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Preface

This master's thesis is written within the field of Innovation and Technology Management. It is the finalizing work of our Master of Science degrees in Industrial Economics at the University of Stavanger. Research started autumn last year and was completed in the spring semester of 2023. The primary theme of this thesis concerns energy solutions of the future. To meet future energy demands in a sustainable and climate friendly way innovative energy solutions should be investigated. There are untapped energy sources present in society today in the form of waste heat emitters. This thesis investigates the potential value of waste heat energy from a data center in Stavanger. The thesis topic relates to data center efficiency and data center waste heat recovery. Digitalization increases demand for data center services, which is an industry consuming large amounts of energy. Waste heat is generated from data center operations and is a potential source of heat energy. Utilization of waste heat energy for heating purposes may help alleviate the electrical power grid which is increasingly affected by societal electrification. It may also contribute to improved societal infrastructure for the future.

We would like to thank our internal supervisor Prof. Raoof Gholami for his insights and guidance. We would also like to thank Lyse Neo for support and data, and for highlighting the important topic of waste heat utilization. We thank our external supervisor and department manager Øistein Fosse Mathisen and technical manager Rune Jelsa at Lyse Neo for providing a strong foundation for this thesis. We would also like to express our gratitude to SINTEF and Statkraft Varme for their valuable insights, and to Tekna for financial support. Undertaking this thesis project has been a challenging endeavor and we have recognized its value through numerous invaluable learning experiences. As a finishing note we would like to extend our deepest gratitude to our loved ones for patience and support.

Stavanger, 15th of June 2023.

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Abstract

The European Union (EU) has set ambitious climate goals through the European Green Deal, aiming for climate neutrality by 2050. As a result, utilization of waste heat has gained a momentum due to its potential value in society. Data centers are known for their significant power consumption and cooling needs and present an opportunity as a waste heat emitter. This thesis investigates the potential value of waste heat energy from a data center in Norway, with focus on the Green Edge Compute data center in Stavanger.

The thesis assessment considers the context of infrastructure and energy grid distribution, aiming to identify sustainable integrated waste heat solutions. Technical feasibility for integrating waste heat from data centers with district heating systems is examined, considering the low output temperature from the data center and the seasonal variations in supply and demand. Key factors such as environmental impact, community development and economy are evaluated to determine the potential value of waste heat utilization. Due to the relatively new nature of waste heat from data centers through liquid medium, the limited availability of data and previous research in this specific field leads to broad and general findings.

To assess the potential value of waste heat energy from data centers a comprehensive literature review was conducted, selecting a relevant case study from Norway as primary source. Collecting and analyzing data, evaluating value factors, identifying limitations, and proposing a solution for high value were the main steps to contribute to the understanding and implementation of waste heat utilization. Quantitative research was the main method applied. To enhance nuanced analysis because of lacking test data, a small-scale anonymous qualitative study was performed, discussing with industry experts to gather professional insights.

This thesis explores the potential value of waste heat energy from a data center and highlights the significance in achieving energy efficiency, environmental sustainability, and economic benefits. By harnessing waste heat, data centers can reduce their reliance on conventional heating systems, resulting in energy conservation and operational efficiency. Implementing waste heat recovery systems offers advantages such as cost savings, economic growth, and employment possibilities. Integrating waste heat into energy grid systems and promoting collaborative initiatives enhances the value of utilizing waste heat from data centers.

Abstrakt

Den Europeiske Union (EU) har satt seg ambisiøse klimamål gjennom European Green Deal og har som målsetning å oppnå klimanøytralitet innen 2050. Som et resultat av dette har utnyttelsen av spillvarme skutt fart på grunn av dens mulige verdi i samfunnet. Datasentre er kjent for sitt betydelige strømforbruk og kjølebehov. De representerer også en mulig kilde for spillvarme. Denne studien undersøker den potensielle verdien av spillvarmeenergi fra et datasenter i Norge, med fokus på Green Edge Compute sitt datasenter i Stavanger.

Oppgaven vurderer sammenhengen mellom infrastruktur og distribusjon av energi, med sikte på å identifisere bærekraftige integrerte løsninger for spillvarmeutnyttelse. Teknisk gjennomførbarhet for å integrere spillvarme fra datasentre mot fjernvarmesystem blir undersøkt, tatt i betraktning det lave temperaturnivået fra datasenteret og sesongvariasjoner i tilbud og etterspørsel. Viktige faktorer som miljøpåvirkning, samfunnsutvikling og økonomi vurderes for å kartlegge den potensielle verdien av spillvarmeutnyttelse. Spillvarme fra datasentre gjennom væskekjøling er en relativt ny måte å effektivisere drift av datasentre på. Dette begrenser tilgjengeligheten til data og tidligere forskning på dette spesifikke området og er en svakhet for funnene i studien.

For å vurdere verdien av spillvarmeenergi fra datasentre ble det gjennomført en omfattende litteraturstudie, der relevant case-studie fra Norge ble valgt som primærkilde. Innsamling og analyse av data, evaluering av verdifaktorer, identifisering av begrensninger og forslag til løsning for høy verdiskapning, var hovedtrinnene for å øke forståelsen og implementering av problemstillingen. Kvantitativ forsknings var metoden som ble benyttet. For å gjennomføre en nyansert analyse, ble det på grunn av manglende testdata utført en anonym kvalitativ studie i mindre skala. Der ble det diskutert med eksperter fra bransjen for å få et profesjonelt overblikk og viktig innsikt.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

MW	Mega watt
TWh	Terra watt hours
LTDH	Low temperature district heating
ERF	Energy recovery factor
PUE	Power usage effectiveness
IoT	Internet of things
ERE	Energy reuse effectiveness
HPC	High performance computing
COP	Coefficient of performance
GDP	Gross domestic product
GHG	Greenhouse gas
CUE	Carbon usage effectiveness
BNP	Brutto national product
GDP	Gross domestic product
CAGR	Compound annual growth rate
NECS	Norwegian registry for elsertificates
UPS	Uninterruptible power supplies

1. Introduction

The contents of this chapter aim to underline the significance of data center waste heat utilization and its relevance in societal context. To pique the interest in this topic the thesis presents a compelling rationale for why waste heat energy from data centers hold value. Waste heat energy is an untapped source of energy, and further investigations into future solutions hold importance and deserve attention. This chapter serves as the thesis foundation and establishes the research question that guided the thesis work. The research backdrop is the European energy context and the potential of waste heat systems to be energy solutions of the future.

1.1. The European Green Deal and climate neutrality

The European Union (EU) has set an ambitious initiative in the European Green Deal, a framework aimed at promoting a green shift and combatting climate change and environmental degradation. As a part of this plan, the EU aims to achieve climate neutrality by 2050 [1]. One significant aspect of this transition involves finding sustainable solutions. Heating and cooling account for half of the energy consumption in Europe, primarily relying on fossil fuels [2]. At the same time, various industries generate significant amounts of waste heat. The exact magnitude of which remains unknown [3]. These factors highlight the need for research and innovation to address the challenges posed by the high energy demand, fossil fuel reliance and the untapped potential of waste heat utilization. Norway has also taken measures to address environmental concerns and pursue sustainable practices.

1.2. Proposed legislation for waste heat in Norway

The Norwegian government has proposed a significant amendment to the law of energy, which would require energy and industrial facilities to conduct a cost-benefit analysis regarding the utilization of waste heat. This legislative change has implications for data centers, as the proposal specifically mandates that new data centers with a total capacity exceeding 2 MW must perform a cost-efficiency analysis. The government does not force data centers to implement waste heat utilization solutions because of this cost-efficiency analysis. Note that the proposed legislation is not yet decided [4]. This indicates however, that there is a potential shift in expectations for waste heat utilization in the future, particularly in the context of data centers [4]. This indicates however, that there is a potential shift in expectations for waste heat utilization in the future, particularly in the context of data centers. In 2021 the Norwegian government released a climate plan outlining ambitious targets for the period leading up to 2030. Within this plan a primary objective was established to achieve the reduction of 50-55% of the emissions by the end of the specified period. This climate plan is aligned with the objectives set forth by The European Green Deal by reinforcing the collective efforts to combat climate change. The realm of politics assumes a vital role in driving initiative for emissions reduction. The climate plan delineates the specific policies, regulations and timelines required to effectively attain the outlined climate goals. By strategically guiding policy implementation this plan seeks to lead to way for substantial progress in reducing greenhouse gas emissions [5].

1.3. The need for sustainable heating solutions

In Europe, the provision of heating and cooling is currently heavily reliant on fossil fuel sources. There is a growing imperative to transition towards renewable energy sources to meet this demand. As depicted in Figure 1 heating and cooling accounted for 51% of the total energy consumption in 2012. Among these, heating represents the largest share of energy consumption. This sector holds immense potential for mitigating the use of fossil fuels by exploring alternative sustainable solutions [2].

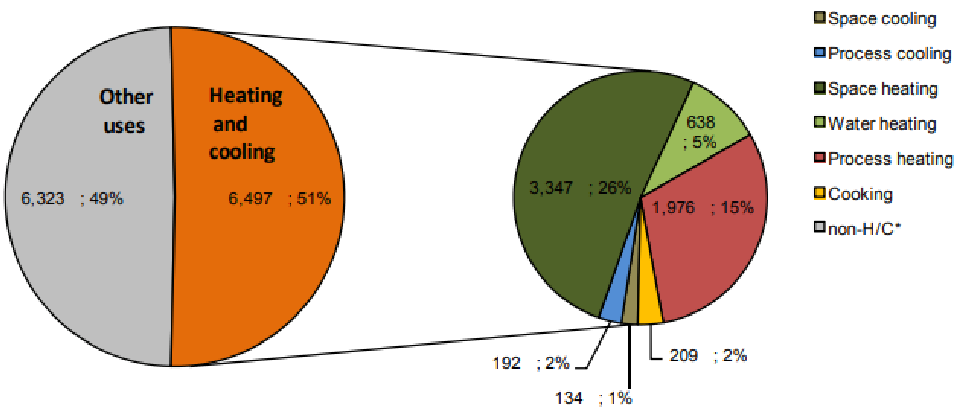

Figure 1 - Energy demand in Europe.

In 2012 heating and cooling was responsible for 51% of the final energy demand in Europe. Illustrated in Fig. 3 in [2].

As a general note, it is important to recognize that energy merely undergoes transformation and does not disappear. Following heating or cooling processes there are always biproducts. In cases where the biproduct is in the form of heat, it is waste heat which can be utilized for other beneficial purposes if recovered and distributed.

1.4. The untapped potential of waste heat

Waste heat is a valuable energy resource that is excess heat energy and a biproduct from various industries. It represents the surplus heat that is not utilized for the primary industrial processes but is a produced biproduct. Waste heat is linked to the potential of sustainable heating and cooling systems of the future. Waste heat is generated in different forms, such as warm air, water, or steam [6]. The emission source of waste heat includes a range of sectors, encompassing industrial processes, building operations, waste incinerations and data centers. The waste heat potential is contingent upon factors such as temperature, efficiency, availability, stability, and quantity. In 2009, Norsk Energi and NEPAS conducted an assessment of the waste heat potential and compiled a table that delineates the various temperature ranges and the corresponding utilization potentials associated with each range, as illustrated in Table 1 [6].

Table 1 – Waste heat temperature ranges.

Purpose and potential of waste heat at different temperatures. Waste heat is categorized based on temperature ranges, table supplied from report for mapping and evaluation of potential for effectivization of heating and cooling in Norway. Presented in tab. 4-2 [6].

Temperature distribution		
Temperature	**Purpose**	**Waste heat potential**
>140℃	Power production District heating	7.0 TWh
60-140℃	Power production District heating	3.1 TWh
40-60℃	Low temperature district heating Heat source for heat pump with a good factor	5.8 TWh
25-40℃	Fish farming Ground heat Heat source for heat pump	3.3 TWh

Based on estimations, the potential for increased power production through the utilization of industrial waste heat is below 380 GWh annually. Waste heat incineration facilities have theoretical potential up to 1 TWG per year [7]. The extent of the potential for waste heat utilization determines its viability as an energy source.

1.5. Waste heat as energy source

The utilization of waste heat as an energy source is dependent on the temperature at which it is generated. If the unutilized waste heat is either lost or released to the surroundings [8]. The effective utilization of waste heat depends on the output temperature, which varies across different industries. Waste heat can be classified into low and high temperatures based on its temperature range. The quantity and temperature of waste heat is a critical factor in determining its viability for utilization [9]. Low-temperature waste heat can be defined as in the range from 20℃ to 200℃. The temperature range is further subdivided into smaller intervals at 20℃, enabling the identification of specific consumers within each interval. The range of potential consumers for low temperature waste heat varies based on the specific temperature range of waste heat. The temperature of heat available is dependent on the waste heat emitters output of waste heat [7]. To utilize available excess heat for recovery and distribution, appropriate infrastructure is essential. This thesis explores a particularly intriguing area of research that encompasses multiple potential approaches. Other than equipment for energy recovery it might be possible to utilize existing infrastructure and energy grids for waste heat energy distribution. If not, establishment of new infrastructure for waste heat utilization might be necessary which represents a significant investment. Location of waste heat emitters are particularly relevant concerning recovery and distribution due to the availability of established infrastructure [7].

1.6. Waste heat emitters

The effective utilization of waste heat depends on several factors such as the location, and the output temperature, which can vary among different industries. In Norway, industries in sectors such as paper, food, chemicals, and certain metals are generating waste heat [6]. These industries are often situated at a distance from populated areas. Data centers are also waste heat emitters and based on the primary operations and services may be situated at various locations based on their need. Edge data centers have the advantage of being more easily located in proximity to city centers. This may be an enabling factor making utilization of waste heat from data centers more valuable. The benefits of location and placement can provide additional value using existing infrastructure such as district heating system grids. An important challenge to note concerning existing infrastructure is that the low-temperature output might not be compliant with the temperature in the district heating system. Putting it crudely, one can either adjust the temperature to match the existing infrastructure or investigate solutions for utilizing the waste heat energy directly. The potential value of waste heat energy from data centers can vary based on the chosen approach for recovery and distribution, and the investment cost plays a significant role in determining this.

1.7. Challenges utilizing waste heat

There are multiple approaches and solutions available for utilizing waste heat and making it usable. Utilization also brings forth various potential challenges that need to be addressed. These challenges encompass locational, quality, and temporal considerations. The establishment of infrastructure for energy grid systems can be a costly endeavor. The output temperature of waste heat plays a crucial role in determining its potential applications. If utilization is achieved by using existing infrastructure such as district heating systems, it will typically require temperatures higher than 75-80℃ [10]. If the generated waste heat output is below this range the implementation of additional heating systems may be necessary to elevate the temperature. Ownership presents another challenge as waste heat utilization may involve different actors with varying purposes and aims. In the example of utilization via district heating systems, it is not necessarily clear who should take responsibility for the investment and upkeep of auxiliary equipment. Which may be the essential investment that enables the waste heat to reach the appropriate temperature matching the existing energy grid and provide value. There must be a clearly defined ownership structure between the different actors. In the case above this would at least involve the data center company and the district heating grid operators. As for the investment cost for equipment, it is important to note that the economic aspect of waste heat utilization is crucial [11].

1.8. Potential value of waste heat from data centers

The central focus in this thesis revolves around the fundamental question: “What is the potential value of waste heat energy from a data center in Norway?” It is estimated that data centers will have an increased power consumption at 3.2-8.2 TWh in 2040 [6]. This immense growth emphasizes the thesis question as the amount of waste heat will increase. Energy efficiency and renewable energy are defined as important measures to achieve targets set by EU [9]. Utilization of waste heat energy from data centers is a possible sustainable solution with an increasing potential [6]. To assess the potential value of waste heat from a data center it is important to establish a crude energy potential that is possible to recover from data center operations. The determination of the potential value of waste heat energy from data centers is crucial in assessing the overall feasibility. The magnitude of this potential value may serve as a determining factor when evaluating the viability of investing resources and efforts into utilizing waste heat. The value concept and process of value creation is a broad term and can be defined by multiple dimensions and quantified through various means. To evaluate the potential value of waste heat energy from a data center in Norway it might be useful with a wide definition of value to ensure investigation of many aspects. The creation of value through waste heat utilization involves many aspects and is not only the sum of its physical parts. By effectively utilizing waste heat, value creation may include economic growth, job creation and enhanced societal energy integration. This highlights the broader societal and economic implications of utilizing waste heat from data centers as a valuable resource.

1.9. Constraints and their impact on project execution

This thesis project work was subject to certain constraints that have influenced its scope and execution. Understanding these constraints is essential for interpreting the findings and recognizing insights of the study. Because of lacking test data, a shift in direction was needed to pivot the thesis content. Instead of only quantifying the actual waste heat output from the data center, the focus area broadened and now encompasses more aspects. By presenting these challenges early a better understanding of gained insights is achieved.

Scope limitation

Utilizing waste heat from data centers is a new concept [12]. As cooling technology evolves, the potential for waste heat recovery increases. Because of a lack of information on the actual data center components in Stavanger, a full picture of the system setup was not possible. The technology mentioned for enabling energy reuse by waste heat recovery may not capture the full spectrum of cooling technologies available and best practices.

Timeframe limitation

The thesis research was primarily conducted within the spring semester duration. Efforts were made to establish collaboration with an industrial company early to increase the potential for collection of necessary quality data. Available data was received at various stages in the thesis project which affected the results. Because of the time constraints not all data points were investigated to the fullest potential. A crucial factor to note is also that the data center market is rapidly evolving because of new technology and demand. The main factor affecting the thesis work was Green Edge Compute data center in Stavanger entering a funding phase during collaborations.

Data availability

Data availability is necessary to do research. In this study the constraint of data availability has been acknowledged and addressed. Resource limitations and availability of data have been proven to be challenging. This constraint impacts the ability to access a wide range of data sources to obtain necessary detailed information for a comprehensive analysis.

Additional goals

The first communications with Lyse Neo and Future Energy Hub (UiS) revealed an incentive to increase awareness of waste heat, waste heat utilization and district heating potentials. This has been a strong influence when composing the thesis text, whilst also constraining the format and content. The primary target audience for this research includes industry professionals involved in data center operations, management, and researchers. As well as developers of sustainable energy solutions of the future. The objective was to provide insights and recommendations, but also generate awareness. Efforts have been made to format the text in a colloquial manner and present the findings and conclusion in a way that is accessible and understandable for the public. This serves as an additional goal of this thesis, to create a thesis that contributes to waste heat utilization awareness, and insights into what affects its potential value. Considering all the constraints mentioned, it is important to interpret the results and conclusions of this study whilst also recognizing the limitations imposed during the thesis progress. Especially concerning the lack of test data, which in part is due to the novelty of the thesis research and research question. Despite the constraints presented, this research endeavors to contribute valuable insights and overview to the potential value of waste heat from a data center in Norway.

1.10. Aim and overview

The aim of this study is to explore and analyze the potential value of waste heat energy from a data center in Norway. By focusing on waste heat utilization and its significance in achieving sustainable energy objectives, the research aims to uncover the potential opportunities and challenges associated with harnessing waste heat from a data center in Norway. By clearly defining the aim of this study and establishing specific objectives, the intention is to contribute to the existing knowledge base on waste heat utilization and highlight the potential value of waste heat from data centers. The findings of this research will offer valuable insights to policymakers, industry stakeholders and researchers interested in exploring the untapped potential of waste heat and promoting sustainable energy practices. The thesis investigation considers the waste heat output temperature from the data center, and how end-users will be able to utilize the waste heat energy at different temperatures. The core of this thesis is the goal to develop a foundation for evaluating the potential value of waste heat from data centers. Considering development and operational costs compared to environmental and economic benefits, as well as evaluating the overall value in the larger societal perspective. Uncertainties uncovered during the thesis work are also discussed. The thesis content is organized in the following manner. Background information to understand the context and rationale behind the research question enabling further understanding of later chapters is provided in Chapter 2. A review of relevant literature is presented in Chapter 3. An overview of collected data is provided in Chapter 4. The methodology used to answer the thesis question is detailed in Chapter 5. Chapter 6 presents the results achieved by implementing suitable methods to transform information collected into tangible insights. Chapter 7 discusses the findings obtained from the information and data presented. The thesis is finalized with Chapter 8 offering concluding remarks on the thesis content, findings, and recommendations for future research.

2. Background

This chapter presents important background information elaborating on the thesis question context. Power consumption and production in Norway are central parts for determining the purpose of utilizing waste heat. The electrification of society combined with the goal of becoming climate neutral underlines the importance of investigating energy sources with future potential. The first section describes the energy situation today, development, reduction of emissions and availability of waste heat. Potential solutions for waste heat utilization infrastructure such as district heating systems are introduced successively. Data centers, their basic functions and operations are described. Governmental incentives are an additional momentum influencing the future of data centers. To understand the thesis content in later chapters, it is useful to have a firm grasp on relevant technical terms and their meaning. Technical concepts and terminology are described together with their application context. The goal of this chapter is to provide a brief explanation of special knowledge that will help understand important aspects in later chapters.

2.1. Energy landscape and future technology development

Reasons for why utilization of waste heat from data centers might be important are explored in this section. The energy context, concerning power production and consumption in Norway with regards to environmental perspectives are explored. Power production and consumption, circular energy, and future energy solutions are all components which affect the power situation today and in the future. The primary reason for why non-traditional energy solutions of the future deserves focus is the pressing issue of increasing power demand [13]. Power production strive to meet demands and rise with increased consumption. Parallelly it is important to incorporate circular energy concepts into future energy systems, to reduce emissions and become more climate friendly.

2.1.1. Power consumption and production in Norway

In 2022 Norway had a power production of 146 TWh and a consumption of 133.5 TWh [14]. Importation of power is necessary to satisfy the power demand even if there is more overall power production than consumption during a year. Not all power can be stored which is why there is export of superfluous power with temporal variations. This occurs when production is larger than consumption and is often observed in connection with renewable energy production. Seasonal snow melting and rainfall increases potential for hydro power [15]. Norway exported 25.7 TWh and imported 13.2 TWh last year. Production of wind power was 14.8 TWh of this total amount, which is about 10% of the total power production. There are apparent production differences within Norway geographically, because of natural resource variation [14].

Increased energy demand

Environmental emissions will be reduced by substituting fossil energy sources with renewable energy sources. The increased societal electrification in Norway is a part of the general technological movement into reducing the environmental emissions and has a considerable influence on the energy market [16]. In parallel with the shift towards increased utilization of renewable energy sources, the energy demand is rapidly increasing. Not only is it necessary to succeed with the shift towards renewables, but the solutions need to be readily scalable providing enough energy to society. Electrification of communities, replacing fossil fuel cars with electric vehicles, electrification of the Norwegian continental shelf and land-based industry all contributes to the increase in power demand. Historical growth and forecasts estimate a lack of energy production in the future. Replacing fossil fuel energy will increase power consumption with 30-50 TWh per year [17]. This increase is dependent on what energy sources are being applied in the future. Use of hydrogen will increase power consumption further because of the large energy consumption needed to create usable hydrogen as an energy source. Some renewable energy sources such as hydro, solar, and wind make the energy production dependent on weather conditions and seasonal changes. Production is consequently not coincident with the demand. There might also be mismatching paradoxes concerning renewable energy, as the time periods with the highest demand are not necessarily the time periods with the largest energy potential. Statnett estimates that electrification will contribute to a reduction in Norwegian emissions at twenty-five million tons CO_2-equivalents and a decreased primary energy consumption at 55 TWh [17].

2.1.2. Electrification of society

The comprehensive electrification of society in connection with the green shift within technology will require increased power consumption as stated earlier. Electrification is going to increase the power demand in Norway with 30-50 TWh per year. This electrification considers increased renewable energy sources and lower greenhouse gases [17]. To facilitate the transition towards a low carbon future, Norway has set a goal to reduce the emissions of greenhouse gases by 50 to 55 percent by 2030 [18]. Innovative technology solutions are needed to achieve this goal. New ways of thinking when considering the power market and energy production is important. Utilization of other heat energy sources to supply heating demand may alleviate the power grid capacity and is an area of improvement concerning future energy systems. Research is needed to drive this change including research on the expanding potential for additional energy sources, which will be driven by climate politics and technological development [19]. The simultaneous goals of wanting to reduce emissions whilst also moving towards increased electrification are contradictory forces. Increased electrification may demand the use of carbon-based energy sources to meet the increasing demand of energy. This is a potential gap considering technological development, as there is a need to resolve both issues. To solve these issues tailored technology for each separate issue may be the answer, but overlapping solutions catering to both needs would also be a possibility by tackling these issues with the same solution. An innovative heat energy system may serve as a solution resulting in effects including reduction of carbon emissions as well as contributing to power grid alleviation. The first element of such an innovative heat energy system will be an alternative sustainable heat energy source.

