current manager at the waste incineration site Henrik Skjoldhøj Nielsen.

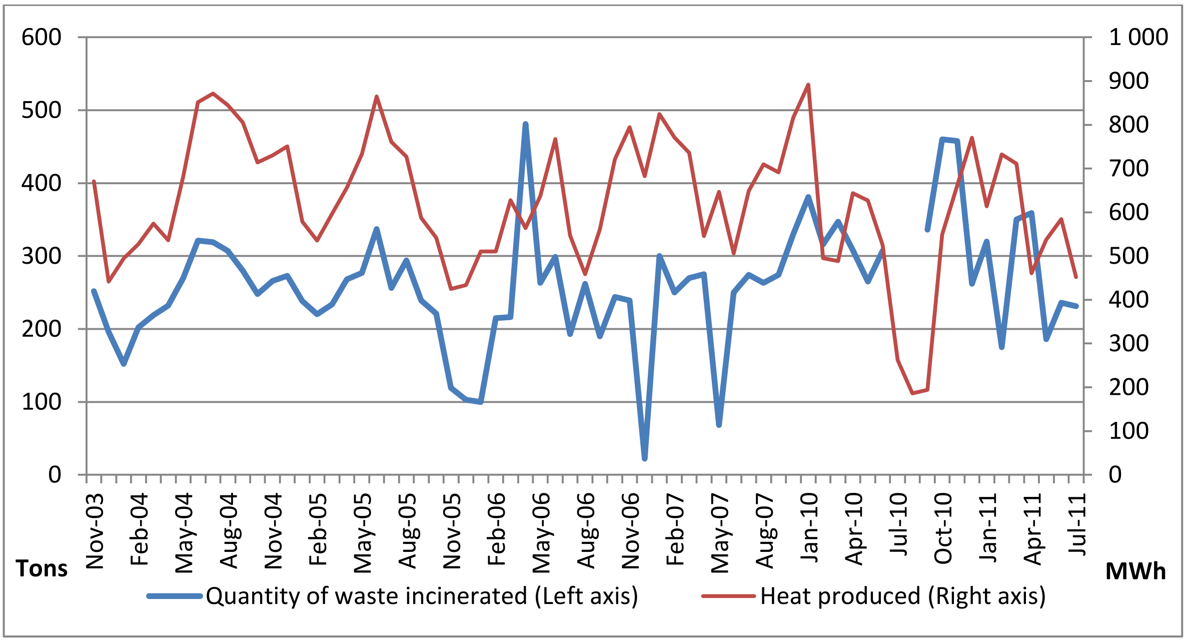


FIGURE 21: WASTE INCINERATION AND HEAT PRODUCTION RECORDS, NON-FILTERED DATA (20).

Figure 21 presents the monthly data values relating quantities of waste incinerated to the corresponding total heat production. Large variations in monthly amounts of incinerated waste are visible, and it can be noticed that the seasonal variation has evolved from high incineration rate in summer-low incineration rate in winter in the years 2004-2005-2006 to an inverse pattern from 2007 until now, with maximization of waste incineration during winter. This change results from the will of the waste incinerator staff to increase heat utilization and decrease the use of ventilation cooling during summer. This operation method is to some extent still being used in 2011, but has regularly been perturbed by unexpected incinerator malfunctions or breakdowns, such as ash-pusher failure or furnace arch collapse. Moreover some data points seem to suffer from large inaccuracies or errors, such as December 2006 and May 2007, when the quantity of incinerated waste drops dramatically whereas heat production remains seemingly unaffected. Points displaying a strong potential for errors or for which data is partially missing are therefore discarded in the following analysis, and the same methodology is used in the different remaining subsections of the report.

The average waste incineration per month and its evolution in time are then plotted in Figure 22, using filtered values. Assuming a linear regression, it is shown that the average measured monthly quantity of incinerated waste is gently rising through time, to attain about 290 tons of waste per month (corresponding to 3 480 tons per year) at the end of 2011. The summer and winter variations around this value are in the range of 25%. It can be commented that since the population in Sisimiut increased by approximately 5% between 2004 and 2010 (22) and that the measured yearly incinerated waste quantity increased by 16% in the same time, the growth in waste generation in Sisimiut was three times faster than the population growth. This trend could indicate an intensification of the consumption in the town, but also changes in the way that the masses of incinerated waste are evaluated. The manager for the waste incineration plant expects the real mass of incinerated waste to be close to 3 000 at the end of 2011 (20), which is equivalent to the same waste incineration level as in 2004 (250 tons per month).

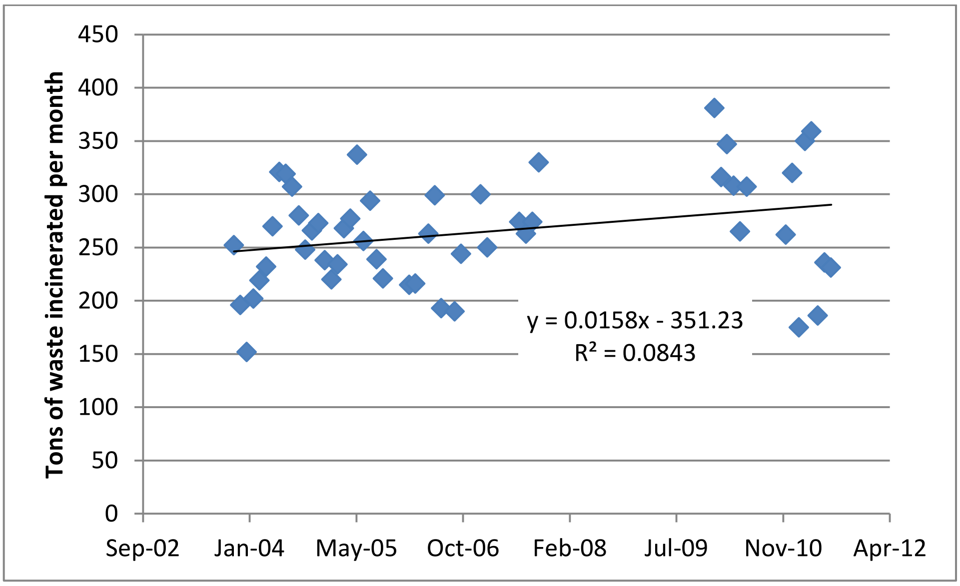


FIGURE 22: DETERMINATION OF AVERAGE MONTHLY AMOUNT OF WASTE INCINERATED, FILTERED DATA (20).

As explained in Section III.3, used oil is also introduced in the furnace to increase the LHV of humid and cold waste, theoretically mostly in winter. Similarly to Figure 22, Figure 23 presents the scatter plot of the amounts of oil incinerated through time, as well as the obtained monthly average and its evolution trend. It is found that used oil is being added to the waste nearly every month of the sampled period, and that the quantities involved vary enormously, sometimes without any seasonal logic. On average, combustion of oil in the incinerator's furnace is relatively stable in time, about 6 tons per month (72 tons per year) in 2011. The observed variations around the average are in 2010/2011 loosely limited to -70% and +130%.

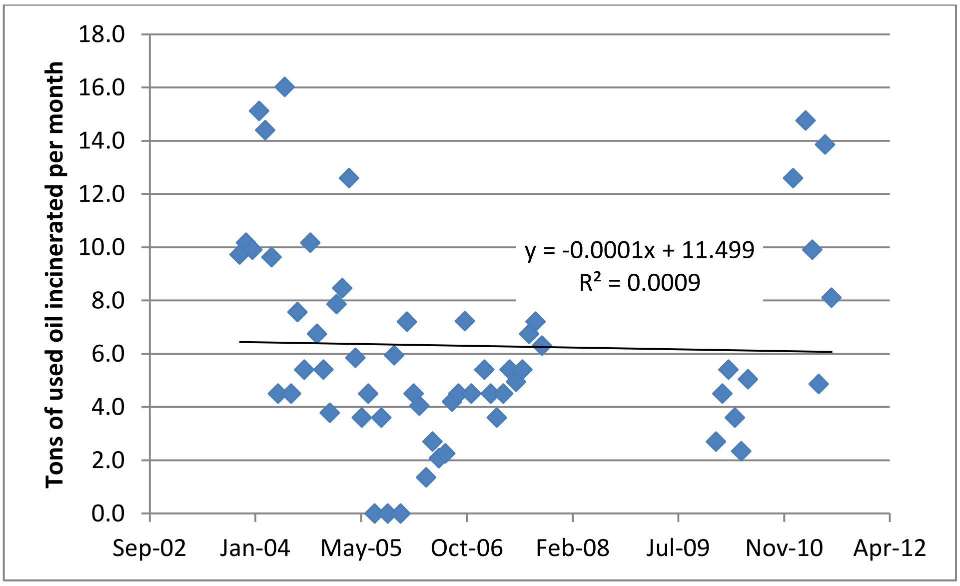


FIGURE 23: DETERMINATION OF AVERAGE MONTHLY AMOUNT OF INCINERATED USED OIL, FILTERED DATA (20).

3. *Waste incinerator operation pattern*

In the years 2010/2011, the incinerator was operated around the clock in periods of two weeks. Every second Friday afternoon, the incineration plant was shut down and let to cool down during the week-end. On the following Monday routine maintenance was performed and the inside of the furnace could be accessed and cleaned, notably from remains of non-combustible waste. The incinerator could then be turned back on Monday evening, and the two week cycle would be starting again, only interrupted once in a while by forced unscheduled maintenance periods following breakdowns. Since November 2011, a new operation pattern is being experimented as the uninterrupted operation period has been extended from two to three weeks (20). The main challenge in this set-up is whether the furnace can be operated without damage for an extra week between routine clean-up operations. The waste incinerator staffs have over time gained experience in smooth conduction of the incinerator and have come to know more of its limits; therefore the transition is expected to be feasible.

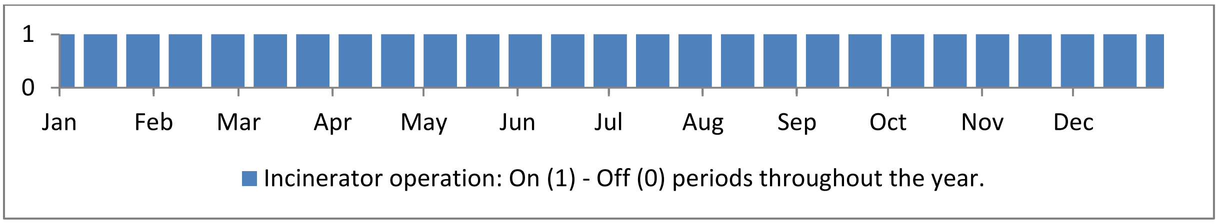


FIGURE 24: INCINERATOR OPERATION PERIODS IN THE TWO-WEEK OPERATION PATTERN

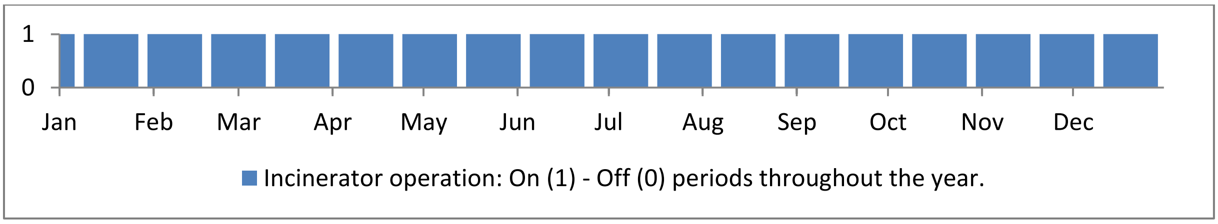


FIGURE 25: INCINERATOR OPERATION PERIODS IN THE THREE-WEEK OPERATION PATTERN

In the excel model it is possible to decide whether the waste incinerator is in operation or not for any hour of the year. The two-week and three-week operation plans are input and compared, both set so that the incinerator is switched off in the 16th hour of the day on Fridays and turned back on during the 16th hour of the day on Mondays. Using this assumption and neglecting any sort of unscheduled breakdown periods, it is found that the incinerator operates 6 914 hours per year in the two-week operation pattern, hence 79% of the time in the year (Figure 24). Shifting to the three-week operation pattern sees operation hours increase to 7 497, equivalent to 86% of the time in the year (Figure 25). Hence the operation time is augmented by nearly 9% in the second case compared to the first.

