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Financially sustainable carbon neutral energy systems in food industry

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Abstract

This master's thesis's objective was to find the most suitable financially sustainable carbon neutral technologies and investments for a Finnish publicly listed multinational food company for it to reach its 2025 carbon neutrality goals. The work consisted of a literature review, which aim was to identify and provide as many possible carbon neutral energy technologies as possible. Due to the fact, that the company buys its electricity already green, the literature review and the experimental part focused on carbon free heat and steam generation. In the experimental part, two factories and their energy systems were assessed from the perspective of reaching carbon neutrality. This included mainly qualitative analysis but also numerical calculations. The most suitable technologies were selected based on technical feasibility, implementation, and investments costs as well as payback. The conclusion of the analysis was that biogas and a centralized thermal waste heat recovery system were the two most important carbon neutral technologies for eliminating the emissions. The more general outcome of the study was, that there is no universal solution to reach carbon neutrality in different cases, for the solution depends on the properties of the circumstance. Moreover, waste heat was concluded to be a significant source of energy and the importance of data in future carbon neutral energy systems was found to be crucial.

Keywords Food industry, carbon neutrality, carbon neutral energy systems, waste heat recovery

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Tiivistelmä

Tämän diplomityön tarkoituksena oli löytää kaikista sopivimmat taloudellisesti kestävät hiilineutraalit teknologiat suomalaiselle monikansalliselle pörssiyhtiölle päämääränä sen 2025 hiilineutraaliustavoite. Työ koostui kirjallisuuskatsauksesta, jonka tarkoituksena oli tunnistaa ja tarjota mahdollisimman monta hiilineutraalia energiateknologiaa kuin mahdollista. Johtuen siitä, että yritys ostaa jo kaiken sähköstään vihreänä, kirjallisuuskatsaus ja sitä seuraava analyysi painottuivat pääasiassa hiilivapaaseen lämmön ja höyry tuotantoon. Kokeellisessa osuudessa tutkittiin kahta tehdasta ja niiden energiajärjestelmiä hiilineutraaliuden saavuttamisen näkökulmasta. Analyysi oli pääasiassa kvalitatiivinen, mutta myös numeerisia laskentamenetelmiä käytetiin. Sopivimmat teknologiat valittiin teknisen sopivuuden, toteutettavuuden ja investointikustannusten sekä takaisinmaksuajan perusteella. Analyysin johtopäätös oli, että biokaasu ja keskitetty hukkalämmön talteenottojärjestelmä olivat kaksi merkittävintä hiilineutraalia teknologiavaihtoehtoa päästöjen eliminoimiseksi. Työn yleisempi johtopäätös oli, että yhtä universaalia ratkaisua hiilineutraalisuuden saavuttamiseksi erilaisissa tapauksissa ei ole, vaan ratkaisut riippuvat olosuhteista. Hukkalämmön havaittiin olevan huomattava lämmönlähde ja datan merkitys korostui keskeiseksi tekijäksi tulevaisuuden hiilineutraaleissa energiajärjestelmissä.

Avainsanat elintarvikeala, elintarviketeollisuus, hiilineutraalius, hiilineutraalit energiajärjestelmät, hukkalämmön talteenotto

Contents

Preface

I want to thank my supervisor Professor Risto Lahdelma and my instructors Paavo Räsänen and Jouni Pesonen for their guidance. I also want to thank experts inside and outside the company for providing support and valuable information.

Sompasaari, 8 February 2022
Tuomas Forsström

Symbols and abbreviations

Symbols

Q_H	heat at the high temperature level [J or MWh]
Q_L	heat at low temperature level [J or MWh]
$Q(t)$	power at a given time t [kW]
Q	energy in a latent heat storage system [kJ]
E	capacity of thermal storage [J or MWh]
W	work [J or MWh]
m	mass [kg]
$\dot{m}(t)$	mass flow at a given time t [kg/s]
$\dot{v}(t)$	volume flow at a given time t [m^3/s]
c_p	specific heat capacity [kJ/kg°C]
ΔT	temperature change [°C]
T_{high}	temperature at the high level [°C]
T_{low}	temperature at the low level [°C]
ρ	density [kg/m^3]
L	specific latent heat [kJ/kg]

Abbreviations

AMR	automatic meter reading
CHP	combined heat and power
CH_4	methane
CO_2	carbon dioxide
COP	coefficient of performance
CTES	cold thermal storage system
ESMAP	Energy Sector Management Assistance Program
FPBO	fast pyrolysis bio-oils
GCHP	ground coupled heat pump
GHG	greenhouse gas
GRI	global reporting initiative
GSHP	ground source heat pump
GWHP	ground water heat pump
GWP	global warming potential
HDPE	high density polyethylene
HFC	hydrofluorocarbon
HTL	hydrothermal liquefaction
HVAC	heating, ventilation and air conditioning
ICE	internal combustion engine

IRR	internal rate of return
LBG	Liquefied biogas
LPG	liquefied petroleum gas
MGT	micro gas turbine
$Mg(OH)_2$	magnesium hydroxide
Nm^3	normal cubic meter
N_2O	nitrous oxide
NO_x	nitrogen oxides
NH_3	ammonia
NPV	net present value
PFC	perfluorocarbon
SCW	standing column well
SF_6	sulphur hexafluoride
SVO	straight vegetable oil
SWHP	surface water heat pump
tCO2e	ton of carbon dioxide equivalent
TES	thermal energy storage system
VAT	value added tax
WBG	World Bank Group

1 Introduction

1.1 Background

As the climate change progresses, the need for greenhouse gas mitigating actions is increased. Consequently, the EU has set a goal to achieve carbon neutrality by 2050, meaning that its net greenhouse gas emissions will be zero by 2050 (European Commission 2021a). Individual countries, such as Finland, have set even more ambitious goals. Finland aims for zero net emissions by 2035 (Finnish Government 2021). Although climate actions often refer to carbon neutrality or zero carbon emissions, there are in fact six main types of greenhouse gases mentioned in the Kyoto Protocol that are used in emissions reporting. Kyoto protocol is an agreement in the United Nations Framework Convention on Climate Change where certain countries were required to achieve reduction targets in 2008 – 2010 relative to their emission levels in the year 1990 (Greenhouse Gas Protocol 2015). The six greenhouse gases used in reporting are methane (CH_4), sulphur hexafluoride (SF_6), perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), nitrous oxide (N_2O) and carbon dioxide (CO_2) (Greenhouse Gas Protocol 2015), which constituted for 76 % of all anthropogenic greenhouse gas emissions in 2010 (IPCC 2014).

In order to compare the effects of the six different greenhouses gases, a universal measure has been developed. Emissions are reported in carbon dioxide equivalents (CO_2e), which is defined as "the universal unit of measurement to indicate the global warming potential (GWP) of each of the six greenhouse gases, expressed in terms of the GWP of one unit of carbon dioxide" by the Greenhouse Gas Protocol (2015). Greenhouse Gas protocol is a multi-stakeholder partnership developing an international standard for greenhouse gas reporting and accounting, which enables calculating a comparable carbon footprint to for example businesses (Greenhouse Gas Protocol 2015). The Greenhouse Gas Protocol is part of larger reporting system called Global Reporting Initiative (GRI), which extends the reporting also to societal and economic factors (GreenCarbon 2021).

When it comes to carbon neutrality goals, it's not just countries that have set carbon neutrality targets. Due to for example increasing emission allowance prices, inexpensive finance from market, ethical reasons, corporate responsibility, company image and political and public pressure, many companies have started to pursue carbon neutrality or "zero carbon" projects. Corporate zero carbon goals are closely linked to the GHG-protocol, since it is the most widely used emission reporting tool to track the annual greenhouse gas emissions. In fact, European Union Directive 2014/95/EU requires companies with more than 500 employees to report their emissions according to the GHG-protocol (European Commission 2021b) (GreenCarbon 2021). Furthermore, it obliges to disclose information on for example how they manage environmental challenges (European Commission 2021b).

In the Greenhouse Gas Protocol, the emissions are divided into three categories called Scope 1, 2 and 3, and they are reported in carbon dioxide equivalents. Scope 1 consists of direct greenhouse gas emissions from company owned sources. Such sources could be for example natural gas burners, industrial process equipment and vehicles owned by the company. It is important to note, that biomass burning is not included in Scope 1 although it releases direct emissions to the atmosphere. (Greenhouse Gas Protocol 2015) This is because biomass such as forest and vegetation are regarded to store carbon dioxide unlike fossil fuels as long as it is used sustainably (Greenhouse Gas Protocol 2021). It is however reported separately. (Greenhouse Gas Protocol 2015) Scope 2 includes indirect GHG emissions, or in other words purchased energy services, such as district heat and electricity. Physically, these emissions are released at the site of generation i.e. at the service provider's site. (Greenhouse Gas Protocol 2015) Scope 3 covers other indirect GHG emissions which are not directly owned or controlled by the company. Reporting Scope 3 is optional. Examples of Scope 3 emissions include emissions occurring from purchased materials, transportation of purchased fuels, waste processing and other bought services.

1.2 Goals of the study

The goal of this study is to find the best financially sustainable investments and technologies for a Finnish publicly listed food company to reach their 2025 carbon neutrality goal. The 2025 zero carbon goal covers Scope 1 and Scope 2 emissions, or in other words, all emissions occurring from the production itself. The company has also set a 2040 Scope 3 carbon neutrality goal, but it is beyond the scope of this study.

The aim of the literature review is to recognize technologies that could be utilized to reach the zero-carbon goal. In the analysis, the aim is to evaluate the technical and financial suitability of the best technologies in two different production plants, one located in Finland and the other in Sweden. Although the experimental part focuses only on two sites, especially the literature review is trying to give some answers to other sites as well, on how they can reach carbon neutrality. Thus, if some technologies are not that applicable to the two sites in question, they still might applicable to company's other sites that operate in totally different areas and environments.

The goal of the work can be also presented in the form of the following research questions:

- What carbon free heat and electricity generation technologies and services are available?
- What is the current state of the two sites in terms of emissions and technologies?
- How do the discovered technologies apply to the two sites in terms of technical feasibility and costs?
- What are the best technologies and investments the company should pursue to reach the 2025 Scope 1 and Scope 2 carbon neutrality goals?

1.3 Scope and constraints of the thesis

In terms of the scope of this work, it is highly important to define what is meant with a zero-carbon goal. This work is not trying to establish a solution with absolute zero emissions locally. However, it does try to reach a solution with net zero carbon emissions globally i.e., the remaining emissions are captured someplace else. For instance, biomass-based combustion solutions do release carbon emissions locally, but due the reporting and the fact that plants capture carbon dioxide, these emissions are generally counted as zero. Thus, although the reported emissions are counted as zero, some emissions may still be released locally.

Furthermore, this work is not specifically trying to reach negative net emissions, as the only way to reach negative net emissions is to have large carbon sinks such as forests or carbon capture technologies. Today, carbon capture technologies are still relatively new technologies and have not yet commercialized, so such investments are most likely financially unsustainable. Forests on the other hand can be utilized especially in compensating emissions that are otherwise impossible to avoid even with green technologies.

The experimental part covers only the two sites located in Finland and Sweden. The company has almost 20 plants in multiple countries, thus covering all of them is a too large task for this study. Yet it is important to highlight, that the 2025 carbon neutrality goal covers the whole company. Moreover, this work covers only Scope 1 and 2 emissions, not Scope 3 emissions.

2 Greenhouse gas free heat and power generation

This section consists of a literature review, that examines the options for carbon free heat and electricity generation from the perspective of the company in question. Thus, for example nuclear power has been intentionally excluded due to technical infeasibility. Since the company already buys all the electricity carbon free, most of the technologies in this literature review are focused on carbon free heat generation.

2.1 Green electricity to carbon free heat with electric boilers

2.1.1 Electric hot water & steam boilers

Technically relatively simple yet energetically very efficient option for carbon free heat generation could be electric and electrode boilers. Using only electricity, electric and electrode boilers can produce hot water or steam at nearly 100 % efficiency at all operation points. Since there is no combustion, no heat is lost at combustion phase and emissions are avoided completely, if the electricity consumed is bought green (CleaverBrooks 2021a). Practically only losses that are accumulated originate from thermal radiation from the boiler to the surroundings (CleaverBrooks 2021a).

Technically the simplest type of electric boiler is a hot water boiler. In such system, water is circulated to vessel containing resistance type heating elements, which are heated by the green energy provided to the system (CleaverBrooks 2021b). Water circulates in the tank absorbing heat, and the hot water can then be circulated in an external system according to the manufacturing processes' needs (CleaverBrooks 2021b). Hot water boilers can reach relatively high capacities: for example, according to one U.S. based supplier, their largest hot water boiler model with 42-inch diameter vessel can provide up to 3,360 kW of power, or about 3.4 MWh of energy in an hour (Cleaverbrooks 2021c).

The second type of electric boiler is a steam boiler. Similarly, hot water is circulated and heated by resistance elements but this time in a pressure vessel, since generating steam increases pressure due to expansion. In the boiler, bubbles are formed to the surface of the heating elements, which then rise to the top of the pressure tank where a steam space is located. From there, steam is provided according to the system's needs. (CleaverBrooks 2021d) Capacities of the boilers are again high: according to the same supplier, a 48-

inch diameter steam vessel can provide up to 2,250 kW of power or 2.3 MWh of energy in an hour (CleaverBrooks 2021e).

2.1.2 Electrode steam boilers

Electrode boilers are a little more complex than electric hot water and steam boilers. Instead of resistance elements, electrode boilers use the water itself as the resistor generating heat. As result, electrode boilers have much larger power need due to high voltage but also significantly higher capacity. (CleaverBrooks 2021f) For instance, the high voltage jet type electrode steam boiler by the same U.S. retailer can provide up to 102 MW of steam (CleaverBrooks 2021g). **Figure 1** below shows an explanatory cross-sectional configuration diagram of the boiler. The actual configuration depends on the selected model. (CleaverBrooks, 2021f)

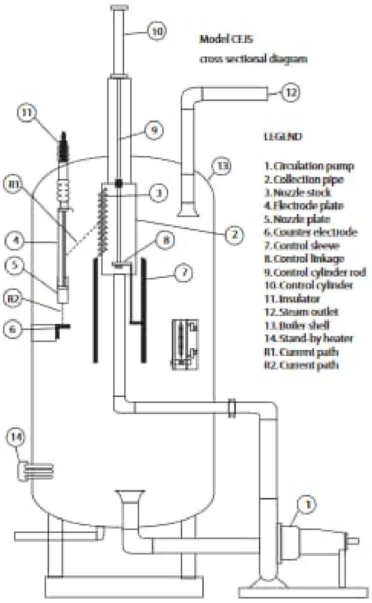


Figure 1: Electrode steam boiler cross sectional diagram (CleaverBrooks 2021f)

In principle, the operation principle of electrode boilers is based on the conductive and resistive properties of water. In the boilers, water is used as a resistor to generate heat and steam similarly to heating elements in electric boilers. Since water is conductive, it can carry electric current. Yet as it has also resistance, heat simultaneously released in the water itself. With enough heat the water evaporates, and steam is produced. Consequently, the more the voltage is increased, the more heat and steam is generated. (CleaverBrooks 2021f)

In **Figure 1**'s electrode boiler, water is first transferred using the circulation pump (1) to the collection pipe (2), where it is discharged at sufficient velocity against the electrode plate (4) using multiple nozzles at the nozzle stock (3). Now the streams of water act as a resistor and as a result, current is formed in the path R1 from the electrode plate to the nozzle stock. Simultaneously, heat and steam are generated, and the steam is conveyed for use via the steam outlet (12). Water, which is not vaporized in this process, is collected to a collector located near the bottom of the electrode plate (4) and from there, it is drained to the bottom of the electrode, the nozzle plate (5). Subsequently, the water falls to the counter electrode (6) and forms a second current path R2. As the counter electrode (6) and nozzle stock (3) are both connected to the boiler shell, a star-connected load is formed. A Stand-by heater (14) is included in some models. It is used for fast ramping of the steam generation by keeping the temperature and pressure at sufficient levels outside steam generation periods. Keeping the temperature and pressure at necessary level has also further benefits such as preventing gasketed joints and insulators from deteriorating. (CleaverBrooks 2021f)

Conductivity is in a key role in the operation of the electrode boiler. Consequently, it is constantly automatically monitored by taking small samples from the water and passing them to a conductivity measuring cell. In the case of too high conductivity, solenoid bleed valve automatically replaces the vessel water with fresh makeup water once it gets the signal from automatic conductivity controller, that is connected to the measuring cell. In the case of low conductivity, a chemical feed pump adds chemicals that bring up the conductivity. Moreover, chemicals can be added to steam condensate return tank, which acts also as a reservoir for the boiler feed water. (CleaverBrooks 2021f)

In addition to zero emissions and high efficiencies, electric and electrode boilers have many further benefits. Compared to combustion boilers, electric and electrode boilers are considerably smaller: they are only about one quarter to one half of the size of a combustion boiler with the same energy output. Furthermore, since combustion and high temperature differentials causing condensation and thermal shock are eliminated, the return water temperature can be almost anything, making the electric boilers versatile for many applications. On top of that, the boilers can be in various locations, since the absence of combustion for example eliminates the need for special fire protection installations. Lastly, due to the simple design and lack of moving parts, the boilers are considerably more quiet than traditional boilers and easy to maintain. (CleaverBrooks 2021a).

2.2 Geothermal power plants

Geothermal energy is thermal energy contained in the earth's core and the crust, the solid outer shell of the earth. Geothermal energy has its origins in the magma arising from the extremely hot core of the earth and the radioactive decay that emits from it. Geothermal energy is usually regarded as renewable energy source since the heat is continuously being replaced by new heat from the core. Yet in some areas, the utilization speed has been faster than the speed that the heat forms, which has formed a risk of over exploitation. In such places, the reservoir has been managed so that the temperature remains constant. (Breeze 2019) The rate of over exploitation is affected by geothermal heat applications, geological time scale and heat reinjection (Moya et al. 2018), which is the "*is the process of returning the geothermal fluids (brine, steam condensates and NCG) back into the geothermal reservoir after energy extraction*" according to the book Geothermal Well Test Analysis (Zarrouk & Mclean 2019). All in all, it is possible that geothermal energy has a large role in the future energy system due to low emissions, low environmental impact, technical feasibility and constant heat supply despite prevalent weather conditions (Moya et al. 2018).

Yet, it is not axiomatic that geothermal energy can be exploited anywhere although it has been estimated, that the first 3 kilometres of earth's crust contain 4 x 10^7 EJ of energy, 10 000-times more than the global energy consumption annually. Only in areas where anomalies occur, i.e. molten or semi molten magma is closer to the surface than normally, geothermal heat can be utilized profitably. (Breeze 2019) This is depicted by geothermal heat gradient, which illustrates the potential amount of energy that can be utilized (Kirppu 2015). The gradient simply states the temperature change per kilometre from earth's surface below. On average the temperature changes 17˚C - 30˚C per km starting from the surface. In anomalous areas the gradients can be 100 ˚C or more. (Breeze 2019)

Generally geothermal energy projects are risky financially, because there is no common database which would show the temperature or the ground type at a given location. In order to gather that data, test drillings are needed, and it has been estimated that in Finland the depth of drilling should be around 6 – 7 km in order to pump 120 ˚C used for example in the district heat system (Kirppu 2015). In addition to missing data, investment costs related to the projects are high. Consequently, modelling and simulations of the power plant should be conducted before actual implementation in order to mitigate the risks. (Kirppu 2015) Energy Sector Management Assistance Program (ESMAP) together with the World Bank Group (WBG) have created a supporting diagram, shown in **Figure 2,** for geothermal heat projects (Moya et al. 2018).

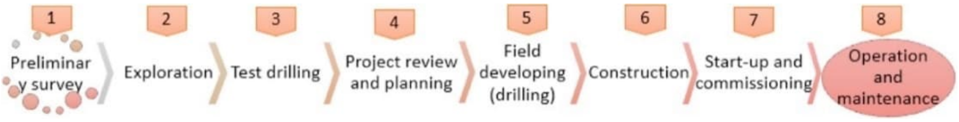
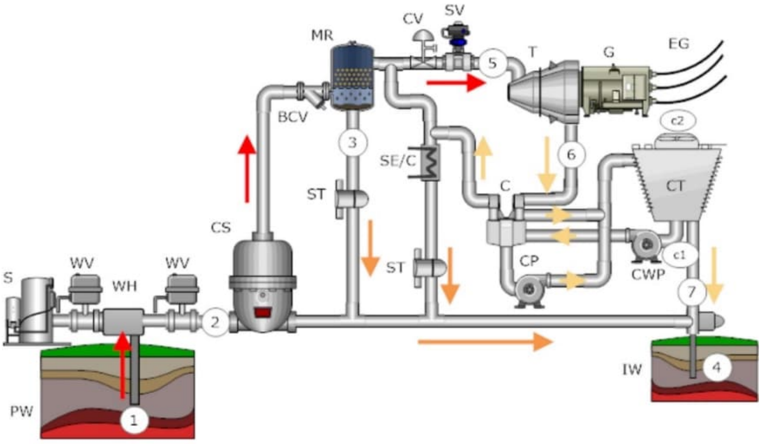


Figure 2: Eight stages of geothermal heat project according to ESMAP and WBG (Moya et al. 2018)

When it comes to the technologies for utilizing geothermal heat for power generation, it has been concluded in scientific literature that there is a consensus of five types of different geothermal power plants: 1. dry steam plants, 2. single flash plants, 3. double flash plants, 4. binary (Organic Rankine – Kalina Cycle) plants and 5. advanced conversion systems such as hybrid single – double flash systems. Yet, it has also been suggested that geothermal power plants would be divided into two groups: steam cycles for higher geothermal well enthalpies and binary cycles for lower enthalpies.

2.2.1 Single flash power plants

Single flash systems are a good option for producing electricity when the geothermal production wells are producing a mixture of steam and brine, i.e. mineral-laden hot water. A 30 MW single flash power plant generally requires five to six production wells and two to three reinjection wells distributed over the thermal heat reservoir. The depth of the well ranges based on the geothermal heat gradient. In addition to the production wells, piping systems are sometimes used to collect the mixture to the system, but they increase the cost of the plant as well as affect the efficiency of the power plant due to pressure loss in the pipes caused by friction. Therefore, the piping configuration, pipe diameter and mass flow rate of the steam should be studied carefully. (Moya et al. 2018)

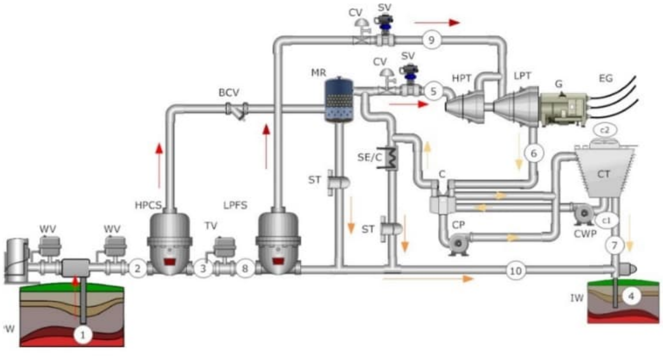


PW	Production well	BCV	Ball check valve	SV	Stop valve
S	Silencer	MR	Moisture remover	SE	Steam jet ejectors
WV	Well valves	ST	Steam tramp	C	Condenser
CS	Cyclone separator	CV	Control valve	CP	Condensate pump
IW	Injection well	EG	Electric grid	CWP	Condensed water pump
G	Generator	T	Turbine	WH	Wellhead

Figure 3: Single flash geothermal power plant (Moya et al. 2018)

Figure 3 shows the operation of the single flash power plant. The word "*flash*" refers to the geofluids transition from pressurized liquid to liquid-vapor mixture. It occurs either in the reservoir, the production wells or in the cyclone separator due to the lowering of geothermal fluid pressure. The process starts at point 1, where the geofluid enters the well at the reservoir's temperature. It then proceeds to point 2 while it simultaneously starts to boil due to a pressure drop. At 2, it enters the cyclone separator, which is used to segregate the steam and the brine based on their high-density difference. After separation, steam is conveyed to point 5 and brine to point 3. At point 3, the brine moves further to point 4, where it is reinjected to the reservoir. Electricity is generated between points 5 and 6, where the steam induces the movement of the turbine due to expansion, which in turn moves the generator producing electricity. In the process, the steam condensates, and eventually the condensate is reinjected in the ground via point 7. Part of the condensate can be used for cooling purposes for example in dry areas with shortage of water. (Moya et al. 2018)

2.2.2 Double flash power plants



PW	Production well	SV	Stop valve	MR	Moisture remover
S	Silencer	SE	Steam jet ejectors	ST	Steam tramp
WV	Well valves	C	Condenser	CV	Control valve
BCV	Ball check valve	CP	Condensate pump	TV	Throttle valve
IW	Injection well	HPT	High pressure turbine	G	Generator
CWP	Condensed water pump	LPT	Low pressure turbine	EG	Electric grid
HPCS	High pressure cyclone separator	LPFS	Low pressure flash separator	WH	Wellhead

Figure 4: Double flash geothermal power plant (Moya et al. 2018)

Practically, double flash geothermal power plant is an improved version of a single flash power plant, and it is used also in brine and steam reservoirs. As the name suggests, the flashing occurs twice, which in turn increases the power output of the same reservoir by up to 25 %. Yet double flash systems are more complex, more expensive and require more maintenance. On the other hand, it has been suggested, that the increased power output justifies the increased costs. The main differences, which one can also see by comparing **figures 4 and 5**, are the low-pressure separator at point 8 and the dual-admission turbine between points 5 and 6 in **Figure 4**. The process is quite similar: the geofluid moves to the production well at point 1 from where it moves to the high-pressure cyclone at point 2 while also starting to boil. In the cyclone separator, high pressure steam is separated and passed to high pressure turbine at point 5, while the brine moves to the low-pressure flash separator, where it is further divided into low-pressure steam and brine. A throttle valve between points 3 and 8 is required, as the pressure difference at the first stage-admission to the turbine needs to match the pressure difference between the separators due to turbine design. Practically this is acquired by increasing the mass flow. (Moya et al. 2018)

2.2.3 Dry steam power plants

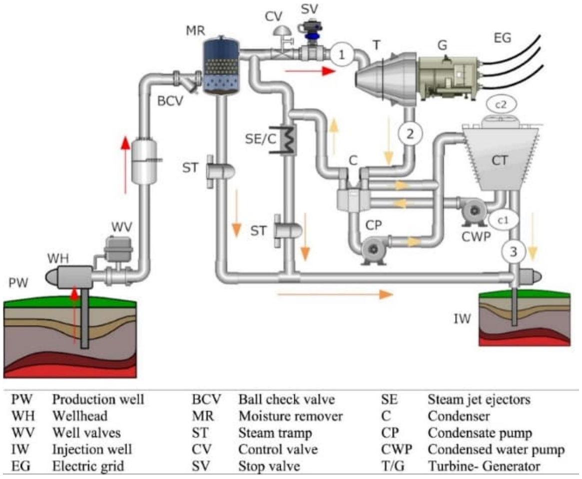


Figure 5: Dry steam geothermal power plant (Moya et al. 2018)

Dry steam power plants are used when the reservoir produces only dry steam. They have been reported to be the most efficient among geothermal power plant technologies converting 50 – 70 % of geothermal heat flow’s exergy to electricity. Technically, dry steam power plants are simple and resemble closely single flash power plants, but the cyclone separator has been replaced with a particulate separator in order to filter small particles such as rock bits and dust from the steam. It is possible that flashing systems are converted to dry steam plants in the future in the case that the geothermal reservoir dries. **Figure 5** illustrates the operation of a dry steam plant which is very similar compared to single flash system depicted in **Figure 3**. (Moya et al. 2018)

2.2.4 Binary power plants

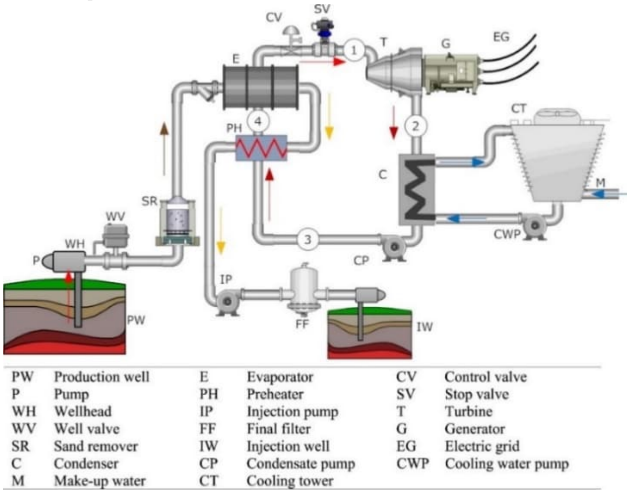


Figure 6: Binary geothermal power plant (Moya et al. 2018)

Binary power plants are technically somewhat different compared to the previously introduced configurations. The word binary refers to the two cycles, or in other words two systems, that exist in such configurations. In binary power plants, a separate geofluid cycle is used to preheat and evaporate working fluid, which circulates in its own separate cycle. **Figure 6** depicts the operation. On the left-hand side, the geofluid is pumped from the reservoir into a well, from where it proceeds to the sand remover, which function is to prevent erosion and scouring in the pipes and in the equipment. It then passes through the evaporator and preheater, from where it returns to the reservoir. The preheater and the evaporator are the key components, when it comes to the heat exchange between the working fluid and the geofluid. In the preheater, the working fluid is heated to its boiling point using the heat from the geofluid. After that, it proceeds to the evaporator, where it turns to saturated vapor using again the heat from the geofluid. It then moves to the turbine where it expands, and electricity is generated by the induced turbine movement. Finally, it condenses, and the cycle begins again. Generally binary systems are versatile due to the secondary system configuration and they are especially suited for low temperature reservoirs, which temperatures range from 120 °C to 150 °C. In addition, maintenance costs may be lower than in other configurations, since erosion and scouring is avoided when the geofluid does not circulate in the whole system. (Moya et al. 2018)

2.3 Waste and environmental heat utilization with heat pumps

Heat pumps are one of the most commonly used technologies for heat generation. In principle, heat pumps convert low temperature heat source to medium or high temperature heat source using electricity. Alternatively, they can be used for cooling by removing heat from low temperature environment to a high temperature environment. Since heat pumps can transfer significantly more energy than they consume, heat pumps can lower the energy consumption and carbon footprint substantially especially, when used with green electricity. (Rosen & Koohi-Fayegh 2017) Coefficient of performance (COP) is a commonly used indicator to describe the heat pumps heat generation in relation to the used energy (electricity), and for a heat pump and a refrigerator (reverse heat pump) it is defined as (Dinçer, & Kanoglu 2010):

$$COP_{Heating} = \frac{Q_H}{W} = \frac{Q_H}{Q_H - Q_L} \tag{1}$$

$$COP_{Cooling} = \frac{Q_L}{W} = \frac{Q_L}{Q_H - Q_L} \tag{2}$$

where
W = net work performed by the system (consumed electricity), $W > 0$
Q_H = heat admitted to the hot reservoir (removed from the system), $Q_H < 0$
Q_L = heat removed from the cold reservoir (added to the system), $Q_L > 0$.