2.1.3. Circular economy and industrial symbioses

Circular economy is a fundamental concept that focuses on the efficient utilization of resources and extending their life cycle [20]. The EU has implemented circular economy in its action plan as a crucial measure in reducing greenhouse gas emissions. The concept of circular economy is applicable to various sectors, including the utilization of waste heat and the development and future technologies [21]. Long-term market analysis from Statnett is estimating a basis scenario with twice the Nordic power consumption, up to 850 TWh in 2050 [22]. The increase in power consumption highlights the need for circularity. Industrial symbioses play a vital role in the context of circular economy. It is a concept closely related to industrial ecology, which explores industrial systems within the framework of the natural environment. Industrial symbiosis considers industries as interconnected ecosystems where diverse industries can exchange resources, including waste heat, for mutual benefit This approach provides a multidisciplinary perspective that enables evaluation from economic, business policy and environmental angles [23]. An example of industrial symbioses is the “waste heat motorway” suggested as a solution at the innovation competition at the district heating days for urban energy. The concept involves extracting cold water from the sea and passing it through a heat exchanger to generate cold fresh water. This water is then transported to power-intensive industries to be used for cooling. The resulting heated low-temperature water can be utilized for applications such as greenhouse and bigas production. Additionally, the waste heat can also be used for fish farming. The envisioned route of this waste heat motorway aims to distribute the waste heat across a larger area as presented in Figure 2 [24].

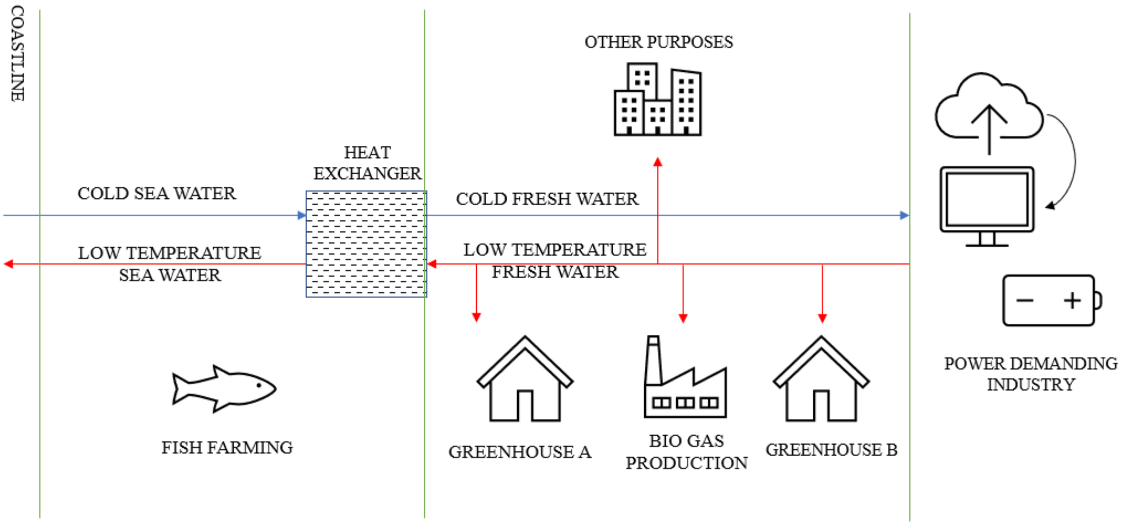

Figure 2 - Waste heat motorway.

Utilization of cooling and heating across a larger area, as presented in the innovation competition at the district heating days for urban energy [24].

In situations where utilizing waste heat in the shape of a liquid transport medium, such as waste heat, industrial symbioses and circular economy principles can be effectively applied. By incorporating industrial symbioses practices, where diverse industries exchange resources for mutual benefit, district heating systems become a key component of the circular economy. It enables the utilization of waste heat from cooling as a valuable resource.

2.2. Waste heat from cooling

Waste heat from cooling has a vital role in industries that heavily rely on colling for their operations. According to estimates by Oslo Economics and Asplan Viak, approximately 72.5 TWh of energy was consumed for cooling and heating purposes in 2018. Most of this energy was produced by renewable sources of electricity. While cooling itself is not power demanding, it generates waste heat as a biproduct [6]. Industries that require cooling often have substantial power consumption needs. Power suppliers assumably recognize both their societal and strategic interest in exploring the utilization of waste heat as a competitive element. This utilization is a potential valuable resource, power suppliers can contribute to sustainability goals. From the meeting with SINTEF [Appendix G] it was made clear that utilization of waste heat also will gain a competitive advantage in the market. Appropriate infrastructure is essential to harness waste heat. The type of waste heat dictates the infrastructure required for its utilization. In the case of waste heat in the form of a liquid medium, a district heating system proves to be a suitable option for its utilization. District heating systems provide the necessary framework for distributing waste heat.

2.3. District heating systems

One effective method of distributing waste heat energy is through the utilization of existing infrastructure designed for liquid medium transportation of heat energy. This infrastructure primarily exists in the form of district heating systems, which are responsible for supplying hot water to various consumers, including both private households and industrial companies [25]. The process beings with the generation of hot water, which can be achieved through various means such as central heaters, waste heat from industries or dedicated water heating systems [26]. To facilitate the transportation of hot water from the supplier to the end-users, a heat exchanger is typically installed along the distribution network as presented in Figure 3. This heat exchanger plays a crucial role in transferring heat energy from the hot water to the desired applications, which can include both heating and tap water usage [25]. The end-user must have a water-based system in place to be able to connect to and benefit from the district heating system. In Norway the district heating systems contributed to the distribution of heat energy with a total of 7.45 TWh supplied in 2021. Notably, 89% of the heat energy distributed through these systems was derived from waste heat generated by waste heat incineration processes. The remaining portion of the heat energy was sourced from industries and energy production [27].

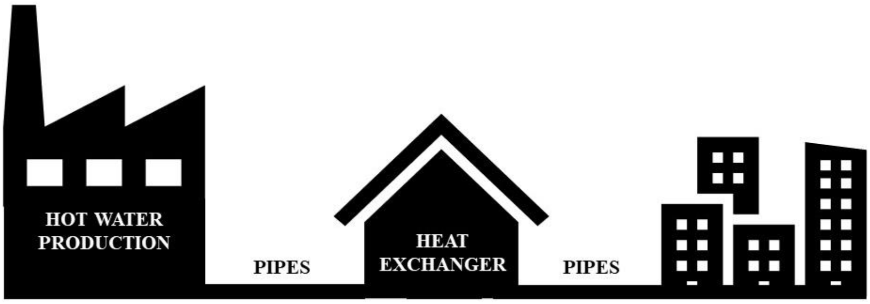

Figure 3 - District heating system.

Hot water is generated to be distributed through pipes to the end-user. The water goes through to heat-exchanger along the distribution network.

2.4. Data center as waste heat emitter

Data centers serve as critical hubs for IT infrastructure, housing computers and servers responsible for data storage and management. The reliable operation of data centers relies on robust infrastructure that ensures sufficient security and availability of power supply. Maintaining optimal temperature levels and air density is crucial for the efficient functioning of the equipment within these facilities [28]. Advancements in technology have facilitated the development of smaller data centers, allowing for their establishment in existing buildings. Consequently, some data centers are now located closer to city centers. This proximity to urban areas presents an opportunity to harness sustainable energy by leveraging the waste heat generated by these data centers. The value of this waste heat hinges on two key prerequisites: the presence of suitable infrastructure for heat transportation and the availability of consumers within a viable radius [29]. Establishment of new infrastructure is expensive [7]. To unlock the potential of waste heat from data centers, it is essential for the centers to be situated near existing infrastructure and in proximity to potential heat consumers.

Societal digitalization

Increased demand for computing power and data centers are a ripple effect of societal digitalization. Data centers have become necessary as a part of technical evolvement and are one of the fastest growing industries in the world. In 2020 the global market for data centers was valued to be $187.35 billion [30]. Data centers are necessary to enable everyday lives with technology, including all devices connected to the internet and data produced by sensors and other IoT (Internet of Things) devices storing data in cloud services. IoT devices usually mean hardware with connectivity functionality for exchanging data online or to local networks, like sensors sending their data to a database. Complex software such as artificial intelligence and blockchain expedite the need for data centers and is important for technological development. Predictions estimate that the data center industry will constitute 3.2% of total global carbon emissions by 2025 and 14% in 2040 [31]. Data centers have a large power consumption, and some of this power goes to cooling systems due to the heat created by IT-components usually in server racks. Data centers are dependent on cooling to keep server racks at optimal operations temperature. The biproduct of this cooling is waste heat, which can be emitted.

2.4.1. Overview of data center types

There are three main types of data centers: hyperscale, colocation and edge. What separates them are size, users and owners. Colocation data centers usually have different owners and are operated by a data center operator. They are used by external customers, such as Microsoft. In 2020 the 18 existing data centers in Norway was all the colocation type [32]. The term colocation is defined by its function as a “server hotel.” The size can be as large as for a hyperscale data center [33]. Hyperscale defines large data centers. They are owned and operated by companies such as Google and Apple and is primary used for the company´s own activity. The data center’s size is related to the need for power. Redundancy and supply security is important and has an impact on the location for the hyperscale type data centers [33]. Edge data centers are defined as small, decentralized units. Their potential is to be placed nearby bigger habitations and close to data sources to supply immediate response [33].

2.4.2. General structure in data centers

Data centers exhibit variations in their construction and design, yet they share fundamental components that enable their operation. Figure 4 provides an illustrative overview of these components. A critical aspect of data center functionality is a robust power distribution system. To ensure uninterrupted power supply and potential disruptions, data centers incorporate generator sets as emergency backup sources. The input switchgear serves as the entry point for power into the data center, facilitating its distribution to various outgoing circuits within the facility. Data centers employ uninterruptible power supplies (UPS) to provide temporary power backup in case of outages, which last for a short period. Power distribution within the data center is facilitated by the power distribution unit, which has a key role in delivering power to individual racks. The remote power panel incorporates panelboards and a monitoring system to oversee and distribute power to the racks effectively. The rack power strip is installed within the IT racks and accommodates servers, networking devices and other computing equipment essential to data center operations. These components collectively form the foundational infrastructure necessary for the reliable and continuous functioning of data centers [34].

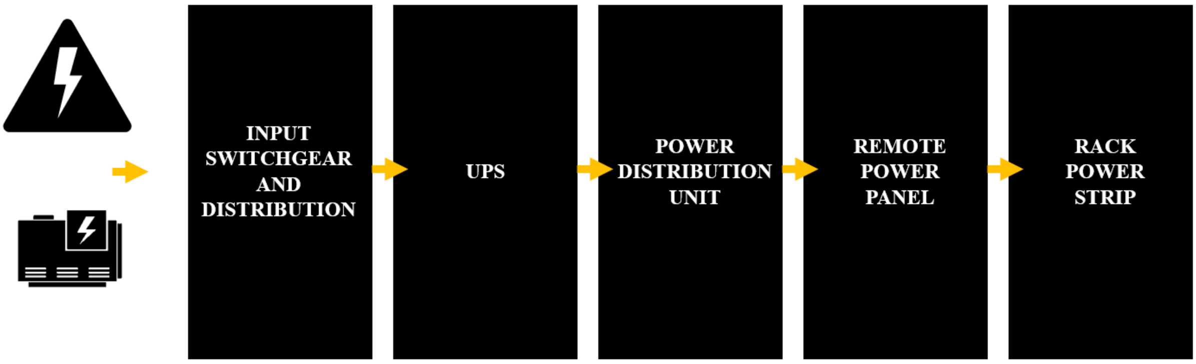

Figure 4 - General structure in data centers.

Illustration of the key components involved in the operation of a data center.

2.4.3. Data centers in Norway

The data center industry in Norway consisted in 2020 of 18 colocation-centers as represented in Figure 5, with a total capacity at 105 MW measured in 2019. Oslo and the area around have 40% of the installed capacity [32]. The rest is spread in south- and mid-Norway and is presented in Figure 5. The increasing number of data centers along with a yearly increased MW-capacity was 17% from 2010 to 2019. It insinuates a substantial trend for growth for the data center industry. According to NVE`s top-down approach, the installed capacity was calculated to be 135 MW in 2019. For 2020 it was estimated to increase by another 19 MW. Low electricity prices have been one of the main drivers for companies to establish data centers in Norway, as they have a large energy consumption [32].

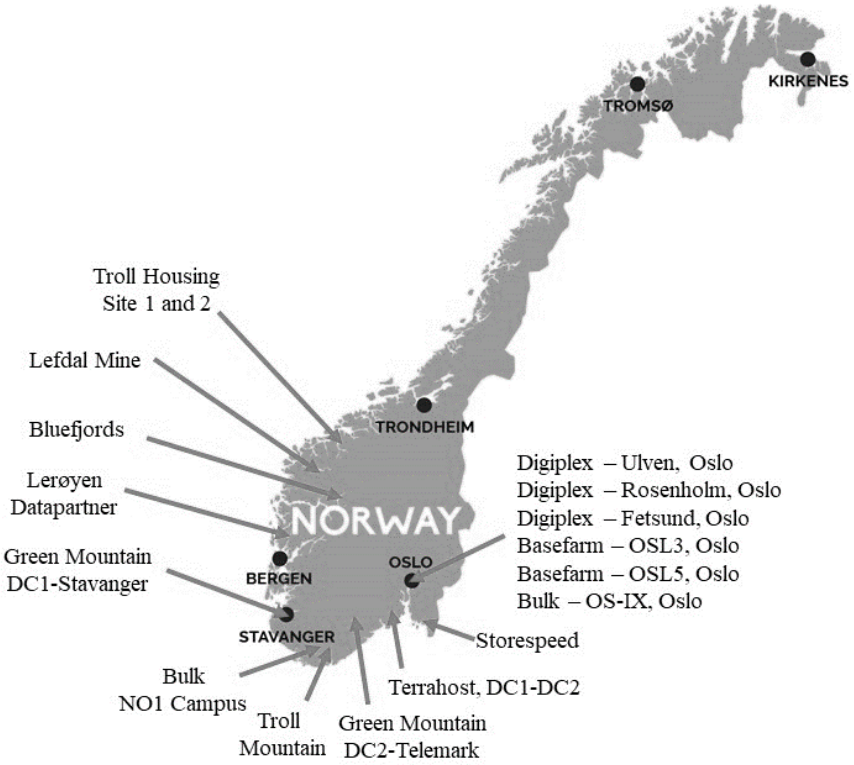

Figure 5 – Data center locations.

Norwegian data center location by 2020. There exist development plans to install more data centers in the future [32].

Analysis of location possibilities for data center development is important also in relation to screening for waste heat utilization potential. Utilization feasibility depends on many factors, especially external conditions meaning nearby industry. Type and number of industries and buildings in close vicinity influence the consumer basis for waste heat utilization [32]. The location of data centers is important for getting the most out of the waste heat generated, as transportation of the heated liquid medium through pipes suffer energy loss over distance and time. Large data centers are normally located outside the cities, due to their need for an affordable area. Smaller data centers may be established nearer the cities because of the reduced sizes. Normally such data centers will be situated in small, enclosed facilities, sometimes making use of existing buildings.

2.4.4. Growth for data centers

Demand for computing power and data center services is increasing and data centers of diverse types is being established all around the world [32]. The data center industry is truly growing rapidly. This growth creates new workplaces and increased value. Data center growth influences other acquisitions, which also uses data as the commodity of value. The data center industry uses a large amount of electricity. With this follows certain specifications and settings to be able to establish a data center. The requirements to where and how these data centers can be established, is dependent on infrastructure. The ripple effects of data center market growth are presented in the report from Implement Consulting Group, in part defined by employees per MW. This rate depends on the type of data center, as diverse types have different requirements for number of employees and has various impact on the ripple effects [32].

Dependencies and future growth

The increase in the data center industry is dependent on fiber capacity, low delay, and sufficient lines out of the country. Business policy, electricity and fiber are considered the most critical to achieve the growth target. Uncertainties for growth are factors as electricity prices, taxes, and expenses. Existing infrastructure can be an issue, due to the data centers' large electricity demand. Getting necessary permissions is time consuming and can affect the expected growth [32]. The Gross Domestic Product (GDP) is a metric for the sum of service delivered subtracted from the expenses and divided by the number of citizens. This metric helps define the economic situation and development in a country [35]. The best economic scenario in Norway is based on a steady growth for colocation-centers and a rapid growth for the edge-centers and establishment of some hyperscale-centers every other year. The BNP is then expected to be 30,9 billion in 2030. Compared with the scenario of normal growth for colocation centers at 15% and small growth for edge-centers, with an expected BNP at 18,9 billion. The 63% difference in BNP illustrates the substantial difference depending on growth and development [32]. Growth for colocation centers has been 15% in Norway per year lately. The Compound Annual Growth Rate (CAGR), which says something about data center growth, was at 17% for the period from 2010 to 2020 [32]. Data centers power consume, and the estimated growth illuminates the need for circulation of energy utilizing waste heat in the most efficient way. It has already been suggested by the oil- and energy department that the energy law should contain a demand for cost-efficiency analysis for utilization of waste heat [4, 36].

2.4.5. Potential for waste heat utilization

Data centers have the potential to utilize waste heat from cooling down computer racks. Using water as a cooling medium in a closed system is one of the most sufficient ways of containing the energy and can give an output to distribution infrastructure like district heating systems [29]. Data centers are a hot topic in the media due to planning of several large data centers for the future. Google is planning a data center in Skien [32] and Green Mountain is planning one of Norway's largest data centers for TikTok in Hamar [37]. There are several types of data centers being separated depending on size and location. There are established several data centers in Norway and the estimated growth indicates that there will be plenty more [32]. Potential waste heat is dependent on several elements such as the capacity of the data center and its energy consumption. Waste heat generated with liquid cooling medium can be recovered and utilized by some form of energy grid infrastructure, exemplified through district heating systems. To utilize waste heat from data centers by transportation in a district heating grid, existing infrastructure must be available nearby if not this will amount to some investment cost [7]. The waste heat temperature generated is defined as low and high temperature. Low temperature waste heat is normally peaked by heat exchangers to be supplied to the district heating system. This solution is presented in Figure 6.

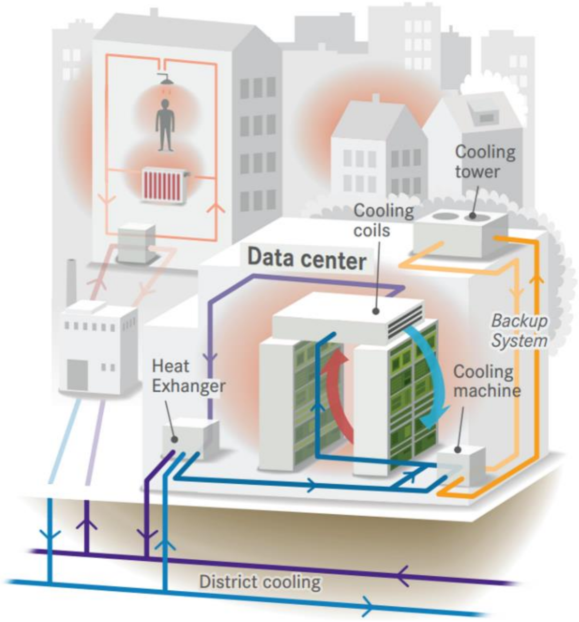

Figure 6 – Data center waste heat for district heating.

Image is borrowed from Stockholm Data Parks presenting utilization of waste heat from data centers to district heating networks [38].

Another possibility for transportation infrastructure is direct supply. The data center’s consumption is even through the year, independent of season. End-users with a continuous low-temperature consumption matching the amount of waste heat and temperature from the data center a possible way to utilize the waste heat.

2.5. Incentives as support

The development in energy transformation has been more rapid in the last years. New directives and support schemes are made to reach the target to cut emissions, due to the government’s goal to reduce greenhouse gas emissions from 50 to 55 percent in 2030. Numbers used to calculate reduction and to compare are values from 1990 [39]. The government is looking into making incentives and requirements to solve the climate crisis. For public acquisitions it is suggested regulations focus on sustainability and to work towards climate goals. Environmental requirements are common designations for requirements and criteria. Wanting to create workplaces and increase value, the government made a strategy for data centers in 2018. A framework is made for making it attractive to invest in data centers in Norway, such as competitive power [40]. One possible incentive, to make the consumers aware, is to increase the power price to reduce consumption. According to NVE`s report for Norwegian and Nordic efficiency balance towards 2030, the end-users was not responding to the increased energy prices and is not considering their efficiency consumptions [13]. At the end of 2021, the power prices rapidly increased in the south of Norway. The electrical spot prices were 345% higher in March 2022 compared to the same time the year before for this area [41]. The variation between the groups of income has increased in parallel with the power prices. The groups with lower income, uses less power compared to groups with higher income [41]. Indirectly, this means that groups with higher income will care less if an increase in power prices is introduced as an effort to reduce power consumption. The power consumption has decreased from 2020 to 2022, which can be explained by the increased energy prices [14].

3. Literature review

Science is inherently cumulative, and it is important to leverage the progressively better understanding of concepts and phenomena when doing innovative research. A good way to absorb available relevant literature is doing a scoped literature review, which is presented in this chapter. Literature directly concerning waste heat utilization from data centers is scarce, especially in Norway which makes this an interesting research topic. There are driving forces that are increasingly making this an area of interest, including technology development and digitalization. Energy technology advancements enable better waste heat recovery, increasing the feasibility of waste heat utilization. Data center prevalence increases with the need for digitalization, essentially increasing the crude waste heat potential. These factors affect the potential for utilization of waste heat from data centers. A combination of literature on data centers, waste heat and district heating systems were reviewed, together with relevant reports and articles covering important concepts within this scope. A structured approach for reviewing literature is presented below which facilitated the research review. Economic aspects concerning the process of waste heat utilization from data centers are included regarding feasibility. There is no industry standard for waste heat utilization screening of data centers, meaning that technical and economic assessments are based on techniques commonly used in the industry. This way evaluations are aligned with industry best practices. The overall goal of the literature review is to highlight important topics in the process of investigating the feasibility and value of waste heat utilization from a data center in Norway.

3.1. Literature review approach

This literature review is a synthesis of findings from past research relevant to the thesis topic and serves as foundation for the thesis investigation. Although the process of gathering and reviewing relevant literature proved to be a non-linear process, a general strategy was established as a guide before starting the in-depth research. The general strategy structure was created with strong influence from NC State University Libraries' recommendations for literature reviews [42]. Utilizing the basic iterative process of reading, summarizing and evaluation seen in Figure 7 helps as a general guideline reviewing comprehensive literature. The research path for this thesis was informed by the knowledge gaps crystalized from the first chapters. In essence this thesis serves to fill a knowledge gap in this relatively new field of research and strives to elucidate important aspects when considering waste heat utilization regarding data centers.

Figure 7 – Review process.

The basic iterative process of literature review research with stated main goals.

The initial step of the iterative review process is collection of relevant literature by utilizing a search strategy presented in Table 2. Notes with important descriptions from reading served as a summary for each relevant piece of literature. Important findings were then analyzed and evaluated both considering relevancy but also for applicability to this thesis topic. Goals of the iterative process include key concept details, which in turn served as organizational headings for the conceptual map in Figure 8. The conceptual map is an important basis towards building a coherent literature review. It is constructed in a way to highlight the integrative goal for this thesis' research. The main concepts within the conceptual map are presented in a way to highlight important aspects of the literature review and serve as the general structure for the following sections.