Considering the same amount of waste to be burned each month in both cases, 250 tons for example, the mean incineration rate in the two-week plan is equal to 0.43 ton per hour compared to 0.40 ton per hour in the three-week case.

4. Heat production

The calculation of the simplified total hourly (or monthly) heat production from the waste incinerator is derived using the following formula:

$$\dot{Q} = \eta_{incinerator} \cdot (\dot{m}_{waste} \cdot LHV_{waste} + \dot{m}_{used\ oil} \cdot LHV_{used\ oil}) \qquad \text{Eq 1.}$$

With:

$\dot{Q}$	the heat production of the incinerator for one hour or one month, in MWh.
$\eta_{incinerator}$	the heat recovery efficiency of the incinerator, assumed to be 80%.
$\dot{m}_{waste}$	the incineration rate of the waste, in ton/hour or ton/month, variable.
$\dot{m}_{used\ oil}$	the incineration rate of used oil, in ton/hour or ton/month, variable.
LHV_{waste}	the Lower Heating Value of the waste, in MWh/ton, assumed constant.
$LHV_{used\ oil}$	the Lower Heating Value of the used oil, in MWh/ton, equal to 11.62 (20).

In the excel model the incineration rates of waste and used oil can be adjusted monthly. As indicated in the example given in the previous subsection, the incineration rates for a given month are a function of the amount of waste (and oil, respectively) incinerated, as well as of the number of operation hours. The incinerator is assumed to run with constant incineration rates for monthly periods, and not to vary every hour or every day. This simplifying assumption allows for a simpler control of the model by the user, and is not considered to entail major inaccuracies since the incinerator has a high inertia and limited dynamic regulation abilities in any case.

In reality staffs in charge of the incinerator do vary the incineration rate of oil on an hourly basis, since the oil is mixed with ‘difficult’ waste in appropriate proportions. The proper waste incineration process is done at a more constant rhythm throughout time in order to prevent waste accumulations and temperature variations in the furnace, even though the pace can be slightly upped when the heat demand in the district heat grid is high (20). On average, the real waste incineration rate at the incineration plant is estimated by the incinerator manager to 0.4 ton per hour on average, in 2010/2011. This corresponds to half of the nominal waste incineration rate indicated in the incinerator’s manual (19), which may indicate that as a result the incinerator’s efficiency and emissions control are below design characteristics.

In order for the theoretical heat production from the incinerator to be calculated with varying incineration rates, an average global LHV must be estimated for the waste. To this effect monthly waste and oil incineration records are compared to their corresponding heat production levels and the sample is filtered from erroneous values. Equation 1 is then applied to the recorded parameter values for each month. The Lower Heating Value of Waste is varied so that the average measured heat production values match the calculated heat production values over the sampled data set. Using this method an average municipal waste LHV value of 3.00 MWh per ton is yielded (equivalent to 10.79 MJ per ton). As shown in Figure 26, the results are convincing since only small deviations are noticed between measured and theoretical production capacities.

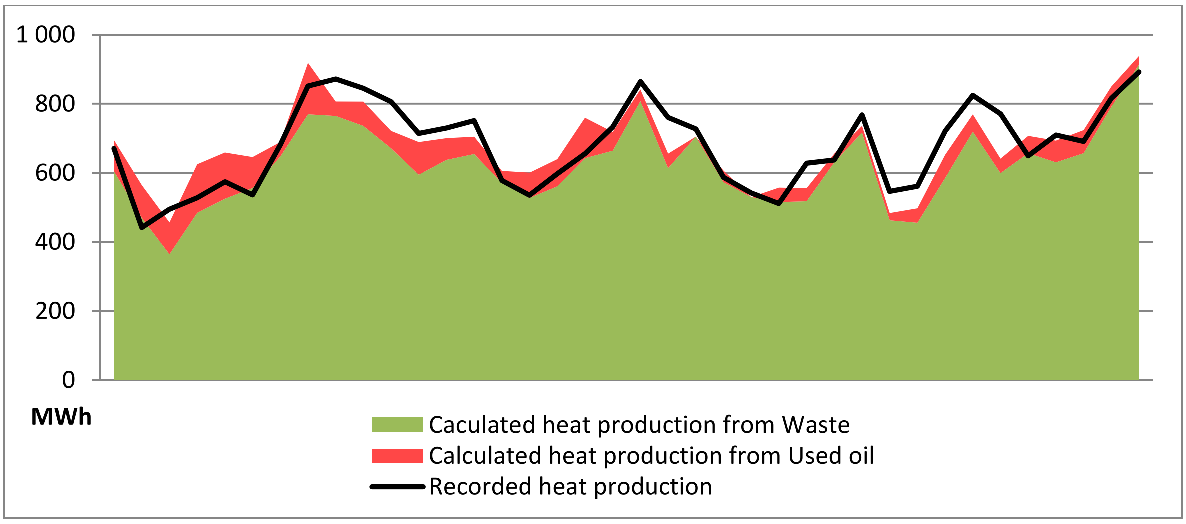


FIGURE 26: COMPARISON OF RECORDED HEAT PRODUCTION AND MODELLED HEAT PRODUCTION (FILTERED DATA).

The obtained theoretical LHV value is 11% lower than the waste LHV of 12.14 MJ per ton the incinerator was designed for (19), which is not considered problematic. As an indication and considering the average waste and oil incineration rates of 250 and 6 tons per month respectively, as determined beforehand, the typical heat production from the incinerator in current operation conditions is found to be 655 MWh per month on average.

5. District heat demand

Monthly net heat production records from the district heating plants VV3 and VV4 are obtained from Nukissiorfiit, covering the period September 2010 to August 2011. They are displayed in Figure 27, where the heat production from VV3 actually includes the heat production from the incinerator. The combined recorded production from both these plants is in this analysis considered as the total heat demand in the district heating grid DH3, including heat losses in pipes and substations.

The incinerator simulation model is based on hourly calculations, therefore it is necessary to analyze the data provided in Figure 27 and 'convert' it to a lower time resolution.
Firstly, it is desired to know which fraction of the district heat demand is more or less constant throughout the year (domestic hot water for showers, cooking, heat losses in substations,…) and which fraction is varying with ambient air temperature (space heating, heat losses in overground pipes,…). DMI weather archives for Sisimiut are consulted, and the monthly mean ambient temperature levels measured between September 2010 and August 2011 are extracted (23). Figure 28 below enables comparison of the mean hourly heat demand values for each month and the matching ambient air temperature. The expected average linear relationship between the two parameters is highlighted, such as:

$$Heat\ demand\ in\ DH3\ [MW] = -0.035\left[\frac{MW}{°C}\right]\cdot Ambiant\ air\ temperature\ [°C] \quad \text{Eq 2.}$$
$$+0.937\ MW$$

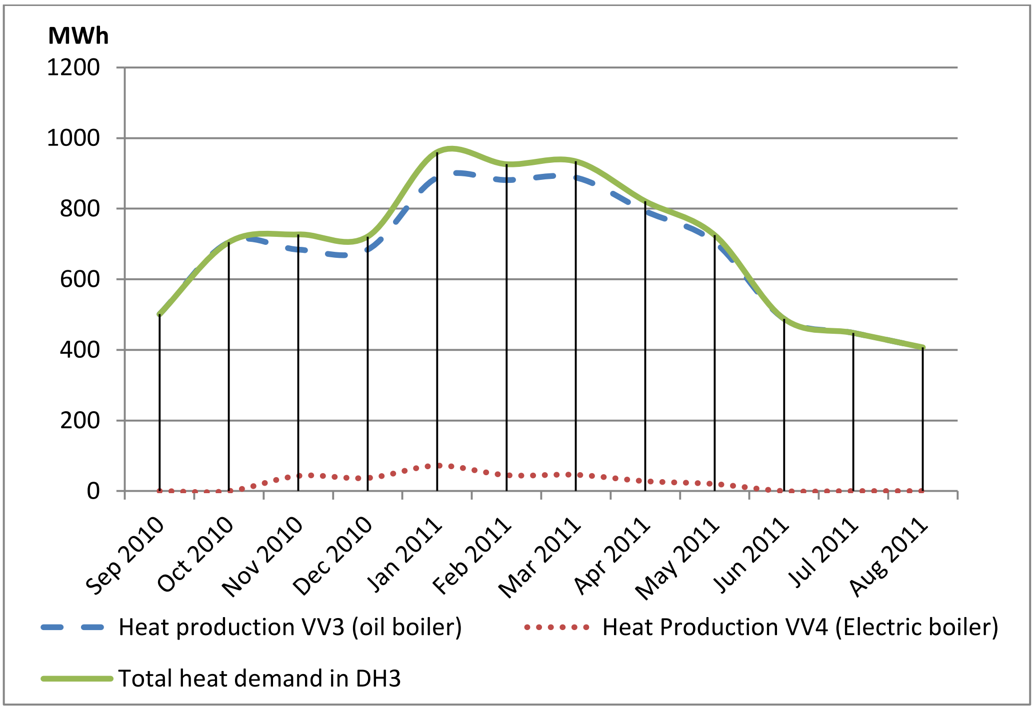


FIGURE 27: HEAT PRODUCTION RECORDS IN DH3, 2010-2011 (13).

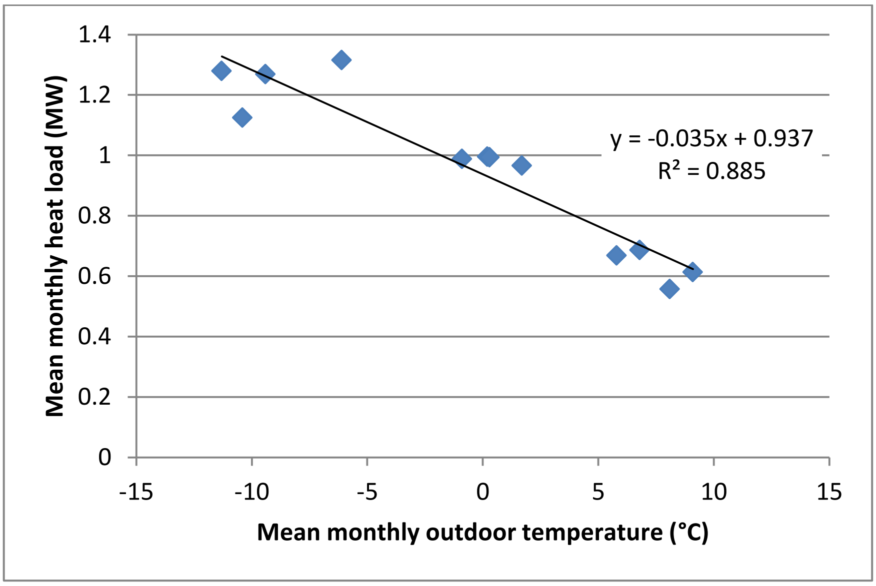


FIGURE 28: MEASURED HOURLY HEAT DEMAND IN DH3 AS A FUNCTION OF AMBIENT AIR TEMPERATURE, FOR DIFFERENT MONTHS.

Hourly ambient air temperature data for Sisimiut is moreover required to estimate hourly heat demand. As a basis this data is obtained from the Test Reference Year (TRY) of Sisimiut, made available by Asiaq (24). The TRY was published in 2004 and provides hourly weather measurements statistically representative of the most prevailing local conditions, based on measurement samples dating from 1993 to 2002.

