Bachelor's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

Simon Holtet Aalmen
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Excess heat from energy intensive industries

Bachelor's thesis in Fornybar Energi
Supervisor: Steven Boles
Co-supervisor: Jon Ingebrigtsen

May 2022

NTNU
Kunnskap for en bedre verden

NORDKRAFT

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og prosessteknikk

Bacheloroppgave

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Preface

This bachelor thesis is written in collaboration between three students at the Norwegian University of Science and Technology (NTNU). The thesis is a final part of a three-year bachelor's degree in Engineering Renewable Energy at the Faculty of Engineering at NTNU Trondheim. Work on the thesis has been going on from January to May with a study load of 20 credits. This corresponds to around 500 working hours per student.

The purpose of the thesis is to look at different possibilities for utilizing surplus heat from a data center. This under the assumption that the data center is located in a rural area, placed in a northern climate and a installed capacity of around 100 MW. Analyzing the efficiency, supplementary energy needs and environmental benefits from the different industries looked into was an important aspect. The group would like to thank supervisor from NTNU Steven Boles for follow-ups and feedback during the project period. A big thank you will also go to Jon Ingebrigtsen in Nordkraft AS for input and help throughout the project.

During the project period, the group has also contacted various companies and professionals with expertise in different technical aspects of the project. This contributed to lift the quality of our thesis. The different contributors are listed on the next page.

Trondheim, 20th May 2022

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We appreciated all your inputs!

Sammendrag

Som en følge av gunstige markedsforhold, høy andel av fornybar energiproduksjon og politisk stabile forhold ser mange bedrifter på Norge som en attraktiv lokasjon for etablering av grønn industri. Utbygging av industri og den generelle elektrifiseringen av Norge er forventet å resultere i et høyere energiforbruk. Dette kan føre til at energiproduksjonen ikke klarer å møte energibehovet. Norge har i dag totalt 20 TWh ubrukt overskuddsvarme, og med flere industrietableringer vil dette tallet øke fremover. Som en konsekvens av dette vil det være viktig å benytte overskuddsvarme på en bærekraftig måte og danne synergier mellom industrier.

Meningen med oppgaven er å presentere ulike muligheter for utnyttelse av overskuddsvarme. En framgangsmåte for dette er at data og erfaringer skal bli samlet inn fra prosjekter og bedrifter i bransjen. Ulike muligheter for bruk av overskuddsvarme skal simuleres, beregnes og evalueres mot hverandre.

I dag eksisterer det flere utfordringer tilknyttet bruk av overskuddsenergi. En stor utfordring er temperaturen. Mye av overskuddsvarmen, spesielt fra datasentre, har relativt lave temperaturer. Dette begrenser utnyttelsesmulighetene betraktelig. En annen utfordring er lokasjon. Energiintensive industrier trenger ofte stort areal og plasseres dermed ofte i grisgrendte strøk. Dette gjør det vanskelig å ta i bruk tradisjonelle løsninger som er tilknyttet oppvarming av bygg, eksempelvis fjernvarme.

Oppgaven baseres på noen antagelser som ble satt av Nordkraft AS: oppgaven skulle ta for seg overksuddsvarmen fra et datasenter på 100 MW, som ble luftkjølt og som var lokalisert utenfor Narvik by.

Gruppen valgte å analysere forskjellige industrier som mottaker av overskuddsvarme fra et datasenter. Varmen ut av et datasenter kan klassifiseres som lavverdig varme, under 40 °C. Dermed ble det undersøkt og valgt industrier som opererer i disse temperaturene. De industriene gruppen valgte å analysere er drivhus, algedyrking, biomassetørking og fiskeoppdrett. Simuleringsprogrammet IDA-ICE ble brukt til å simulere energiforbruk for et drivhus og et biomassetørke-anlegg. Varmebehov, ytterligere energibehov og energigjenbruksfaktor ble beregnet for industriene. Resultatene ble deretter sammenlignet og diskutert.

Resultatene viste at det var mulig å tilrettelegge for en rekke industrier, men med en svært varierende effektivitet. Ved sammenligning av resultatene fra de forskjellige simuleringene, viste det seg at å danne en symbiose mellom datasenter og et anlegg for fiskeoppdrett hadde høyest energigjenbruksfaktor, *energy reuse factor*, på 47 %. Kalkulasjonen for drivhuset impliserte at ved å samarbeide med datasenteret kunne drivhuset produsere 161 tonn med avokadoer per år. Denne mengden kan spare 323 tonn med CO_2-utslipp sammenlignet med det importregimet som er i dag.

Abstract

As a result of a high share of renewable energy production, stable political and favorable market conditions Norway is a preferred location for the establishment of new green industries. These establishments and the ongoing electrification in the society are both expected to contribute to a higher consumption of energy. This could lead to a scenario where energy becomes a limiting resource. As of today Norway has a total of 20 TWh unused surplus heat, and this is expected to rise. Therefore, it is important to utilize the surplus energy and make the Norwegian energy intense industry more sustainable.

The purpose of the thesis is to present various possibilities for utilizing surplus energy. Data and experiences are also going to be collected from projects in comparable climates. Different solutions for utilization of excess heat are calculated and simulated. Ultimately the different solutions are analyzed and compared against each other.

Today, there are several challenges associated with utilizing surplus energy. One challenge is the temperature of the heat. Much of the surplus heat, especially from data centers, has relatively low temperatures. This limits the utilization possibilities. Another challenge is location. Industries located in rural areas must find creative solutions for using the surplus heat. Widely used solutions such as district heating cause large losses when transported over longer distances. Therefore, district heating is not an efficient solution in rural areas where industries are located far from urban areas.

Early in the process some assumptions were provided by Nordkraft in relation to the basis of the thesis. A prerequisite was that the thesis should focus on surplus heat from a data center. The data center had a size of approximately 100 MW, with air cooling and was located in a rural area near the city of Narvik.

In the thesis, the group has chosen to look at surplus heat from a data center for heating of various industries. These industries are classified as industries operating in low heat. Since the heat out of the data center is below 40 ℃, it was important to find relevant industries in this temperature range. The chosen industries receiving the surplus heat are greenhouse/agriculture, algae cultivation, biomass-drying and fish farming. the simulation program IDA-ICE was used to simulate a greenhouse and for the case of drying of biomass. Heat demand, additional energy and the energy reuse factor was calculated for all of the industries. The results of these calculations were compared to each other and are discussed.

The results showed that by utilizing excess heat it was possible to impact all the industries considered here, but with high variance in efficiency. The optimal industry turned out to be the fish farming facility which could achieve an energy reuse factor of 47 %. The calculations also showed that a greenhouse in symbioses with a data center facility could produce 161 tonnes of avocados per year. Which could save 323 tonnes of CO_2 compared to the situation today.

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Abbreviations

CCS	Carbon Capture And Storage
COP	Coefficient Of Performance
CRAC	Computer Room Air Conditioning
CRAH	Computer Room Air Handling
CVC	Calibrated Vectored Cooling
DHA	Docosahexaenoic Acid
EEA	European Environment Agency
EPA	Eicosapentaenoic Acid
ERF	Energy Reuse Factor
EU	European union Union
FT-G	Flow-Through With Gravity Water Supply
FT-P	Flow-Through With Pumped Water Supply
GDP	Gross Domestic Product
GHG	Greenhouse Gasses
HR	Human Resources
HVAC	Heating, Ventilation and Air Condition
LED	Light- Emitting Diode
NEPAS	New Energy Performance AS
NOK	Norwegian Kroner
NVE	Norwegian Water Resources and Energy Directorate
PAR	Photosyntetically Active Radiation
PO	Flow- Through With Pure Oxygen
PR	Partial Reuse System
PR-T	Partial Reuse With Heating
PUE	Power Usage Effectiveness
RU	Reuse System
SDG	Sustainable Development Goals
SI	International System Of Units

Technical glossary

Term	Explanation
Air- based cooling systems	Cool air is relased into server rooms. To avoid mixing of cold and hot air and control the air flow, server racks are placed in cold and hot corridors
Calibrated vectored cooling	Cooling method to optimize cooling of high-density systems
Computer room air conditioning	Unit inside the server rooms to control the temperature, humidity and air distribution
Computer room air handling	Air is cooled when transported across a coil with cold water.
Data center	Building with a large number of severs and components. These are used to process, store and organize data.
Energy	Defined as the ability to do work. Energy cannot arise or disappear, only change form.
Energy reuse factor	Factor that shows the reuse effectiveness of the excess heat from a data center.
Excess heat	Thermal energy that is a biproduct of industrial processes
Greenhouse	A house where plants are grown in a regulated climate
Heat	Energy that transfer from one place to another because of temperature differences.
Heat exchanger	Device used to transfer heat between different mediums
Heat pump	Pump used to move heat from a low to high temperature
Heating, ventilation and air condition	System that controls the temperature and air in a room.
High grade waste heat	Waste heat with a temperature above 400 degrees celsius
Low grade waste heat	Waste heat with a temperature below 100 degrees
Medium grade waste heat	Waste heat with temperatures between 100 and 400 degrees celsius
Power usage effectiveness	Gives the ratio between the amount total energy usage and energy used for operating servers and computing power.
Smolt	Smolt is a fish of anadromous salmonids. This can be a salmon, trout or char. The fish is called a smolt when it is ready for migration from freshwater to saltwater.

1 Introduction

The introduction contains the background, purpose of the thesis, the problems which is being addressed and the approach for the thesis.

1.1 Background

The data center industry is growing rapidly. NVE expects steady growth in power consumption from data centers in the future. The estimation is that consumption will increase to between 4 and 9 TWh in 2040. When data centers are running they generate a large amount of heat. This means that an increase in data centers, will lead to an increase in waste heat. In Norway the potential for utilizing waste heat is massive. As Norway currently has as much as 20 TWh of unused surplus heat from industrial operations.[1] [2]

Electricity consumption in Norwegian industry will also grow fast in the future. Relatively low power prices and favorable market conditions have led to an increased use of electricity in Norwegian industry. NVE estimates that the total electricity consumption in Norwegian industries will increase from 56 TWh in 2016 to 73 TWh in 2035. [3]

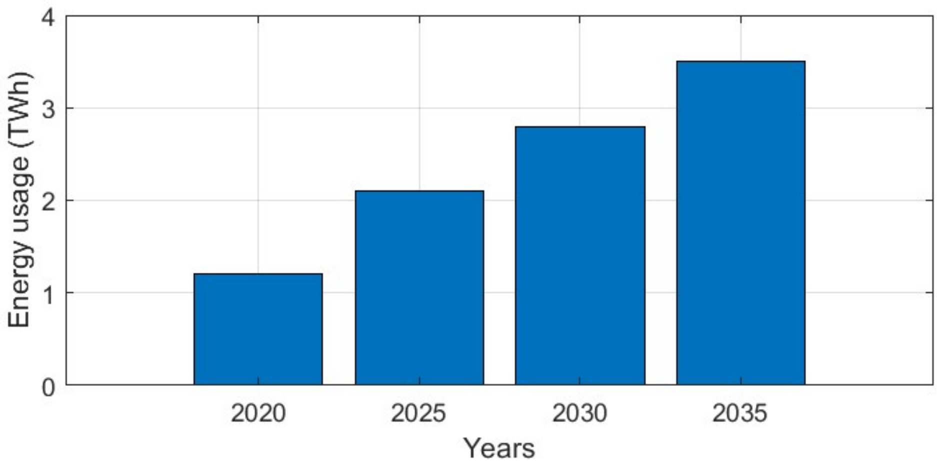

Figure 1: Projected energy consumption from data centers in Norway [3]

From figure 1 it can be observed that the Norwegian electricity consumption from the data center industry is expected to develop rapidly. Norway is a desirable location to establish data centers, as Norwegian power production has a minimal carbon footprint. Which in turn increases the sustainability of future data storage. Due to the ever increasing electricity and energy demand it is vital to establish effective energy recovery solutions in data centers. It is important to research different solutions and facilitate for co-operation with data center companies in the future. [3]

There are several challenges today related to the utilization of surplus heat. For example, the exhaust air from the data center does not hold more than 20-40 degrees ℃. This will lead to a limitation in possibilities for utilization of the excess heat. Another challenge is location. Data centers are often established in rural areas due to good access to space, electric power and the ability to achieve efficient cooling using natural conditions. Data centers located in rural areas have other possibilities for utilizing surplus energy compared to urban location. This is a limiting factor.[4]

1.2 Purpose of the thesis

The thesis's theme was given from the energy group Nordkraft, located in northern Norway. Nordkraft is currently working on a strategic level towards establishing green industries in Narvik. Examples are industries such as data centers, battery factories and green steel. As a part of the company's high energy production and the low local consumption, it is desirable to establish industries as a goal of local exploitation, leading to employment and economic growth. It is more attractive to establish an industry in Narvik if different solutions for utilizing excess heat is researched beforehand.

1.3 Problem to be addressed

The problem to be addressed in this thesis is the different opportunities for utilization of excess heat from the industries in question, especially data centers. The thesis is handed to students as part of exploring the field and obtaining knowledge.

1.4 Approach

The approach chosen by the group is to analyze four different industries co-located by a data center. These are greenhouse, algae cultivation, biomass drying and fish farming. Relevant data was collected to make realistic calculations and simulations. IDA-ice was utilized as a simulation tool for energy needs of different buildings located in a comparable climate. In the end the industries was compared in regards to efficiency of utilizing the excess heat, supplementary energy needs and environmental benefits.

2 Situation in Norway

In this section the situation in Norway today is to be analyzed. This regards the energy situation, futuristic goals for IT, green industries and data centers.

2.1 Energy situation in Norway today

Norway is a country rich in energy resources. Blessed with a nature filled with water, wind and fossil fuels Norway has a long history of energy production, which has provided wealth to the country. In 2020 Norway was the European country with the highest percentage of the electricity production originating from renewable sources. With a total of more than 37 GW installed capacity, mostly from hydro-power, the country produces about 154 TWh of electricity per year. Norway is also a large producer of oil and gas, mostly exporting it to Europe. [5]

Table 1: Energy production in Norway [5]

Source		**Unit**
Oil	1113	TWh
Natural gas	1140	TWh
Electricity	154	TWh
Bioenergy	13	TWh

In table 1 the distribution of different energy production is tabulated, with a total of 2420 TWh. As shown, the majority originates from oil and natural gas. These resources are exported and sold outside Norway, which has made the country rich. The production of electricity mainly originates from hydro-power, but also about 10 % from wind power. Norway is planning for large investment over the coming years, especially within the offshore wind and solar sectors. [6]

To fully understand the energy situation in Norway its needed a thorough analysis of the energy consumption. As well as having a large production, Norway also have a large energy consumption per capita. The large wealth of the country has made it into one of the best countries to live in. The extent of the social and technological development in Norway leads to a higher energy consumption. The Norwegian energy consumption consists of a variety of resources. [7]

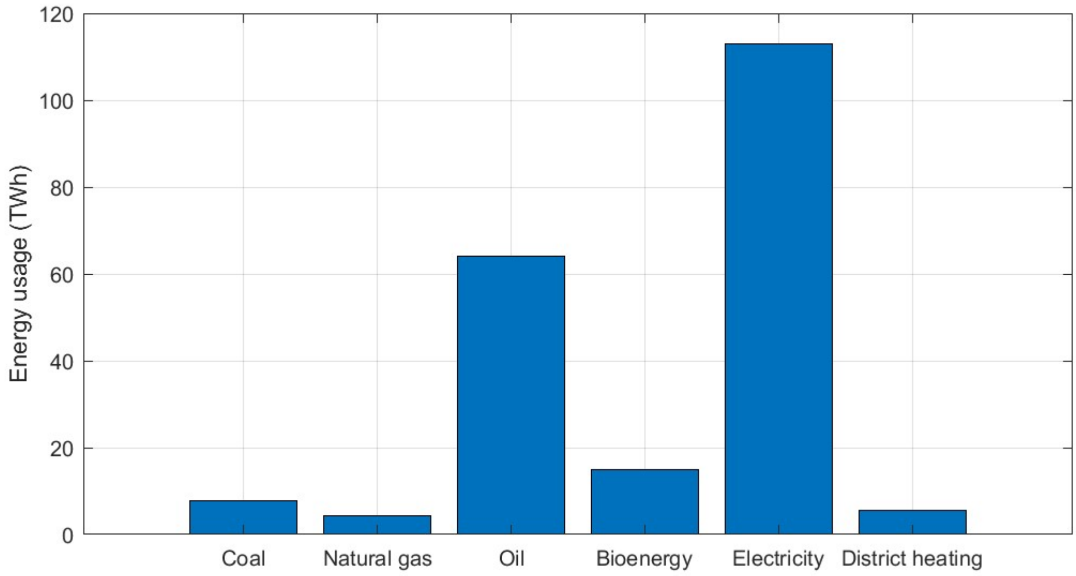

Figure 2: Energy consumption Norway 2020 [5]

As seen in figure 2 the Norwegian energy consumption largely consists of electricity consumption. Domestic usage, the service sector and industries is the main sources of electricity consumption. In addition there is a substantial usage of fossil fuels. This originates from transport and industries, which generates large GHG-emissions. As mentioned previously, the country exports large amounts of energy per year. The excess electricity were about 41 TWh in 2020. To this day, this is being exported to nearby countries. It would be desirable for the Norwegian government to use this energy to establish industries locally. [6]

2.2 The Norwegian goal for IT

In 2018, the government announced its plan for Norway to be an attractive nation for data centers and other computerized businesses. They want to facilitate digital innovation and local employment in Norway. They want to reach these goals by subsiding the technological research and implementation of data centers. IT is seen as a exciting resource for the nation in the future. It could accelerate innovative communities and companies in Norway in the future. These businesses could offer a great economic growth for Norway.[8]

The government also prioritises international cooperation. Norway is a part of the EEA cooperation and has EU as a trading partner. An important priority for the government is for Norway to be part of the digital single market in Europe. Here the technical and legal barriers to the free flow of data are desired to be removed, to ensure better access for consumers and businesses. The Government supports the EU's work on the digital single market and work to remove unfounded national requirements for data localization. Norwegian companies will get access to a marked with more than 500 million consumers, if the European digital market is open. [8]

2.3 Green industries in Norway

In the latest years, the world has transitioned its focus to one of the centuries biggest problem: global warming. As the concentration of CO_2 in the atmosphere accelerates, natural systems are pushed into imbalance. This leads to numerous negative consequences. Drought, floods and more extreme weather will appear more frequently. This pushes the society to a big transition. To ensure a continuing economic growth, the industries needs to adapt to the situation.[9]

As mentioned previously, Norway has a large amount of excess power. In this concern its desirable to establish green industries in Norway from its excess electricity, visualized in figure 3. This could lead to a number of positive effects, such as: innovative technology competence, higher employment and a boost for the economy. By using our green energy originating mostly from hydro-power, Norway could produce services and products with one of the worlds smallest carbon footprint. Industries related to green industries are data centers, battery factories, hydrogen production or production of green steel. [10]

Norway has been heavily involved in the oil and gas sector for a long time. With export of about 42 % of the total national export, it reflects the importance for the nation. As the world is transforming, its also important for Norway to keep up. The demand for oil and gas is set to decrease in the future, therefore its important for Norway to keep up its revenue stream, and generate new jobs. By utilizing the nations resources, both in capital and HR, Norway could take a leading role in this segment. By investing now, Norway could become a pioneer and generate competence which could become of international importance. [5]

Figure 3: Freyr battery factory in Mo i Rana [11]

In Norway as per 2022, there are vast numbers of projects for green industries in the starting phase. Freyr aims to provide the worlds most environmental-friendly batteries in Mo i Rana in northern

Norway. Figure 3 illustrates the proposed battery factory. Freyr intend to produce batteries with a yearly capacity of 83 GWh by 2028, this will lead to Norway becoming an important exporter of batteries. Aker presented their plan to restructure their business into the green segment. With plans to establish a green hub, consisting of green steel, battery factory and data center in northern Norway. This could possibly lead to thousands of new jobs. This shows the possible gigantic positive outcomes of the Norwegian investment in green industries. [12] [13]

2.4 Data centers in Norway

Norway has a good starting point for developing computerized business activities. This is because the country has many beneficial natural resources used for data centers. This applies to the stable and cold climate, which makes the cooling process easier and cheaper. In addition Norway has a political stability, competent workforce and functioning capital markets. [8]

The Norwegian government will work towards sustainable framework conditions for businesses and industries. This in the form of a better infrastructure, more growth-promoting tax system and a competent workforce. They will also facilitate increased trade and investment for Norwegian businesses. These factors will contribute to Norway being a good location for establishing a computerized business in the future. [8]

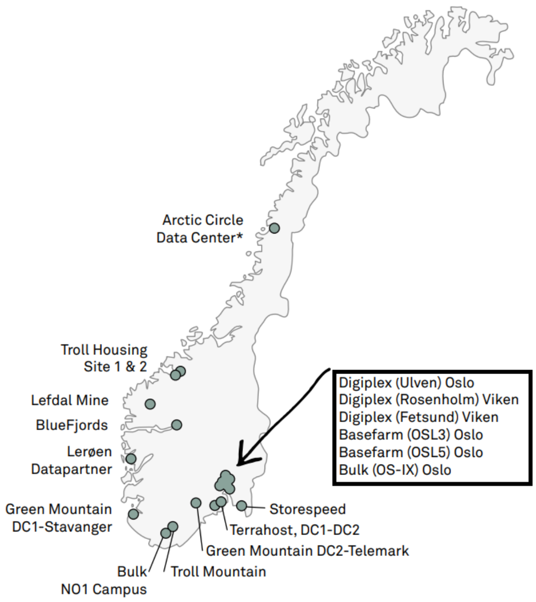

Figure 4: Overview of data centers in Norway [8]

As of 2020, the data center industry in Norway consists of approximately 18 data centers.This can be seen from figure 4. The data centers are mainly of the co-location data center type. They range from a small size of (< 2 MW), to a medium-size of (2-8 MW), and a large size of (> 8 MW). The growth of the data center industry has been by 17 percent in average per year since 2010. This is measured in MW capacity. The magnitude in Norway is the same as the global growth. In the last two years 2019/2020, the industry has increased its pace. Approximately 2.7 billion is invested in new data centers. [14]

A ripple effect analysis has been performed that calculates value creation from today's established data centers in Norway. The analysis shows that the data center industry contributes with 2376 jobs in Norwegian business and industry. The industry also contributed in 2019 with 3.1 billion NOK, corresponding to approx. 0.1 percent of annual GDP. Additional productivity effect for the companies also comes from the location of data centers in Norway. This is in the form of cost savings, use of new technology and increased flexibility. [14]

3 Data centers

A data center is a building with a large number of servers and components, which are used to organize, process, store and disseminate large amounts of data. In addition to the data rooms, data centers consist of administration premises, cooling systems, reserve power generators and connection to power and fiber networks. [8]

Data centers can be a part of a company‘s internal structure, or a product of the company in form of data center services to external costumers. All companies operating today require some sort of data handling, which is provided by a data center. In addition when private communication, entertainment and information have been digitalized, the total need for storage of data increases. [8]

Figure 5: Volkswagen's data center in Rjukan [15]

Figure 5 shows the external view of Volkswagen's data center in Rjukan.

The data centers are divided into four categories by the National Communications Authority [8]:

1) Hyper-scale data center: International actors who establish data centers to support their own services. Examples are companies like Google, Microsoft, Apple and Meta.

2) Large co-location center: A data center that offers rental to big national and international companies.

3) Medium co-location center: Data centers that offers rental to public enterprises. Where the main emphasis is on national and regional enterprises.

4) Cloud service provider: Offers computing power. Tenants pay for utilizing the data centers cloud storage service. Its normal to pay for the amount of services they utilize.

3.1 Energy efficiency for data centers

The energy efficiency of data centers is measured on the basis of PUE. PUE stands for power usage effectiveness, and measures the ratio between the total energy used and the energy used on IT equipment. [16]

$$PUE = \frac{Total\, facility\, power}{Energy\, used\, on\, IT equipment} \tag{1}$$

The equation 1 shows the calculation of PUE. The amount of power that the facility uses is called the total facility power. It includes lighting, cooling and heating. Energy used on IT equipment is linked to energy used to power the networking equipment and storage. The closer the PUE is to 1, the more energy efficient the system is. [17] [16]

PUE does not provide a good indicator of how a data center uses its surplus heat. The reason is that a data center can achieve a low PUE by, for example, using the ocean as a cooling sink, and dumping excess heat in the ocean. In this case, the data center will use a small amount of energy to cool down the servers. Data centers can therefore be regarded as quite energy efficient without the surplus heat being used in any particular degree. [17]

$$ERF = \frac{E_{reuse}}{E_{DC}} \tag{2}$$

Energy Reuse Factor (ERF) have been introduced to calculate the reuse effectiveness of the excess heat from a data center. As opposed to PUE, ERF is a better way to express the impact of utilizing excess heat from a data center. ERF is composed of E_{reuse}, which is the utilized excess energy, and E_{DC}, which is the total energy usage in the data center, as seen in equation 2. [18]

3.2 Electricity tax

From the 1st of January 2016 electric power delivered to large data centers received a reduced rate in the electricity . The tax reduction was intended to make Norway attractive for international actors, and to increase the number of establishments of data centers. The condition for getting a reduced tax rate was having a load of more than 5 MW. This follows a similar provision that Finland implemented April 1st, 2014. [8]

In 2017, data centers which were planned or already established in Norway had still not reached the expected installed capacity of 5 MW. With regard to further development of data centers in Norway, the condition for receiving a reduced tax rate was reduced to 0.5 MW from the first of January 2017. [8]

The ordinary rate is 0.1632 NOK per kWh and the reduced rate is 0.0048 NOK per kWh in 2017. This is a relief in expenses of approximately 7 million NOK for a data center of 5 MW. It is approximately 700 000 NOK for a data center of 0.5 MW per year. The reduced rate for large data centers is considered compatible with the EEA Agreement. [8]

3.3 Components of a data center

Data centers are composed of multiple important modules to ensure a good and stable delivery of services to its customers. Some of the most important modules are: servers, racks, network connectivity infrastructure, fire protection and monitoring structures. Other important modules are security measures and appliances, storage infrastructure, cooling and air flow systems and backup-power systems.

3.3.1 Servers and racks

Servers are one of the most important parts of a data center. When buying servers data centers often have to test multiple types before they are satisfied. They need to find satisfactory results in multiple categories, such as: compatibility, capacity, energy efficiency, size and upgradeability. Server racks are chosen depending upon the server type and the cooling method. This also has to be tested on site. [19]

3.3.2 Cooling and air flow systems

Every data center needs a heating, ventilation and air condition (HVAC) system. This is a system which controls the temperature and air in a data room. The most common example of this is a normal air conditioning unit found in most modern houses. [20]

Computer room air conditioning (CRAC) is a unit placed inside the servers rooms to control the temperature, humidity and air distribution, replacing regular air conditioner units used beforehand. The CRAC units are placed strategically around the room, and effectively works the same way a traditional AC unit would. It utilizes a built in compression and expansion system, and a cooling coil with a refrigerant where the air is cooled down. In turn, the refrigerant runs through an external condensing unit. In Figure 6 a CRAC unit is schemed and compared to a CRAH unit. [20] [21]

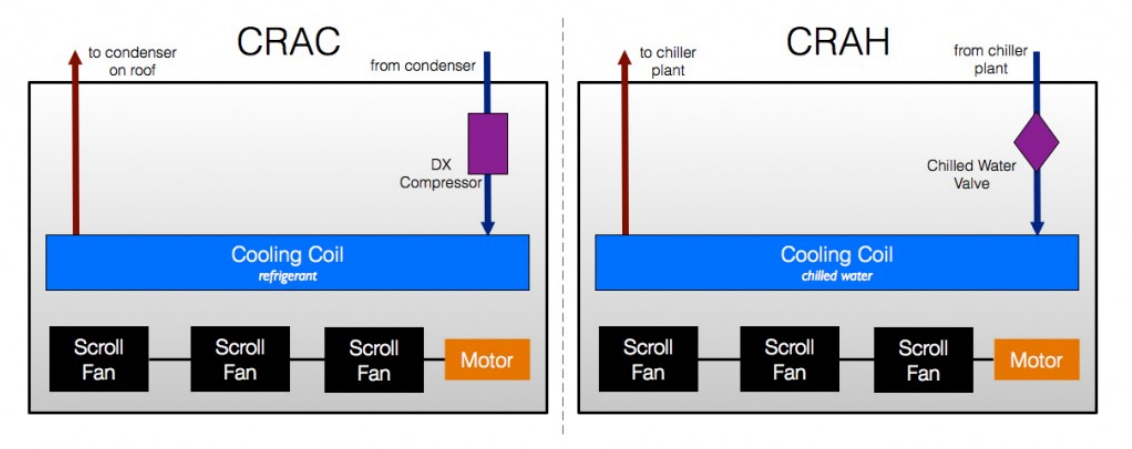

Figure 6: Comparison of CRAC and CRAH units [20]

Computer room air handling (CRAH) units are quite similar to chilled water air handling units, as the air is cooled when its transported across a coil filled with cold water. The cooling water is in turn cooled down in an external cooling tower. CRAH units utilize less energy as opposed to CRAC units, due to not having any compressor, which can be seen in Figure 6. [20]

Calibrated vectored cooling (CVC) is a cooling method designed to optimize the cooling of high-density systems. The CVC operates directly with dense server-racks and feeds cold air into the hottest part of the rack, improving not only the efficiency of the rack, but also the cost efficiency by reducing the required number of cooling fans. [22]

3.3.3 Back-up generator

The service a data center is most dependant upon is electrical power. It requires power to run its hardware and cooling systems, and to ensure a stable product to its customers. The historical data center have been run on local grids powered by fossil fuels and having fossil fuel generators as backup power. Modern data centers are a contrast to this, with their increasing share of renewable power and several types of alternative backup generators. [23] [24]

Backup power for data centers are often split into 4 tiers, where: [25] [26]

- Tier 1 is the basic data center, with just the amount of on site power it requires to run its IT load.
- Tier 2 adds one or more generators to the Tier 1 system.
- Tier 3 achieves a state of concurrent maintainability, because all power paths and components are replaceable.
- Tier 4 represents a system which is totally fault tolerant, as it has both a concurrent maintainability and it responds automatically to failures.