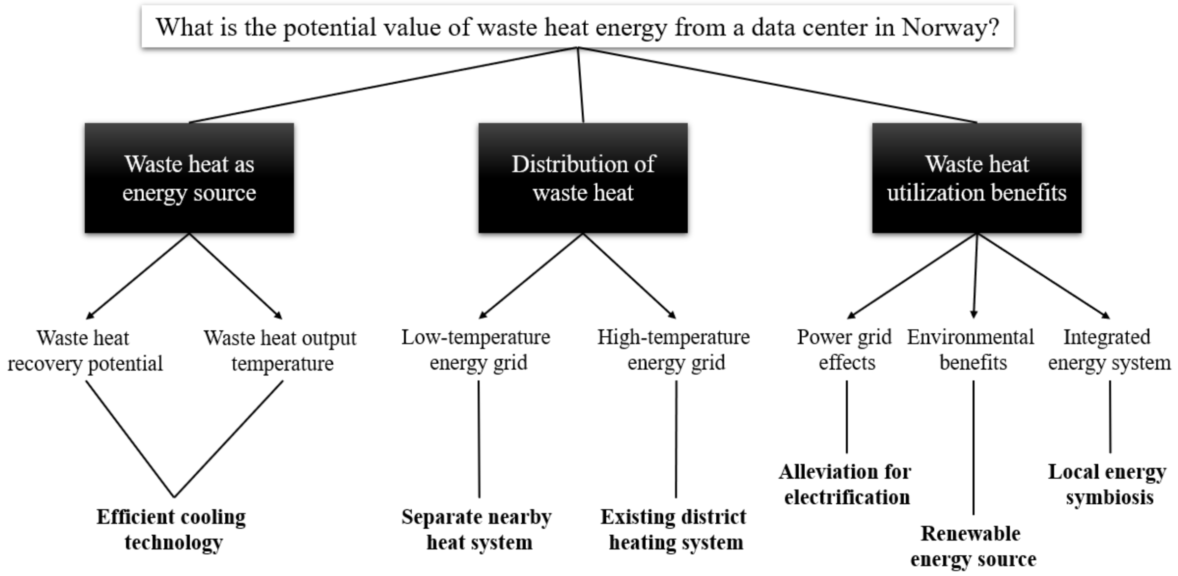

Figure 8 – Thesis concept map.

Map organizing key concepts and ideas from literature review.

3.1.1. Search strategy

The process of gathering relevant literature was shaped by the natural chronological steps that occur when evaluating the value of waste heat from a data center. The division into areas of interest was reinforced along the iterative review process. The resulting areas being waste heat energy potential, waste heat energy utilization feasibility, and possible benefits of waste heat energy utilization. Evaluation of the recoverable energy produced by waste heat generation is the first point of interest as it provides the basis which determines the overall potential. When the energy potential is evaluated, the proceeding point of interest is how to convert available energy potential into accessible and usable heat energy for consumers. The final point of interest are the overarching potential benefits from the utilization of waste heat. For the literature search strategy, certain keywords have been highlighted to provide transparency about the literature gathering process. These keywords were categorized by the main concepts from the conceptual map in Figure 8, which coincides with the areas of interest from the steps of investigation. If researchers are inept at providing high quality and relevant literature, the resulting findings will suffer consequences regarding quality and validity. This is the primary reason for using a structured literature review approach. It is important to mention that academic relevance and temporal industry importance was established together with internal supervisor at UiS and external supervisor at Lyse Neo. From initial meetings and preparatory literature screening good quality search phrases provided basis for literature gathering.

Table 2 – Search phrases overview.

An overview of search phrases from the search strategy divided into areas of interest. Areas of interest coincides with the main concepts explored in the literature review. The search phrases overview includes phrases in Norwegian and English, divided in a way to maximize the expected yield of relevant substance.

Energy potential	Utilization feasibility	Benefits
GE Compute Stavanger	Nærvarmeanlegg	Datacenter emissions
Datacenter lifecycle	Strategi Norske datasenter	Datacenters of the future
Datacenter waste heat	Waste heat energy grids	Datacenter heat value
Datacenter computing power	Decentralized waste heat	Data center investment analysis
Energy usage datacenters	Heat pumps for datacenters	Future data center trends
Datacenter forecasting	Modern datacenter screening	Modern datacenters

3.1.2. Scope overview

The review of relevant literature was divided into three areas of interest defined in the previous section. Energy potential evaluation, energy utilization feasibility, and possible benefits. The main goal being evaluation of value potential for waste heat from a data center in Stavanger. The waste heat energy pathway that is illustrated in Figure 9 depicts the three areas of interest as concrete steps. It includes the data center as the energy source, with a transportation system to possible consumers. This overview was generated to give context to later sections exploring the value of waste heat from a data center in Stavanger. Understanding the general waste heat energy pathway figure is useful to follow later investigations.

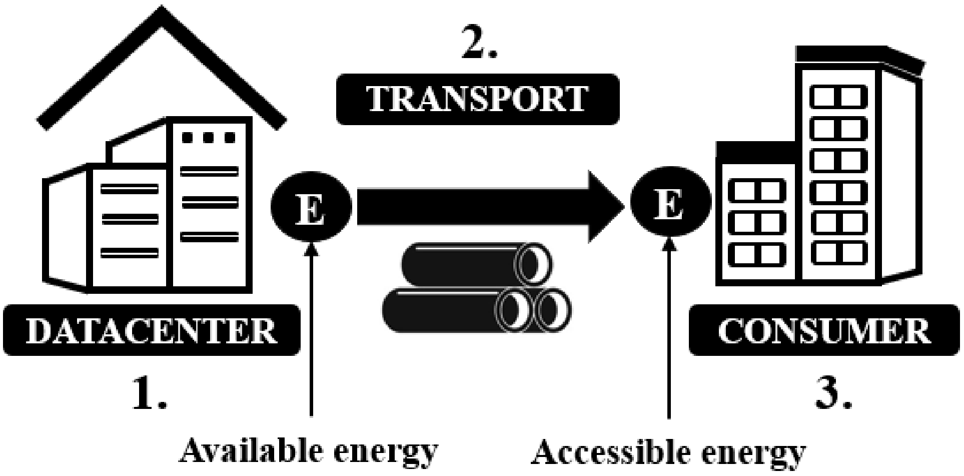

Figure 9 – Waste heat energy pathway.

Graphical illustration showing a simplified overview of the waste heat energy pathway for the process of waste heat utilization from a data center. "E" constitutes the waste heat energy entity. Waste heat is generated (1) and available energy is made accessible by integration with an energy grid (2) which distributes to potential end-users (3).

The theoretical waste heat energy pathway highlights the different areas of interest, with the data center in Stavanger providing the waste heat energy potential. The available waste heat energy is hypothetically transported through a type of heat energy grid. This grid system is expected to transport heat energy using liquid transport medium, which will reach target areas with specific heat energy temperatures. This process of transportation converts what is described as available energy to accessible energy. It is important to note that the step of transportation is estimated to have a reduction impact on the heat energy over time and distance. From conversations with Lyse Neo, a general phenomenon is that hot liquid medium transported over longer distances at slow speeds will consequently result in reduced temperatures at the target area. Temperature demand and consumer radius will affect the feasibility of utilization. The target area is defined as the area within the feasible radius of transportation with or without boosting the temperature by using auxiliary equipment. For both cases the feasibility region can be visualized as in Figure 10. It consists of potential consumers connected to an energy grid system which may or may not hold auxiliary machinery to adjust the waste heat temperature. This basic grid system must be able to transport low-temperature waste heat from the data center in a pipe grid to consumers within the theoretical feasible range for distribution.

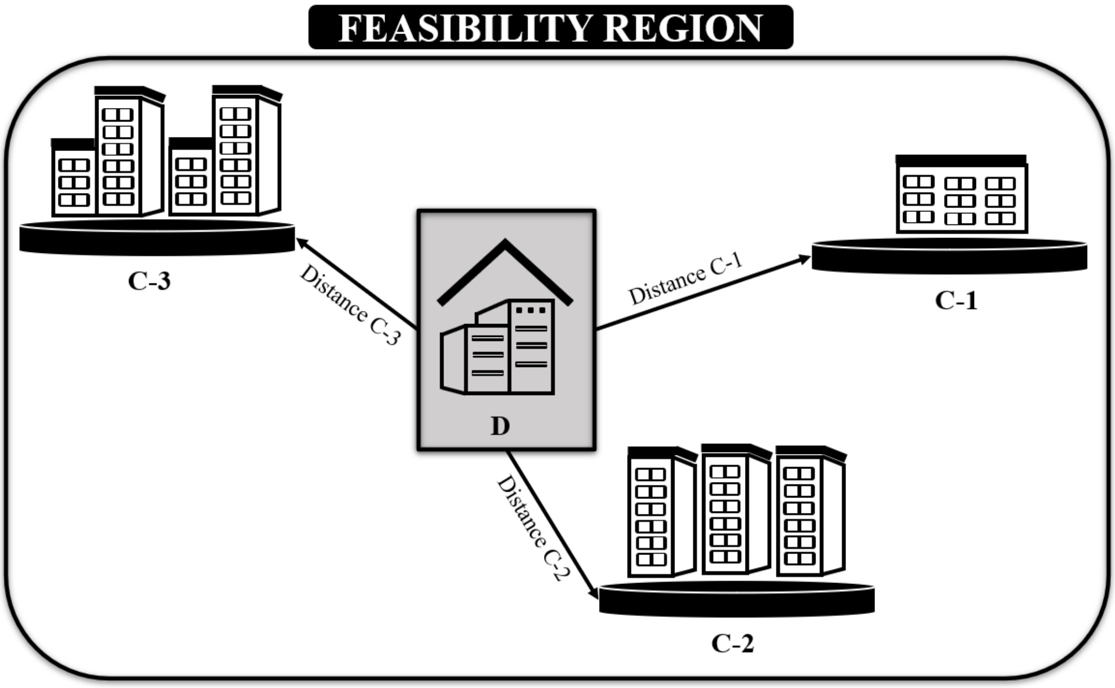

Figure 10 – Distribution feasibility region.

Theoretical illustration of a simple distribution grid for waste heat energy from datacenter (D) to consumers (C-1, C-2, C-3) within a hypothetical feasibility region of transportation. Distribution lines are demarcated with distance labels, to point out the possible difference in distances to consumers.

The last stage of the waste heat energy pathway investigated in this thesis considers the energy transfer to potential end-users. If connected to an energy grid supplying data center waste heat, consumers may be able to utilize this accessible waste heat energy for their own purposes. The potential value for consumers will be evaluated as a benefit of implementing a waste heat energy recovery and utilization system. The array of potential consumers is expected to vary based on the feasible distribution temperature of waste heat from the data center and the type of energy grid connection. When considering the holistic picture including all three areas of interest, it constitutes the hypothetical waste heat utilization system which is investigated to find the potential value of waste heat energy from the data center in Stavanger.

3.2. Waste heat potential

The fundamental starting point to find the potential value of waste heat energy from the data center in Stavanger is to investigate the waste heat potential entity. Meaning the overall potential output of waste heat energy from data center operations. Primary properties of this entity will be energy amount, temporal differences, generation stability, recovery potential, and dissipation medium. Data center operations will determine these factors, which is why a review of the data center type is important.

3.2.1. Modern data center

The Green Edge Compute data center in Stavanger is a modern edge data center. A modern data center in this context means an efficient data center utilizing modern cooling technologies. There are several factors that drive the market towards developing modern data centers. A major factor is that the data center industry consumes large amounts of energy, a large portion going to server cooling. This contributes to capacity issues for power grids and increased pollution. Sustainable data centers of the future are the branding Green Edge Compute leverages to be competitive in the market [29]. The technology implementation with the biggest impact for Green Edge Compute is liquid cooling. As seen in Figure 11 the power supply for cooling systems is a large fraction of the overall electricity consumption for a data center. By implementing innovative cooling systems, it is possible for a data center to reduce its electricity consumption to a substantial degree.

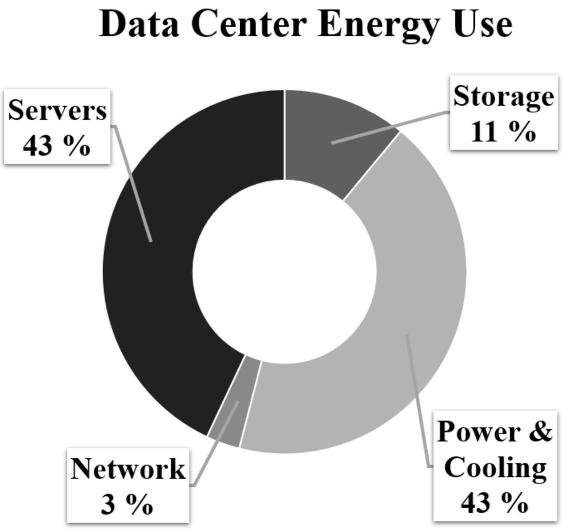

Figure 11 - Data center electricity consumption.

Showing the consumption in the United States for 2014, divided into technology types [43].

Liquid cooling systems enable Green Edge Compute to develop data centers with a much higher server density. Meaning they do not need large-scale facilities. This makes it easier to reuse existing buildings, cutting construction emissions. Liquid cooling systems also facilitate High Performance Computing, a service Green Edge Compute offers. Powerful equipment and components generate more heat, which calls for heavy duty cooling systems.

Edge Computing

Green Edge Compute develops edge data centers. The edge notation comes from Edge Computing, which is an emerging technology changing the computing paradigm. As more and more smart devices connect to the internet, capacity and performance issues occur. Including bandwidth problems, response speed impact, security- and privacy issues. Edge Computing combats such problems and issues by computing at the network edge. Meaning servers and services closer to users and sources of data [44]. Green Edge Compute presents a way for creating local green edge data centers in line with current needs and technological trends. They also point to a future with more IoT devices and services, and 5G networks which require modern edge data centers. Edge data center location needs to be close to customers, which is made possible by the implementation of innovative cooling systems as stated above. Modern data centers also enable the possibility for waste heat utilization, as liquid medium from the cooling systems holds heat much better than air. Recovered waste heat energy will affect the overall energy accounting. As a generalization the possible benefits of modern edge data centers can be reduced energy cost, higher performance, and low latency. Green Edge Compute established their first modern edge data center in Trondheim, 2021. With further aspirations to be presented in most of the Nordic cities by 2025 [29].

3.2.2. Liquid cooling technology

By implementing liquid cooling systems, Green Edge Compute state that they can reduce cooling power by up to 90% and reduce total energy consumption by up to 40%. By implementing new high-density equipment in relation to the new cooling system, they are also able to reduce the physical size by up to 90%. The reduction in size enables geographical location near urban areas. With the implementation of new technology as Green Edge Compute is doing, waste heat energy can potentially become a separate biproduct. And because of the urban location waste heat energy can be utilized in local areas as a renewable heat energy resource. Reuse is possible for 90% of utilized energy for the data center, and in future scenarios this may create a separate stream of income depending on the consumer grids [45].

Cooling methods

A transition from traditional air-cooling to liquid-cooling begs the question for what available liquid cooling methods exist. There are many different types of liquid cooling systems, including chip cooling solutions and immersion solutions. Chip cooling solutions provide cooling directly to the components accounting for the major heat generation, the processing units. This is possible by utilizing a micro-channel flow system and cold-plate heat exchange system [46] sketched in Figure 12. Studies have been conducted on the efficiency of this type of cooling system, and possible improvements have been explored as in [47]. This is a Norwegian publication on a data center in Sweden which focused on minimizing control effort and maximizing the outlet temperature. Indicating a momentum in research towards cooling systems enabling higher quality output heat for reuse purposes.

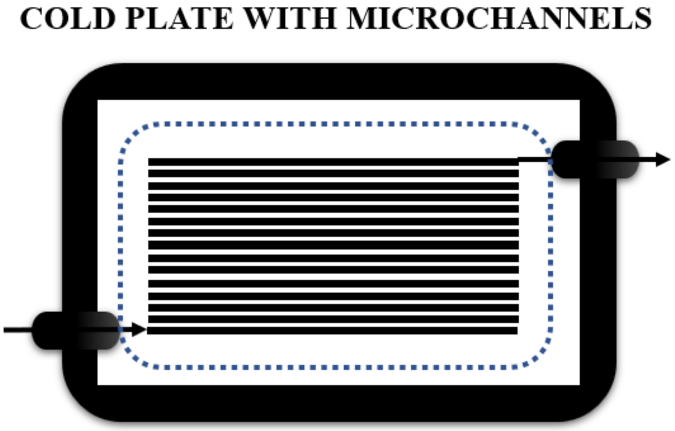

Figure 12 – Chip cooling solution.

Simplified schematical structure of a cold plate with micro-channels inside guiding flow of liquid medium inspired from Fig. 3. in [48]. The cold plate is situated on the processing unit, with cold liquid flowing in (arrow into channels) and hot water flowing out (arrow out from channels).

Immersion solutions with electronics in direct contact with the low-conductive coolant medium is also a type of liquid cooling system. From the meeting with SINTEF (Appendix G) it was made clear that immersion cooling can be divided into single-phase and multi-phase cooling. Single phase meaning the use of a liquid medium as heat exchanger, so that when heat generating component increases the surrounding coolant temperature it is pumped out of the server racks in liquid form. Multi-phase or two-phase cooling includes a secondary phase, meaning that when the liquid heats to boiling point it converts form into gas. This way it does not have to increase the temperature of surroundings, it rather changes phase to extract heat. Microsoft are testing two-phase immersion cooling systems and implemented the technology for a hyperscale data center in 2021 to prove viability. This is a part of their long-term strategy to keep up with demand and make data centers more sustainable and efficient. Possible benefits of two-phase immersion cooling systems include reduced costs, reduced energy consumption, increased reliability, and increased performance [49]. It is also worth noting that the cooling method with the highest capacity for heat energy removal is two-phase flow cooling as it leverages the latent heat of the coolant fluid. This enables higher quality output, with potential output temperature in the range of 70-80°C [46].

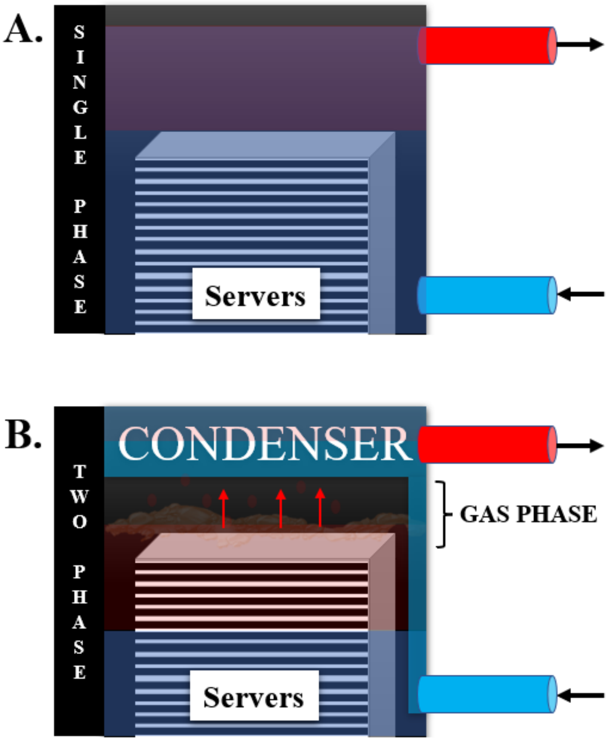

Figure 13 - Immersion cooling solution.

Single-phase with liquid coolant (A), and two-phase with coolant in liquid and gas form (B), both showing cold input in blue and warm output in red. In "A" Liquid medium is pumped into a heat exchanger to extract heat energy. In "B" heat energy is recovered by low-temperature evaporation and condensation. Inspired by figure in [50].

3.2.3. Common efficiency metrics

To understand the waste heat energy potential of the data center in Stavanger, a connection between energy consumption, waste heat generation, and recovery potential is needed. The Green Grid is a non-profit collaboration across supply chains for technology companies and energy companies concerning data center resource efficiency. They have developed the technical basis for a variety of metrics for improved understanding of data center operations [51]. According to Green Edge Compute there are two primary methods used in the data center industry to measure sustainability efforts, namely PUE and ERE. PUE describes how much of the overall energy that is used by servers and data equipment [52]. PUE is defined as a quotient where total energy is divided by IT energy with formula presented as an equation in (1). The Green Grid further explains the total energy consisting of multiple quantities. Cooling energy, power energy, lighting energy, and IT energy. IT energy mainly constitutes server energy, network energy, and storage energy which makes sense considering the overview of data center electricity consumption in Figure 11 [52].

$$PUE = \frac{Total\ Energy}{IT\ Energy} \tag{1}$$

As more data centers implement ways to recover and distribute waste heat energy from operations, a method describing this factor is needed. ERE considers this waste heat utilization and describes energy efficiency taking this into account. ERE is presented in equation form in (2). This additional evaluation of energy efficiency concerning waste heat utilization is important to measure how technology investments are affecting modern data center operations [52], [53].

$$ERE = \frac{Total\ Energy - Reuse\ Energy}{IT\ Energy} \tag{2}$$

$$ERF = \frac{Reuse\ Energy}{Total\ Energy} \tag{3}$$

A related factor can be derived from ERE with ratio defined in (3). The ERF is useful as it links ERE to PUE, so that they can be evaluated together. The relationship between ERE and PUE is described in (4) [53].

$$ERE = (1 - ERF) \times PUE \tag{4}$$

A simple way of looking at PUE and ERE would be to divide them into focus areas. The former focusing on internals and the latter focusing on externals. Internals meaning the data center itself, externals meaning outside of the data center. ERF links these quantities together to give a fuller picture of the energy efficiency situation for data centers as a whole [53].

Future efficiency metrics

The Green Grid works on improving data center efficiency and defining other key metrics as tools for optimization. Their focus includes low carbon solutions [51]. Metrics such as GEC (Green Energy Coefficient) and CUE (Carbon Usage Effectiveness) may help describe the carbon footprint of data center operations. GEC relates to how much of the total energy consumption is sourced from renewable energy providers. Renewable energy sources may be wind power, solar power, hydro power, geothermal energy and many more [54]. There are several systems in place on how to determine if energy providers produce renewable energy. According to the Norwegian Electricity Certificate Act special certificates are issued for every 1 MWh that has been generated from renewable sources and contributes to increased income for renewable energy producers [55]. On the NVE registry for electricity certificates it is possible to view all approved facilities and their installed effect [56]. The Energy Act §4-3 describes Guarantees of Origin, which is the second certificate scheme of NECS (Norwegian registry for Elcertificates and Guarantees of Origin) together with the elcertificate scheme. The Guarantees of Origin (GO) certificates is documentation of production of renewable energy, which gives producers additional income from renewable energy [57]. Meaning that there are means to find the origin of energy for GEC calculations using the equation form in (5). The data center must however own the rights to green energy certification for it to be valid in these calculations [54].

$$GEC = \frac{Green\ Energy}{Total\ Energy} \tag{5}$$

The maximum GEC value possible is 1.0, as then 100% of the total energy consumption would be from renewable energy sources. Other than GEC, the metric CUE is useful to evaluate the carbon impact of operations. The metric pertains mainly to operations and does not consider emissions concerning development of buildings, materials, and equipment. CUE is a composition of two factors, CEF (Carbon-dioxide Emission Factor) multiplied with PUE. The CEF are kilograms of CO_2 generated per kWh of electricity consumption, which depends on location and energy grid connected to the data center. CUE is presented in equation form in (6) [58].

$$CUE = \frac{Emissions}{PUE} \tag{6}$$

$$CUE = \frac{kgCO_2eq}{kWh} \times \frac{Total\ Energy}{IT\ Energy} \tag{7}$$

CUE ideal value is 0.0, meaning that there are no carbon emissions from data center operations, and will in the other end have no maximum boundary. From The Green Grid recommendations CO_2 monitoring equipment from real time consumption should be implemented but will not be feasible for many. Estimates can be made by utilizing equipment data and energy source information and evaluating it over time with a defined profile for load. Such calculations are not in the scope of this thesis but are an important note for data center companies. The Green Grid recommends data center companies to begin thinking on how to implement such metrics for more sustainable and measurable operations. To establish standards with regards to new types of efficiency metrics, comparison is paramount and encourages the industry to be transparent on data analysis [58].

3.2.4. Waste heat generation

As seen in the example for data center energy use distribution in Figure 11, approximately 57% are used for IT-purposes including storage, servers, and network components. A newer study from Europe presents energy consumption for IT-equipment at approximately 60% for data centers in Germany for 2017 [59]. It seems safe to say that most of the energy consumption goes to IT-components, which is also the primary source of waste heat energy from operations. Cooling systems either by use of air ventilation or by some kind of liquid medium dissipate the heat energy from IT-components. This is the basis for waste heat recovery from data centers.