Finally, a method is chosen to implement hourly variations of heat demand resulting from Domestic Hot Water (DHW) consumption and other non-temperature dependant loads throughout the day. These variations are estimated from district heating demand measurements made in Copenhagen in July 2001 (25), in a summer period when no space heating was needed, and therefore no parasitic perturbation is assumed. The acquired hourly variations are scaled so that the daily average is equal to one, and shown in Figure 29. The fluctuation factor is then applied to the average constant heating load. This constant heating load is based on monthly averages, intrinsically to the method detailed above, and is found by inputting an ambient air temperature of 15.5°C in Equation 2. It is assumed that above this temperature (seldom attained in Sisimiut) the buildings do not need to be heated through their space heating system, and therefore that is the point at which only DHW heat load and heat losses need to be covered.

The average constant component of the heat demand in DH3 is in this way estimated to 0.39 MW. With applied correction from the fluctuation factor, hence taking morning and evening peak loads into account, the temperature-independent heat demand in DH3 is found to oscillate between 0.33 and 0.50 MW.

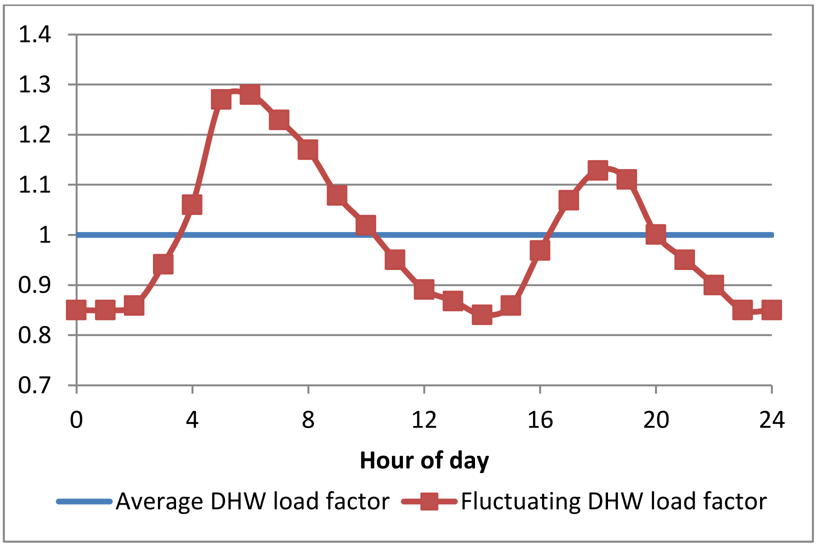


FIGURE 29: MODELLING OF HOURLY FLUCTUATIONS OF NON-TEMPERATURE DEPENDANT HEAT DEMAND THROUGHOUT THE DAY

Applying the methods described in this subsection enable the modelling of hourly heat demand in the district heat system DH3 with a certain level of dynamism and accuracy. One of the limits is the assumption that the hourly variations of non-temperature dependant heat demand remain constant all year long, in 24 hours cycles, and are similar to the ones observed in Copenhagen. Another limit is the TRY used to model hourly temperature levels in Sisimiut, due to its now aging source measurements and to the fact that weather can vary greatly from year to year in Sisimiut.

To ensure that the simulation model can reflect updated temperature measurements or in order to analyse the impact of specific weather conditions on heat utilization from the waste incinerator, the user is given the possibility to set monthly temperature variations in the model. The temperature variations are expressed as a difference of monthly average temperature compared to the TRY, and all hourly temperature values corresponding to the given month are automatically upscaled or downscaled by the same variation level. This feature is a compromise between simplicity of input for the user on one hand, and the necessity to preserve realistic temperature variation amplitudes between each hour on the other hand.

6. *Maximum heat utilization at present*

With the Excel model set using the previously-described methods, the operation of the waste incinerator is simulated in order to estimate the heat utilization achievable in the present context. The amounts of incinerated waste are varied between 250 and 350 tons per month, with the highest levels in winter period, for a total of 3200 tons per month. The incineration of 72 tons of used oil per year is considered, with monthly variations between 4 and 10. Figure 30 illustrates these variations.

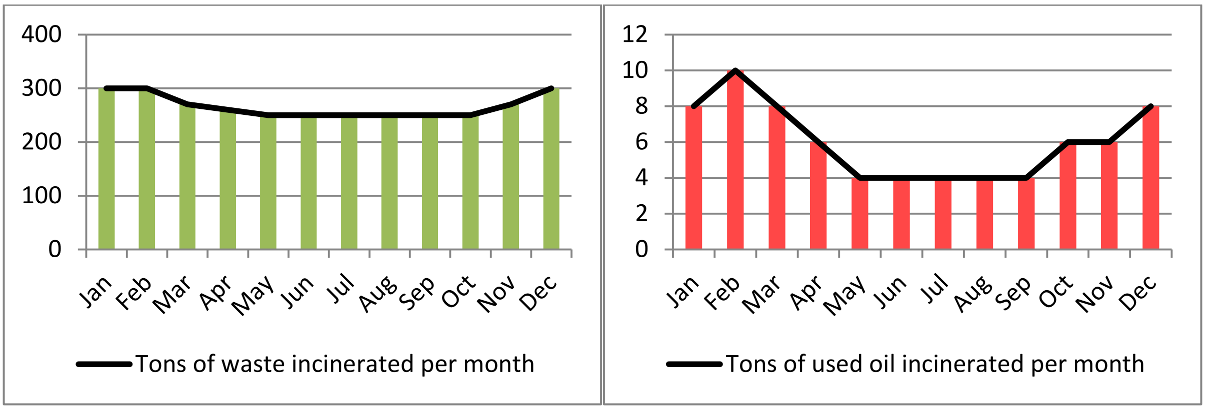


FIGURE 30: GRAPHS FROM THE EXCEL MODEL, DISPLAYING MONTHLY VARIATIONS OF INCINERATED WASTE AND OIL.

The hourly heat demand values in the district heat network are increased by 10% by the use of a simple input, in order to take into account the ongoing extension of DH3 to some new buildings, such as the engineer's collegium, some accommodation buildings for elderly people and a kindergarten (26). Other parameters such as operation plan, annual temperature data and breakdown periods are investigated in different states. These assumptions and the corresponding results in terms of heat utilization are presented in Table 1.

TABLE 1: SCENARIOS IN PRESENT CONTEXT AND RELATIVE RESULTS (YEARLY VALUES).

Scenario	**1**	**2**	**3**	**4**
Operation plan	Two-week	Three-week	Three-week	Three-week
Weather data	TRY 2004	TRY 2004	2010-2011	TRY 2004
Breakdown	No	No	No	15 days in Sep
Heat demand [MWh]	10 323	10 323	9 235	10 323
Heat production [MWh]	8 348	8 348	8 348	8 348
Heat utilization	87%	90%	85%	87%

Results from scenarios 1 and 2 show that the heat utilization benefit from shifting from a two-week operation plan to a three-week operation plan is only 3%. The result from scenario 4 demonstrates the large influence of weather on heat utilization. Temperatures from 2010-2011 are on average superior by 3.3°C to the TRY. This is enough to lower the utilization by 5%. Furthermore, it is shown in Scenario 4 that the gain in heat utilization achieved by changing operation plan in Scenario 2 can be easily neutralized by a forced maintenance period of two weeks only.

The heat duration curve corresponding to the simulation of Scenario 3 is presented in Figure 31. This plot is obtained by sorting all the hours of the years from the ones having the largest district heat demand to the ones having the lowest, instead of considering their chronological order. It appears that the peak heat demand in DH3 is about 2.25 MWh per hour, but peak load is limited to very few hours throughout the year. The slope of the heat duration curve is relatively lean, confirming that ambient air temperature variations are well spread around the year. The most interesting observation is the location of the main intersection point between the heat demand and the heat production from the waste incinerator, at roughly half of the total number of yearly hours. To the left of this point the heat demand is globally higher than the heat production from the waste incinerator, and recovered heat can be sold for the most part. To the right of the intersection point, however, the heat demand is inferior to the heat produced by the incinerator and the cooling stations need to be used. The chronological heat curve for the Scenario 3 is given in Figure 32, displaying in details the variations of district heat and heat production (and cooling) from January to December.

Due to the hourly variations of heat demand (which do not only depend on ambient temperature), and because it is not desired that the incinerator supplies the district heat load dynamically, full heat utilization is not possible in the current state of things. The calculated maximal heat utilization values can seem high enough with 85% to 90%, but it should be noticed that the scenarios are based on purely ideal incinerator operation and waste management, with optimal seasonal variation in the incineration of waste and oil. A few prolonged non-scheduled breakdowns could significantly hinder the performance, by increasing the waste incineration rate after the plant is restarted, and producing heat with a higher power. This is especially problematic in the summer months, when the heat demand is already at its lowest.

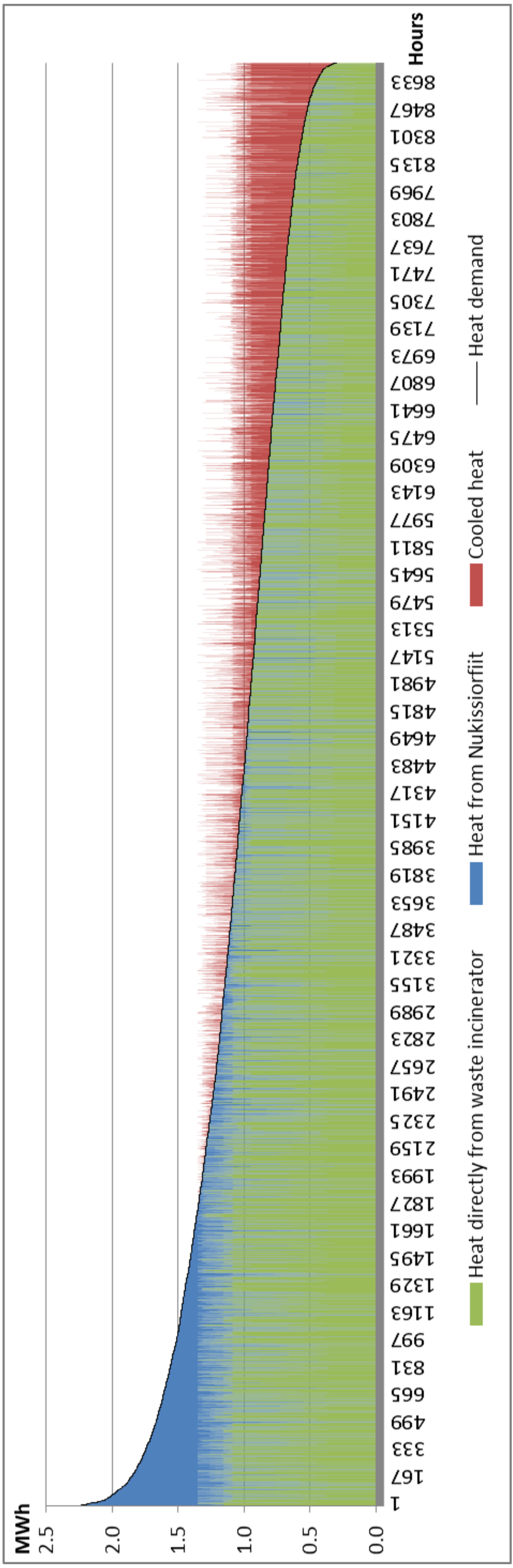


Figure 31: Heat duration curve for Scenario 3.