Often the COP is around four, which means that for each unit of electricity consumed, the heat pump supplies or removes four units of heat. Consequently, the higher the COP, the better the pump. Yet, the COP lowers as the difference between the two heat media increases, so in order to achieve maximal efficiency, a reasonable temperature difference should be selected. This can be also interpreted in another way: the lower the heat source's temperature, the higher the electricity consumption, if the pump is used for heating (Rosen & Koohi-Fayegh 2017). The theoretical maximum COP for a heat pump that can be achieved is defined by Carnot-process as follows (Rosen & Koohi-Fayegh 2017):

$$COP_{Ideal} = \frac{1}{1-\frac{T_{Low}}{T_{High}}} \tag{3}$$

The Carnot process is assumed to be fully reversible, and the COP is assumed to only depend on the temperature difference between the heat media. Thus, the ideal COP is not affected by for example losses caused by friction in the heat pump. (Rosen & Koohi-Fayegh 2017)

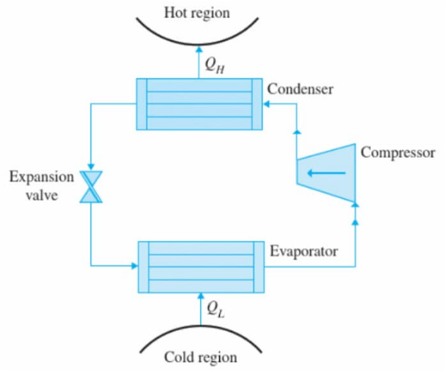


Figure 7: Operation of a heat pump (Rosen & Koohi-Fayegh 2017)

Figure 7 exemplifies the operation of a heat pump. At the condenser, a fluid, which is typically a refrigerant such as ammonia, exits as a liquid in high pressure. The fluid then proceeds to the expansion valve where the pressure is decreased. From the expansion valve, the liquid fluid moves to the evaporator, where it evaporates as a result of absorbing heat from the low temperature heat source. The vaporized fluid then advances to the compressor, where it is pressurized in order to increase the temperature. Lastly, the high temperature vapor returns to the condenser where it releases heat to the high temperature heat sink. Simultaneously, it condenses back to liquid due to a phase change caused by a pressure and a temperature drop, and the cycle starts again. (Rosen & Koohi-Fayegh 2017)

2.3.1 Waste heat pumps

In general, there are two types of waste heat sources: air and water sources. In terms of this work, these two sources could be for example exhaust heat from ammonia cooling compressor plants and wastewater heat. Usually in the case of waste heat, the temperatures are quite low but, in order to reach the required temperature level, heat pumps can be connected to series (Kirppu 2015). Yet, utilizing the waste heats it not self-evident, for it first requires detailed technical mapping, in order to find the magnitude, the place and time when the sources occur, in order to evaluate the technical and economic potential of such project (Kirppu 2015).

Although using wastewater heat for heat production might not sound like the first option for high amount heat production, the potential is in fact surprisingly high as demonstrated by Katri Vala Heating and Cooling plant, which is the world's largest heat pump plant located in Helsinki, Finland. The plant is owned by Helen, which is the district heat provider in the city. The plant has five large heat pumps and they absorb heat from purified wastewater and warm district cooling return water. (Helen 2021) According to a phone call with Helen's expert, the pumps are connected in parallel, except one that is connected in series, and they use R134-a as a refrigerant. Although more efficient, ammonia as a refrigerant was omitted due to safety reasons. The plant produces both district heating (105 MW) and district cooling (70 MW) in a single process, which makes the plant exceptionally efficient. (Helen 2021)

What is particularly interesting about the plant in terms of energy production, is the temperatures from which the pumps produce the heat. Depending on the season, the temperature of the purified wastewater is only 10 – 20 ˚C and district cooling return water temperature 16 – 19 ˚C, while the temperature required for the district heating network is circa 88 ˚C (Helen 2021). The fact, that the plant is performing successfully for district heating purposes demonstrates that the temperature does not need to be very high in order to produce large amounts of heat, if there is enough supply of the low temperature heat flow. However, in the case of Katri Vala plant, the low temperature heat flow is quite extraordinary, which is probably the number one factor why the plant is so efficient. The flow rate of the purified wastewater is

260 000 m3 per day, which is equal to two and a half Finnish parliament houses volumetrically (Helen 2021).

2.3.2 Ground source heat pumps

Ground source heat pumps (GSHP) are among the most efficient types of heat pumps, due to the heat source and sink being the ground, which is cooler in the summer and warmer in the winter than air. Indeed, it is approximately a constant temperature medium after certain depth, as seen from **Figure 8**. (Soltani et al. 2019) GSHPs differ from other ground source heat applications in the sense, that they utilize solar energy absorbed by the surface layers of the ground, not geothermal heat from radiation or magma. Or at least in theory. Whether this is always the case is up for debate. (Kirppu 2015)

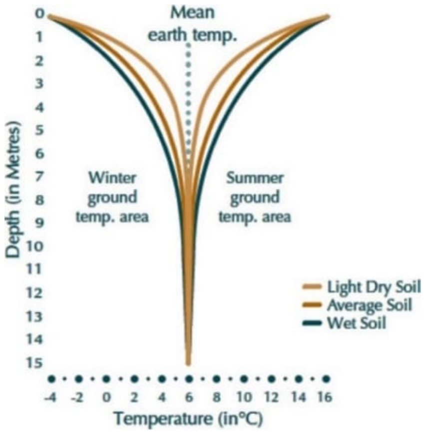


Figure 8: Temperature – Ground depth diagram from Ottawa, Canada (Soltani et. al 2019)

When designing a ground source heat pump system, geological features such as ground temperature, thermal properties of the ground source heat pump's heat exchanger and hydrological conditions are decisive factors. According to Soltani et al. (2019), there are four types of GSHPs which are: Ground water heat pumps (GWHPs), Ground-coupled heat pumps (GCHPs), Surface-water heat pumps (SWHPs) and Standing column wells (SCWs). All of them involve excavating or drilling in some form which means, that all GSHPs have relatively high initial costs. In addition, they lack modularity. On the other hand, GSHPs are superior under many circumstances, and they are very well suited for zero carbon projects due to their uninterrupted operation, small carbon footprint, great efficiency (high COP), easy integration with other systems and weather independency. **Figure 9** below shows a generic ground source heat pump system design with a desuperheater. **Figure 10** provides an overview of the different designs. (Soltani et. al 2019)

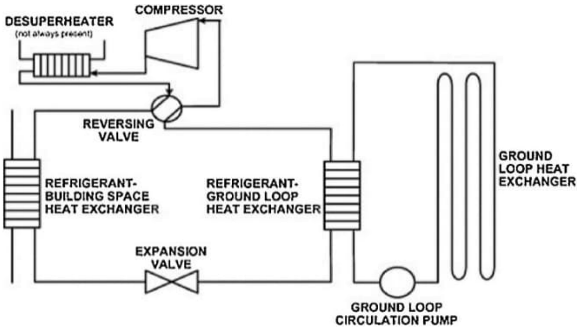


Figure 9: Generic GSHP system with desuperheater (Soltani et. al 2019)

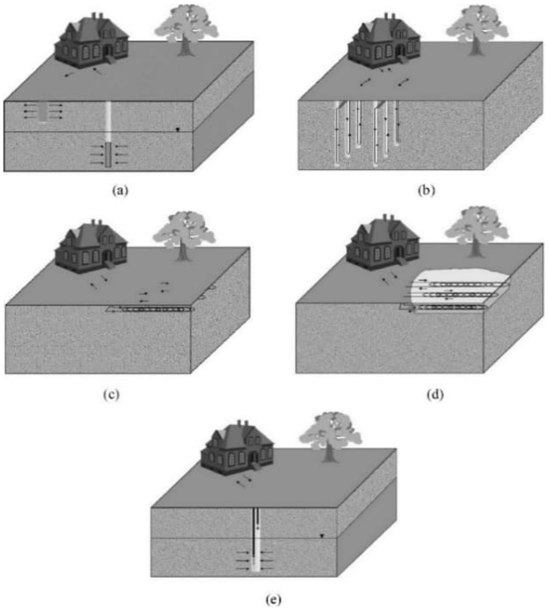


Figure 10: Different GSHP system designs: a) GWHP, b) Vertical GCHP, c) Horizontal GCHP, d) SWHP and e) SCW (Soltani et. al 2019)

Ground water heat pumps (GWHPs), also known as open-loop systems, are vertical systems, that pump ground water from wells for heat pumps or to direct use. Once the heat (or cooling) is extracted, the water is released back to the ground usually at different point. According to Soltani et al., the ground water quality and availability are key factors when designing a GWHP system. Indeed, without sufficient ground water supply, such system is infeasible. Factors that affect ground water availability are for example ground porosity, permeability volume, competition for its use (Soltani et. al 2019) and legislation. For example, in Finland there is a law that obliges to have enough good quality ground water while it also prohibits contaminating it (Ministry of Environment 2021). Moreover, when it comes to the ground water quality, too poor quality can cause corrosion and scaling in the system. Yet, open-loop systems have notable advantages such as low costs and relatively low ground water need compared to other designs. (Soltani et. al 2019)

Ground-coupled heat pumps (GCHPs) are practically an improved version of GWHPs. Also called closed-looped systems, GCHPs were developed in 1970s to overcome the challenges related ground water availability and quality with GWHPs. Instead of wells, GCHPs use high density polyethylene pipes placed in vertical boreholes or horizontal ditches to absorb the heat from ground water via heat exchangers. Antifreeze agents are typically used in the pipes to prevent freezing. GCHPs use less energy compared to GWHPs due to less elevation even though vertical boreholes depth typically ranges from 30 to 120 meters. The boreholes' diameter usually ranges from 76 to 127 mm. In horizontal systems the diameter is 20 to 40 mm, and 100 – 200 meters of pipes placed in one to three meters depth are needed per ton of heating or cooling. Challenges with GCHPs include for example the sizing and diameter of boreholes in vertical systems and variable COP in horizontal systems due to changing temperature as demonstrated by **figure 9**. (Soltani et. al 2019) Furthermore, too close boreholes and horizontal pipes can lower the COP, due to insufficient heat, and horizontal pipes are in danger to be damaged by later excavation works in the area. (Kirppu 2015)

Surface water heat pumps (SWHPs) use surface water reservoirs such as lakes and sea as the heat source. SWHPs can be configured as an open-loop or a closed-loop system. The advantage with open loop system is high flexibility given satisfactory water supply, but the downside is the need for screening and filtering of the water. Closed-loop system overcomes this problem, but it needs more piping; 20 to 40 mm pipes 30 to 100 meters in length are needed per each ton of cooling or heating in closed-loop systems. The most important factor when designing SWHP systems is the annual water temperature at the required depth. If there is no available data, one to two years temperature survey might be required due to the fact, that the water profiles may be very different even for lakes in the same area. For instance, bathymetric profile, water flow and climate conditions affect the water temperature significantly. If there is no data, also meteorological and hydrological data can be used to estimate the temperature profiles. (Soltani et. al 2019)

Standing column wells (SCWs) use vertical borehole wells to supply ground for a heat pump via heat exchanger. SCW have a semi-open loop structure and they use about 15 cm boreholes up to 450 meters deep to circulate the ground water. Due to their depth, standing column wells have significant installation costs. Although SCW mainly circulate the water and thus do not consume it, the operation of the well during peak loads can cause part of the water bleed, which reduces the amount of circulating water in the system. This is caused by ground water flowing to the borehole and its surroundings to cool the surrounding rocks, when heat is injected during cooling season, and vice versa during heating season. (Soltani et. al 2019)

2.4 Biomass & Bioenergy

According to Liu et al. (2020) biomass "*is plant or animal material that stores both chemical and solar energies, and that is widely used for heat production and various industrial processes.*" Moreover, it is a common fuel for renewable electricity production, although only 13 % of the annual global energy generation was generated using biomass in 2017. Yet, with its 70 % of all renewable energy sources, it was the largest renewable energy source globally in 2017. (World Bioenergy Association 2019). Due to its generally agreed renewable status, wide applicability and vast feedstock basis, focus and research in bioenergy has expanded immensely in recent years (Vassilev et al. 2015). For example, the feedstock can be any organic matter that is regarded as renewable (Opia et al. 2021), such as municipal solid waste, agricultural waste, poultry waste, animal manure, food waste, micro-algae, forestry waste, energy crops and sewage sludge (Khan et al 2021), which indeed greatly increases the potential for different use cases globally. Furthermore, the wide range of possible fuels increases energy security, and many of the possible fuel options have also further benefits such as low amount of ash compared to coal, the use of non-edible biomass, reduction of residues and waste, the use and restoration of contaminated lands and decrease of hazardous emissions from them (Vassilev et al. 2015).

Nevertheless, biomass has also major disadvantages. To name few, the first major disadvantage from energy production perspective is the low energy density both in terms of bulk density and caloric value compared to traditional fossil fuels (Vassilev et al. 2015). Consequently, one needs enormous storages to produce the same amount of energy, that one would produce using for example much more energy dense coal. Generally, standard biomass to electricity plants have an efficiency of only about 20 % (Liu et. al 2020). Yet, the efficiency can be increased by refining the biomass via various processes, but it increases the costs and thus decreases the economic efficiency compared to other fuels. Furthermore, due to for example the large spatial need, biomass plants have high investment costs and when it comes to the biomass production, a large amount of production can damage local ecosystems via for example water use, pesticides and fertilizers. Biomass farming can also compete with edible biomass production and although large number of possible feedstocks, biomass energy generation can still suffer from feedstock supply and lack of developed markets. (Vassilev et al. 2015)

When it comes to utilization of biomass, it can be for example directly combusted as such. This is what has also been done: in 2015, approximately 95 – 97 % percent of biomass was directly combusted (Vassilev et al. 2015). Yet, biomass can be also refined further in order to increase efficiency and use it in wider number of applications. It can be processed to gaseous, liquid and solid biofuels as well as chemicals (Vassilev et al. 2015). **Figure 11** provides an overview of different biomass conversion processes.

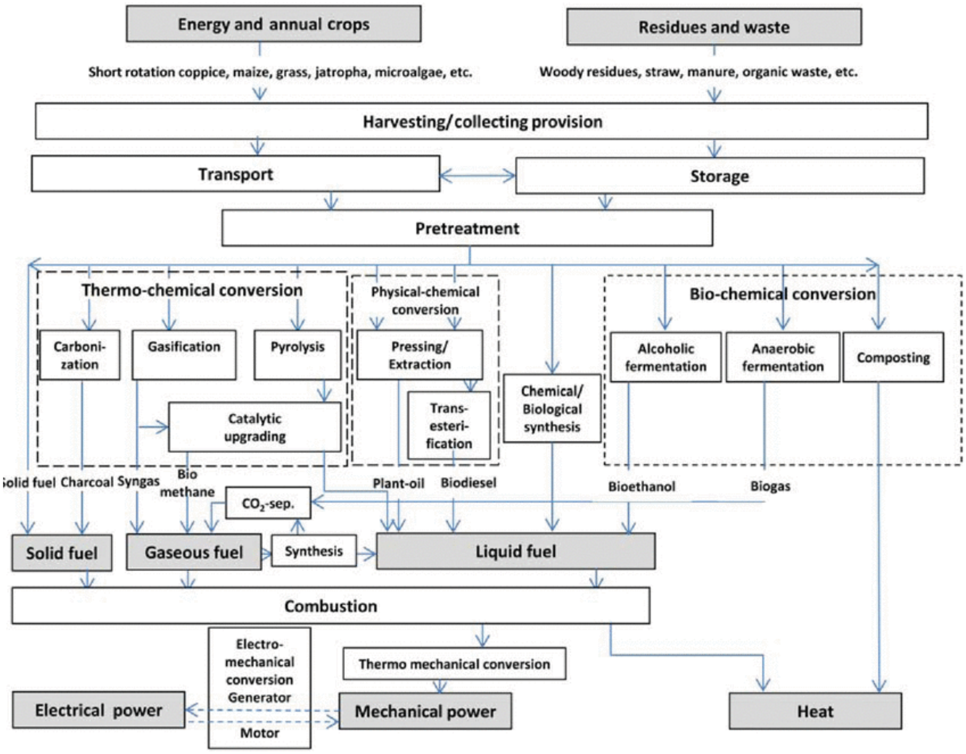


Figure 11: An overview of biomass conversion processes (Vakkilainen 2017)

Biochemical conversion processes are the most efficient and sought-after technologies for producing chemicals, oils, fuels and other materials with biomass. In the process, enzymes, bacteria and microorganisms are used together with heat and chemicals to break cellulose and hemicellulose to sugar and other products. The second main conversion class is physical-chemical conversion, or in other words oil extraction, and it is commonly used for producing biodiesel and biolubes. It involves a process called trans-esterification, which consists of a catalytic reaction of oil product together with short-chain aliphatic alcohols such as ethanol. The end-product is glycerol, which can be further processed to different derivatives such as "enols". The last main conversion class is thermo-chemical. According to Opia et al. (2021), it is "*a process of decomposition of lignocellulosic derivatives under inert condition in oxygen deficient environment*", and it is mainly used for generating heat or electricity, liquid fuels and liquid or gaseous products of different chemicals. It consists of multiple technologies which are specified by the end-product. For instance, pyrolysis is mainly used for producing liquid bio-oil, solid bio char (solid carbonaceous material) and gas, whereas gasification produces only fuel gas. (Opia et al. 2021)

2.4.1 Biogas

Particularly interesting biomass derivative based on the scope of this work is biogas, as the plant in Sweden uses biogas in vast amounts already today. Its production can be divided into three main categories: anaerobic digestion, thermic and biological production. Anaerobic digestion is usually considered the best biogas production technology due to its higher energy output/input ratio. Biogas consists mainly of methane CH_4 and carbon dioxide CO_2 but other gases that can affect the properties of the biogas are at present too. These gases include for example water vapor (5 – 10 %), nitrogen (0 – 3 %), oxygen (0 – 1 %), hydrogen sulfide (0 – 10,000 ppm), ammonia (0 – 200 mg/m^{-3}) and siloxanes (0 – 40 mg/m^{-3}). The exact amount of these gases depends on the biogas feed material and conditions in the reactor. Biogas production covers a range of feed materials such as municipal solid waste, agricultural waste, poultry waste, animal manure, food waste, micro-algae, forestry waste, energy crops and sewage sludge. Typical CH_4: CO_2 ration from sewage sludge or animal waste is ca. 60:40. (Khan et al 2021)

As biogas contains more impurities than natural gas, biogas is often "up-graded" in order to use it in existing natural gas burners (Khan et al 2021). Wobbe index is acquired by dividing the heating value of a fuel with the square roof of its relative density, and it expresses the suitability of a fuel to a burner (Alakangas et al. 2016). If the Wobbe index of biogas is sufficiently close to the index of natural gas, then biogas can be directly used in existing burners without modifications to nozzles or pressure regulators. However, it should be noted that the margins for different Wobbe index fuels for burners are low. (Kirppu 2015) In Finland, the biogas that can be bought from the gas grid, is pure enough to be used in all existing natural gas applications that are connected to the grid.

Anaerobic digestion is a process where the feed material i.e. biomass is converted to gases by micro-organisms in the absence of air (anaerobic conditions). Without going into detail in exact chemical reactions, the process of anaerobic digestion is quite simple, as simply begins by inserting biomass to a closed vessel or a digester together with micro-organisms, which results in the production of biogas. The main challenges with anaerobic digestion biomass production are large space and biomass requirements (Wiggins 2021). The process requires immense amounts of biomass and vast vessels in order to be economically efficient (Wiggins 2021), and thus it has relatively high investment and operational costs. Another major challenge is the low methane content (Khan et al 2021) as it should be at least 95 % for the biogas to be fed to the gas grid and be directly used by the existing machinery (Khan et al 2021) (Kirppu 2015).

Low methane is not however the only challenge when it comes to the biogas composition itself. Hydrogen sulfides in raw biogas can corrode pipes, engines and metal parts of the boilers. Moreover, once ignited, the presence of ammonia and halogenated hydrocarbons can cause the biogas to corrode pipelines and combined heat and power (CHP) engines due to the fact, that they influence the ignition properties of the biogas. Carbon dioxide and water vapor should be also removed, because they lower the heating value and Wobbe index of the biogas. In order to purify or "upgrade" the biogas from these unwanted elements, many technologies have been proposed and developed. (Khan et al 2021)

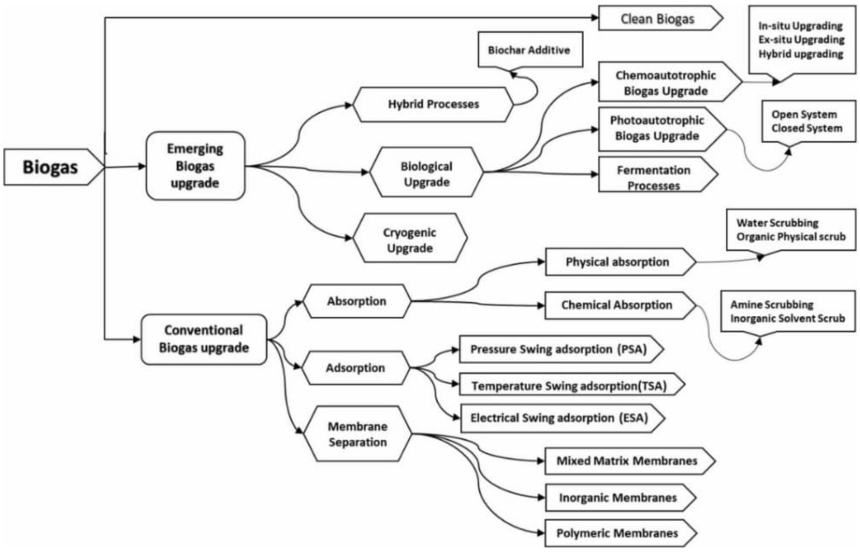


Figure 12: Biogas upgrading technologies (Khan et al 2021)

Figure 12 presents an overview of the existing biogas upgrading technologies. The number of alternatives imply that there is no ideal technology, which has been also concluded in research. Yet, each technology has its pros and cons. Today, conventional upgrading methods i.e. absorption, adsorption and membrane separation account for 99 % of the upgrading plants. Furthermore, water scrubbing is the most popular technology with 41 % share of all upgrading plants. It is used for separating carbon dioxide CO_2 and hydrogen sulfide H_2S from the raw biogas, and it is based on the gases' higher solubility to water than to methane. There are two main water scrubbing technologies: single pass scrubbing and regenerative scrubbing. In single pass scrubbing, treated water from wastewater plants is used for the process which is send back to the wastewater treatment plant after utilization. In regenerative scrubbing, the water is good quality freshwater i.e. water from a lake. In it, water is regenerated in the process by passing air to desorption column. The problem however with both technologies is high water use. In order to make water scrubbing more efficient, both secondary and tertiary effluents from wastewater plants should be used instead of freshwater. (Khan et al 2021)

2.4.2 Bioliquids & biofuels

According to a systematic technology review by Seljak et al. (2020), liquid bioenergy resources can be classified into two categories bioliquids and biofuels. Bioliquids covers all liquid biofuel purposes other than transport, i.e. cooling, heating and electricity generation. In other words, bioliquids include stationary energy generation and cooling. Moreover, there is crucial technological difference. The technology used in stationary electricity generation can be adapted for the use of bioliquids whereas in transport this is not directly possible, since the biofuels need to be first upgraded in order to meet the strict specifications defined in engine norms and standards. (Seljak et al. 2020) This implies, that bioliquids have wider fuel stock (Seljak et al. 2020) but also lower fuel generation costs. Indeed, raw liquids, biocrudes and intermediate energy carries, such as agricultural waste, can be used as bioliquids. Yet also bioliquids have physical and chemical properties, that make them challenging to use. (Seljak et al. 2020) For example, the bioliquid end-products are almost impossible to upgrade to biofuels (Seljak et al. 2020), which implies that they are not very pure compared to for example traditional fossil fuels or even biofuels.