3.2.5. Energy recovery

A higher consumption fraction going to IT-equipment will in theory provide a higher potential for waste heat generation. PUE describes how much of the energy consumption for a data center that goes to IT-components, as explored earlier. Lower PUE gives a higher fraction of energy to IT purposes. The evolution of PUE since 2007 has changed significantly, however mostly the first seven years according to a global survey of IT and data centers from 2021 with 566 respondents. The PUE direction over the years 2007 to 2021 is depicted in Figure 14.

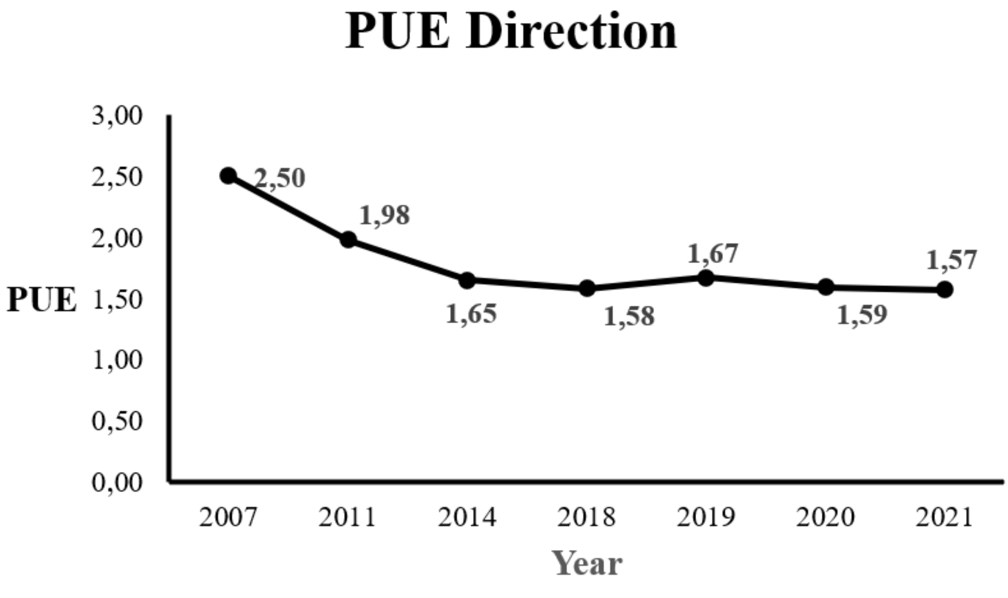

Figure 14 - Average yearly PUE values between 2007-2021.

Includes the largest data centers reported by data center managers in survey from 2021. Based on Figure 1 in [60].

There seems to be a somewhat stagnation in reported PUE values according to survey results presented in the figure above. Even though PUE values are helpful, it does not give a good enough representation of existing waste heat energy potential. ERF values would give a fuller picture of the waste heat potential, but there are no available calculations on real test data from the data center in Stavanger as it does not utilize waste heat energy today. ERF (3) describes the reuse energy for a data center, which entails having a waste heat utilization system already. To evaluate the waste heat potential, it is useful to base estimations on specifications on the data center. Information from the SINTEF study [61] investigating Green Edge Compute's data center in Trondheim are presented in Table 3.

Table 3 - GEC One specifications.

Includes area, final capacity, operative racks, and PUE [61].

Data center size	**IT-power**	**Server number**	**PUE**
135 m^2	2000 kW	20 racks	1.1

According to Green Edge Compute, when establishing a modern GE data center, they try to find locations that open for approximately 100-200 m^2 operational space. This would entail between 20-40 server racks at full space capacity with their current equipment structure. Concerning the power demand, if the setup is full capacity at 4 MW, the general capacity would probably be around 2 MW which is the same case as in the table above. There has been some ambiguity concerning the capacity terminology concerning power consumption, so the primary assumption is that capacity is referring to the IT-power consumption. Meaning consumption of power for IT-components.

Heat capture rate

The estimated heat capture rate regarding generated heat for the data center in Trondheim is approximately 87% according to the SINTEF study [61]. Meaning that the ERF is 87%. There are approximately 8760 hours in total during a year. The estimated recovery hours for waste heat to be distributed in Statkraft district heating systems from the data center in Trondheim is stated to be 4000 hours, which is approximately 46% of the year. When incorporating this fact into the ERF value it reduces to approximately 40%. The total data center electricity consumption for GEC One is 2206 kW per hour. Calculating with the estimated ERF we get recoverable average waste heat energy at approximately 877 kW per hour that is distributed in the local district heating grid for consumers to utilize. In total this amounts to 7680 MWh of utilizable waste heat energy to the local district heating grid in the duration of a year.

Output temperature

When trying to quantify the waste heat energy potential, energy amount, time variations, and heat quality is important. The primary factor influencing the heat energy quality is the output temperature. A higher grade energy will have higher temperatures, reflecting a larger energy potential. This will in turn affect the utilization potential, so it is important to evaluate the possible and probable output temperature of waste heat from the data center in Stavanger. The theoretical output temperature possible from the server structure and cooling system utilized by Green Edge Compute opens for output temperatures approximately at 60°C. The system overview presented in the SINTEF study from the GEC One data center in Trondheim does not include output temperatures of this level [61]. Verified numbers were not available for their calculations, so the number basis comes from the cooling system supplier, Cool IT. The inlet temperature of coolant was stated to be 39.3°C, and the outlet temperature of coolant was stated to be 46.6°C. Green Edge Compute have stated that the liquid cooling solution they have planned should be able to operate under higher temperatures, giving a higher temperature waste heat output. The estimated output temperature would ideally be 60°C, but the cold-plate enables for higher operating temperatures. Intel does not recommend operations with higher temperatures than what is recommended as it involves higher risks of component damage. The component lifetime and guarantee are dependent on the equipment damage risk. It is therefore assumed an output temperature of 60°C concerning the setup depicted in Figure 15.

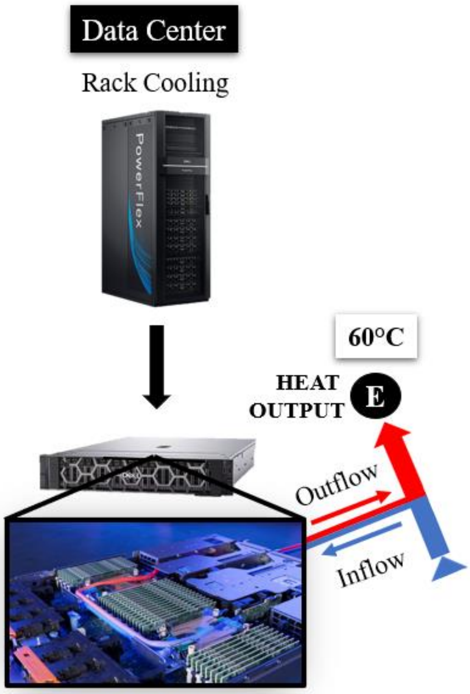

Figure 15 - Simplified overview of the waste heat recovery pathway utilizing a rack cooling system.

Includes Dell PowerEdge servers with direct liquid cooling. Cooling system is based on cold-plate technology [62]. Assumed waste heat output temperature is 60°C [61].

3.3. Utilization feasibility

A critical part of waste heat utilization is the second pathway step for the process of waste heat utilization from a data center visualized in Figure 9. Energy grid infrastructure is needed to enable the waste heat potential to be transformed from available energy to accessible energy for consumers. A study on 17 data center projects around the world from 2007 to 2019 presented an overview of cooling systems in use and if waste heat was utilized. Most data centers make use of either air-cooling technology or water-cooling technology for heat dissipation from IT-components. Of the data centers that reused waste heat, most of them utilized district heating systems, and some utilized the waste heat for nearby demand. Like an office building, adjoining rooms, and a swimming pool [63]. This study investigates the two main pathways for waste heat utilization, being direct heating or indirect heating. Direct heating is meant as a separate heat energy grid for transportation of heat energy to nearby areas of demand. Indirect heating is meant as a supply to an existing district heating system, enabling the delivery of energy to a variety of consumers, possibly in a larger radius from the energy source being the data center in Stavanger. A critical part of waste heat utilization is the second pathway step for the process of waste heat utilization from a data center visualized in Figure 9. Energy grid infrastructure is needed to enable the waste heat potential to be transformed from available energy to accessible energy for consumers. A study on 17 data center projects around the world from 2007 to 2019 presented an overview of cooling systems in use and if waste heat was utilized. Most data centers make use of either air-cooling technology or water-cooling technology for heat dissipation from IT-components. Of the data centers that reused waste heat, most of them utilized district heating systems, and some utilized the waste heat for nearby demand. Like an office building, adjoining rooms, and a swimming pool [63]. This study investigates the two main pathways for waste heat utilization, being direct heating or indirect heating. Direct heating is meant as a separate heat energy grid for transportation of heat energy to nearby areas of demand. Indirect heating is meant as a supply to an existing district heating system, enabling the delivery of energy to a variety of consumers, possibly in a larger radius from the energy source being the data center in Stavanger.

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3.3.1. Influencing factors

The available waste heat potential can be quantified by a variety of factors including the feasible energy amount, output temperature, and delivery stability. This waste heat potential will inform the decision-making process for how to best transform this energy into an accessible resource for end-users. It is particularly important to evaluate the heat energy demand in relation to the possible waste heat supply for consumers within the feasibility region of the hypothetical integrated energy grid investigated.

3.3.2. Nearby heat energy grid

For a direct waste heat supply system an envisioned separate district heating type energy grid would be a potential distribution solution. Consumers within a feasible radius would be able to connect to the nearby heat energy grid and utilize the supplied waste heat from the data center in Stavanger. This type of energy grid would be a low-temperature heat energy grid, utilizing the same setup as district heating grids, but with a lower liquid medium temperature. Meaning a lower grade energy output. This type of solution depends strongly on consumers with a demand profile suitable for the waste heat supply profile. This demand profile would be a contribution of demands from a variety of consumers within the feasibility area. Some consumers have more heating needs in the colder months, and some have the entire year. The major point of interest when considering a low-temperature waste heat energy grid, is that there is no need for temperature boosting to meet delivery demands. From communications with Lyse Neo, a heat pump system would be a costly addition to an energy grid. With this low-temperature solution this cost is eradicated, which may affect the investment analysis for the development of a waste heat utilization system.

3.3.3. District heating connection

Another distribution solution with indirect supply of waste heat energy to consumers is enabled by a connection to the existing district heating grid in Stavanger. The district heating grid in Stavanger is primarily supplied with heat energy from the waste incineration plant at Forus operated by Forus Energigjenvinning, seen in Figure 16.

Figure 16 - The incineration plant at Forus.

Forus Energigjenvinning incinerates waste and produces electricity and waste heat for district heating systems in Stavanger. With operation all hours of the year, the incineration capacity is approximately 110000 tons of waste per year. Making it the primary source of heat energy for the district heating grid in Stavanger [25].

Forus Energigjenvinning has a combined capacity of 110 000 tons a year and comprises two separate lines, each owned by different entities. These owners consist of a mix of companies involved in real estate, waste heat distribution and the municipality. Prior to reaching the waste incineration stage, the waste passes through IVAR, a waste sorting facility. The energy generated from the incineration process is then sold to Lyse, the entity responsible for the infrastructure. At the incineration plant, the sorted waste is incinerated, resulting in the production of flue gas and steam. These biproducts are utilized to generate electricity and heat. The process of generating 50 GWh electricity and 225 GWh waste heat from incineration is depicted in Figure 17 [25].

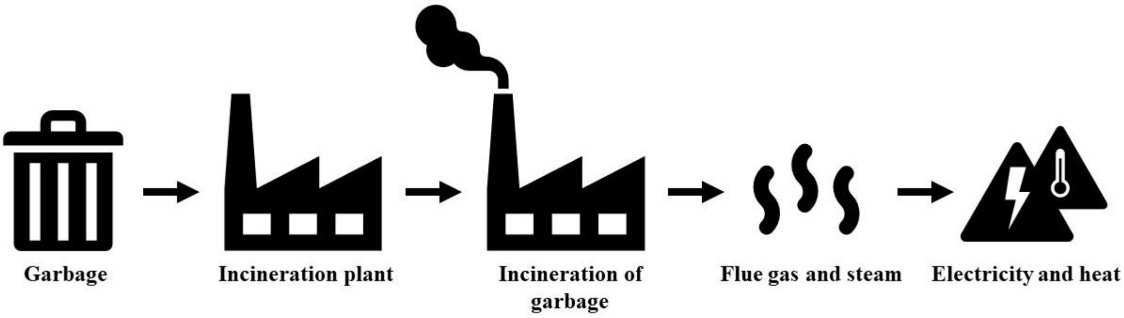

Figure 17 - Electricity and heat pathway from incineration at Forus Energigjenvinning.

Garbage is delivered to the plant where it undergoes sorting and incineration, producing flue gas and steam. These biproducts are then used to generate both electricity and heat [25].

The waste heat energy from the data center in Stavanger is a lower grade heat energy than what is supplied through the district heating system, as it delivers heat energy with output temperatures around 85-90°C. This would entail some sort of heat energy upgrade of the waste heat energy supplied from the data center. This upgrade would enable the data center to supply waste heat energy to the same district heating system that Forus Energigjenvinning supplies to. This transformation of energy grade will come with costs. This temperature boosting may be achieved by utilizing a heat-pump system like the setup explored in the SINTEF study for the data center in Trondheim [61]. This additional cost begs the question of economic feasibility. There might be an increase in the potential value of waste heat from the data center in Stavanger, making up for this increased cost.

3.3.4. Challenges

The recovery and utilization of waste heat from a data center is a complex systematic setup, with the expectance of a multitude of actors with individual goals. The major challenges with the aspects mentioned in previous sections include the temperature challenge. It is hard to evaluate the potential value differences concerning the different methods of distribution. If enough consumers can utilize a lower-grade energy, it might be the option that will generate more value. If connecting to the district heating system makes the waste heat energy from the data center last longer, meaning there is demand for heat energy to a higher degree and across seasons this might shift the decision towards district heating integration.

Drinking water temperature

A heat pump system as described in the SINTEF study [61] will increase the inlet temperature into the district heating grid. By increasing waste heat temperatures, delivery of waste heat energy can span a larger variety of consumers. Increased temperature helps fulfill drinking water deliverable criteria primarily by eradicating the risk for Legionella bacteria. This will enable delivery of hot water to private households and A heat pump system as described in the SINTEF study [61] will increase the inlet temperature into the district heating grid. By increasing waste heat temperatures, delivery of waste heat energy can span a larger variety of consumers. Increased temperature helps fulfill drinking water deliverable criteria primarily by eradicating the risk for Legionella bacteria. This would enable delivery of hot water to private households and other consumers with this delivery demand. From conversations with SINTEF there does not seem to be any viable alternative method to secure against Legionella bacteria.

3.4. Possible benefits

The utilization of waste heat in data centers has the potential to generate a range of benefits that extend beyond the immediate context of energy consumption. This section explores the various benefits by considering environmental impact, energy efficiency and economy.

3.4.1. Environmental impact

Utilizing the excess heat produced by data centers is one step towards a greener and more sustainable future. The pollution accounting for data centers is complex. The biggest sources of carbon emissions include construction, especially concerning the cement industry and fossil fueled industrial machinery. A lot of the equipment for the data centers must be shipped or transported, which is secondary pollution. Depending on the energy source used for powering the data center and running the cooling systems, this may also contribute to overall pollution [64]. Many data center companies set goals for net-zero emissions, which is different from absolute zero emissions as it does not mean the data center will not pollute. Midway goals such as carbon-neutrality may help the shift to sustainable data centers by reducing the carbon footprint. The main tactics used by Green Edge Compute is the following. Utilizing existing buildings for servers and equipment. Using renewable sources of energy. Improving operations with new technology and new material. Recovering waste heat and enable the reuse of heat energy [64, 45]. By establishing data centers in existing infrastructure, they abstain from occupying untouched land contributing as an environmental benefit [Appendix G]. Electricity for powering modern HPC data centers in Norway come mostly from renewable sources as stated above. In conjunction with waste heat utilization, this impacts the carbon footprint. Waste heat utilization as a low-grade energy source may alleviate the power grid, enabling more electricity and power. By utilizing waste heat, data centers are creating a better environment for their own operations, as they are very power consuming. According to the SINTEF study for the GEC One data center in Trondheim the annual emission is estimated to be 348 tonCO_2eq/kWh using 18 gCO_2eq/kWh as electricity emission factor. Which is based on the total data center electricity consumption being 19’324 MWh a year [61]. The implementation of liquid cooling in data centers enhances power consumption by improving cooling efficiency [29]. Norway is a country with a significant proportion of renewable energy sources in its power production and had 50.5% of its energy generated from renewables in 2021 [65]. The reduction of greenhouse gas emission may not be regarded as a substantial benefit in Norway due to renewable energy sources. The extent of this benefit depends on the reliance on fossil fuels as an energy source.

3.4.2. Energy efficiency

Reducing resource consumption and minimizing negative environmental effects are positive concerning increased energy efficiency. Green Edge Compute increases the energy efficiency by several measures. Liquid cooling is efficient and reduces the power consumption. Using existing buildings for purpose of housing data centers is a sustainable solution. Their concept also enables utilization of waste heat through district heating systems, which makes the most of the energy consumed for running the data center [29]. The utilization of waste heat can also be a factor that accelerates the implementation of High-Performance Computing (HPC) data centers. In essence, these are computer systems that work in the speed range of one million times the speed that an ordinary personal computer works at. HPC will for many companies only be accessible as a service, meaning cloud services provided by data centers. These data centers can possibly run at higher temperatures which will increase the temperature on waste heat. This will have a positive impact on the energy efficiency [66]. An example of this is Volkswagen Group which moved their computing operations to Green Mountain, a data center in Rjukan, Norway. Modern data centers with HPC capacities can be attractive for companies for the multitude of beneficial effects. For Norwegian data centers such effects have been described to include renewable electricity for power, low electricity prices and high levels of stability [67]. Increased implementation of modern data centers providing HPC services will consequently mean a higher degree of potential waste heat. Energy efficiency has an impact on the economy, potentially for both data centers operators and the end-users.

3.4.3. Economy

Economic benefits connected to waste heat utilization from data centers has a potential value, both internally within the data center and in the macroeconomic context. Internally, the implementation of technological solutions such as liquid cooling reduces power consumption, leading to cost savings in operational expenses for data center operators. Additionally, by utilizing waste heat and integrating it into district heating systems, there is a potential to generate economic value through the sale of excess heat to district heating distributors or low similar distribution grids. For data center operators, implementing waste heat utilization strategies also provides a competitive advantage by positioning them as sustainable entities contributing to the green shift in energy consumption [Appendix G]. Externally the establishment of data centers can have a ripple effect on economic growth in a small and large context. A report made on behalf of Ministry of Local Government and Modernization brings forth the substantial growth in possible employments with an estimated increase in the range from 12600 to 15800 jobs towards 2030. The presence of data centers and the associated employment opportunities and economic growth have a positive impact on the overall development of the Norway’s economy [32].

3.5. Main challenges

The recovery and utilization of waste heat from data centers present a complex and multifaced system, with the expectance of a multitude of factors and actors with individual goals figuratively presented in Figure 18. The challenges associated with the endeavor encompass several aspects, including the temperature challenge and the evaluation of potential value differences across different distribution methods. It is difficult to determine the optimal solution when considering the utilization of lower-grade energy and the potential for greater value generation. Integrating with a district heating system can extend the lifespan of waste heat energy by meeting higher demands for heat energy across different seasons, thus influencing the decision-making process. The challenges involved in utilization of waste heat from data centers encompass production, demand, temperature, policy location, infrastructure, and economy. These challenges are interconnected, with each one influencing and being influenced by others within the system.

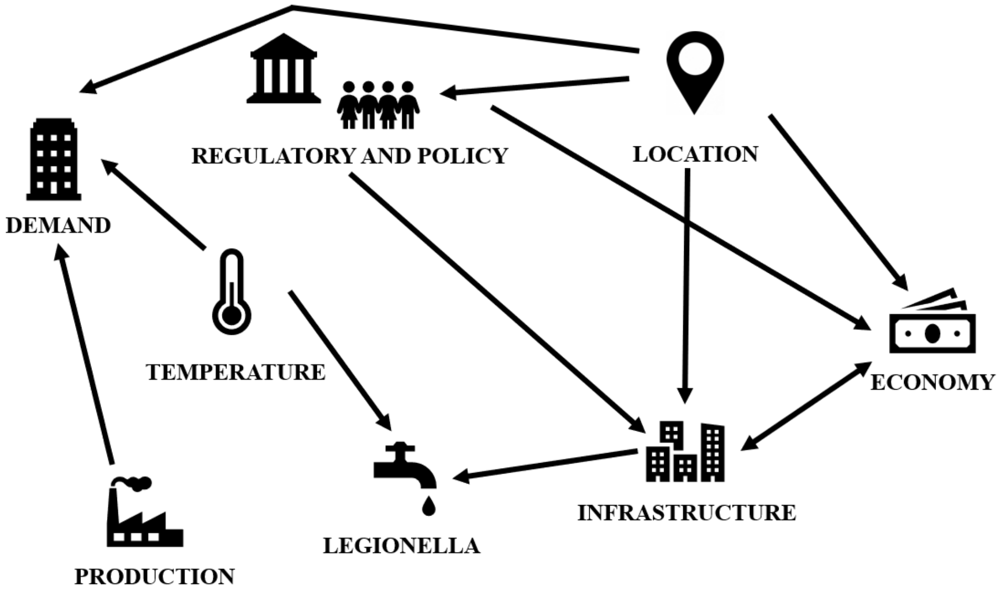

Figure 18 - Complexity of challenges.

Effective utilization of waste heat from data centers is complex and multifaced, influenced by various challenges across different aspects.

Regulatory and policy

Clear guidelines and framework conditions regarding power prices, taxes and other expenses regulated by the Norwegian government are crucial for the establishment and growth of data centers. Given their significant power consumption, data centers require predictable pricing structures to make informed investment decisions. In 2020, the parliament eliminated the full electricity tac, which has had an impact on the tax burden faced by data centers. Additionally, taxes may vary depending on the customer and the scale of the services provided by the data center. Slow bureaucratic processes and delays can create obstacles in the planning and establishment of data center, impeding their potential for growth [32].

Infrastructure

The establishment of data centers is contingent upon having access to adequate power capacity. To operate effectively, data centers require infrastructure that can supply sufficient power, robust fiber capacity and the ability to connect to the district heating grid. These dependencies are directly associated with substantial investment cost [32]. Infrastructure is costly to establish [7].

Production and demand

According to the meeting with SINTEF [Appendix G], data centers have the highest demand for cooling during the summer when the outdoor temperatures are at their peak. However, this coincides with the lowest demand for heat. As a result, there is a mismatch between the production of waste heat in data centers and the demand for heat energy during this period [Appendix G].

3.5.1. Incentives for waste heat utilization for data centers

The Norwegian government has developed a strategy for promoting electrification and ensuring a reliable power supply. This strategy is outlined in Meld. St. 36 (2020-2021), which focuses on a long-term value creation from Norwegian energy resources and aligns with the government's climate plan [68]. As a part of this strategy, the government aims to facilitate the establishment of data centers and is also considering the need for regulations pertaining to electronic communication [40, 69]. In the climate plan for 2021-2030, data centers are recognized as a crucial sector for driving the green transition [5]. However, there are currently no specific regulations or requirements regarding the utilization of waste heat from data centers. Data centers must conduct a cost-efficiency analysis, the is just necessary if the total capacity exceeds 2 MW. The government does not mandate the implementation of waste heat utilization solutions solely based on this cost-efficiency analysis [4].

3.5.2. Data center testing data

Future testing will provide a broader data foundation for understanding the performance and characteristics of data centers. One potential approach is to conduct testing of the equipment planned installed in Stavanger in Trondheim where Green Edge Compute have already established a modern data center. Testing data center necessitates the availability of essential equipment, infrastructure, and qualified personnel. The literature reviewed in this study indicates the emergence of forthcoming regulations that will mandate cost-efficiency analysis.