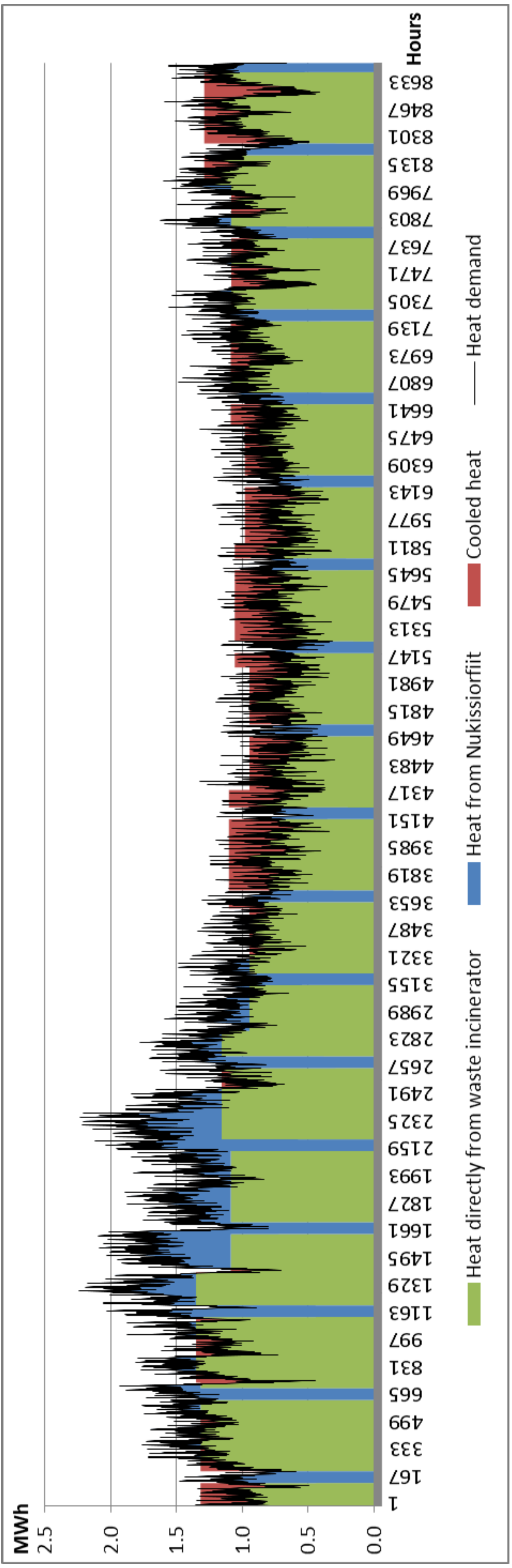


Figure 32: Chronological heat curve for Scenario 3.

7. *Maximum heat utilization with forecast developments*

The analysis carried out in this part is similar to the one looking at maximal heat utilization in the present context, but further investigates the effects of parametric changes likely to be observed in the coming 15 or 20 years. These identified parameters are in order of importance the district heat demand, the amount of incinerated waste and the ambient temperature.

- Discussions and plans are already made to progressively enlarge the district heat network DH3. This perspective is especially sought by the manager of the waste incinerator, as a way to increase heat utilization (20). A 50% increase in the heat demand is therefore modeled in this work.

- The quantities of combustible waste generated in Sisimiut seem to be slowly growing, as shown in Section V.2. This phenomenon is driven by the combined population and economic growth of the city as well as by the globally increasing amounts of imported goods. On the other hand, new waste management systems are expected to emerge in Greenland in the future (27), which could ultimately see the amount of incinerated waste decrease to the profit of more recycling.

- Temperature records from the last 70 years suggest that the ambient temperature in Sisimiut has been gradually increasing, by an average of 0.022°C per year if a linear evolution is considered, as seen in Figure 33. The trend seems even more pronounced from the 1990s until 2011. Therefore it is judged relevant to investigate the effects of a positive evolution of 5°C on mean monthly temperatures compared to the TRY in the presented analysis, and to otherwise consider the weather year 2010-2011 (already warmer than the TRY by 3°C) as a reference for forecast climate in ten years.

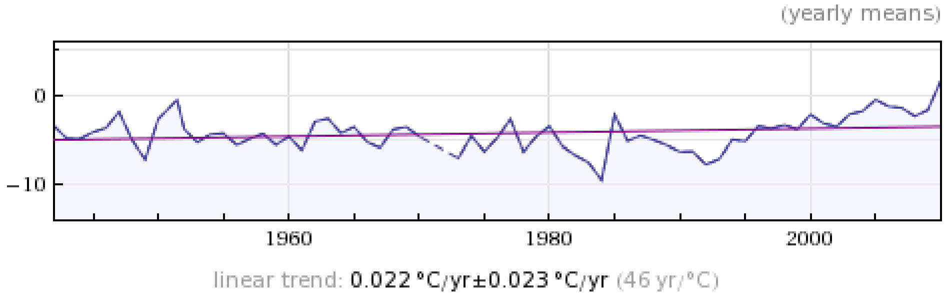


FIGURE 33: EVOLUTION OF YEARLY MEAN TEMPERATURES IN SISIMIUT, BETWEEN 1941 AND 2011 (28).

Four new scenarios are defined, and their effects on heat utilization from the waste incinerator are presented in Table 2. The operation plan is three-week and seasonal waste incineration optimization is integrated, in each case. The amount of used oil incinerated is kept at the same value as in 2010-2011.

TABLE 2: SCENARIOS IN FUTURE CONTEXT AND RELATIVE RESULTS (YEARLY VALUES).

Scenario	**5**	**6**	**7**	**8**
Heat demand factor	1.1	1.5	1.5	1.5
Waste incinerated [tons]	3 600	3 600	3 600	3 200
Temperature increase [°C]	5	5	3	3
Heat demand [MWh]	8 851	12 070	12 594	12 594
Heat production [MWh]	9 308	9 308	9 308	8 348
Heat utilization	76%	89%	93%	96%

The results suggest that although the potential for maximal heat utilization from the waste incinerator could increase in the future, there is also a possibility that heat utilization declines if the district heat network is not extended (Scenario 5). In this case, the yearly heat production of the incinerator would even exceed the district heat demand. The effect of a serious global warming on heat utilization is non-negligible as evidenced by a comparison between Scenarios 6 and 7, with a difference of 4% in this case. Scenario 8 reveals that an excellent heat utilization factor could be obtained by simply increasing the heat demand in the district heating network DH3, as figured by the manager of the incineration plant. Still, some heat would have to be ventilated, almost exclusively during summer as shown in Figure 34.

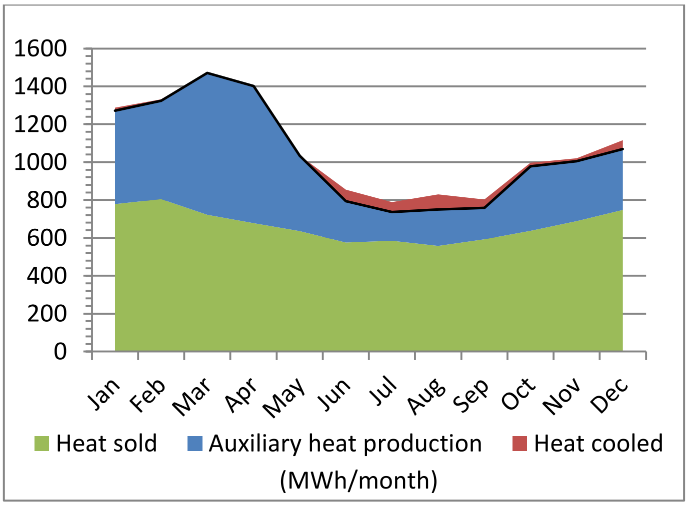


FIGURE 34: MONTHLY HEAT DEMAND AND PRODUCTION LEVELS IN SCENARIO 8.

VI. Further recommendations to improve heat utilization

1. *Extension of district heating grid*

The obvious way to achieve a better heat utilization from the waste incinerator is to increase the size of the connected district heat grid in order to supply more customers. Considering present parameters for the amounts of incinerated waste and the ambient temperature, as well as optimal operation conditions, without breakdowns and along a three-week operation plan, it is found that the head demand must be increased by 277% compared to the actual level (including most recent building connections) in order to reach a utilization factor of 99.9%. The annual heat demand would then be 23 240 MWh. This solution would most likely benefit to the global efficiency of the heating system in Sisimiut even though most of the supplied heat would then be produced by oil boilers (if no new investment in hydro power or other renewables is made in the meantime). The savings would be obtained due to the generally higher energy and cost efficiency of district heating over individual oil boilers.

If the decision is made to enlarge the district heat network DH3 in important proportions, it might be beneficial to actually consider interconnecting the three district heat grids found in Sisimiut. Economies of scale based on the already significant works could indeed improve the economic feasibility of the larger project, although calculations from a local engineering office suggest that good financial and energy-efficiency incentives to the creation of an extended district heat grid in Sisimiut are achieved on their own (29).

2. *Heat storage*

One of the reasons behind the non-utilization of heat from the incinerator is the non-flexibility characteristics of the heat production, unable to cover dynamically changes in the heat demand. This is particularly true in periods when heat demand varies between levels successively inferior and superior to the heat generation from the incinerator, typically during spring and autumn seasons. An example is given in Figure 35, where heat levels are shown for two consecutive April days, in the simulation model of Scenario 3.

The opportunity of adapting a cylindrical heat storage hot water tank between the waste incinerator and the district heat network DH3 is therefore assessed in this report, as a way to match otherwise distinctive heat production and heat consumption periods in time, and therefore to ‘shave’ heat demand peaks otherwise covered by district heat plants. The heat storage is also expected to create a large buffer between the incinerator and the Nukissiorfiit heating plants, effectively allowing some thermal inertia between the two systems. This could help in preventing the occurrence of fast ‘emergency’ situations at the heating plants, when the incinerator suddenly stops supplying hot water to the grid due to a malfunction but still keeps its supply pump in operation. A layout for a water tank adapted to the suggested plant conversion is given in Figure 36. The tank is proposed to be mounted on an overground structure in order to prevent downwards heat conduction resulting in potential permafrost thawing, which could weaken the tank construction and stability over time. A location for the tank construction is also suggested in Figure 37.

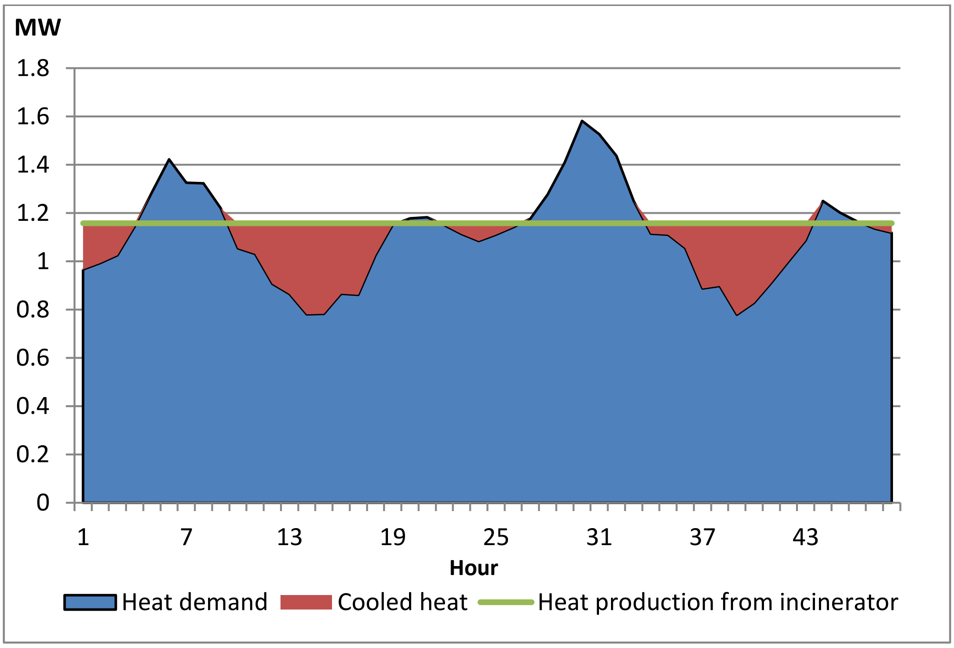


Figure 35: Example of situation resulting in heat cooling, without heat storage.