Based on the definition of a bioliquid, there are four types of bioliquids: fast pyrolysis bio-oils (FPBOs), hydrothermal liquefaction biocrudes (HTL biocrudes), liquefied wood, straight vegetable oils (SVOs) and bioalcohols. Furthermore, they can be separated into two groups based on their chemical and physical characteristic. First group consists mainly of straight vegetable oils, which have qualities like conventional liquid fossil fuels. The second group consists of FPBOs, glycerol and liquefied wood i.e. bioliquids with high viscosity. Utilizing the liquids in the first group requires less modifications to micro gas turbines (MGTs) and internal combustion engines (ICEs) which are used in power generation. Liquids in the second group need extensive adaptations to the fuel system, injection system and to the control system due to the high viscosity. Moreover, the liquids in the second group limit primary air temperature and power output of the system, which makes the whole system less flexible. Yet, the liquids in the second group can be produced with thermo-chemical methods from low-cost feedstock in most cases, which opens substantial opportunities to for example waste stream feed stock utilization. **Figure 13** below shows the viscosity of different bioliquids as a function of temperature from which one can see, that the viscosity of liquefied wood is over tenfold compared to straight vegetable oil at 100 °C. (Seljak et al. 2020)

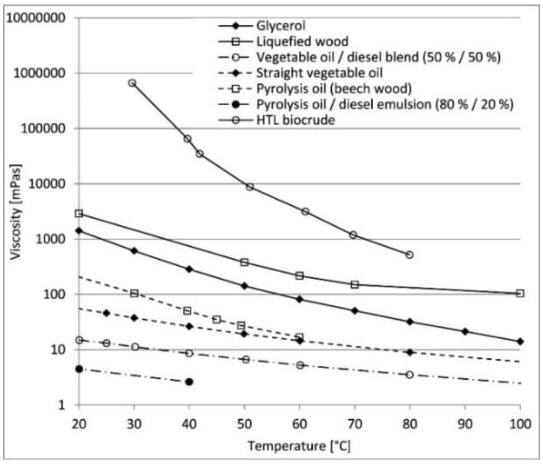


Figure 13: Viscosity of different bioliquids as a function of temperature (Seljak et al. 2020)

The production of fast pyrolysis bio-oils (FPBOs) is based on a thermochemical process called pyrolysis. In pyrolysis, biomass feedstock is processed in atmospheric pressure in temperatures of about 600 °C. The end-product is bio-oil, solid carbonaceous material (char) and non-condensable gas. Reactors used for the process are either rotating cone reactors or circulating bed reactors, from which the latter has been extensively researched and commercialized in Finland by companies Metso, UPM and Fortum. In addition, companies BTG and TechnipFMC have agreed to build four industrial scale fast pyrolysis plants in Finland. The pyrolysis itself lasts only a few seconds or less, and the general energy requirement is about half of the end-product's lower heating value. In other words, the process consumes energy, which implies, that the break-even selling price is highly dependent on the plant size. Calculations in previous studies have given values of about 10 – 19.5 €/GJ, which are in most cases higher than the fuel oil market price, which is about 10 €/GJ. (Seljak et al. 2020)

Compared to conventional fuels, FPBOs are in many ways inferior. Due to their high viscosity and high surface tension, FPBOs usually need additives such as ethanol for them to be properly atomized and used for example in internal combustion engines. Furthermore, high moisture content causes delay in the ignition and lower flame temperature. Moreover, its low pH value and traces of other process products such as ash can cause corrosion, while char in the oil can cause reduced performance and obstructions in the equipment. As a result, multiple adaptations to engines and materials are needed. For instance, it has been suggested, that polypropylene piping could for example replace corroding mild steel. (Seljak et al. 2020)

Hydrothermal liquefaction (HTL) is a thermochemical process, which is notably more complex than pyrolysis. In HTL, biomass with high moisture content is converted to biocrude i.e. a substitute for conventional crude oil. The biocrude has a high heating value (calorific value 32.0 - 34.7 MJ/kg) and it can be produced from a variety of feedstocks such as manure, hardwood and sludge. Like pyrolysis, HTL consumes energy, for it needs subcritical water with temperature ranging from 250 to 370 ˚C and pressure from 10 to 30 MPa. With economically optimized HTL process, the production costs are estimated to be 13.6 €/GJ. Using catalytic processes, biocrudes can be further converted to biofuels such as biodiesel. (Seljak et al. 2020) Due to HTL biocrude's high viscosity, which can be also seen from **Figure 13**, biocrudes used present the same combustion challenges as FPBOs, when used in internal combustion engines and micro gas turbines.

Liquefied wood is produced in a process called catalytic solvolysis. In the process, lignocellulosic materials like raw wood are liquefied using a solvent such as polyhydroxy alcohols or glycerol with the help of an acid catalyst such as p-Toluensulfonic acid. Although producing liquefied wood also consumes energy, it consumes it significantly less than pyrolysis or HTL. Temperature required for solvolysis is only 160 – 200 ˚C compared to for example 600 ˚C in pyrolysis. Catalytic solvolysis is performed in atmospheric pressure. As a result, the energy requirement is only about 9 % of the end-product's lower heating value. Overall, the process is quite efficient at least in mass terms; 97 to 98 % of the feedstock's mass is converted to the end-product. Significant challenges with liquefied wood are its acid pH value (2.5 – 3.5) and high viscosity. Thus it has the same technological challenges such as FPBOs in power generation. Yet, viscosity has been successfully lowered by blending polar liquids such as alcohols with liquefied wood. Due to its high polarity, liquefied wood does not blend with nonpolar solvents at all. (Seljak et al. 2020)

Straight vegetable oils (SVOs) are the closest form of bioliquids to conventional fuels based on their physical and chemical properties. Consequently, they have been proposed and assessed for replacing diesel in internal combustion engines. They are also the simplest form of bioliquids, and they can be produced from many plants by relatively simple mechanical means, but also with chemical and biological processes, which however require much longer processing times and can produce hazardous wastewater. Typical plants used for SVOs are for example rapeseed, sunflowers, soybeans and palms. The greatest advantages with SVOs are renewability, biodegradability and low Sulphur content while the largest disadvantage is again, much higher viscosity compared to conventional fossil fuels. Yet again, viscosity can be lowered by preheating, blending with e.g. diesel or biodiesel or by further processing, which improves the heating value and oil quality overall. In addition, globally widespread transesterification can be used to upgrade SVOs to biodiesel. (Seljak et al. 2020)

When SVO use in engines have been studied, it has been found out that carbon-based emissions tend to be reduced, but not always. Furthermore, NO_x emissions seem to show great variance, and, in many cases, they are not lowered at all. What is however quite consistent, is that SVOs tend to lower torque, brake power and exhaust gas temperature when used in engines, which can result in lower mechanical stress and combustion noise. It is concluded, that the engine effects of SVOs are highly dependent on the system and the composition of the SVO i.e. what blend is used. Yet even with blending, SVOs can suffer from challenges associated with bioliquids in general. Incomplete evaporation and combustion together with degradation of lubricating oil can lead to carbon deposits in the engines which in turn decrease efficiency, increase maintenance and can cause engine failures. Nevertheless, an overall durability is sufficient in many cases, and numerous suppliers offer internal combustion engine CHP-units with SVOs as the primary fuel. In these units, power output ranges from 8 to 340 kW. Yet, it is noteworthy that no groundbreaking modifications have been made to injection systems in these plants, which implies that the unit might require more maintenance. (Seljak et al. 2020)

Research about SVO use in micro gas turbines (MGTs) is still limited due to the fact, that they are almost always studied in commercial setups or dedicated test rigs, and thus public information is limited. Regardless, SVOs are the best choice among bioliquids for use in MGTs since they resemble conventional fuels and do not require large adaptations. Indeed, previous studies have been performed with the help of existing, non-modified equipment. However, startup and shutdown sequence has been tuned. All extensive studies covering the use of a MGT over several hours have shown, that SVO tend to form deposits on injection nozzles and vaporization tubes. This is explained by SVO's high viscosity, which leads to improper atomization. Slower evaporation and droplet impingement affect as well and evaporation residue in particular can cause lowered hot corrosion resistance, inferior flow dynamics and thermal loading. As a result, the turbine engines are more instable, but interestingly, power and efficiency are usually maintained. Compared to ICEs, emissions from MGTs are usually lower with SVOs due to higher operation temperatures, which help to mitigate unfavorable combustion products. **Figure 14** below shows deposits on a vaporization tube and an injection nozzle that have resulted from using SVO and waste grease in MGTs. (Seljak et al. 2020)

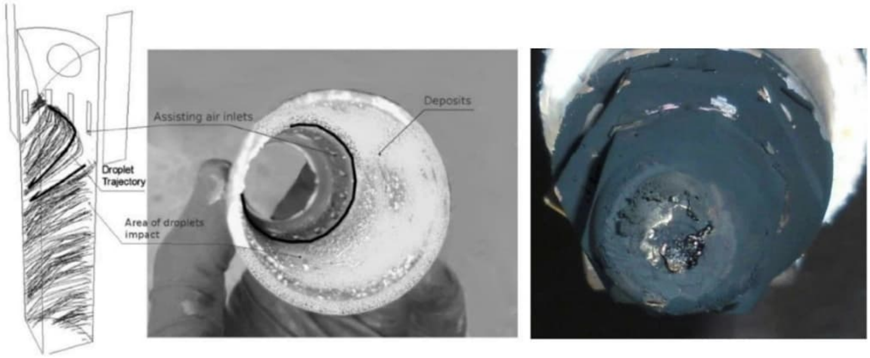


Figure 14: Left: Deposits on a vaporization tube caused by SVO use, right: Deposits on an injection nozzle caused the use of waste grease (Seljak et al. 2020)

Although bioalcohols and biodiesel are not by definition bioliquids, they could still have a large role in the company's energy system by for example replacing fossil fuels in transport. For instance, in Brazil, where ethanol is derived from sugarcane, 73 % of all cars are equipped with technology that enables the use of ethanol and gasoline together (Rapid Transition Alliance 2018). Bioethanol can be produced by traditional fermentation or by hydrolysis-fermentation, gasification-fermentation or by gasification-synthesis from feedstocks, that generally contain starch or cellulose in addition to sugarcane. Biodiesel is produced via transesterification as mentioned before, and it is already a widespread transportation fuel for conventional compression ignition engines in Europe and Asia with 2 – 10 % conventional diesel blending. Compared to traditional diesel, biodiesel has a shorter shelf life due to microbial degradation. In addition, its high oxygen content and flash point lower the performance in low temperatures. (Seljak et al. 2020)

2.4.3 Solid biofuels

Solid biofuels are commonly used biofuel in Finland. Solid biofuels can be obtained from processed or unprocessed biomass, and they can be further categorized as natural or synthetic fuels (Knapczyk et al. 2019). Natural solid biofuels are fuels that are in the state as they were obtained e.g. chopped small wood or peat, while synthetic fuels such as biochar have undergone either mechanical or chemical treatment, and they usually require industrial scale production and production facilities in order to be produced profitably (Knapczyk et al. 2019) (Niskanen & Karjalainen 2014). Especially common solid biofuels in Finland are wood-based biofuels such as woodchips and forest residue, which are obtained as a by-product from wood industry (Kirppu

2015). Other commonly used wood-based biofuels are wood pellets and briquettes, which are produced from for example sawmill industry's waste streams like sawdust (Niskanen & Karjalainen 2014). In addition, waste wood from construction and demolition has also been suggested for solid biofuel use. When it comes to the actual use of solid biofuels, the composition and quality of the biofuel is what determines combustion technology and storage. For instance, wood chips can contain up to 60 % water while pellets contain only 8 – 10 %, which means that the combustion process can be quite different. Furthermore, pellets require dry warehousing such as vessels in order to preserve the low water content while wood chips do not. On the other hand, due to the low energy density, wood chips do require a large area for storing. (Kirppu 2015)

Conventional wood pellets and their physically larger alternative, wood briquettes, are produced by mechanically pressing dry and clean wood into the desired dimensions, which are for example in the case of wood chips, 6 to 8 millimeters in diameter and 10 – 30 millimeters in length (Niskanen & Karjalainen 2014). Yet, wood pellets can be further processed in order to use them in a wider selection of plants. Since processed pellet's properties resemble coal more closely, it can act as a good substitute for coal (Kirppu 2015). Indeed, processed pellets are also called biochar or torrefied biochar, depending on the temperature in which the biochar is produced. Torrefied biochar is generally acquired in dry and anaerobic temperatures under 300 ˚C while biochar production covers temperatures from 300 to 400 ˚C. Biochar production resembles very closely the production of pyrolysis bio-oil, and thus biochar production is also referred to as slow pyrolysis. Consequently, same feedstocks apply for biochar and bio-oil. The most commonly used biochar production technologies are Torbed-reactors, which use a process called torrefing, drum reactors and moving bed reactors. Not one of the three technologies are superior, for they are all at least adequate in terms of scalability, performance and fuel blending for example. (Niskanen & Karjalainen 2014)

Another option for pellet processing is steam exploding i.e. steam pellets. In steam exploding, 180 – 240 ˚C hot saturated water vapor causes mechanical and chemical alterations in the wood, which leads to cellulose, hemicellulose and lignin decomposition. Simultaneously, water is autohydrolysed and removed, since the vapor causes adiabatic expansion of water in the wood. Research suggests, that steam pellets are better than torrefied pellets in terms of moisture tolerance and hardness. (Kirppu 2015)

In addition to wood-based solid biofuels, peat is a commonly used solid biofuel in Finland. However, it is not classified as a renewable energy source due to the fact, that it renews in a couple thousand years (Turveinfo 2021). Thus, it really cannot be used in decarbonization projects. Yet with its current use, it is considered renewable by one source regardless of the long renewing time, because the current use does not exceed the amount of new peat that forms every year (Turveinfo 2021). In fact, in 2014 new peat was formed twice as fast as it was used. When it comes to the actual use, peat has some advantages such as enabling the use of low-quality wood feedstock in boilers, when they are blend together, and corrosion prevention. (Niskanen & Karjalainen 2014) All in all, even if peat was declared renewable in the future, there is still the question of availability. Peat production requires large swamps which might not be very close to consumption, which lowers the availability and increases the price.

When it comes to the use of solid biofuels, generally they are burned in a boiler. Most common boiler types include grate boilers, bubbling fluidized bed boilers, circulating bed fluidized boilers and pulverized coal fired burners, where coal is replaced with peat or pulverized wood. (Kirppu 2015) When designing a boiler system, the operator needs to consider at least the following factors: steam/power requirement, the availability and usability of fuels, the location of the boiler, equipment, future needs and permits (Vakkilainen 2017). In addition, when it comes to the fuel, logistics, warehousing, space requirement, handling and reserve capacity need to be addressed. Generally, the best option for the use of a wide variety of different fuels are different bed boilers, since they allow the use of humid, heterogenous fuels while maintaining energy efficiency. Pulverized coal fired burners on the other hand have the strictest fuel requirements, for they require more homogenous, less humid fuels. (Kirppu 2014)

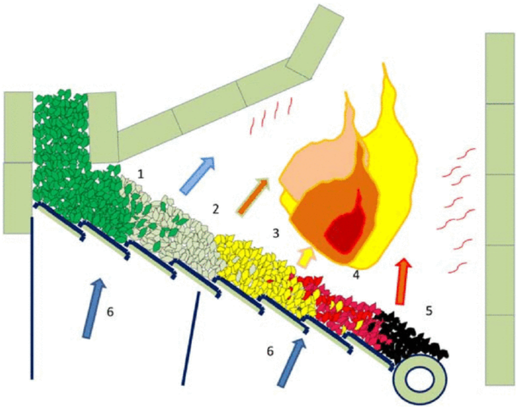


Figure 15: Mechanical inclined grate (Vakkilainen 2017)

Grate firing is the oldest industrial type of direct firing of solid fuels and the first (stationary) grate was used over 200 years ago for steam generation with coal. Grate boilers can be used for heat generation in applications up to 60

MW, and they are the most popular choice for applications under 10 MW. (Vakkilainen 2017) In principle, grate firing is very simple, and it resembles a common fireplace equipped with some sort of an automatic fuel feeding system. This feeding system i.e. the grate, can be either stationary with no moving parts or mechanical, with moving parts (Vakkilainen 2017). In stationary grates, the grate has an inclination from horizontal (30 – 50 degrees in the case of wood chips), which function is to utilize gravity for the fuel feeding. As the fuel is burned, gravity gradually pulls more fuel in to the furnace, which keeps the process ongoing. Mechanical grates are also practically always inclined, but they have an automatically controlled moving bed such as a conveyor belt, which reduces the inclination angle to about 15 degrees. In addition, they have automatic ash removal. **Figure 15** illustrates the operation principle of a mechanical grate. At point 1 fuel is fed, from where it proceeds to point 2, where it is dried. At 3, the fuel is devolatilized, i.e. volatile matter is combusted to form a visible flame. At 4 char is burned, which makes it glowing hot, and lastly at 5 ash is formed and removed. 6 is the primary air that is injected from under the bed. Secondary and tertiary air are generally injected from above. (Vakkilainen 2017)

Notable challenges with grate burning are for example issues related to combustion. As the combustion happens in stages as depicted in **Figure 15**, local temperature and flue gas variations are quite high. Consequently, for example the grate area should be substantially larger for humid fuels than for dry fuels. Furthermore, humid fuels increase the drying time at point 2, which can lead to unburnt fuel or holes of burnt ash and increased emissions. In addition, the flame front is moved further down towards point 5, which slows the drying even further. To overcome the challenges with uneven burning, one needs monitor bed cameras or emissions and flue gas oxygen content. Moreover, the operator should have good understanding of heat transfer, gas flows, fuel properties and chemical reactions in order to prevent the unevenness of the combustion. (Vakkilainen 2017)

Fluidized bed reactors are technically more complex than grate boilers, but on the other hand, they are superior in terms of high combustion efficiency, higher capacity, cheap Sulphur removal, low NO_X emissions, good emission control, and the possibility to use high variety of fuels including fuel blends and fuels with high moisture content. The two main types of fluidized bed boilers, bubbling and circulating boilers, are both based on the same technological principle with some minor nuances. In fluidized bed combustion, hot air is injected through the bottom of the furnace through a sand and ash medium, which is also called the bed. The sand and the ash are in a very fine particulate form, and as the air is injected, these light particles are suspended to air. This results in a phenomenon called fluidization, where the particle-gas mixture behaves like a fluid, hence the name fluidized bed combustion. The fuel is then also injected from the bottom of the furnace, where it contacts hot solid particles and combusts. (Vakkilainen 2017)

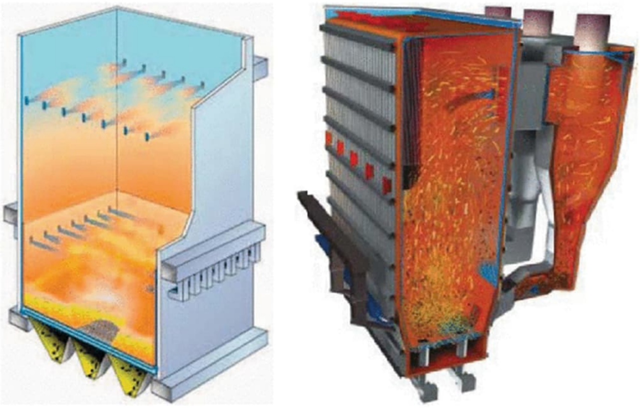


Figure 16: Bubbling fluidized bed boiler with secondary and tertiary air injection (left), Circulating fluidized bed boiler (right) (Vakkilainen 2017)

Figure 16 shows a schematic of a bubbling fluidized bed boiler and a circulating fluidized bed boiler. The main differences between the two reactor types is the fluidizing velocity, which is lower in a bubbling boiler, and the cyclones, which are attached to the circulating boiler on the right. As the fluidizing velocity in bubbling boiler is lower than in a circulating boiler, but higher than the minimum fluidizing velocity, the air that is passed through the bottom of the boiler forms bubbles on the surface of a distinct bed. This bed is not suspended to air, apart from some particles on the top of the bed. (Vakkilainen 2017) In a circulating boiler, there is no distinct bed, rather the whole bed is suspended to air, and as a result, the sand, the ash and the unburnt fuel circulates through the cyclone back into the furnace with the help of flue gases (Kirppu 2015).

Important downsides with fluidized bed boilers are their high energy consumption since the bed technology causes a large pressure-drop in the furnace as the primary air is injected (Kirppu 2015). Coarsening of the particles is also a major problem, because it changes the dynamics inside the furnace. For instance, clustering particles can hinder fluidization and impede mixing, which in turn causes many further problems such as non-uniform heat distribution and high temperatures, usability problems, melting ash and impaired emission control, which occurs when air, fuel and sorbents are mixed unevenly. A key method to overcome these problems is the regular removal of bottom ash, which also reduces the number of coarsened particles, since they are typically found at the bottom. (Vakkilainen 2017) Lastly, because of the mixing of the fuels and the conditions in the furnace, heat exchanger pipes are prone to erosion if they are not coated properly (Kirppu 2015).

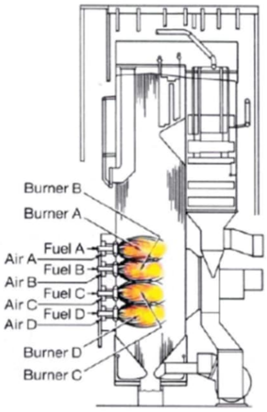


Figure 17: Pulverized coal fired burner (Flyktman et al. 2011)

Figure 17 shows a schematic of a pulverized coal fired burner. In pulverized coal firing, pulverized coal is injected to the burners A, B, C and D together with air. Pulverized coal fired burners can burn pulverized peat or wood as mentioned before, but they impose much larger limitations for the fuels for example in the terms of particle size and humidity. (Flyktman et al. 2011) Consequently, fluidized bed boilers are replacing pulverized coal burners in biomass applications because of their larger thermal capacity, better mixing and overall better utilization of different fuels and fuel blends (Vakkilainen 2017) (Flyktman et al. 2011). In addition, fluidized bed boilers are much cheaper when it comes to flue gas emission control, because for example limestone, which absorbs Sulphur dioxide, can be directly injected to the bed whereas with pulverized coal firing, a separate reactor is needed in order to remove Sulphur dioxide. Additionally, fluidized bed boiler's lower temperature reduces NO_x emissions. (Flyktman et al. 2011)

2.5 Variable renewable heat and power generation: wind & solar power

Variable renewable energy generation, wind and solar power, is characterized by intermittent, emission free generation, which in many cases does not match the consumption that well. For example, in the case of solar power, the peak generation occurs at midday while the peak consumption occurs in the evening, when people return to their homes and start cooking, washing etc., which creates problems from grid stability perspective. Furthermore, at night the sun does not shine at all and there are quite many cloudy and non-windy days. Consequently, many wind and solar power installations need some sort of an energy storage in order to be economically viable. Yet, the storage options are not very cheap. For example, the largest battery in the Nordics, owned by a Finnish energy company Fortum, cost 1.6 M€ and the capacity is only 1 MWh (Fortum 2017). Nevertheless, wind and solar power are the cheapest form of energy generation due to their relatively low investment costs and zero fuel costs.

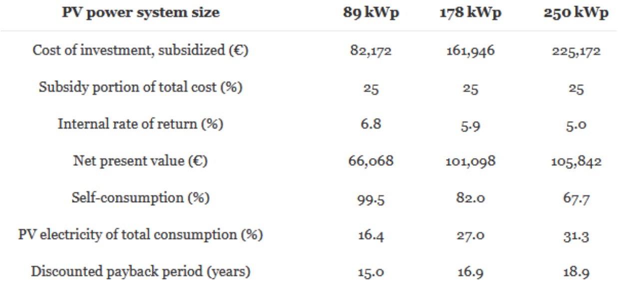
Although wind and solar power are the cheapest forms of energy generation, the options for utilizing them in this study's setting are limited. For instance, building a wind turbine with any reasonable power output (relative to the energy use in the sites) such as anything over 1 MW, is just not possible in a middle of densely populated suburb. Consequently, power-to-heat applications with wind power are also out of the question. However, the company could participate in a wind power project together with other actors, which would be directly reported as zero emission energy generation and energy use, once the plant would be commissioned. Participating in a wind project could be a feasible way to generate emission fee electricity in a large scale, and it has been done by for example the S-Group, which is a Finnish network of companies mainly known for its large number of grocery stores. The S-Group owns a wind power company called Gigawatti Ltd, which owns three wind parks. Also, fourth is on its way as well as multiple development projects (S-Group 2020).

When it comes to solar power, the possibility for its use is a little better than in the case of wind power. In both production plants, the roof is flat, and the roof area is large, without shadows caused by the environmental objects such as trees. As such, they could be a feasible place to install solar panels. However, it is the economic viability that determines whether such project would be carried out. Fortunately, there is some relevant data from Mikkeli in southern Finland, which gives some economic justification for their use. In a 2018 study by Simola et al. (2018), the profitability of a photovoltaic system for self-consumption was evaluated using internal rate of return (IRR) and net present value (NPV) in three cases: dairy farm, grocery store and a domestic house from which only the first two will be considered due to the small size of the domestic house system. In practice, the study was an Excel-based simulation with real-world data from 2015. Consumption data was collected using AMR meters with 1-hour resolution while irradiation and weather data were obtained from NASA's HOMER Pro software. December, January and February, which accounted for about 2.7 % of the annual production, were excluded from the calculations in order to simulate snow. Losses caused by shades were assumed to be minimal and 0.5 % annual panel deteriorating was taken into account. The system was assumed to be connected to the grid, i.e. surplus energy could be sold to the grid, and the lifetime was assumed to be 30 years. (Simola et al. 2018)

In the case of a grocery store, which annual consumption was 485 MWh, it was concluded that the optimal PV-system size was 89 kWp with optimal IRR and 250 kWp with the best NPV, when the panels were installed facing south with a 30° inclination. kWp is the unit used to compare PV-systems, and it describes the peak power production in certain standard circumstances (Kuluttaja 2019). Moreover, the 89 kWp system yielded a profit of 6.8 %. It is important to note however, that the optimal systems were assumed to receive a 25 % subsidy to cover investment costs. (Simola et al. 2018) Currently this subsidy for companies is 20 % (Business Finland 2021).

As the case grocery store was studied further, it was concluded that increasing the system size does not necessarily increase the discounted payback period significantly, but it does cover a larger portion of the buildings energy consumption, and it lowers the self-consumption rate, which leads to more sold electricity. Moreover, IRR decreases when the system size is increased beyond 89 kWp while NPV increases all the way to 250 kWp. When it comes to peak production and peak consumption months such as June and October respectively, larger systems produce more than what the building consumes. In October, the darkest month of the year, while no system can cover all consumption. Lastly, it was concluded that the 89 kWp system is still viable even if electricity prices fell 3.6 % annually with investment aid or 1 % without investment aid. The figures for the 250 kWp system were 1.7 % and 0.7 % respectively. **Table 1** below concludes the results for the case grocery store with subsidies. (Simola et al. 2018)

Table 1: Profitability of a grocery store PV-system with 25 % investment aid (Simola et al. 2018)



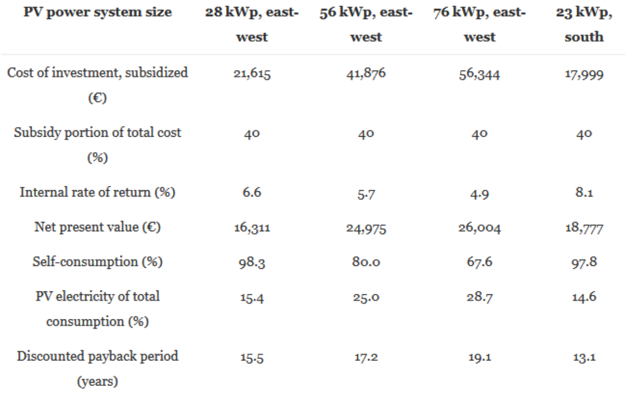
PV power system size	89 kWp	178 kWp	250 kWp
Cost of investment, subsidized (€)	82,172	161,946	225,172
Subsidy portion of total cost (%)	25	25	25
Internal rate of return (%)	6.8	5.9	5.0
Net present value (€)	66,068	101,098	105,842
Self-consumption (%)	99.5	82.0	67.7
PV electricity of total consumption (%)	16.4	27.0	31.3
Discounted payback period (years)	15.0	16.9	18.9

In the case dairy farm, the annual consumption was 133 MWh. Unlike in the case grocery store, this time two different system configurations were assessed, because of the relatively uncommon consumption profile. In dairy farms, the consumption peaks in the mornings and in the evenings when the cows are milked, and the milk is cooled. Thus, one system had 50 % of the modules facing west and 50 % facing east with 20 ° inclination while the other system was facing completely south. It was found, that the optimal IRR was 6.6 % with 28 kWp system in the east-west orientation and 8.1 % with 23 kWp system with the south orientation. The optimal size with the largest NPV was 76 kWp in east-west orientation and about 90 kWp in south orientation. Studying the NPV it was found, that the it does not increase substantially when the system size is increased, which implies that increasing the system size might increase the risks more than the profit. Increasing the system size did not affect IRR as much. (Simola et al. 2018)

As in the grocery store system, increasing the system size in the dairy farm covered a larger portion of the consumption while decreasing the self-consumption ratio. Increasing the size increased also the payback, but it remained smaller than the system lifespan. Unlike in the grocery store case, all the studied systems were able to cover the demand in October while in the summer, 56 - 76 kWp systems produced surplus, which was sold to the grid. For farms, the subsidy was larger: 40 %, and it was concluded, that the 28 kWp east-west system was still economically viable, if electricity prices dropped 3.3 % annually during the lifetime of the system. Without aid the number was 1 %. With a larger 76 kWp east-west system, the prices could drop 1.6 % with the subsidy while without it, the prices would need to increase 2.2 % for the system to stay economically viable. (Simola et al. 2018) In the case of farms, the PV-subsidy has not changed, and it is still 40 % for costs without value added tax (Powera 2021).