3.6. Thesis contribution

Scientific insights from previous sections highlight the gap in knowledge when it comes to utilization potential for low temperature waste heat from data centers. Data centers' large energy consumption and the resulting waste heat created by server computing makes it a clear choice when evaluating waste heat energy utilization benefits. There are several under-examined areas concerning this theoretical energy pathway that is presented in Figure 9. New data center cooling technology and space minimization strategies make for an increased waste heat temperature output potential. Meaning that modern data centers can produce waste heat at a higher temperature than before without diminishing computing power or damaging equipment. Waste heat in Stavanger is currently being used on a large scale by distribution from Forus Energigjenvinning. Incineration of non-recyclable plastics and other waste generates a high temperature waste heat energy, that is being transported by liquid medium through a district heating grid. The incineration plant is located on Forus, and the extent of supply grid output includes nearby cities of Sandnes, Stavanger, and areas in between. To utilize waste heat energy with a lower temperature the district heating grid radius will be less. There are two main possibilities of a low temperature waste heat energy grid. A separate nearby heating grid with a small radius not connected to the overall district heating grid of the region. Alternatively, it is possible to connect this nearby heating grid with the district heating grid at a premium, with a one-way valve to ensure delivery temperature at the nearby heating grid.

4. Data

This chapter serves as an extension of the literature review, providing an overview of the data variables, sources, and timelines for data collection. With emphasis on the necessary compilation of data and literature data substitution for missing test data to assess the value of waste heat energy from the data center in Stavanger. Further elaborations concerning uncertainties and bias are presented within this chapter. Throughout the thesis project, boundaries were established and realigned to account for the aspects of scope and data availability. Especially considering the limited project time at disposal together with the limited relevant test data. This thesis concerns mostly a general evaluation of data center waste heat value. It is however useful to utilize available data points to define specific phenomena providing a stronger basis for evaluation. The most prominent data points concern waste heat energy quantities and waste heat energy temperatures. Data points concerning energy demand from Bjergsted near the data center in Stavanger are also included. The input data used in this thesis are outlined in this chapter. It is important to underline that the data collection and resulting values are based on limited sources.

4.1. Input data

Assessed and verified data from operational data centers should be the base for operational analysis. Green Edge Compute was expected to contribute data sets needed to answer the thesis question for the specific data center in Stavanger. They were only able to contribute on a small scale due to their intensive work and lack of capacity while working with funding for the establishment of the data center. It is also important to note that the enabling technology, which in this case is the modern liquid-based cooling technology, is another reason for limited data. Because of this technological novelty, waste heat from liquid cooling is not extensively researched. The thesis data were obtained from a diverse range of sources presented in

Table 4, and are mostly secondary data obtained from existing sources. Furthermore, data sets from Lyse Neo, literature, and best practice are used as a substitute when no appropriate testing data are available. Green Edge Compute has an equivalent data center established in Trondheim. Available data sets from this data center are applied. Expected contribution of test data was not received due to testing difficulties at Trondheim and early-stage development in Stavanger. The uncertainty concerning calculated values from literature is important to have in mind for the data centers evaluation. Uncertainties caused by the limited access to data are mentioned at the end of this chapter. The evaluation conducted in this thesis builds upon studies conducted by NVE, SINTEF and the Norwegian government. These research efforts have provided a solid foundation for the assessment and analysis presented in this study. Expert resources from Lyse Neo, SINTEF, Statkraft and Green Edge Compute have contributed with knowledge. Collecting data sets from comparable data centers is necessary to establish a comparison and for evaluation of important values.

Table 4 - Input data overview.

An overview of what data is collected and the source which it is collected from.

Input data overview			
Key metric	**Quantity**	**Source**	**Comment**
Size of data centers	m^2	SINTEF, GEC Stavanger*	Based on future scale, estimation
IT power consumption	kW	SINTEF, literature	
Annual total power consumption	kW, TWh	SINTEF, Literature	
Heat capture rate	%	SINTEF	
Annual waste heat recovered	kW	SINTEF	Based on 4000 hours
Annual net energy supply to DH	GWh	SINTEF	Based on 4000 hours, included, HTHP energy consumption
Input temperature server cooling	℃	SINTEF, literature	
Output temperature liquid cooling	℃	SINTEF, Literature	
Output temperature air-based cooling	℃	Literature	
Maximum temperature servers	℃	GEC Stavanger*	
Annual greenhouse gases emissions	Ton CO_2	SINTEF	Considered with electricity emission factor
PUE	-	SINTEF, GEC Stavanger*	
ERF max	%	SINTEF, GEC Stavanger*	
ERF average	%	SINTEF, Literature	
Capacity range	%	GEC Stavanger*	
Distribution of energy consumption		Literature	
Data sets local heating Bjergsted	kW	Lyse Neo	Received 01.06.2023
Waste heat temperature ranges	℃	Literature	
Waste heat potential dependent on temperature	TWh	Literature	
District heating production Norway	TWh	Literature	
BRP	Billion	Literature	
Value creation		Literature	

**Most data from GEC Stavanger were received 20.05.2023*

4.1.1. Data from SINTEF - GEC One

SINTEF conducted a screening life cycle assessment for a new data center in Trondheim on behalf of Green Edge Compute. The assessment used GEC One as a reference point for calculations, estimations, and evaluations. Due to missing testing and verified data, a large part was based on information from equipment manufacturers, literature, and best practice. GEC One shares certain similarities with the planned data center in Stavanger, such as the use of liquid cooling, establishment within an existing building, and the utilization of waste heat potentially through district heating systems. However, a notable difference between the two data centers lies in the utilization system of waste heat. In the case of GEC One, a heat pump is employed to raise the temperature, enabling integration with the existing district heating grid. Conversely, for the data center in Stavanger, a possibility might be to utilize the output temperature from the cooling systems without resorting to temperature elevation. The data center has an approximate size of 135 m^2 and an initial capacity of 1 MW, with a future goal of scaling up to 2 MW. This upscaling would accommodate the operation of 20 server racks. The maximum recovered waste heat for the data center amounts to 1920 kW. PUE is 1.1, which is lower than the EU reference for average PUE of 1.7 [70]. The supply and return temperatures for the server coolant are measured at 39.3℃ and 46.6℃, respectively. According to the SINTEF study the calculated ERF is 87% based on maximum values. The recovery of waste heat significantly impacts the ERF, which drops to 39.9% when considering four thousand hours of waste heat recovery directed towards district heating systems. Heat supply to district heating system is not considered due to the needed HTHP condenser increasing the output temperature [61].

4.1.2. Preliminary data from Lyse Neo

Lyse Neo provided on 14th of March 2023 a spreadsheet with an investment estimate in NOK/kW. The estimates provided are approximate and consider the required construction for the placement of installations. Operational and maintenance costs are estimated at a fixed percentage at 3% of the investment amount. The investment cost for the heat pump varies depending on its COP, which is the ratio Coefficient of Performance. Fewer operating hours results in higher production costs. It implies that the production output in kW is spread over a shorter period, resulting in higher costs per kW produced. The capital costs are considered when evaluating the impact on energy costs. The capital costs include the initial investment, profit demand and lifespan. If the production of kW is spread over a longer period, there may occur several costs, increasing the production costs further. The spreadsheet illustrated the relationship between the number of operating hours per year to produce waste heat and how it affected the actual energy cost, considering the capital cost.

Nearby heating grid demand

The first data set from Lyse Neo pertained mostly to the potential case of a low-temperature district heating system without a heat pump system. The data set concerning heat demand for Bjergsted area where the GEC data center is situated, was provided 01st of June 2023. It contained information about efficiency requirements per hour during a year and served as basis for the effect duration curve of Bjergsted presented in the results chapter.

Heat pump supplier data

The second data set from Lyse Neo concerned an investment scenario for a heat pump system making connection to the existing high-temperature district heating a possible solution. Lyse has provided a technical and economic substrate from a heat pump supplier for a potential heat pump solution for utilizing waste heat from data centers to the district heating system. The setup contained two times 1000 kW isobutane heat pumps which is suitable for data centers with temperature order between 30°C to 60°C. Economically the heat pump cost is at 2500 NOK/KW excluded surcharge.

4.1.3. Data from Green Edge Compute

On the 20th of May 2023 Green Edge Compute provided a limited amount of data pertaining to the data center in Stavanger. Due to their active involvement in securing funding for the project, their key resources were constrained, preventing them from supplying additional data or participating in extensive meetings to share their expert experience. Despite these limitations, data provided by Green Edge Compute offers valuable insights into the operations of the data center in Stavanger. While the scarcity of data may present certain challenges, the available information still serves as a foundation for evaluations and conclusions. Green Edge Computes dedication to the data center project in Stavanger is acknowledged. An overview of data received from Green Edge Compute is presented in Table 5. The power consumption of servers in data centers, including auxiliary equipment for air-cooling, is estimated to be about half of the power consumed by the servers themselves. This normally results in a PUE value from 1.5 to 1.6. For the data center in Stavanger the PUE is 1.03. Liquid-cooling systems offer advantages such as being approximately 1000 times more efficient than air cooling and enabling high-performance computing (HPC). Liquid-cooling also reduces power consumption and allows for higher server density leading to space optimization. Liquid cooling generates excess heat which can be utilized. In Stavanger they have primarily used server equipment from Dell. The server equipment and its specifications have a significant role. The temperature endurance for server equipment decides output temperature. Servers from Intel have an optimal operating temperature up to 75℃ [Appendix D].

Table 5 - Data from Green Edge Compute Stavanger.

Information provided from Green Edge Compute for the data center in Stavanger.

Data from Green Edge Compute Stavanger	
Variable	**Value**
Ideal power consumption	4 MW
Average PUE	1.5-1.6*
PUE data center Stavanger	1.03
Efficiency rate liquid vs. air cooling systems	x 1000
Operating temperature servers' liquid cooling [℃]	>75
Max temperature servers' liquid cooling [℃]	90**
Operating temperature servers air cooling [℃]	40
Computing power [%]	40-70
Input temperature cooling system [℃]	30
Heat capture rate [-]	0.9
Future size of data center [m^2]	100-200
Future racks	20-40

**Based on a 1000W server and 500-600W for other equipment*

***May impact warranties and guarantees*

4.1.4. Data from literature

Data from literature is an essential component of the master thesis process. It serves multiple purposes, including establishing theoretical framework, informing research methodologies, providing a comparative perspective, and enhancing the credibility of the research. By exploring existing knowledge and previous studies, a comprehensive understanding of the topic has been gained. Data from literature has been gathered since the beginning of the thesis project start with consecutive progress from January 2023 to June 2023. Important collected data is presented mostly in the literature review and results. Important aspects concerning the topic were also mentioned in the earlier chapters of introduction and background, to establish the thesis context.

4.2. Omitted considerations

To keep in line with the established scope for this thesis, some important external aspects have been omitted from the thesis research. Power prices is a hot topic in Norway currently, as there have been a significant rise in electricity prices over the last years, in contrast with the historical low electricity prices that Norway has been known for. Even though this aspect has not been investigated thoroughly regarding the potential value of waste heat from a data center in Norway, it is important to make note of it. Changes in the power price can have several impacts on the financial and operational aspects of waste heat utilization form a data center. If the power price increases it can lead to increased operational costs. The cost per kW of production will potentially reduce profit margins. An increase in the power price will directly impact on the overall financial performance of a data center. Changes in power price can have a broad implication for the financial performance, operational costs, and the investment decision for development projects. The impact of power price fluctuations is important when evaluating feasibility and profitability of establishing improvement technologies like liquid cooling systems. Perhaps in relation to environmental benefit. This is however not included in this thesis scope, so no further considerations will be included for power prices.

4.3. Uncertainties and bias

The utilization of waste heat from data centers is an area of research that lacks verified testing data. The data required to fully explore the topic is either unavailable, undiscovered, or incomplete. Uncertainties in the thesis research are largely due to the utilization of input data from various sources with varying levels of reliability and completeness, which presents challenges in addressing the specific thesis question. The innovative and niche nature of Green Edge Compute’s concept further compounds the difficulty of obtaining comparable data for validation purposes. The limited ability of relevant data from various sources hinders the ability to ensure accuracy and consistency in the analysis. The data used from the SINTEF study [61], also relies on data derived from literature to some extent, which introduces additional uncertainty.

Data variables

Calculations of PUE vary, as they can be based on either optimal conditions or average values. PUE values obtained from various sources may have different baseline measurements, further complicating the comparability and reliability of the data. Regarding GEC One in Trondheim, a test was conducted to gather key data for analysis, but the results of this test were inconclusive. Consequently, uncertainties arose in the analysis conducted for the Trondheim data center due to the use of test data obtained from different sources. To address uncertainties, measures have been implemented to expand the range of input data and assess the resulting changes. Expert judgement from Lyse Neo and the internal supervisor, as well as professionals in relevant industries, has been employed to navigate these uncertainties to the best of current knowledge. To mitigate the impact of uncertainties stemming from limited date sources, transparency is crucial. Assumptions and limitations of the data are clearly communicated, enabling readers to understand the research’s limitations and the potential implications of uncertainty on the results.

5. Methodology

To answer the thesis question, which explores the potential value of waste heat energy from data centers, a robust methodology is crucial. This methodology considers various factors that influence value of waste heat energy. This chapter presents the methodology developed to investigate and analyze the thesis question. Evaluation of the scope helps to define the boundaries and to focus on the primary objective of the study. This chapter aims to provide a comprehensive and systematic approach to investigate potential value of waste heat energy from data centers and its content is provided through the descriptive stages in Figure 19. The subsequent sections will delve into the specific details of each methodology component.

Figure 19 - Methodology approach.

This figure provides an overview of the robust technology employed to investigate the thesis question and encompasses several key components and stages that are essential for the evaluation.

5.1. Scope

The scope of this study encompasses the investigation of waste heat energy derived from data centers and its potential value. The analysis is conducted through multiple sublevels, each addressing specific aspects of waste heat analysis and utilization. Figure 20 depicts a basic overview of the three scope breakdown sublevels. The first sublevel focuses on calculating crude estimates for waste heat potential and investment. By considering the value of waste heat energy that can be readily transported into heat energy grids, we gain insights into the value of recoverable waste heat. In the second sublevel, the practical feasibility of transporting waste heat through liquid mediums within district heating energy grids is examined. This evaluation provides estimates of the investment costs associated with grid infrastructure required for waste heat transportation. The last sublevels concern the assessment of expected benefits that can be achieved through waste heat utilization. The study investigates the potential effects and benefits, clarifying positive impacts of integrating a waste heat utilization system. The three sublevels are aiming to answer the thesis question “What is the potential value of waste heat energy from a data center in Norway?”.

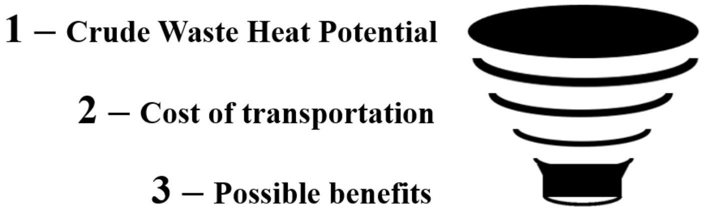

Figure 20 - Scope levels explored in this thesis.

The funnel shape represents the expected diminishing output when considering limiting factors.

5.2. Primary objective

The primary objective of this thesis is to answer the question: “What are the potential value of waste heat energy from data centers in Norway?” A focused screening for a data center in Norway is done and utilized with available data to analyze the energy consumption and possible waste heat available from data center operations. A theoretical integration of waste heat recovery is evaluated and energy- and emissions savings are taken into the value consideration. Consequences of the innate qualities of heat energy result in energy dissipation over distance and time and will affect the potential value. Waste heat with higher temperature holds more energy and will have a broader and deeper utilization span. The scenario of a direct waste heat supply system is therefore the most interesting case. Where waste heat is supplied to a nearby heat energy grid which eliminates the use of auxiliary heat pump systems to boost the waste heat temperature. Heat pump systems are expected to be a major additional cost and will be investigated superficially in later sections. As not all waste heat energy is created equal, it is important to evaluate the waste heat temperature from the data center, and the actual output temperature that is realistic for end-users. The main considerations concern existing technology, but comments are included on the expected future evolution and potential. Together with the expectation of an established liquid cooling system this scenario is expected to present with a larger waste heat recovery potential and a broader utilization span for end-users.

5.2.1. Collaborations

To obtain an answer to the primary objective several connections were established to enhance data quality and get industry insights. Collaboration with Green Edge Compute data center and Lyse Neo power company was paramount to be able to provide quality answers to the thesis question. To fully understand the possible benefits of waste heat utilization it is useful to understand the different perspectives involved. From the point of view of the data center company, utilizing waste heat can reduce environmental impact and may give a competitive and economical advantage. To achieve these benefits, research is necessary on end-users and their energy needs, as the utilization of low temperature waste heat is limited by the usage potential. It is also important to evaluate the environmental and economic benefits in relation to the investment and maintenance costs. The environmental benefits are determined by waste heat utilization, and waste heat utilization will vary depending on the economic situation and power market. To properly evaluate the waste heat potential, it is important to consider the theoretical competition in the power market by other viable energy sources.

Lyse Neo

This thesis is written in collaboration with Lyse which is an energy company in Rogaland. Lyse operates within several different business areas, including power, district heating, infrastructure, and telecommunications. Their subsidiary company Lyse Neo specialized in business development within the energy sector and are actively working towards utilizing local resources. They offer a range of services including consulting for clients within the energy sector, including the data center company Green Edge Compute. Lyse Neo has a current connection to Green Edge Compute regarding a specific data center in Stavanger city [71].

Green Edge Compute

Green Edge Compute came to life about six years ago, starting with a feasibility study. The concept has been adapted to fit modern cities of today and is focusing on Nordic cities. Their first data center was recently developed in Trondheim [29]. The same concept was developed for a data center in Stavanger, in collaboration with Green Edge Compute Norway [45]. CGI is working with IT and business consulting services and is one of the biggest companies in the world [72]. Green Edge Compute has contributed information considering the data center planned in Stavanger. Establishing the world´s most sustainable data center in Stavanger is a collaboration between CGI and Green Edge Compute. It concerns the specific data center that is considered in this thesis [45]. The sustainable data center has been established in CGI´s current premises, at Bjergsted in Stavanger. Green Edge Compute has a vision to develop "green data centers in urban areas with innovative cooling technology that accommodates optimal use of excess heat and enables efficient energy utilization" [29]. Scientific research forms the basis for Green Edge Computes' contribution to technology development. Green Edge Compute utilizes traditional data center knowledge as a starting point and makes modern green data centers [29].

5.3. Thesis stages

The stages of thesis progression show the planned approach on how to achieve the thesis objective is presented in Figure 21.

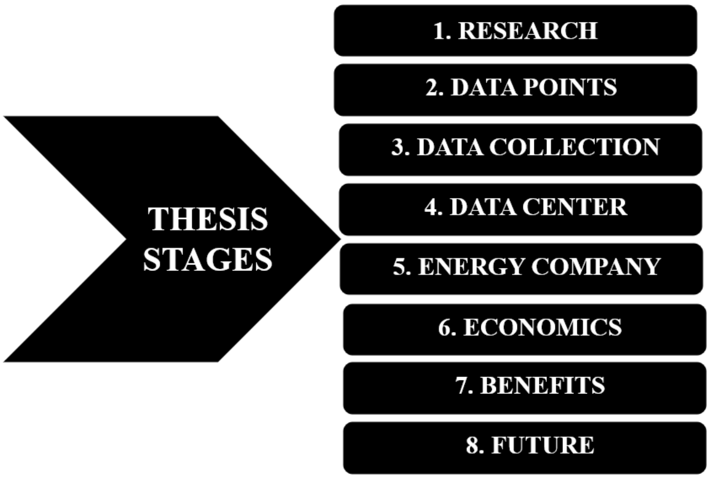

Figure 21 - Thesis stages overview.

The thesis objective is achieved by the planned approach of progression to evaluate potential value of waste heat energy from data centers.

1. RESEARCH
   Obtain relevant and updated information about data centers, waste heat and district heating systems from research. Review the status of energy systems. Investigate the energy situation in Norway at current time and in the future. This research requires independence along with important collaborations and judgement experts.

2. DATA POINTS

   Decide on what data points are needed to establish an estimate on the energy- and emissions savings as benefits of waste heat recovery and integration with waste heat energy distribution systems.
3. DATA COLLECTION

   Collect defined and relevant data from Green Edge Compute data center, Lyse Neo energy company and from quality literature.
4. DATA CENTER

   Investigate operational data from GEC One and Green Edge Compute data center in Stavanger. In areas where data is missing, knowledge and numbers from literature and best practice estimations has been applied.
5. ENERGY COMPANY

   Analyze possible distribution systems based on possible temperature ranges from the data center, existing infrastructure and distance between the end-user and the data center. Investigate the amount of waste heat that is realistically recoverable and transportable from data centers. Evaluate distribution feasibility in scenarios for low temperature waste heat and high temperature waste heat.
6. ECONOMICS

   Economic research for the cost-efficiency of the waste heat utilization system theorized for data centers. The economics behind waste heat energy recovery systems and needed infrastructure will in part reveal the degree of feasibility. The economically realistic output temperature will limit possible end-users, and in turn affect the overall benefits and positive environmental impact. Evaluate the value of economic ripple effect for society.
7. BENEFITS

   What are the benefits of integrating a waste heat energy utilization system for the data center. Benefits are evaluated from evaluation of value creation based on potential waste heat energy from data centers. Other benefits from waste heat recovery and integration with waste heat energy distribution systems are included, also considering societal and environmental benefits.
8. FUTURE

   What part does waste heat utilization have in the future energy mix where renewable energy sources are on the rise. Evaluation of possible incentives and regulations that encourage the data center industries’ incorporation of waste heat recovery and waste heat distribution. Changes in technology will have an evolution potential that may affect the degree of feasibility of a data center waste heat utilization system. Especially concerning the degree of available crude waste heat.

5.4. Data collection

The plan for collection of data ensured relevant and quality input data and makes it possible to replicate easily in future research. Input data is collected from the specified data center in Stavanger, from the stated regional energy company and from relevant and quality literature. Studies developed by institutions like NVE and SINTEF, and relevant journals are necessary to produce estimates for the data center in Stavanger. This is because there is a lack in operational testing data, as testing phases for waste heat energy potential are set in the future. Independent research was conducted to fill the footprint of missing data.

5.4.1. Input data

Input data is needed to perform analysis on waste heat potential, distribution feasibility and expected benefits. Input data have three origins, Green Edge Compute´s data center in Stavanger [Appendix D], the energy company Lyse [Appendix E], and relevant literature. All input data which was aimed to overtake through the data collection are listed in Table 6.

Table 6 - Table showing most important metrics for calculation input data including designated quantity.

FROM DATA CENTER		
Key metric	**Time scale**	**Quantity**
Computational power consumption	Daily, Weekly, Monthly, yearly	MW
Data center energy consumption	Daily, Weekly, Monthly, Yearly	MW
Data center emissions	Monthly, Yearly	Kg CO_2 equivalents
PUE	Now, Future Goal	%
ERF	Now, Future Goal	%
Data center heat energy supply	Daily, Weekly, Monthly, Yearly	MW
Data center waste heat production	Daily, Weekly, Monthly, Yearly	MW
Cooling power consumption	Daily, Weekly, Monthly, Yearly	MW
Investment cost liquid cooling	Initial Cost, Maintenance Cost	NOK
Investment cost air cooling	Initial Cost, Maintenance Cost	NOK

FROM ENERGY COMPANY		
Key metric	**Time scale**	**Quantity**
Investment cost nearby heat energy grid development	Initial Cost, Maintenance Cost	NOK
Heat loss district heating systems	Distance / Time	ΔT
Existing and future end-users	Now, Future	Number of consumers
FROM LITERATURE		
Necessary and possible temperatures for end-users	Daily, Weekly, Monthly, Yearly	°C
Missing data from the data center or power company	All times scales mentioned	All units mentioned

5.5. Data analysis

The intended quantitative research method for this study relied on the availability of comprehensive data sets to effectively address the research question. Due to limitations such as incomplete testing for GEC One and resource constraints and time pressures faced by Green Edge Compute concerning the data center in Stavanger, an alternative approach was adopted to collect independent data. Consequently, the quantitative approach was adopted to collect data independently. The quantitative study heavily relied on the information obtained from relevant literature sources and data provided by Lyse Neo. To broaden the scope of the research, a qualitative study was conducted on a smaller scale, involving in-dept discussions with experts to gather their professional insights and judgements. In terms of data analysis, statistical analysis method was considered, including descriptive statistics, which facilitated the transformation of large and complex data sets into a more manageable subset of values that conveyed a clearer and more intuitive understanding [73]. Descriptive statistics were applied to the data sets acquired from Lyse Neo, enabling an evaluation of the input data. Heuristic method was implemented to the study as the last constraint to quickly gather appropriate overview [74]. This method is utilized to leverage knowledge and experience from collaboration participants that hold vital insights on the industry. The knowledge and experience extracted for this thesis were obtained through experts who have relevant expertise in the subject matter. To broaden the understanding and knowledge of professionals working in this specific and emerging field, meetings were conducted with key individuals at Lyse Neo [Appendix E], SINTEF [Appendix G] and Statkraft [Appendix H]. These meetings provided valuable perspectives, new ideas and insights into future possibilities from a research perspective, as well as offering insights from a distribution standpoint. By engaging with relevant individuals, a comprehensive understanding of the business landscape, potential challenges, and the scope of the thesis question within the field was acquired.