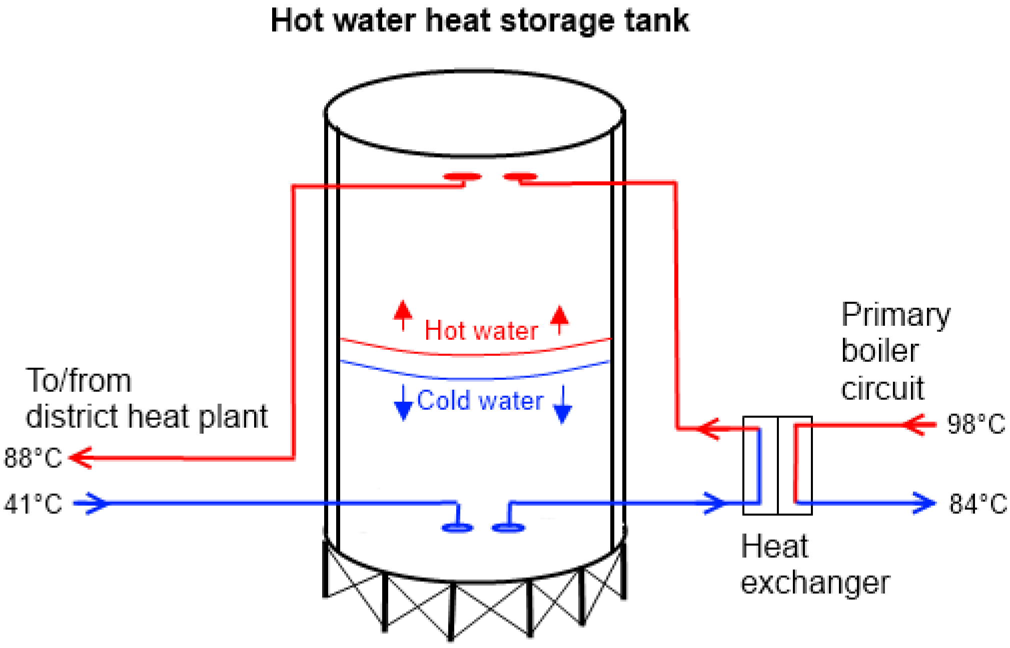


Figure 36: Basic layout for the proposed heat storage tank. Temperature values estimated after (20).

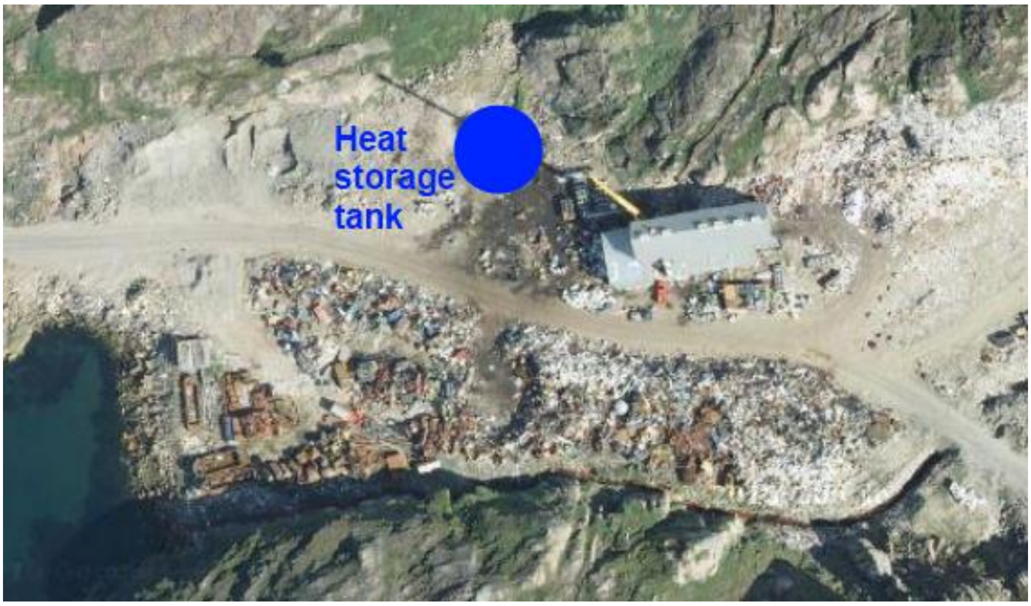


FIGURE 37: SUGGESTED IMPLEMENTATION LOCATION FOR THE HEAT STORAGE TANK (17).

Two elements are key to the heat storage efficiency achieved by the tank:

- The insulation on the sides, the top and the bottom of the tank must ally good thermal properties and a sufficient thickness to shelter the tank from the roughness of arctic winter. Special care must be taken in the piping connections so that no thermal bridges create 'heat sinks' in the insulation layer. The use of U-shaped heat traps is suggested to be implemented for the pipes, within the insulation layer itself.

- The cold and hot water inlets should be designed so as to minimize swirl and vertical movements of water inside the tank. Indeed, the heat storage capacity of the tank and the 'quality' of the output heat are highly dependent on the cold and hot temperatures found at the bottom and the top of the tank. Experiments led by the solar thermal energy group at DTU (30) have demonstrated that a good thermal stratification[2] of water can be achieved in the tank only if the water intakes and outtakes do not create perturbations in the thermal layers. This can be obtained by using 'horizontal plate' inlet and outlet covers (as pictured in Figure 36) or, better, inlet stratifiers. Some of these technologies are still in the research and development stage but showed impressive potential for improved heat storage efficiency.

The influence and behaviour of hot water heat storage applied to the waste incinerator are analysed by simulation in the Excel model. The user inputs are the size of the water storage in cubic meters, the hot water supply temperature from the incinerator, the district heat return temperature from the Nukissiorfiit plant, and the insulation thickness and thermal conductivity. Additionally, the level of heat storage in the initial time step of the simulation is also required to be précised, as a percentage of the maximal heat storage capacity.

---

[2] Natural separation of hot and cold water based on density differential.

The maximal heat storage capacity is determined as follows:

$$Q_{heat\ storage}\ [MWh] = \dot{m}_{water}\ [tons] \cdot Cp_{water} \left[\frac{MWh}{ton.°C}\right] \cdot (T_{hot} - T_{cold})\ [°C] \qquad \text{Eq 3.}$$

The specific heat capacity of water Cp_{water} is considered to be 4180 J/kg.°C, and the mass of water is determined from the volume using a density of 980 kg/m^3. The temperatures T_{hot} and T_{cold} are respectively 88 and 41 °C, from data communicated by the manager of the incineration plant (20).

Heat losses from the tank are taken into account in the model, assuming a uniform temperature inside the tank. The heat losses are calculated as the product between the tank's heat loss coefficient and the temperature difference between the mean temperature inside the storage and the ambient air temperature, for every hour of the year. An overall heat loss coefficient is determined for the tank, as the sum of distinct heat loss coefficients for the sides, top and bottom, as detailed in equations 4 to 6. The dimensions referred to in the equations are shown in Figure 38. The insulation is in the model assumed to have the same thickness on all sides of the tank. Regardless of insulation properties, the optimal ratio of inner tank height over inner diameter is proven to be 1 in all situations (31), therefore this ratio is assumed in the model calculations.

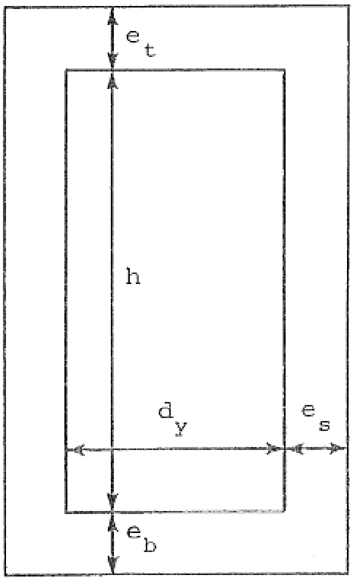


FIGURE 38: SKETCH SHOWING DIMENSION NOTATIONS FOR INNER TANK (d_y,H) AND INSULATION (e_T,e_S,e_B) (31).

Heat loss coefficient from the top:

$$U_t = \frac{\frac{\pi}{4} \cdot (d_y + e_s)^2}{\frac{e_t}{\lambda} + 0.13} \left[\frac{W}{°C}\right] \qquad \text{Eq 4.}$$

Heat loss coefficient from the bottom:

$$U_b = \frac{\frac{\pi}{4} \cdot (d_y + e_s)^2}{\frac{e_b}{\lambda} + 0.13} \left[\frac{W}{°C}\right] \qquad \text{Eq 5.}$$

Heat loss coefficient from the sides:

$$U_s = \frac{\pi}{\frac{1}{2 \cdot \lambda} \ln \frac{d_y + 2e_s}{d_y} + \frac{0.13}{d_y + 2e_s}} \left[\frac{W}{°C}\right] \qquad \text{Eq 6.}$$

With λ the heat conductivity of the insulation (by default 0.045 W/m°C in the model). The overall heat loss coefficient U is the sum of Ut, Ub, and Us. The amount of heat stored at a given hour is taken into account in the heat loss calculation, as it impacts the mean temperature in the tank:

$$T_{tank\ mean} = T_{cold} + \ \%\ Charge\ in\ storage \cdot (T_{hot} - T_{cold})\ \ [°C] \qquad \text{Eq 7.}$$

For each hour, the heat loss from the tank is then:

$$Q_{loss}[MWh] = \ U \left[\frac{MWh}{°C}\right] \cdot (T_{tank\ mean} - T_{ambient\ air})\ [°C] \qquad \text{Eq 8.}$$

As an example, the heat storage capacity of a 1000 m^3 cylindrical tank is 53.6 MWh (roughly 48 hours of uninterrupted waste incineration). The inner diameter and height of the tank are 10.8 meters, and considering a 30 cm thick insulation with conductivity of 0.045 W/m°C the overall heat loss coefficient is 84.5 W/°C. With a fully charged heat storage ($T_{tank\ mean} = 88°C$) and an air temperature of -10°C, the hourly heat loss is 8.3 kWh. Hence in this case only 0.015% of the heat contained in the tank is lost to the environment every hour, if the charge remains complete and the outdoor temperature constant. The calculations behind this result consider a perfectly insulated tank, without any thermal bridges, so in reality the heat loss can be expected to be slightly higher, depending on the quality of the tank design.

It is assumed that all the heat produced by the incinerator is transferred to the tank before being processed to the district heat network, even if the demand matches the production. If the demand exceeds the production, the heat storage is emptied (cold water progressively reaching the top of the tank), until a temperature-sensor based controller stops pumping water to and from the Nukissiorfiit heat plant. When the production from the incinerator exceeds heat demand, the tank automatically feels up with warm water. If the maximal heat storage level is reached and heat production still exceeds heat demand, then the fan cooling stations are put in operation.

This control system does not manage provisional heat storage, which takes into account future heat consumption forecasts to optimize the use of the heat storage. The compared opportunity of such a system could be investigated, but the results are expected to show a restricted interest since the incineration plant can only regulate its production within small limits.

Investment costs of the heat storage tank are estimated, so as to determine the optimal storage capacity to install with respects to simple yearly economics. The optimal sizing provides the best compromise between storage capacity (high capacity resulting in extra earnings from increased heat sales) and investment and maintenance costs (logically increasing with higher capacity).

Four new scenarios are developed and modeled using the Excel spreadsheet. The construction of a heat storage tank is assumed to take place within the next five years in all cases. Scenario 9 is based on Scenario 3 (see page 38), and Scenarios 10 to 12 cover various possible evolutions of the modeled parameters in future years.

Investment costs are estimated for the construction of the heat storage tank in present situation (Scenario 9), and yearly maintenance costs are estimated for a subsequent lifetime of 20 years (which could see the scenario evolve to 10, 11 and 12). The tank sizing is optimized with respects to simple yearly economics in the present scenario. Optimal sizing provides the best compromise between storage capacity (high storage capacity resulting in extra earnings from increased yearly heat sales) and investment and maintenance costs (logically increasing with higher capacity). The optimization is achieved by maximizing the following simple profit function, with an assumed heat storage tank lifetime of 20 years:

$$Total\ profit\ from\ heat\ storage\ project = \\ 20 \cdot (Extra\ yearly\ revenue\ - Yearly\ maintenance\ costs) - Investment\ costs \qquad \text{Eq 9.}$$

The extra yearly revenue corresponds to the heat sale benefits directly generated by the heat storage, and that would not be earned with the basic plant layout. The revenue calculation considers the current heat sale price of 476 DKK/MWh (from the municipal incinerator to Nukissiorfiit), but this value is evolving on a regular basis due to nation-wide tariffs set by Nukissiorfiit. Therefore the heat price is easily and directly adjustable in the model by the user. The heat sale price from the incinerator to the district heating plant has been constantly increasing since the incinerator was put in operation in 1999, implying that the attractiveness of heat storage implementation could be expected to be also higher as the heat sale tariff is updated in the future.