Redundancy is characterized as the duplication of critical components to serve as backups in case of failure. If N were to be the amount of generators needed to produce the power to run the data center, a N+x redundancy strategy could be chosen for the backup. x is here the amount of backup generators on site. With a consumption of 12 MW for a data center it is possible to have three 4 MW generators in backup when utilizing the N-strategy. Using N+1 strategy one would require a total of four 4 MW generators to have one in spare, in case the one of the three generators in use is damaged or in need of maintenance. This N+1 is categorized as a Tier 2 system. Similarly a N+N strategy could be used, where the four 3 MW generators are complemented with four more 3 MW generators. This would provide an absolute backup in case all of the four generators fail. This is similar to Tier 4 systems. [25] [26]

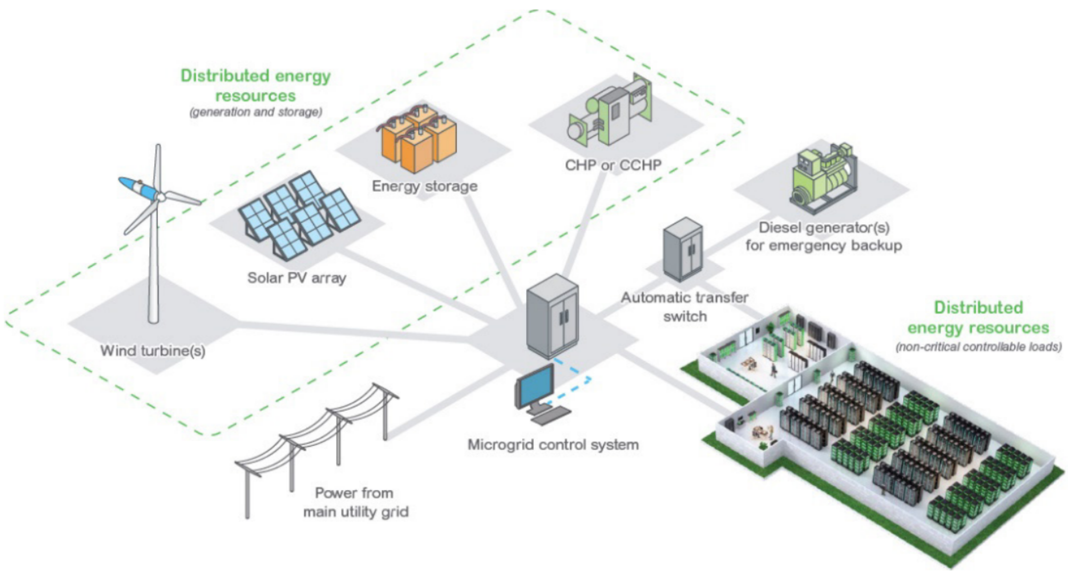

Figure 7: Data center with power from both grid and renewable sources, alongside a generator backup [27]

It is possible to create a system where the data center is powered by the grid, and the backup generator originates from a renewable energy system, for instant a hydro power plant. This hydro power plant usually delivers power to the grid, but is connected directly into the data center and activates if the data center loses its power supply from the grid. This would be classified as a Tier 4 system or a N+N strategy. Effectively this would have the possibility to operate as a micro-grid facility, if grid power is lost, see figure 7 for an example of this. To build both a data center and a hydro power plant at the same time would be extremely expensive. The most realistic would be to find a hydro power plant with both the required capacity and willingness to join such a project. [28]

4 Energy

Energy is defined as the ability to do work. It comes in different forms and can be transferred from one form to another. The law of energy conservation states that energy cannot arise or disappear, only change form. [29]

Two concepts within energy are energy sources and energy consumption. Energy sources are energy that can be transformed into a form that humans utilize. For instant will a solar panel create electric energy from sunlight, which could be utilized by humans for domestic use. Energy consumption is energy that transitions from a useful form to a less useful form. For instants when humans utilize electricity to cook, the energy will then be transferred to heat to the food and its surroundings. [29]

Energy has a standard unit in joule (J). Other units for energy are kilocalories (kcal) used to measure energy content in food, kilowatt hours (kWh) when referring to energy supplied by energy plants, and electron volts (eV) when referring to amounts at particle levels.[29]

4.1 Heat

Heat is energy that travels from one place to another due to a temperature differences. Heat travels from a place with a higher temperature to a place with a lower temperature. The SI- unit for heat is joule (J). [30]

4.1.1 Convection

Convection is defined as the transport of energy, heat, matter or electricity from one place to another by a flow in motion. The liquid can be either a liquid or gas between two points. [31]

Convection heat transfer happens when fluid moves across a solid surface. A prerequisite for heat transfer is that there is a temperature difference between the fluid and the surface. The convection heat transfer can be observed from Newton‘s cooling law. [32]

$$q\text{“} = hA(T_s - T_\infty) \tag{3}$$

In equation 3 h is the heat transfer coefficient, A is the cross sectional area, q“ is the heat transfer flux, T_∞ is the surface temperature and T_s is the fluid temperature. [32]

4.1.2 Conduction

Conduction is explained as transfer of heat through collisions of atoms in motion. The heat is transferred along a temperature gradient from a high temperature to a low temperature place. [33]

Heat transfer in the form of conduction can be described from the equation:

$$q''_w = -k \cdot \frac{\Delta t}{\Delta x} \tag{4}$$

In equation 4 k is the thermal conductivity and $\frac{\Delta t}{\Delta x}$ is the temperature gradient. Heat transfer occurs by thermal collisions between molecules along a temperature gradient. [33]

4.1.3 Radiation

Radiation is described as the transfer of mass or energy in the shape of waves or particles, along straight lines and at high speeds. If a material is not isotropic, radiation can also move in other ways. Radiation can be used for electromagnetic radiation, radioactive radiation, acoustic radiation and cosmic radiation.[34]

Heat transfer rate in form of radiation can be found from Stefan-Boltzmann law of radiation [35]:

$$\frac{Q}{t} = \sigma\epsilon A T^4 \tag{5}$$

In equation 5 ϵ is the emissivity, A is the surface area, σ is the Stefan- Boltzmann constant and T is the absolute temperature in Kelvin [35].

4.2 Free convection

As mentioned above, as a fluid in motion interacts with a medium with a different temperature, heat transfer will happen due to convection. The fluid in motion may be caused by a fan or pump and this is called a forced convection. When convection occurs in situation when there is no external force, its called free or natural convection. [32]

$$\frac{\delta\rho}{\delta T} < 0 \tag{6}$$

The correlation between temperature and density shows that the density decreases as the temperature rises, showen in equation 6. When there is a density gradient in an gravitational field, buoyancy will occur. Denser air will be pushed down, and the less dense hotter air will be pushed upwards. Free convection transfers heat in two ways. By thermal diffusion, which is the random motion of molecules. Advection is the second, which is a phenomenon by the large scale motion of current in a fluid. [36]

To change the density of a fluid there are two ways: change pressure or temperature. By increasing the temperature the density falls, by increasing the pressure the density rises. The magnitude of the free convection heat transfer is decided by the flow rate. The more molecules in motion, the more heat is able to be transferred. [36]

To calculate the heat transfer in natural convection, the calculation is based on experimental data. The Nusselt number is used to calculate the ratio between the heat the fluid convected, and the heat conducted within the fluid. In terms of free convection, Rayleighs number is often used. The correlation is shown below:

$$Nu_x = C * Ra_x^n \tag{7}$$

The number of C, in equation 7 depens on the geometry of the surface. N is a constant depending on the flow regime. Varying from laminar to turbulent flows. [36]

Free convection concept could be utilized when having a source of hot fluids, which could provide heat within buildings or etc. Instead of pumping the fluid in, one could heat the system from the bottom. This only by utilizing the free flow of hot air into the system. [36]

4.3 Heat loss by distribution

Heat loss by distribution depends on thickness, insulation material, temperature of energy carrier and ground temperature. The loss is also determined by resistors R_i, R_m and R_s. R_i is heat resistance through the insulation and determines heat leakage from the pipe. R_m is a resistance in the ground in series with R_i, and a function of the ground‘s nature and moisture content. R_s is a resistor placed between the tour pipe and the return pipe. [37]

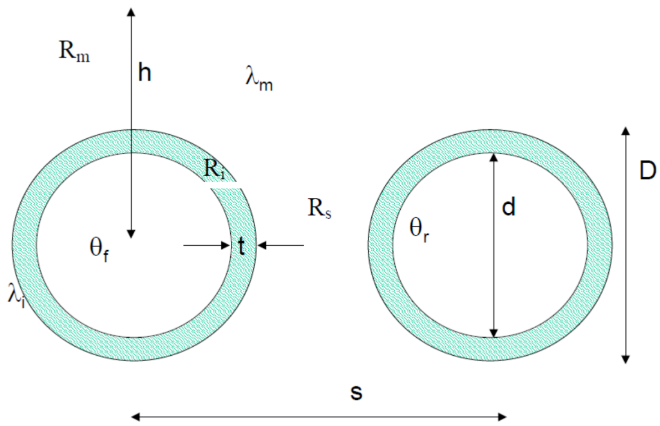

Figure 8: Cross section of district heating pipes [37]

Figure 8 visualizes the different parameters in heat losses due to distribution.

$$Q_{vs} = \frac{L\pi d \cdot (\theta_f + \theta_r)}{R_m + R_i + R_s} \tag{8}$$

Equation 8 shows the formula for total heat flow Q_{vs}. L is the length of the pipe in meters, d is pipe diameter, θ is temperature difference between the medium in the pipe and the ground temperature, R_m is ground resistance, R_i is insulation resistance and Rs is the resistance between the pipes.[37]

$$R_m = (d/2\lambda_m) \cdot ln(4h/D) \tag{9}$$

$$R_s = (d/2\lambda_m) \cdot \sqrt{ln(2h/s)^2 + 1} \tag{10}$$

$$R_i = (d/2\lambda_i) \cdot \sqrt{ln(D/d)} \tag{11}$$

The equations 9, 10 and 11 displays formulas for ground resistance R_m, resistance between the pipes R_s and insulation resistance R_i. In the formulas, λ_m is the thermal conductivity of the field, λ_i is the thermal conductivity of the insulation, h is the distance between the pipe center and the ground surface in meter, S is the center distance between the pipes, d is the inside diameter of the of the pipe and D is the outside diameter of the pipe. [37]

4.4 Heat exchangers

Heat exchanger is a device used to transfer heat between different mediums. Typical mediums are gasses or liquids. The mediums exchanging heat may be separated by a wall, or in direct contact with each other. Heat exchangers are specially useful in systems where heat is needed in one location, and in excess in another. When transferring heat in a heat exchanger there are different designs, depending on the fluids interacting and the location. There is normally two different ways of categorising a heat exchanger, by the ways of flows and of the equipment used for construction. Cross, parallel or counter flow are examples of flow categorization. By equipment its normal to divide into regenerative or recuperative, where recuperative has a separate flow path and the heat is being exchanged through a surface in between. In regenerative, the flow has a single path where the hot and cold alternately flows within. [38]

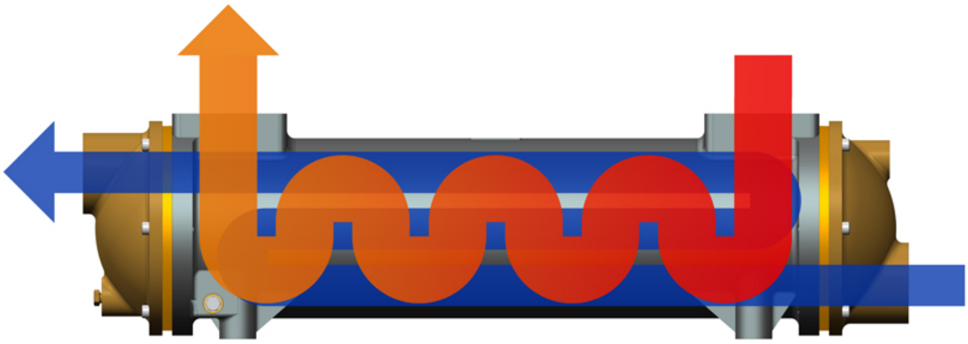

Figure 9: Parallel flow heat exchanger [39]

Figure 9 shows the concept of a parallel flow heat exchanger. Cold water flows to the left, being heated up by the hot water flowing in the same direction. The hot flow is being cooled down. For the system the concept of energy balance stands. The most efficient heat exchanger is considered to be the counter flow heat exchanger. As the name suggests, the streams of fluids are flowing in opposite direction causing the heat to be transferred more efficiently. [36]

$$Q_{in} = Q_{out} \tag{12}$$

As seen in equation 12 the energy entering the system, equals the amount leaving. This originates from thermodynamics first law. When there is no work done on an adiabatic system the amount of heat entering, is the same as the amount leaving. For a heat transfer to happen, it also depends on a temperature-difference between the two fluids. And as the second law of thermodynamics states, the heat will always go from the highest temperature to the lowest. [40]

$$\dot{M} \cdot (H_{c1} - H_{c2}) = \dot{M} \cdot (H_{h2} - H_{h1}) \tag{13}$$

As seen in equation 13, the energy transferred depends on the change in enthalpy for the cold and hot stream. It also visualizes that the amount of heat transferred also correlates to the mass flow. The higher the flow, the more energy is transferred between the two flows. [36]

$$\dot{Q} = c_{p,air} \cdot \dot{m}_{air} \cdot (T_{air,in} - T_{air,out}) \tag{14}$$

Equation 14 returns the extracted or injected energy when moving air through a heat exchanger. Variables are heat capacity of air, $c_{p,air}$, mass flow rate of the air, $\dot{m}_{air}$, temperature of the air when entering and exiting the exchanger, $T_{air,in}$ and $T_{air,out}$. [36]

For a system using a heat exchanger the requirements and needs of the application, determines the type of heat exchanger. As an example it could be the thermal output of a system. Within a high energy factory it could generate a lot of heat as a product of its processes, and it would need to remove this to keep a steady process over time. Then it would need a heat exchanger with high conductivity and one who handles high pressure. Then a double pipe system could be optimal. For a laboratory, where energy recovery is installed, where chemical processes are conducted, it would need a system where there is no contamination of the air coming into the room. Contamination could possibly lead to critical health hazard. [41]

4.5 Heat pump technology

A heat pump can move heat from low to high temperatures. This happens by adding energy to drive the system. The equipment can be used both for cooling and for heating a room. Heat pumps are widely used for cooling in, for example, the air conditioner or refrigerators. For heating, one example is upgrading the heat to desired temperatures. Heat pump is very beneficial to use if a combination of heating and cooling is required at the same location. This will lead to a doubling of the cost-effectiveness of the installation. Renewable energy from ground, air, water and waste heat sources are energy sources used in the heat pump. [42]

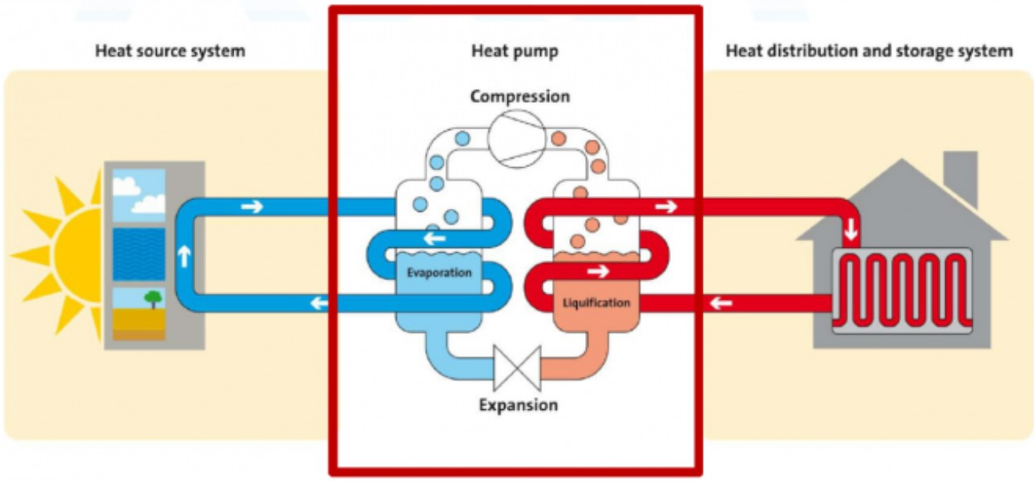

Figure 10: Heat pump [43]

Figure 10 shows a heat pump system.

4.5.1 COP factor

Coefficient of performance (COP) says something about how efficient a heat pump is. The power supplied to the compressor W is analyzed to the ratio of to the heat output from the condenser Q.[44]

$$COP = \frac{Q}{W} \tag{15}$$

Equation 15 shows that COP can be calculated by dividing the heat output Q by power supplied W. [44]

5 Cooling solutions for data centers

Cooling technology is important to ensure steady operations of data centers. Efficient cooling systems can reduce energy consumption and improve the utilization of surplus energy. This is done by capturing the heat at higher temperatures. There are various forms of cooling systems for data centers today. Examples are air-based cooling systems, liquid-based cooling systems and two-phase cooling. Figure 11 represents the view as one would walk down between the racks in any given data center. [45]

Figure 11: Inside a data center [46]

5.1 Deciding factors

The main deciding factors towards data center cooling are reliant upon the capacity and the density of the data center. When both the capacity and the density are high, the subsequent cooling requirement is also at its highest. If neither one are high, then the cooling requirement is equally low. The heat dissipated from lighting and personnel operating the data center must also be accounted for when calculating the cooling load. Equally important are the thermodynamic properties of the data center facade. [47][48]

5.2 Air-based cooling systems

In air-based cooling systems, cool air is released into the server rooms to withdraw heat. Server racks are placed in hot and cold corridors, to control the air flow and avoid mixing hot and cold air. In figure 12 an air cooled rack is seen through a thermal image. [49]

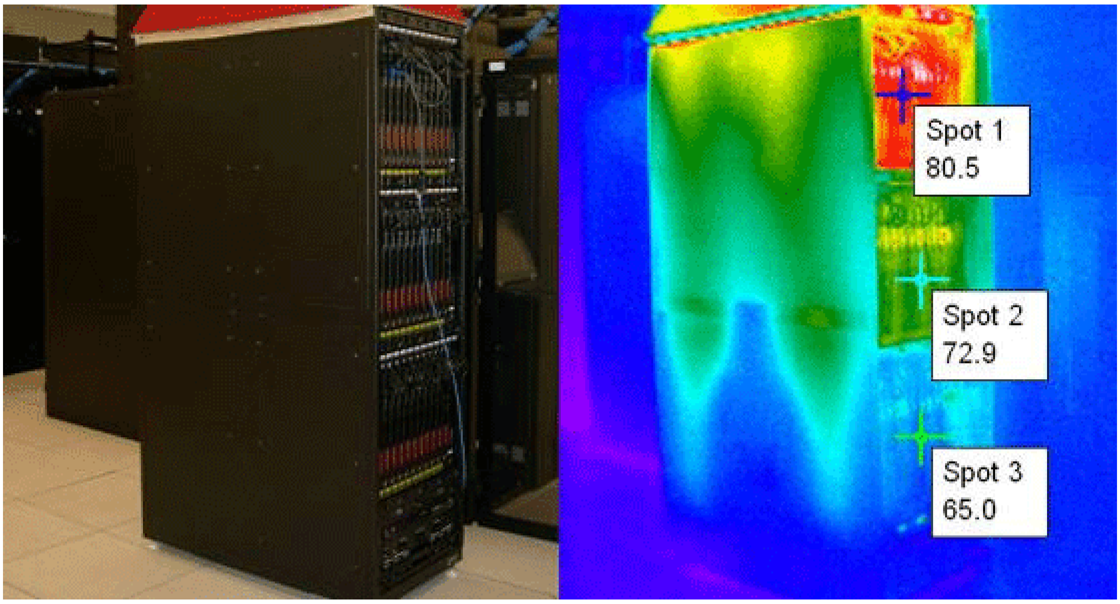

Figure 12: Thermal view of a rack [50]

Today most of the data centers use air-based cooling solutions. The reason for this is because these are cheap and easy to operate. A disadvantage with the solutions is the low heat capacity and heat transfer coefficients, as seen in figure 12. Evidently the top rack is cooled less than the bottom rack. This makes it difficult for the air on top to transfer sufficient heat. This results in high energy consumption, low cooling efficiency and limitations towards the density of servers. [49]

5.3 Current systems and methods

The cooling system most frequently used today is air to air cooling. Various streams of cold air are passed through the racks of the data center. This helps cool down the servers by transporting the hot air into a cooling unit. A system which is becoming more and more popular is air to fluid cooling. Here the hot air transported from the server room are exposed to either a free-flowing source or a closed source of fluid. The hot air transfers heat to the fluid, and then returns to cool the racks. [49]

5.4 Legacy contra aisles design

Legacy data centers are usually designed with racks all facing the same direction. This leads to the warm air from the first racks to be absorbed by the second racks, and so on and so forth, as seen in figure 13. This results in a cooling solution which relies upon a high density of cooling units. As a result of many cooling units, nearly 1 per row of racks, a high energy consumption is expected. [51]

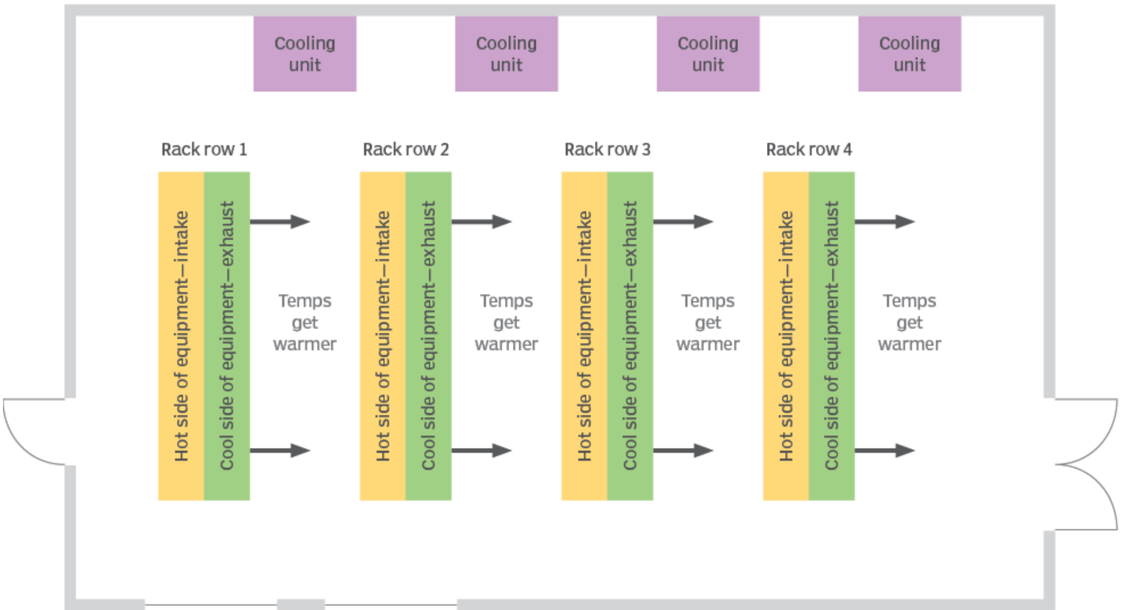

Figure 13: Legacy layout of a data center [51]

A method known as cold aisle/hot aisle have been developed to improve the efficiency of the cooling of data centers. As opposed to the legacy design, the racks are placed with their fronts facing each-other to create closed aisles where there is cold air flowing in and hot air going out. A hollow floor and roof are utilized to transport the air, both from and to the aisles. The cold air is brought through the floor and into the cold aisle where the air flows through the racks, cooling down its components before it rises to the roof. The air is then brought through the roof to the cooling unit. Empty racks are occupied by blanking panels to maximize the efficiency. A blanking panel is usually just a plastic cover to prevent the air from flowing through the empty racks. To achieve the full potential of cold aisle/hot aisle cooling, a high number of cooling units are still needed. But fewer than with the legacy design.[51]

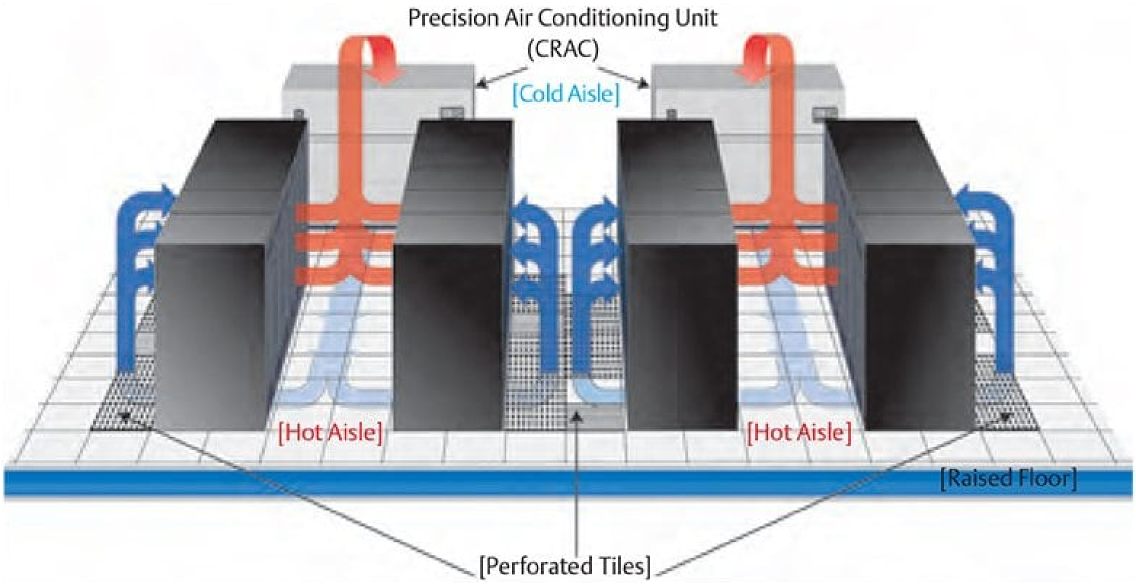

Figure 14: Hot aisle/cold aisle layout of a data center [52]

Figure 14 visualizes the hot aisle/cold aisle layout. In relation to every two rows of racks a designated CRAC unit is implemented.

5.5 Chilled-water system

A chilled water system removes heat from the air by circulating cold water inside the walls of the server room. The water then rids the energy by transporting it to a cooling tower or similar. This system is suitable for mid to large scale data centers and is generally more cost effective at locations with colder climates. It is also possible to diminish the costs further by designing the cooling system as one closed system, rather than designing many smaller systems. [53]

5.6 Evaporative cooling

When hot air is cooled by evaporating water it is called evaporative cooling. A membrane is soaked with water, and then the hot air from the data center passes through it. The water in the membrane evaporates and the air cools down. To ensure an even spread of water on the membrane a special water delivery system is required. This cooling method is most effective at high temperatures and with dry air, thus a good match for a data center. [54]

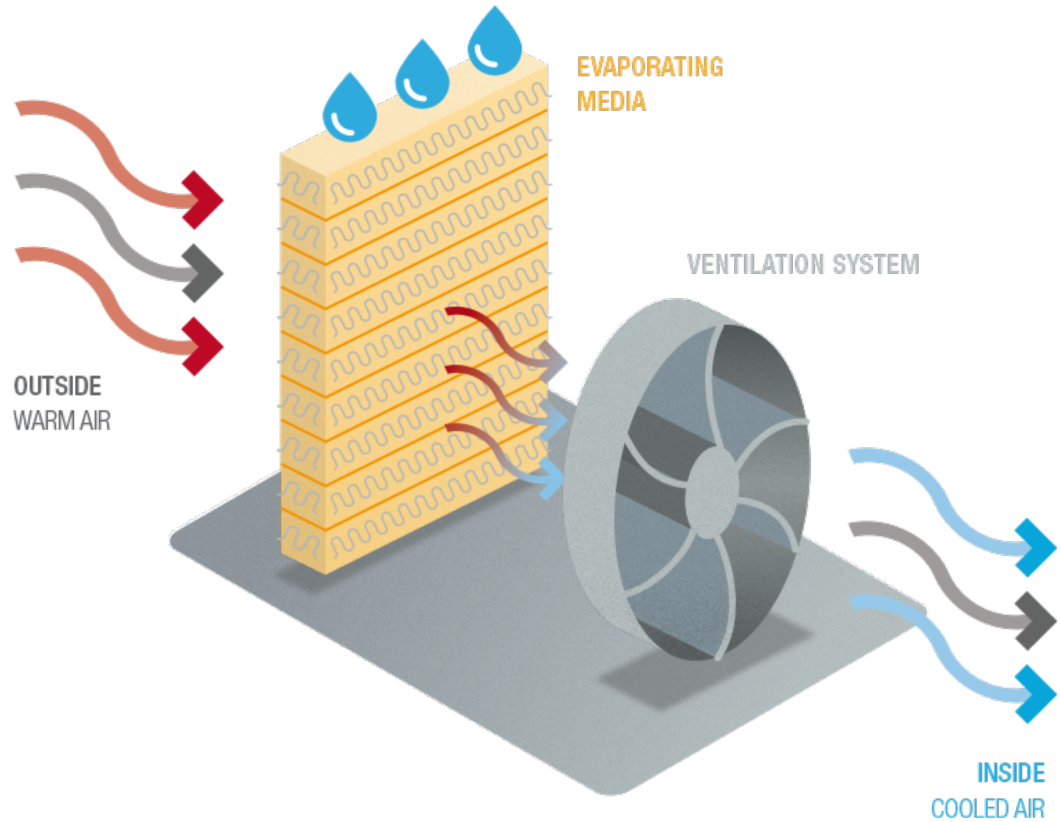

Figure 15: Schematic of evaporative cooling [55]

Figure 15 visualizes the steps in evaporative cooling.