Table 2 below summarizes the results for the case dairy farm.

Table 2: Profitability of a dairy farm PV-system with 40 % investment aid (Simola et al. 2018)



PV power system size	28 kWp, east-west	56 kWp, east-west	76 kWp, east-west	23 kWp, south
Cost of investment, subsidized (€)	21,615	41,876	56,344	17,999
Subsidy portion of total cost (%)	40	40	40	40
Internal rate of return (%)	6.6	5.7	4.9	8.1
Net present value (€)	16,311	24,975	26,004	18,777
Self-consumption (%)	98.3	80.0	67.6	97.8
PV electricity of total consumption (%)	15.4	25.0	28.7	14.6
Discounted payback period (years)	15.5	17.2	19.1	13.1

2.6 Thermal energy storage systems

Thermal energy storages (TES) can be one of the most inexpensive ways to save heat, cut heating costs and move to carbon neutrality, since their simplest form, a thermal storage can consist just of a water tank with good insulation that stores energy that would be otherwise wasted. For instance, one of the most effective ways to utilize a thermal storage is to charge the storage during times of low consumption with surplus heat or cheap green electric heating, and then discharge during peak consumption. (Kirppu 2015) Although the word “thermal” is usually associated with heat, cold TES systems are also one type of thermal storage and they can be used for cooling. Generally, thermal energy storages are classified into two groups: diurnal and seasonal/long duration systems which further divide into three types of storages: sensible, latent and chemical heat storages. (Alva et al. 2018) Next, these two groups and three types are discussed in detail as well as cold TES systems, due to the large cooling needs in the food industry.

2.6.1 Diurnal heat storages

Diurnal heat storages operate on a cycle that occurs diurnally i.e. in terms of days or a couple of hours (Kirppu 2015). An easily comprehensible example of a diurnal storage is a solar thermal system, in which the storage charged during the day using sunlight and then discharged in the night (Alva et al. 2018). The most common diurnal heat storage is a hot water tank while caverns are also sometimes used especially in district heat applications. In addition to covering peak consumption, diurnal heat storages are typically used for other unexpected variations in the cooling or heating needs. (Kirppu 2015)

2.6.2 Seasonal and long duration storages

Seasonal storages are much larger both in terms of capacity and the amount of required storage materials compared to diurnal heat storages. The main difference is however the fact, that they are charged and discharged much less often than diurnal storages, and the lifespan is much longer, typically 20 – 30 years. Seasonal storages are a good option at high latitudes like in Finland and Sweden, because summers are long and sunny, while winters are cold and long. In such places, the storage can be charged during summer with excess heat, and then discharged over the winter during high demand for space heating. In addition to large capacity, stable temperature, high recovery efficiency and reliable discharge are key parameters in seasonal storing (Alva et al. 2018).

Typically, seasonal TES systems are placed underground due to their large spatial need. Underground storing technologies include for instance underground pits, aquifers, boreholes, caverns, old mines and water tanks, which are also used above ground for longer term storage. **Figure 18** illustrates the operation of an underground pit. The pit is first insulated using for example plastics such as HDPE. It is then filled with gravel and water, which store the heat. The charging/discharging occurs either via gravel's direct contact with hot water or via plastic pipes such as in the picture. Pit TES has the lowest specific cost in addition to aquifer TES, but due to gravel's low specific heat capacity, it requires more space than for example a water tank. (Alva et al. 2018)

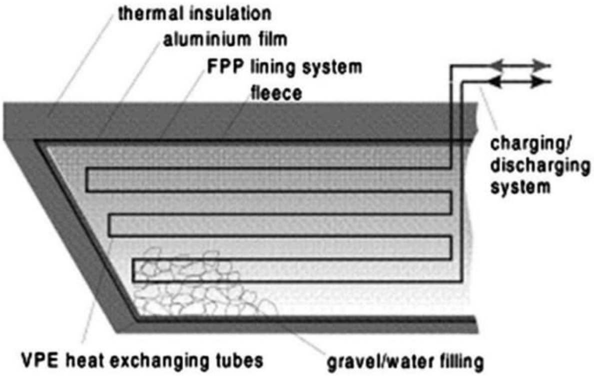


Figure 18: An underground pit TES (Alva et al. 2018)

2.6.3 Sensible heat storage systems

Storage systems like water tanks, underground pits and aquifers are sensible heat storages. In sensible storing, the heat is stored in a heat medium such as water without a phase change. The amount of energy stored depends on the material's specific heat capacity c_p (kJ/(kg·°C), and the amount of energy stored can be expressed as:

$$Q = m \cdot c_P \cdot \Delta T \tag{4}$$

where Q is the energy (kJ), m is the mass (kg) and ΔT is the temperature change. In addition to specific heat capacity, the amount of energy stored is proportional to volume, density and temperature variations in the storage materials. Besides water and gravel, common sensible heat storage materials include thermal oils, molten salts, concrete blocks, rocks, sand and liquid metals, which are however suitable mainly for high temperature storages. (Alva et al. 2018)

Sensible heat storage pros are their thermal stability, which has made them the most popular choice for high temperature applications, and low-cost storage materials, apart from thermal oils and liquid metals. The largest downside is the temperature stability during discharge. When a sensible storage is discharged, the outlet temperature does not remain constant, rather it decreases gradually over time. Moreover, the energy storage density is rather small especially compared to latent heat storages, which can possess 50 – 100 larger energy density. Yet some sensible heat storages, such as liquid metal heat storages, can still have a large energy storage density due to the high temperature and density. (Alva et al. 2018)

2.6.4 Latent heat storage systems

In latent heat storing, heat is stored or discharged during a constant temperature phase change (Alva et al. 2018). In other words, the energy exchange is the change in the material's enthalpy that occurs during a phase change while the temperature remains constant (Wikipedia 2021a). The energy that is stored or discharged can be calculated using the following equation:

$$Q = m \cdot L \tag{5}$$

where Q is the energy (kJ), m is the mass (kg) and L is specific latent heat (kJ/kg) of the storage material. Most often, latent heat storages are based on solid-liquid phase change however solid-solid phase changes are also used as well as liquid-gas phase changes. Compared to solid-liquid systems, advantages with solid-solid systems include no leakage and the absence of encapsulation. The largest disadvantage is lower specific latent heat. Liquid-gas systems have the highest specific latent heat overall, but due to gas's natural high volume and space need, these systems are rarely used. Latent heat storage system materials consist of for example organic materials such as paraffin, fatty acids and alcohols, and inorganic materials such as salts, metals and metal alloys. (Alva et al. 2018)

The largest advantages in general with latent storages are their high energy density and steady discharge outlet temperature. The largest drawback is bad thermal conductivity. Less major drawbacks include certain material's flammability and corrosivity, when stored in metal containers. In addition, many organic materials such as esters and long chained fatty acids cannot be stored or transported in plastic containers. (Alva et al. 2018)

2.6.5 Chemical heat storage systems

Due to the fact, that chemical heat storages are still at laboratory stage and not a commercial scale technology, they aren't be discussed in detail here. However, the basics and most important advantages and disadvantages will be covered. Chemical heat storages are based on reversible chemical reactions, that involve absorption and release of heat. Most of the time chemical heat storages operate in the temperature range of 200 – 400 °C and are thus suitable for relatively high temperature applications. The greatest advantage with chemical heat storing is its highest energy storage density compared to all other storage types both in terms of per-unit mass and per-unit volume. Yet, there are still technical challenges that need to be overcome for the technology to become commercialized. Some materials such as $Mg(OH)_2$ may experience grain growth and sintering that leads to lower porosity, which in turn decelerates discharging rate by disturbing the rehydration process. Also, in some cases the dehydration reaction is slow, which leads to slow charging rates. (Alva et al. 2018)

2.6.6 Cold thermal storage systems (CTES)

Cold thermal storage systems comprise of systems with temperatures under 10 °C. CTES can be used to reduce cooling costs but also to reduce the mechanical load on building HVAC cooling compressors. Economically, the optimal way to use CTES is to charge the storage at night and discharge it during the day, because cooling requires mechanical work, which is usually produced by electrically driven compressors. Moreover, at night there is little electric load and energy is cheap. Generally, CTES is either a sensible storage, like chilled water storage, or a latent storage, such as a solid ice storage. (Alva et al. 2018)

A relatively simple type of a chilled water storage is a thermocline water storage, which is a sensible storage that operates in the temperature range of 4 to 6 °C. According to the U.S. National Ocean Service (2021) a thermocline *"is the transition layer between the warmer mixed water at the surface and the cooler deep water below"*, i.e. it is a distinct layer where the water temperature changes rapidly. In a thermocline water storage, a thermocline is formed as follows. During the day when the storage is discharged, chilled water from the bottom of the tank is pumped to the building's HVAC system via cooling coil. Simultaneously, warm water that needs to be cooled, is pumped from the HVAC system to the top of the tank. As a result, the tank has two distinct hot and cold layers and a thermocline is formed in between. At night, the warm water on top of the tank is pumped to the cooling chiller in order to be cooled, while chilled water is pumped from the bottom to the top. (Alva et al. 2018)

When thermocline water storages have been studied, it has been found that the performance improves as the aspect ratio improves up to the value of 3. The aspect ratio is the storage's height to diameter ratio, and after it reaches the value of 3 (in a cylinder-shaped storage), no significant improvement is perceived. The reason why the performance increases as the aspect ratio increases is in the thermocline's degradation. If the aspect ratio is too small, considerable amounts of heat is transferred from the environment to the tank. Moreover, thermal diffusion, axial wall conduction and mixing of water during charging and discharging start to deteriorate the performance. (Alva et al. 2018)

One type of latent cooling CTES is a coil pipe cooling storage system. In such system, the phase changing latent medium can be for example water which turns to ice. Coil pipe cooling system works by circulating a heat transferring fluid via an indirect heat exchanger such as a coiled tube. During charging, the fluid is obtained from the cooling chiller's evaporator, and is injected in the tank containing the latent medium using a coil. The fluid's temperature is about 3 °C below the freezing point of the latent medium, and thus it cools the latent medium by absorbing heat. Discharging is very similar however it works in the opposite way. During discharging, the fluid's temperature is higher than the freezing point of the medium, and the medium absorbs heat from fluid. A major problem with coil pipe cooling storage system is poor thermal conductivity, which hinders charging and discharging. Inside the tank containing the liquid latent medium such as water, heat is transferred via natural convection. As the storage is charged for instance, the water around the coil is solidified i.e. turned to ice first. As a result, in such areas conduction starts to gradually dominate convection. Due to poor thermal conductivity of latent storage materials, the charging rate starts to drop as the heat is not transferred as effectively. (Alva et al. 2018)

2.7 Achieving carbon neutrality in the food industry: two examples from around the world

2.7.1 The first carbon neutral food company: Maple Leaf Foods Inc.

Maple Leaf Foods Inc. is a Canadian food and meat company created through a merger in 1991. Yet the company has roots dating all the way back to 1836. (Maple Leaf Foods Inc. 2021) Maple Leaf Foods was the first food company in the world to achieve carbon neutrality in November 2019 as a result of a company-wide sustainability project started in 2013. Yet the company did not stop there, and it has pledged to reduce its scope 1 and 2 emissions by 30 % by 2030 from 2018, which is used as a reference base year. In addition, it has pledged to reduce its Scope 3 emissions by 30 % per ton of produced product in the same time period. (Maple Leaf Foods Inc. 2019)

Maple Leaf's first steps to achieve carbon neutrality included hiring competent staff and retaining an engineering company in order to identify improvements in water, energy and solid waste to create an action plan for facilities to reduce their carbon footprint. After the engineering company conducted an energy audit and action plans were created, the company started to convert all their lights to energy efficient LEDs in 2016. Simultaneously, the company started heat recovery projects to capture surplus heat from boilers, compressors and other equipment. Furthermore, Maple Leaf started to research many sustainable energy technologies such as geothermal heating and cooling, electric & hybrid vehicles, solar power and battery storages. (Maple Leaf Foods Inc. 2019)

In 2017 and 2018 the company completed its lighting retrofit programs. At the same time, it adapted a utility management system to monitor consumption and assess environmental performance. Moreover, the company continued its partnership with a local biodigestion to turn their organic waste (biomass) into green energy. Furthermore in 2019 Maple Leaf started to explore its own biogas production by reviewing the possibility to capture methane from its facilities as well as pig manures in barns. In addition to green electricity and heat projects, the company reduced its natural gas use by boiler optimization, low-flow sanitation guns and steam trap repairs, which reduced leakages and gas use by approximately 174 000 m^3 (330 tCO2e). (Maple Leaf Foods Inc. 2019)

On top of the company's own projects, Maple Leaf has supported and supports 10 high-impact environmental projects to neutralize emissions that cannot be otherwise avoided. These projects include wind parks, landfill gas collection system, waste biomass to energy-project, forestry programs and waste diversion program to avoid the production of methane from organic waste. (Maple Leaf Foods Inc. 2019) The large number of collaboration projects imply, that achieving carbon neutrality by one company alone is difficult or even impossible. All in all, carbon neutrality can be expected to take time and consume significant amounts of money.

2.7.2 JBS S.A. – A global food company on its way to net-zero greenhouse gas emissions

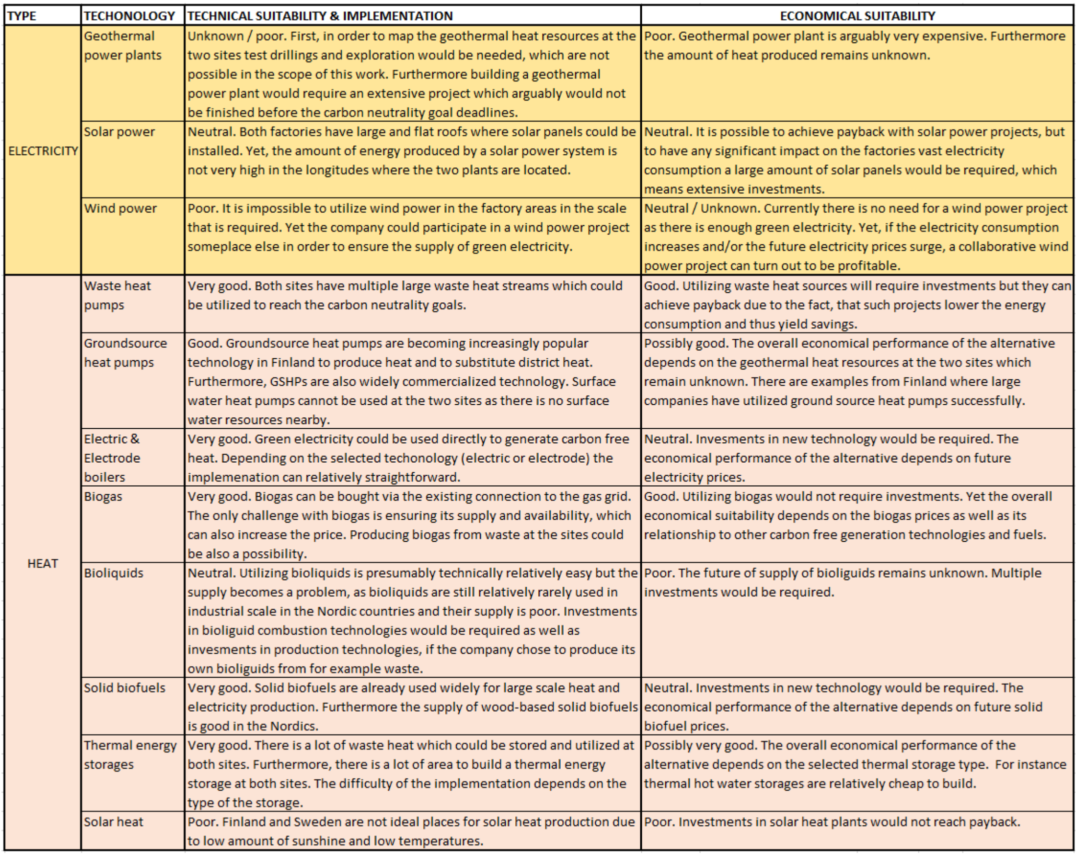
JBS S.A. is a global food company with its headquarters and origins in Brazil (Wikipedia 2019b). It is the world's largest beef and poultry producer as well as the second largest pork producer in the world (JBS Foods Group 2021a). Despite the company's enormous size, it has committed to reach net-zero greenhouse gas emissions by 2040. Furthermore, it has promised to reduce its Scope 1 and 2 emissions by at least 30 % by 2030 compared to the base year 2019. The budget for the emission reducing projects is over one billion U.S. dollars. (JBS Foods Group 2021b)

JBS's ways to reach their emission reduction targets include elimination of deforestation in the supply chain, the use of 100 % renewable electricity in all the group's facilities and investments in innovative projects (JBS Foods Group 2021b). Moreover, a look at JBS Foods' actions, an U.S. based subsidiary of JBS S.A., reveals that the company focuses highly on energy efficiency; JBS Foods has invested in LED-lighting, more efficient equipment, real-time measurement systems, electric heating devices, predictive maintenance and more efficient equipment and refrigeration systems. In addition, 12 plants have adopted biogas instead of natural gas and seven have their own solar energy systems. (JBS USA 2021)

2.8 Conclusions from the literature review

Table 3 below concludes the literature review and shows the preliminary evaluation of the carbon free heat and electricity generation technologies.

Table 3: Preliminary evaluation of the carbon free heat and electricity generation technologies



TYPE	TECHONOLOGY	TECHNICAL SUITABILITY & IMPLEMENTATION	ECONOMICAL SUITABILITY
ELECTRICITY	Geothermal power plants	Unknown / poor. First, in order to map the geothermal heat resources at the two sites test drillings and exploration would be needed, which are not possible in the scope of this work. Furthermore building a geothermal power plant would require an extensive project which arguably would not be finished before the carbon neutrality goal deadlines.	Poor. Geothermal power plant is arguably very expensive. Furthermore the amount of heat produced remains unknown.
	Solar power	Neutral. Both factories have large and flat roofs where solar panels could be installed. Yet, the amount of energy produced by a solar power system is not very high in the longitudes where the two plants are located.	Neutral. It is possible to achieve payback with solar power projects, but to have any significant impact on the factories vast electricity consumption a large amount of solar panels would be required, which means extensive investments.
	Wind power	Poor. It is impossible to utilize wind power in the factory areas in the scale that is required. Yet the company could participate in a wind power project someplace else in order to ensure the supply of green electricity.	Neutral / Unknown. Currently there is no need for a wind power project as there is enough green electricity. Yet, if the electricity consumption increases and/or the future electricity prices surge, a collaborative wind power project can turn out to be profitable.
HEAT	Waste heat pumps	Very good. Both sites have multiple large waste heat streams which could be utilized to reach the carbon neutrality goals.	Good. Utilizing waste heat sources will require investments but they can achieve payback due to the fact, that such projects lower the energy consumption and thus yield savings.
	Groundsource heat pumps	Good. Groundsource heat pumps are becoming increasingly popular technology in Finland to produce heat and to substitute district heat. Furthermore, GSHPs are also widely commercialized technology. Surface water heat pumps cannot be used at the two sites as there is no surface water resources nearby.	Possibly good. The overall economical performance of the alternative depends on the geothermal heat resources at the two sites which remain unknown. There are examples from Finland where large companies have utilized ground source heat pumps successfully.
	Electric & Electrode boilers	Very good. Green electricity could be used directly to generate carbon free heat. Depending on the selected techonology (electric or electrode) the implemenation can relatively straightforward.	Neutral. Invesments in new technology would be required. The economical performance of the alternative depends on future electricity prices.
	Biogas	Very good. Biogas can be bought via the existing connection to the gas grid. The only challenge with biogas is ensuring its supply and availability, which can also increase the price. Producing biogas from waste at the sites could be also a possibility.	Good. Utilizing biogas would not require investments. Yet the overall economical suitability depends on the biogas prices as well as its relationship to other carbon free generation technologies and fuels.
	Bioliquids	Neutral. Utilizing bioliquids is presumably technically relatively easy but the supply becomes a problem, as bioliquids are still relatively rarely used in industrial scale in the Nordic countries and their supply is poor. Investments in bioliguid combustion technologies would be required as well as invesments in production technologies, if the company chose to produce its own bioliguids from for example waste.	Poor. The future of supply of bioliguids remains unknown. Multiple investments would be required.
	Solid biofuels	Very good. Solid biofuels are already used widely for large scale heat and electricity production. Furthermore the supply of wood-based solid biofuels is good in the Nordics.	Neutral. Investments in new technology would be required. The economical performance of the alternative depends on future solid biofuel prices.
	Thermal energy storages	Very good. There is a lot of waste heat which could be stored and utilized at both sites. Furthermore, there is a lot of area to build a thermal energy storage at both sites. The difficulty of the implementation depends on the type of the storage.	Possibly very good. The overall economical performance of the alternative depends on the selected thermal storage type. For instance thermal hot water storages are relatively cheap to build.
	Solar heat	Poor. Finland and Sweden are not ideal places for solar heat production due to low amount of sunshine and low temperatures.	Poor. Investments in solar heat plants would not reach payback.

3 Research material and methods

This section presents the operational environments and energy systems of the two factories in the study, as well as the source of the materials used for this study. Furthermore, the research method and the associated quantitative measures are introduced.

3.1 Production plant overview: Vantaa, Finland

3.1.1 General view of the plant

Vantaa is the company's largest production plant in Finland. It is located in the Helsinki metropolitan area in the city of Vantaa. Vantaa specializes solely on processed products i.e. for example slaughtering does not occur at the site. Processed end-products include ready meals, packed products and meat products such as minced meat. The plant has 350 – 400 production workers depending on the season, as well as numerous office workers. The factory works mainly in two shifts from 6.00 to 22.00, but depending on the season, some production lines may operate seven days a week up to several months without interruptions. As hygiene is an important aspect in the sector, production equipment and facilities are cleaned at the end of every production day, starting in the evening. As a result, in 2020 the weekly water consumption was around 9000 cubic meters on average, which is notably high. **Figure 21** below shows the layout of the production plant.

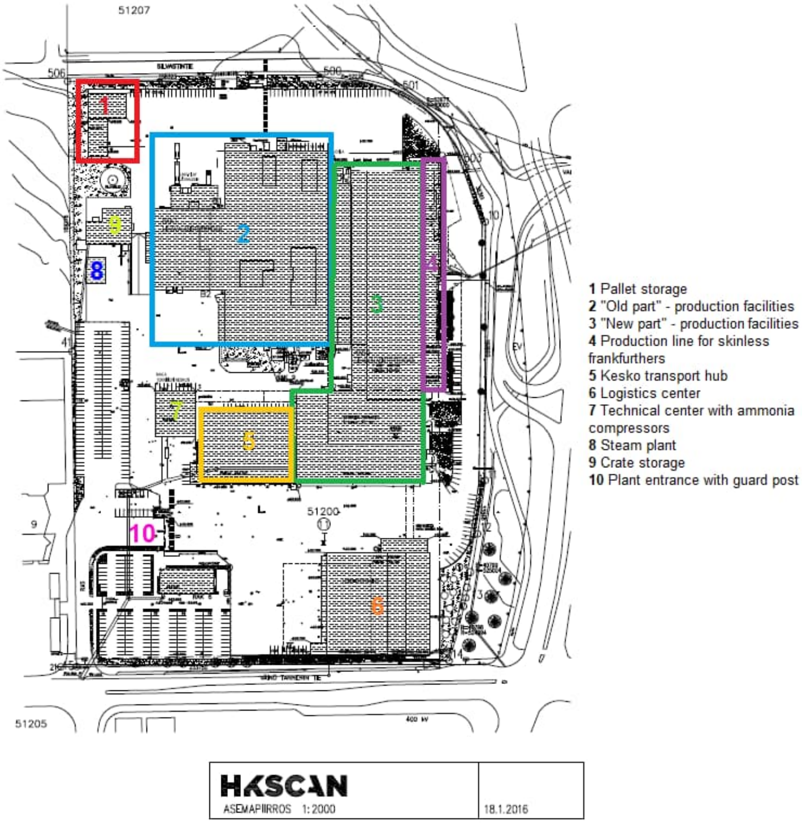


Figure 19: City plan of Vantaa factory

3.1.2 Energy use & emissions

The energy use in Vantaa is characterized by large cooling and heating need, as well as enormous district steam use. Due to for example strict food quality and safety requirements, many parts of the production require constant cooling, which is driven by large, electrically powered ammonia cooling compressors. As at least one compressor is running all day every day, the amount of electricity consumed in cooling is substantial. Yet, a part of this energy is recovered in the form heat by a water-glycol heat recovery system. Still, a very large possibility for further heat recovery remains. District heat in Vantaa is used for conventional heating purposes such as space heating, warm water heating and air conditioning while district steam is used almost exclusively to production via cooking processes, product moisturizing and cleaning (ÅF 2017a). The district steam is produced with natural gas in its own steam plant, the number 8 in **Figure 19**. Although the steam plant is located at the site, it is owned and operated by the local energy utility company Vantaan Energia. In addition to natural gas use in steam generation, the plant has its own direct connection to the gas network. The network supplies natural gas, which has two use cases, that are heat generation in production ovens and thermo-oil heating.