5.6. Economic evaluation and estimation methods

The first section of the economic evaluation focuses on investment evaluation. Investment costs have been provided by Lyse Neo, serving as a reliable source for assessing this data. The second section involves the assessment of economic opportunities related to social measures, infrastructure, and operational costs. This evaluation serves to gauge the potential value of waste heat energy utilized from data centers. To gather relevant data and insight, research is conducted, drawing from various sources and best practices in field. The economic perspective is carefully considered throughout the evaluation process. Crude investment estimation is performed for liquid cooling for data centers. Calculation of potential value of waste heat energy contains more than just economic measures. Analysis of investment costs for transportation not carried out in this thesis but is necessary when considering the total infrastructure costs. Benefits include direct impacts on the power grid, and indirect impacts from the environmental perspective. To ensure proper estimations, cost-estimation methods are utilized, leveraging the Project Management Book of Knowledge [75]. General investment analysis principles, economical concepts and expressions are also leveraged to tie estimations together in a meaningful and truthful manner.

5.7. Methodology evaluation

The methodology evaluation section assesses the chosen scope and method in this study. It examines data constraints and the steps taken to address them. The section evaluates the availability, accuracy and credibility of the data utilized. The evaluation focuses on four key aspects that play a crucial role in assessing the reliability and validity of the research methodology employed. The pivot Table 6 is a listing of quantitative data needed for the study and is not exhaustive to answer the thesis question. A small-scale qualitative approach reaching out to anonymous judgements experts was necessary to widen the point of view and achieve the wanted fortitude to the study.

5.7.1. Choice of scope and methods

To achieve the research objective, a multi-level approach was adopted. The first sublevel involved estimations of crude waste heat potential. The second sublevel focused on examining the practical feasibility of transporting waste heat within district heating energy grid. Lastly, the third sublevel encompassed expected benefits. The choice of scope and methods refers to the careful selection of the research boundaries and the approach adopted to address the research objectives. This evaluation examines the appropriateness of the chosen scope and the thesis framework.

5.7.2. Thesis framework

The methods used to answer the research question are based on available data concerning the different elements that are analyzed. By using a structured screening framework that details progress and stages it makes it easier to relay the underlying phenomena more readily. The feasibility of utilizing waste heat energy and the possible benefits for data centers in Norway is explored by analyzing literature and datasets that are available and relevant.

Topic relevancy

The chosen topic is very relevant in society now, and at current times waste heat utilization is mentioned in debates, energy plans and by key actors in the energy sector. This type of energy system is a possible future energy solution also for larger scale operations that holds unknown potential. The increased relevance for this topic is due to a multitude of events. Momentum onset was perhaps because of the energy crisis in Europe after the Covid 19 pandemic. The momentum is still growing and may be exacerbated by emerging power grid constraints that arise from increased societal electrification. There is a definite discernable momentum for waste heat energy recovery technology implementation. Lyse and Lyse Neo are currently exploring optimal societal energy solutions for the future to minimize the environmental footprint and strain on the power grid. It is this relevancy and possible environmental impact potential that spurred the choice of topic, which then consequently informed the choice of methodology.

Future importance

Future trends underline the importance of this topic. Especially considering increased electrification. In many industrial countries the electrical grid capacity may not evolve rapidly enough to keep up with societal electrification and power needs. The green shift in technology innovation and new subsidy regulations may serve as the primary driver towards this accelerated electrification. That is why waste heat recovery may prove to be more valuable in the future, as low-grade heat energy may need to fill a larger relative proportion of the energy-mix supplied to consumers. In this context low-grade heat energy has limited usage areas, while high-grade heat has near unlimited usage areas concerning heating needs. By utilizing waste heat energy, the capacity constraints on the electrical grids may be alleviated. The local surplus of waste heat energy that exists in many societies usually coming from industrial processes, supports the need to recover and extract this energy value.

5.7.3. Data constraints

The first point of defined importance when evaluating methodology concerns considerations in Figure 22, methodology and data constraints. To prevent methodological errors resulting in conclusion bias, the observed results are discussed as to what extent it represents the population and society in question. To ensure a high degree of confidence the methodology in this thesis is chosen to reflect the methods most used in the energy sector and within this specific topic. The study design is thus aligned so that results and uncertainties are comparable to other studies. In total this would accumulate a strong foundation for internal validity. Reflections on causality and relationships are presented in later sections using statistical analysis, and influencing factors are discussed to provide transparency for the results presented. Constraints regarding data access and time have been taken into consideration, evaluating the risk for getting access to required data. Where datasets are not provided by the collaborating parties, namely energy company and datacenter. Literature based data and best practice estimations are used and clearly stated in the text when these data gap mitigations are used.

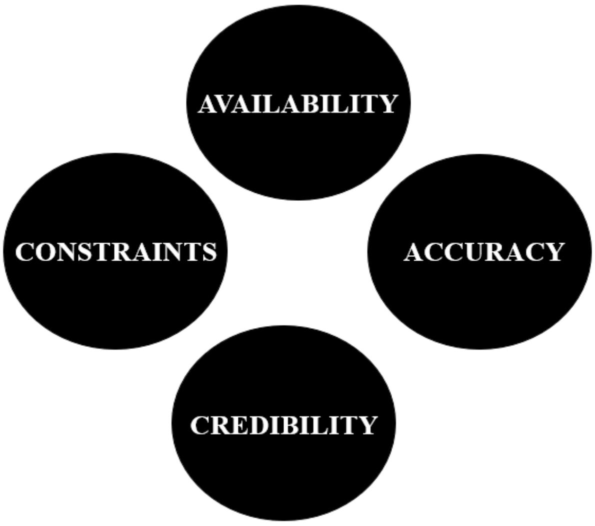

Figure 22 - Methodology selection considerations.

Strongly inspired by Figure 4: Methodology Selection considerations presented in lecture note week 1 in the subject IND550 spring 2022, made by Sindre Lorentzen.

5.7.4. Data availability and accuracy

The second and third point of defined importance when evaluating methodology is given by Figure 22, and concerns methodology, data availability and data accuracy. Performing the methodology steps in a structured manner was important to ensure having a proper overview to better give a granulated conclusion to the research question. The data needed is obtained in collaboration with Lyse Neo. Lyse Neo facilitated data collection by giving access to their primary research data and acting as a relay medium between researchers and data center. The datasets have been collected from a wide range of sources. This includes data from the literature review research section presented earlier. Literature data fills the missing parts in the input data from collaborators. This is in part due to uncertainty in the preliminary datasets and generally missing data from the data that was available and accessible pertaining to this specific case study. It is important to highlight that most of the data used in this thesis is from other research sources and is not obtained directly by experimental testing. The influence on experimental design is therefore absent, meaning total reliance on choices made by other researchers. Joining input data with literature data affects the uncertainty of results. Validity of external testing and measurement validity consequently holds a higher degree of uncertainty. The degree of external validity therefore limits other researchers in using the results obtained in this thesis directly. It is only recommended to utilize conclusive remarks from this thesis within similar contexts, as it pertains to the specific societal situation described previously. Results will however depict the prevailing phenomenon and the framework for potential assessment presented in this thesis are readily repeatable.

5.7.5. Data credibility

The fourth and last point of defined importance when evaluating methodology is given by Figure 22, and concerns methodology and data credibility. By utilizing a plethora of data credibility evaluation frameworks, a thorough evaluation of data credibility is possible. Data credibility was established through multiple means including the use of reputable sources such as the SINTEF study [61] and communication with expert judgment [Appendix E, Appendix G, Appendix H]. Data constraints and availability posed challenges. As the research within the subject for the research question is scarce, estimates and theoretical potential bring out the uncertainty of the study.

6. Results

This chapter unveils the discoveries obtained from research and analysis by methodology implementation. Significant emphasis lies on data points derived from literature investigation, because of lacking test data. The presented results serve as the basis for later discussion by presenting potential waste heat utilization pathways and benefits that may emerge. The thesis context is the data center industry evolution towards more sustainable and efficient practices. Waste heat utilization from data centers has potential for creating value. Exploration of waste heat value encompasses analysis of waste heat potential, distribution possibilities, and possible resulting benefits and effects. The concise justification for why this line of research is important concerns the need for future energy solutions that are in line with increased digitalization and electrification. The increasing number of data centers reflects the demand for societal digitalization, and with a large energy consumption it should be an area of research focus. Data center power consumption puts strain on the power supply grid, which is why it makes sense to do screening on the potential for utilizing the data center waste heat that is generated. Waste heat energy may replace electricity supply to a certain extent, reducing the net strain from data centers on power grid supply. High temperature waste heat already has purpose in district heating systems, but not much research exists on utilization of low-temperature waste heat from data centers.

6.1. Main findings

The potential value of waste heat energy from the data center in Stavanger depends on many factors and may have unknown effects in the future. Key insights from the thesis research concerns important aspects on the technical and economic basis for waste heat utilization. The main findings pertain to the energy recovery and distribution pathways of waste heat energy that enables reuse of excess heat energy from the data center. The effect of modern liquid-cooling systems and their impact on data center power consumption and waste heat recovery possibilities are illuminated by the increased output temperatures. Which is a key factor for the value proposition utilizing waste heat from the data center in Stavanger. A simplified overview of the energy pathway for waste heat energy was presented earlier in Figure 9. Resulting insights for each pathway step are consecutively presented in the following sections. A simplified illustration in Figure 23 highlights the findings that is covered.

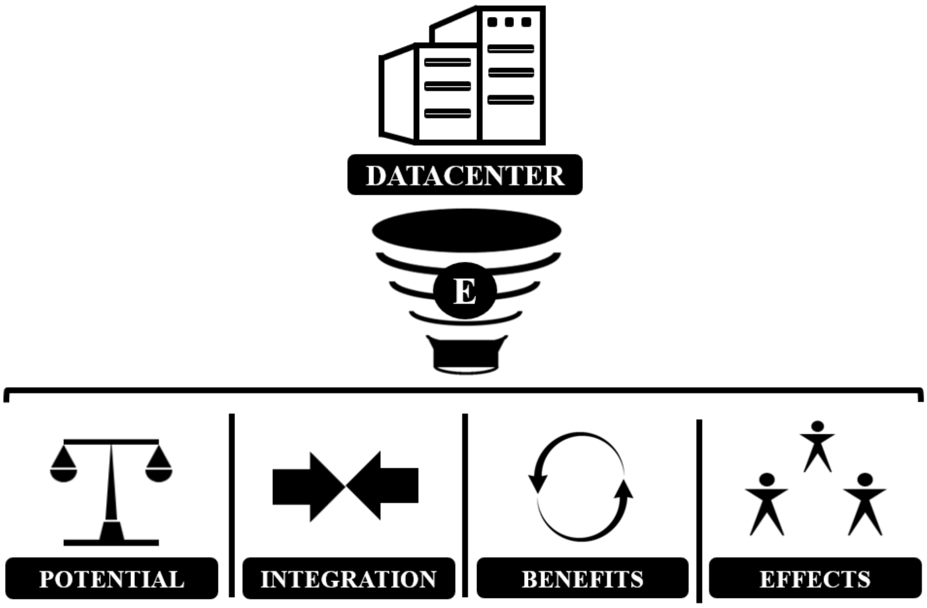

Figure 23 – The main areas of investigations provide the main areas of findings in this thesis.

The scope definition and methodology provided the frame for investigation. Findings include waste heat potential considerations for various contexts, integration possibilities to energy grids, possible utilization benefits, and macroscopic effects that might find place as a result.

General overview

By utilizing the power of liquid-cooling technology, data centers experience a substantial increase in efficiency enabling them to deliver high-performance computing capabilities which previously was unattainable with air-cooling. This advancement turns into tangible benefits such as reduced power consumption, increased server density and more compact infrastructure. This allows data centers to maximize their operational capacities while minimizing their environmental footprint. In part by the potential for waste heat utilization. By managing operating temperatures and exploring alternative cooling solutions such as liquid cooling, data centers can achieve higher efficiency levels while ensuring longevity and optimal performance of their server components. Which also provides higher coolant output temperatures, and with higher grader energy there exists an increasing potential for feasible waste heat utilization. Collaboration within the data center industry has great value. Some data center companies build and own facilities which they rent to IT companies or directly to IT clients. Sharing resources and infrastructure can reduce costs for both facility providers and tenants. The value proposition of waste utilization from data centers is the primary focus for the thesis. Value is created in many forms with different stakeholders involved. The results chapter provides comprehensive information regarding these aspects.

6.1.1. Available waste heat potential

The available waste heat energy from data center operations depends on many factors. The crude waste heat potential calculated from the expected heat capture rate tells part of the story and is subject to limitations concerning distribution solutions. Available waste heat energy is the amount of energy recoverable from data center operations, while the accessible waste heat energy is the amount of energy on the other side of energy grid integration.

Data from Lyse Neo

To provide waste heat for distribution, planned liquid cooling systems are necessary for Green Edge Compute’s data center at Bjergsted. The role for Lyse Neo in the possible implementation of a waste heat utilization system for the data center near Stavanger city center concerns feasibility evaluations and possible distribution infrastructure. Estimates on investment cost for liquid cooling test equipment and resulting waste heat produced for test scenario are presented in Table 7 and holds values from communications with Lyse Neo.

Table 7 - Crude estimates for liquid cooling test implementation and waste heat energy test potential.

Crude investment estimate	Crude waste heat estimate
10 MNOK	100 kW*

* Green Edge Compute estimated 100-200 kW power capacity as a starting point for the data center in Stavanger

Data from Literature

From Table 3 in the literature review, the estimated IT-power was presented by SINTEF as 2000 kW for the GEC data center in Trondheim [61]. Considering the maximum starting power capacity for the data center in Stavanger at 200 kW, there is a tenfold difference.

Data from Green Edge Compute

To understand the waste heat energy potential for the new data center in Stavanger, GEC referred to the SINTEF study relating to their Trondheim data center [61]. Data presented in this study marked as data from GEC in 2022 serves as the basis for our evaluations concerning data center operations. Estimates on the specifications for the data center in Stavanger are based on communications with Green Edge Compute. Expected specifications are presented in Table 8.

Table 8 – Expected initial specifications for the GEC data center in Stavanger.
Together with the final ideal specifications.
Data received from communications with Green Edge Compute.

	Data center size	Power consumption	Rack type	Number of racks	Number of servers
Initially	50 m^2	100-200 kW	48U	1	40
Ideally	100-200 m^2	2000-4000 kW	48U	20-40	1600-3200

From communications with Green Edge Compute, an estimated PUE of 1.03 can be achieved for their data center models. For the future ideal maximum scenario with 4 MW total power consumption, the estimated IT-power consumption would be approximately 3883 kW. From communications with Green Edge Compute, an ERF value of 90% is considered maximum for their solutions. Calculating with the 90% ERF the waste heat potential would be approximately 3600 kW. This equates to approximately 31.5 GWh of waste heat energy yearly considering full capacity of 8760 hours. To put this into perspective, Forus Energigjenvinning as primary energy source for the district heating grid in Stavanger can supply up to 225 GWh for heating purposes each year [76]. Which means that the potential for waste heat energy considering complete harvesting from the data center in Stavanger at full capacity in the future is approximately 14% of the current maximum supply of waste heat from Forus Energigjenvinning. Primarily waste incineration covers approximately 15% of the heating needs for the three nearby municipalities of Sola, Stavanger, and Sandnes [76]. Using these values, we get that approximately 2% of heating demand for the three municipalities near Stavanger could be covered if all waste heat energy from the data center could be utilized. This is the maximum potential value of waste heat from the data center in Stavanger only considering heating supply. Efficiency metrics for this ideal scenario are summarized below.

Table 9 - Summary of common efficiency metrics for ideal data center scenario for GEC in Stavanger.

PUE	ERF	ERE
1.03	0.9	0.103

PUE (1), ERF (3), and ERE (4) describe important ratios concerning power consumption and waste heat recovery. Note the 0.103 in ERE, meaning the unused energy potential as ratio over IT-power consumption. What this means is that if a larger fraction of the total energy consumption goes to IT-components or a larger fraction of waste heat is reused the ERE diminishes. In essence this is a positive efficiency trend for a data center.

6.1.2. Feasible integration solutions

The two main solutions for transforming available waste heat energy to accessible waste heat energy are presented in Figure 24.

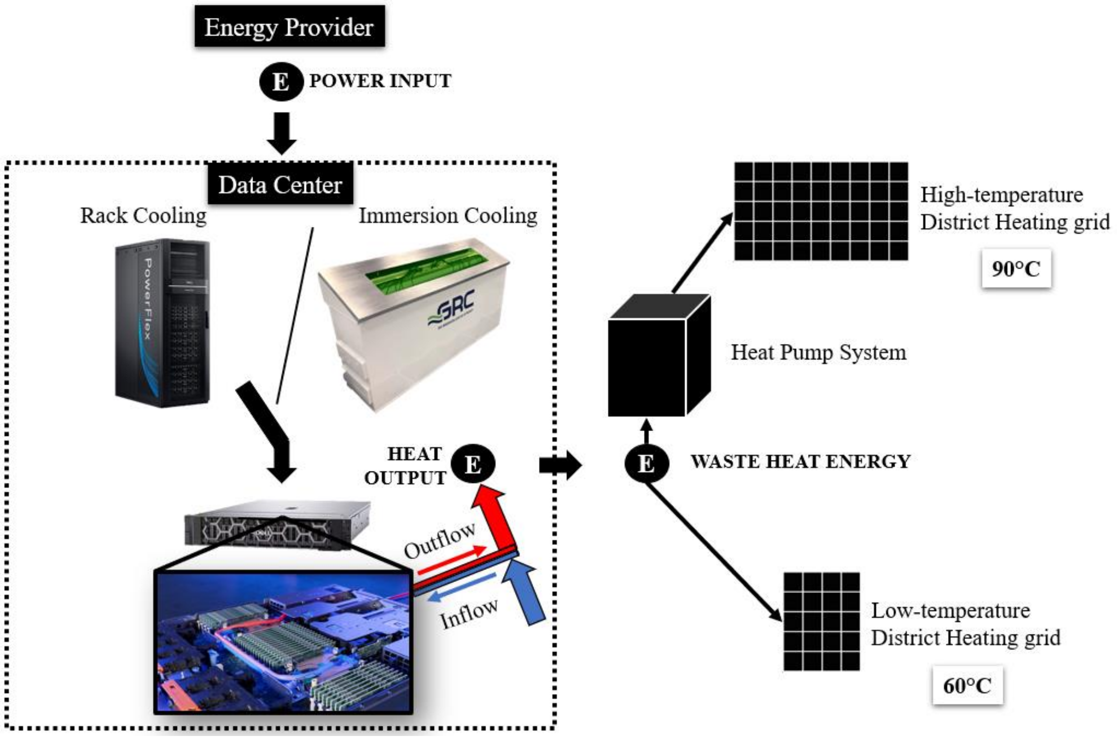

Figure 24 - Simplified overview of distribution solutions.

Includes the pathway from power provider to data center and potential end-users in an energy grid. The main outlined pathway goes through the rack cooling system reflecting the current cooling technology implemented by Green Edge Compute [61].

Includes the pathway from power provider to data center and potential end-users in an energy grid. The main outlined pathway goes through the rack cooling system reflecting the current cooling technology implemented by Green Edge Compute [61]. From literature review and from key insights from industry actors, two main pathways possible for distributing waste heat energy to potential consumers are presented as feasible. In principle the waste heat energy can either be transported through a high-temperature district heating grid or a low-temperature district heating grid. The existing district heating grid near the data center location in Bjergsted is a high-temperature district heating grid. Lyse Neo has developed separate low-temperature energy grids before, which would make it possible to distribute lower temperature heat energy. A type of hybrid solution was also explored as a final third possibility.

Low-temperature district heating grid

A low-temperature district heating grid for nearby areas is a possibility that might exclude the need to elevate the waste heat energy output temperatures. Meaning that the energy from the emitter source being the data center in Stavanger, can be utilized directly. It is important to evaluate the distribution solution closely with its effects on the waste heat potential. The amalgamation of literature data and meeting notes allows for evaluation of the waste heat potential for the data center in Stavanger. Literature data from the SINTEF study [61] concerning the GEC One data center in Trondheim together with information from communications with Green Edge Compute [Appendix D] enabled the possibility of more accurate waste heat potential evaluation. As presented in the previous section, the data center specifications affect the crude waste heat potential. The operational specifications for the data center in Stavanger are however not yet fully defined, but estimations help to understand different scenarios and their effect on the waste heat potential. To discern the variable waste heat potential for different scales of operation a scenario overview was generated for the data center in Stavanger in Table 10. The data from GEC One [61] makes it possible to generate a kW per m^2 ratio and rack per m^2 that was utilized to find estimates on power consumption and rack numbers for the different size scenarios.

Table 10 - Theoretical specifications for future operations of data center in Stavanger.

Includes area, IT-capacity, operative racks, and estimated PUE. Based on data from the SINTEF study [61] and information from GE Compute [Appendix D].

Scenario 1			
Data center size	**IT-power consumption**	**Rack number**	**PUE**
40 m^2	635 kW	6 racks	1.03
Scenario 2			
Data center size	**IT-power consumption**	**Rack number**	**PUE**
200 m^2	3173 kW	30 racks	1.03
Scenario 3			
Data center size	**IT-power consumption**	**Rack number**	**PUE**
240 m^2	3808 kW	36 racks	1.03

IT-power consumption in Table 10 is estimated based on PUE being 1.03, which was the estimated best case PUE from communications with GE Compute. Utilizing the ratios constructed from the SINTEF study [61] three scenarios were established. The reason for choosing 40 m^2, 200 m^2, and 240 m^2 as data center sized is due to the building constraints in Stavanger. According to GE Compute, the initial size of the data center in Stavanger will be 40 m^2, which makes this a suitable starting point. From communications with GE Compute, there are extension possibilities for their operations in Stavanger. There is another room in the same building with appropriate infrastructure, as there have been data center operations there before. This room is over 200 m^2. It is however unclear if GE Compute will move their operations to that space in its entirety or if they will expand to include this room. Either way, scenario 2 and 3 was naturally chosen as 200 m^2 and 240 m^2. Scenario 2 depicting a situation of excluding transition, and scenario 3 a situation of including expansion. Utilizing the reported heat capture rate of 96% from GEC in 2022 [61] it is possible to calculate the annual waste heat potential for recovery. From communications with Green Edge Compute in 2023 an ERF of 0.9 was stated as feasible, meaning that 90% of the total energy consumption is reused [Appendix D]. Theoretical values were calculated from the heat capture rate and ERF for each scenario and are presented in Table 11. Important to separate the two values, as the heat capture rate is defined as the percentage of waste heat from IT-power consumption that can be captured. ERF, however, is the percentage of waste heat from the total power consumption that is reused.

Table 11 - Theoretical waste heat potential for future operations of data center in Stavanger.

Includes recovered waste heat for both 96% heat capture rate [63] and 90% ERF [Appendix D]. Assumption is full load hours all year of waste heat capture, with yearly hours being 8760. Utilizing the scenarios defined in Table 10.