5.7 Free cooling

Free cooling is a cooling method best suited for a cold and dry climate. When the air is cold and dry it is possible to use the outside air directly inside data centers. This is the most cost-effective way to cool down data centers, when optimized. However this also poses the greatest risk to the hardware. [56]

5.8 Liquid-based cooling systems

Even though the air-cooled data centers have evolved and become a lot more effective in recent years, the future lies with liquid cooled systems. The air-cooled systems require a lot of energy and space to operate. When utilizing air based cooling the hardware has to deal with humid air, which can cause corrosion. Implementing liquid cooling is a lot more effective. Earlier when liquid cooling still was an early science, it was expensive and troublesome. But as the technology have developed over the years it has become cheaper and more reliable. Two of the most common liquid cooling technologies are immersion cooling and Direct-to-Chip cooling. [49]

In fact, in accordance to a study performed by Microsoft, immersion cooling could also reduce the maintenance and downtime of the servers by submerging them in a liquid. Microsoft built two identical sets of racks where one was destined to run on land, and the other one to run in a nitrogen filled tank on the seabed. The land based racks had eight times as many failures as the submerged racks, during the same time span. This was due to, as theorized by the researchers, the less corrosive nature of nitrogen compared to air and the lack of physical human interaction. This is not a direct analogue to immersive cooling, but the results are transferable. Specifically, the corrosive effect of air is negated by the liquid which the hardware is immersed in, as well as reducing the impact of direct human interaction. [57]

5.9 Immersion cooling

Immersion cooling is a cooling technology where the hardware is immersed in an open or closed bath of some dielectric fluid. A dielectric fluid is a fluid which has a high resistance to electrical breakdowns. It‘s thermal conductivity and specific heat capacity are higher than that of air and is therefore more efficient at removing heat from servers. Immersion cooling can be separated into two, single-phase cooling and two-phase cooling. Single-phase cooling happens in an open bath, where the fluid stays in the liquid state. The fluid in the bath is subject to a heat exchanger, and a coolant which is cooled by a cooling tower. One possible setup for single phase immersive cooling is presented in figure 16. [58]

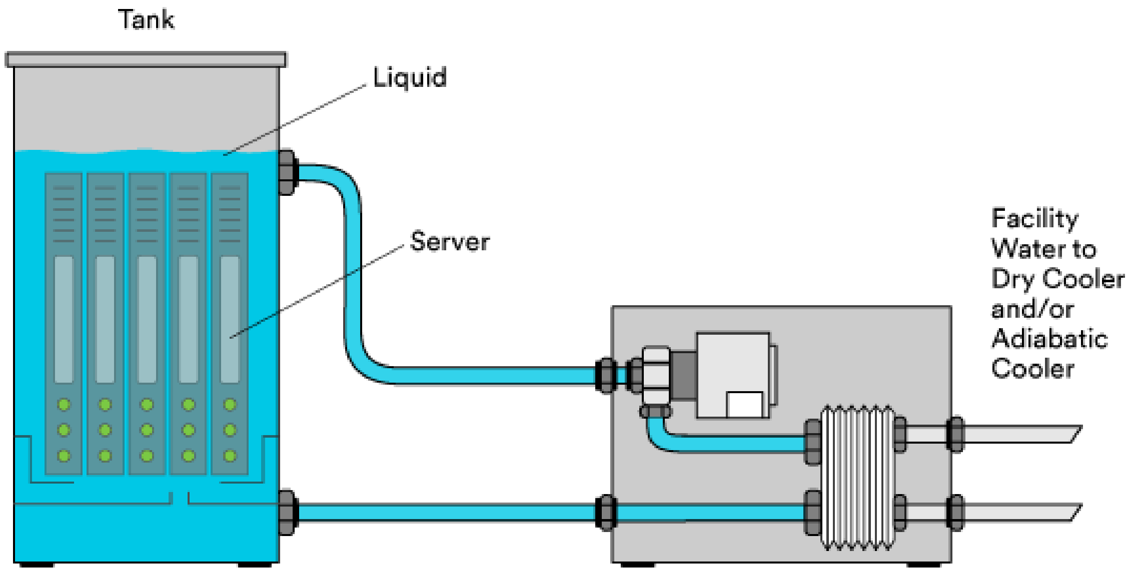

Figure 16: Single phase immersive cooling [59]

Two-phase cooling happens in a closed bath, where the fluid's properties give it a boiling point lower than 100℃. As the hardware heats up the fluid inside the closed bath, the fluid evaporates up into the top of the container. The top is connected to an absorbing material with a condenser integrated. The condenser is cooled by an external coolant, as seen in figure 17. The evaporated fluid condenses and rejoins the bath, thus cooling down the hardware. [58] [60] [61]

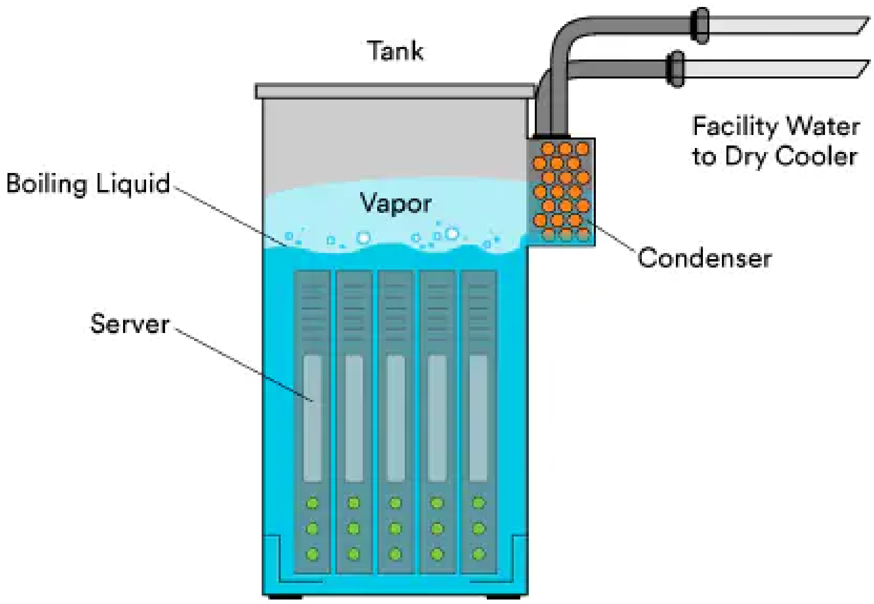

Figure 17: 2-phase immersive cooling [59]

5.10 Direct-to-Chip cooling

Direct-to-Chip cooling is a liquid cooling which relies on a cooling loop attached directly onto the hottest parts of the hardware, for example a motherboard's chips as seen in figure 18. The loop is attached to a larger system which either exchanges the heat with an external loop, or directly to the outside air. Another loop can be a chilled-water loop or similar. This requires a lot of fine tubing but is overall one of the most effective methods to cool down hardware. [62]

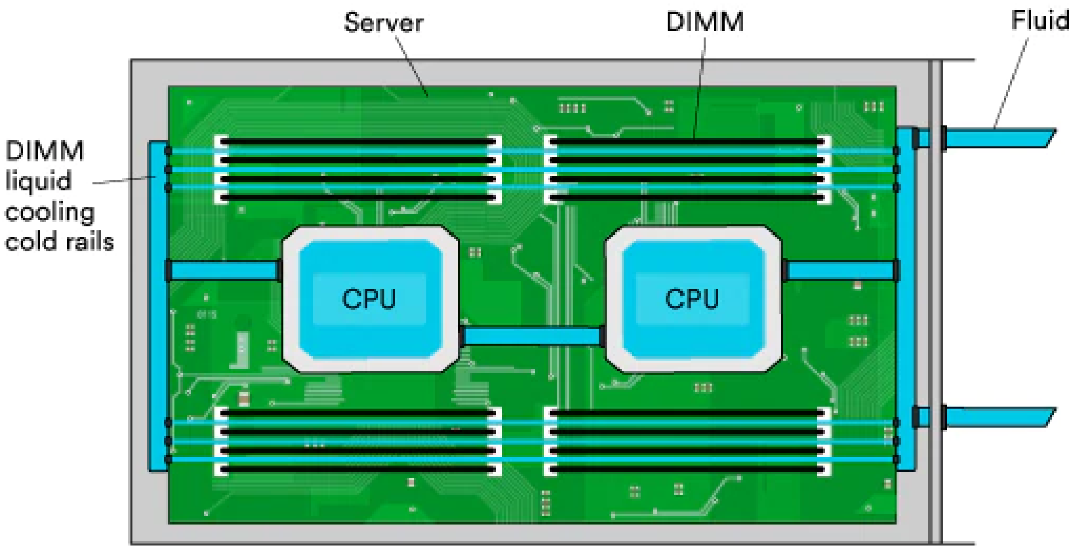

Figure 18: Direct-to-chip immersive cooling [59]

5.11 Comparison

Table 2: Retrievable temperatures of the different cooling methods [60]

Temperature [°C]	Cooling method
60	Direct-2-Chip cooling Immersive cooling
50	Chiled water system
30	Air-Air cooling, aisles
20	Air-Air cooling, legacy, Free cooling

Table 2 presents the exhaust temperature of different cooling solutions. The liquid cooling solutions tolerate higher temperatures than the air cooling, but require a very different setup. Thus, what is best for a data center is not always the method that can operate at the highest temperatures. [60]

6 Excess heat

Excess heat is also known as waste heat, which is thermal energy that is a bi-product of an industrial process. In Norway the traditional industry producing excess heat has been aluminium production, but lately data centers have become a larger producer of excess heat. Excess heat from high intensity industry could prove valuable in form of heating or by supporting less energy demanding industries. The utilization possibilities depends on the temperature of the heat and the heat reuse technology.[63]

6.1 Excess heat in Norway today

Norsk Energi, in collaboration with New Energy Performance AS (NEPAS), conducted a potential study for the utilization of waste heat from Norwegian industry in 2009. Industries such as wood distribution, chemical industries, ferro-alloys, aluminium, food, cement and leca, and other industries participated in the study. [64]

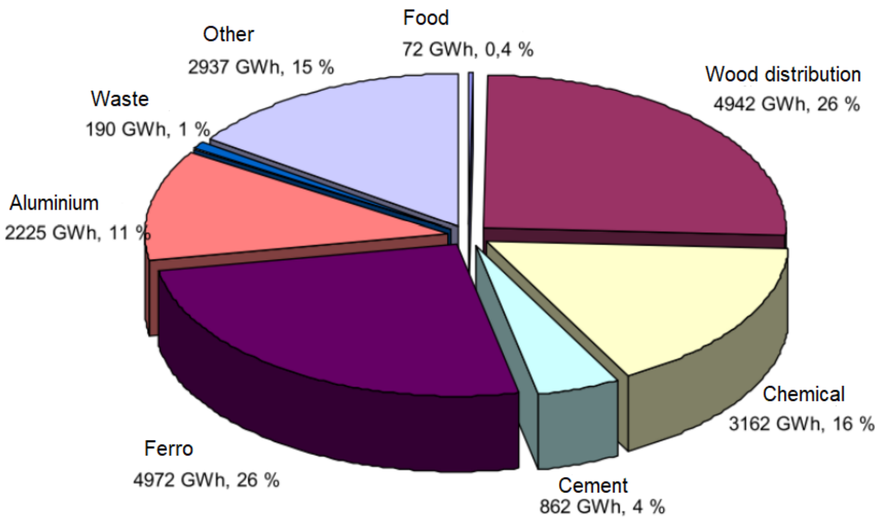

Figure 19: Waste heat potential in Norway by industry [64]

The figure 19 shows the waste heat potential in Norway in GWh and percentage by industry. A total of 72 industries participated in the study. The energy use was 53,7 TWh. For heat sources above 25 degrees, the waste heat potential was calculated at 19,4 TWh/year. Heat sources with temperatures of 60-350 degrees had a potential for power production of 250 GWh/year. [64]

Table 3: Temperatures and waste heat [1]

Temperatures	Purposes	Waste heat potential 2009
>140 °C	-Power generation -District heating	7,0 TWh
60-140 °C	-Power generation -District heating	3,1 TWh
40-60 °C	-Low temperature district heating - Heat source for heat pump with good heat factor	5,8 TWh
24-40 °C	-Fish farming -Geothermal heat -Heat source for heat pump	3,3 TWh

The table 3 presents waste heat potential at different temperatures and numerous of industries operating in the temperature range. It can be observed that the total waste heat potential of 19,4 TWh extends over four temperature ranges. Since the data is collected from 2009, it can be assumed that the surplus heat potential from Norwegian industry is higher per 2022. This is a result of the development of new industries such as data centers.[64]

Technology development in several areas is necessary to be able to utilize the waste heat in an optimal manner. Examples are power production from heat sources with temperatures lower than 60-70 degrees, heat pumps for high temperatures, power production from waste heat sources down to 60-70 degrees and low-pressure steam turbines in Norway. [64]

6.2 High grade

High grade waste heat is considered as waste heat with a temperature above 400 degrees Celsius. This grade of heat is mostly linked to ferrous and non-ferrous industries with both high energy demanding and advanced processes. It is generally considered easier to utilize waste heat with high temperatures, as opposed to waste heat with low temperatures. When used alongside a heat pump, high grade waste heat can be used to pre-heat to cover the heat demand of other industries. For example, the heat waste from ferrous industry can be used to pre-heat the water into an electrically powered steam turbine by a passive heat exchanger. This reduces the total required energy and makes the initial ferrous industry more sustainable. [65]

6.3 Medium grade

Medium grade waste heat is considered as waste heat at temperatures between 100 and 400 ℃. This grade of waste heat is often a product of food and chemical processing industries. The largest economic benefits are associated with the medium grade waste heat, as this thermal energy is compatible with many other processes, such as district heating. When the temperatures are so high, it is more convenient to distribute the energy carrier. This is due to the high energy flow rate at a low mass flow rate. [65]

6.4 Low grade

The term low grade waste heat is used to define the waste heat with temperatures below 100 ℃. This grade of heat is a product from most low-end industries and general buildings, such as data centers. Low grade waste heat is regarded to have the least economic benefits, as it requires a heat flow with a high density and a recipient with a continuous need. [65]

When considering low grade waste heat used from a data center, it is practical to classify the temperatures obtained further. Most often the hot aisle in data centers operate between 25 ℃and 45 ℃. By laws of conservation of energy, the energy dissipated by the data center cannot be fully utilized by the recipient. This is of course depending on the cooling and transportation technology, and the proximity and the need of the recipient. [65]

6.5 Evaporation

Evaporation is a form of vaporization that occurs on the surface of a fluid as it changes into the gas phase. Evaporation happens at all temperatures between the boiling point and the freezing point of the fluid, but at a higher frequency the closer to the boiling point the temperature is. As mentioned earlier, evaporation can also be utilized as a cooling method, e.g. sweating. Evaporation is caused by the addition of energy by convection to liquid molecules, which in turn causes the temperature and kinetic energy levels to rise, leading the molecules to break the force of attraction imposed on them and transforming into gases. The surface area is an important factor for the amount of evaporation. Therefore, a hot stream of air exposed to a fluid over a large area results in a higher grade of evaporation than a cold stream of air exposed to a fluid across a small surface. Another important factor is the relative humidity. The air is able to sustain a higher evaporation if the relative humidity of said air is low. This is due to air with a high relative humidity being closer to being saturated, i.e. reaching its max potential fluid absorption. [66]

7 Industries operating in low heat

To create an industrial symbiosis between excess heat from one industry to a receiver its important to analyze the different industries operating in the temperature range. In the same temperature range, the heating mechanism vary a lot. With different operations, there are different criteria to flowrate, humidity levels and temperatures. [67]

Table 4: Temperatures and applications [67]

Temperature range	**Process**	**Example**
$100-80°C$	Pasteurization	Dairy
$80-60°C$	Drying	Bricks, algae, grain
$60-40°C$	Pasteurization	Beer
$40-20°C$	Aquaculture	Fish farming
$40-20°C$	Greenhouse	Tomato, cucumber and salad
$20-0°C$	Cooling	Processes in industry
$20-0°C$	Melting snow	Underheating a football field or the street

Table 4 shows temperatures for different processes and their area of application. As visualized, the processes vary from 0-100 ℃. From the highest industries operationing in 100 ℃like pasteurization to melting of snow from football fields or others which needs approximately 10 ℃. To operate these processes in a cold climate in northern Europe it needs a lot of energy. With energy usage comes emissions. Energy and emissions could have been cut considerably if waste heat from industry had been utilized on a larger scale. This excess heat could replace the combustion of natural gas used in processes such as pasteurization of milk, drying of products and cultivation of plants today. By utilizing waste heat it also could lead to lowering the investment in the local electricity grid and a higher delivery security. [67]

There is a lot of unused low-temperature waste heat in the Norwegian process industry. Low temperature waste heat can be used for drying products, in greenhouses and in dairy processes. For example, a lot of food production takes place at temperatures around 100 ℃, such as pasteurization of milk. Drying of wood and bricks also takes place at a little over 100 ℃. In addition, growing plants in greenhouses happens at around 15-25 ℃. [67]

7.1 Greenhouses

A greenhouse is a facility which ensures a regulated climate optimal for photosynthesis in plants to be executed. Humidity, temperature, CO_2 content and light are controlled and optimized in the greenhouse. This is done to achieve the best possible conditions for growing plants. Greenhouses that only use sunlight for heating are called cold houses. Most greenhouses are constructed of iron or aluminium. Roofs and walls in the greenhouse are made of glass or duct plates. The material in duct plates can be of either acrylic or poly-carbonate. [68]

Figure 20: Greenhouse in Gotham Greens in New York [69]

Figure 20 shows an example of a large greenhouse. In Norway, the area used for professional cultivation is around 1700 acres per 2018. This is a reduction of 16.5 percent from 2010. As of 2018, there are 309 agricultural holdings with greenhouses. Compared to the level in 2010, is this a reduction of as much as 51,5 percent. Tomatoes, cucumbers, lettuce and flowers are grown in greenhouses in Norway at 15-25 ℃. The greenhouse industry is largest in Rogaland, but is also big in Viken and Oslo. 80 percent of the total tomato production takes place in Rogaland, as well as a quarter of the total greenhouse area. [70] [68]

Greenhouses require approximately 350 kWh / m^2 heat supply per year.The heat comes different sources. Examples are waterborne heating in pipes that maintains a temperature of around 80 degrees Celsius. Low temperature waste heat can be utilized as a source for heating in greenhouses. One possibility is utilizing heat pumps. The heat pumps raise the temperature to a range that greenhouses uses for heating. [71]

Greenhouses uses a lot of energy both for heating and lighting. Therefore, it can be interesting to look at the Norwegian power price to analyze different locations. Norway is currently divided into five price areas for electricity. Northern Norway is in price area 4. The power price in Norway is closely linked to the amount of precipitation, and the resulting amount of water in the reservoirs. In southern Norway, the power price is also dependent on the European power market. The power price in northern Norway (area 4) was at an average of 0.36 NOK / kWh in 2021. The power price is more stable and predictable compared with southern Norway, because it does not depend on the power market in Europe. [72]

7.2 Drying of biomass

As seen in figure 2, approximately 7% of Norways total energy consumption originates from biomass. This accounts for about 15 TWh. This amount is substantial, mostly originating from burning wood for domestic heating. For heating in domestic usage, bio-energy is a great alternative to electricity, as the demand for development and scaling over time is negligible. In the opposite part of the scale, a further increase in electricity usage will lead to higher cost and pressure on the power price. Bioenergy also has a neutral climate footprint, meaning it will lead to a decrease in emissions in relation to heating originating from fossil fuels. [5]

The quality of biomasses for combustion mostly depends on the moisture levels. To decrease the moisture level of the biomass, its essential to dry it before combustion. This will to reduced weight and lead to more of the energy will go to heat, instead of energy to evaporate water. This leads to a higher calorific value and leads to biomass becoming a more valuable fuel. Research done by Skog og Landskap in the western part of Norway show that the calorific value of chip increased with 57% over three days. This shows the great potential the industry brings.[73]

Figure 21: Drying of biomass in Ringerike Norway [74]

Figure 21 shows the drying facility in Ringerike, where they utilize waste heat from one data center. By drying biomasses it increases energy content and lowers the weight, due to the water evaporation. To ensure economic sustainability in drying projects, its important to dry in high quantities. There is a large logistical component related to freight of the raw material. Utilization of biomass to energy is related to many Norwegian and international sustainability goals. This shows the importance of awareness and investment in facilities for drying of biomasses. As the heat source in this symbiosis is in excess, the utilization leads to a more circular energy system.[75]

7.3 Algae cultivation

To ensure a drastic revolution towards sustainability, the world could utilize an ancient natural resource: algae. Recent research on the aquatic organism has shown that it contains a large amount of useful resources which could be utilized for fuels, feed for fishes and many more areas of applications.

Regarding the preceding revolution in the transport sector where the classic fossil fuels vehicles like diesel and gasoline, are changing to renewable energy-technologies to ensure a sustainable transport8 sector. One technology which could prove to be important is biofuels. Biofuels originates from various raw materials, depending on the extraction method. One could produce ethanol by fermentation of sugars, or by extraction of oils from the separated triglyceride from the algae. These fuels are considered renewable, as long as it planted the same amount which will capture the amount of carbon dioxide emitted when combusted. [76]

(a) (b)

Figure 22: (a) Algae production steps, and, (b) Algae Hawaii facility [77][75]

To cultivate algae, there are several steps which operates in the low heat segment. To grow algae, there is four products needed: light, water, CO_2 and nutrients. The optimal temperature for algae cultivation is between 16-26 ℃. To create a phototropic growth, the two most important nutrients are Phosphor and Nitrogen. To ensure low costs, its most economical with a free access of the important nutrients, here wastewater is really interesting. With high values of these nutrients, which has no value for companies could be utilized in this process. As for lighting, algae cultivation optimizes when the pigments in the cell receives lighting with 430-600 nanometer. This equals red, blue and yellow lights. As for CO_2-concentration the optimal scale is about 1%. As seen in figure 22(a) there are several steps after the cultivation is done. All steps after this has one thing in common: to increase the TS(total solids). With increasing temperatures, the faster the cultivation will dry out, and more lipids could be extracted. [78] [75]

To create biodiesel from the algaes, there is a need to extract the lipids from the biomass. This could be done in two ways: by using a solvent, or by solvent-free solutions. The main goal by extraction is to disrupt the cell structure, and extract the lipids. Researchers have experienced that by using a solvent, there is many negative consequences. For instance they experienced a local intoxicated environment, which could be dangerous for the scientists. It also created a toxic waste, which could not be reused for any purposes. Other solvent-free solutions like mechanical, microwave-assistant, osmotic shock all prove to extract lipids in a good manner. By solvent-free extraction, a reusable bi-product is created with important nutrients which could be utilized by humans or as animal feed. All solvent-free extraction methods are all expensive and hard to scale up to an industrial feasible level. [79]

The Norwegian government has stated that they stand by their goal to reach a zero emission-society. As an important factor to reach that goal they have stated that biofuels will be an important path to reach the goal. Especially heavy traffic like trucks and airplanes could benefit from utilizing biofuels. To ensure a steady flow of fuels, the Norwegian government is especially interested to invest in a local value-chain for biofuels. This would lead to an economical boost, and more sustainable transport sector. [80]

In 2016 a test facility for the cultivation for algaes was opened. In Mongstad in Norway a 200 m^2 greenhouse was opened. The facility utilizes waste heat from Mongstad oil refinery for heating. Since the opening the facility has been a great success and produces about 40 kilos of mikroalgae-pasta each week. By placing the facility next to Mongstad oil refinery it has a large excess of CO_2 available. By photosynthesis, the algae works as a CCS by the way it binds it in its cells. This could possibly be a great solution for different industries to become more eco-friendly and reducing the overall emissions. The two mentioned above are just some of the utilization opportunities for algae usage. Other areas of implementation are: food applicants, fertilizer, pharmaceuticals, or food colorants. The opportunities are massive, and algae could be a large contributor to reach the SDG goals. [81]

7.3.1 Algae cultivation parameters

Regarding the cultivation of algae on an industrial scale, its normal to categorize into two systems: open and closed. As seen in figure 22(b), its an open system in touch with the natural surroundings. This makes it an open system. A closed system occurs in tubes, bags or plates. In a closed system it is easy to control all parameters. But it consumes more energy. Open ponds are regularly in operation in areas where the climate allows it. In an open pond solution, its normal to pump CO_2 into the water to make the concentration high enough. One large problem with open pond system, is that a large amount of the sunlight goes to evaporation of the water, and not to the algae cell. For lighting, a Greece research team concluded that the spectrum for maximal growth was between 130-520$\mu mol/m^2$ per second. With increasing lighting intensity gave higher Lipids percentage. Open ponds system are usually equipped with a paddlewheel which rotates and makes sure the right mixing and flow rates are present. A report by Laboratory of Air Pollution and Climate Change and others stated that the stochiometric relationship between algae absorption and CO_2 is 1.92 gram CO_2 pr algae produced. To estime the production its hard to say precisely, but for open ponds system, its normally to assume about 0.05-0.5 g/L per day of algae production. [75] [82] [83]

7.3.2 Algae utilization in fish growth

In addition to biofuels algae could also be utilized in the feed stock for fishes. The algae contains a vast amount of the fatty acids EPA and DHA. These are a substantial source to Omega-3 for food processing. To this day fish oil and fishmeal from Chile is being utilized as a source for Omega-3 for farmed salmon. This comes with a substantial negative environmental aspect to it. [84] [85]

7.4 Fish farming

For Norway fishing has been an important industry for decades. In the latest years, fish farming has had an incredible increase in the country. It's actually the fastest growing sector in food production globally. In 2021 Norway exported seafood for 23.6 billion NOK, with the majority income originating from salmon. As fish farming generates a lot of value for Norway, however it comes with some disadvantages as well. Fleeing, soy usage, utilization of important resources like phosphor and significant emissions related to transportation are all big problems for the industry today. As a solution to these problems, a new industry has been growing lately: land based fish farming. Here one could reuse the important resources, and there would be none local fleeing of salmon or pollution on the bottom like today. Land based fish farming can operate with water temperatures from 10℃to 40℃, depending on the reared fish. When rearing fish on land it opens up possibilities to recreate tropic climates in northern regions. This could possibly lead to farming of tuna, catfish and tilapia. Meaning the import would decrease, and emissions could be lowered. [86]

Figure 23: Fish farming facility in Nigeria [87]

Figure 23 visualises an example of a land based fish farming facility. As of today the Norwegian data center-company Green Mountain is planing a facility in cooperation with Hima seafood for utilizing waste heat to farm 9000 tons of trout annually. This lowers the total energy usage, when the waste heat is being reused. For fish farming onshore the opportunities in Norway are vast. Available land and low energy prices makes Norway optimal for the industry. [88]

When rearing fish it is important to control the water temperature to make sure the water stays inside the preferred temperature range. The pen is heated by makeup water, which is heated to the appropriate temperature by a heat source. The water is brought into the pool from an external source and afterwards it can either be released or reused. Reusing the water may benefit the costs towards heating and feeding the fish, but it does require a higher degree of technology to operate. Furthermore, a fish rearing which rears freshwater fish may draw makeup water from either a freshwater bedrock basin or a free stream. If the water is drawn from a bedrock basin, it is required to utilize technologies which adds oxygen to the water. When drawing water from a free stream (e.g. river or lake) the oxygen is already present in the water due to the nature of a stream. Additionally, the water from a bedrock basin inhabit a steady temperature all year, whereas the water from a free stream depends upon the ambient temperature of the air, i.e. the season. [86]

$$\dot{Q} = (T_{TW} - T_{MW}) \cdot c_{p,MW} \cdot \dot{m}_{MW} \tag{16}$$

The equation 16 details the factors towards the required energy for heating, $\dot{Q}$, in the rearing tank. The factors are: temperature of the tank water, T_{TW}, temperature of the makeup water, T_{MW}, heat capacity of the makeup water, $c_{p,MW}$, and, mass flow rate of the makeup water, $\dot{m}_{MW}$. [36]

7.4.1 Land-based production systems

There exist six types of land-based fish farming production systems. They are the following: FT-G, FT-P, PO, PR, PR-T and RU. FT-G, FT-P and PO are flow- through with respectively gravitational water supply, pumped water supply and pure oxygen. PR, PR-T and RU are abbreviations for partial reuse system, partial reuse with heating and reuse system. [89]

7.4.2 Water replacement

For land-based facilities, water replacement takes place in the range from 0.14-0.4 l/kg per minute. In salt water, the minimum limit is 0.2-0.3 l/kg per minute in a system with a flow and oxygenation. Minimum requirement for water replacement depends on temperatures and the water‘s buffer capacity. The buffer capacity in fresh water can be regulated by means of calcium carbonate and water. [90]

7.5 Rainbow trout

Salmon fish such as Atlantic salmon, sea trout and rainbow trout are farmed in Norway. In 2017, 65350 tonnes of rainbow trout worth 3022 million NOK were farmed. Rainbow trout is a species that has regular migrations between freshwater and seawater. A shiny salmon fish that migrates from freshwater to seawater for the first time is called a smolt. [91][92]

Figure 24: Rainbow trout[93]

Figure 24 presents an example of a rainbow trout. Rainbow trouts are characterized by a purple/pink stripe along the side. This stripe can be observed from figure 24.

7.5.1 Farming of rainbow trout

Breeding of rainbow trout begins in vessels on land, where the roe is fertilized in fresh water. The hatchlings feeds on the yolk sac, after the eggs are broken. After 30-60 days it is fed with pellets. As the fry get bigger, it is moved into a bigger tub. When the fish has been through the smoltification process and reached a certain size, it is released into cages in the fjords to grow further. The trout then stays in these cages, until it has reached a slaughter-ready size of approximately 2-5 kg. [94]

7.5.2 Water temperature

The water temperature for trout farming depends on the level of dissolved oxygen in the water. It is therefore challenging to determine the optimal water temperature. Observations and research shows that adult lake rainbow trout prefer a temperature between 7 and 18 ℃. Rainbow trout is not comfortable in warm water. Thus making exposures to temperatures above 23 ℃can be fatal for the rainbow trout. [95]

7.5.3 Smoltification

Smoltification is a process that is necessary for a smolt to have a good chance of surviving the migration from freshwater conditions to seawater. The process involves a systematic and coordinated reorganization of physiological processes and mechanisms in the rearing tank. These are to ensure that the fish can maintain a normal body function in terms of water and salt balance when transitioning to salt water. Smoltification also changes the behavior and appearance of the fish. [92]

7.5.4 Different types of smolt

There are two different types of smolt: 0-year-olds and 1-year olds. The 1-year olds have a production time of 16-18 months. They are placed in pools outside in January and therefore exposed to a natural light regime. The fish are smoltified spring naturally when the day length increases the following year. 0-year olds have a production time of 9-10 months. It became possible to produce 0-year olds in the late 90‘s as a result of the introduction of artificial lighting programs. This shortened the production time of the smolt. [96]

7.5.5 Smolt growth phases

The smolt has different growth phases and temperatures that are linked to the different phases. In the initial feeding process the smolt has a temperature of 12-13 ℃, and a size of 0-15 grams. When the smolt reaches a size of 5-15 grams, it thrives in temperatures from 10-12 ℃. In the growth phase when the smolt is 15-40 grams, optimal temperatures are 8-10 ℃. During the smolt production phase, the smolt thrives in temperatures from 6-10 ℃. [97]

7.5.6 Heating efficiency of smolt facility

The heating efficiency of a smolt facility can be measured by looking at the ratio between usable and supplied heat. Usable heat is related to the heat demand, while supplied heat is seen in relation to the heat supplied. [98]

$$\eta = \frac{Q_{usable\ heat}}{Q_{supplied\ heat}} \tag{17}$$

Equation 17 shows the ratio between the heat needed to produce smolt, and heat supplied from a facility.