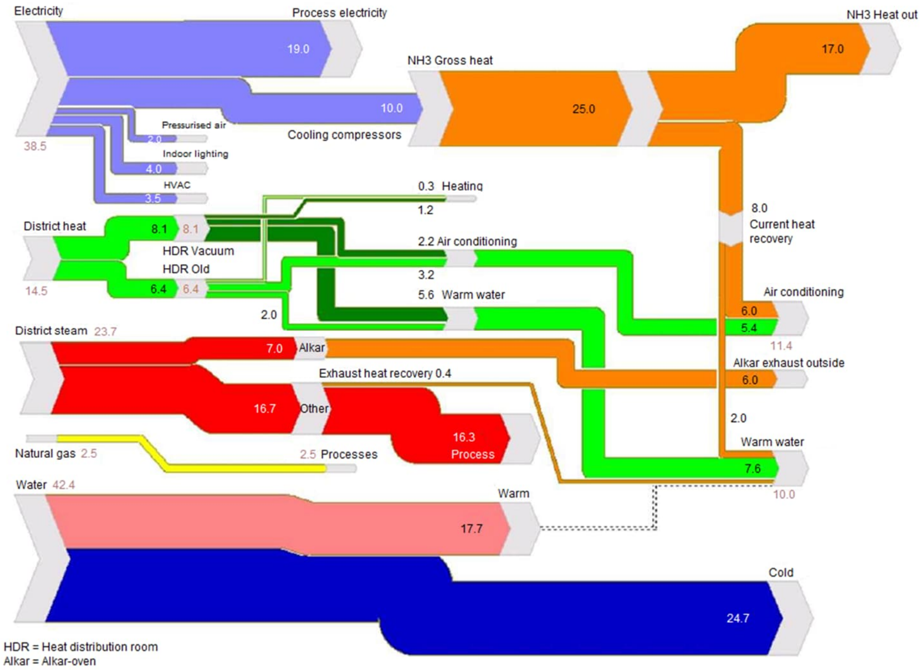
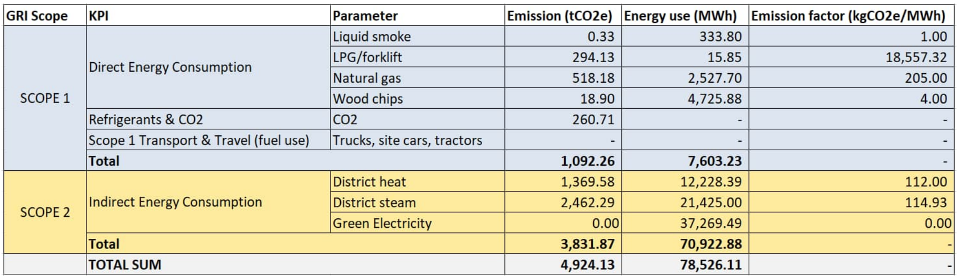


Figure 20: A Sankey-diagram showing the annual primary energy flow and consumption (GWh) as well as water use (m^3/10000) in Vantaa (ÅF 2017a)

Figure 20 shows a Sankey-diagram, that visualizes the main energy flows in the factory. A Sankey-diagram is a flow diagram, where the width of the flows corresponds to quantity (SankeyMATIC 2021). The numbers represent energy and water use over a year, and they have been scaled so, that energy is represented in GWh while water in m^3 has been divided with 10 000. The diagram has been acquired from an energy audit performed by an external company in 2017, however the flows and technologies are still valid today (the total primary energy use in 2020 was ca. 79.9 GWh compared to 79.2 GWh in the figure). An interesting notion is, that when district heat, district steam and natural gas are counted together as heat use, the primary energy use is divided approximately 50-50 to heat and electricity (40.7 GWh vs. 38.5 GWh in the picture, 36.1 GWh vs. 37.3 in 2020).

Table 4: Vantaa 2020 Carbon footprint & Energy consumption according to ToFuture Corporate Sustainability Management-reporting system



GRI Scope	KPI	Parameter	Emission (tCO2e)	Energy use (MWh)	Emission factor (kgCO2e/MWh)
SCOPE 1	Direct Energy Consumption	Liquid smoke	0.33	333.80	1.00
		LPG/forklift	294.13	15.85	18,557.32
		Natural gas	518.18	2,527.70	205.00
		Wood chips	18.90	4,725.88	4.00
	Refrigerants & CO2	CO2	260.71	-	-
	Scope 1 Transport & Travel (fuel use)	Trucks, site cars, tractors	-	-	-
	Total		**1,092.26**	**7,603.23**	-
SCOPE 2	Indirect Energy Consumption	District heat	1,369.58	12,228.39	112.00
		District steam	2,462.29	21,425.00	114.93
		Green Electricity	0.00	37,269.49	0.00
	Total		**3,831.87**	**70,922.88**	-
	TOTAL SUM		**4,924.13**	**78,526.11**	-

Table 4 shows Vantaa's carbon footprint and energy use from 2020 as well as the emission factor, which has been calculated by dividing the emission with the corresponding consumption. The data has been retrieved from ToFuture Corporate Sustainability Management -reporting system. CO_2 is used as packaging gas and is thus omitted in this work, as it is not directly related to energy technology. Similarly, wood chips will not be considered, as they are used for smoking in the production, not to generate heat or steam. When it comes to transport, the fuel use and greenhouse gas emissions from transport are not actually zero, for all company owned emissions that are accumulated from transport in Finland are reported separately under the group's headquarters. However, what are zero, are the emissions from electricity since it is bought green. Thus, the actions proposed in this work are focused on carbon free heat generation, which accounts for 50 % of energy and the vast majority of emissions. Yet, there is the question of how to produce electricity when electricity from the grid is not available due to for example a line fault or a grid blackout. Furthermore, it is not evident that green electricity is available all the time in the future if for example the demand surges.

3.2 Production plant overview: Kristianstad, Sweden

3.2.1 General view of the plant

Kristianstad is a large multifunctional plant with about 650 employees located in the very of South Sweden, about 100 km North-East from Malmö and about 140 km from Copenhagen, Denmark. The plant has its own pig slaughterhouse, and it specializes in sliced, smoked, processed and deboning products as well as in red meats. Mainly, the plant operates five days a week from 6.00 to 16.00 in one shift in three production areas that are slaughtering, deboning and processing. In high demand seasons, such as the time around midsummer, some production areas operate more often. All the production equipment is cleaned every production day starting in the evening and continuing all the way to 1.30 in the night. In 2020, the weekly water consumption was little over 11 000 cubic meters on average. **Figure 21** presents the map of the production plant.

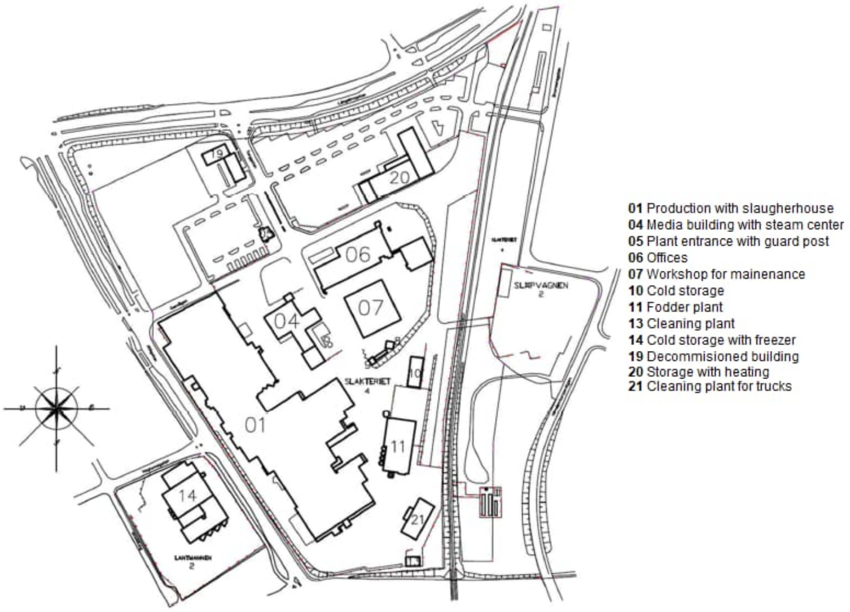


Figure 21: Map of production plant Kristianstad (ÅF 2017b)

3.2.2 Energy use & emissions

Like Vantaa, Kristianstad has a large need for heating, cooling, electricity and steam. But unlike in Vantaa, steam is produced with biogas and propane rather than with district steam in a natural gas fired plant. The plant has a direct connection to a local biogas plant, which is located about 10 km from the site. Kristianstad plant does not just buy biogas, it is also part of the production by producing feedstock for the biogas plant. As in Vantaa, Kristianstad uses district heat for space heating, warm water and ventilation as well as large ammonia cooling compressors for cooling. Some of the compressors are in general very old, as some of them have been commissioned as early as 1960s.

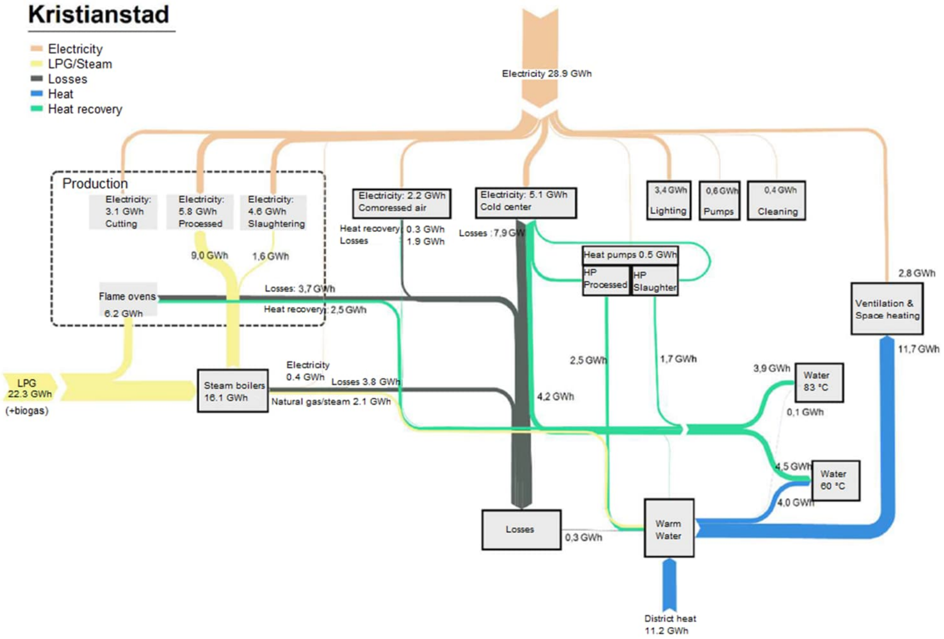
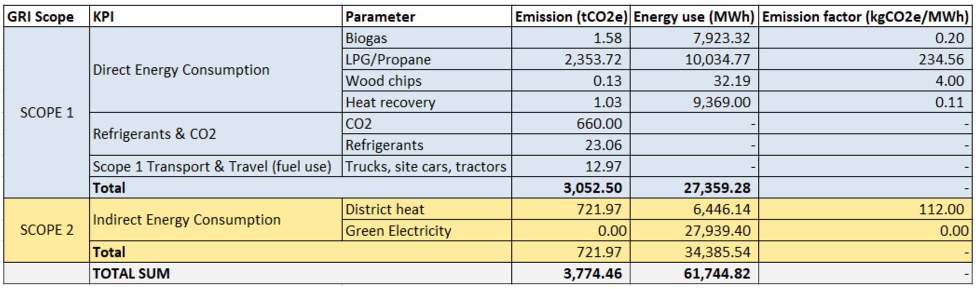


Figure 22: A Sankey-diagram showing the annual primary energy flow (GWh) and consumption in Kristianstad in 2017 (ÅF 2017b). Biogas was not yet used at the time the diagram was compiled.

Table 5: Kristianstad 2020 Carbon footprint & Energy consumption according to ToFuture Corporate Sustainability Management-reporting system



GRI Scope	KPI	Parameter	Emission (tCO2e)	Energy use (MWh)	Emission factor (kgCO2e/MWh)
SCOPE 1	Direct Energy Consumption	Biogas	1.58	7,923.32	0.20
		LPG/Propane	2,353.72	10,034.77	234.56
		Wood chips	0.13	32.19	4.00
		Heat recovery	1.03	9,369.00	0.11
	Refrigerants & CO2	CO2	660.00	-	-
		Refrigerants	23.06	-	-
	Scope 1 Transport & Travel (fuel use)	Trucks, site cars, tractors	12.97	-	-
	Total		**3,052.50**	**27,359.28**	-
SCOPE 2	Indirect Energy Consumption	District heat	721.97	6,446.14	112.00
		Green Electricity	0.00	27,939.40	0.00
	Total		721.97	34,385.54	-
	TOTAL SUM		**3,774.46**	**61,744.82**	-

Figure 22 presents a Sankey diagram of the annual energy flows. The diagram has been acquired from an energy audit completed in 2017, however it is not as accurate as in the case of Vantaa due to complete renewal of the slaughter line and the addition of biogas in steam generation in 2020. Yet, the total energy use is still in the range (62.4 GWh in the diagram, 61.7 GWh in 2020). **Table 5** shows Kristianstad's carbon footprint as well as the energy consumption and emission factor from 2020. Although biogas is considered emission free, some emissions are still accumulated since biogas production, and biofuel production in general, consumes energy. The energy consumed in the biogas production phase has its own emission factor, and it has been determined by the Swedish Energy Authority. District heat in Kristianstad is mainly produced with pellets however, during peak load times such as in the

coldest months of the winter, oil is used to "*top up*" the production and thus the district heat is not absolutely emission free. Yet reportedly in terms fuel use, almost all the district heat in Kristianstad was produced with pellets in 2020.

3.3 Research method

The main goal of this study is to find the best financially sustainable carbon neutral technologies and investments. In order to reach this, the system is analyzed qualitatively i.e. by collecting and analyzing non-numerical data (SimplyPsychology 2019), which is used to derive a solution to find the best technologies and investments with the lowest payback. The three main criteria which are used to select the best technologies are technical feasibility, implementation of the project and costs. In other words, this study tries to assemble an *ad hoc solution* for the given energy systems. Yet, although this is mainly a qualitative study, numerical data has an important role when selecting the most promising investments, as otherwise it is impossible to give any monetary justifications. Thus, 2020 and 2021 monthly consumption and price data is used as well as very limited hourly consumption data. The data has been mainly provided by the company, but for example the hourly district heat data has been provided by Vantaan Energia, the current district heat provider.

Although qualitative research is much more limited than quantitative research, the selected research method is relatively reasonable for this study's setting, due to shortage and bad availability of hourly data, but also because of the enormous size and complexity of the system. It is simply not possible for one person to present detailed investment calculations of every subsystem and investment considering the time, available resources, constraints of the work and expertise required to understand each subsystem.

The non-numerical data has been acquired mainly from previous energy audits but also by consulting and interviewing different experts, technicians and utility managers. Energy audits are an excellent source of information, because by law, these relatively extensive reports must be assembled every fourth year in companies with over 250 employees, with sales over 50 million euros or with a balance sheet total of over 43 million euros (ÅF 2017a). Experts opinions and suggestions on the other hand are very valuable when estimating the investment costs, as the costs of for similar projects by other companies are not usually public information. Furthermore, the technology providers almost never have public and easily accessible cost data, as the solutions are often tendered and tailored for the customer's needs.

3.3.1 Quantitative methods

As this study is mainly qualitative, numerous mathematical tools are not used. Yet, there are some essential equations that are required. Paybacks for investments, which are presented in this work, are calculated using the simple payback time, which is defined as:

$$PB = \frac{Investment\ cost}{Yearly\ revenue} \tag{6}$$

As the calculations in this work are mainly directional and contain considerable uncertainty due to shortage of data, it is not very meaningful to provide detailed investment calculations especially considering that further, more detailed, analyses are anyway needed in all cases. The yearly revenue in the denominator can also be interpreted as a saving in costs, as many of the investments presented in this work do not necessarily increase productivity or sales but cut down energy costs. The second equation, which is used in the analysis is the amount of energy stored in a body of water, or in other words, a thermal storage (The Engineering Toolbox 2021a):

$$E = m \cdot c_p \cdot \Delta T \tag{7}$$

where
E = capacity of thermal storage,
c_p = specific heat capacity of water,
m = mass of water in storage,
ΔT = temperature change.

The third equation used is the heating power of flowing water, i.e. the power of a flowing fluid exchanging heat, which is defined as (Wooley et al. 2018):

$$Q(t) = \dot{m}(t) \cdot c_p \cdot \Delta T(t) = \rho \dot{V}(t) \cdot c_p \cdot \Delta T(t) \tag{8}$$

where
Q(t) = power at a given time,
$\dot{m}(t)$ = mass flow at a given time t,
c_p = specific heat capacity of water,
ΔT(t) = temperature change at a given time t,
ρ = density,
$\dot{V}(t)$ = volume flow at a given time t.

4 Results

This section presents the results of analyzing the available data and material.

4.1 Vantaa, Finland

This section presents the results of the analysis in the case of Vantaa factory.

4.1.1 Substituting district heat with centralized thermal storage waste heat system

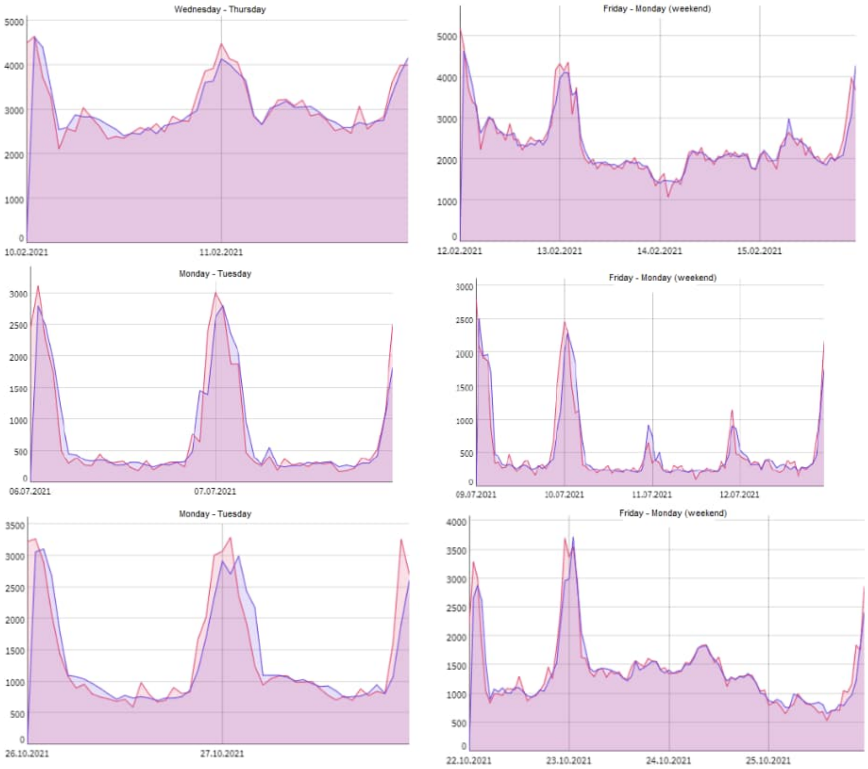


Figure 23: Diagrams showing the hourly district heating power (kW) and district heat water use (m3) over different time periods in 2021. Heat is marked with red and water consumption is blue. Seasonal variation between different months is clearly visible.

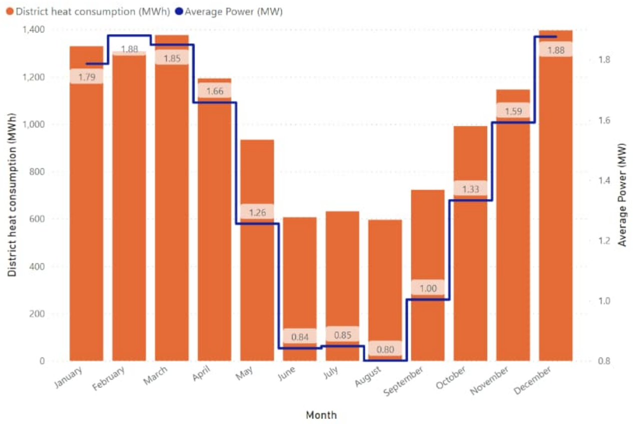


Figure 24: 2020 monthly district heat consumption & average monthly heating power in Vantaa

Figure 23 shows the consumption profiles of district heat in typical production days in different months. Seasonal variation is clearly visible, as both the base load and peak consumption are substantially higher in February than in July. In the summer, the baseload is around 300 MW whereas in the winter it is 2000 MW. **Figure 24** shows the total district heat consumption per month as well as the average power, which has been acquired by dividing the heat consumption with the hours in each month. As seen, the average power in winter is almost 2 MW whereas in the summer it is under 1 MW. This gives some power range of where the carbon free system should mainly operate. However, what determines the size of the system is the peak load, as the system must always produce the required heat for it to really achieve carbon neutrality. Yet, specifying the peak load is not self-evident, as it is mainly determined by outside temperature in the winter, which is next to impossible to forecast months or even weeks into the future. Thus, in order to approximate the peak load, one must study historical peak load data from several years, as the weather can change considerably between them. Yet, since there is no access to historical district heat data, the peak load is assumed to be 5.7 MW as suggested in the 2017 energy audit (ÅF 2017a).

Studying **Figure 20** as well as the 2017 energy audit, it is clear that there is a very large potential to substitute district heat with Alkar-oven and ammonia cooling compressor exhaust heat. As seen from **Figure 20**, the Alkar-oven process is extremely inefficient in terms of energy consumption, as ca. 86 % of the energy input is approximately wasted. Based on the figures in the picture, if all the Alkar waste heat could be recovered and directly used to substitute district heat, roughly 41 % of district heat consumption could be eliminated. Using the same logic, if all ammonia cooling compressor condensate heat could be recovered and used directly, 100 % of district heat could be substituted with ammonia condensate alone, and one would still have 2.5

GWh of excess heat. The reality is however a little different, as all the heat can never be recovered due to losses, but also the consumption does not match production perfectly, which sets limits for recoverable energy. In other words, temporality and the different consumption profiles of district heat and waste heat become a challenge. For instance, comparing **Figure 23** and **Figure 29**, shows that district heat and steam have quite different consumption profiles especially in the evening and at night. This is challenging for example in the case of the Alkar-oven, as it uses only steam. To overcome the problems in temporality and to use waste heat effectively, one needs to have a thermal storage.

As there is no active metering for Alkar exhaust heat or any other consumption data apart from the 2017 energy audit data, nor is there time to conduct actual field measurements in this study, the 2017 energy audit data, measurements and conclusions are used for estimating the amount of recoverable Alkar waste heat. According to the audit, there are six Alkar exhaust channels in total, from which the first four could be used for heat waste recovery as they convey hot steam in atmospheric pressure, which is good for energy recovery as heat can be recovered effectively via condensation (ÅF 2017a). The mean temperature for the first four channels was measured to be 62 ˚C in the audit, which implies significant heating power, but also simple heat recovery, as the heat could be recovered using just a heat exchanger rather than a heat pump. According to the audit, if the temperatures of the four streams dropped to 0 ˚C, the heating power in total would be about 3 MW, which is significant, yet not very realistic. Thus, in the audit a more realistic temperature drop from 62 ˚C to 30 ˚C is also considered. The total heating power with this assumption is 2.4 MW, which is still significant. Although more realistic, it is still impossible to capture all the heat due to losses. Thus, it is concluded, that the heating power which can be harvested realistically with for example heat exchanger directly to water is about 1 MW. With the use hours of 4000, this equals 4 GWh of energy in a year, which is equal to 28 % of the district heat consumption in 2017. (ÅF 2017a)

Figure 25: Ammonia cooling compressor exhaust heat condensers on top of the technical center (number 7 in figure 21)

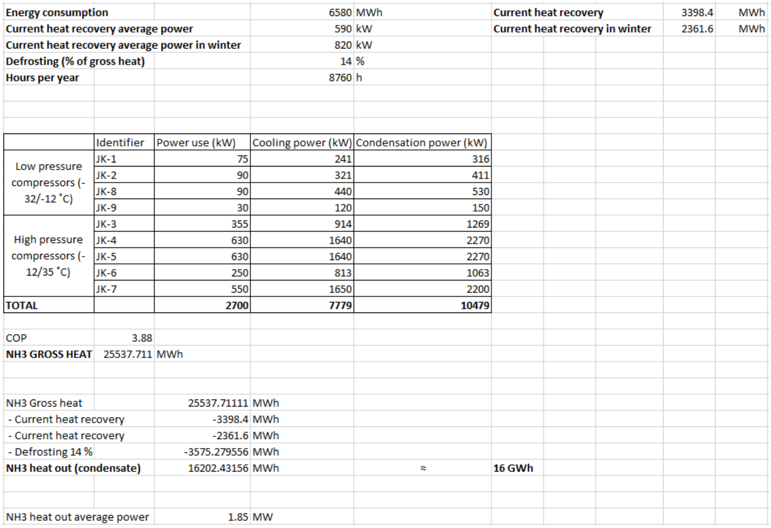
Figure 25 shows the ammonia cooling compressor exhaust heat condensers which are used to remove the 17 GWh of *"NH3 heat out"* in **Figure 20**. As with the Alkar-oven, giving exact figures for the possible heat recovery is difficult, as there is currently no metering or data, which would directly tell the hourly amount of heat that is released outside, according to a site visit and discussion with two technicians. The power use of the ammonia cooling compressors is monitored, and it could be used to calculate the amount of excess heat each hour directly, but unfortunately this data is saved for only two weeks. Thus, if one wanted to calculate the exact amount of recoverable energy with the current set up, one had to monitor the power consumption in two-week periods for months in order to capture also the effect of seasonal variation. To sum up, it is impossible to calculate the exact amount of recoverable energy with the time and resources allocated to this study. As a result, the same method, which was used in the 2017 energy audit is used to estimate the amount of gross heat and the resulting waste heat. But before going into detail of this method, it is important to understand how the gross heat is distributed in the technical center.

Currently, the *"NH3 Gross heat"* (25 GWh) in **Figure 20** consists of four sub-streams which are not evident from the picture. First, as the compressors include motors and thus require constant cooling whenever running, about 14 % of the gross heat consists of motor oil cooling according to the audit. This heat could be recovered by the existing heat recovery system, but at the time of the audit, and currently, the valve which would enable this is shut and the heat is transferred to the outside air by fan radiators at the roof. This waste of heat is quite significant, as 14 % of the NH-3 gross heat is 3.5 GWh annually, which equals almost 25 % of the district heat use in 2017. Yet, during the site visit when the technicians were asked why the center was operated this way, it was revealed that opening the valve results in a pressure rise in the current heat recovery circulation system which causes the circulating liquid to move to another circuit and leak through a safety valve in the factory. According to one of the technicians, this could be avoided by installing more heat exchangers to the main heat recovery circuit line.

The second stream, also visible from the Sankey, is the current heat recovery system which uses hot gas from high pressure compressors as a heat source. The heat is captured with a plate heat exchanger which uses ammonia and water/glycol mixture as heat media. The heat is used for water heating, but also to warm up HVAC radiators and to defrost glycol-water operated cooling radiators. According to a technical center technician, it could be possible to save great deal of energy by moving to temperature-based cooling in radiator defrosting. In other words, the radiators should be defrosted only when there is need for it. Currently the defrosting is time-based, which means that radiators are defrosted at pre-set intervals. This often results in unnecessary defrosting as in many cases there is no need for it. In practice, moving to temperature-based cooling would mean installing thermostats but the challenge where to install the thermostats and sensors, as the frost is not evenly distributed in the radiator.

The third stream is defrosting of ammonia vaporizers, which uses hot air from the cooling compressors as a heat source. According to the energy audit, the amount of energy consumed in this is relatively small. There are only 9 radiators, 3 chilling cabinets and one refrigeration spiral which need to be defrosted. The defrosting in these is also time based, and energy could be saved by installing thermostats as explained above.

The last stream is the compressor waste heat, or in other words condensate, which has a temperature of 30 ˚C on average. As there is no direct hourly data of the gross heat or the waste heat, only rough approximations can be presented as the compressor data is saved for only two weeks as explained before. In the 2017 energy audit, the amount of gross heat is estimated by approximating the average power and energy use for high pressure compressors, which is used to calculate a COP for the cooling compressors. The COP is calculated using the name plate values of the cooling compressors, shown in **Figure 26**, and it can be directly used to calculate the amount of gross as it is just a reversed heat pump i.e. a refrigerator. The amount of waste heat or condensate can be then calculated by subtracting the other three streams from the gross heat. As one can notice from the cooling compressor name plate values, condensation power is just a sum of power use and cooling power.