The investment costs are modeled following a non-linear trend taking economies of scale into account, based on return of experience from different German seasonal heat storage projects for solar district heating plants (see Appendix 4). The investment ratio curve used in the Excel model is displayed in Figure 39. The yearly maintenance costs are assumed to be constant in time, equal to 1% of the investment cost.

Table 3: Description of Scenarios considered for heat storage implementation and results without storage

Scenario	9	10	11	12
Heat demand factor	1.1	1.3	1.5	1.5
Waste incinerated [tons]	3 200	3 200	3 600	3 600
Ambient temperature [°C]	2010-2011	2010-2011	2010-2011	TRY + 5
Heat demand [MWh]	9 235	10 915	12 594	12 070
Heat production [MWh]	8 348	8 348	9 308	9 308
Heat utilization	85%	92%	93%	89%

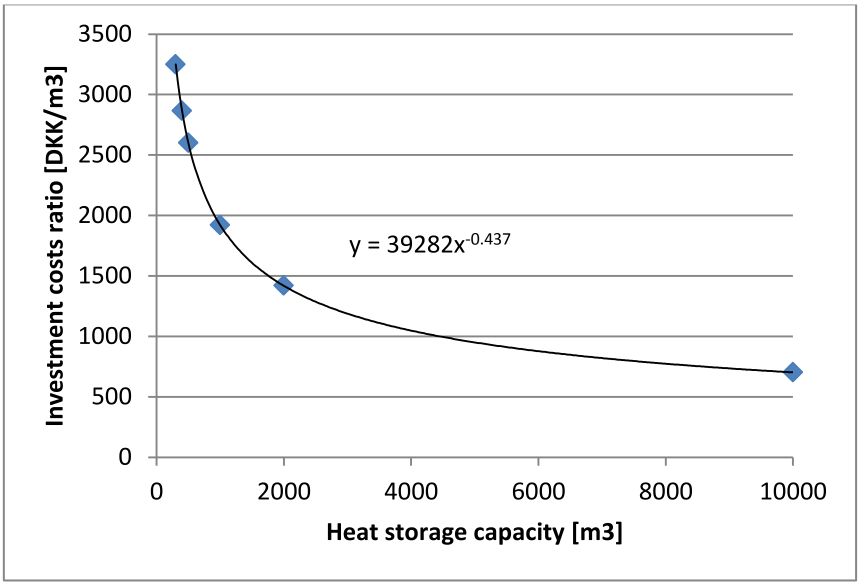


Figure 39: Evolution of heat storage investment ratio as a function of heat storage size (32).

Table 4: Summary of results for Scenarios 9 to 12, with heat storage implementation.

Scenario	9	10	11	12
Heat storage capacity [m3]	1 240	1 240	1 240	1 240
Heat storage capacity [MWh]	66.5	66.5	66.5	66.5
Tank inner diameter [m]	11.6	11.6	11.6	11.6
Average heat storage charge	37%	16%	14%	23%
Heat loss [MWh]	50	42	41	43
Heat utilization	95%	99%	99%	98%
Extra earnings [kDKK/year]	386	305	302	355
Investment costs [kDKK]	2 167	2 167	2 167	2 167
Maintenance costs [kDKK/year]	22	22	22	22
Simple payback time [years]	6.0	7.7	7.7	6.5

Additionally, an estimation of simple payback time for the heat storage project is calculated based on the investments costs and the additional revenue generated by the heat storage installation:

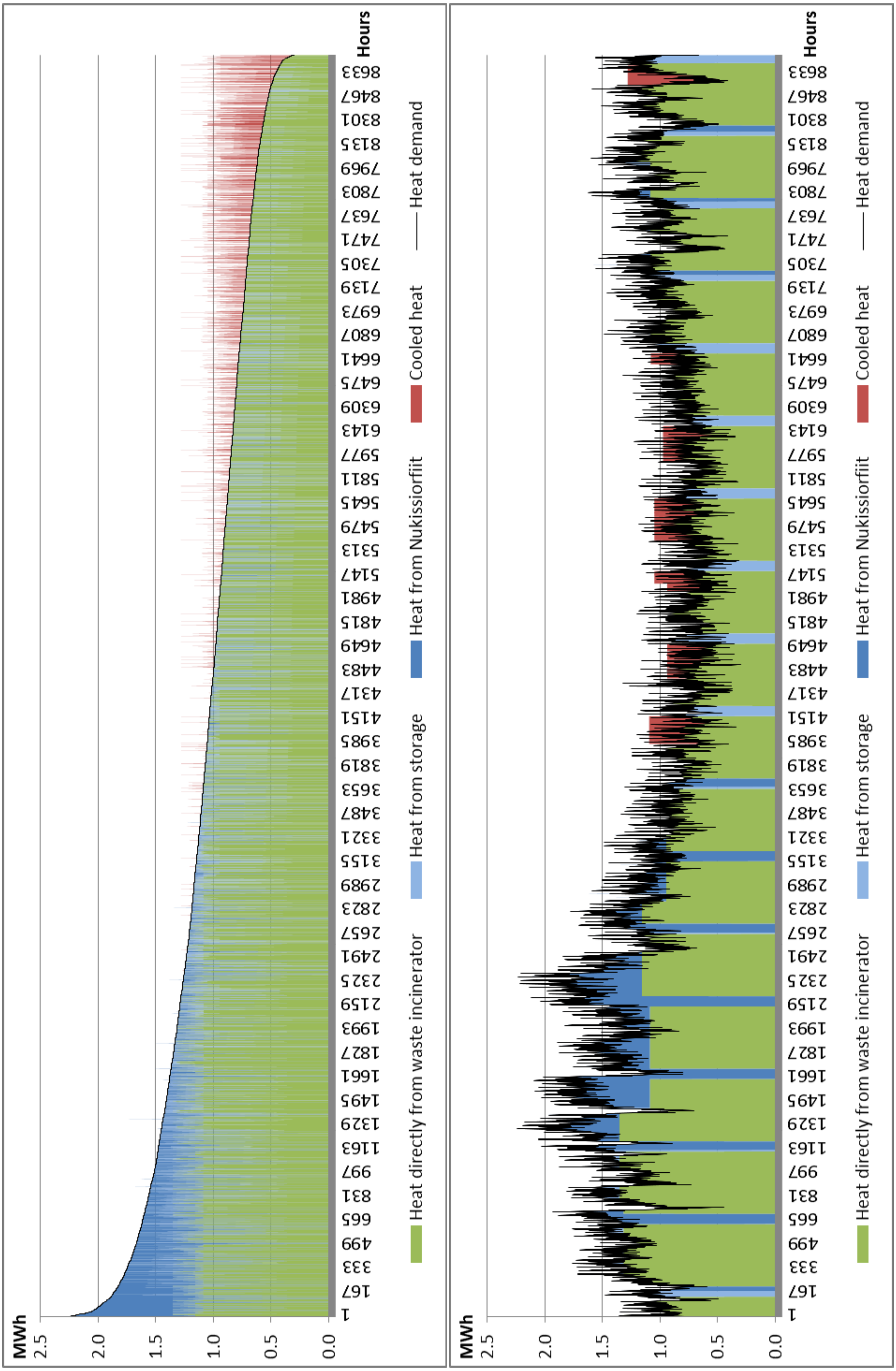
$$Simple\ payback\ time = \frac{Investment\ costs}{Yearly\ extra\ revenue - Yearly\ maintenance\ costs} \qquad \text{Eq 10.}$$

The results for the economic optimization on heat storage capacity are displayed in Table 4. The optimized heat storage capacity is found to be 1 240 m^3 if the storage is to be built in the present scenario (9), yielding a total profit of 5.1 million DKK after 20 years if it is assumed that the heat demand, waste quantities and climate remain the same.

The chronological heat curve and heat duration curve for this scenario with heat storage are given in Figures 40 and Figures 401 respectively, as an example of the effect of heat storage on coverage of heat demand in the district heat network. These curves can be directly compared to the curves for Scenario 3 (page 40) since Scenario 3 and 9 are identical. Moreover, the level of charge in the heat storage throughout the year and the heat cooling periods are shown in Figure 42.

The storage is used through most of the year, except for periods with the highest heat demand (in March and April using temperatures from 2010-2011). The heat storage is purely used as a balancing regulator in mid-season, with efficient shaving of peak heat demand by heat produced beforehand during low demand periods. In summer however, the storage accumulates significantly more heat than it delivers, until the storage reaches full capacity and the cooling stations have to be used. The heat storage can in this situation and to some extent be seen as a passive coolant for the extra heat, with the small heat losses incurred by the tank. This side-effect effectively lowers the electric consumption from the cooling fans, compared to the present situation.

It is observed that the sizing chosen for the hot water tank provides enough heat storage capacity to cover the whole heat demand of the district heating network DH3 during week-ends of maintenance in the summer, every three weeks. The tank is typically completely charged before the given week-ends, with additional heat cooling taking place. The heat storage automatically covers the heat load once the incinerator is put out of operation, without causing any disturbance to the system operation and to Nukissiorfiit’s plant control system. The Nukissiorfiit plant is in this way not required to take over heat production during these weekends, and the otherwise ventilated heat is fully utilized.



Figures 40 and 41: Heat duration curve and chronological heat curve in Scenario 9, with heat storage.

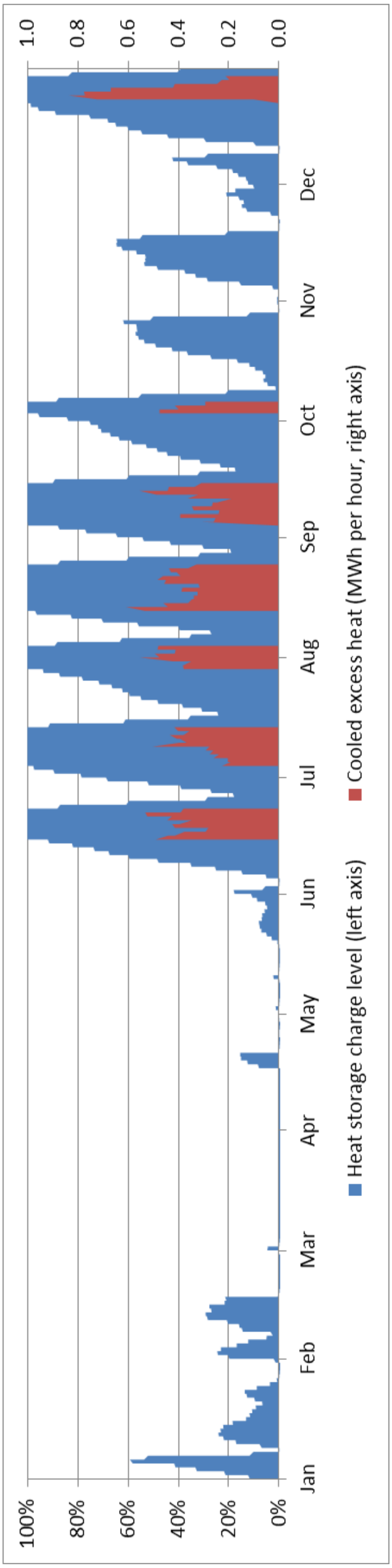


Figure 42: Hourly heat storage charge and cooled excess heat in Scenario 9

The overall improvement on heat utilization is estimated to 10% in the present context scenario, leaving only 5% of the heat produced every year to be cooled. If the incineration context evolves to scenarios 10, 11 or 12 with time, which is to be expected during the 20 years lifetime of the heat storage tank, nearly all heat production can then be utilized. Only very few MWh will still need to be cooled using the fan stations, during exceptional summer days. The model determines that in order to reach a 100% heat utilization in the present case scenario the heat storage capacity has to reach a minimum of 6 670 m^3, equivalent to 20.5 meters of diameter (and height), 363 MWh of storage and more than five times the proposed storage size. This design would logically prove un-economic due to investment costs increased by a factor of 2.6 and compensated by only modest improvements on income from heat sale.