7.5.7 Marine Harvest

An example of a smolt facility is the Marine Harvest smolt facility in Fjæra. This facility is Norway‘s 10. largest facility per 11th of April 2018. It produces 7.5 million smolt per year, has a total volume of 13000 m^3 and an average smolt weight of 150 grams. [99] [100]

7.6 District heating

District heating is a waterborne heating system. It uses surplus energy from sources as for example waste, biofuels and industrial heat waste. The use of district heating means that resources that would otherwise be unused is utilized. This contributes to the reduction of greenhouse gases and a more circular economy. Today, there are 27 district heating facilities, 1.2 TWh total district heating production and 869 MW installed district heating power in Norway. [101]

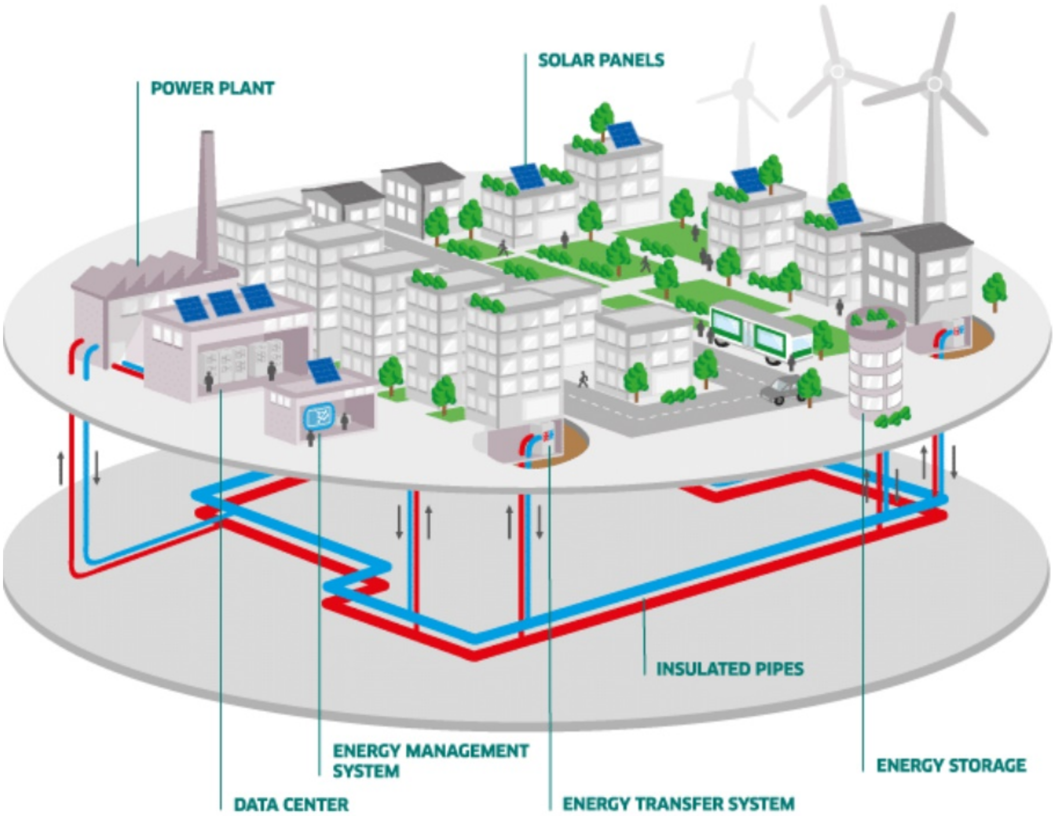

Figure 25: District heating system [102]

Figure 25 shows a sketch of a district heating system. District heating systems work by transferring energy from the district heating plant in form of hot water in insulated pipes. This energy is transported on further to buildings and residential areas in cities and neighborhoods. District heating has either been expanded or is being expanded in most Norwegian cities today. The main suppliers of district heating are Statkraft heat in Trondheim, BKK in Bergen and Hafslund heat in Oslo as of 2017.[103]

7.7 Heating for pools

Excess heat can be used to heat water in a pool. In Zurich, Switzerland, for example, a data center is used to heat a public swimming pool. Here there is a storage area where the excess heat from the data center computers is collected. This heats transfers to water which is passed on to a heat exchanger located by the pool's systems. The heated water will heat the pool water. [104]

Also in Kristiansand in Norway, there has been discussions about using surplus energy from companies such as Glencore nickel plant and Elkem to heat the bathing beaches. This utilization of surplus heat is still in its planning phase. [105]

8 Agriculture in greenhouses

In this section greenhouses and its conditions for growing vegetables are emphasised. To replicate natural conditions inside, there are many factors to be considered: CO_2-levels, lighting, humidity, water, temperature and heating.

8.1 Technical considerations for green house agriculture

Optimal growth conditions are needed to ensure the best possible yield in a greenhouse. Generally a greenhouse aims to simulate the native climate of its products as correctly as possible. This requires close monitoring of lighting, temperature, $\mathrm{CO_2}$ saturation, humidity and water supply. The recreations ensure one of the oldest and most common processes on earth: photosynthesis, as seen in equation 18.

$$CO_2 + H_2 0 \xrightarrow{Sunlight} C_6H_{12}O_6 + H_2O \tag{18}$$

To ensure correct conditions inside a greenhouse technology plays a vital part. As sustainability is being more and more important, the research on the subject are ever growing. In this chapter there will be a comprehensive analysis on the important parameters and how different technologies affects cultivation. [75]

8.1.1 Heating

The use of heating oil for heating has fallen sharply over the last years. From 2006 until 2018, the use of heating oil has decreased from 12 million to 1.8 million liters annually. Heating oil is now used more as a supplement to other energy sources. [106]

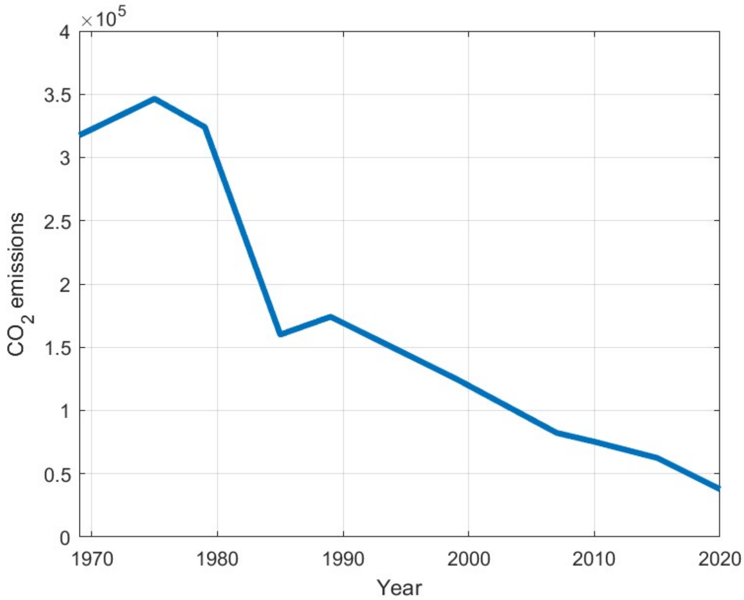

Figure 26: CO_2 emissions(tonnes) from burning oil to heat in greenhouses [107]

The graph above, figure 26, represents the reduction in CO_2-emissions from the use of heating oil from 1968 to 2020. Today, several different methods are used to heat a greenhouse. Examples are air heating, gas heating, electric heating of water and use of a boiler. [108]

Air-heating works by one end of a pipe going into the greenhouse while the other goes outside. A hot source is used to direct hot air through the pipe and into the room. Gas heating is a technique that uses gas to heat the room and releases carbon dioxide into the air. A ventilation system must be installed to prevent the carbon dioxide in the air from impeding the activity of the plants. Electric heating of water functions by a raising the temperature of water to approx 60 ℃, then transported inside to provide heat to the air in the room. A boiler with fuel is another method that can be used for water heating. [108]

The greenhouse industry is working to reduce greenhouse gas emissions from heating. Today, the industry uses natural gas that has high carbon footprint. The goal is to switch to a more climate-friendly electricity-based heating technology. Additionally, by implementing smart lighting, productivity will increase and CO_2 emissions will be reduced. [109]

One challenge with the conversion process from oil heating to electricity is the lack of capacity in the power grid. The power grid must be expanded to supply enough power to support the extra load the greenhouses represent. Unpredictable electricity prices are another challenge for electrical heating in greenhouses. [109]

8.1.2 Lights

As seen in equation 18, sunlight is essential for photosynthesis and cultivation of plants. The sunlight is the driving energy force for the process, giving energy to chlorophyll's, which turns CO_2 into other carbon compounds. For lights there are different wavelengths for different radiation. The visible spectrum of light is from 380-700 nanometers. Plants need different wavelengths for different processes, and the photosynthesis is only active at 400-700 nanometers, also known as photosynthetically active radiation (PAR). The unit for energy in light is watts. As a means to analyze how much energy which could be utilized by the plant in photosynthesis to grow, the unit PAR W is introduced. This takes into account the total energy in the radiation which exists in wavelengths of 400-700 nm. Photons are the energy carriers in light, therefore the more photons, the more energy. When measuring how many photons hits a surface per time, we introduce the unit $\mu mol/m^2$ per second. This takes into account how many photons in the PAR spectrum that hits a surface per time. This unit is the best measurement for lighting used in horticulture for different plants and fruits. [110]

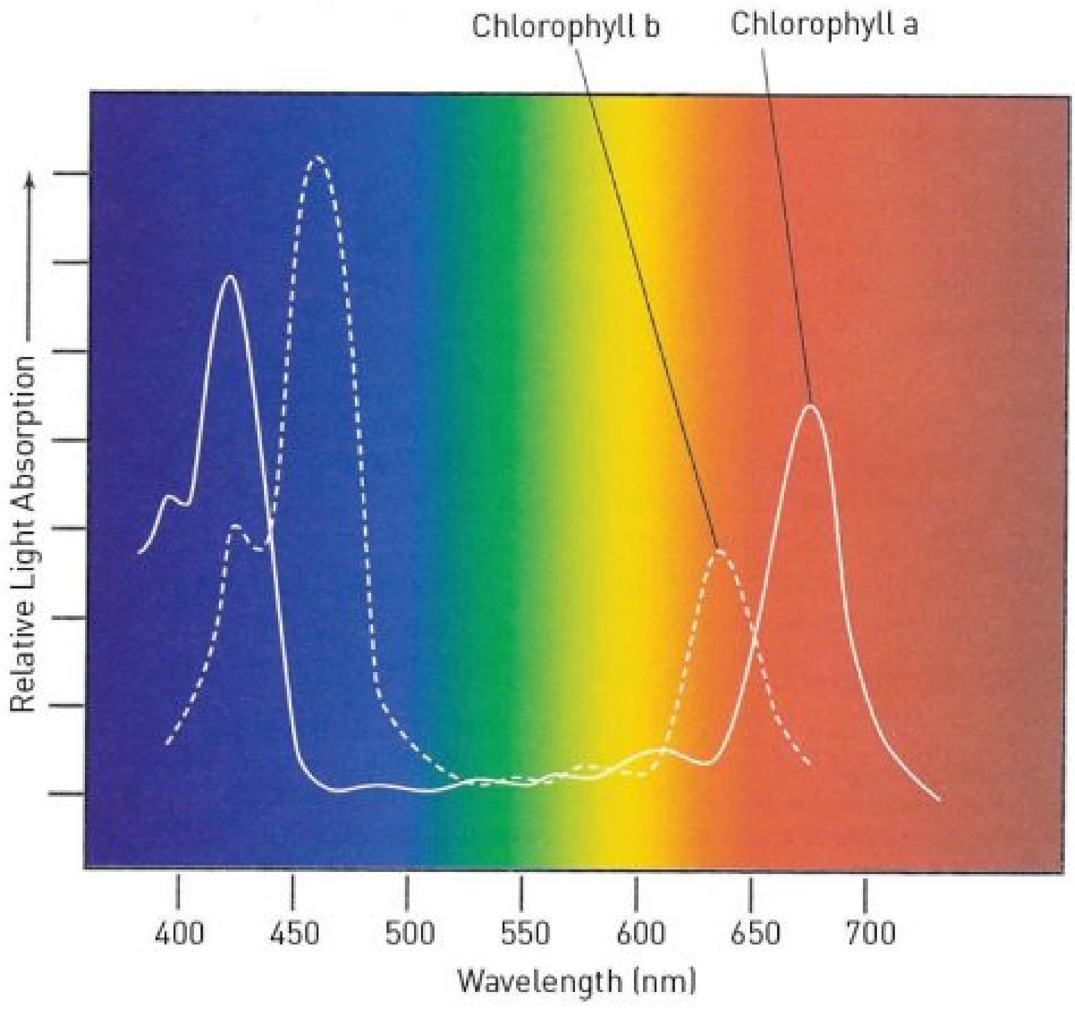

Figure 27: Absorption rate by wavelength [111]

As seen in figure 27 different chlorophyll's optimizes their light absorption at different wavelengths. This shows that chlorophyll a and b, absorbs best at blue and red. Photosynthesis depends on other factors than lighting, such as other chemical processes which utilizes a different part of the light spectrum.

Traditionally, greenhouses have been most popular in the middle parts of the hemispheres, where the temperatures are lower but the natural lighting is good. Now, with the advancing technology surrounding artificial heating and lighting, the possibilities to utilize greenhouses are reaching the northern parts of the world. Grow-lights are used in the darker areas to supply enough lighting to sustain crops. These lights are often LED. [110]

The installation of growth-lights into greenhouses are however seldom non-problematic. To reduce the costs its most beneficial to run these in addition to natural lighting, but the LED lights take up a lot of space. This causes the natural light to be partially blocked, thus increasing the active time of the artificial lights. Alternatively it is possible to not depend upon natural lighting altogether, and just produce crops relying on the artificial lighting. [112]

8.1.3 CO_2

Plants need to perform photosynthesis to grow, and one of the key ingredients for this is CO_2. A normal estimation of the CO_2 saturation in the atmosphere is 412 part-per-million (ppm). To enhance the growth in a greenhouse it is desirable to enrich the CO_2 saturation up to 1100 ppm. In accordance with *Liebig's Law*, which states that growth is not determined by the total available resources but by the scarcest available resource. It was discovered roughly 100 years ago that the limiting factor in agriculture was CO_2. Greenhouses gave farmers an opportunity to create CO_2-enriched environments to grow their crops in, and this resulted in a larger yield. [113]

The CO_2 used for enrichment is often transported in a pressurized state. The gas can have many different origins, for example carbon capture and storage (CCS), byproduct from natural gas combustion or animals. The people working inside the greenhouses are contributing to the CO_2 saturation when they are breathing. With CCS becoming more and more widespread, greenhouses present a different solution, as opposed to storage. CO_2 as a byproduct from the hydrogen production is another possible origin. [110] [113]

8.1.4 Water

Globally, water has been a source for conflict for millenniums because everyone, and everything, requires freshwater to hydrate and grow. Norway have a high amount of freshwater supplies, ensuring fresh water for its entire population. In 2014 10 percent of the Norwegian population received freshwater from surface water basins and private wells, meanwhile 90 percent originated from lakes, streams and ponds, of which all require approvals. Similarly the Norwegian agricultural sectors have a steady access to freshwater, with 2018 being the only very dry summer for a long time. That summer many farmers had to utilize irrigation systems to secure a decent yield, causing a disruption in the field. People were worried for the future of Norwegian agriculture if faced with multiple droughts, however no studies suggest any increase in number of droughts per decade. But according to climate change scenarios droughts are expected to increase in frequency. At the other side of the water shortage spectrum, there is floods. Floods are effectively too much water at the wrong time in the wrong place. Rivers and streams are prone to flooding during the spring, causing farmland to take damage. As a contrast to droughts, floods can be avoided by dimensioning canals to the workload of the spring floods. [114]

Figure 28: Sprinkler irrigation system [115]

Every plant requires a specific amount of water to receive the optimum growth rate per day. The amount of minimum and maximum water differs from plant to plant. To be the most cost effective it is cheapest to monitor the total water delivery to the plants closely. This is quite difficult out in the field, but in a greenhouse its a lot easier. A desirable greenhouse irrigation system consists of enough censors and gauges to monitor the amount of delivered water to each row of plants. A sprinkler irrigation is presented in figure 28. Additionally the irrigation system makes it easier to distribute fertilizers evenly. This is done by creating a solution of water and fertilizer and feeding it through the pipes. [116]

8.1.5 Humidity

Another important parameter inside greenhouses is humidity levels. Ordinary greenhouse plants thrives at 80% relative humidity. Relative humidity is a indicator for the present state of absolute humidity relative to the maximum humidity at the same temperature. Greenhouses are naturally humid, often causing them to become too damp. Commercial greenhouses usually have a automated controller which calculates the relative humidity at the given temperature. It subsequently humidifies or dehumidifies the air. Private greenhouses often relies on manual venting, and therefore humidity levels are less precise. When optimizing for humidity it is significantly easier to have one type of plant or several types which enjoy the same humidity. [117] [118]

8.1.6 Temperature

The temperature inside a greenhouse is monitored by multiple sensors around the room, and controlled by a temperature control unit. This unit heats up or cools down the room via heating units or venting. Plants usually thrives when there is a higher temperature at day than at night. For common plants often found in greenhouses, the typical temperature is 18℃at night and 24℃at day time. The temperature have to be optimized depending upon the cultivated plant. [119]

Table 5: Comparison between desired temperatures of different vegetables [119][120][121]

Plant	Day temperature [℃]	Night temperature [℃]
Cucumber	24-27	>19
Tomato	21-27	>13
Avocado	23-29	>15
Warm season vegetables	>16	>13
Cold season vegetables	10-22	8-13

A comparison between different types of vegetables are tabulated in table 5. Warm and cold season vegetables are collectives for vegetables with equal demands. Warm season vegetables refers to, amongst others, beans, eggplants, cantaloupes and summer squash, whilst cold season vegetables refers to beets, cabbage, carrots and leafy greens, amongst others. Cucumbers are classified as a warm season vegetable. [121]

8.2 Products

The goal of a greenhouse is to cultivate plants. Depending upon multiple economic factors, such as demand, yield, frequency and purchase price, the crop is chosen. Cucumber is the crop which is most frequently in Norwegian greenhouses. The second highest is tomatoes. [122]

8.2.1 Tomatoes

Norwegian tomatoes represent approximately one third of the total Norwegian vegetable production. This production amounts to about 11000 tons per year, making tomatoes the product with the second highest percentage of the Norwegian total greenhouse vegetable production, at 37%. It is possible to collect three yields of tomatoes per year as their growing period only lasts 90-150 days. To reduce the risks of pests and infestations the tomatoes can be grown in rotation with other vegetables with a similar growth span. [122]

Figure 29: Tomatoes planted in a greenhouse [123]

Figure 29 visualises a potential tomatoe setup inside a greenhouse. The global average tomato yield under irrigation varies from 4.5-6.5 kg/m^2. Due to sophisticated technology the Norwegian average is about 32 kg/m^2, which is the 7th highest yield in the world. [124]

8.2.2 Cucumbers

The share of domestic cucumbers totals for more than 50% of the entire Norwegian vegetable production. This is the the single most produced vegetable in Norway, and the fourth most consumed. The time period between the seeds are sown and the fruit is ripe can be everything between a month to two and a half months. This leads to multiple crops each year, but because they are fast growers they require a lot of nourishing and a steady flow of nutrients. Cucumbers are prone to diseases which, if not treated chemically, spreads to the entire crop and destroys it. They are sensitive to high temperatures and does not tolerate sub-zero temperatures. This is due to the plants consisting of about 96-97% water. The optimum temperatures for growing cucumbers are between 23 and 27°C. With sophisticated lighting technologies the density of the cucumbers can reach up to 180 kg/m^2. [125]

8.2.3 Avocados

In recent years the consumption of avocados has had a rapid increase in Norway. With its good flavour and rich nutrients the interest of this tropic fruit has increased dramatically. In 2020 the Norwegian consumption of avocados was about 14 000 tons. This means Norway is one of the biggest consumers of avocado per capita, and the demand is only assumed to grow in the coming years. [126]

The majority of avocados consumed in Norway is grown from Hass trees today. The conditions of growing an Hass tree depends on temperature, lighting, soil quality, humidity and fertilization. As of today the majority of avocado cultivation is located in central America. Here the conditions appear naturally and the trees are planted outside in large areas. In regards to temperature avocados thrives at 20-30 °C, but could survive until 0 °C. For humidity avocado trees are grown in climates of 40-50 % relative humidity. They demand a direct sunlight for 6 hours or more each day. The daily requirement of the sunlight is expected to be around 18 $Moles/m^2$ each day. The soil quality is quite sandy. The best pH for growth of avocado trees are 5-7 and its very sensitive to alkaline soils. One avocado tree produce about 200-400 fruits per year, with the average weight of 215 gr per fruit. [126]

Avocado – EU-28 – Consumption

Markets	2019		Trend (g)		Population (millions)
	Volume (000 t)	g per capita	/2018	/2014	
EU-28, incl.	**607**	**1 179**	**+ 1**	**+ 500**	**515**
France	138	2 091	+ 33	+ 557	66
United Kingdom	97	1 508	- 185	+ 721	64
Germany	79	982	+ 9	+ 586	81
Scandinavia, incl.	58	2 247	+ 54	+ 434	26
Sweden	20	2 039	- 126	+ 25	10
Denmark	17	2 998	+ 275	+ 1 084	6
Norway	14	2 737	+ 232	+ 679	5
Spain	68	1 453	- 10	+ 993	47
Eastern Europe	49	487	+ 15	+ 292	100
Italy	25	417	+ 80	+ 279	61

Source: Eurostat | Processing: CIRAD

Figure 30: Avocado consumption in Europeen countries 2019 [127]

Figure 30 shows the avocado consumption in European countries in 2019, and the change since 2018 and 2014. In the Scandinavian countries one sees a large increase in consumption per capita in the period. As of today, there are no local production of avocados in Norway. The import today originates from southern American countries like Mexico, Peru and Chile. [127]

8.3 Ethical benefits

There are ethical advantages to Norwegian food production compared to foreign production. The reason for this is that foreign production often are related to problems such as water shortages, CO_2-emissions from transport, diseases from pesticides, deforestation and exploited by criminal societies. [128]

8.3.1 Humanitarian

From a humanitarian perspective, there are several advantages of production in Norway compared to production abroad. The reason is that there exist ethical issues with growing vegetables such as avocados abroad. [128]

Avocado cultivation requires a lot of water. An avocado, for example, needs a high amount of water during the cultivation period. The high water demand for avocados has led to the formation of illegal water systems that fetch water from both rivers and groundwater. Water prices are also very high. This results in water shortages, and for the inhabitants to be forced to drink polluted water. [128]

Another problem with the avocado production is the formation of avocado cartels that take control of the production. Violence and threats are used as a tool for the cartels to gain power. For example, drug cartels have taken over ten percent of avocado plantations in the Michoacan region of Mexico. [129]

Pesticides and deforestation are also challenges associated with avocado production. Deforestation is destructive to both wildlife, plant life and the environment. Pesticides can cause disease in the population living in the area around the plantations. [128]

8.3.2 Self-sufficiency

Self-sufficiency means that an area consumes as much of the goods and services as it produces. Degree of self-sufficiency in Norway is defined as the proportion of wholesale consumption of food that comes from Norwegian production. According to the Norwegian Directorate of Health, the degree of self-sufficiency was 46.5% in 2020. It is important that a country has a high degree of self-sufficiency in relation to self-rescue. It is considered a political goal in Norway to increase the self-sufficiency of goods in Norway. [130][131]

8.4 Environmental benefits

There are several climate benefits of production in Norwegian greenhouses compared with foreign production. An advantage is related to transportation. Production in Norway means that emissions of CO_2 are avoided in relation to import and export of fruit and vegetables from abroad. [128]

Norway also uses less water in its production compared with other countries. According to the Horticultural Association, Spain uses 60 liters of water per kilo of tomato produced, while only 10 liters are used in Norway. There are major challenges with pests and diseases in relation to greenhouse production in warmer countries as well. This contributes to making greenhouse production favorable in Norway, due to avoided use of pesticides. [132]

The low plastic use is also a positive aspect in Norwegian greenhouses compared to other countries. In Spain for example, plastic use is an environmental problem, because tomatoes are grown in cheap greenhouses made of plastic. This plastic is replaced every three years, thus contributing to plastic pollution. [124]

Norway has access to climate-friendly energy from hydropower as well. Use of this energy in greenhouses can reduce greenhouse gas emissions and create jobs, income and self-produced food.[109]

8.4.1 Footprint

According to the Horticultural Association, the production of one kilo of cucumber in Norway corresponds to a climate footprint of 290 grams of CO_2 equivalents. In Spain, the emissions are 370 grams of CO_2 equivalents for growing cucumbers, as well as an emission of 360 grams of CO_2 equivalents in transport from Spain to Norway. Compared with Spain, the total emissions are significantly lower in Norway. [132]

Year-round production of tomatoes is estimated to have a climate footprint of 1.2 kg CO_2 equivalents. This is lower compared to Spanish and Dutch tomatoes. These have a climate footprint of 1.6 kg and 2.3 kg, respectively. As for avocados, according to a research conducted by Carbon Footprint Ltd, a dobble pack of avocados has a carbon footprint of 832 gr CO_2 equivalents. This equals to 1.932 kg CO_2 pr kg avocado equivalents. [124] [133]

9 Method

The methods utilized in this thesis is described in this section. For the thesis there were two specifications given by the supervisor from Nordkraft: A data center with a computer capacity of 100 MW and air cooling.

9.1 System

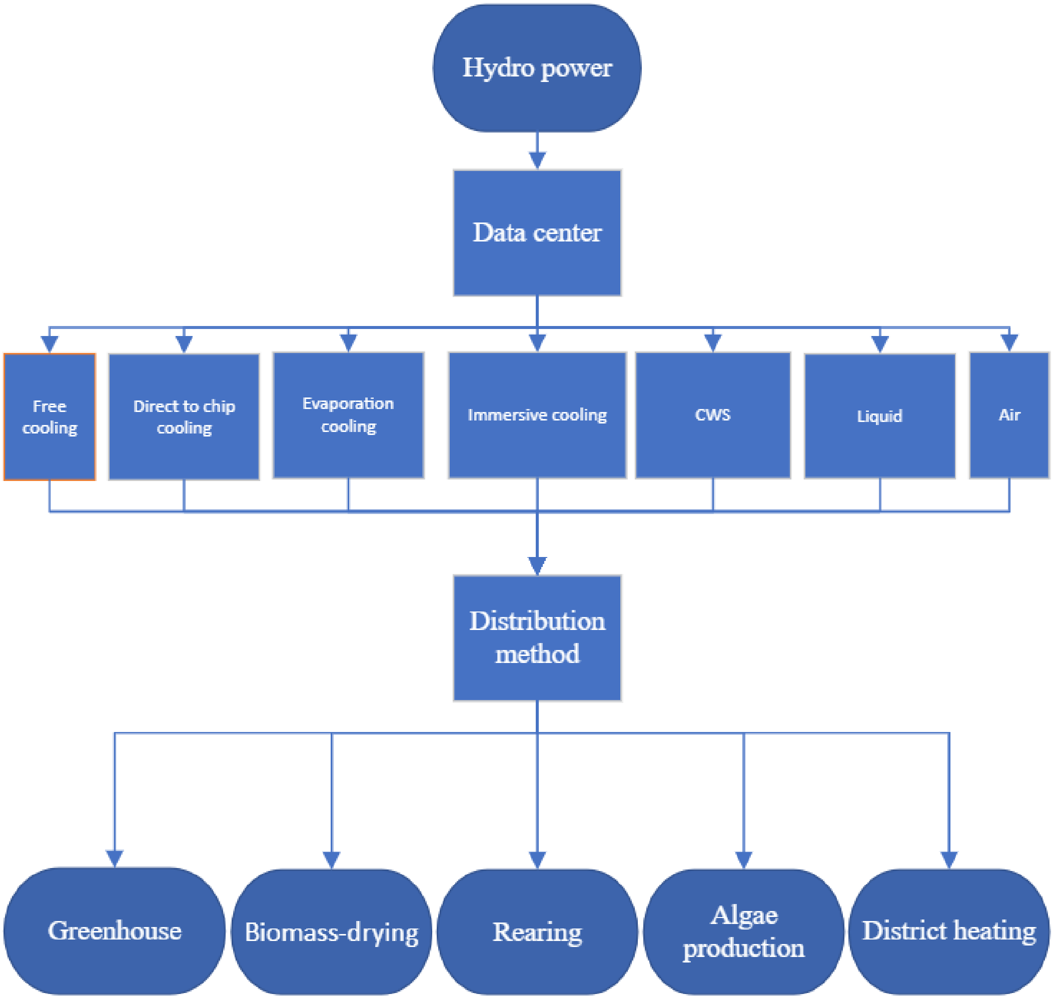

Figure 31: Energy flow chart of the system showcasing different design opportunities

The base system begins with a producer of energy, whom provides a data center with electric energy. A rough energy flow chart of the system is presented in figure 31. When the electric energy is processed in the data center, the energy, now in form of heat, is removed by cooling methods. At this stage the size of the squares represent the different quality of heat exhausted from the cooling method. The bigger the squares the higher temperatures can be recovered from the heat leaving the cooling method. Then energy flows into the distribution system, which may consist of pipes, heat exchangers and/or heaters. In the end the excess energy reaches a recipient.