Energy consumption	6580	MWh	**Current heat recovery**	3398.4	MWh
Current heat recovery average power	590	kW	**Current heat recovery in winter**	2361.6	MWh
Current heat recovery average power in winter	820	kW			
Defrosting (% of gross heat)	14	%			
Hours per year	8760	h			

	Identifier	Power use (kW)	Cooling power (kW)	Condensation power (kW)
Low pressure compressors (-32/-12 ˚C)	JK-1	75	241	316
	JK-2	90	321	411
	JK-8	90	440	530
	JK-9	30	120	150
High pressure compressors (-12/35 ˚C)	JK-3	355	914	1269
	JK-4	630	1640	2270
	JK-5	630	1640	2270
	JK-6	250	813	1063
	JK-7	550	1650	2200
TOTAL		**2700**	**7779**	**10479**

COP	3.88			
NH3 GROSS HEAT	25537.711	MWh		

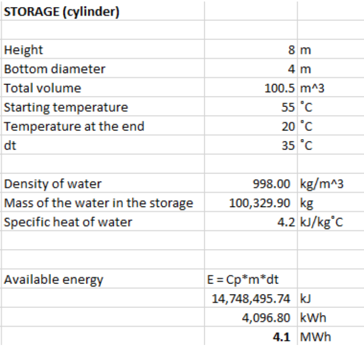
NH3 Gross heat	25537.71111	MWh		
- Current heat recovery	-3398.4	MWh		
- Current heat recovery	-2361.6	MWh		
- Defrosting 14 %	-3575.279556	MWh		
NH3 heat out (condensate)	16202.43156	MWh	≈	**16 GWh**
NH3 heat out average power	1.85	MW		

Figure 26: Estimating ammonia cooling compressor gross & waste heat

Figure 26 shows an estimation for the waste heat. Like in the case of cooling compressor power use, there is no historical data about the amount of the current heat recovery apart from data that is saved for two weeks. According to an engineer from an external company who was part of a recent control system overhauling project for the technical center, it is possible to install a mass flow/volume flow sensor and get the heat recovery data in MWh directly, but it has not yet been done. Thus, the amount of recovered heat can only be estimated with temporary two week's pressure and temperature change values, as they give the power of the heat recovery system. With power data, the amount of energy can be calculated by multiplying it with the time of the recovery system operated in the observation period. As the system has remained practically unchanged from 2017, and the effect of seasonal variation is anyway impossible to capture, the audit's estimations for the average power of the current heat recovery are used in the calculation in **Figure 26**. According to the audit, the summertime average power was calculated from two weeks data from site visit, while the winter power was estimated from the temperature and pressure values approximated and given by the technicians.

In this study's calculation in **Figure 26**, it was assumed that the winter heat recovery power is the average power for the current heat recovery for four winter months. These four months have been selected based on **Figure 24**, where it can be seen, that the amount of district heat noticeably higher in December, January, February and March. The amount of energy was then calculated by multiplying the power with the hours in these months. The same applies for *"current heat recovery"*, where it was assumed that the remaining eight months are summer months with the average power of 590 kW. When it comes to the gross heat, it was derived by calculating a COP for all the machines, i.e. the total condensation power was divided by total power use, and then multiplying the COP with high pressure compressor electricity use in a year. The value for the electricity use was acquired from the energy audit as no measurements of the electricity use could be found during the site visit. In the audit, the electricity consumption was estimated based on two week's compressor power use. Lastly, the amount of condensate was calculated by subtracting the other streams from gross heat. Average power was acquired by dividing the power with hours in a year. Unlike in **Figure 20**, the resulting amount of condensate is 16 GWh rather than 17 GWh. This partly explained by the fact, that 10 % is for defrosting in the audit's calculation instead of 14 % as suggested earlier. Why 10 % is used in the audit's calculations instead of 14 %, which is presented also in the audit, remains unclear.

In order to estimate the total cost and payback of the centralized thermal storage system, it is necessary to address the size of the required storage first. Based on the energy, audit as well as a discussion with a heat pump supplier, it is assumed that 1.174 MW of energy can be harvested from cooling compressor condensate with an ammonia heat pump during weekdays, and 0.5 MW during weekends. Without taking a stance on the temporal dimension of the system, the total peak power of the centralized waste heat recovery system is arguably 2.174 MW. This implies, that the heating power of the storage should be at least about 3.6 MW, as the peak consumption of district heat is assumed to be 5.7 MW. When temporality is considered, even larger storage might be required. A simple calculation in **Figure 27** shows, that for example a cylinder shaped water storage with total volume of 100 m^3 is sufficient to provide 4 MW of power over one hour, if the temperature of the water is assumed to decrease from 55 ˚C to 20 ˚C and all the energy can be transferred without losses. 55 ˚C has been selected as the temperature of the storage, as it is the same temperature as the temperature in the heating circuit of the plant. According to a discussion with a utility manager at the site, 100 m^3 storage would cost roughly 150,000 €.



STORAGE (cylinder)		
Height	8	m
Bottom diameter	4	m
Total volume	100.5	m^3
Starting temperature	55	˚C
Temperature at the end	20	˚C
dt	35	˚C
Density of water	998.00	kg/m^3
Mass of the water in the storage	100,329.90	kg
Specific heat of water	4.2	kJ/kg˚C
Available energy	E = Cp*m*dt	
	14,748,495.74	kJ
	4,096.80	kWh
	4.1	MWh

Figure 27: Thermal storage calculation using equation 7

Giving exact numbers for the size of the storage is impossible as the hourly data is missing. Yet, temporality has been tried to address in the 2017 energy audit with approximated average values. **Figure 28** shows the hourly heat consumption as well as the heat production by the centralized waste heat thermal storage system. In the audit, it is not explicitly stated, that what exactly the production in the figure is. As the total power of the centralized heat recovery system is 2 MW as suggested in the audit, it is unclear how exactly the available heat is constantly over 1.5 MW in the figure especially in the weekends, when there is usually no heat from the Alkar-oven as there is no production. Most likely, the blue line in the figure is the amount of available gross waste heat, not the actual heat harvested by the centralized system. Nevertheless, it is important to notice, that during weekends the waste heat from the compressors alone is most likely sufficient to cover the whole heat consumption for the whole weekend.

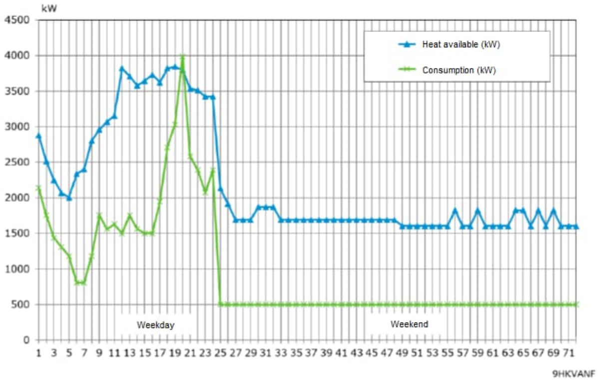


Figure 28: Hourly average heat consumption & heat produced by the centralized thermal storage waste heat system according to the audit (ÅF 2017a)

To sum up the costs and the savings of the centralized waste heat storage system, it is assumed that with a correctly sized system, the use of district heat can be substituted completely. In a year, with a power of 1.174 MW during weekdays and 0.5 MW during weekends, the ammonia heat pump would produce about 8600 MWh of energy, as the cooling is running constantly. Similarly, the Alkar-oven with a power of 1 MW would produce 4000 MWh with 4000 use hours in a year. In total, this equals about 12.6 GWh in a year, which is just enough to cover the district heat use in 2020, which was roughly 12.3 GWh according to **Table 4**. In a year, this would save about 580,000 € in district heating costs based on 2020 realized costs. Yet, the heat pump also uses electricity, which generates running costs. According to data provided by heat pump supplier, a sufficiently sized ammonia heat pump with heating power of 1174 kW has a COP of 6.42. Consequently, using the COP the pump would consume ca. 183 kW of power, which equals about 1600 MWh of energy in a year with 8760 use hours. With 2020 realized average electricity price of 61.2 €/MWh, the electricity would cost roughly 100,000 €. To conclude, the net saving of the system would be around 480,000 €/year.

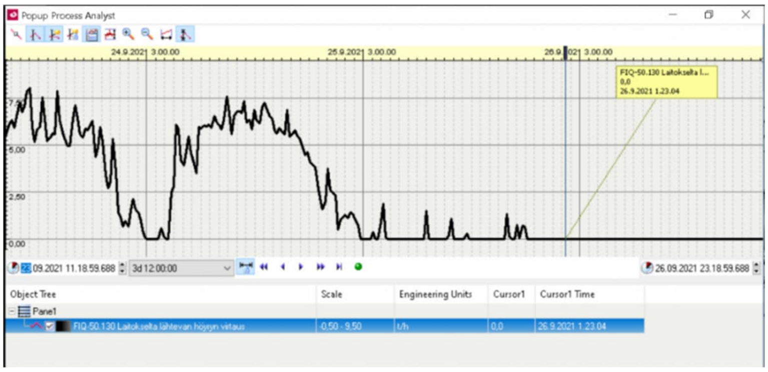
In order to calculate a payback for the whole system, it is assumed that the storage costs 150,000 €. According to the heat pump provider, the heat pump would cost around 230,000 € with hauling, installation, testing, piping, documentation, inspection and other costs included. Yet, it is important to notice, that this approximation does not include any detailed information about the site, apart from the information of the required heating power, and thus the real price can be different. When it comes to the Alkar-oven heat recovery, the heat pump supplier told that their company does not have the required technology for such heat recovery, as it would require some sort of a duct radiator and/or heat exchanger due to the fact, that the heat is transferred from steam to water, i.e. from gas to liquid. After sending an inquiry to six other possible suppliers, two told that they do not have the required technology. However, the other told that they will forward the inquiry to another company, who could have the required technology. Three of the remaining four did not reply anything during the time of the study while the last one told that they will investigate it. Consequently, it was difficult to provide even a rough estimate for the real price of Alkar-oven heat recovery. Thus, it was assumed, that it cost as much as installing the ammonia heat pump, which is arguably more expensive. With this assumption, the total cost is 610,000 €. With net saving of 480,000 €/year, the simple payback is about 1.5 years.

4.1.2 Eliminating the emissions from steam generation: three alternatives

19.09.2021 23.18.59.688 | 3d 12:00:00 | 23.09.2021 11.18.59.688

Object Tree	Scale	Engineering Units	Cursor1	Cursor1 Time
Pane1				
FIQ-50.130 Laitokselta lähtevan höyryn virtaus	-0,50 - 9,50	t/h	8,1	22.9.2021 13.23.04

Figure 29: Hourly steam consumption from Tuesday 21.9.2021 to Wednesday 23.9.2021



23.09.2021 11.18.59.688 | 3d 12:00:00 | 26.09.2021 23.18.59.688

Object Tree	Scale	Engineering Units	Cursor1	Cursor1 Time
Pane1				
FIQ-50.130 Laitokselta lähtevan höyryn virtaus	-0,50 - 9,50	t/h	0,0	26.9.2021 1.23.04

Figure 30: Hourly steam consumption from Thursday 24.9.2021 to Sunday 26.9.2021

Figure 29 and **Figure 30** show the hourly steam consumption profiles in tons per hour from a regular manufacturing week in late September 2021. As seen, steam generation is ramped up relatively fast each weekday during one hour around three o'clock in the morning to a level, which is close to the peak consumption levels of the steam. This implies, that the technology required to generate the steam must be flexible with a response time of one hour. After the ramp up, the steam consumption varies, but stays, in a relatively high level until it starts to decline towards zero over several hours around 18 o'clock. From midnight to about two o'clock in the morning, there is no consumption. In the weekend on Saturday, there are scattered hours when steam is consumed. On Sunday there is no consumption since the factory is closed. In order to calculate the average power of the district steam, it is estimated based on these figures, that a typical weekday has 22 hours of steam consumption, Saturday eight hours and Sunday zero. This yields a total of 118 hours per week, 6200 hours per year and circa 17 hours per day on average.

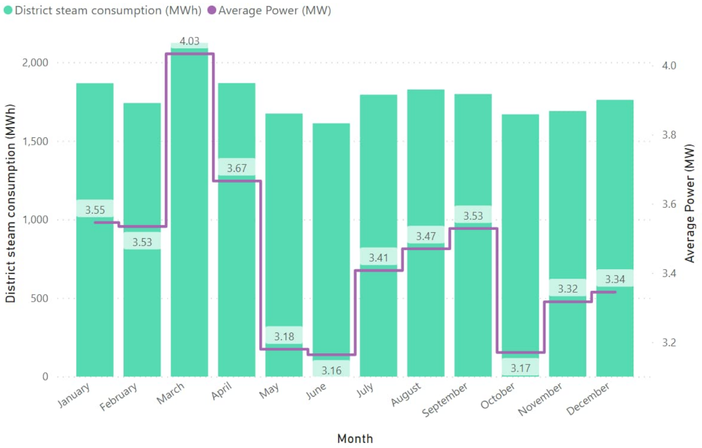


Figure 31: 2020 district steam consumption & average monthly steam power in Vantaa

Figure 31 shows the actual monthly district steam consumption from 2020 as well as the estimated average monthly steam power in Vantaa. The average power has been calculated by dividing the monthly consumption in MWh with average use hours in a day multiplied with days in each month. What is particularly interesting about figure, is that there is no visible seasonal variation there is in the case of district heat. Indeed, the monthly consumption does not change nearly as much as in the case of district heat in **Figure 24**, for it stays all the time close to 1,750 MWh. The lack of seasonal variation's effect is explained by the district steam's dependency of the process. As seen from **Figure 20**, all the steam energy is consumed in the manufacturing processes. The processes do not correlate as much with weather as for instance air conditioning or heating, rather they determined solely by production needs, which are much more correlated to for example sales and markets than weather. Based on the figure, the average power is around 3.5 MW, which also does not change as much as in the case of district heat. Again, this gives some estimation of the average power for the carbon free system, but when deciding between alternatives for carbon free steam generation it must be remembered peak consumption is what determines the size of the system.

The easiest solution for green steam generation in terms of actual implementation of the project and technical feasibility is to simply replace the natural gas with green biogas. As the steam plant is connected to the gas network, biogas could be directly bought and supplied from it, since biogas is traded and transmitted using the same gas grid as natural gas in Finland. Switching to biogas would be just a matter of negotiation and reconciliation with Vantaan Energia, which is the energy utility, that owns the steam plant located in the site. In addition to easy access to supply, expensive investments would be avoided completely, since it is possible to burn and use the biogas directly using the current equipment. This has been confirmed by both utility experts as well as by the current gas supplier. Moreover, the capacity and fast ramp-up would not be a problem using biogas, because the system would remain in its current technological state.

Since switching from one fuel to another is not an investment but more of a change in operational costs, calculating payback for such project is impossible. Nonetheless, in order to give some cost estimate of switching to biogas, 2020 realized monthly average natural gas prices and district steam prices are compared to estimated biogas prices. The data is provided by the company, i.e. the prices per MWh are indeed the prices the company has paid on average in 2020. Another reason why 2020 data is used is, that natural gas and biogas prices are formed in a spot market, thus giving future price estimates is highly difficult even for the gas suppliers. Yet, it is quite certain that biogas will be remain more expensive than natural gas at least in the near future, due to its lower supply and growing interest compared to natural gas. Historically, biogas has always been more expensive.

According to a discussion with the current gas supplier, the price of biogas is determined by the price of natural gas i.e. the price is bound to the price of natural gas, and the buyer pays a premium when choosing biogas. Exploring further in their website, it is revealed that the price of gas is bound either directly to the European gas spot markets forwards or to their own index called the “SK-Index” (Suomen Kaasuenergia 2021). The SK-Index prices are further bound to three-month forwards, which are traded in a German spot market called the Gaspool. Three months forwards are used instead of for example one-month forwards in order to keep the price more stable. All in all, the pricing of the gas is supervised by the Finnish Energy Authority. (Suomen Kaasuenergia 2021)

Apparently, the price index is not public data as it cannot be found from their website. Furthermore, no other historical price data can be found from the supplier’s website. Referring to the discussion with the supplier earlier, they also told that they are unable to provide data historical data at this point. Yet, the gas supplier told, that the premium for biogas has been about 12 €/MWh on average in the last months. As a result, the historical price of biogas is estimated by adding the premium to the monthly natural gas prices provided by the company. It could be in theory possible to get the historical price data from gas spot markets such as Gaspool, but because for example the taxation of buying gas from spot markets is unclear and the premium of the biogas seller is unclear, it is simply more accurate to add the estimated premium to the existing price data, as they arguably contain the information of these costs.

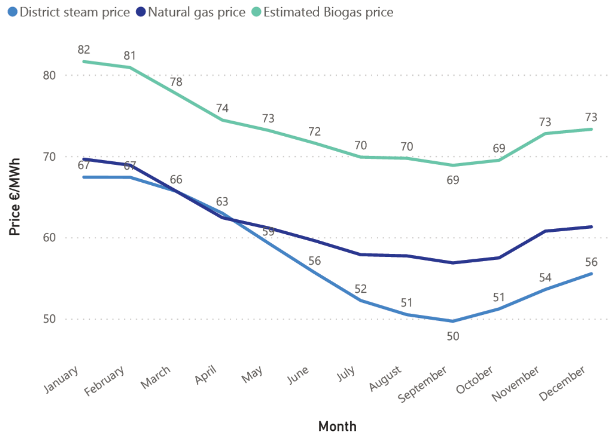


Figure 32: 2020 realized natural gas and district steam prices & estimated biogas price

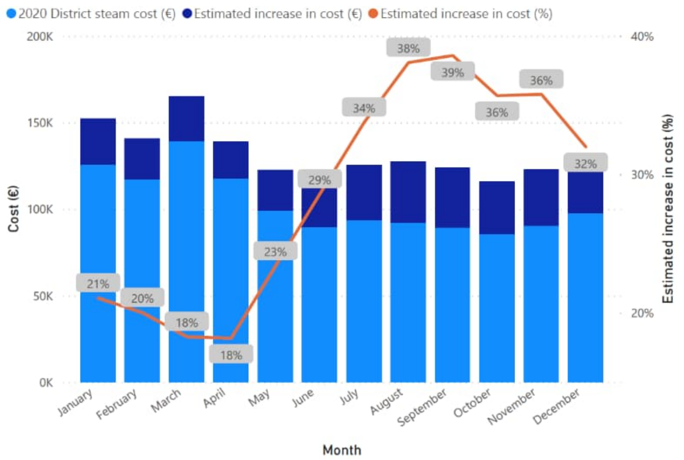


Figure 33: 2020 realized monthly district steam costs and estimated increase in district steam costs when the steam is produced with biogas

Figure 32 shows the realized natural gas and district steam prices in €/MWh as well as the estimated biogas price with the 12 €/MWh premium. Interestingly, most of the time the average district steam price is lower than the price of natural gas although the steam is produced with natural gas. This could be explained for example by the fact, that Vantaan Energia as an energy company has a taxation advantage compared to company in this study, or they are able to buy gas cheaper from wholesale markets. **Figure 33** shows 2020 realized district steam costs as well as the estimated extra cost, if the steam was produced using biogas. In a year, the district steam costs would increase on average by 29 % if the steam was produced with biogas, which equals about 350,000 € in a year. Although the increase is significant, there are important factors which can lower the price of biogas in the future, and thus also the possible expenses.

According to the discussion with the current gas supplier, they are highly confident, that the price of biogas will drop due changes in the Finnish Energy Legislation. Investigating further, it has been presented by the Finnish Government, that new laws would promulgate EU directive RED II, which would guarantee certificates of origin to all renewable gas suppliers, including gas bought from international markets as well as gas that is supplied outside the gas grid (Suni 2020)(Finnish Goverment 2020). The new laws should come into force in 1.1.2022 according to the Finnish Energy Authority (Suni 2020). This would affect the price of biogas significantly, as the supply of biogas arguably surged. Another factor that would affect the price substantially are the changes in taxation as currently, only certificates of origin issued by Gasgrid Finland Oy, the gas network operator in Finland, are valid to recognize biogas consumption in taxation (Finnish Goverment 2020). The taxation of biogas is an important aspect, as it has greater effect on the price of the biogas than the cost of the certificate of origin or administrative costs related to the certificate (Suomen Kaasuyhdistys 2021).

In addition to the legislative changes discussed above, the gas supplier told that biogas projects have received a lot of support from the government and at least one large biogas plant is being built in Finland. This could also lower the price of biogas as supply increased, but the effect is obviously impossible to quantify. All in all, the gas supplier estimates, that the future biogas prices could drop to the levels of natural gas prices. Although optimistic, it is not completely impossible as the demand of natural gas can also increase, or its supply decrease, and emissions trading can make it more expensive. If the biogas prices dropped to for instance the price of realized monthly natural gas price levels in 2020, as the supplier suggests, the yearly steam costs would increase by 100 k€ or by ca. 7 %.

When it comes to the downsides of biogas, the largest disadvantage is uncertain supply and bad energy security. Although the origin of the biogas can be verified, there is not guarantee that there will be enough of it for everyone. This implies, that during times of low supply, energy costs could increase immensely as the spot market prices surged due to high demand. During these times, one could still of course buy natural gas in order to keep the production running, but virtually it is not an option due to the zero-carbon goal. One option would be to store liquefied biogas (LBG) for times of low supply, but the question then is, that how much can be stored, how long it can be stored and is there some supplier that is ready to supply it. As biogas is mainly methane, and methane has a boiling point of – 161.5 °C in atmospheric pressure, the liquefied biogas must be stored in a very well cooled and highly insulated tank (Swedish Gas Technology Centre Ltd 2012). When it comes to the supply of LBG, according to YLE, the national public broadcasting company of

Finland, Finland's first LBG plant was opened just about a year ago in 2020, which implies that the domestic supply of LBG in Finland is not yet very well developed (YLE 2020).

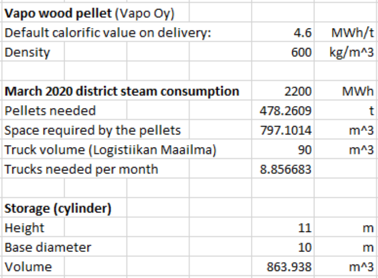
The second option for green steam generation would be solid biofuel combustion i.e. wood pellets or briquets. Wood and especially pellets would be a natural choice for the site, due their abundance in Finland and the fact, that the technology is already relatively widely commercialized. Moreover, compared to other commonly used wood-based biofuels, pellets have higher calorific value, which means that they require less storage space. Compared to for instance forest residue chips, which are an abundant side product of forest industry in Finland, the default calorific value for pellets and briquettes is 17 GJ/ton while for wood chips it is 10 GJ/ton (OSF 2021a). This means, that storing for example one ton of pellets requires 70 % less space than a ton of wood chips.

Comparing solid biofuels to switching from natural gas to biogas in the current steam plant, the main advantage is improved energy security and lower fuel costs. Yet, when it comes to the energy security and fuel supply, it is more or less complicated than it the case of biogas, depending on which perspective it is examined at. The delivery of the fuel is certainly more complicated, as the only way to supply the fuel is to haul it with trucks, wherein the case of biogas the supply is handled simply by the existing gas grid. This raises questions of the transportation costs as well as the CO_2 effect of the transportation. The supply of pellets can be located quite far from the site, which means that hauling costs as well as emissions can be significant especially because of the fact, that several trucks per month are needed. The less complicated part of the supply is the better supply of the fuel itself and more stable price. Demonstrated further, the historical data shows that the price of pellets has been almost constant in the last six years, which implies stable and good supply as otherwise the prices be more volatile.

The disadvantages compared to biogas are more complicated implementation, the possible need for environmental permits and large initial investments. As said, switching to biogas would require no investments if the LBG storage is considered as an optional investment. Yet, although presumably large, it is possible that the required investments can acquire a relatively good payback as demonstrated further. The first that would be needed would be a pellet boiler. This implies installation costs as well as costs, that arise from adapting the system to the existing system. Second, a pellet storage would be needed, as there is no other constant supply of fuel like there is in the case of biogas. This is probably the more expensive part of the project, as the storage is arguably quite large and heavy, and thus requires quite extensive foundation works. Third, a fuel supply system is required. This could be for example a conveyor belt system such as the ones used in mechanical grate fired boilers.

In order to give some evaluation of the size of the storage, it is assumed that the storage would contain enough pellets to run the plant for one month. Although it is important to have a large storage from energy security perspective, this results in a tradeoff, as the size of the storage naturally increases in proportion to the time to which the plant prepares for. For a reference, it is assumed that the storage is sized according to the month with most consumption which is, based on the 2020 consumption data, March when the of consumption of district steam was 2,124 MWh or about 2,200 MWh. In the analysis, the storage is assumed to be a large silo as in **Figure 34,** which shows a pellet silo from Helen's power plant in Salmisaari, Helsinki.

Figure 34: 1000 m^3 pellet silo in Salmisaari power plant, Helsinki (Helen 2016)



Vapo wood pellet (Vapo Oy)		
Default calorific value on delivery:	4.6	MWh/t
Density	600	kg/m^3
March 2020 district steam consumption	2200	MWh
Pellets needed	478.2609	t
Space required by the pellets	797.1014	m^3
Truck volume (Logistiikan Maailma)	90	m^3
Trucks needed per month	8.856683	
Storage (cylinder)		
Height	11	m
Base diameter	10	m
Volume	863.938	m^3

Figure 35: Excel calculation for estimating the size of the storage (Vapo Oy 2019)(Logistiikan Maailma 2021)

Figure 35 shows a simple Excel calculation of an estimation of the pellet storage size as well as the approximation of the needed amount of standard sized trucks to transport the pellets, if it was assumed that each of them would be filled completely with pellets. As can be seen, for example a silo with a height of 11 meters and a diameter of 10 meters would be sufficient to store

2,200 MWh worth of pellets. Such silo could be placed for example between the pallet storage (9) and crate storage (1) close to the current steam plant (8) as illustrated by **Figure 19**. Yet, it is the profitability of the investment that determines whether the project is carried out. As the pellets alone would weigh around 500 tons, substantial foundation works would be required for the silo in addition to the cost of the silo itself. When the possible contamination of the pellets caused by humidity is considered, it is possible that even larger storage and more transportation would be required to store 2,200 MWh of pellets as the calorific value decreased.

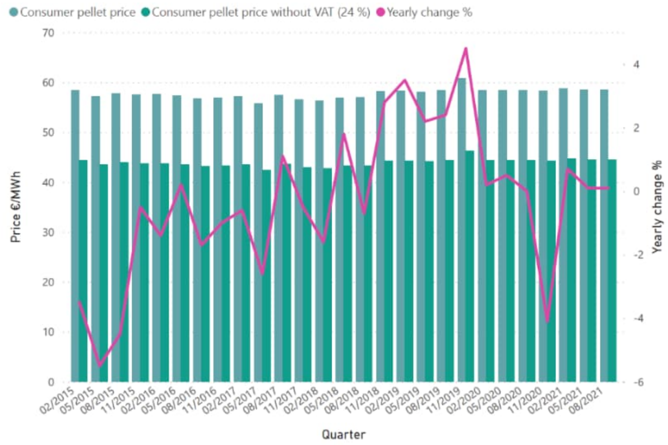


Figure 36: Pellet consumer price per quarter 2015 – 2021 according to Statistics Finland Producer Price Index 2021 with and without value added tax including yearly change in the index (OSF 2021b)

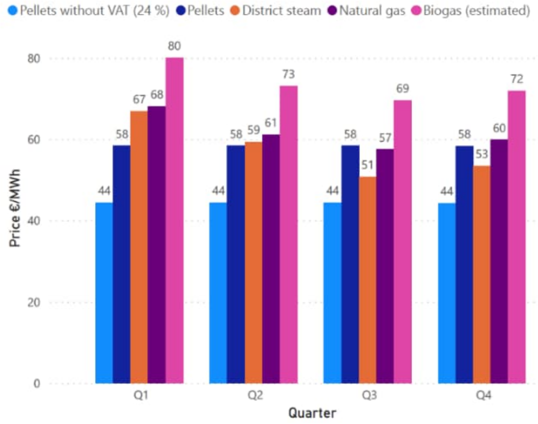


Figure 37: 2020 quaterly average prices for different fuels

To further analyze the profitability of such project, historical pellet prices are considered as well as the difference to other fuels such as biogas. Since the company does not use pellets at any of the sites in Finland, there is no historical price data from the company. For this reason, Statistics Finland’s Producer Index is used for assessing historical pellet prices. **Figure 36** shows historical pellet consumer price, i.e. the price including all costs and taxes (OSF 2021c) and historical pellet consumer price without value added tax (VAT) assuming, that the company would not pay VAT for the pellets, since companies do not pay VAT for their purchases. **Figure 37** shows the difference of the pellet price with and without VAT compared to realized district steam and natural gas prices as well as to the estimated biogas price, where 12 €/MWh premium is added to the natural gas prices as explained before. Due to the fact, that pellet prices are reported only as a quarterly average by Statistics Finland, 2020 district steam, natural gas and estimated biogas prices have been calculated as quarterly averages in order to enable analysis.