Recovered waste heat	
With 96% heat capture rate	**With 90% ERF**
Scenario 1	
5337 MW	5153 MW
Scenario 2	
26683 MW	25766 MW
Scenario 3	
32020 MW	30919 MW

As seen from the table above, an estimated ERF of 90% will yield a smaller quantity of reused energy than the heat capture rate at 96%. From communications with GE Compute the estimated capacity for the data center in Stavanger will be around 2 MW, but they will have a security margin for up to 4 MW [Appendix D]. Utilizing an estimated PUE at 1.03 and 96% heat capture rate [61] we get 16329 MWh of recovered waste heat for a 2 MW power capacity data center. For the 4 MW scenario we get 32659 MWh of recovered waste heat. In the previous section approximately 31.5 GWh of waste heat energy yearly was achieved by utilizing a 90% ERF for calculations. For the 4 MW with 96% heat capture rate, 32.7 GWh of waste heat energy yearly is possible. For all scenarios it is assumed that the full load hours of operations are 8760. The total amount available for supply annually to the district heating system in an ideal situation is 32.7 GWh.

Nearby heat demand

The solution of a low-temperature or high-temperature district heating integration to distribute waste heat energy from the data center in Stavanger either way relies on heat demand of the area. The data center in Stavanger is situated in Bjergsted, of which Lyse Neo has provided demand data. A low-temperature district heating system will be very dependent on the nearby area, whilst high-temperature district heating integration is expected to be able to supply to areas over longer distances. This is because of the higher energy grade. As such the direct supply solution by utilizing a low-temperature grid is more vulnerable to the demand profile for the nearby area. To get an understanding of the annual energy needs an effect distribution curve for the nearby heat demand at Bjergsted was created. Also called a load duration curve. The data basis from Lyse Neo is the overall production of the existing energy central at Bjergsted consisting of three primary gas boiler units. The dataset included energy production for these units for the entire year of 2021. From the dataset the energy production scenario for Bjergsted area can be visualized, which reflects the energy demand variation.

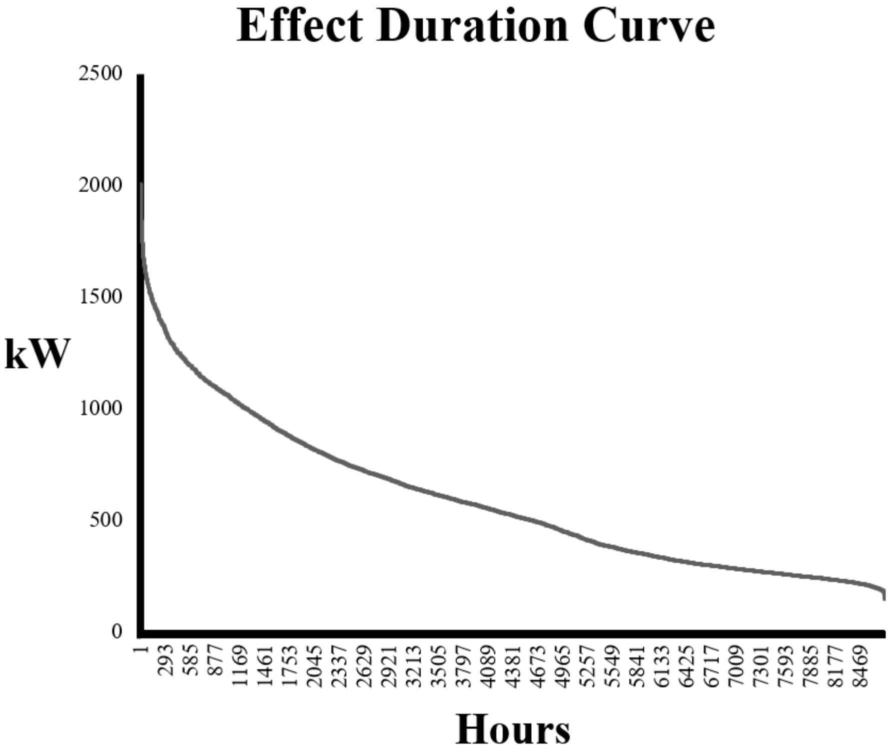

Figure 25 - Load duration curve of Bjergsted in 2021.

Showing effect distribution and duration curve for a designated nearby heating grid in Bjergsted for a year. Base load spans the entire year, medium load spans a lesser part of the year, and peak load only covers the highest effect needs during the year. Raw data from the energy central was provided by Lyse Neo.

The duration chart depicted in Figure 25 was created for the heat produced in the existing nearby heating grid at Bjergsted in 2021. The local heating grid is today a separate system from the district heating grid. It will however according to Lyse Neo be part of the district heating grid in the future. What the figure shows is the load duration curve for Bjergsted, with peak load up to the left and base load underneath. From communications with Lyse Neo such figures can be interpreted as winter to the left and summer to the right. Meaning that there is less heating demand overall in the warmest months, therefore covered only by primary heat energy source. For the coldest months there exists demand above that of the base energy load, calling for additional sources of energy to cover the demand peaks. To explain the figure to greater detail it can be useful explaining a district heating duration curve containing more energy contributors. Below is a how a duration curve can look like in 2030 for the district heating system with Forus Energigjenvinning as primary heat energy source.

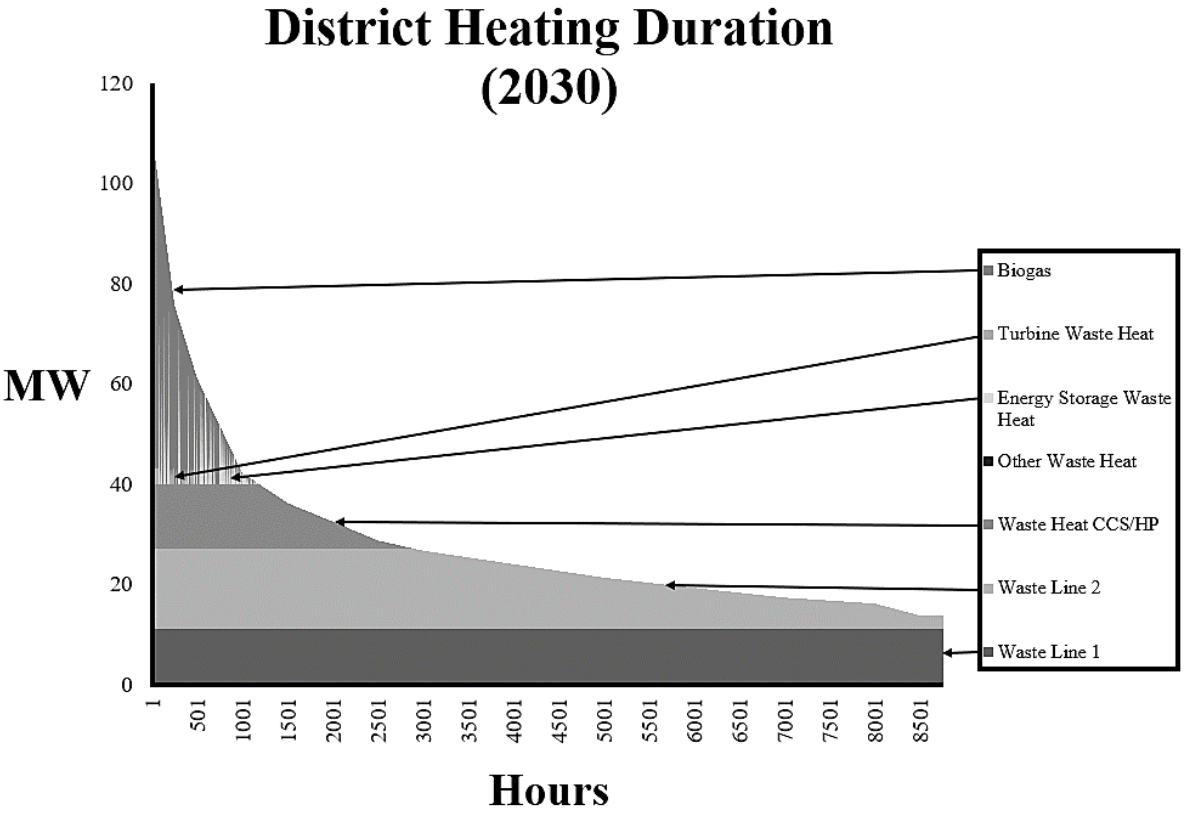

Figure 26 – Theoretical load duration curve for the district heating grid in Stavanger in 2030.

Showing effect distribution and duration curve for the entire grid including all contributions to heat energy supply for a year. Base load spans the entire year and consists mainly of the waste incineration lines at Forus. Medium load spans a lesser part of the year and includes in part waste heat from carbon capture and storage as well as heat pump. And peak load covers the highest effect needs during the year with major contributions from energy storage, turbine heat and biogas. The other waste heat is where the data center in Stavanger comes in. Raw data and duration curve template provided by Lyse Neo.

Here the production to fill the entire grid demand will consist of a multitude of energy contributors. The base load would be covered by waste incineration heat and the middle load by carbon capture and storage waste heat together with heat pump waste heat. Peak load would in essence be covered by turbine waste heat and biogas. There is however momentum to include other sources of waste heat to cover demand, in particular peak demand.

High-temperature district heating grid

Integration with a high-temperature district heating grid depends on a variety of factors. As stated above, there are specific demand profiles for needed energy effect duration. For the district heating system in Stavanger, Sandnes, and Sola the main energy contributor is the incineration plant at full operation the entire year. As this incineration has a limit, this would be the limit in vertical axis for the load duration curves, meaning that the primary contributor will cover base load only. This means that they cannot incinerate manyfold the operations of today for cold winter days. The question is, can waste heat energy from the data center in Stavanger contribute to the load duration profile of the district heating system in Stavanger in a meaningful way. To explore the value of integration with the existing district heating grid, it is useful to have a theoretical load duration curve for the ideal data center situation. Data center load duration curve is depicted in Figure 27, which is a theoretical simulation leveraging the abilities of the Microsoft Excel Add-In: Solver [Appendix I], together with a tailor made Visual Basic for Applications Subroutine Macro Code Segment [Appendix J].

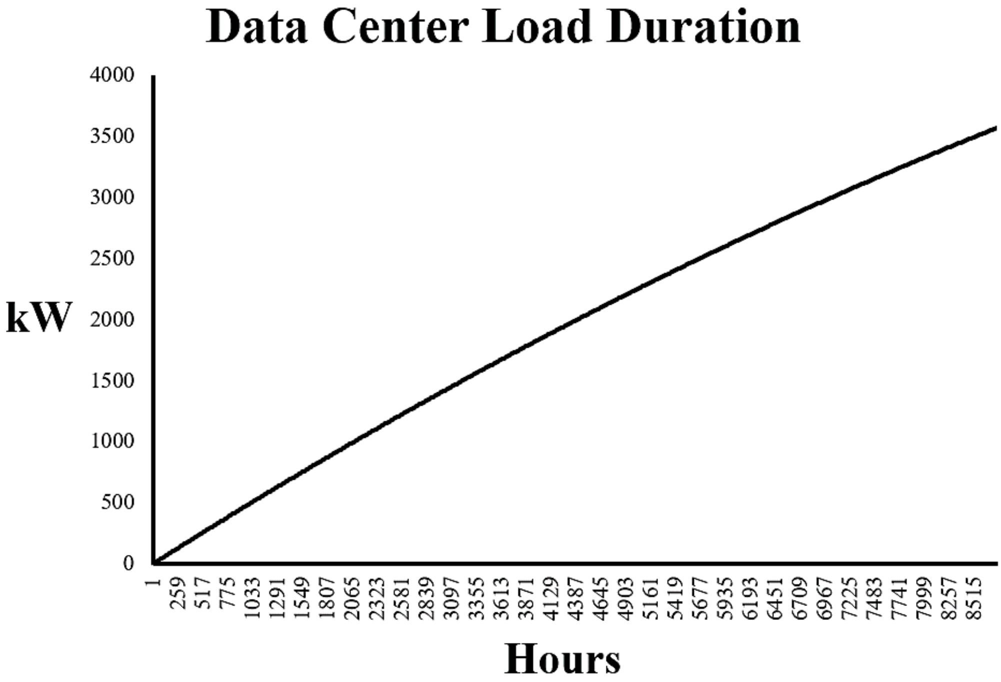

Figure 27 - Load duration curve for the data center in Bjergsted.

Depicting a duration curve for a year in a hypothetical integration solution with the existing district heating grid in Stavanger. Basis is 50% waste heat utilization as per dialogue with GE Compute, with 100% being 32.7 GWh of waste heat energy as yearly maximum. This reduction is because the district heating grid cannot utilize the data center waste heat in the coldest months. Since the supply depends on season, it cannot work as base load. Feasible purpose in the district heating grid would be peak load.

The most feasible high-temperature district heating grid available for waste heat energy transportation is the existing district heating systems in place in the Stavanger area developed by Lyse. To modulate the waste heat potential from the previous scenario evaluations it is important to incorporate actual full load hours that are feasible for waste heat recovery input into the district heating system. A theoretical supply profile was presented in Figure 27. According to Green Edge Computes’ dialogue with Statkraft Varme in Trondheim they estimated to be able to utilize the recovered waste heat for half of each year. Meaning approximately six of the coldest months. The theoretical duration curve aimed to depict a smooth boundary between the different seasons of the year, which is a more feasible scenario as the environmental temperatures in Stavanger do not flip from winter to summer within days usually. Based on the previously evaluated waste heat potentials in Table 10 for scenario 1-3, adjusted values are presented in Table 12. The total amount of hours in a year is calculated by using 365 days, giving 8760 hours in total each year on average. By assuming viable transfer of waste heat energy to district heating systems for 4380 full load hours each year, modulated waste heat potentials were calculated giving a better understanding of the waste heat energy supply potential for a high-temperature district heating system.

Table 12 – Theoretical modulated waste heat potential for future operations of data center in Stavanger.

Potentials pertains to waste heat available for supply to district heating systems. Includes recovered waste heat for both 96% [63] and 90% heat capture rates. Assumption is 4380 full load hours of waste heat capture [Appendix D].

Scenario 1		
Recovered waste heat (96%)	**Recovered waste heat (90%)**	**Full load hours**
2492 MW	2336 MW	4380
Scenario 2		
Recovered waste heat (96%)	**Recovered waste heat (90%)**	**Full load hours**
12459 MW	11680 MW	4380
Scenario 3		
Recovered waste heat (96%)	**Recovered waste heat (90%)**	**Full load hours**
14950 MW	14016 MW	4380

Modulation is also needed for the estimations from GE Compute concerning the capacity of 2 MW, and security margin capacity at 4 MW [Appendix D]. The results for capacity at 2 MW being 8410 MW of recovered waste heat with 96% heat capture rate, and 7884 MW with 90% heat capture rate each year. And for security capacity at 4 MW the resulting modulated waste heat potentials are 16819 MW of recovered waste heat with 96% heat capture rate, and 15768 MW with 90% heat capture rate annually. For all scenarios it is assumed that the full load hours of operations are 4380. Considering a future ideal scenario with 4 MW capacity, the total amount of waste heat energy available for supply yearly to the existing district heating grid would be 16330 MWh or 16.3 GWh.

Cost of integration

To be able to utilize the waste heat energy from the data center in Stavanger, the waste heat temperature needs to be elevated. According to Lyse Neo a feasible solution would be a heat pump system, which is also the scenario investigated in the SINTEF study from the GEC One data center in Trondheim [61]. Estimations from supplier based on an isobutane heat pump system together with evaluations from Lyse Neo, an estimated 16 MNOK would account for 2 MW of heat pump capacity. If considering a 90% ERF as stated by Green Edge Compute, 3.6 MW would be the waste heat energy output at full capacity. Considering half capacity, which is the feasible scenario for integration with the district heating system this would entail 1.8 MW. A purely theoretical assumption would then be that the 2 MW heat pump capacity is enough for this energy transfer need.

Table 13 – Cost of heat pump system.

Estimated cost of heat pump system with values from supplier and evaluations from Lyse Neo. It is a very rough estimate to gauge the size of the cost of integration. The estimated cost includes installation, operation, and maintenance.

Heat pump system	Estimated cost
2 MW Isobutane (30-60°)	16 MNOK

Duration effect

An important phenomenon to consider when investing in an energy system to cover peak demand, is the duration effect on cost. Meaning that if there are more full load operating hours, this would decrease the cost over time. To describe this effect, a theoretical data set from Lyse Neo considering different peak load sources is depicted in Figure **28**.

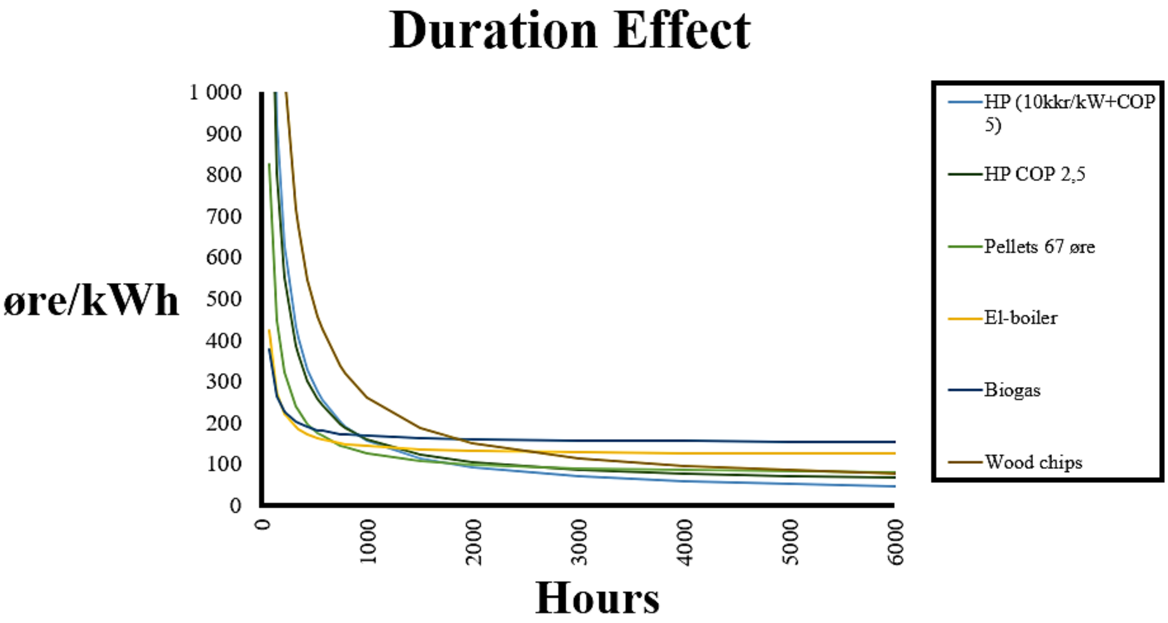

Figure 28 – Duration effect curve.

Duration effect on cost for different peak load sources. As the operational hours increase the investment cost decreases. An important phenomenon to consider when evaluating waste heat with unknown hours of full load. Based on example data set from Lyse Neo.

From the figure above a clear relationship between operational hours and cost per capacity is visible. The basic principle involved here is the difference in effect between initial cost and cost per input factors. To exemplify it may be useful to view only the curve for el-boiler, with the curves for heat pump (COP 5 and COP 2.5). The el-boiled may not cost much according to Lyse Neo but depends to a large extent on the input factors, which in this case would in part include cost of electricity. The heat pumps may cost more to buy and install but will with longer duration lower the total cost. The el-boiler may be a good choice for shorter durations, whilst heat pumps might be a better choice for longer durations. For the scenario depicted in Figure 28, these curves cross each other above the 1000 hour mark and for the heat pump with COP 5, it is half the price of the el-boiler at the 6000 hour mark. To describe a simplified overview of investment analysis framework for how Lyse Neo calculates effect and cost in relation to duration hours, two example production cost scenarios are described in Table 14.

Table 14 - Production costs scenarios.

Calculation of total cost for two scenarios, one with operating time of 2000 full load hours, and another with operating time of 3000 full load hours. Relevant cost factors are included for modeling and calculation of total cost.

	Scenario 1	**Scenario 2**
Return requirement [%]	5	5
Lifetime [years]	20	20
Effect price [NOK/kW]	10 000	10 000
Unit [kW]	6 000	6 000
Unit cost [MNOK]	60	60
OMC [% of investment]	3	3
Energy price [øre/kWh]	120	120
COP	3.5	3.5
Cost of goods [øre/kWh]	34	48
Operating time [full load hours]	**2 000**	**3 000**
Delivered energy [MWh]	12 000	18 000
Total cost [øre/kWh]	**89.4**	**71.0**

The total cost calculation from the figure above consists of many separate calculations. Firstly, the cost of goods is received by diving energy price by COP. The Excel function called PMT is leveraged to analyze the profitability based on present values. The PMT rate is the return requirement of 5%, whilst the total number of years is given as 20 years. The present value is an arbitrary unit cost of 60 MNOK, which is just an example to prove the phenomenon of duration effect. The capital cost is then calculated by using the PMT divided by delivered energy. The OMC (operations- and maintenance costs) is calculated by multiplying the unit cost with the OMC percentage of 3%. The total cost is the result of goods cost, capital cost and OMC. By giving a detailed breakdown it is possible to see where the cost influences are. From the two scenarios the scenario with longer full load duration has lower total cost. Which is important to be aware of for the solution of high-temperature district heating grid integration. Which is why a consideration for the waste heat load profile from the data center was explored.

Hybrid district heating grid solution

A possible hybrid energy grid solution may be possible, as Lyse Neo stated that there exists a separate nearby heating grid near Bjergsted. As the strategy for Lyse Neo is to connect this separate grid in the future, this would also align with a hybrid district heating grid solution. A basic schematical figure was created to better understand the waste heat energy pathway from a low-temperature nearby heat energy grid to a high-temperature district heat energy grid. The figure includes a heat pump system for temperature elevation and is depicted in Figure 29.

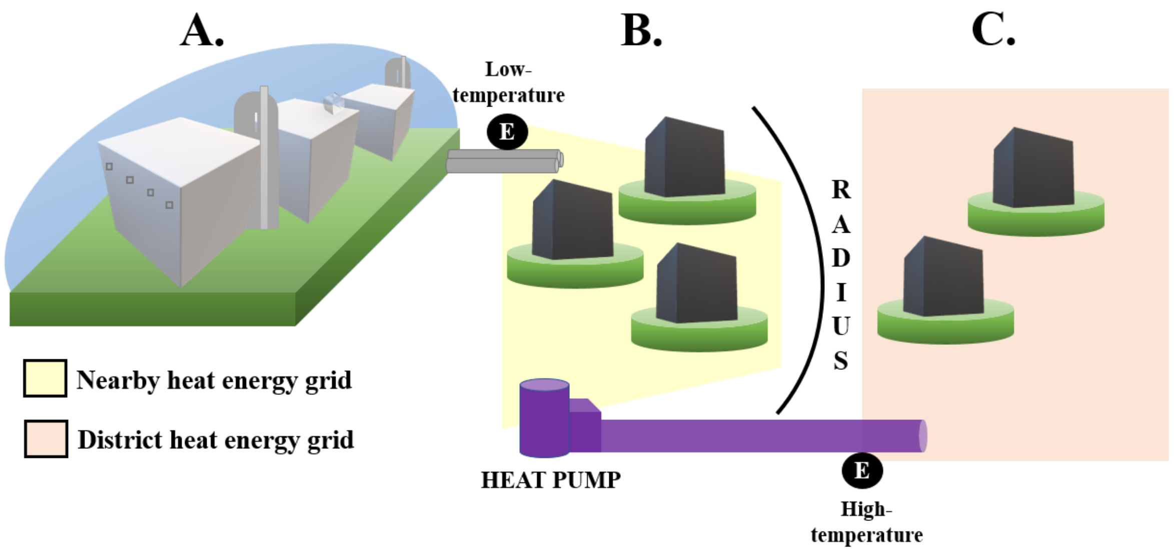

Figure 29 - Figure showing a theoretical hybrid heat energy grid.

With a low-temperature nearby heating grid (yellow) including connection to existing district heating grid (red). The grids are divided by the optimal radius where the drop in temperature over time and distance urges the need to boost the temperature to meet delivery demands. Primary components are data center (A), consumers with black buildings (B, C) and heat pump system (purple). Low-temperature waste heat is distributed from the data center source to consumers in nearby areas. This low-temperature grid has a connection to a boosting system made up of heat pumps. Remaining un-utilized waste heat will then have the possibility of temperature elevation. This way it can travel through the existing district heating grid serving as a secondary distribution option.