9.2 Dimensions of the data center

The size of the data center with an installed capacity of 100 MW is calculated with a basis in the sizes of Cardiff Data Center, Hamina Data Center and the Citadel Campus Data Center. When utilizing free cooling it is normal to assume roughly 7-15 kW of power consumption per rack. The power usage for this project is assumed to be 9 kW per rack. The temperatures assumed for the hot and cold air in the data centers were respectively 35℃and 23℃. Assumed that 1 kW of cooling is needed for each kW put into the data center.

In this thesis two different cooling solutions are used as a base for calculating how much excess heat is available. The first system will be based upon a CRAC CW unit from Rittal of the type 3300.387, when considering air to water heat exchanger. The dimensions and properties of this CRAC unit can be seen in appendix A.

The water that is utilized to cool the air from the data center is assumed to be taken from a free stream and then directed via the data center. After the data center it is assumed to be transported by the means of gravity to a nearby location where the energized medium is used for heating, e.g. in a rearing or a algae plant. The idea is to regulate the mass flow rate of the water based on the need of the recipient by monitoring the amount of water let into the pipe.

The second system use a Excool air-air cooling as a base. One Excooler provides 250 kW cooling At Δ T 12. The dimensions and properties of this Excool unit can be seen in appendix B.

To analyze the placement of a reciving industry its important to analyze heat losses due to transmisson. Several properties of materials and substances are required when calculating this. The pipes are assumed to be made out of concrete and produced by *Ølen Betong* of the type 5440 127, as seen in appendix I.

9.3 IDA-ice

IDA Indoor climate and energy (IDA-ice) is a Swedish simulation tool. It was started in 1995 by the Swedish company EQUA. IDA-ice performs year around simulation for building optimizations. Both for energy usage and and comfort for occupants. The results vary on different parameters. Location, building body, system components and many more. IDA-ice offers 3D simulation, where there is a possibility to build a model which fits any profile of a building. The program is well respected, and simulations made is shown to be very accurate compared to current buildings.

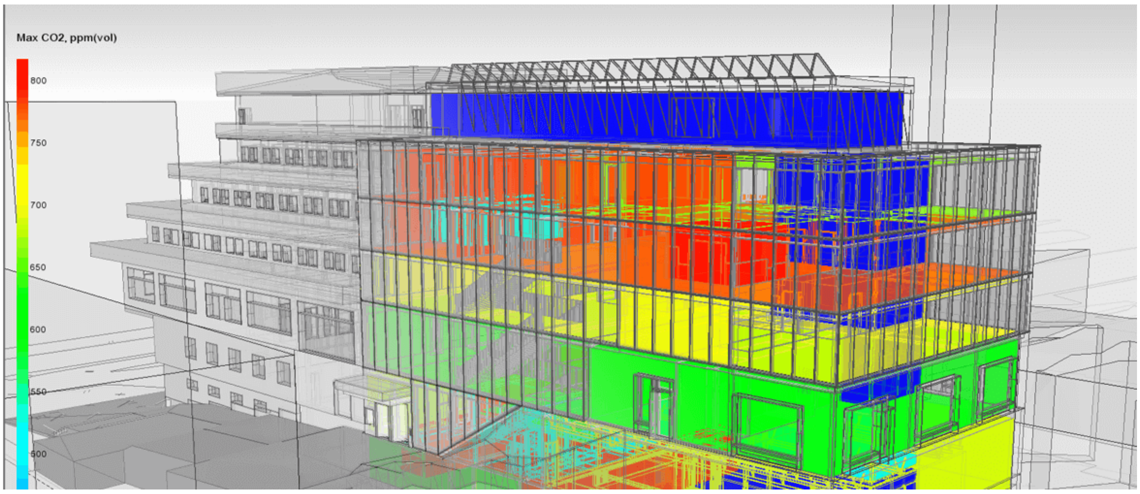

Figure 32: Example building design from IDA-ice [134]

Figure 32 shows an example of a model from the program. Here the different colours visualizes the different concentrations of CO_2 in the building. Outputs are represented in charts, tables, plots and reports. Different outputs from the programs are: heat distribution, air flows, complex energy visualization and more.

9.4 Collection of data

To ensure accurate and realistic results, the phase of collection of data is important. The data center-industry operates with a high degree of security and secrecy.

In the early phase of collecting data relevant to the thesis, it was decided to contact many different partners and reach as many companies as possible. Meta, Microsoft and Google as they are several of the worlds largest facilitators in data centers. It proved to be difficult to reach the right department and individuals that would be able to help. When asking for specifications and dimensions, especially regarding the excess heat, there were limited responses.

In Norway there are two main data center-facilitators: Green Mountain and Digiplex. It was desirable to establish a cooperation with these two companies, as their knowledge on the subject would be valuable for the credibility of the project. Green Mountain ended up being very accommodating both via e-mail and meetings, and overall a great resource for the project.

For the calculations completed in this thesis the data used was collected from various sources and comparable projects. For coolers used in data centers different catalogues were analyzed to find the optimal cooler. For the different industries there were a big need to find up to date data and as precise dimensions as possible. It proved to be difficult and several assumptions were necessary.

9.5 Greenhouse

The first industry analyzed in this thesis is a greenhouse. The initial step was to create a realistic building model in IDA-ice. At this point it was especially important to collect building specific data. U-values, dimensions, window classifications were all equally important. The greenhouse was placed in Sortland in IDA-ice, which proved to be the most comparable weather data to Narvik available in the program.

Simulations were done on an annual scale. This to calculate the total efficiency regarding the recovery of the waste heat.

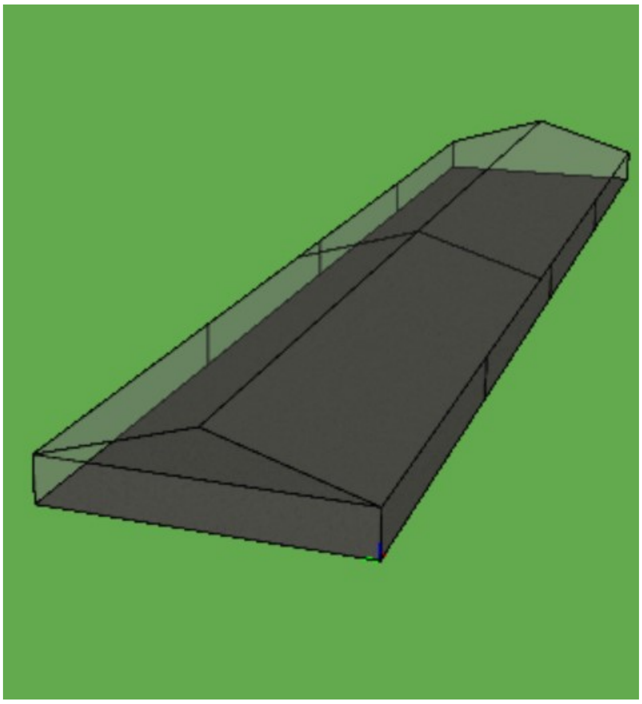

Figure 33: Greenhouse model created in IDA-ice

Table 6: Properties of the greenhouse model

Specification		**Unit**
Width	20	meters
Length	100	meters
Height	6	meters
U-value	5.4	$W/m^2 \cdot K$

Figure 33 visualizes the model created in IDA-ice, and table 6 gives the properties of the model.

The model created had a total area of 2000m^2. The U-value was assumed to be excact the same for all windows. This value was collected from interview with Henk Maesson from NIBIO. The U-value vary during the year due to the use of an isolation cloth during the winter months, when there is low solar radiaton and reduced outside temperatures. U-value was set to a predefined value in the program, 1 pane glazing. The floor was set to be adiabatic, therefore no heat loss through the floor.

When analyzing a greenhouse, its important to take into account that a large amount of the surface will be covered by plants, equipment for lighting, a water system and other relevant equipment. The greenhouse is assumed to be placed on top of the data center, to utilize the fact that warm air rises. This way the warm air can be put under minimal work during the transportation from the data center to the greenhouses.

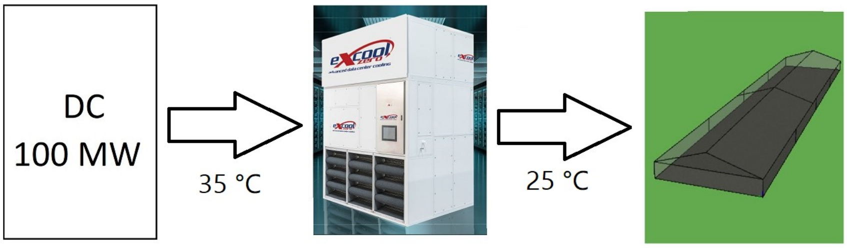

Figure 34: Energy flow data center to greenhouse

Figure 34 visualizes the energy flow from the data center to the greenhouse. The exhaust air from excooler is set to be delivered directly to the greenhouse at 25 ℃.

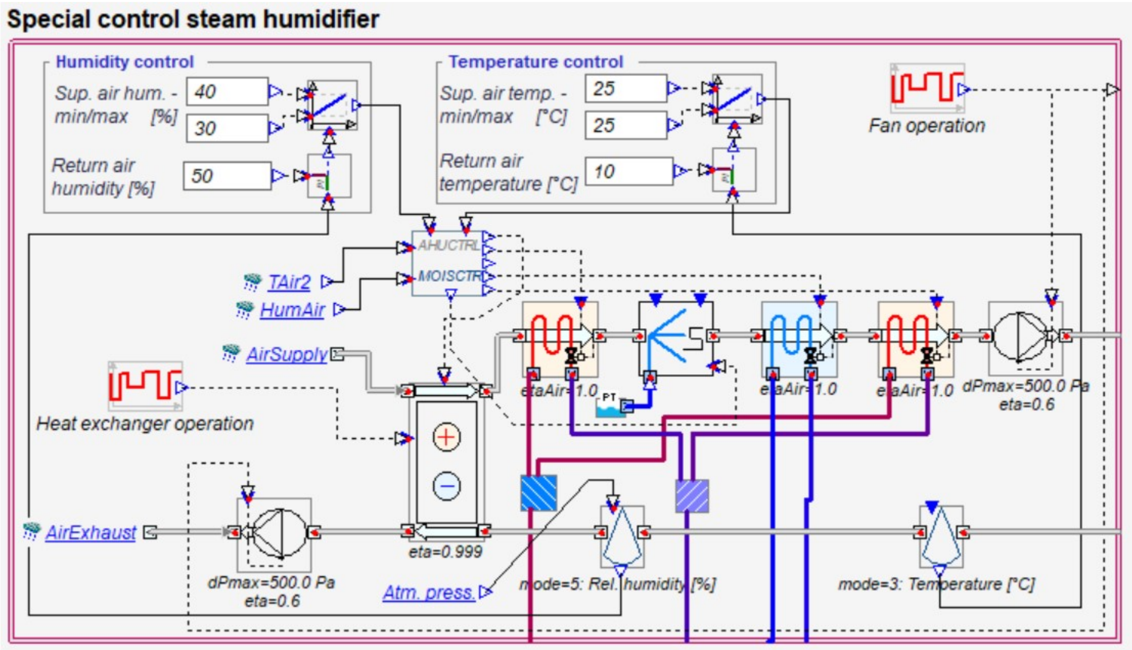

Figure 35: Heating, cooling and fan system created in IDA-ice

It was assumed to be a steady state flow of exhaust air leaving the data center, as a data center has as high as 99.9 % up-time. The temperature used for the supply air to the model was 25 ℃. As for the heat transferring, visualized in 35 it was assumed a air handling unit with a heat exchanger wit aan infinite area and an efficiency of 0.999. This is to examine the efficiency when all the heat exiting the data center is utilized for heating in the model. The heating and cooling setpoints was set to be between 18-32 ℃. The relative humidity was set to be 50% as avocados thrives at these levels. This also means that the relatively dry exhaust airs humidity levels are controlled by a humidifier.

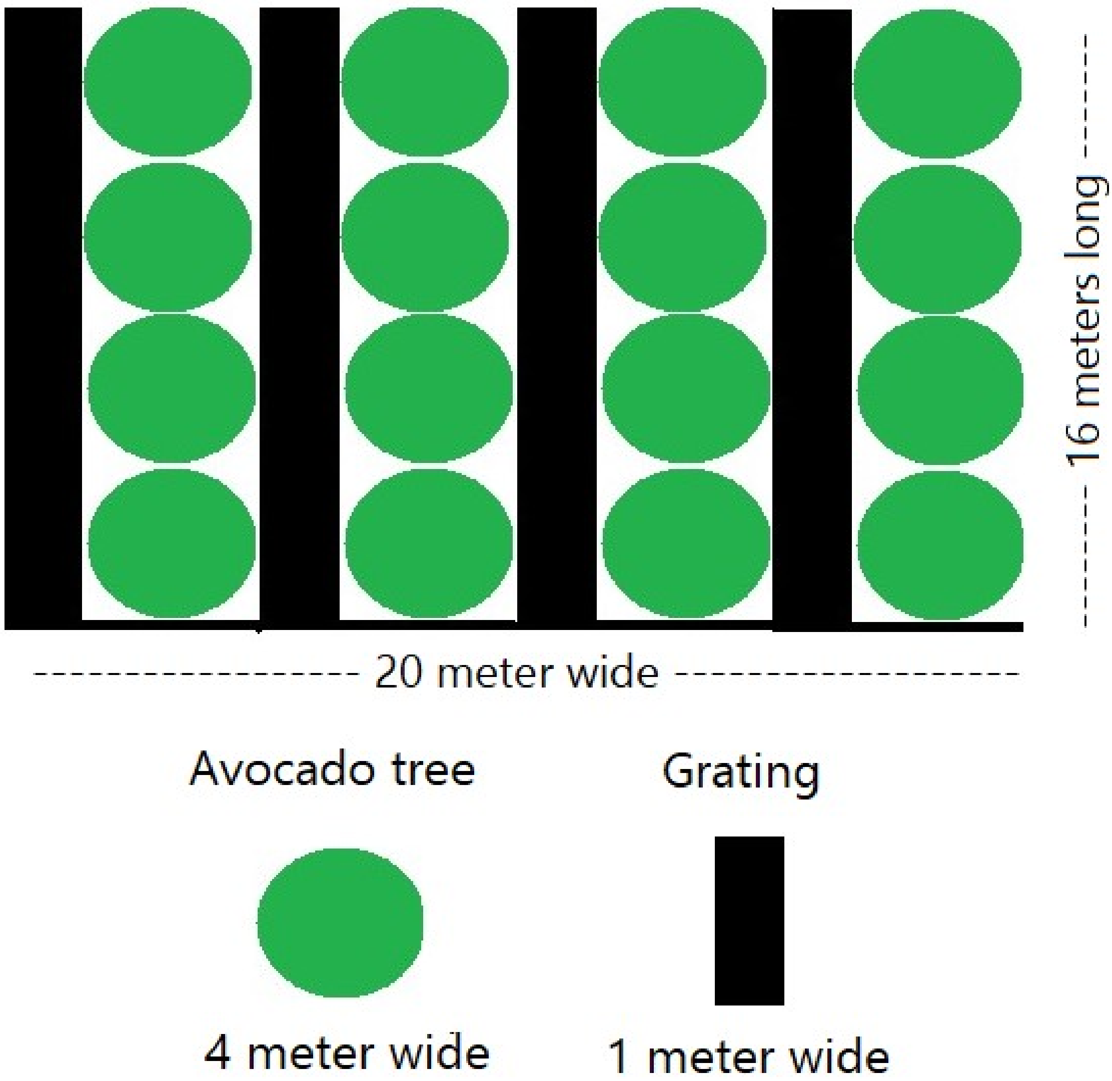

Figure 36: Snippet of the greenhouse lay-out as seen from top down view

As seen in figure 36 the green circles represents the avocado trees of the Hass type. It was assumed that they needed 4 meters in diameter because of its roots distribution. These dimensions are inspired by the traditional method for outdoor planting of avocado trees. The black field are grating in the floor of 1 meter in between each tree. It was assumed that the hot air from the data center flows in these rails. There is a total of 400 m^2 of rails where the airflow enters. The Norwegian labor inspection has set a limit of 0.15 m/s for a working environment. This will be accounted for.

For the lighting requirements, HLG Saber 150-model was used for calculating the specific dimensions for avocado cultivation. The growth-light emits 370 $\mu moles \cdot$ per second and the need for direct lighting for avocados was 18 DLI. DLI are measured in amount of photones per square meter per day, $Moles/m^2 day$. It was also assumed a yield of 300 avocados per tree each year. And a weight of 0.215 kg per avocado.

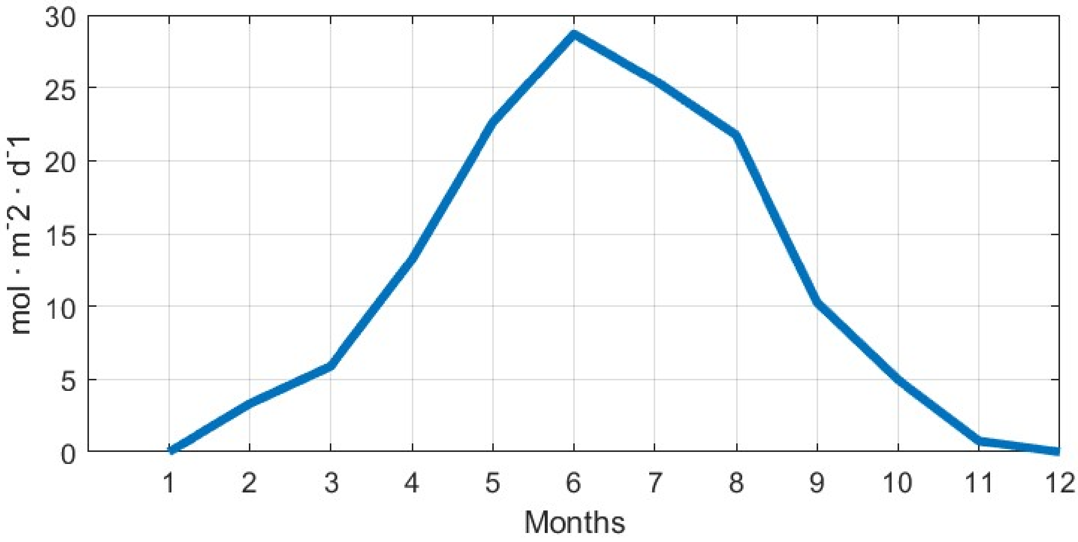

Figure 37: Daily Light Requirement Bjerkvik over a year [135]

Data for the direct light irradiance for Bjerkvik was collected. Figure 37 visualizes the variance over the course of a year. During the winter months there is only a small amount of direct irradiance, which the figure reflects.

9.6 Algae cultivation

The second industry which is analyzed for the utilization of excess heat is algae cultivation. To precisely calculate the efficiency there were numerous steps.

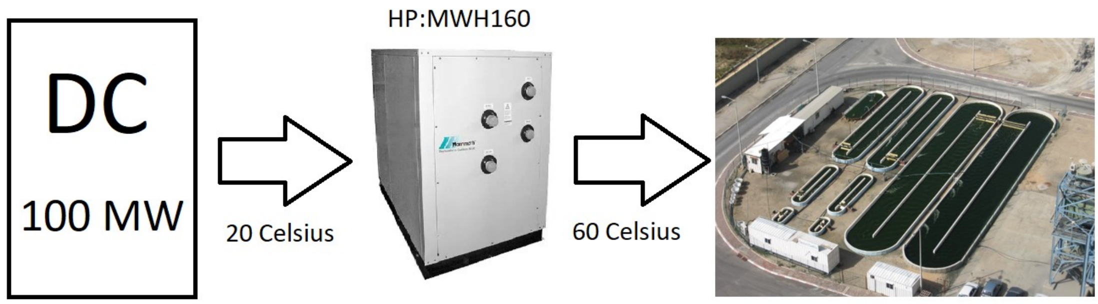

Figure 38: Flow scheme system algae cultivation

As visualized in figure 38 the heat leaving the data center was assumed to be 20 ℃and were utilized as a heating source for a water-water heat pump. The temperature is 60 ℃which provides the heating for the open pond algae facility. The temperature of the excess heat has to be upgraded, to provide enough heat for an operational pond. In these calculations, data was collected from Carbon Capture Storage Program's (CCSP's) report from 2016. They assumed a heating need of 600 w/m^2 in northern climate to maintain optimal temperature. The number is based on a winter night with no covering and facility around. For this thesis the number is assumed to be 200 W/m^2 as a yearly average when the pond is covered within a greenhouse. Dimension found from report [136]

To provide sufficient temperatures and heat, MWH160 heat pumps were utilized in the system. The model originates from Mammoth, its specifications are presented in Appendix H. Each model provides 753 kW of heating, with a power capacity at 123.2 kW. This assumed a water temperature of 20 ℃on the cold side and a leaving temperature of 60 ℃, from the heat pump visualized in figure 38.

To supplement the calculations a total area of 20 000 m^2 of open pond system was assumed. A pond height of 0.3 meter is assumed.

When calculating an algae growth open pond system, its required to analyze the energy need for paddling the pond. Paddling is performed to make sure sufficient amount of nutrients and CO_2 levels are establish throughout the pond. The CCSP's report stated that facility found the electric power for mixing to lay in the range of 0.08-0.6 W/m^2 with mixing velocities of 15-40 cm/s. For the calculations performed 0.3 W/m^2 will be assumed.

For the lighting required in a facility with these dimensions, precise calculations were needed. Lighting intensity vary from algae specie to specie. The lighting intensity is assumed to be 150 µ$moles/m^2 * s$. Other numbers are based on previous theory. As a base for calculating effective energy use for lighting figure 37 was used as a base.

9.7 Drying of biomass

The third industry analyzed as an industrial process who receives excess heat from a data center is drying of biomass. To ensure precise calculations, simulations programs and industrial experience will be utilized.

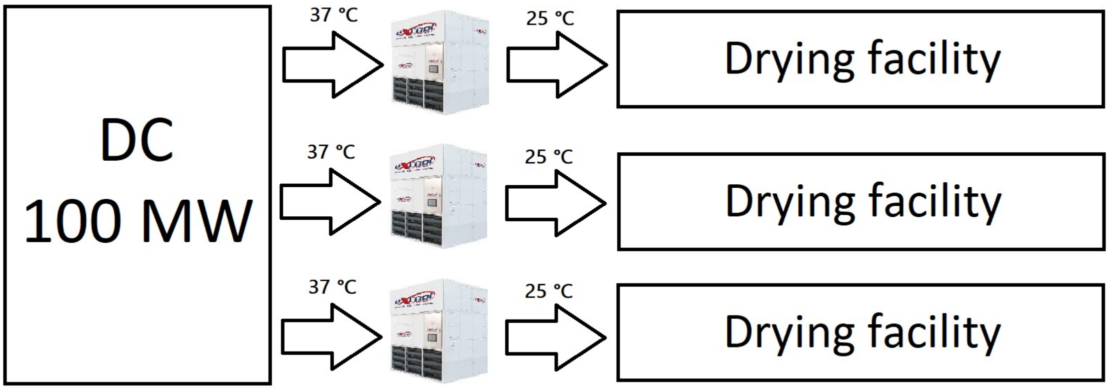

Figure 39: Setup of the biomass-drying facility

The energy flow scheme of the bio drying facility is visualized in figure 39. The heat is transferred from the data center to a Excooler, and then air at 25 °Centers the drying facility. One drying container is assumed to be connected to each Excooler, therefore the calculations are performed for a single unit.

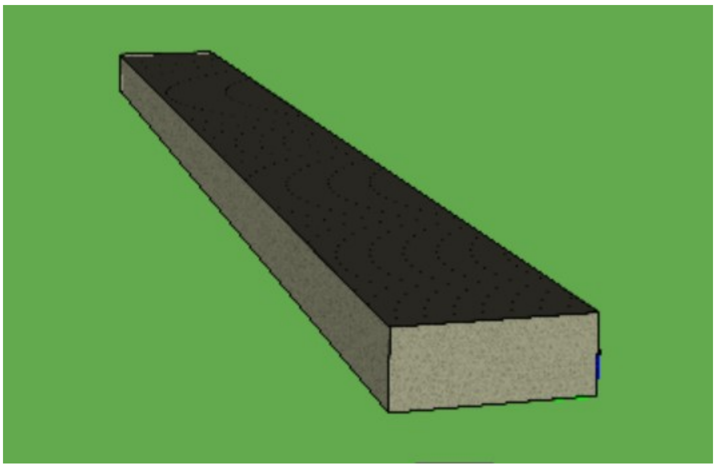

Figure 40: Model of the biomass-drying building

Table 7: Properties of the building

Specification		**Unit**
Width	5	meters
Length	50	meters
Height	3	meters
U-value	3	$W/m^2 \cdot K$

For calculations in this thesis a base model was created in the simulation tool IDA-ice, shown in figure 40 and the specifications in table 7. For this base model values for containers were used. This means an average U-value of 3 W/m^2K. The width of the building simulated was 5 meter, and a length of 50 meter, with a total area of 250 m^2.

The assumed cooling method for biomass-drying is air to air cooling, where ambient air exchanges heat from the inside air. The exhaust air from the Excooler is assumed to have a temperature of

25 °Cand a volume-flow of 17200 L/s, see appendix B. This exhaust air is then directly injected into special containers. Inside these containers the biomass which is to be dried is placed. This could possibly be algae, firewood or pellets. The hot air flows through these containers, resulting in the enhanced drying process. The drying phase depends on a variety of factors. Wind velocity, temperature and humidity are especially important. To conduct precise assumptions to this thesis an interview with Svein Bjerke from the wood company Varma AS was performed. They utilize excess heat from a cryptocurrency facility for drying of firewood.

From the interview these parameters were noted.

- They place wood inside a container, with hot air flowing from underneath.
- Varma dries from 50 % to 20 % moisture content. This takes 4-7 days.

From this interview these assumptions were made to the given base model drying facility.

Table 8: Assumptions for drying calculations

	Day 0	**Day 10**	**Unit**
Humidity	50	20	%
Density	500	300	kg/pall
Energy content	2.23	4.87	kWh/kg

With the difference in drying setup, it was assumed that the drying time would take 10 days, as presented in table 8. Here logistics in regards to moving large amount of EUR-pallet in and out the facility is not taken into account. Energy content was collected from previous lectures [137].

9.8 Fish farming

The last industry analyzed was fish farming as a recipient of the excess heat. To calculate the transfer of heat from the data center to a fish farming facility it required multiple different operations.

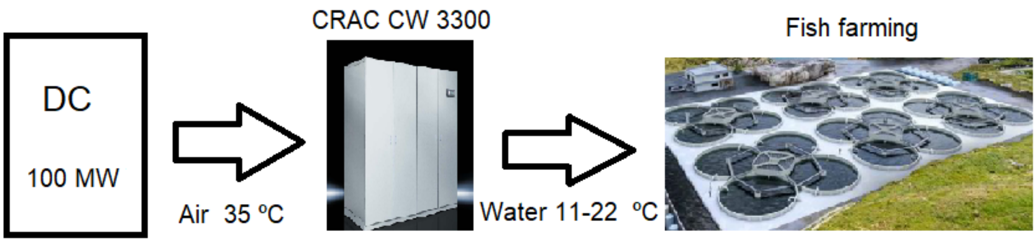

Figure 41: Flow scheme system fish farming

In figure 41 it can be observed that heat leaves the data center at approximately 35 ℃. This heat is later transferred through a heat exchanger to convert heat from air to water. The water leaving the heat exchanger is between 11 and 22 ℃with a mass flow of 2000 kg/s. This water is further used to heat the fish farming facility.

One assumption used was that water got transported by gravity from the data center to the fish farming facility. This makes the facility a flow-through with a gravitational water supply (FT-G).

Heat demand for a fish farming facility located near Narvik was to be investigated using the excess heat from the data center. It was assumed that the facility was a smolt facility with a capacity of 2,5 million smolts. It was assumed that the facility shared some of the same properties as Marine Harvest‘s facility on Fjæra, where 7.5 million smolt require 13000 m^3 of water. Hence, the assumption of 4300 m^3 of water required for 2.5 million smolt were made. For simplicity the facility was seen as one system. Another assumption were weight of 150 grams per smolt.

The additional power requirement from light and nutrition was assumed to be 5,34 GWh. This number was found by comparing the smolt facility with a facility in the Pacific Northwest with similar dimensions. [89]

An excel spreadsheet was used to calculate the heat demand of the smolt facility. In relation with calculations of the heat demand, some assumptions were made. One assumption was that 1-year- old smolts were produced. Another assumption was the use of a water replacement of 0,32 l/kg/min.

An assumption was also made in regard to temperatures used in the tank water and makeup water. For the tank water, smolt temperatures in the growth phases were taken into account. The temperature of the tank water was set to 12 ℃the first month, 11 ℃in the second month and 10 ℃the remaining months.

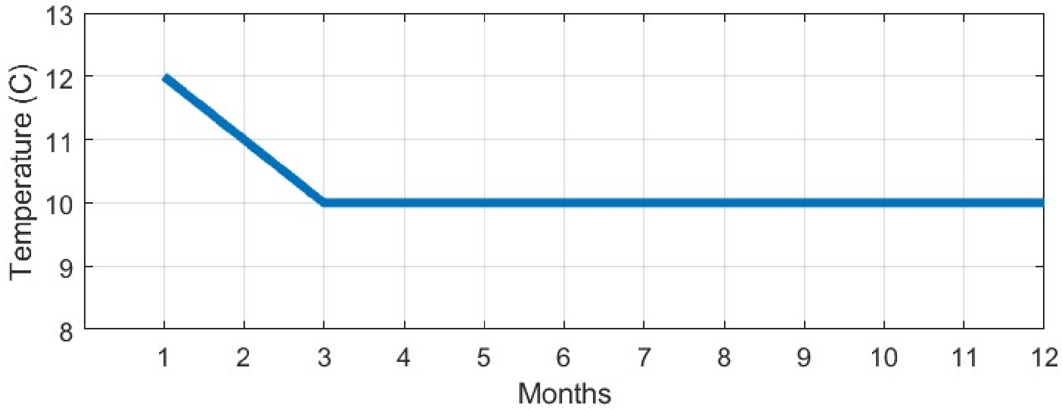

Figure 42: Temperatures of the tank water

Figure 42 represents the temperatures in the smolt facility over a year.