The economic incentive to the project realization is on the other hand considered worthy using a 1 240 m^3 tank, with a simple payback time lying between 6 and 7.7 years in all cases. It can be appreciated that the economic attractiveness of the heat storage remains good even when the context evolves to Scenarios 10 to 12. The improvement on heat utilization obtained from the tank implementation can actually be expected to be even higher when considering a more realistic and less optimized waste incineration distribution over the months, as well as long maintenance periods due to unexpected breakdowns. Hence the simple payback time could in practice be slightly reduced compared to the model results. This economic indicator remains nevertheless largely imprecise and does not consider potential financing costs (eg. bank loan), which could burden the profitability of the scheme.

VII. Conclusion

The description of the energy and waste management frameworks in Greenland and Sisimiut has shown the particular interest of waste incineration with heat recovery, in a context of small isolated communities highly dependent on imports of energy commodities, and vulnerable to local contaminations from waste. Despite some issues with sorting of hazardous waste and unknown flue-gas pollution emissions, the municipal waste incinerator in Sisimiut allows the city to sustain a continued growth in population and life standards, without the negative backlash of increasing landfill area and degrading sanitary conditions.

The issue of low heat utilization from the waste incinerator has been analyzed, and it arose that the limited size of the connected district heat grid is largely responsible for the forced cooling of heat (during summer for the most part). Other parameters do however have a role in the present issue, such as yearly repartition of incinerated quantities of waste, operation pattern and maintenance quality of the plant. From bad utilization records in the previous years, the incinerator is now moving towards more balanced and optimized operation patterns, under the influence of a new managing crew. The results of the work presented in this report suggest that under present conditions of heat demand, waste generation and climate, the achievable heat utilization from the district heating remains limited to 85%, which is equivalent to a waste of heat of about 1200 MWh per year.

An examination of current trends and expected evolutions of key factors affecting heat utilization has further been carried out, and some scenarios have been developed to estimate how the future incineration and district heating contexts might evolve in the near future, within a range of 20 years. The most sensitive of these parameters are found to be the heat demand in the district heat grid, which is likely to increase with planned extensions, and despite globally increasing ambient air temperatures in Sisimiut; as well as the amount of waste generated in the city. This parameter is slowly increasing together with the local population and economic growth, which tends to expand the heat production capacity from the incinerator and lower the heat utilization factor. Overall, considering large extensions of the district heating resulting in a heat demand 40% higher than the one observed at the end of 2011, it is found that heat utilization from the incinerator should 'naturally' increase to a level of 90% to 95% in the defined timeframe. There again these values are only valid if the incinerator is operated in optimal conditions (three-week operation plan, no breakdowns, maintained efficiency, etc.).

Two methods can be recommended to further improve the heat utilization factor. The first considers a more ambitious district heat grid extension, which could actually see all district heat grids in Sisimiut merging to the profit of better heat supply flexibility and improved system efficiency. The extension required to ensure a 100% heat utilization factor would see the demand in the district heat increase by at least 2.8 times. The second assessed method looks at constructing a hot water heat storage tank as an intermediary between the incinerator and the existing district heat plant. The benefits of the thermal storage include the introduction of more inertia and elasticity in the interface between heat supply and demand, which could solve control issues encountered by Nukissiorfiit at the moment, and the reduction of heat cooling at the incinerator plant. Based on a simple economical optimization, a storage capacity of 1240 m^3 is proposed, which would translate in a heat utilization factor between 95% and 99%. Such a scheme is expected to be economically feasible, with estimated investment costs of 2.2 million Kroner, and a simple payback time close to 6 or 7 years. The implementation of the heat storage would prove most profitable if initiated as early as possible, but would still be highly compatible with future district heating grid extensions in terms of practicality, savings on heat utilization and economic attractiveness.

Finally, an Excel spreadsheet model simulating the hourly operation of the waste incinerator was created within the course of this work. It is designed to be easily adaptable to various contexts, with direct inputs of the most influent parameters by the user. It still retains a high level of automation to make it usable by new persons in a pleasant way. It is hoped that this tool can be somehow useful to the waste incinerator staff in Sisimiut, and to any other person interested in this work or wishing to apply the model to another case within a similar context.

VIII. Appendices

1. Map of district heat networks in Sisimiut

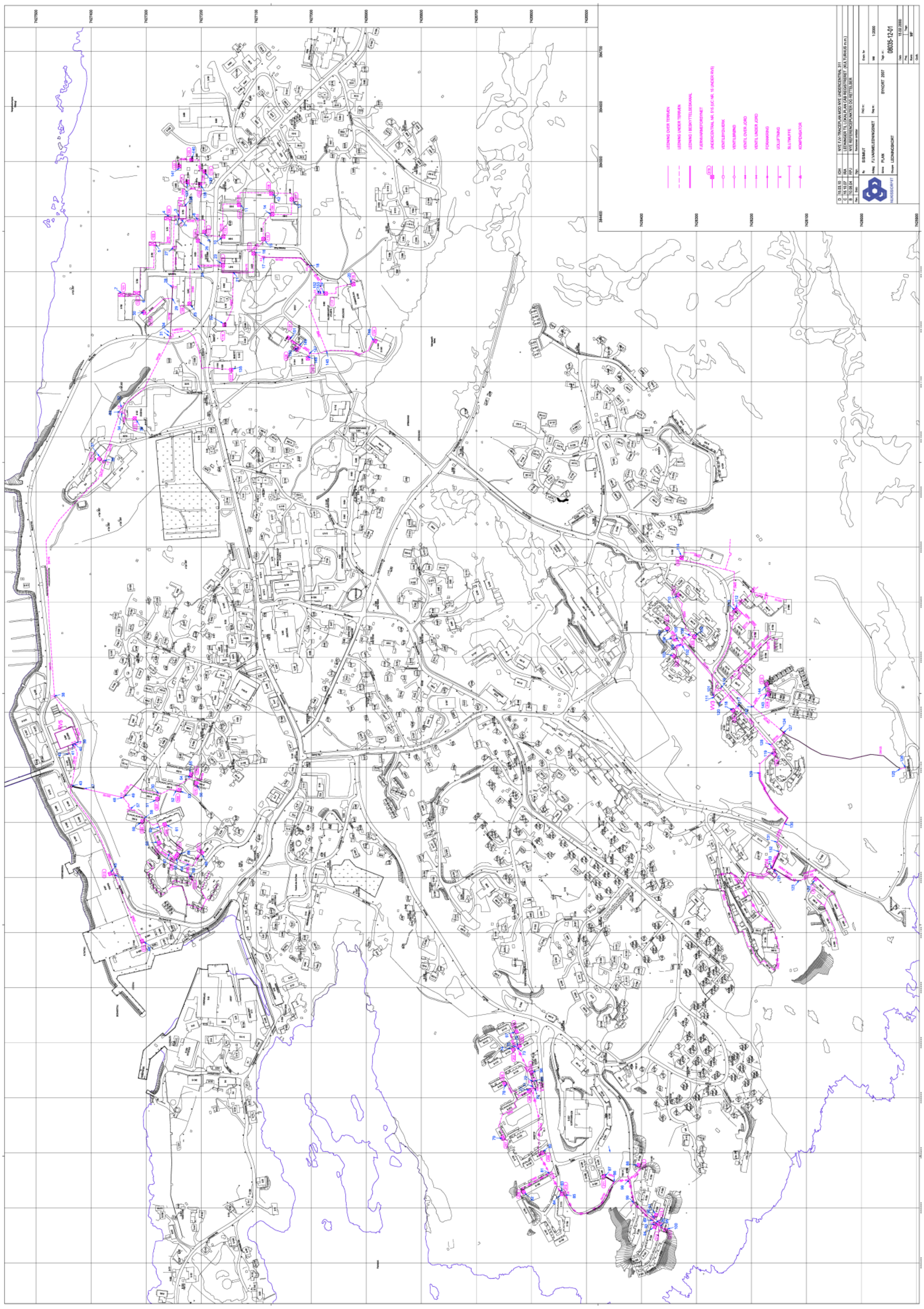


FIGURE 43:MAP OF DISTRICT HEAT AREAS IN SISIMIUT (PIPES SHOWN IN PURPLE) (15)