Compared to other fuels, the price of pellets is substantially more stable, almost constant. The price of pellets without VAT is noticeably lower than the price of other fuels, which encourages to adopt the fuel even without the zero-carbon project, as it would decrease energy costs. Consequently, there is also a payback for the pellet project. However, it must be emphasized that these pellet prices are only approximations, as hauling and other costs for adopting the fuel are unknown, and there is no historical data from the company. Yet, the pellet consumer prices arguably contain some hauling costs, as the pellets must be transported either to a store or to the customer's home. What the costs would be in terms of the company's volume remains unclear.

If it was assumed, that the pellet price without VAT would be a realistic forecast of the pellet price for the company, the district steam costs would decrease by almost 300,000 €/year or by 23 %, which implies a favorable payback even for a larger investment. If the pellet price was the consumer price, the district steam costs would increase by about 13,000 €/year or by 1 %, and there would be no payback, at least not in the sense that it could be calculated using energy savings. Compared to the estimated biogas price with the 12 €/MWh premium (350 k€ / 29 %), as well as to the gas suppliers forecast (100 k€ increase / 7 %) that the gas prices would drop to the levels of natural gas, pellets are still in all cases less expensive. Yet switching to pellets requires vast investments whereas switching to biogas arguably does not.

Estimating the investment cost of pellet heating and calculating payback is quite difficult due to the complexity of such system, but it is safe to say that the initial investment is in the order of millions and payback in the order of several years, as demonstrated in a moment. The peak power of the current steam system is unknown, but as the peak power of the two steam boilers in Kristianstad is 6.4 MW, and Kristianstad is about the same size as Vantaa, it can be assumed that it is around 6 MW. Consequently, the power of the pellet plant should be about 6 MW. Using this assumption, a suitable plant is selected for reference from data provided by a Finnish pellet plant producer.

Figure 38 shows a 6 + 5 MW district heating pellet plant in Karjaa, Finland with a 1,200 m^3 storage. **Figure 39** shows the 6 MW boiler inside. **Figure 40** shows an illustrative cross-sectional diagram of the plant and lastly, **Figure 41** an illustative 3D-model. Based on these pictures and looking the city plan in **Figure 19**, it is quite clear, that the plant is considerably large in terms of the available space at the plant. As the boiler itself is so large, most likely it would not fit in the current steam plant, and a completely new plant would have to be built. Even if it did fit, a storage would still need to be built as well as a fuel handling system. And before all this, it had to be approved by the current steam provider, which not something taken for granted. All in all, even though the supplier did not give any cost data for their plants, it can be concluded that the plant arguably costs several millions, as the required buildings already cost several hundreds of thousands of euros.

Figure 38: 6 + 5 MW district heating plant in Karjaa, Finland with 1200 m^3 storage. Photo by courtesy of Laatukattila Oy.

Figure 39: 6 MW pellet heating boiler. Photo by courtesy of Laatukattila Oy.

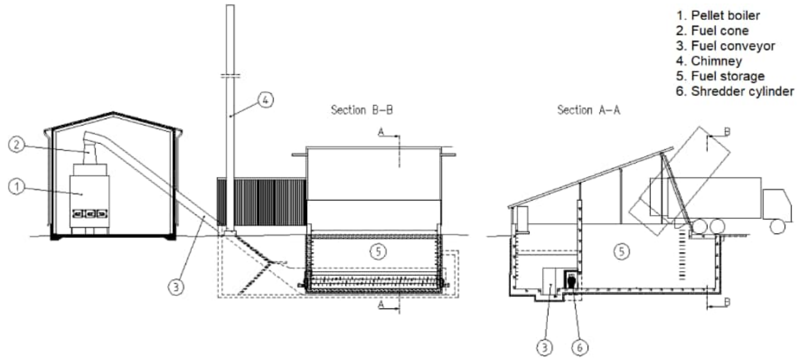


Figure 40: Illustrative cross sectional diagram of a 0.5 – 10 MW pellet plant. Photo by courtesy Laatukattila Oy.

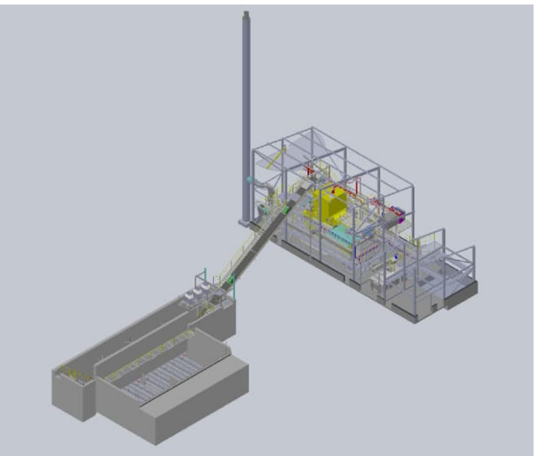


Figure 41: 3D-model of a pellet plant. Photo by courtesy of Laatukattila Oy.

Another option for cutting the emissions would be to electrify the steam generation i.e. produce the steam electrically with an electrode boiler. A regular electric steam boiler would not suffice for large scale steam production, due to its low capacity and slow ramp-up, i.e. the ability to produce power or energy fast. With an electrode boiler, the capacity is not a problem and full capacity steam generation can be reached even in under five minutes (Parat 2021). However, a transition to electric steam generation has numerous factors, make the investment extremely expensive.

According to a discussion with a former electric and electrode boiler retailer, the boiler, which costs about 500,000 € according to a supplier, is just one part of the expensive investment and costs. First, the boiler would require its own transformer and the transformer its own foundations, as it would weight tens of tons. As power of the boiler would need to be around 6 MW, the transformer alone would cost at least 150 k€ according to the expert, which told that 25 k€/MW is somewhat reasonable estimate for the price of a transformer. Second, the steam system would most likely require a pressure equalization tank in order to effectively work using the boiler. Third, the maintenance costs are potentially very high, as the electrodes themselves cost "*a fortune*". Furthermore, replacing them is costly and can cause downtime, as the whole steam generation must be halted, since electrodes can't be replaced without accessing the insides of the boiler.

Another factor that raises the costs to millions, is the grid connection. Currently, the total peak load for the existing connection is 6.5 MW, however, capacity has been bought for 9 MW. Maximum capacity for a 20-kV connection is 10 MW, according to an inquiry to the grid operator. Thus, if such boiler was used, it would require a new connection to the 110-kV grid as the new total peak load would exceed 10 MW. According to the grid operator, the connection would cost around one million euros as the company had to cover all the expenses which include, to name the largest, a new switching station, a 110/20 kV transformer and underground cabling. Moreover, the large power need of the boiler and its fast ramp up means challenges to grid balancing, which can further increase transmission costs. In total, the investment cost would be at least about two million euros. A reasonable payback is impossible to achieve, as the realized average electricity prices are already today higher than the current district steam costs i.e. switching to electricity would not lower the energy costs and yield savings. To sum up, it is not worthwhile to explore the possibility of electric steam generation further in Vantaa's setting, as the first two options are easier to implement and arguably better in terms of costs.

4.1.3 Replacing natural gas in direct gas consumption

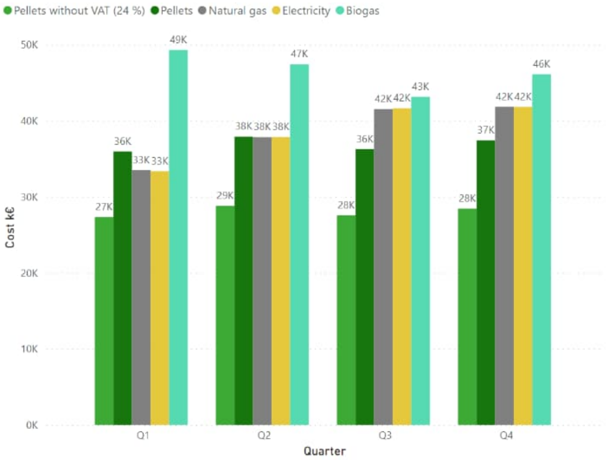


Figure 42: Comparison of 2020 quaterly fuel costs in thermo-oil heating

As discussed earlier, the plant has direct natural gas consumption in addition to the steam plant's connection. This gas is used mainly for the heating of thermo-oil, and its consumption is just a fraction of the gas consumption in steam generation as demonstrated by **Figure 20**. **Figure 42** shows the quarterly average costs, if thermo-oil heating was performed with natural gas (status quo), pellets, pellets without VAT, electricity or biogas. Figures has been calculated as quarterly averages as before in order to enable comparison with pellets, and 12 €/MWh premium has been added to natural gas prices to simulate biogas prices. The reason why electricity is included here is, that it is in this case it could be a viable option. Compared to district steam, electric heating in the case of thermo-oil does not require an electrode boiler or a connection to the 110-kV grid due to low power need and lower ramp-up need. According to the data from the site, the thermo-oil boiler power is "*only*" 2.5 MW.

As in the case of district steam, switching to biogas in thermo-oil heating is the easiest solution, as it can be implemented with the current equipment without investments. Yet, it is also the most expensive option based on the estimated fuel costs as demonstrated by **Figure 42**. With estimated 2020 biogas prices, the yearly heating costs would increase by about 30,000 € or 20 %. Yet, it must be again emphasized that the prices can change considerably in the future due legislative changes. If the gas suppliers forecast of the future supply proved to be accurate and the price of biogas would drop to the levels of natural gas, there would be no change in the heating costs if 2020 prices are used as a reference.

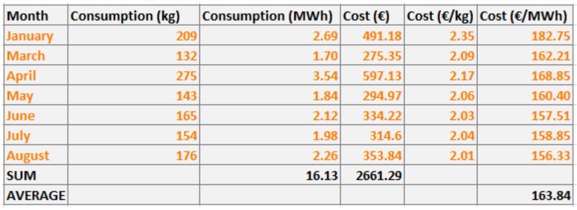
Interestingly, natural gas and electricity prices fall very close together. In fact, the difference in 2020 average natural gas and electricity price was only about 1 €/MWh; 61.62 €/MWh vs. 60.6 €/MWh. This is probably also the reason why electric heating has not yet been implemented as there is a relatively long payback for such investment. Based on the calculated quarterly averages, heating thermo-oil with electricity would save just little over 50 euros per year. With monthly realized prices rather than quarterly averages, the saving is little under 1000 euros. In other words, whatever the price of the required electric boiler investment was, the payback is practically non-existent, or at least very long, based on 2020 price data. Indeed, it is possible that there is no payback at all in the future, as there is so little margin for the prices to move. Due to for example the growing number of electric cars, electricity prices are unlikely to fall substantially in the future.

According to **Figure 42**, pellets are again the cheapest option based on fuel prices only. In a year, the fuel costs would drop either 7,200 € (- 5 %) or 43,000 € (-28 %) depending if VAT is included or not. Yet again these prices are only an estimate as the real price is unknown. When it comes to the investment, it is likely to be more expensive and more complicated than electric heating. Both require a new heating mechanism but unlike electricity, pellets also require a pellet storage as well as a fuel feeding system. If the investment was implemented together with district steam pellet investment, the investment would be more reasonable in the big picture and in terms of costs. If the pellet price without VAT is proved to be good approximation of future pellet prices, the investment could achieve a somewhat reasonable payback in the future in the best-case scenario.

4.1.4 Electric forklifts

Currently, liquefied petroleum gas (LPG) is used as a forklift fuel in Vantaa. The consumption is rather low, about 1.3 tons a year, but the emission is still relatively high as seen from **Table 4**. The data regarding LPG consumption is limited compared to other figures, since there is data from only seven months, and it is reported in euros and in terms of mass, not in €/MWh. In order to enable analysis, the data was converted to €/MWh. According to a thesis by Saara Lippo, the calorific value of LPG is 12.86 kWh/kg or 0.01286 MWh/kg (Lippo 2016). Using this value, the consumption is converted to €/MWh as depicted in **Table 6**.

Table 6: 2020 LPG consumption & costs



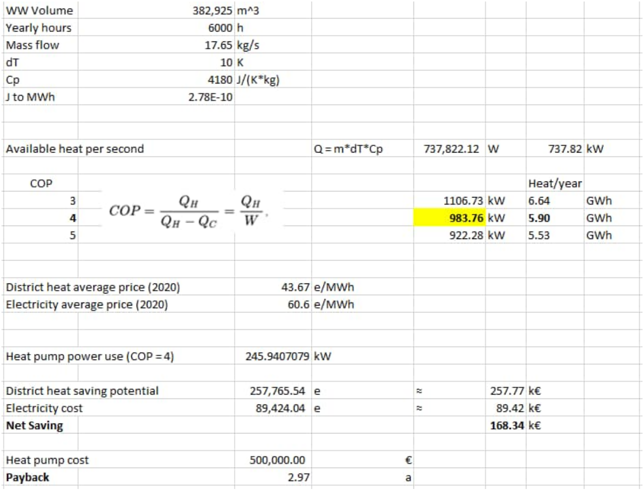
Month	Consumption (kg)	Consumption (MWh)	Cost (€)	Cost (€/kg)	Cost (€/MWh)
January	209	2.69	491.18	2.35	182.75
March	132	1.70	275.35	2.09	162.21
April	275	3.54	597.13	2.17	168.85
May	143	1.84	294.97	2.06	160.40
June	165	2.12	334.22	2.03	157.51
July	154	1.98	314.6	2.04	158.85
August	176	2.26	353.84	2.01	156.33
SUM		16.13	2661.29		
AVERAGE					163.84

The first thing that is distinctive about LPG is that the average price in €/MWh is extremely high compared to other fuels. However, as the consumption is low, the costs are only about 3,000 € per year. This implies, that although there is a lot of potential to save in costs per MWh, the absolute monetary effect of switching fuels is low and payback for possible investments is long.

Due to relatively easy implementation as well as lower fuel costs compared to estimated biogas prices, it is proposed here that the existing forklifts are either converted to operate on electricity or replaced with new electric forklifts. In the case of forklifts, biogas is not as good option, since it would require building an expensive service station to fuel the forklifts. As the energy consumption is so low, new grid connection is obviously not required and electric forklifts would avoid expensive auxiliary investments. Estimating with 2020 monthly electricity prices, about 1,700 € can be saved in a year by switching to electricity, which is ca. 64 % of the current LPG costs. Since for instance the number of forklifts and their technical requirements are unknown at this point, detailed payback calculations cannot be provided. Yet, the webpage of one arbitrarily selected retailer suggests, that the price without VAT for preowned electric forklifts varies from 10,000 € - 20,000 € (Trukki Timlin Oy 2021). Assuming, that charging the forklift batteries does not require further investments, the payback for one preowned forklift would range from six to twelve years. For a new forklift, the price and the payback are arguably higher. If the company wanted, it could also lease the forklifts which would bypass all the investments.

4.1.5 Wastewater heat recovery

Based on 2020 monthly wastewater consumption data, the total amount of wastewater was 382,925 m^3 in 2020 and temperature on average 30 °C. According to the 2017 energy audit as well as experts at the site, there is no detailed wastewater monitoring, which would yield the mass or volume flow of the wastewater directly (ÅF 2017a). Thus, the amount of energy in wastewater can only be calculated approximately. Using values $\rho = 995.67$ kg/m^3 and $c_p = 4.18$ kJ/kg*K for water at 30°C (The Engineering Toolbox 2021b & 2021c), it is estimated that with average use hours of 6000 h/a (ÅF 2017a), the average mass flow of wastewater is $\dot{m} \approx 17.7$ kg/s.



WW Volume	382,925	m^3					
Yearly hours	6000	h					
Mass flow	17.65	kg/s					
dT	10	K					
Cp	4180	J/(K*kg)					
J to MWh	2.78E-10						
Available heat per second			Q=m*dT*Cp	737,822.12	W	737.82	kW
COP						Heat/year	
3	$COP = \frac{Q_H}{Q_H - Q_C} = \frac{Q_H}{W}.$			1106.73	kW	6.64	GWh
4				**983.76**	kW	**5.90**	GWh
5				922.28	kW	5.53	GWh
District heat average price (2020)		43.67	e/MWh				
Electricity average price (2020)		60.6	e/MWh				
Heat pump power use (COP=4)		245.9407079	kW				
District heat saving potential		257,765.54	e	≈	257.77	k€	
Electricity cost		89,424.04	e	≈	89.42	k€	
Net Saving					**168.34**	k€	
Heat pump cost		500,000.00	€				
Payback		2.97	a				

Figure 43: Wastewater heat pump calculation

Assuming that $\Delta T = 10$ °C of energy could be recovered using a heat pump, which is certainly possible according to a heat pump supplier and technical experts at the site, using **equations 1 and 8** it is concluded that on average, almost 1 MW of power can be harvested with a heat pump with COP of 4 as detailed by **Figure 43**. In a year with 6000 use hours, this would equal almost 6 GWh of energy. With the calculated power output and proposed COP, the power use of the heat pump would be ca. 250 kW.

Assuming, that all the harvested heating power could be directly used to substitute district heat, around 48 % of district heat could be saved in a year, which would yield a tCO2e saving of about 700 tCO2e per year. In monetary terms, the company could save approximately 260,000 €/year in district heating costs. However, this is not the net saving as the heat pump also uses electricity. With a power use of 250 kW, the heat pump would use 1.5 GWh of energy in a year. With average electricity price of 60.6 €/MWh (2020), the electricity would cost the company about 90,000 €/year, which yields a net saving of about 170 000 €/year. If the heat pump would cost for instance 500,000 €, as an expert at the company would estimate, the simple payback calculated using **Equation 6** would be little under three years for the heat pump only

Although the figures for wastewater heat recovery in Vantaa are indeed promising, the reality of such project is quite different. First and foremost, the largest obstacle for such investment is the physical location of the wastewater pipe. The point of the wastewater sewer where the pump could be installed lies about three meters underground, which means that installing the pump would require expensive groundworks and excavation. Moreover, according to the 2017 energy audit, the point is located on the opposite side of the property compared to the systems where the heat could be utilized (ÅF 2017a), which implies that long pipe works would be also required. A quick look at arbitrarily selected Finnish earthworks company reveals, that a sewer renovation project with a pumping station installation for a municipal water company in Finland has cost 1.5 M€ (RTA-Yhtiöt 2021). Using this as a reference, the total investment cost of 2 M€ for the investment would mean a simple payback of almost 12 years.

But even if the excavation works and piping proved to be less expensive and the payback would be lower, another great challenge for the project is temporality. As there is no hourly data of district heat consumption or the flow of wastewater, it is impossible to calculate the real amount of energy that can be utilized. Virtually, as the peak of wastewater consumption occurs in the evening and production in the day, a thermal storage or connection to the centralized system would be required in order to match the supply with the consumption. This would also raise the costs even further. Lastly, two other factors which can affect the implementation of the project and possible energy output of the heat pump, are the amount of grease and solids in the wastewater as well as the water utility's opinion of lowering the temperature of wastewater (ÅF 2017a).

In conclusion, due to high costs and challenging implementation, as well as the availability and sufficiency of better waste heat sources, wastewater heat recovery is not suggested as one of the primary methods for substituting district heat, or at least not now. In the future, if heating costs or the consumption increased considerably, the investment could be more topical. Nevertheless, it is important to acknowledge, that the wastewater can contain considerable amounts of energy with such high daily consumption.

4.2 Kristianstad, Sweden – moving to 100 % biogas

As depicted by **Table 5,** most emissions at Kristianstad originate from propane and district heat. Visualized by the Sankey in **Figure 22**, biogas and LPG are used in steam boilers for steam generation and in flame ovens in slaughtering. District heat is used for ventilation, space heating and warm water production. According to the data provided by the site, there are two brand new steam boilers, which both have a power of 3.2 MW. In other words, the peak power capacity for the steam system is 6.4 MW. Furthermore, there is also one hot water propane fired boiler, which can be used to substitute district heat, but it has not been used for several years, according to a technician at the site. The power of the boiler is 4.1 MW. According to the latest energy audit from 2017, one steam boiler is enough to provide steam throughout the day under normal circumstances, which in practice means continuous steam generation around the clock in variable quantities (ÅF 2017b).

When it comes to choosing new emission free technologies for Kristianstad, the answer is rather unambiguous, but rather complicated due to uncertain supply of the fuel. De facto, the most suitable technology choices for Kristianstad are biogas and heat recovery, but evaluating the latter is virtually impossible in this study, as the 2017 energy audit from Kristianstad is deficient in terms of quantifying and determining the current heat recovery, and there is no data or measurements of it from the site, according to its experts. Thus, the system is analyzed with the assumption, that all the emissions are cut down by moving to a biogas-based system. Yet, as missing data is not a sufficient rationale for moving to biogas only, the system is also evaluated in economic terms as well as in terms of actual implementation of such project compared to other alternatives.

According to the site, large scale electric heating and steam generation is completely out of the question, as it has been forbidden by law in Sweden due to too unstable grid. Indeed, as visualized by **Figure 44**, the grid in Sweden is divided into four different price areas and sub-grids, which pose great challenges for grid balancing compared to for example Finland, where the grid is one uniform area. As visualized by the figure, the different prices between the Swedish price areas imply, that electricity is not transferred effectively between them, and lines are congested. In the figure, Kristianstad in located in area SE4.

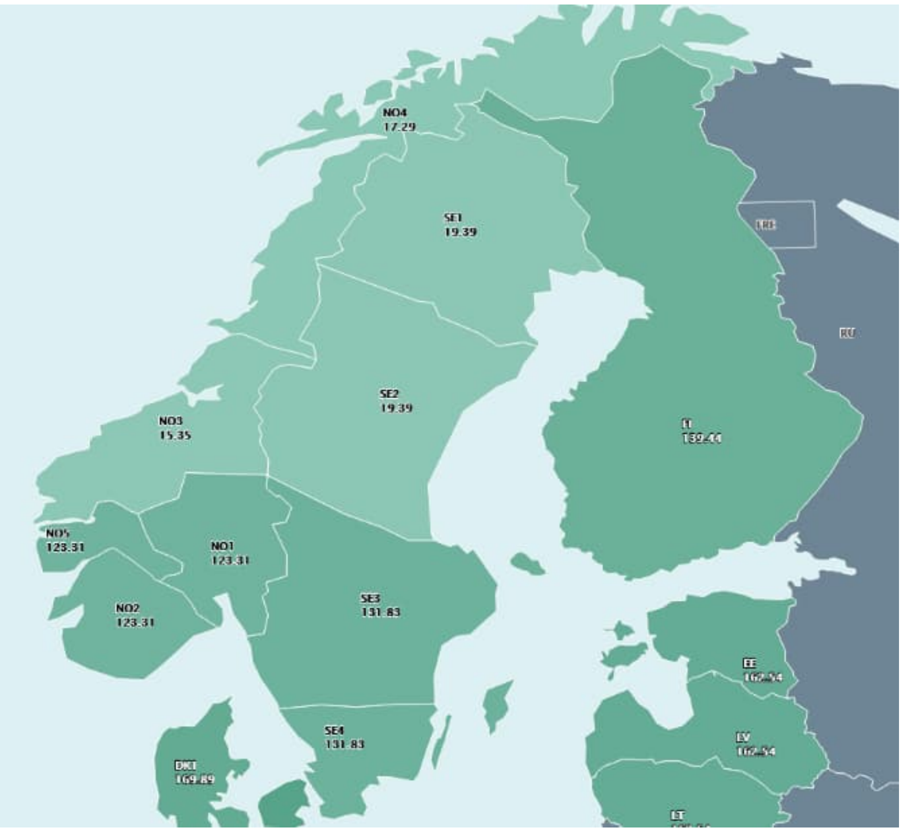


Figure 44: A screenshot taken 22 November 2021 13:40 from Nordpool, the leading power market in Europe, showing different electricity price areas and their temporal prices in Nordic countries (Nordpool 2021)

Compared to solid biofuels, economic arguments and the system's dependency of gas, support adopting biogas. According to the site's experts, slaughtering cannot operate without some sort of gas as the flame ovens, which are used to burn hair from pork carcasses, are completely dependent on it as their direct source of heat. Furthermore, the two gas-fired steam boilers are brand new, which implies, that the vast capital expenditure would be largely wasted, if the system moved to for solid biofuels. Also, when it comes to biomass-based system, expensive investments to boiler technology, fuel storage and handling would be required as demonstrated in the case of Vantaa, as there is no existing technology for them. In the case of biogas, the only investment that would be required according to the current knowledge, is modifying the hot water propane boiler to burn biogas. This would require at least new nozzles and modifications to safety system. The exact cost is unknown at this point, but according to an energy manager at the company, it is definitely under 100,000 € i.e. 1 MSEK. Apart from that, the whole system is already fitted to move to biogas. According to a technician at the site, the hot water boiler would be enough to cover all the district heating consumption in the site, and the steam boilers can run on biogas only already today.

Figure 45 shows 2020 monthly district heat consumption as well as the monthly average power, which varies from under 0.1 MW to about 1 MW. The monthly average power has been calculated by dividing the consumption with the hours in each month. With total average power of about 0.6 MW, it is clear that the 4.1 MW hot water propane boiler is sufficient to cover the district heat demand. However, peak power must also be addressed as it sets the boundaries for the system, but it remains unknown due to shortage of data. Yet, in the case of Vantaa with average power of 1.4 MW the peak power was assumed to be 5.7 MW. Using these values as well as the expert's opinion, that the boiler is enough to cover the heat demand, it is assumed that 4.1 MW is sufficient to cover also the peak demand, and no further investments are needed.

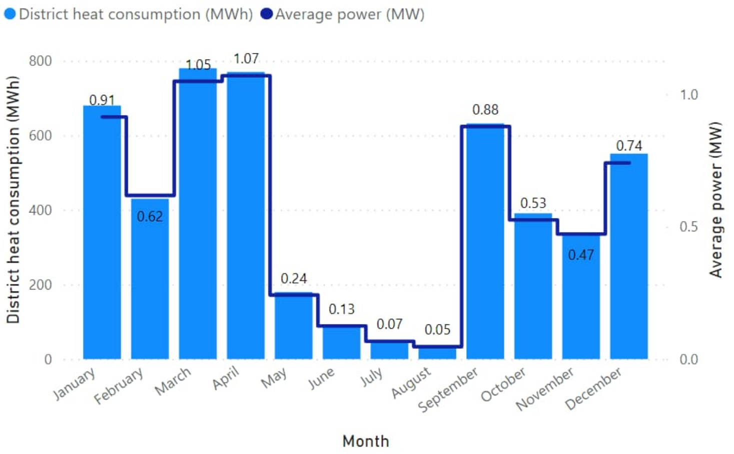
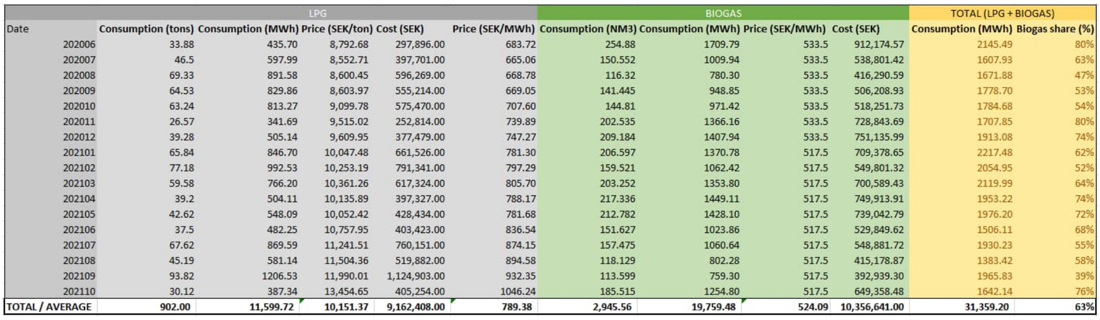


Figure 45: 2020 district steam consumption & average monthly steam power in Kristianstad

Table 7: 2020 & 2021 monthly gas consumption & associated costs in Kristianstad. The costs and prices are in Swedish crowns (SEK).