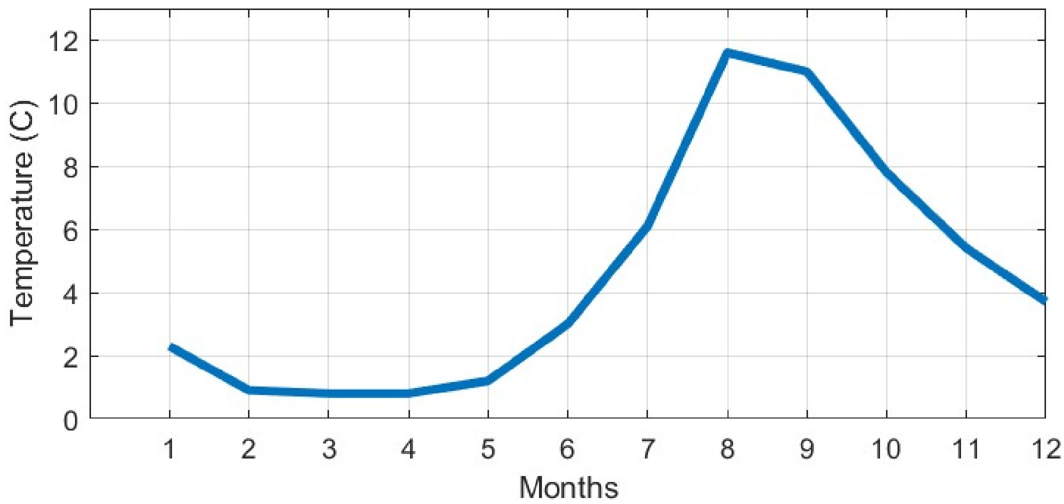

Figure 43: Measured temperatures over a year in Forsanvatnet [138]

Temperatures of the makeup water is based on the temperature profile of Forsanvatnet, represented in figure 43. Forsanvatnet is a lake located in Nordland. It is assumed that the makeup water used in the smolt factory in Narvik, has roughly similar properties to Forsanvatnet.

Excel spreadsheets were also used to calculate the energy efficiency of the smolt facility per month. The energy efficiency can be measured by looking at the ratio between required and supplied heat.

Required heat were found by calculating the heating need of the smolt facility per month. The data collected was only one temperature per month. And therefore it was assumed that it was at this given temperature for the entire month. This resulted in the heating need for one month was calculating by the 732 hours per month.

Supplied heat is the heat that is delivered from the data center to the smolt facility. Originally 100MW of heat was supplied from the data center. It is assumed in this case that the data center supplies a maximum of 80 MW of heat to the smolt facility, due to losses. Equation 17 was used to calculate the efficiency of the smolt facility.

Excel spreadsheet were used to calculate the energy reuse factor as well. This factor was calculated by looking at the relationship between utilized excess heat E_{reuse} and total energy usage in the data center E_{DC}.

10 Results

In this section the different results obtained from calculations and simulations are presented. The section presents the results from calculations regarding data center, greenhouse, biomass drying, algae cultivation and a fish farming facility.

10.1 Data center

The size of the data room is assumed to be 50000 m^2. This was calculated with a basis in Cardiff Data Center, Hamina Data Center and the Citadel Campus Data Center. The sizes of the different data centers are tabulated below in table 9.

Table 9: Scale of the different data centers

DC	Load [MW]	Area [m^2]	Size [$m^2/100MW$]
Cardiff	270	135000	50 000
Hamina	81	16000	19753
Citadel Campus	815	668901	82073

The average of the "Size" column in table 9 results in 50608 $m^2/100MW$. Due to this, the assumed size of the data room is 50000 m^2.

One Rittal CRAC unit processes 24200 cubic meters of air each hour, that is approximately 6.72 m^3/s. The cooling coil supports 22.3 m^3/h, which is approximately 0.373 m^3/min. The assumed capacity per rack was 9 kW, which gives 12 racks per CRAC unit. This in turns returns that the number of CRAC units required is approximated as 918.

By assuming a T_{in} and T_{out} of 23°Cand 35°C, respectively, for the air into the heat exchanger from the data center. The heating capacities air were found in scientific tables, resulting in $c_{p,air}$ equal to 1.0 kJ/kgK. The CRACs were observed as one unit, i.e. performance of 918 units summarized into one. This resulted in a total air mass flow rate, $\dot{m}_{air}$, of 7557 kg/s.

The exchanged heat out from the data center can be calculated using equation 14.

$$\dot{Q} = 1kJ/kgK \cdot 7557kg/s \cdot (23°\mathrm{C} - 35°\mathrm{C}) \tag{19}$$

Equation 19 retrieves a $\dot{Q}$ equal to 90684 kW, which is the energy transferred to the cooling fluid.

To provide sufficient cooling from the Excool model it proved that one model provided 250 kW cooling at Δ T 12. This results in 400 Excoolers to provide 100 MW cooling. Each model provides 36444 CFM / 17199 L/s. Which is equal to 6 879 854.5 L/s.

10.2 Greenhouse

In this section the results obtained from simulations and calculations regarding the utilization of the excess heat for a greenhouse is presented. Transportation of air is neglected, and its assumed to be placed on top of the data center. From IDA-ice simulation these results were obtained. Due to the total area required for a data center 50 000 m^2 it was found to be possible to place 25 greenhouses of 2000 m^2 on top.

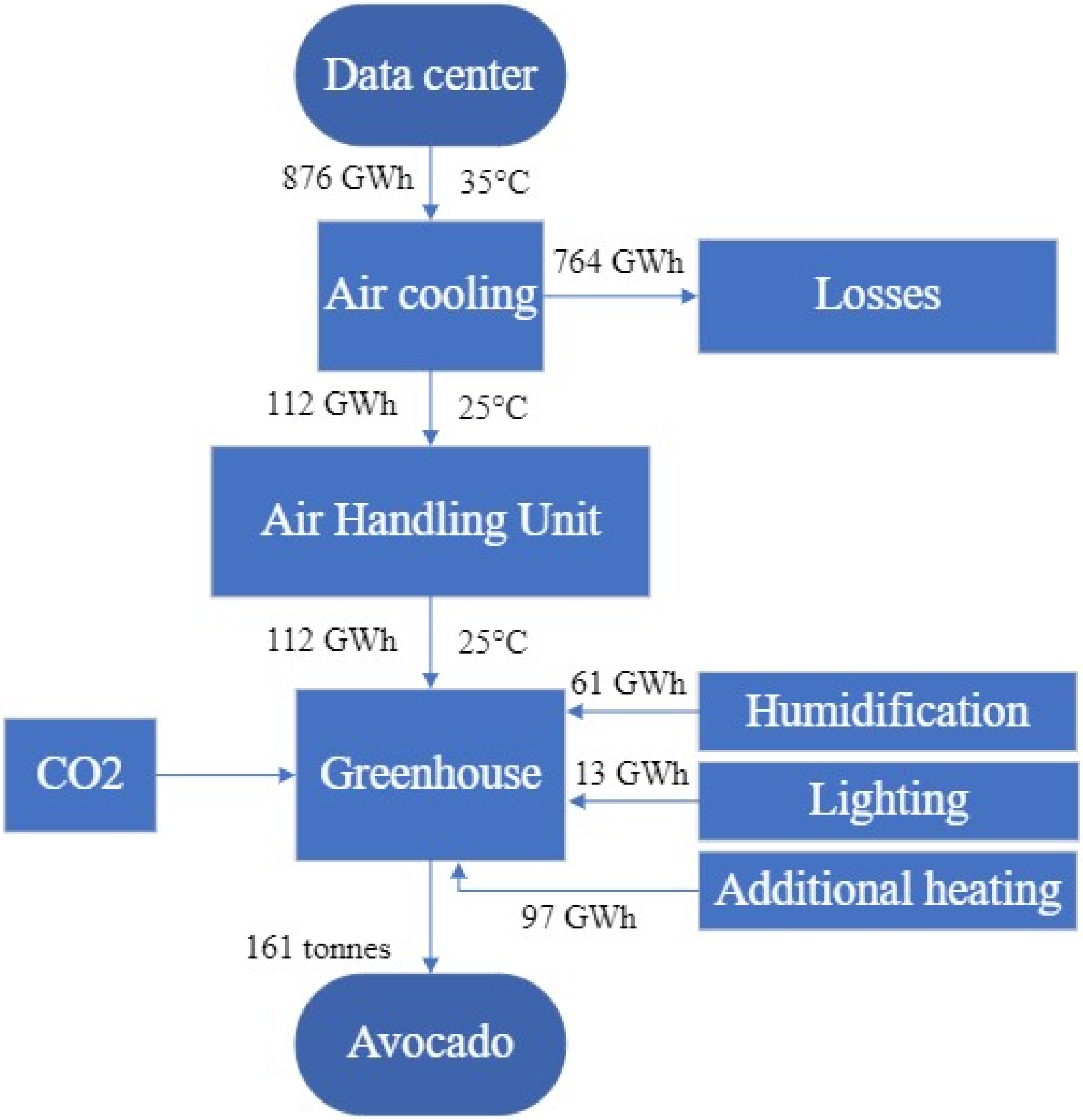

Figure 44: Energy scheme for greenhouse utilization of excess heat

In figure 44 the overall energy scheme for 25 greenhouses of 2000 m^2 is presented. A data center of 100 MW with no downtime will consume 876 GWh yearly. Losses represents the heat lost and the heat to the greenhouse is the amount reused. This accounts for a ERF of 12.7 % in the greenhouse All numbers will be further visualized and presented below.

All results and plots are for one 2000 m^2 greenhouse.

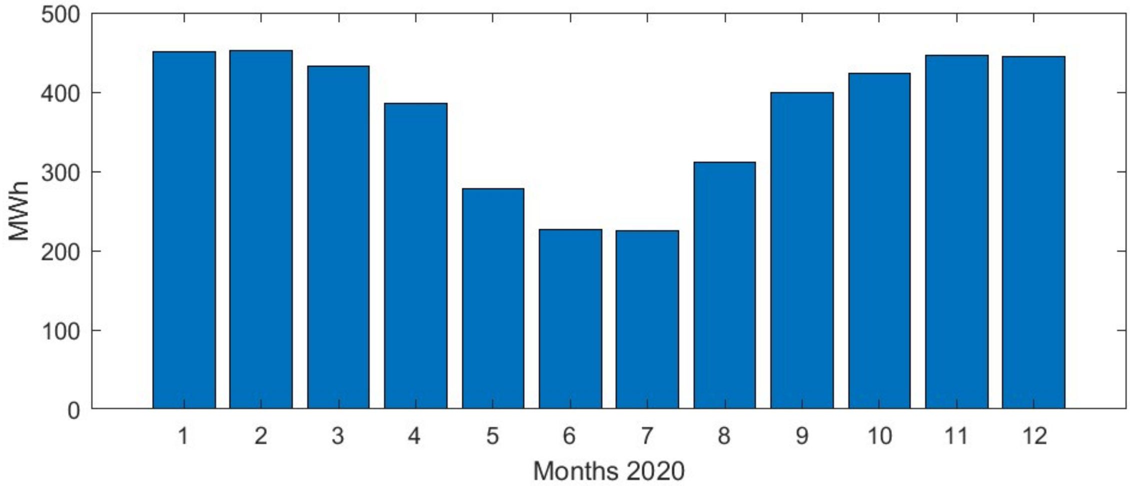

Figure 45: Utilized free energy AHU

Figure 45 visualizes the distribution over the consumption of free energy delivered to the greenhouse in 2020. This originates from the heat in the exhaust air from the data center. A total of 4476 MWh is recovered and utilised for heating in one 2000 m^2 greenhouse.

When calculating the air velocities within the greenhouse, a total supply airflow of 60 m^3/s applied under the rails. The rail cover an area of 400 m^2, which results in an airflow of 0.15 m/s. This is with the assumption of equal flow across the area. This air velocity does not surpass the limit for a working environment given by the Norwegian government, which is 0.15 m/s.

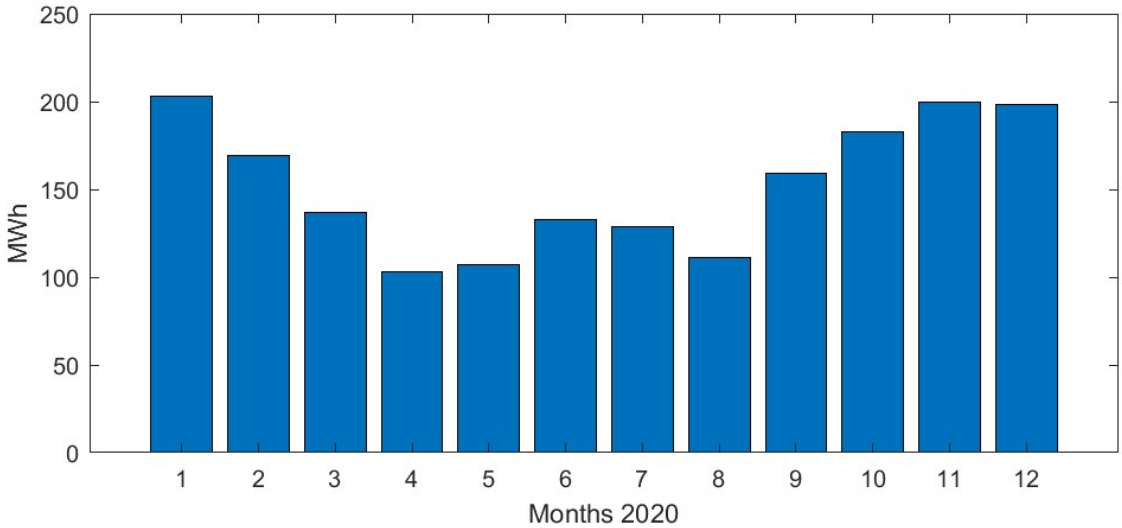

Figure 46: Extra electric energy for air heating

Figure 46 visualizes the supplementary electric energy utilized for air heating in the greenhouse. It varies from 200 to 100 throughout the year. With a total of 1831 MWh.

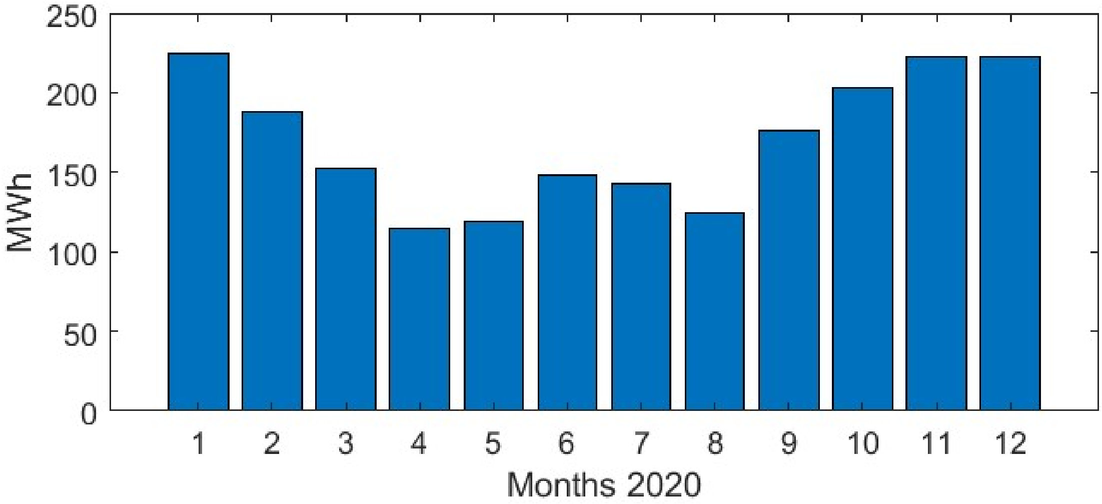

Figure 47: Supplementary fuel heating

Over the course of the year the heat demand cant be met solely by the excess heat and electric heating. Figure 47 represents the fuel heating demand during 2020. Seasonal variations are observable, with the highest demand during the winter months. For 2020 it adds up to 2037 MWh over a year.

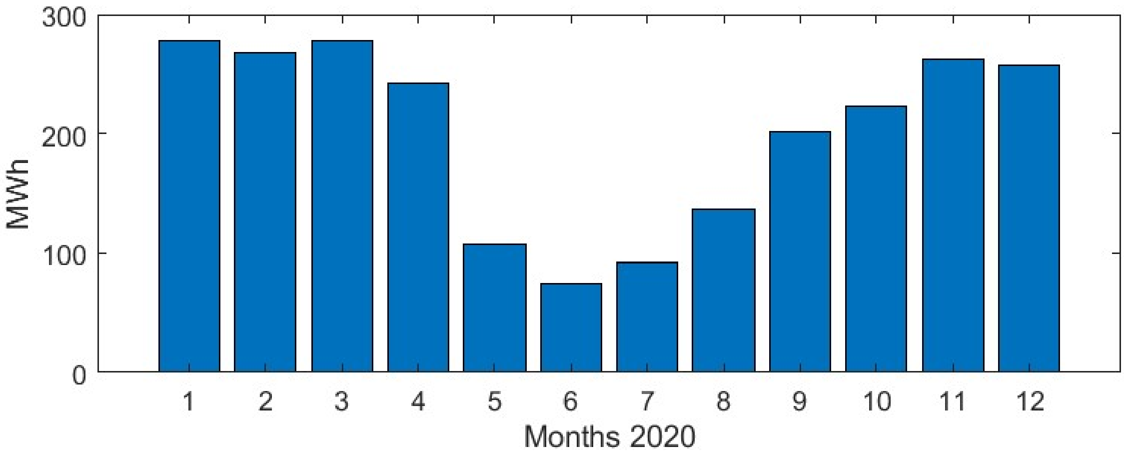

Figure 48: Energy consumption for humidification

In the greenhouse a large amount of air is processed, this provides a large need for external energy to ensure the optimal levels regarding humidity is met. In figure 48 the energy needed for humidification is presented over the course of 2020 is visualized. It adds up to 2420 MWh for 2020.

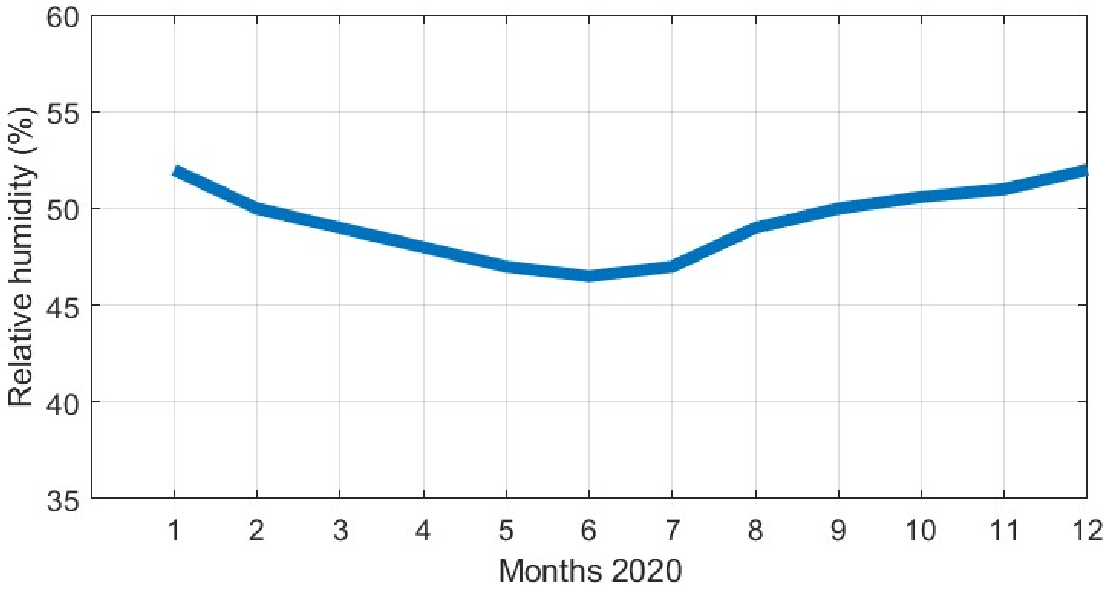

Figure 49: Relative humidity levels in the greenhouse

To ensure a high yield of growth, its important to consider humidity levels. Avocados thrive in relative humidity levels of about 45-65 %. Figure 49 shows the distribution of RH in the greenhouse over the course of a year.

From the simulation the CO_2-level showed to be steady at 400 ppm throughout the year. The simulations did not take into account the change in CO_2 through fossil combustion or humidification processes.

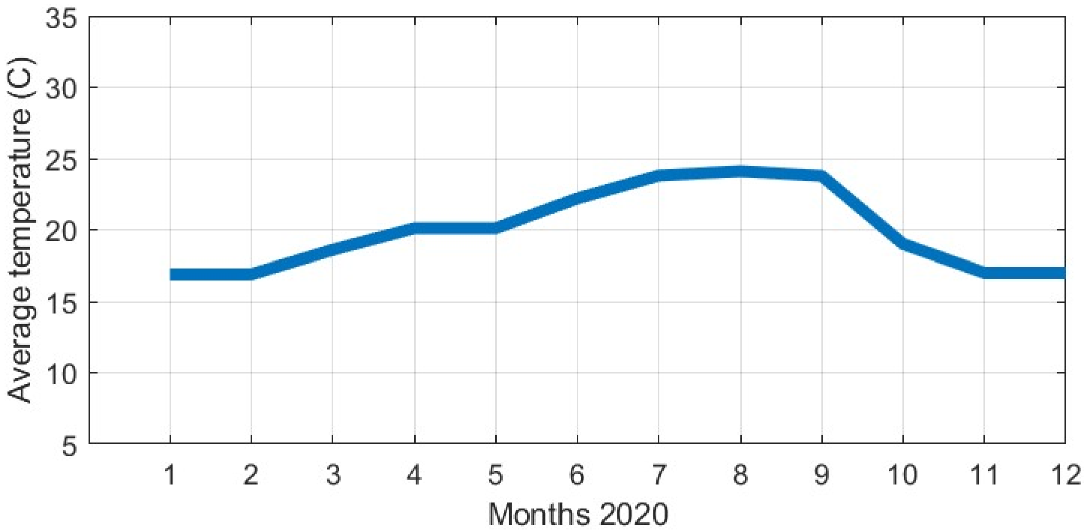

Figure 50: Mean temperature greenhouse

As mentioned previously, temperature is a critical parameter for high greenhouse yield. Figure 50 represents the average temperature distribution over the course of 2020 inside the simulated greenhouse.

10.2.1 Lighting requirement

Table 10: Lighting for avocados in a 2000m^2 greenhouse

Specification		**Unit**
Avocado (DLI)	18	$Moles/m^2 day$
Area avocado	1256	m^2
Total light requirement	22619	$Moles/day$
HLG saber 150 W	367.5	$Moles/m^2 \cdot s$
Light emitted (12 hours)	15.87	$Moles/lamp \cdot day$
Total lamp	1426	Lamps

As seen in table 10 the need for a total of 1426 lamps of HLG saber 150W with 12 hours of operational time. The total installed lighting capacity equals 214 kW.

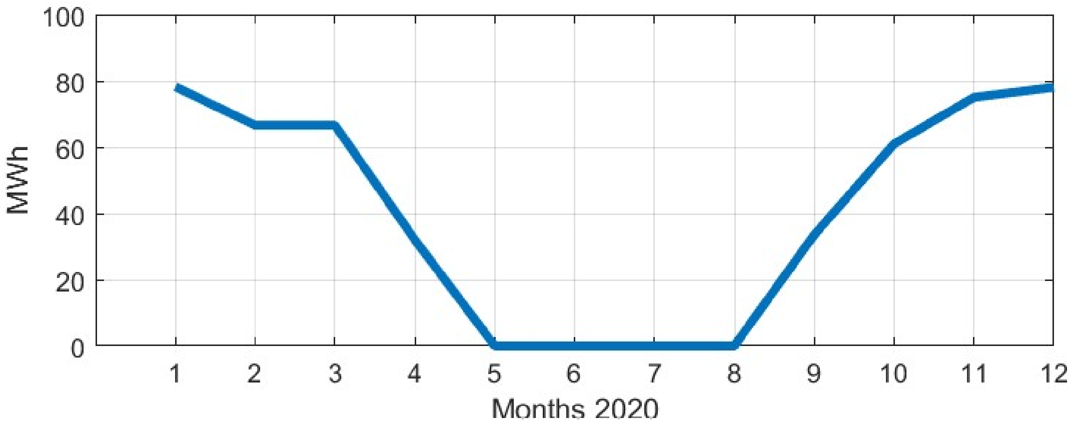

Figure 51: Power usage for lighting in the greenhouse

When calculating the actual electrical lighting required, as seen in figure 51, the DLI from Bjerkvik was utilized, from figure 37. Over the course of the summer there was no need for additional lighting. But in the darkest months, the installed lighting had to provide all the DLI. This summed up to 491 MWh. Calculations are presented in appendix F.

Table 11: Yearly production per 2000 m^2 of greenhouse

Specification		**Unit**
Avocado trees	100	
Yearly yield	30000	Avocados
Weight avocado	0.215	kg
Production	6450	kg
Specific yield	3.225	kg/m^2

To evaluate the efficiency of the greenhouse set up, its interesting to calculate the specific yield.

With the set up assumed in this thesis, it was room for 100 trees per greenhouse, this made the production was 6450 kg per greenhouse. Table 11 represents the yearly production of per 2000 m^2 of greenhouse.

Table 12: Total production of avocados

Specification		**Unit**
Liter/greenhouse	60 000	L/s
Total greenhouse	25	
Specific Avocado yield	6450	kg/gh
Theoretical yield	161.25	Tonnes

161 tonnes of locally produced avocados could possibly save 323 tonnes of CO_2, as seen in table 12. kg/gh represents kilograms of avocado per greenhouse.

10.3 Algae cultivation

In this section results from algae cultivation calculations is presented. A pond area of 20 000 m^2 was assumed.

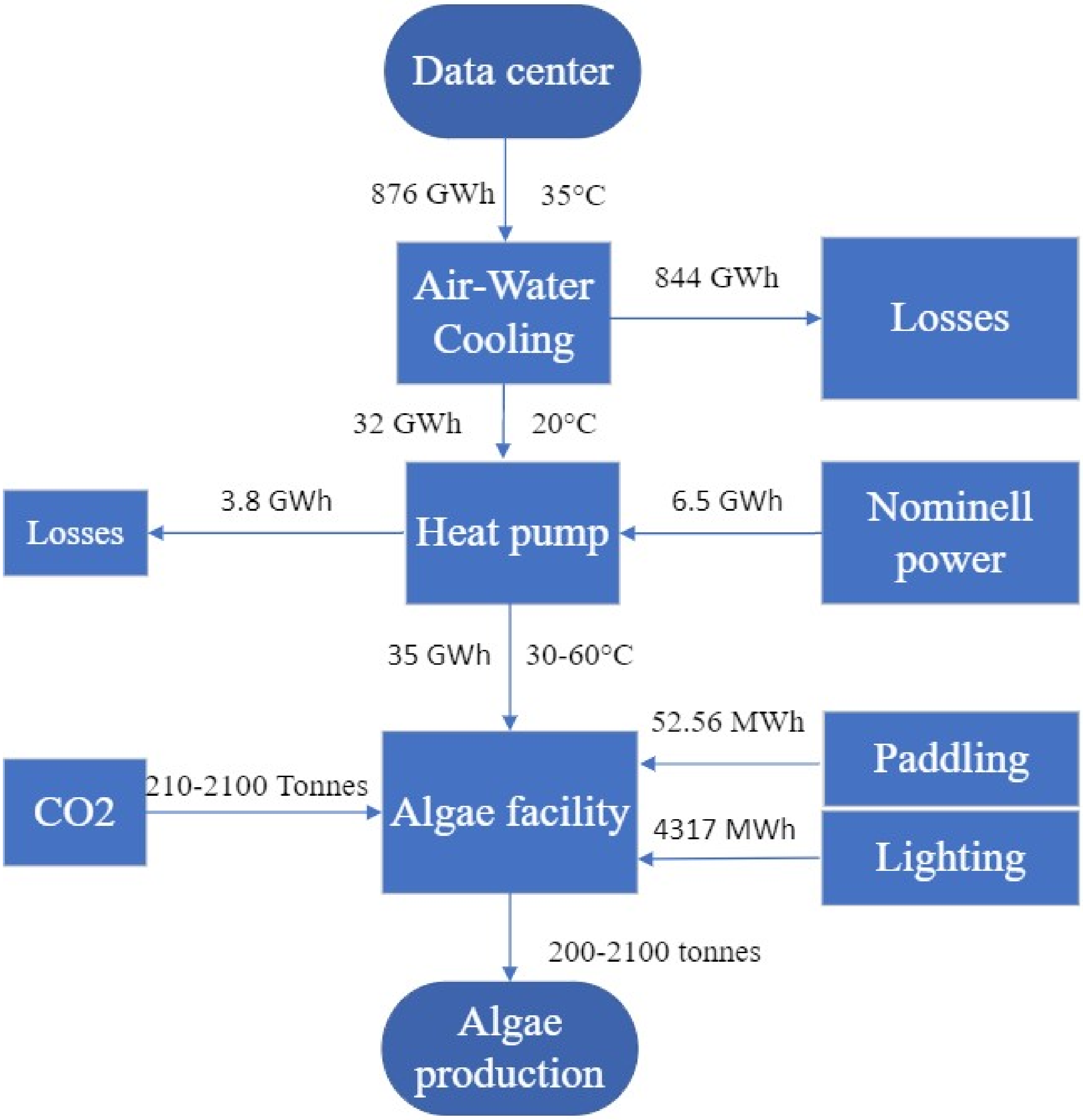

Figure 52: Energy flow chart of the algae cultivation plant

Figure 52 illustrates the heat flow from the data center to the algae facility. The total ERF for the algae facility was 3.7 %.