2. *Cover page from the REKA incinerator's operation manual*

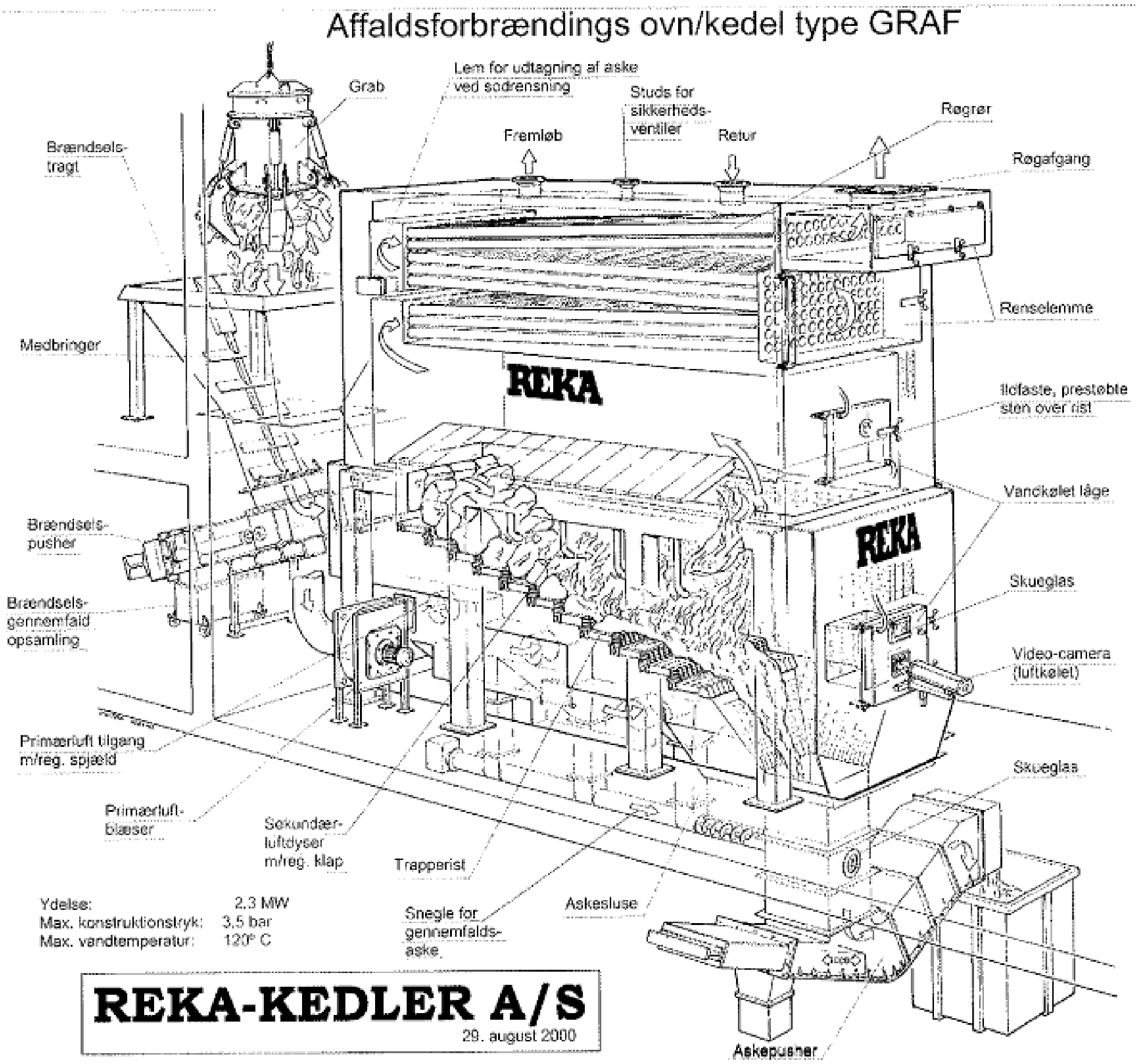
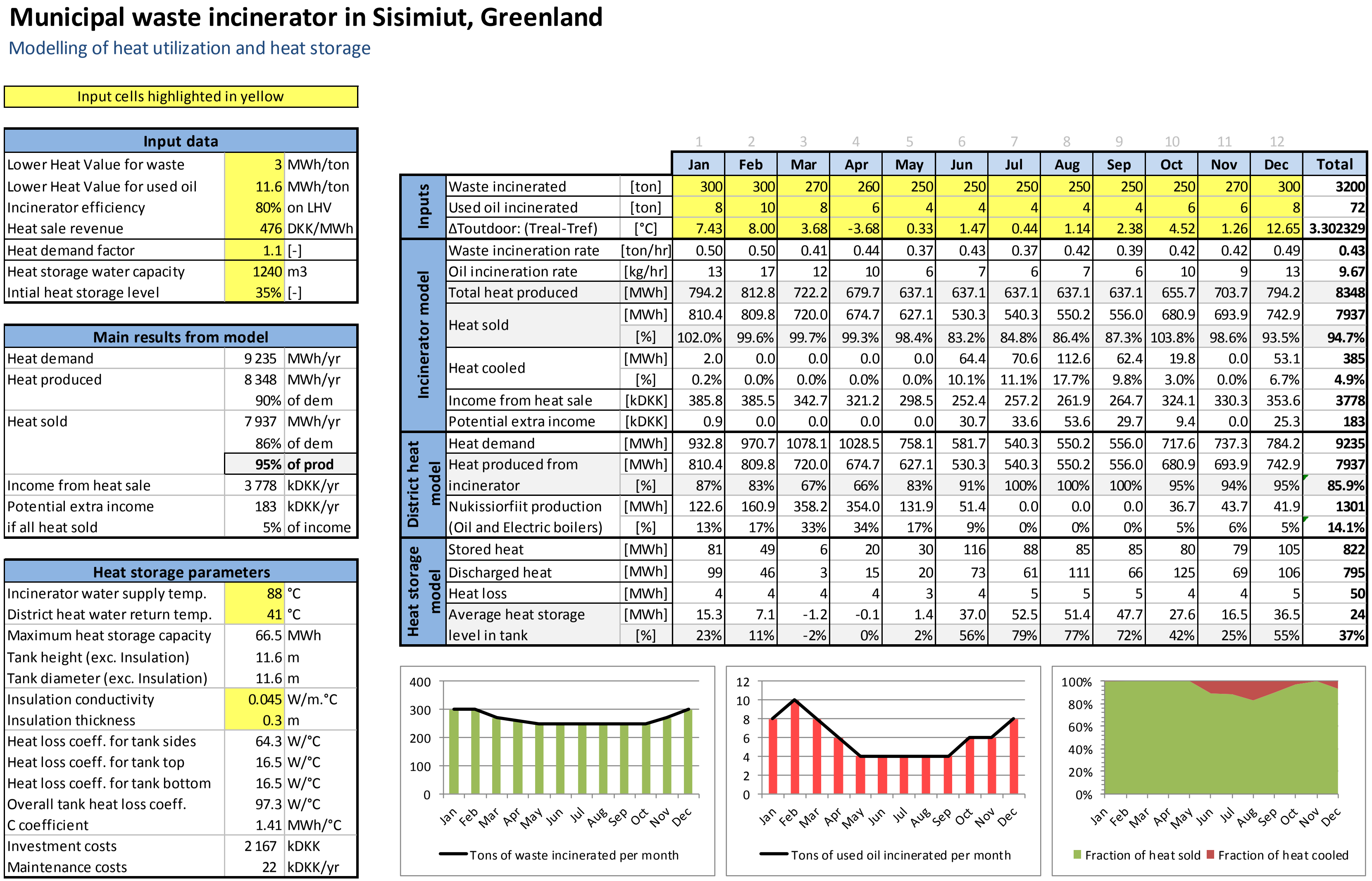


FIGURE 44: DRAWING PRESENTING THE MAIN CONSTITUENTS OF THE WASTE INCINERATOR (19).

3. *Screen capture from the developed Incinerator model*

Main input parameters and results only, data corresponding to Scenario 9 (page 49).



Municipal waste incinerator in Sisimiut, Greenland

Modelling of heat utilization and heat storage

Input cells highlighted in yellow

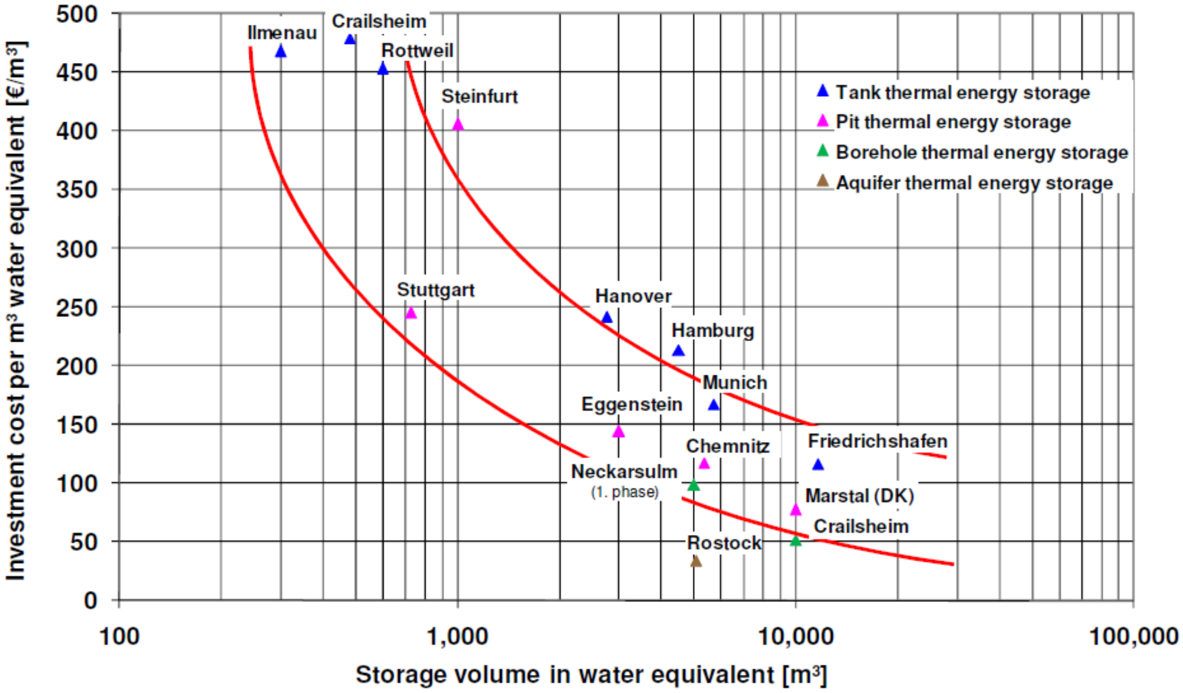
Input data		
Lower Heat Value for waste	3	MWh/ton
Lower Heat Value for used oil	11.6	MWh/ton
Incinerator efficiency	80%	on LHV
Heat sale revenue	476	DKK/MWh
Heat demand factor	1.1	[-]
Heat storage water capacity	1240	m3
Intial heat storage level	35%	[-]

Main results from model		
Heat demand	9 235	MWh/yr
Heat produced	8 348	MWh/yr
	90%	of dem
Heat sold	7 937	MWh/yr
	86%	of dem
	95%	**of prod**
Income from heat sale	3 778	kDKK/yr
Potential extra income	183	kDKK/yr
if all heat sold	5%	of income

Heat storage parameters		
Incinerator water supply temp.	88	°C
District heat water return temp.	41	°C
Maximum heat storage capacity	66.5	MWh
Tank height (exc. Insulation)	11.6	m
Tank diameter (exc. Insulation)	11.6	m
Insulation conductivity	0.045	W/m.°C
Insulation thickness	0.3	m
Heat loss coeff. for tank sides	64.3	W/°C
Heat loss coeff. for tank top	16.5	W/°C
Heat loss coeff. for tank bottom	16.5	W/°C
Overall tank heat loss coeff.	97.3	W/°C
C coefficient	1.41	MWh/°C
Investment costs	2 167	kDKK
Maintenance costs	22	kDKK/yr

			1	2	3	4	5	6	7	8	9	10	11	12	
			Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Total**
Inputs	Waste incinerated	[ton]	300	300	270	260	250	250	250	250	250	250	270	300	**3200**
	Used oil incinerated	[ton]	8	10	8	6	4	4	4	4	4	6	6	8	**72**
	ΔToutdoor: (Treal-Tref)	[°C]	7.43	8.00	3.68	-3.68	0.33	1.47	0.44	1.14	2.38	4.52	1.26	12.65	**3.302329**
Incinerator model	Waste incineration rate	[ton/hr]	0.50	0.50	0.41	0.44	0.37	0.43	0.37	0.42	0.39	0.42	0.42	0.49	**0.43**
	Oil incineration rate	[kg/hr]	13	17	12	10	6	7	6	7	6	10	9	13	**9.67**
	Total heat produced	[MWh]	794.2	812.8	722.2	679.7	637.1	637.1	637.1	637.1	637.1	655.7	703.7	794.2	**8348**
	Heat sold	[MWh]	810.4	809.8	720.0	674.7	627.1	530.3	540.3	550.2	556.0	680.9	693.9	742.9	**7937**
		[%]	102.0%	99.6%	99.7%	99.3%	98.4%	83.2%	84.8%	86.4%	87.3%	103.8%	98.6%	93.5%	**94.7%**
	Heat cooled	[MWh]	2.0	0.0	0.0	0.0	0.0	64.4	70.6	112.6	62.4	19.8	0.0	53.1	**385**
		[%]	0.2%	0.0%	0.0%	0.0%	0.0%	10.1%	11.1%	17.7%	9.8%	3.0%	0.0%	6.7%	**4.9%**
	Income from heat sale	[kDKK]	385.8	385.5	342.7	321.2	298.5	252.4	257.2	261.9	264.7	324.1	330.3	353.6	**3778**
	Potential extra income	[kDKK]	0.9	0.0	0.0	0.0	0.0	30.7	33.6	53.6	29.7	9.4	0.0	25.3	**183**
District heat model	Heat demand	[MWh]	932.8	970.7	1078.1	1028.5	758.1	581.7	540.3	550.2	556.0	717.6	737.3	784.2	**9235**
	Heat produced from incinerator	[MWh]	810.4	809.8	720.0	674.7	627.1	530.3	540.3	550.2	556.0	680.9	693.9	742.9	**7937**
		[%]	87%	83%	67%	66%	83%	91%	100%	100%	100%	95%	94%	95%	**85.9%**
	Nukissiorfiit production (Oil and Electric boilers)	[MWh]	122.6	160.9	358.2	354.0	131.9	51.4	0.0	0.0	0.0	36.7	43.7	41.9	**1301**
		[%]	13%	17%	33%	34%	17%	9%	0%	0%	0%	5%	6%	5%	**14.1%**
Heat storage model	Stored heat	[MWh]	81	49	6	20	30	116	88	85	85	80	79	105	**822**
	Discharged heat	[MWh]	99	46	3	15	20	73	61	111	66	125	69	106	**795**
	Heat loss	[MWh]	4	4	4	4	3	4	5	5	5	4	4	5	**50**
	Average heat storage level in tank	[MWh]	15.3	7.1	-1.2	-0.1	1.4	37.0	52.5	51.4	47.7	27.6	16.5	36.5	**24**
		[%]	23%	11%	-2%	0%	2%	56%	79%	77%	72%	42%	25%	55%	**37%**

4. *Reference for heat storage investment costs*



Source: (32). The projects relevant to the present work are the ones belonging to the 'Tank thermal energy storage' category.

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