	LPG					BIOGAS				TOTAL (LPG + BIOGAS)	
Date	Consumption (tons)	Consumption (MWh)	Price (SEK/ton)	Cost (SEK)	Price (SEK/MWh)	Consumption (NM3)	Consumption (MWh)	Price (SEK/MWh)	Cost (SEK)	Consumption (MWh)	Biogas share (%)
202006	33.88	435.70	8,792.68	297,896.00	683.72	254.88	1709.79	533.5	912,174.57	2145.49	80%
202007	46.5	597.99	8,552.71	397,701.00	665.06	150.552	1009.94	533.5	538,801.42	1607.93	63%
202008	69.33	891.58	8,600.45	596,269.00	668.78	116.32	780.30	533.5	416,290.59	1671.88	47%
202009	64.53	829.86	8,603.97	555,214.00	669.05	141.445	948.85	533.5	506,208.93	1778.70	53%
202010	63.24	813.27	9,099.78	575,470.00	707.60	144.81	971.42	533.5	518,251.73	1784.68	54%
202011	26.57	341.69	9,515.02	252,814.00	739.89	202.535	1366.16	533.5	728,843.69	1707.85	80%
202012	39.28	505.14	9,609.95	377,479.00	747.27	209.184	1407.94	533.5	751,135.99	1913.08	74%
202101	65.84	846.70	10,047.48	661,526.00	781.30	206.597	1370.78	517.5	709,378.65	2217.48	62%
202102	77.18	992.53	10,253.19	791,341.00	797.29	159.521	1062.42	517.5	549,801.32	2054.95	52%
202103	59.58	766.20	10,361.26	617,324.00	805.70	203.252	1353.80	517.5	700,589.43	2119.99	64%
202104	39.2	504.11	10,135.89	397,327.00	788.17	217.336	1449.11	517.5	749,913.91	1953.22	74%
202105	42.62	548.09	10,052.42	428,434.00	781.68	212.782	1428.10	517.5	739,042.79	1976.20	72%
202106	37.5	482.25	10,757.95	403,423.00	836.54	151.627	1023.86	517.5	529,849.62	1506.11	68%
202107	67.62	869.59	11,241.51	760,151.00	874.15	157.475	1060.64	517.5	548,881.72	1930.23	55%
202108	45.19	581.14	11,504.36	519,882.00	894.58	118.129	802.28	517.5	415,178.87	1383.42	58%
202109	93.82	1206.53	11,990.01	1,124,903.00	932.35	113.599	759.30	517.5	392,939.30	1965.83	39%
202110	30.12	387.34	13,454.65	405,254.00	1046.24	185.515	1254.80	517.5	649,358.48	1642.14	76%
TOTAL / AVERAGE	**902.00**	**11,599.72**	**10,151.37**	**9,162,408.00**	**789.38**	**2,945.56**	**19,759.48**	**524.09**	**10,356,641.00**	**31,359.20**	**63%**

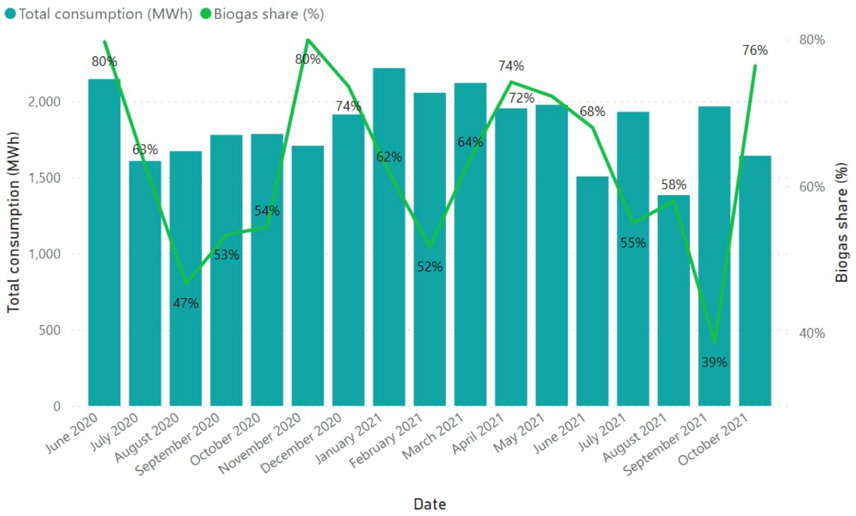
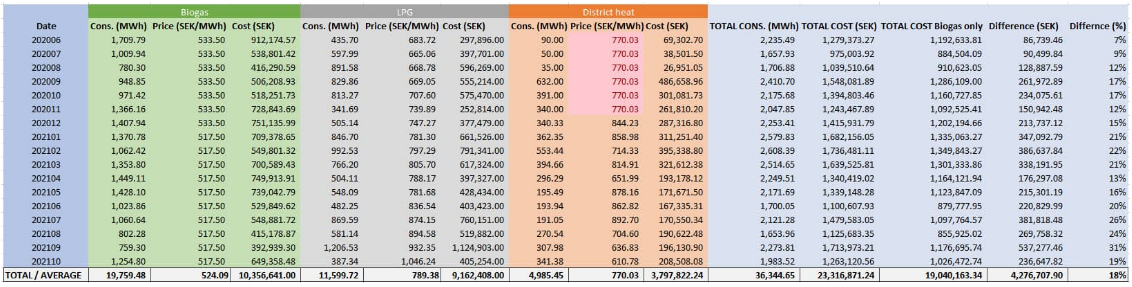


Figure 46: 2020 monthly total gas consumption and biogas share in Kristianstad

Table 7 shows the monthly LPG and biogas consumption, prices and costs. The numbers start from June 2020, as it was the first month when biogas was ever used in Kristianstad. **Figure 46** visualizes the last two columns of the table i.e. the total gas consumption and biogas's share of it. As seen, there is no clear trend in gas consumption, and the effect of seasonal variation and outside temperature is only perhaps slightly visible, as the consumption seems to be a little higher in winter months than in the summer or autumn. However, this could be explained by other factors as well, as for instance the consumption in July 2021 was higher than in December 2020. When it comes to the share of biogas, or in other words supply of it, it seems to be quite random as there is notable variation even between consecutive months. The supply seems to surge in October and November, but whether this is yearly recurring phenomenon, is impossible to say based on size of this dataset. This brings us to the weak link of the biogas-based system, as there is currently no information whether there is enough biogas in the future two run the whole plant. According to the experts at the site, all the biogas that is available is already bought today, and the current supplier cannot provide any data or guarantee the amounts in future. With the current supply and its variation, it is clear that the system cannot move to 100 % biogas.

If it was assumed, that a solution is found to provide enough biogas by for example providing feedstock for a biogas plant, the energy costs would drop quite substantially, if the future prices remained close to the historical realized fuel costs and prices as demonstrated. Yet, it cannot be stressed enough, that the following calculations are only limited approximations based on historical data. Using historical consumption and price data, roughly 4.3 MSEK (18 %) or about 0.43 M€ could be saved, as **Table 8** concludes if the price of biogas remained close to its realized prices in the future. Yet, when the growing interest in biogas is considered, it is unlikely that the prices remain in their historical levels in the future. Furthermore, moving to 100 % biogas itself increases the supply, which could increase the price. If the system moved to biogas only, the consumption of biogas would rise on average by 92 % compared to biogas consumption in 2020 and 2021. In other words, biogas would be needed twice as much compared to the current situation, which is a great challenge, as there is currently no extra biogas, at least not from the current supplier. Thus, the focus in the future should be in finding a sufficient source of biogas.

Table 8: Comparing Biogas only-system to the current situation. The price in red cells was estimated with an average of prices in 2021 since the data was missing.



	Biogas			LPG			District heat							
Date	Cons. (MWh)	Price (SEK/MWh)	Cost (SEK)	Cons. (MWh)	Price (SEK/MWh)	Cost (SEK)	Cons. (MWh)	Price (SEK/MWh)	Cost (SEK)	TOTAL CONS. (MWh)	TOTAL COST (SEK)	TOTAL COST Biogas only	Difference (SEK)	Differnce (%)
202006	1,709.79	533.50	912,174.57	435.70	683.72	297,896.00	90.00	770.03	69,302.70	2,235.49	1,279,373.27	1,192,633.81	86,739.46	7%
202007	1,009.94	533.50	538,801.42	597.99	665.06	397,701.00	50.00	770.03	38,501.50	1,657.93	975,003.92	884,504.09	90,499.84	9%
202008	780.30	533.50	416,290.59	891.58	668.78	596,269.00	35.00	770.03	26,951.05	1,706.88	1,039,510.64	910,623.05	128,887.59	12%
202009	948.85	533.50	506,208.93	829.86	669.05	555,214.00	632.00	770.03	486,658.96	2,410.70	1,548,081.89	1,286,109.00	261,972.89	17%
202010	971.42	533.50	518,251.73	813.27	707.60	575,470.00	391.00	770.03	301,081.73	2,175.68	1,394,803.46	1,160,727.85	234,075.61	17%
202011	1,366.16	533.50	728,843.69	341.69	739.89	252,814.00	340.00	770.03	261,810.20	2,047.85	1,243,467.89	1,092,525.41	150,942.48	12%
202012	1,407.94	533.50	751,135.99	505.14	747.27	377,479.00	340.33	844.23	287,316.80	2,253.41	1,415,931.79	1,202,194.66	213,737.12	15%
202101	1,370.78	517.50	709,378.65	846.70	781.30	661,526.00	362.35	858.98	311,251.40	2,579.83	1,682,156.05	1,335,063.27	347,092.79	21%
202102	1,062.42	517.50	549,801.32	992.53	797.29	791,341.00	553.44	714.33	395,338.80	2,608.39	1,736,481.11	1,349,843.27	386,637.84	22%
202103	1,353.80	517.50	700,589.43	766.20	805.70	617,324.00	394.66	814.91	321,612.38	2,514.65	1,639,525.81	1,301,333.86	338,191.95	21%
202104	1,449.11	517.50	749,913.91	504.11	788.17	397,327.00	296.29	651.99	193,178.12	2,249.51	1,340,419.02	1,164,121.94	176,297.08	13%
202105	1,428.10	517.50	739,042.79	548.09	781.68	428,434.00	195.49	878.16	171,671.50	2,171.69	1,339,148.28	1,123,847.09	215,301.19	16%
202106	1,023.86	517.50	529,849.62	482.25	836.54	403,423.00	193.94	862.82	167,335.31	1,700.05	1,100,607.93	879,777.95	220,829.99	20%
202107	1,060.64	517.50	548,881.72	869.59	874.15	760,151.00	191.05	892.70	170,550.34	2,121.28	1,479,583.05	1,097,764.57	381,818.48	26%
202108	802.28	517.50	415,178.87	581.14	894.58	519,882.00	270.54	704.60	190,622.48	1,653.96	1,125,683.35	855,925.02	269,758.32	24%
202109	759.30	517.50	392,939.30	1,206.53	932.35	1,124,903.00	307.98	636.83	196,130.90	2,273.81	1,713,973.21	1,176,695.74	537,277.46	31%
202110	1,254.80	517.50	649,358.48	387.34	1,046.24	405,254.00	341.38	610.78	208,508.08	1,983.52	1,263,120.56	1,026,472.74	236,647.82	19%
TOTAL / AVERAGE	**19,759.48**	**524.09**	**10,356,641.00**	**11,599.72**	**789.38**	**9,162,408.00**	**4,985.45**	**770.03**	**3,797,822.24**	**36,344.65**	**23,316,871.24**	**19,040,163.34**	**4,276,707.90**	**18%**

5 Conclusions

The goal of this master's thesis was to find the most suitable financially sustainable carbon neutral technologies and investments for a Finnish publicly listed multinational food company, for it to reach its 2025 scope 1 and scope 2 carbon neutrality goals. This was done by conducting a literature review, to identify suitable carbon free technologies, and by studying the energy systems of two manufacturing plants, one located in Finland and the other in Sweden. Due to the fact, that all the electricity at the two plants was, and still is, already bought carbon free, the focus of the thesis was on carbon free heat and steam generation. At both sites, these were also the largest sources of emissions.

The literature review studied several carbon free electricity and heat generation technologies in order to provide as many alternatives as possible to find the best technologies and investments to reach the carbon neutrality goals. The technologies included electric heating i.e., electric and electrode boilers, geothermal power generation technologies, waste heat pumps, different ground source heat pumps, different biofuels and their generation, variable renewable heat and power generation and thermal storages including cold storages. Finally, two food companies were studied to provide an overview of what is done around the world in similar companies. The first was the world's first carbon neutral food company from Canada while the other was a vast global food company from Brazil on its way to carbon neutrality.

Next an overview of the two plants was provided, which included general information of the plants, the current state of the plants' energy systems and their 2020 energy use including scope 1 and 2 emissions. The two plants were then analysed using a qualitative research method due to shortage of data as well as the enormous size and complexity of the two energy systems. In practice, this meant analysing and interpreting non-numerical, which was acquired from previous energy audits as well as from a site visit and different experts inside and outside the company. Together with the information from the literature review, the analysis focused in finding *ad hoc* solutions for the two plants. The main criteria, which were used to select the most suitable technologies, were cost, which included rough payback calculations for possible investments, and technical feasibility. In the end, the few quantitative methods which were used, were also introduced.

In the case of Vantaa, it was found that it could be possible to substitute district heat completely by building a centralized waste heat thermal storage system and eliminate the corresponding emissions. Using figures from 2017, the estimated waste heat was about 23 GWh, while the consumption of district heat was noticeably lower, 14.5 GWh. In the plant, there were two major sources of the waste heat, which are exhaust air and steam from a steam powered Alkar-oven and low temperature condensate from ammonia cooling compressors. The gross heating power of these two sources is estimated to be 2.4 MW and 1.85 MW respectively and in order to utilize these, one would need to install a duct radiator and/or a heat exchanger for the Alkar-oven and a heat pump for the cooling compressor condensate, which was assumed to be an ammonia heat pump with a COP of 6.42, as suggested by real data from a heat pump supplier. Yet, due to losses, it is impossible to capture all the gross heating power. Thus, the net average heating power for Alkar was approximated to be 1 MW as suggested in the energy audit and for the heat pump 1.174 MW during weekdays and 0.5 MW on weekends as suggested by heat pump provider data and data from the energy audit. With this power output, the Alkar-oven would produce approximately 4000 MWh of energy in a year with 4000 use hours, and the heat pump about 8600 MWh, as it would be producing some heat constantly at all hours. In total, the yearly energy output was estimated to be 12,600 MWh, which was just enough to cover the 2020 12,300 MWh district heat demand.

Yet, losses were not the only factor affecting the recoverable heat. An important aspect was also temporality i.e. how the waste heat profiles match with the consumption. Based on previous energy audit and its estimated energy profiles as well as general information of the waste heat sources, it was clear that a thermal storage was needed. However, it was impossible to determine the size of the storage accurately as the hourly data was deficient and no hourly consumption profiles could be compiled. There were no sensors in the Alkar-system, which would have directly told the flow and temperature of the exhaust stream i.e. the heating power, and thus it was impossible to compile the real power profile for the Alkar-oven exhaust heat. In the case of the ammonia cooling compressors, the situation was not much better.

In the case with ammonia cooling compressors, the compressor power use data, which could have been used to estimate the amount of waste heat, was saved for only two weeks. Therefore, if would have wanted to compile at least a somewhat accurate power profile for the cooling compressors and their waste heat, it would have required at least a year long monitoring in two weeks periods, which was not possible in the scope of this study. Furthermore, there was no long-term data or energy profiles of the current heat recovery, as there was no flow sensor in the heat recovery system which would have measured the amount of current heat recovery. The current heat recovery could only be approximated with the temperature and pressure data, which was also saved for only two weeks. As a result, data and approximations from previous energy audit were used to estimate the amount of low temperature waste heat. This was done first by calculating a combined COP for the cooling compressors using their name plate values. Next, the resulting amount of gross heat was approximated with the calculated COP together with approximated high-pressure cooling compressor electricity use data from the 2017. Lastly, the amount estimated recoverable heat was acquired by subtracting the sub-streams to defrosting and current heat recovery from the gross heat.

Since accurate hourly power profiles could not be compiled, the size of the needed storage was approximated using the constraint, that the system must be able to also cover the yearly district heating peak power. As the presumed total power of the waste heat streams was 2.174 MW and the yearly peak power of district heat was assumed to be 5.7 MW, a thermal storage with a power output of 3.6 MW was required to cover the peak demand for one hour. It was approximated, that this could be achieved with for example a 100 m^3 thermal hot water storage, where the temperature of the water decreased from 55 °C to 20°C over one hour and the energy was transferred without losses.

The possible payback for the centralized waste heat storage system was approximated with the assumption that all district heat could be substituted with the centralized system. Using 2020 consumption and price data, this meant a net saving of 480,000 €. The storage was assumed to cost 150,000 € while the heat pump was assumed to cost 230,000 € with all costs included as suggested by a heat pump retailer. Due to the fact that costs for the Alkar-oven heat recovery could not be acquired for this study, it was assumed to cost the same as the heat pump i.e. 230,000 €. With a total cost of 680,000 €, the simple payback for the centralized thermal storage waste heat system was calculated to be roughly 1.5 years.

In order to eliminate the emissions from district steam in Vantaa, three fuels and technologies were considered. These were biogas, pellets and electric steam generation. In terms of technical feasibility and implementation, biogas was by far the best option as it did not require any investments or modifications to the current steam system. In short, switching the natural gas to biogas was seen to be just a matter of negotiation with the current steam provider. Yet, notable downsides with biogas were its availability, energy security and the highest price per MWh compared to the two other alternatives with the approximated prices. The price of biogas was modelled with 2020 realized monthly natural gas prices by adding a 12 €/MWh premium to the natural gas prices per MWh as suggested by the current gas supplier. Using this approximation with 2020 price data, it was concluded, that the heating costs would rise with about 350,000 € in a year or by 29 % if the assumption proved to be accurate. Yet, due to legislative changes regarding the taxation and certificates of origin for biogas, it is plausible that the price will drop substantially in the future. According to a discussion with the current gas provider, the price of biogas could be as low as the price of natural gas in the future. If this proved to be accurate, there would be no significant change in the heating costs with biogas.

When it came to pellets, they were by far the cheapest option in terms of approximated fuel costs. Using pellet prices from Statistics Finland, it was approximated that about 300,000 € per year or 23 % could be saved in fuel costs in the best-case scenario, which would yield a sensible payback even for a larger investment. Yet, the pellet prices were just an approximation and the real cost, which depends on multiple factors such as transport, was left unknown. Nevertheless, the price of pellets was observed to have remained relatively stable over the years, which implies a buyers' market. Also, the supply was assumed to be relatively good based on the data. Thus, the energy security was found to be one of the greatest advantages with pellets. The largest disadvantage with pellets were their high initial investment costs as most likely adopting pellet technology, or any other solid biofuel combustion system, would require building its own heating plant which would include investments to fuel storage, fuel handling system and a biomass boiler as well as buildings. Arguably this would cost millions of euros, which is a large capital expenditure also considering the risk that is associated with the future energy prices.

In terms of technical feasibility and implementation, electric steam generation was found to be inferior both to biogas and pellets. In terms of fuel costs, it was found to be cheaper than biogas depending on future prices, but more expensive than pellets. All in all, the investment costs were found to be substantial and in the order of millions. Adopting electric steam generation would require building an expensive electric steam generation system but also a connection to higher voltage grid, which alone costs presumably at least a million. Using 2020 fuel prices it was concluded that such system would not acquire payback, at least not with savings in energy costs, as the prices of electricity per MWh were higher than the current district steam prices.

In addition to natural gas use in the steam plant, the plant had its own direct use of natural gas. Due to the low volume of the consumption, and the fact that investments were not needed, it was suggested that direct natural gas consumption would be substituted using biogas. Since the volume was so much lower than in steam generation, the availability of biogas was arguably a lesser problem. Using the 12 €/MWh premium assumption together with consumption data from 2020, it was concluded that the heating costs would increase with about 30,000 €/year or by 20 %. Yet, when the legislative changes regarding biogas are taken into account, the increase in costs is presumably lower, if it exists at all. Substituting natural gas with electricity was also considered, and it was concluded that about 1000 €/year could be saved using 2020 prices and consumption data. Yet, as the price of electricity can increase in the future, it was possible that no savings were made at all, or the costs were even higher with electricity. Furthermore, choosing electric thermo-oil heating would require an investment, which would have a long payback based on the low possible saving.

Another minor source of emissions compared were forklifts and their propane use. Although low in terms of consumption volume, the emission factor for propane was found to be the highest and as well as the price per MWh. Due to easy implementation, it was suggested that the gas forklifts were replaced with electric forklifts or converted to electric forklifts. Estimated with 2020 prices, it was concluded that 64 % could be saved in fuel costs, which equated only about 1,700 € due to low volume of consumption. The saving would yield a payback of 6 – 12 years for a preowned electric forklift, depending on the price of the forklift as well as future electricity prices.

Lastly in the case of Vantaa, wastewater heat recovery using a heat pump was investigated. Although the estimated amount of recoverable energy was found to be substantial, almost 6 GWh per year, the implementation of the project was found to be challenging and expensive. Due to the fact, that the point, where the wastewater could be utilized, was located far from the consumption of the heat and three meters underground, significant excavation works would be required, which raises the price of the project to estimated 2 M€, with a payback of 12 years. Moreover, the use of wastewater heat would require a thermal storage due to different consumption profiles of heat consumption and wastewater heat generation. All in all, as the other source were more easily accessible and less expensive to utilize, wastewater heat recovery was not seen as a topical investment with the current heating costs.

In the case of Kristianstad, biogas was found to be the best option to eliminate the emissions from district heat and propane, which accounted for practically all emissions. Waste heat was found to be another major source for carbon free energy in Kristianstad, but due to the fact, that there was no data of it, it was impossible to quantify or analyse it in the scope of this work. Thus, the system was analysed with the assumption, that all propane and district heat was substituted with carbon free biogas. Using historical realized biogas price data, it was concluded that around 4.3 MSEK or about 430,000 € could be saved in a year in heating costs if there was enough biogas and its price remained close to its historical prices in the future. Yet, the availability of biogas was found to be a fundamental question, as there is currently not enough of it, and the situation in the future remains unclear. At the moment, the share of biogas in its current use cases was found to be only about 63 % on average. If biogas use was extended to the whole system, its volume would have to increase on average by 92 %. In other words, almost twice as much biogas would be required compared to the current situation.

Despite the uncertain availability of biogas in Kristianstad, it was found to have many major advantages compared to the other two alternatives considered, which were electric steam and heat generation and solid biofuels. First, large scale electric steam and heat generation was found to be impossible due to the fact, that it has been politically banned in Sweden as a result of too unstable grid. Second, solid biofuels were inferior in terms of costs and implementation. First and foremost, the biogas/propane fired steam boilers at the site were brand new, which implied that replacing them with pellet technology would waste a large amount of capital expenditure. Replacing the steam boilers is also something that the site is quite hesitant to do according to a discussion, which is completely understandable. Furthermore, it was concluded that utilizing solid biofuels would require investments in the order of millions, as there is no existing, suitable technology at the site. In the case of biogas, the whole system was already equipped with suitable technology, apart from a hot water propane boiler, that would be used to substitute district heat in a biogas-based system. The boiler would require some modifications to for example nozzles, which arguably costs less than 100,000 € or 1MSEK. With the estimated saving of 4.3 MSEK, the payback is less than a quarter of a year. When it comes to the steam boilers, they can run on biogas only already today.

To sum up, the main conclusion for the sites is, that biogas is the most important trajectory the two sites should pursue in addition to waste heat recovery. As the largest uncertainty is the availability of biogas, it is proposed that the company starts to immediately explore options to ensure it, since there is only little over three years to the 2025 carbon neutrality goals at the time of writing this thesis. Another major developmental target is data collection from the energy systems. Currently for example in the case of the technical centre in Vantaa, nobody knows what the actual amount of current heat recovery is, although it could be derived easily by installing a flow sensor to the system. Furthermore, for instance the cooling compressor power use data should be gathered from this point on and saved indefinitely, as otherwise it will be impossible to size the centralized waste heat thermal storage system or even calculate the amount of available waste heat and related costs.

Moreover, the waste heat from the Alkar-oven should be started to quantify, as currently the approximations for the powers are only based on one time *"handmade"* site visit flow and temperature measurements. The same applies for Kristianstad, where the time and place of waste streams should be determined, and data collected of them.

Other minor developmental targets in the case of Vantaa are installation of thermostats in the glycol defrosting radiators and insulation of the cooling pipes from the ammonia cooling plant to the actual manufacturing plant. In other words, the cooling pipes between building 7 and 3 in the **Figure 19** should be re-insulated. According to the cooling plant technician, the insulation of the pipes has deteriorated due to moisture since they have been insulated last in the 1990s. Reportedly, the pipes drip water in hot summer days, which implies that they are absorbing heat from the sun and the surroundings. The energy loss is presumably significant, as the pipes are about 50 meters long and 50 cm in diameter with visual inspection. Fixing the insulation would mean more efficient cooling as well as decreased electricity costs.

More general conclusion of this thesis is that there is no ready-made universal template to make businesses or factories carbon neutral, although the discovered solutions for the two sites were surprisingly similar. The most suitable technologies for different instances are determined by the properties and operational environments of each case. In terms of implementation and costs, the simplest solution is often the best and unconventional or new technologies such as wastewater heat recovery and solid biofuels can prove to be expensive. Yet, the amount of energy from un-conventional source cannot be underestimated, for there they can be significant sources of energy as demonstrated. Overall, an important message is that waste heat sources should not be taken for granted as they facilitate the achievement of carbon neutrality goals significantly.

Another key message is the importance of data in the future energy systems. As the systems move more and more towards unconventional energy sources, the need for data increases, as many of them have much more significant temporal perspective compared to traditional energy sources. As demonstrated in this work, it is for instance completely impossible to size a thermal storage and use it effectively it without hourly data. Furthermore, it is impossible to estimate costs accurately without for example the information of the size of the storage or its effect on CO_2 emissions. Hourly consumption profiles are in a central role in the future systems, as they are one factor, that sets the boundaries in future energy systems. They are what determine for example the amount of recoverable heat, and thus cannot be omitted.

Lastly, it is important to highlight that the calculations and numerical analyses in this study contain considerably uncertainty, and they should not be taken as an exact assessment of the current situation, or the situation in the future. Indeed, the calculations are mainly directional in order to point out the best developmental paths and more detailed calculation are needed in all cases. Especially when it comes to for example the investment costs of the proposed technologies, they are exceedingly difficult to quantify accurately, as in most cases the suppliers do not provide any public cost information of their products or services. Furthermore, many solutions in energy technology are quite complex systems, which costs depend on precisely determined properties and boundaries of the circumstance.

Moreover, many of the analyses in this work rely on historical price data, which might not be a good approximation for future energy prices, as in most cases they are in stochastically behaving spot markets. Furthermore, the energy consumption can vary between different years due to weather conditions, which can also shape the outcome. Indeed, one of the largest challenges in this study was the lack of good quality data over multiple years, and the less one has data, the more uncertain the approximations and analyses become. In the future analyses, such as sizing the centralized thermal storage waste heat system, it is important to gather and use high resolution hourly data from many years to also capture the seasonal effects and reach the desired outcome.

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