Table 13: Parameters of the algae cultivation plant

Specification		Unit
Total area	20 000	m^2
Total heating demand	4 000	kW
Heat capacity per heat pump	753	kW
Heat pumps	6	

By providing 6 heat pumps from Mammoth, the heating need for a 20000 m^2 algae facility could be met, and optimal temperatures could be maintained. These parameters are presented in table 13.

Table 14: Electricity usage of the heat pumps

Specification		Unit
Nominell power	123	kW
Total power	738	kW
Operative	8760	Hours
Electricity use	3690	MWh

Table 14 tabulates the electricity usage of the heat pumps in the algae production plant. The heat pumps are assumed to run at maximum capacity all year around.

10.3.1 Paddling

For paddling the need for paddling installed capacity was 6 kW. By continous load throughout the year, this accounts for 52.56 MWh.

10.3.2 Lighting

Lighting is a crucial factor to ensure a high yield of algae growth.

Table 15: Lighting usage

Specification		Unit
Algae (DLI)	13	$Moles/m^2day$
Area algae pond	20 000	m^2
Total light requirement	260000	$Moles/day$
HLG saber 150 W	367.5	$Moles/day$
Light emitted(16 hours)	23.8	$Moles/lamps * day$
Total lamp	10922	Lamps

With a total area of 20 000 m^2 it was showed to be needed with a total of 10922 lamps. Table 15 represents the lighting use in the algae cultivation facility.

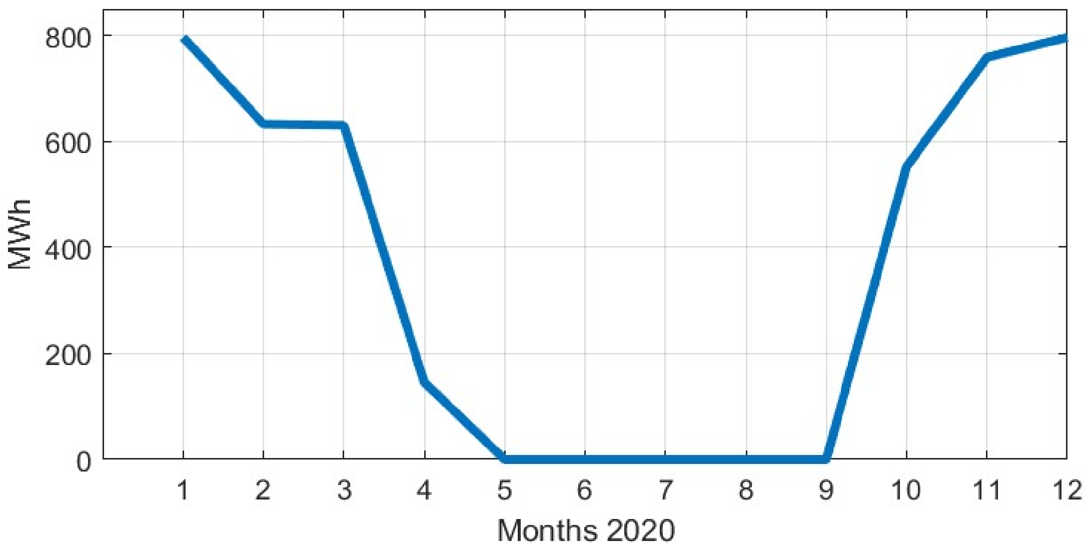

Figure 53: Electricty usage for lighting

With the given solar irradiation in Bjerkvik, as presented in figure 53 the total of electric lighting needed sums up to 4317 MWh over the course of a year. Calculations presented in appendix G

10.3.3 Production

With the given dimensions of the ponds, the production capacity is calculated.

Table 16: Production capacity of the given plant

Specification		**Unit**
Algae production min	0.05	g/L*day
Algae production Max	0.5	g/L*day
Algae volume	6	Million L
CO_2/algae	1.92	g

As seen in table 16 there is a significant dispersion between minimum and maximum possible production of algae. This means that the total algae growth will vary between 109-1095 tonnes of algae crops assuming growth over the span of a year.

With a production by these dimensions the captured CO_2 will vary in the range of 209 tonnes to 2102 tonnes over a year.

10.3.4 Efficiency

By implementing the Mammoth HP, the system manages to recover about 3700 kW at optimal conditions. This makes the ERF factor to be 3.7 % at the given dimensions.

10.4 Drying of biomass

In this section results from biomass drying is presented.

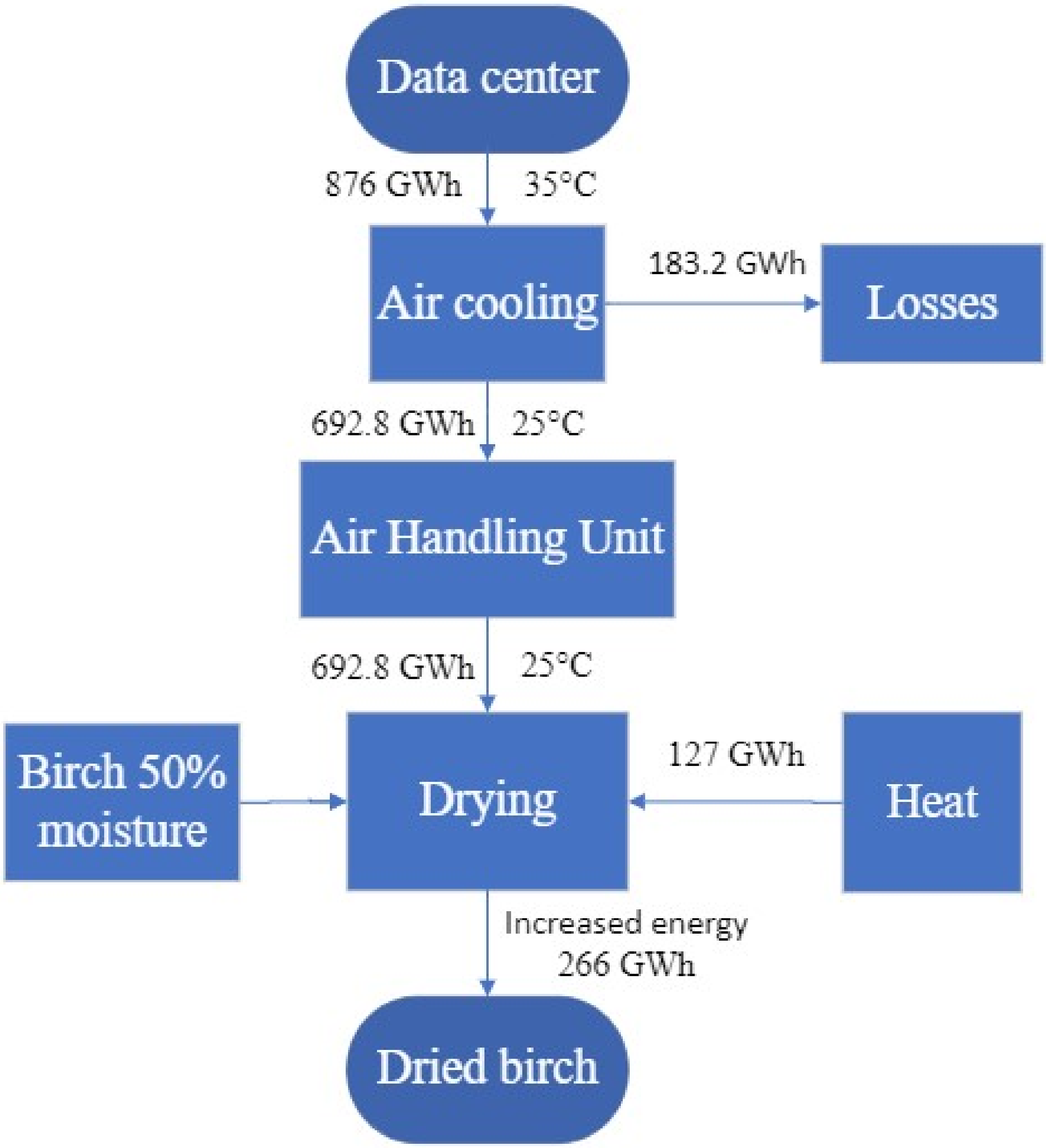

Figure 54: Energy flow scheme based upon the process of drying biomass

Figure 54 represents the energy flow within the bio-mass drying system. The different energy distribution within the system is explained further down in this section.

Table 17: Results of bio-mass drying from IDA-ice

	Container 250 m^2	**Unit**
Mean air temperatue	24	℃
Recovered energy	1732	MWh
Fuel heating	160	MWh
Humidity	26	%
AHU heating	159	MWh
Ventilation velocity	2.5	m/s

Table 17 presents the results obtained from IDA-ice simulation. It shows that over the course of a year the average temperature is 24℃with a relative humidity of 26 %. A ventilation velocity of 2.5 m/s provided by one Excooler. This is due to the flow of 17.8 m^3/s through a circle with 1.5 in radius. As the data center required 400 Excoolers, 400 containers could be utilized for drying.

Table 18: Pallets of wood and their energy

	Day 0	**Day 10**	**Unit**
Humidity	50	20	%
Density	500	300	kg/pall
Pall	62	62	palls
Total weight	31000	18600	kg
Energy content	2.3	4.83	kWh/kg
Total energy	71.3	89.8	MWh

As visualized in table 18 the change in total energy over the span of 10 days is 18.5 MWh in one container. By multiplying this by 36 drying periods over a year and 400 containers, this adds up to 266 GWh in increased energy over a year. This makes the ERF for drying of biomass to 30 %.

10.5 Smolt and fish farming

Results from the smolt facility case are presented in this section.

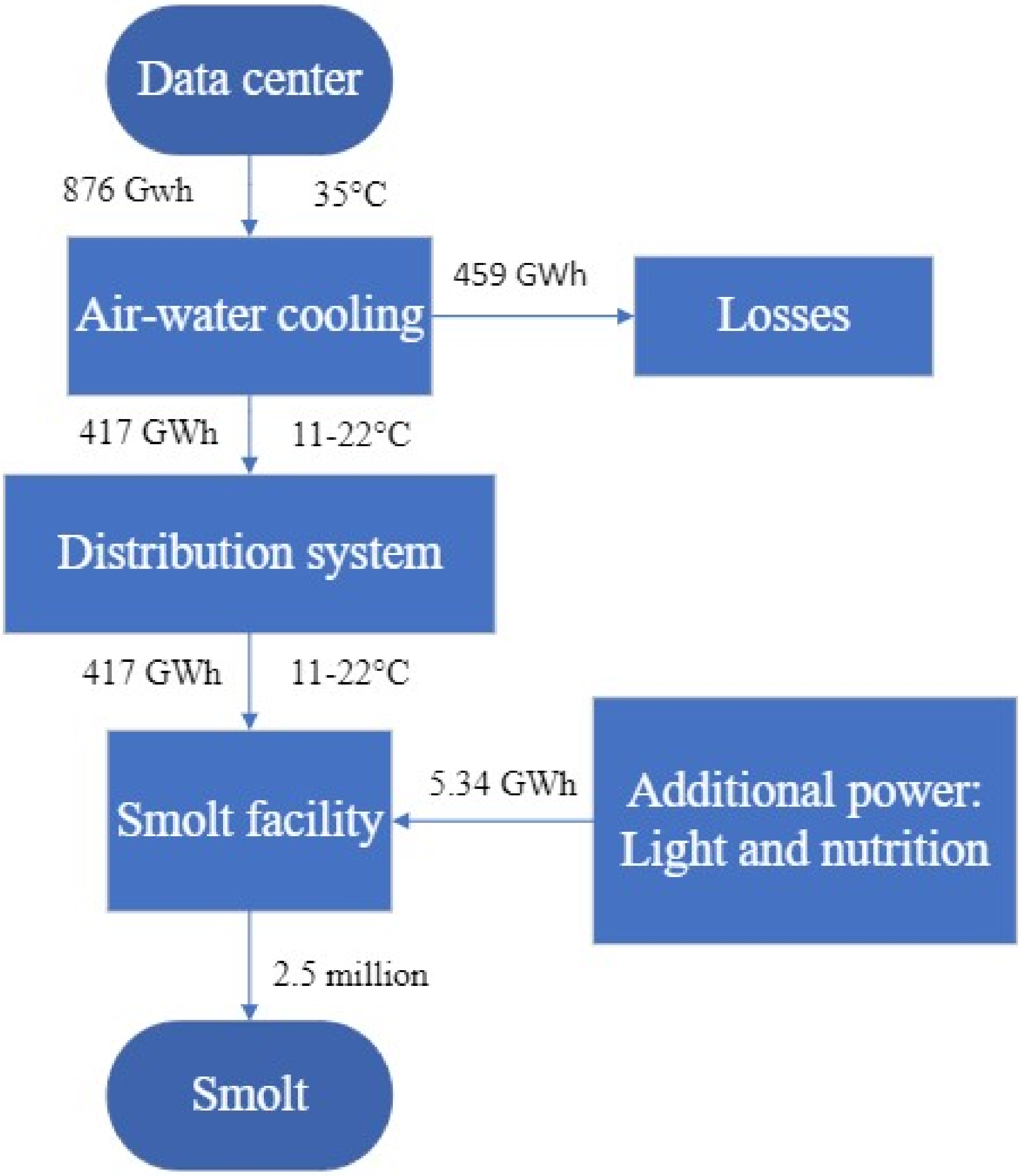

Figure 55: Flow chart of the smolt facility

In figure 55 the overall energy flow scheme for a smolt facilty is presented. The facility produced a total of 2.5 million smolt per year.

10.5.1 Heat demand smolt facility

By using the assumptions from the method chapter, a mass flow of 2,0 m^3/s is required for a facility with a production of 2.5 million smolt. By using 0.32 L/kg per minute of water replacement, the total mass flow rate of the make up water is calculated.

$$0.32L/kg/minute \cdot 2.5millionsmolt \cdot 0.15kg/smolt = 120000L/minute \tag{20}$$

The water replacement is required to be 120000 L/minute when there is 2.5 million smolts, as seen in equation 20. This value is equal to 2 m^3/s, as seen here in equation 21.

$$\dot{m}_{MW} = \frac{120000L/minute}{60s/minute} = 2000L/s = 2m^3/s \tag{21}$$

Equation 16 was used to calculate the energy requirement Q in the rearing tank. The parameters used in the calculations were heat capacity $c_{p,MW}$ of water of 4.18 $kJ/kg \cdot K$, mass flow rate $\dot{m}_{MW}$ of 2000 kg/s, temperature of tank water from figure 42 and temperature of makeup water from figure 43. The energy requirement was calculated over the months of the year.

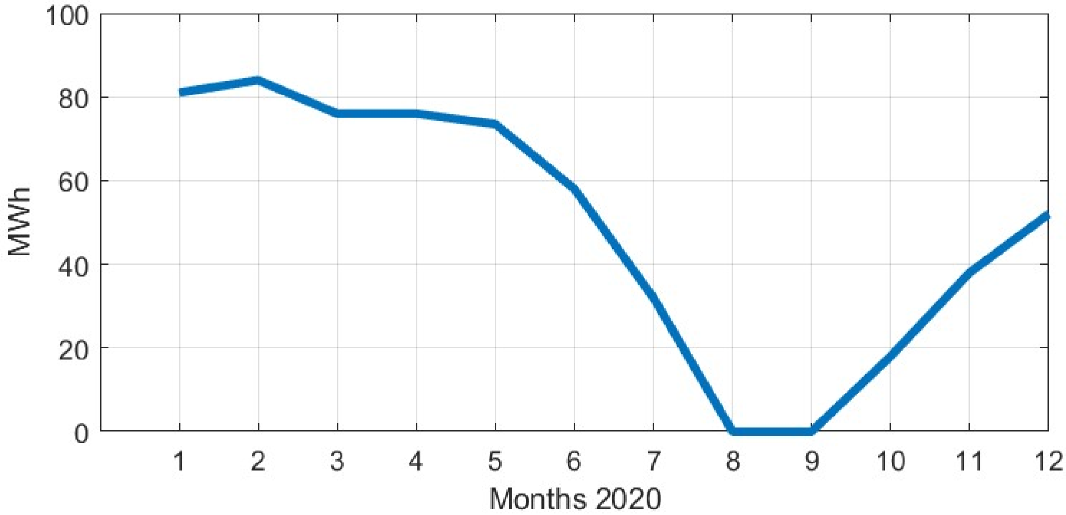

Figure 56: Heat demand over a year for the smolt facility

Based on the results in figure 56, the greatest energy need can be observed in the months from January until May. During the autumn months, energy requirements was at its lowest. In both August and September, the heat demand was zero. The values calculated for the heat demand of the smolt facility are seen in appendix C.

Table 19: Stream temperatures after the heat exchanger at different times of the year and different mass flow rates

		Mass flow rate [kg/s]			
Month	$T_{water,in}$ [°C]	2000	2200	2400	2600
January	2.3	13.06	12.08	11.26	10.57
February	0.9	11.66	10.68	9.86	9.17
March	0.8	11.56	10.58	9.76	9.07
April	0.8	11.56	10.58	9.76	9.07
May	1.2	11.96	10.98	10.16	9.47
June	3	13.76	12.78	11.96	11.27
July	6.1	16.86	15.88	15.06	14.37
August	11.6	22.36	21.38	20.56	19.87
September	11	21.76	20.78	19.96	19.27
October	7.8	18.56	17.58	16.76	16.07
November	5.4	16.16	15.18	14.36	13.67
December	3.7	14.46	13.48	12.66	11.97

Table 19 uses a version of the equation 16 to calculate the values of the heated water based upon the in-temperatures and the mass flow rate.

10.5.2 Efficiency smolt facility

The efficiency η of the smolt facility was calculated by using equation 17. Parameters used in the calculation were usable heat $Q_{usable\ heat}$ and supplied heat $Q_{supplied\ heat}$.

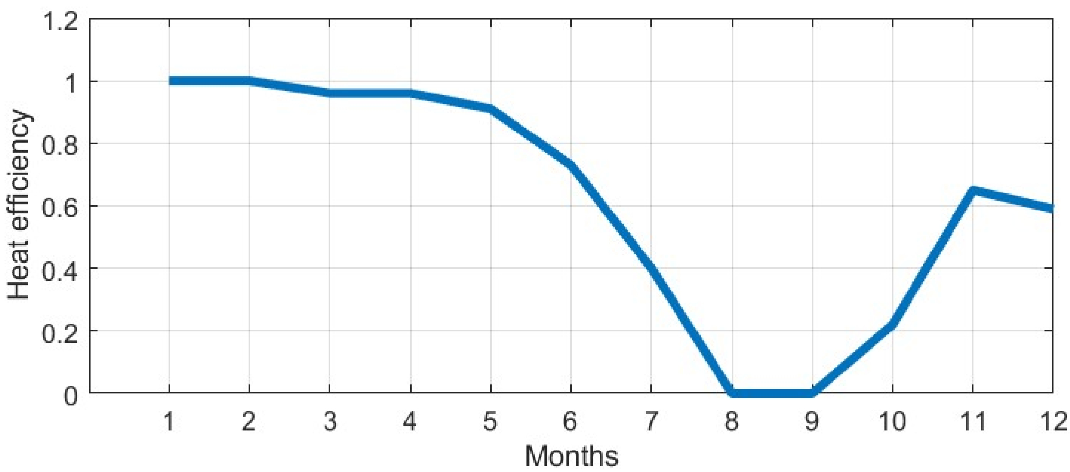

Figure 57: Energy efficiency smolt facility

Figure 57 shows the energy efficiency of the smolt facility over the months of the year. It can be observed that the efficiency is highest in the first months of the year up to and including May.

The efficiency is lowest in the months of August and September. This corresponds well with the heat demand calculated for the smolt facility over a year. The values of the effeciency of the smolt facility over the months of the year can be observed from appendix D.

The total efficiency of the smolt facility over a year was also calculated. It was calculated to be 59.6 %. This means that it was possible to utilize 59.6 % of the heat from the data center for heating smolts. The total efficiency can be seen from appendix D.

10.5.3 Energy reuse factor

Equation 2 was used to calculate the energy reuse factor (ERF) of the excess heat from the data center. The parameters used in the equation is utilized excess heat E_{reuse} and total energy usage E_{DC}.

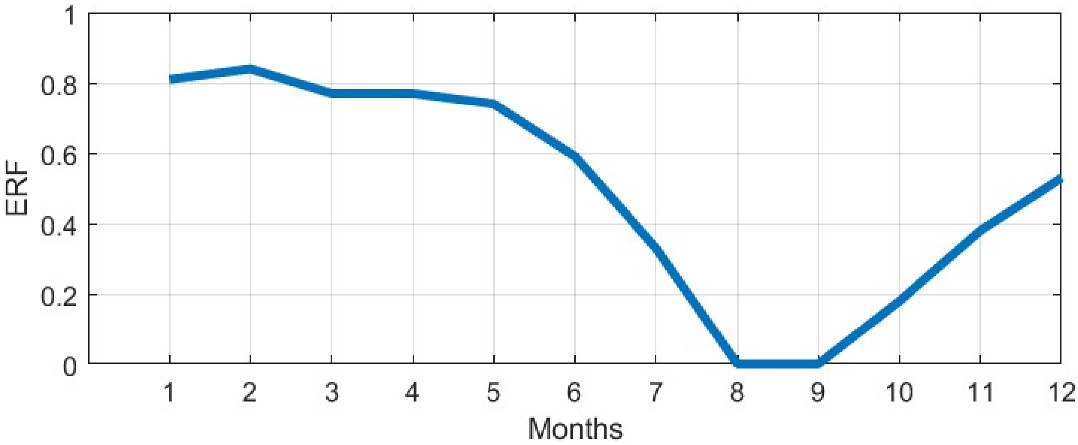

Figure 58: Energy reuse factor for the smolt facility

Figure 58 illustrates the energy reuse factor of the data center over the months of a year. The total energy reuse factor was calculated to 47 %. Values of the energy reuse factor of the smolt facility over the months of the year can be observed from appendix D.

10.5.4 Heat loss due to transmission

To calculate a smolt facility its important to take into account the heat losses in transmission, as it plays a vital part in placement of the facility. Therefore, distribution losses are calculated by equations 8, 9 and 11, where the values used are provided in table 20.

Table 20: Values used for calculating the distribution losses

Variable	Value	Unit
d	1.2	m
D	1.472	m
h	2.668	m
θ_f	Varying	℃
λ_m	0.7	W/mK
λ_i	0.3	W/mK

θ_f, which is the difference in temperature between the soil and the medium inside the tube, is listed as varying because the distribution losses are affected with a varying degree from the different temperatures in the water throughout the year. In the following figure 59 the θ_f values are found from the heated stream temperatures of a 2000 kg/s stream in table 19.

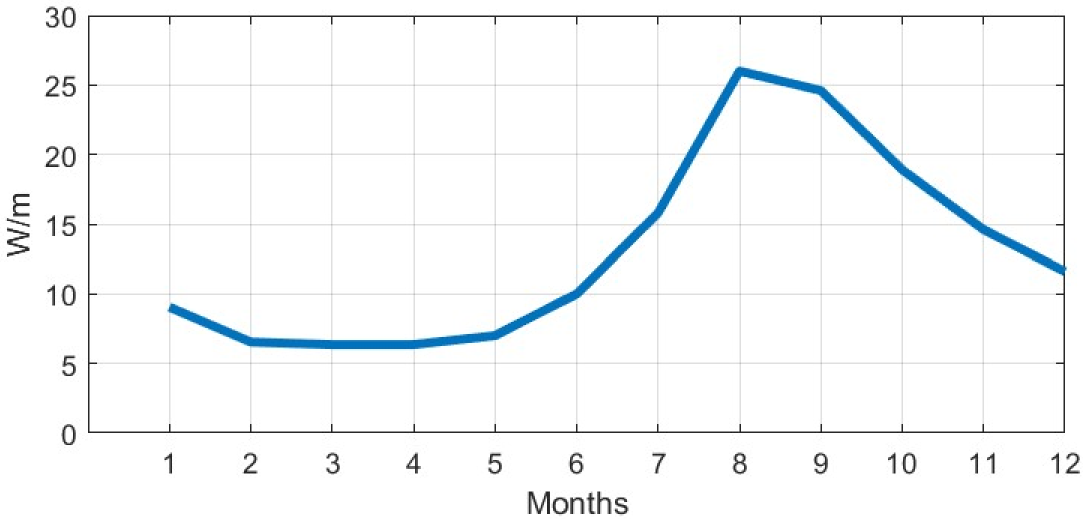

Figure 59: Distribution losses per meter across the year for mass flow rates of 2000 kg/s

In figure 59 the distribution loss from the pipe are presented, depending upon months, i.e. temperature of the cold water.

11 Discussion

In this section the results will be compared and discussed.

11.1 Data center

To assume the floor area for the data center with a capacity of 100 MW data for existing data centers was collected. This gave a total area needed for the data room of 50 000 m^2 which seems to be plausible.

The calculated amount of CRAC units were 918. It would have been cheaper with less units, but it is important the cover the cooling demand during summer months, when δ T between outside air and hot aisle air is low. Therefore a large amount of CRAC units are needed. The total air mass flow rate of all of these units were multiplied, thus resulting in 7557 kg/s. This number was based upon the capacity per rack in the data center which was set to 9 kW. As the ordinary capacity per rack for an air cooled data center is 7-15 kW, 9 kW was chosen as an approximate mean value.

By assuming a hot aisle temperature of 35 ℃and a cold aisle temperature of 23 ℃the required heat exchange in the CRAC was calculated, as seen in section 10.1. The ΔT of these temperatures could have been larger. However, since the desired temperature for the cold side of a data center is between 20 and 24 ℃, it is the temperature at the hot aisle that must be extended.

To estimate the amount of air-air coolers that were needed, Excool model was utilized. It resulted in a total of 400 excoolers to provide 100 MW of cooling. This is with the assumption of δ 12. The exhaust flow from the excooler will vary strongly throughout the year, as the outside temperature varies. But to provide sufficient cooling during the summer months, its normal to estimate a low δ T when calculating numbers of coolers. To ensure cost reductive measures, it would be beneficial to install less Excoolers. But to deliver sufficient cooling, its important to scale in regards to low δ T. For simplicity, 17200 L/s was utilized for the span of the year. As an example this is utilized in biomass-drying.

11.2 Greenhouse

When calculating a greenhouse its normal to analyze the crops normal conditions and in the best possible way recreate these conditions inside. Key parameters here are temperature, humidity, lighting and CO_2-levels. For the utilization of excess heat from data centers, in the form of hot air, its was shown that the airflow was not big enough to meet the heating needs during the coldest months. This is mainly because the supply air could not surpass the Norwegian labor inspections limit for a working environment. As seen in figure 44 the excess energy accounted for a total of 53.6 % of the heat need for the greenhouses. In the summer months the greenhouse was almost only heated by the excess air. This shows that to reach sufficient temperature levels a large amount of excess heat was needed.

The simulations showed that it was almost possible to recreate the average yearly temperature of 21 °C. This is less than the optimal temperature for steady avocado growth, which could possibly decrease the potential yield. To analyze the impact this reduced temperature has on the yield, further research and trials have to be conducted.

In addition to temperature, the humidity levels where shown to be met. But this requires a substantial amount of energy to reach. This accounted for 61 GWh over a year. This is mainly due to the large continuous airflow into the greenhouse throughout the year. By heating a greenhouse with a airflow exhausted from a data center, the humidifiers has to put in a lot of energy to keep steady humidity levels. This is also a big challenge in greenhouses in Norway today, and has proved to be a problem for using the excess heat for heating in a greenhouse.

For the lighting requirement, calculating with natural irradiance, the yearly electric consumption was 13 GWh. This is especially high in the winter months, when there is little to no natural irradiance. By placing the greenhouse in a more southern location, this energy need would be significantly reduced.

When analyzing the yield of avocado growth inside the greenhouse, visualized in 11 the specific yield is not very high. One tre only produces about 300 avocados each year, and it requires a significant area per tree. Compared to cucumbers, tomatoes and other its very low. The assumptions with 4 meters diameters for each tree, is quite conservative. The assumptions here were based on the outside technique for planting. Regarding the planting inside, there is little to none research on the field as per now. By increasing the density, the production would rise quickly.

One important aspect is the environmental benefits of local growth of avocados. Abroad production of avocado comes with negative climate impacts because of transportation, a high usage of water and area of land. With the utilization of excess heat locally, these avocados could be one of the most environmental friendly avocados in the world. The large amount of water accessibility contributes largely to this. With a theoretical yield of 161 tonnes, this could account for 1 % of the Norwegian total yearly consumption. This is the *potential for avocado farming from one data center facility. This shows the great national potential when a large amount of energy intensive industries are being planned.*

When utilizing excess heat, the transmission heat losses to the greenhouse was not taken into account when calculating the heating efficiency. When placed on top of the data center it provided a total of 25 greenhouses, which provides negligible transmission losses. This shows the great potential the roof of a data center actually provides regarding energy recovery.

11.3 Algae cultivation

When utilizing excess heat for algae growth, there were numerous of interesting factors to analyze. First of all the heat demand could not be met solely by the excess heat. By implementing 6 heat pumps, the assumed heat demand was met. This resulted in steady temperatures for optimal growth of algae in a open pond. Each heat pump provided a COP factor of 6, which shows the great potential a industrial heat pump has in collaboration with excess heat. To ensure steady concentration of both nutrients and CO_2 through the pond, a large amount of power toward paddling is needed. A total capacity of 6 kW is installed, which results in 52.56 MWh over a year. For a pond of these large dimensions, this energy usage is not seen to be large enough to be a restricting factor.

One important problem with algae cultivation is the lighting requirement. Since the process happens in a pond filled with water, a lot of the lighting energy is wasted due to evaporation of water. Almost 11 000 lamps are needed, with a total energy use of 4317 MWh over a year. These are large numbers and something that limits the possibilities for the industry to be utilized in the northern parts of Europe, where the direct sunlight is very limited.

The most noticeable result was the production rate. Algae grows at a high rate, and with optimal conditions this facility could produce almost 1100 tonnes of algae per year. With a maximal capturing rate at 1.92 g_{CO_2}/g_{algae}, this works excellent as a CCS alternative. This adds up to a potential capture of 2100 tonnes CO_2. This shows the great potential to reduce carbon emissions algae growth inhabits.

The numbers used for calculating the algae yield vary significantly. This is due to the yield vary enormously from specie to specie. This makes the potential yield hard to calculate and more research in these climates are necessary.

When dried up to a TS of ¿95 algae could be an important resource with lots of areas of applications. As a part of fishing feedstock it could lower the demand for fishing oil, which accounts for large emissions and negative humanitarian consequences. It could also be utilized as a source for biofuels. By extracting the lipids, it could make biodiesel. This would lower the need for fossil fuels, and make the transport sector more environmentally friendly.
As for the energy efficiency of the system the heat pumps totally recovers about 3700 kW of heat. This accounts to a total ERF of 3.7 % which only shows the great potential for algae growth. Only 3.7 % of the data center capacity is recovered, and it provides energy effective reuse for a heat pump, which gives 20 000m^2 of algae pond and a production of 1300 tonnes of algae each year. If one could assume to recover all of the heat from the data center, this could apply to sufficient

heating for a 540 000 m^2 of algae pond. This is of course unrealistic, but it shows the potential.

11.4 Drying of biomass

As Norway has a large share of energy usage originating from biomass, its interesting to analyze the results from drying processes when utilizing excess heat. A realistic the model created in IDA-ice. As seen in table 17, the building provides a stable temperature of 24 °Cwith the free energy, fuel heating and AHU heating. With the excess energy from the data center representing 85 % of the heating need. Furthermore, the heat from the data center also provides a dry and optimal environment, with a relative humidity of 26%, which accounts for good conditions for drying. Its important to note that a lot of energy is used for additional heating during the winter months.

When analyzing the drying process it was found to be quite fast. A process which was assumed to be 10 days in total, from entering as a recently chopped wood, to be ready for domestic usage in 10 days is impressive. This alternates in 3 changes per month, and about 36 each year. With the assumption that it goes from a humidity from 50 % to 20 % this makes a total ERF over a year of 30 %. This is quite impressive, as Norway utilizes about 13 TWh of biomass fueled energy each year. Therefore, this drying facility could provide high value material to fuel approximately 1.5 % of the heating.

The amount of pallets per building resulted in 62 pallets per building per drying period. By multiplying this with the total number of drying periods per year and number of buildings, the amount of dried pallets per year is found. This resulted in 892800 pallets. This represents more than 267 million kg of dry wood. This represents 1.8% of trees cut down annually in Norway. To use this percentage as fire wood might be possible, however it might be more problematic to organize the logistics.

Its important to note that a lot of energy is used for additional heating during the winter months. If the drying only were to happen in the summer, one could diminish the energy usage for additional heating, due to it only being a requirement during the winter. It could be beneficial to create a system where the excess heat could be delivered to another recipient in these parts of the year.

11.5 Fish Farming

As seen in the results, visualized in 56 it is observed that the heat demand for the fish farming facility was greatest from January to May. It was lowest from August to September. This is due to the water temperatures natural variation during the year. Since the temperature in the smolt facility operates at steady temperatures of around 10 ℃, the heat demand was at it‘s greatest during the winter periods. The opposite was the case in the autumn months of August and September, when the heat demand was 0.

The heat demand in the smolt facility ranged from a maximum value of 84.4 MW to a minimum value of -13.4 MW.

80 MW is supplied from the data center to the smolt facility. Originally, the data center capacity is 100 MW, to calculate efficiency the heat delivered from the heat exchanger was set to be 80 MW. The losses occurred in pipes, the surroundings and in the transition between water and air. Calculation in 19 shows that about 9.5 MW was lost in the heat ex-changer between air and water. From the figure 59, the distribution losses are seen in relation to different water temperatures. It can be observed that the distribution losses in the pipes are quite small per meter. This means that the fish farming facility can be placed at long distances from the data center. It is estimated that around 10.5 MW is lost in pipes and to the surroundings. As the table 20 and the figure 59 respectively presents the values used for calculating the energy losses in the distribution line and the losses in the distribution line as a function of date and W/m. If there were to be a theoretical loss of 1 MW in the distribution line, the distribution line would have to be 40 km long. There are some significant chances the flow would see other problems, e.g. pressure losses, before dissipating 1 MW of energy to its surroundings. Often it is more economically sensible to place the distribution lines on top of the ground, but this would lead to higher losses.

Efficiency per month and total efficiency per year were also calculated. The efficiency per month ranged from 0-100 percent as seen in figure 57. Since the efficiency depends on heat demand $Q_{usable\ heat}$ and supplied heat $Q_{supplied\ heat}$ is constant, the effect will vary with the heat demand. Therefore, the results showed that efficiency was largest in the winter months January and February (100 percent). It was lowest in the autumn months August and September (0 percent). The total efficiency per year was calculated to be approximately 60 percent. This is a fairly good efficiency for the facility.

The energy reuse factor per month (ERF) was found as well. It varied from 0-0,84 as observed in figure 58. This factor depended on the utilized excess heat E_{reuse} and the total energy usage E_{DC}. Utilized excess heat was the heat demand, while total energy usage was the total power input to the data center. The total power input was at 100 MW, causing the effect to vary with the heat demand. The energy reuse factor was therefore lowest in August and September (0), and highest in January and February (0,81, 0,84).

System FT-G is the land-based production system assumed in the facility. FT-G has a big water requirement. A sufficient access to water in the area is required to be able to utilize this system.

In Norway there are many rivers and lakes, the water demand will not be a problem for a facility placed in Norway. The system also has a low supplementary energy demand. This is positive in terms of the environment and efficiency of the system. It is important to focus on low energy solutions because of the ever increasing energy demand in society. Low energy solutions for industry could lead to overall lowered greenhouse gas emissions.

One negative aspect of the facility is that the immediate area can also be affected by water flowing out of the smolt facility. This water is not recycled and released direct to the surroundings. This is due to the water from the smolt facility being filled with effluents from the smolt. These can disturb the water balance and ecosystems in surrounding water.

11.6 Comparison of the different industries

A wide span of industries have been researched as a receiver of the excess heat from a data center. As the results vary significantly its important to compare the pros and cons across industries. The four industries have very different heating mechanisms. Direct air heating in greenhouses and biomass-facility, utilization of an industrial heat pump and water flow which utilizes the excess heat in fish farming. Important parameters compared in this subsection are usage of area, supplementary energy, environmental benefits and the overall ERF.

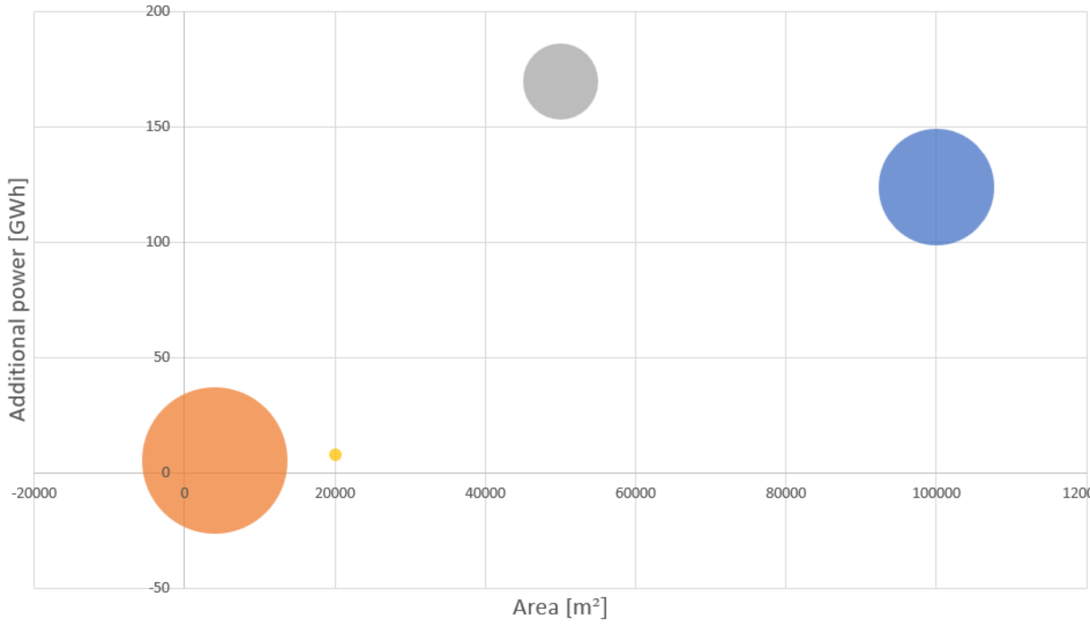

Figure 60: Diagram comparing the ERF, additional energy requirement and area usage of the different cases

Figure 60 represents the comparison between area, additional power requirements and energy reuse factor. Area is situated along the x-axis, additional power requirement is situated along the y-axis and the ERF is represented as the size of the dots, i.e. by the area of the dots. The orange dot represents the smolt case, the yellow dot represents the algae case, the blue dot represents the biomass-drying case and the grey dot represents the greenhouse case.

If one is to use the figure 60 to determine which case is the most suitable one, it is by finding the case which require the least additional power, the least amount of area and retains the highest energy reuse factor. In terms of orientation on the figure this would mean the point closest to the origin with the largest dot.

11.6.1 Area usage

As for area usage, the results vary significantly. As for the establishment of a symbiosis between a data center and a receiving industry, areal needed for the industry is a critical parameter. As urbanization, conservation of wildlife and effective area usage are important for governments, area required is a essential parameter for new industries. As seen in the result section a pond for algae cultivation is assumed to be 20 000 m^2 and for fish farming its 4000 m^2 . An optimal industry would require as small area as possible with a high efficiency.

The area usage for algae cultivation and biomass drying is large. A 20 000 m^2 pond would be unrealistic to establish, as it needs flat area. Its also in this thesis assumed that the overall area for biomass drying is 100 000 m^2. This is a large area, but comes with great uncertainty. This vary upon the density of wood per square meter, drying method and wind velocity. To optimize this, the more biomass one could dry with minimum area should be researched further. This could decrease the assumed area in this thesis.

In the establishment of a receiving part, there is a very interesting area available: the roof of the data center. This area is mostly available, and by placing an industry on top one would save the local nature and still potentially gain a high ERF. One interesting aspect of this is the rise of hot air. The need for pumps would be significantly reduced, as the receiver is placed as close as possible. Its assumed that all the greenhouses are placed on top of the data center, with a total area required of 50 000m^2. One could view this as zero extra area required, due to the fact that this area already is utilized and developed for industries. But for the calculations here, it assumed to be 50 000m^2 of required area. In terms of area usage, greenhouses are a great option when placed on top of the data center facility. As for the rest, fish farming requires the least area. An interesting part of fish farming is that the facility is not needed to be located nearby the data center. The transferring of heat in water is significantly easier with less losses compared to air. This extends the possibilities for location compared to the other industries evaluated.

11.6.2 Energy usage

In terms of supplementary energy, the results vary strongly in the industries accounted for. To establish photosynthesis indoors, one needs large amounts of energy. Heating is an important factor, especially in northern Europe. A total supplementary need for 171 GWh per year proves that greenhouses in terms of energy usage, is a bad implementations. Especially the energy to keep optimal humidity levels, was found to be extreme. The air exchanged had a low relative humidity, which is undesirable in greenhouses. The supplementary energy reduces the probability of the establishment of a greenhouse as a receiver of excess heat from a data center.

As for algae cultivation, it needs large amount of heat. The excess heat was needed to be upgraded with an industrial heat pump to a higher degree of heat. A heat pump proved to be a energy efficient utilization of the excess heat but the power required is high. Analyzing energy needs for algae cultivation, lighting is found to be at extreme levels. A total of 4317 MWh makes this establishment unrealistic as well. This is especially due to the low irradiance in the winter months in nothern Norway. Locating the facility in more sunny conditions would be beneficial, which also applies to greenhouse.

For biomass drying it was found that one needed extra heating to reach desirable temperatures. This accounted for 127 GWh which reduces the overall efficiency. More heat equals more energy, thus reducing the probability for an alliance with a data center. By lowering the area for drying, the facility would need less supplementary energy, and could probably solely rely on excess heat. This would reduce the drying capacity and thus the total ERF. One way to abolish the high requirement for extra energy is by limiting the up-time of the facility. This means to not dry any wood in the periods of high energy demand, namely the winter. This is where most of the supplementary energy is needed. This reduces the energy usage of the drying facility, therefore enhancing the sustainability of the biomass-drying facility.

For fish farming and smoltification it was found to be negligible supplementary energy needed. The demand for lighting is low, and other energy sources like for feeding, transportation was small.

11.6.3 Environmental benefits

Energy is saved by utilizing excess heat in industries. Meaning that if the industry is located somewhere else, it would need another heat source to cover the same amount of energy over a year. An establishment in cooperation with a facility with a lot of excess energy reduces the overall energy usage. Meaning that if either of these industries are operative it would have an beneficial contribute to the environment.

For greenhouses it produces locally grown fruits or vegetables with possibly the worlds smallest environmental footprint. The energy for heating is a reuse energy source, originating from hydro-power and fed with some of the excess water resources in the country. As seen in results, when avocados are grown one could potentially save 323 tonnes of CO_2 and provide 1 % of self sufficiency of the total national need. This with a quite conservative planting strategy.

The algae cultivation provides very interesting environmental benefits. As algae growth require large amounts of CO_2 to ensure a steady growth, an algae facility could operate as a CCS facility. The potential is substantial with an overall yearly capacity to capture 2100 tonnes of CO_2. Once grown and dried algae could also be utilized as feedstocks for fish farming and as part of human feedstocks in the future.

Its more difficult to see the direct environmental benefits when analyzing the environmental benefits of biomass drying and fish farming. If the produced fish was consumed locally it would have increased the self-sufficiency in the area, but would probably be exported in the same way as a large part of the Norwegian fishing industry is today.

11.7 Energy reuse factor

As seen in 60 the energy reuse factor vary in the different industries. Algae cultivation had the lowest ERF at only 3,7 %. To achieve a higher ERF It would require an extremely large pond to be able to potentially utilize all of the 100 MW from the data center.

Greenhouses achieve an ERF of about 13 %, which is not quite impressive. By utilizing higher volume flows of air into the greenhouse it could achieve a higher value, but that would increase the area required for gratings.

Biomass drying achieved the second best ERF of 30 %, which is impressive. This is based upon some assumptions, for example that wet biomass is obtainable throughout the year. The ERF could be improved by altering the properties of the building the biomass is dried in.

The best in regards to utilizing excess energy is fish farming which was at an ERF of 47 %. This is quite remarkable reuse of the data centers energy. And this could prove the data center to be very sustainable.

12 Sources of error

In this thesis there are several sources of errors to the results obtained. None of the calculations were based upon trials or researches performed by any of the authors. The phase of collecting data was difficult, mainly due to the secrecy within the data center industry and this made the need for assumptions big. To perform calculations with as high relevance to actual industries, data for industries operating in comparable situations were collected. How these parameters

In figure 43 temperatures are collected from autumn 2007 and spring/summer 2008. It does not give an insight into how the temperature in the water has been in other years. This can also lead to uncertainties with regard to the temperature profile of Forsanvatnet. Furthermore, the values are for one day each month, and not a monthly average.

IDA ICE is a program designed to calculate indoor climates, which it excels at. It is more debatable whether the program is suitable to calculate industrial facilities operating at conditions which does not share conditions similar to those of offices or homes.

13 Recommendation for future work on the subject

For future work it is recommended to analyze a symbiosis between multiple receiving industries for the excess heat. The results obtained from this thesis shows that multiple industries have different heat demand over a year. It can therefore be interesting to look at several industries operating on the side of a data center. Where the excess heat alternates during periods of the year.

It is also recommendable to perform more practical research in the future. One could for example build a small scale data center and test the implementation of different industries in relation to a data center.

To ensure a high accessibility of the heat for a receiver its also recommended to do a more thorough research on the laws and legislation on the roof of the data center. To achieve as low losses as possible it could potentially be a great area for industries which utilizes the excess heat.

14 Conclusion

Excess energy is energy which is a bi-product from an industrial process. The amount of excess energy in Norway today exceeds 20 TWh, and this amount is expected to increase in the next years. As a result of this it is important to utilize the excess energy to improve the energy effectiveness of the Norwegian industry.

As a conclusion when comparing the results by ERF, requirement of additional energy and total area usage, it was the fish farming facility which proved to be the most suitable industry for the excess heat. It required only 5.34 GWh of additional energy, 4000 m^2 of ground area and the ERF reached 47%. Fish farming was also the only industry where distribution losses were accounted for, which in the end proved to be relatively small. This gives the placement of the industry more possibilities compared to the other industries.

Furthermore, local avocado production is without doubt beneficial for the environment. This as a result of the reduced emissions related to the requirement of transportation and less pressure on resources such as water and land in the producing lands today. Avocado production in Norway could also lead to the country being more self sufficient. But avocado growth in Norway proved to have a very low yield and came with high supplementary needs, which makes it not suitable for local production.

The biomass-drying facility is also worth mentioning, as it is the least costly industry to perform. When comparing it to the other industries in this thesis, it only requires a building and a steady flow of biomass to operate. However the total area requirement is very large, at 100 000 m^2.

The algae facility proved to capture a potential amount of 2100 tonnes of CO_2 which is beneficial for the environment, but due to its large area and lighting needs, its not suitable as a receiver of excess heat.

During this bachelor thesis, the group have gained insight into an exciting new part of the industry developing energy effective solutions. The group have been supported throughout this thesis by a wide variety of specialists in different fields, and gained a lot of useful information thanks to them.

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Appendix

A Rittel CRAC CW 3300.387

Computer Room Air Conditioner

CRAC CW

Model No.	P. of	3300.384	3300.385	3300.386	3300.387	3300.388	Page
Rated operating voltage V, ~, Hz		400, 3~, 50	400, 3~, 50	400, 3~, 50	400, 3~, 50	400, 3~, 50	
Width mm		1085	1305	1875	2499	2499	
Height mm		1925	1980	1980	1980	2580	
Depth mm		775	930	930	930	930	
Weight kg		313.0	366.0	513.0	640.0	555.0	
Cooling - cold water 7°C/12°C and air inlet 24°C/50% relative humidity							
Cooling output, total kW		34.1	60.9	98.9	130	167	
Cooling output, sensible kW		28.8	52.2	81.7	109	139	
Fans							
Quantity		1	1	2	3	3	
Air throughput m^3/h		6600	12200	18000	24200	30950	
External static compression Pa		20	20	20	20	20	
Power consumption, total kW		1.19	2.09	2.96	4.91	5.64	
Rated current A		2.7	2.77	6.16	8.1	9.24	
Current rating (OA) A		1.73	3.41	5.23	6.68	9.89	
Current rating max. (FLA) A		4.18	4.3	9.6	12.54	14.4	
Cold water coil							
Quantity m^3/h		5.84	10.4	17	22.4	28.6	
Loss of pressure from the device and valve Pa		35	58	70	66	86	
Frost protection %		0	0	0	0	0	
Cooling - cold water 10°C/15°C and air inlet 26°C/45% relative humidity							
Cooling output, total kW		27.2	49.5	76.5	102	130	
Cooling output, sensible kW		26.4	48.4	72.8	97.6	125	
Air filters							
Quantity		2	3	4	5	10	
Filter class to DIN EN 779		G4	G4	G4	G4	G4	
Noise pressure level							
At a distance of 1 m from the air outlet dB(A)		65.2	68.3	67.9	73.4	72.6	
At a distance of 1 m from the front dB(A)		47.1	50.2	49.8	55.3	54.5	
Technical specifications optional							
Steam humidifier: Volume 3 kg/h, 2.3 kW, 3.2 A		■	–	–	–	–	
Reheater: Thermal output 6 kW, 8.7 A, 2 levels		■	–	–	–	–	
Base frame, max. height = 350 mm		■	■	■	■	■	
Base frame, max. height = 450 mm		■	■	■	■	■	
Base frame, max. height = 510 mm		■	■	■	■	■	
Steam humidifier: Volume 8 kg/h, 6 kW, 8.7 A		–	■	■	–	–	
Reheater: Thermal output 9 kW, 13 A, 3 levels		–	■	–	–	–	
Reheater: Thermal output 13.5 kW, 19.5 A, 3 levels		–	–	■	–	–	
Steam humidifier: Volume 15 kg/h, 11.3 kW, 16.2 A		–	–	–	■	■	
Reheater: Thermal output 18 kW, 26 A, 3 levels		–	–	–	■	■	

CRAC Rittal

B Excooler

Data sheet

Model: EXHR2500 CE

Features

- Unique design plate heat exchanger; Manufactured from non-corrosive composite plastic with lifetime guarantee.

  Hermetically sealed joints to ensure zero leakage.
- Multiple adiabatic discharge matrix's.
- High pressure variable speed water distribution system.
- UPS for control panel.
- High pressure control solenoid valves.
- Latest programmable controls, with user & communication interface.
- Temperature Sensors.
- High & Low Water Pressure sensors.
- 24hrs integrated water storage.
- On board water treatment system.
- High efficiency multi stage integrated DX cooling section.

Equipment Selection		
Model Number	EXHR2500 UL	
Nominal Operating Data per Unit		
Cooling Capacity at 12degC dT	250	kW
Supply air volume per unit	36.444	CFM
Design Internal static air pressure	0.4	in.w.g
Design External static air pressure	0	in.w.g
Power Input – Fans	38	kW
Power Input – Pumps	3	kW
Power Input – Compressors	52	kW
Total Power Input	93	kW
Nominal Max running current on 400V with 0.91 P.F	132	Amps

Excooler catalogue

C Heat demand smolt factory

Months	T_{MW} [C]	$_TW$ [°C]	Cp [kJ/kg*K]	m [kg/s]	Q [kW]
January	2,3	12	4,18	2000	81092
February	0,9	11	4,18	2000	84436
March	0,8	10	4,18	2000	76912
April	0,8	10	4,18	2000	76912
May	1,2	10	4,18	2000	58520
June	3	10	4,18	2000	32604
July	6,1	10	4,18	2000	-13376
August	11,6	10	4,18	2000	-8360
September	11	10	4,18	2000	18392
October	7,8	10	4,18	2000	38456
November	5,4	10	4,18	2000	52668
December	3,7	10	4,18	2000	65208

D Efficiency and energy reuse factor for a smolt factory

Months	Q_usable heat [kW]	Q_supplied heat [kW]	η	ERF
January	81092	80000	1	0,81
February	84436	80000	1	0,84
March	76912	80000	0,9614	0,77
April	76912	80000	0,9614	0,77
May	73568	80000	0,9196	0,74
June	58520	80000	0,7315	0,59
July	32604	80000	0,40755	0,33
August	-13376	80000	0	0,00
September	-8360	80000	0	0,00
October	18392	80000	0,2299	0,18
November	38456	80000	0,4807	0,38
December	52668	80000	0,65835	0,53
Total	571824	960000	0,59565	0,47

E Greenhouse calculations

High Efficiency Water to Water Heat Pump Technical Specification (Water Loop)

Item \ Model				MWH020	MWH030	MWH040	MWH050	MWH060	MWH080	MWH100	MWH120	MWH160
Cooling Capacity			kW	77	100	133.7	164.2	202	260	328.4	404	520
Cooling Power Input			kW	14.6	19.3	25	30.7	39	49	61.4	78	98
Heating Capacity			kW	112.5	145.2	193.2	237.3	295	376.5	474.6	590	753
Heating Power Input			kW	18.5	24.5	32.2	39.5	49.6	61.6	79	99.2	123.2
Load Water	Cooling	Water Flow	m^3/h	13.2	17.2	23.0	28.2	34.7	44.7	56.5	69.5	89.4
		Water Pressure Drop	kPa	24	25	32	37	35	33	37	35	33
	Heating	Water Flow	m^3/h	13.2	17.2	23.0	28.2	34.7	44.7	56.5	69.5	89.4
		Water Pressure Drop	kPa	24	25	32	37	35	33	37	35	33
Source Water	Cooling	Water Flow	m^3/h	16.6	21.5	28.7	35.3	43.4	55.9	70.6	86.9	111.8
		Water Pressure Drop	kPa	33	35	35	42	47	47	42	47	47
	Heating	Water Flow	m^3/h	16.6	21.5	28.7	35.3	43.4	55.9	70.6	86.9	111.8
		Water Pressure Drop	kPa	33	35	35	42	47	47	42	47	47
Heat Recovery (Optional)	Heating		kW	85.5	110.7	148	181.2	225	288.8	362.4	450	577.6
	Water Flow		m^3/h	14.7	19.0	25.5	31.2	38.7	49.7	62.3	77.4	99.3
	Water Pressure Drop		kPa	33	33	35	42	47	46	42	47	46
	Pipe Connection Size			G2		$G2^1/_2$			G3	$G2^1/_2$		G3

Mammoth heat pump

F Avocado lightning

	Natural irradiance	Deviation from 18	MolesE/day (Electric lightning)	Lamps	Watt	MWh
January	0	18	22608	1424,574669	213686,2004	78,20914934
February	2,6688	15,3312	19255,9872	1213,357732	182003,6597	66,61333946
March	2,698	15,302	19219,312	1211,046755	181657,0132	66,48646684
April	10,584	7,416	9314,496	586,9247637	88038,71456	32,22216953
May	>18	0	0	0	0	0
June	>18	0	0	0	0	0
July	>18	0	0	0	0	0
August	18	0	0	0	0	0
September	10,28	7,72	9696,32	610,984247	91647,63705	33,54303516
Oktober	3,968	14,032	17624,192	1110,535098	166580,2647	60,96837686
November	0,62	17,38	21829,28	1375,505986	206325,8979	75,51527864
December	0	18	22608	1424,574669	213686,2004	78,20914934
						491,7669652

Calculations lighting Excel

G Algae cultivation calculations

	Natural irradiance	Deviation from 12.96	MolesE/day (Electric lightning)	Lamps	Watt	MWh
January	0	12,96	259200	10890,7563	1633613,445	797,2033613
February	2,6688	10,2912	205824	8648,067227	1297210,084	633,038521
March	2,698	10,262	205240	8623,529412	1293529,412	631,2423529
April	10,584	2,376	47520	1996,638655	299495,7983	146,1539496
May	>12,96	0	0	0	0	0
June	>12,96	0	0	0	0	0
July	>12,96	0	0	0	0	0
August	>12,96	0	0	0	0	0
September	>12,96	0	0	0	0	0
Oktober	3,968	8,992	179840	7556,302521	1133445,378	553,1213445
November	0,62	12,34	246800	10369,7479	1555462,185	759,0655462
December	0	12,96	259200	10890,7563	1633613,445	797,2033613
Total						4317,028437

Algae lighting calculations Excel

H Heat pump catalogue

High Efficiency Water to Water Heat Pump Technical Specification (Water Loop)

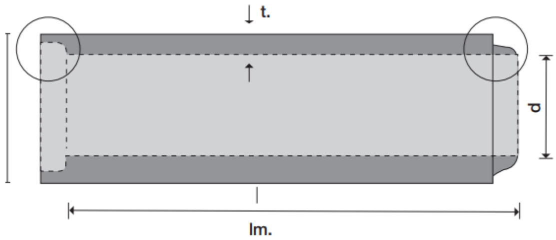
Item \ Model			Unit	MWH020	MWH030	MWH040	MWH050	MWH060	MWH080	MWH100	MWH120	MWH160
Cooling Capacity			kW	77	100	133.7	164.2	202	260	328.4	404	520
Cooling Power Input			kW	14.6	19.3	25	30.7	39	49	61.4	78	98
Heating Capacity			kW	112.5	145.2	193.2	237.3	295	376.5	474.6	590	753
Heating Power Input			kW	18.5	24.5	32.2	39.5	49.6	61.6	79	99.2	123.2
Load Water	Cooling	Water Flow	m^3/h	13.2	17.2	23.0	28.2	34.7	44.7	56.5	69.5	89.4
		Water Pressure Drop	kPa	24	25	32	37	35	33	37	35	33
	Heating	Water Flow	m^3/h	13.2	17.2	23.0	28.2	34.7	44.7	56.5	69.5	89.4
		Water Pressure Drop	kPa	24	25	32	37	35	33	37	35	33
Source Water	Cooling	Water Flow	m^3/h	16.6	21.5	28.7	35.3	43.4	55.9	70.6	86.9	111.8
		Water Pressure Drop	kPa	33	35	35	42	47	47	42	47	47
	Heating	Water Flow	m^3/h	16.6	21.5	28.7	35.3	43.4	55.9	70.6	86.9	111.8
		Water Pressure Drop	kPa	33	35	35	42	47	47	42	47	47
Heat Recovery (Optional)	Heating		kW	85.5	110.7	148	181.2	225	288.8	362.4	450	577.6
	Water Flow		m^3/h	14.7	19.0	25.5	31.2	38.7	49.7	62.3	77.4	99.3
	Water Pressure Drop		kPa	33	33	35	42	47	46	42	47	46
	Pipe Connection Size			G2		G2½			G3	G2½		G3

Heat pump catalogue

I Concrete pipe

1.20 Falsrør ig

Detalj skjøt



Falsrør ig, armert

Varenummer	Innvendig diam. (mm) (d)	Byggelengde (mm) (lm)	Tykkelse (mm)	Vekt (kg)	Klasse	Overdekning (m)	Pris KR
5440 060	600	1000	94	510	T	5	3 515
5440 065	600	2250	94	1250	T	5	4 470
5440 080	800	1000	110	810	T	4	5 110
5440 085	800	2250	110	1880	T	4	6 710
5440 100	1000	1000	125	1140	T	4	7 975
5440 109	1000	2250	125	2575	T	4	8 110
5440 120	1200	1000	136	1480	T	4	8 465
5440 127	1200	2250	136	3325	T	4	12 335
5440 140	1400	1000	156	1900	T	3	13 410
5440 145	1400	2250	156	4400	T	3	14 215
5440 172	1600	2250	176	5500	T	4	22 760
5440 200	2000	1500	215	5700	T	3	21 065
5440 210	2400	1500	250	8200	T	3	35 015

Snip of catalogue from Ølen Betong

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