As seen in the figure above, the heat energy grid is divided into two areas by the optimal radius for distribution without boosting the temperature. Meaning that the area closest to the waste heat energy source needs no additional heating to obtain the needed temperature for supply to consumers. These would be a specific type of consumers, with a lowered heat temperature need. The connection between the low-temperature grid and the high-temperature grid is in effect a heat pump system. This enables the waste heat to have a secondary purpose if no nearby consumers are established. This is estimated to be a costly process of temperature boosting, so this secondary distribution option includes significant investment cost. Utilization for the nearby heat energy grid will be at lower temperatures, perhaps entailing a smaller consumer base. As there is an existing separate nearby heating grid in the same region, the cost for connection is expected to be much lower than for an entire grid development process. And since this grid is already planned to be connected to the district heating network, there probably exists some form of decision-making basis for why this is a good investment. If that is the case, this waste heat utilization project would serve as additional backing for that future strategy. Since the starting phase of the data center includes low amounts of waste heat generated, there will be some time before the utilization of waste heat would make sense. Difficult to be certain of course, but most likely this will be the case.

Grid integration cost

To be able to connect a low-temperature energy grid to a high-temperature energy grid a sub-station for energy transfer is needed to make this transition feasible. Lyse Neo estimates approximately 5000 NOK / kW in investment cost, with a stencil operations and maintenance cost at approximately 3%. For the 2 MW heat pump system a cost estimation is presented in Table 15.

Table 15 – Estimation for cost of energy transfer sub-station.

The sub-station enables energy transfer from a low-temperature energy grid to a high-temperature energy grid. Bear in mind that these are just rough estimates to get an understanding of the different cost elements concerning a hybrid energy grid system.

Energy transfer unit	Estimated cost
Sub-station	10.3 MNOK

The different distribution solutions include some of the same cost factors and some that pertain to the specific solutions. The overall goal being to maximize the value of waste heat utilized from the data center in Stavanger. It is important to emphasize that value in this study context includes many aspects, particularly the macro perspective.

6.2. Macro perspective

Assuming a solution for transforming the waste heat energy potential from available to accessible to consumers, with an ideal future scenario for the data center in Stavanger. The resulting benefits to the data center, Lyse Neo, other affected actors, and the society are important for evaluating the overall value of waste heat utilization from the data center in Stavanger.

Data center heat capture benefits

Starting from the waste heat energy source, implementation of waste heat energy recovery systems will result in several benefits for the data center itself. By heat capture utilizing liquid cooling systems, a large amount of the IT-power consumption can be recovered. By waste heat energy utilization, the data center becomes more energy efficient, as instead of dissipating the waste heat to the environment, it will be repurposed for reuse at other locations. This in turn reduces the target end-users need for additional heating energy sources. Another important benefit concerns the environmental impact. Waste heat energy reuse can facilitate carbon footprint reduction for the data center. Through technology investments like new liquid cooling systems, the data center optimizes the overall energy usage. Increased server density, more efficient cooling, reduced power consumption for cooling systems and so forth.

Benefits of waste heat reuse

Target areas where the recovered waste heat energy is utilized can reduce their reliance on traditional heating systems. For some this would mean a transition from fossil fuel driven systems to renewable energy in the form of waste heat. This would contribute to overall energy conservation, and reduction in GHG emissions. This aligns with the sustainability goals for Stavanger, Norway, and Europe. The greener approach that Green Edge Compute is leveraging their business model on, may also contribute to increased industrial symbiosis, meaning more sharing and collaboration between companies and industries.

Cost reduction benefits

For the data center cost savings follow the improved cooling system, as they can reduce their power consumption and the associated cost concerning cooling system operation and maintenance. The captured waste heat energy may also have a larger value potential in the future even though Green Edge Compute does not expect any pay for the waste heat initially. However, when the infrastructure is established, and the data center operations is scaled up, there might be pivotal moments where they can charge some amount for waste heat utilization. This way the data center would be producing power and generating a separate income stream from such operations. Lower power consumption, lower operational expenses, and potential income stream in the future for waste heat energy all contribute to a net lower cost for the data center.

Local heating hub

Depending on the distribution solution for transforming the available waste heat to accessible waste heat for utilization, many benefits may ensue. Waste heat energy from the data center may be distributed to nearby areas either private households or local industry for heating purposes. It may also be distributed by integration with the existing district heating system, with temperature elevation by heat pumps and transportation through piping. Another solution is a hybrid system, where nearby facilities in need of energy can have direct access to the waste heat energy at output temperatures. If consumers would demand heat energy all year, it would make it possible for the data center to utilize more available waste heat energy. In the warmer months most of the waste heat energy would go to all year around consumers or consumers with heating needs beyond ambient temperatures. Together with district heating integration, for providing heat energy to a larger consumer base at longer distances, supplying from the colder months when the district heating systems needs to cover more peak demand. By connecting to the data center, either directly or indirectly, a symbiotic relationship is created. By industrial symbiosis, an efficient local heating hub may be a future for the data center. Providing efficient and sustainable heating to local networks of end-users.

Industrial symbiosis

By connecting data centers with other industries or infrastructures through district heating systems or nearby heating grids, the waste heat from data centers can be integrated into an industrial symbiosis. This extends the life cycle of the large power consumption of the data center, by changing the shape of the energy most efficiently to fit to other purposes [23]. The utilization of waste heat from data centers can be integrated to industrial symbioses by exchanging and reusing the resources. This synergistic relationship between different sectors is dependent on industries or end-users with a demand suitable for the low temperature waste heat. Surplus low temperature waste heat can be peaked through heat pumps to be adjusted to supply the district heating system. The return temperature for the district heating system normally has a lower temperature which can be reused as cooling medium for the data center.

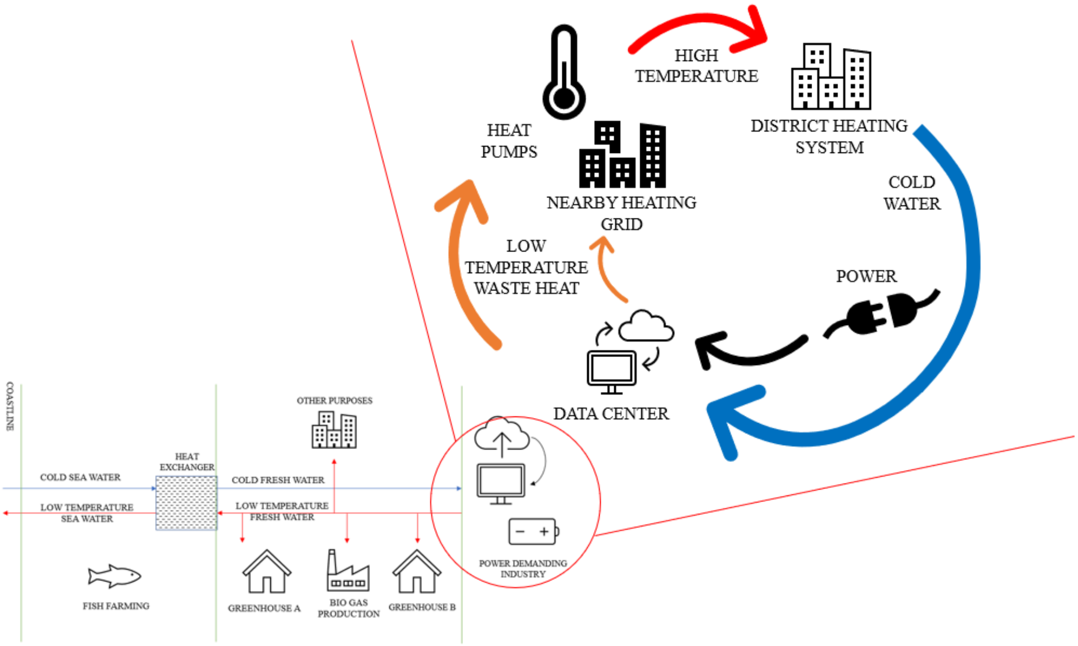

Figure 30 - Data center symbioses.

A hybrid solution for utilizing low temperature waste heat, supplying customers with higher temperature demand in the warmer periods of the year. Return water from district heating systems can possibly be customized to be reused as cooling liquid for the data center, creating an industrial symbiosis.

Industry benefits

If the data center position in the future is a local heating hub, it would enable industrial connections and establishments. If the data center provides waste heat energy for free or at low costs in the future, industries might want to establish their operations near the data center location to take advantage of this resource. Depending on the industrial application or process, many industry actors would need cheap heating sources. Including water treatment, manufacturing, aquaculture, and agriculture. If the infrastructure in the future enables the data center to be reliable and significant heat energy source, it may facilitate local industry and improve operational efficiency.

Technology innovation

The significant recovery potential of waste heat for the data center is to a large extent because of the technology investment strategy of Green Edge Compute. Modern cooling technology enables better heat capture, and with liquid medium heat capacity also enables distribution. If the data center can prove to be a reliable local heating hub, others might also join the industrial symbiosis. By increased availability of waste heat, new possibilities may be unveiled, and new technology may spur consequently. Especially concerning evolving heat recovery systems, thermal energy storage and better integration and utilization of waste heat in terms of heating purposes. Technology innovation for future energy systems concerning sustainable and renewable energy may drive adoption for even more adoption of sustainability practices.

Future upscaling and integration

It is important to underline the fact that the future is not known when it comes to what position waste heat energy will take in the future societal energy mix. Factors influencing the value of waste heat from data centers include waste heat quantity and quality in terms of output temperature. More applications and purposes for low-temperature waste heat would lower the threshold to utilize waste heat sources of lower quantity and quality which is a major benefit. More data centers and better technology for heat capture would entail a substantial upscaling of waste heat potential. Improved technology and solutions considering integration possibilities would also be a beneficial advancement. Better integration possibilities both to nearby heating grids, but also district heating grids and hybrid energy grid solutions would enable further networks and infrastructure for a waste heat motorway of sorts. New ways of integration and an expanding horizon of future possibilities and better collaboration is paramount to enhance the value of waste heat from data centers. In particular energy grid systems, which enables for more constellations and ways for the waste heat energy to be utilized to its fullest, an example being a hybrid energy grid system depicted in Figure 31.

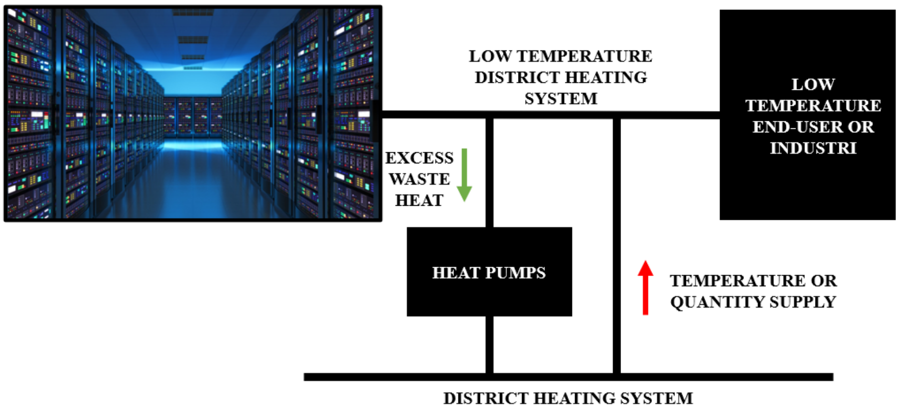

Figure 31 – A theoretical illustration of how waste heat energy may move between energy grids.

The simplified pathway shows waste heat from low-temperature energy grid to high-temperature energy grid, with additional connections enabling for supply from district heating grid back to nearby separate grids. This enables security for the smaller grid to deliver if energy demand is not met. Making the system less vulnerable.

6.2.1. Value of waste heat

To evaluate the value of waste heat from the data center in Stavanger, the economic profitability and environmental impact are taken into consideration among other factors. These are both factors influenced by the actual utilization of waste heat energy. The degree of utilization is influenced by the ease of access and demand. Ease of access depends on the geographical closeness to the waste heat energy source, namely the data center. Using the distance between the data center and the end-user as a constraint, it is possible to compare location alternatives for maximal benefits. Waste heat energy supplied from data center are also compared with alternatives, meaning other energy sources available from the energy market. Meaning that there should be convincing arguments for why consumers should choose waste heat energy for heating purposes not from other sources. An overview of factors affecting the value of waste heat energy from the data center in Stavanger is presented in Table 16 below.

Table 16 – The main factors affecting the waste heat energy value.

With waste heat output from the data center in Stavanger. Main findings of value factors for the data center in Stavanger utilizing the modern liquid cooling system.

Main factors of value contribution	
Environmental impact	Reduced power consumption
	If transition from fossil fuel the GHG emissions will decrease
	Needs less space and can thus be established in existing buildings
	Contribution to environmental sustainability
Energy efficiency	High-performance data centers generate higher temperatures
	Reduced power consumption
	Cost saving for data center operators
	Potential cost reduction for end-users with cheap heating
Economic opportunities	Generate new jobs for involved actors
	Contribution to local economic development
	Sustainable infrastructure
	Reduced operational costs
Sustainable infrastructure	Supporting green initiatives
	Reduces energy waste compared to air-cooling
	District heating integration for higher temperatures
	Needs less space
	Maximizing efficiency
Social and community benefits	Collaboration can promote community engagement
	Generate new job opportunities
	Contribution to local economic development

Factors influencing the value of waste heat utilization are manyfold, including proximity to data center, and demand for the consumer base. Waste heat energy quantity and quality will determine the crude waste heat potential. The need for infrastructure to distribute liquid medium as energy carrier is costly and is decisive when implementing waste heat utilization systems. Governmental regulations and industry policies also affect the feasibility of waste heat utilization. Both the technical end and the market end is important, considering technical feasibility of waste heat utilization systems in integration with the existing infrastructure. Also considering the market landscape, and temporal context in society.

Demand distance

The proximity of potential consumers affects the distribution feasibility. A large distance between the data center and end-users affects the overall availability, having a crucial impact on value. This depends on the distribution grid, but generally the closer the better. It is expected to be more feasible and more cost-effective to be closer to the heat energy demand. Demand profile of the consumer base is also very important, concerning the availability of nearby consumers and the nature of their heating needs. Having nearby industry, private households, offices, and district heating networks enhances the consumer base. Which affect the value of waste heat utilization.

Waste heat measures

The quality of the waste heat output depends on the requirements of the consumers. Recovered waste heat from the data center will hold lower temperatures than would be needed for hot tap water delivery criteria. The most important quality measure for waste heat energy is the temperature of output, which is enhanced by liquid cooling system implementation. Quantity is also an important measure, not just quantity in total but the effect over time. Meaning the supply profile of the data center, which depends on the distribution grid used. Increasing number of applications for low-temperature waste heat would increase its utility. District heating systems will also increase utility by increasing the waste heat temperature. Higher temperature waste heat will be more versatile, with a wider range of applications, which affect the waste heat utilization value. Attractiveness of low-temperature waste heat may be lower currently in society, but this might change in the future depending on availability.

Enabling infrastructure

Internal infrastructure is needed at the data center to capture waste heat in liquid medium. External infrastructure is needed to transfer the energy for potential utilization. For Green Edge Compute, there is associated costs with each implementation of new infrastructure. It is however not clear which actor involved would take responsibility for what costs. Concerning liquid cooling systems, the cost would most definitely lie with GE Compute. Costs concerning energy grids and heat pump systems might not fall on GE Compute, at least not solely. The complexity and total cost of implementation of heat recovery systems and distribution networks affect the waste heat value. Infrastructure also encompasses the building for data center operations, and with modern data center model of GE Compute, existing buildings may be utilized.

External influence

Regulations and policies together with industry frameworks and governmental strategies all can affect the waste heat value. Supportive plans might include incentives, recommendations, sustainability practices, energy efficiency, waste heat recovery, and renewable energy. This may affect the economic feasibility of waste heat utilization implementation, which in turn affects the value of waste heat. Market conditions are also part of the external influencing factors and have not been within the primary scope of this thesis. Market factors may include price of energy and availability of alternative heating sources. Also, the competitive landscape can influence the value proposition of waste heat utilization. It is important to consider the market dynamics of current society, and the area of establishment as well as prognosis and forecasts of the future. Contingency plans may help alleviate risk factors. Future scenarios concerning shift in external factors may include a potential revenue stream from waste heat utilization. Which will affect the value of waste heat.

Technical hurdles

Technical feasibility of waste heat utilization is an important enabling factor as assessment of what is possible illuminates what possibilities that presents. New heat recovery technology, modern heat transfer mechanisms, better compatibility between energy grids and consumers are all important factors for technical feasibility. Bear in mind the nature of technological innovation, as new technologies might open new doors. Which can affect the waste heat value. It may also affect the scalability and future possibilities of the waste heat utilization systems. The ability to scale down and expand are important considerations, being factors of flexibility.

The macro aspect

Considering all these factors and optimizing the waste heat utilization implementation strategies in the best way possible will affect the waste heat value. Being aware of important factors affecting the waste heat value is important as analysis basis for effectivization and maximization of value. Sustainable and efficient data center operations are perhaps the overarching goal.

7. Discussion

In this chapter important arguments are discussed concerning the potential value of waste heat from a data center in Norway. The data center model by Green Edge Compute may prove to be a success story considering waste heat utilization. Waste heat utilization implementation from data centers in Norway are not common, which makes this an interesting area of discussion. By sharing considerations made for a real-world data center case in Stavanger, and presenting the process of gauging the waste heat value the hope is continued momentum for this energy solution type. Arguments considering waste heat utilization from a data center in Norway may provide practical examples and inspiration for further research. The discussion goal is to demonstrate factors of utilization feasibility, potential benefits, and lessons learned when gauging the waste heat utilization project for the data center in Stavanger.

7.1. Crude potential value

Estimating crude potential value of waste heat energy from data centers in Norway require a consideration of all relevant aspects of value. The crude potential value, meaning the potential waste heat energy output from the data center operations serves as the starting point for further investigation. Since there are many assumptions concerning the crude estimates, and because the current plans for the data center in Stavanger involve a small initial service it is hard to forecast future scenarios. The investigations yielded some insights.

7.1.1. Magnitude factors

The most important factors of magnitude for understanding the heat output would be temperature, volume profile, scale of operations, and stability. For the data center in Stavanger at initial phases there are not enough for recovery. At ideal later stages of upscaling the temperature output may be in the range of 60°C, with a stabile volume profile, and large scale of operations at 4 MW capacity. Stability is determined by the client base for the data center concerning computing needs and dedicated servers.

7.1.2. Substantial investment costs

To gauge the potential value of waste heat from the data center in Stavanger, the investment costs associated with waste heat utilization implementation was expected to be a decisive factor. The data center has not yet implemented liquid cooling systems, which for testing purposes pose an investment cost in the order of 10 MNOK, only gaining a minimal waste heat energy output from the initial setup.

7.1.3. Distribution effects

Depending on how the waste heat utilization implementation is planned at GE Compute, the question of distribution solution will be interesting. For the testing phase with the investment cost, to prove the principle of waste heat output it is difficult to ascertain if there would be any benefits of connection to an energy grid. There is however an existing nearby heating grid in the Bjergsted area reported by Lyse Neo, which may pose an interesting opportunity. The cost for a sub-station in the scenario for connection between low-temperature energy grid and high-temperature energy grid the estimated cost of investment was in the order of 10.3 MNOK. Assuming a cost with the same magnitude for connection to the existing nearby heating grid, the resulting total investment cost including this initial distribution solution as a start at 20.3 MNOK.

7.2. Feasible transfer solution

The discussion of various waste heat utilization technologies is essential. This involves exploring options such as heat capture systems, heat pump systems, district heating networks, and integration with local industrial processes. Understanding the technical aspects, the need for efficiency, and the overall suitability of these technologies for a distribution solution for waste heat energy is important for the potential of effective waste heat utilization.

7.2.1. Effect of end-users

The types of applications for different grades of heat energy determine the potential end-users and is a key discussion point. Low-temperature waste heat applications will enable direct supply from the data center, while high-temperature waste heat application calls for district heating systems. Depending on the type of solution the mix of consumers should match the supply profile of the data center, or in the case of district heating system integration it should serve its purpose as specific load. Applications and processes that can benefit from waste heat energy must match the delivery specifications from the data center and will receive free heat energy at least initially. The proximity of end-users to the data center in Stavanger and their heating demands is crucial to gauge the potential value of waste heat, as it determines the feasible degree of utilization. For the load duration curve from Bjergsted a left skew is visible, meaning a base load for the whole year, with medium load some months, and peak load the coldest time of year. Considering the simulated hypothetical data center supply curve, it is skewed in the other direction, with primary supply to the district heating grid in the coldest months to cover peak load. This does not mean that there is no more waste heat potential, there is just no demand for it in the warmer months in the high-temperature energy grid. Which is why consumers of low-temperature waste heat could meet this supply with an appropriate demand profile.

7.2.2. Optimal solution for value

A higher crude potential would give the greatest number of possibilities, and there exists other types of cooling systems which would entail a higher crude potential. Like that of immersion cooling seen in Figure 24. The solution Green Edge Compute has planned concerns a rack-based liquid cooling system. From communications with Green Edge Compute, the most feasible scenario would be to deliver waste heat to cover peak demand via the district heating grid in the coldest months. If there are nearby all-year demand consumers, like that of a swimming pool, office buildings or private households, the utilization would increase. The optimal solution would therefore be to investigate a hybrid solution like in Figure 29. With an initial investment for connection to the already existing nearby heating grid, and a later investment for integration with the high-temperature district heating grid.

7.2.3. Heat pump system

The primary enabler for waste heat utilization in a district heating system is temperature elevation by a heat pump system. The estimated investment cost is in the order of 16 MNOK, which is higher than the cost for integration between the different grade energy grids as well as the testing equipment for liquid cooling. Together with the cost for liquid cooling equipment for testing, and the assumed connection cost, the total is in the order of 36.3 MNOK.

7.2.4. Additional value

Considering the macroscopic perspective there is value in developing infrastructure in general. The expected outlook in the long run for Forus Energigjenvinning would be a larger fraction of recycling, and not so much for incineration. Meaning that in the long-term there is a need to cover base load for the district heating grid. By creating new infrastructure more in line with the newer generations of district heating system enabling a lower flow temperature, it enables for a larger portion of waste heat sources. The additional value of infrastructure in the long-term considering the future of district heating systems in Stavanger is important to note.

7.3. Major benefits and effects

The benefits of waste heat purpose awareness from potential excess heat emitters are important, so that they can potentially evaluate their own potential waste heat value. The major driver for Green Edge Compute to screen for the potential value of waste heat for their data centers is the environmental impact. The competitive advantage of offering a CO2 friendly product is essential for their business model of green data centers. They do not expect to earn revenue from waste heat distribution, but they do want to increase energy efficiency, and exploit the excess heat as energy. This type of energy conservation is related to circular economy, with emphasis on the reuse of renewable energy. Best practices for waste heat management may also be an important effect if more excess heat emitters in Norway do potential value screening. This would also be aligned with governmental strategy, which serves as momentum for this type of research. Collaboration on the path to better industrial symbiosis is also a potential macroscopic effect of waste heat utilization and infrastructure development. Engaging in such discussion can also help raise waste heat awareness, drive energy system collaboration, and facilitate the adoption of waste heat utilization strategies in the context of data centers and other potential major emitters, leading to more efficient and sustainable operations in society in general.

7.3.1. Utilization limitations

Waste heat utilization involves important limitations, which includes many of the same factors as for potential benefits and effects. These include the temperature of waste heat, proximity to end-users and necessary infrastructure, timing and seasonal variations in heat demand, technical compatibility and energy grid integration, overall cost considerations, regulatory incentives, and scalability. These factors may help optimize waste heat utilization but may also pose limitations. Ideally these factors would lead to enhanced energy efficiency and reduced environmental impact.

7.4. Study weaknesses

The study encountered two notable weaknesses that should be acknowledged. Firstly, the reliance on news articles as a necessary source to establish relevancy might have introduced a degree of bias, as news articles tend to provide more limited and time-sensitive perspective. This could have potentially excluded relevant research studies or alternative viewpoints that would have enriched the analysis. The comprehensiveness and depth of the literature review may have been compromised. Secondly, the scarcity of existing literature specifically focused on data center waste heat utilization posed a challenge on obtaining a comprehensive understanding of the subject matter. Conduction of thorough analysis was obstructed by the limited availability of literature on this specific topic. Further research of test data from data centers with liquid cooling will clarify the uncertain aspects concerning the practical utilization of waste heat energy from data centers. Acknowledging these weaknesses underscores the importance of future research to address limitations. This will enhance the validity and reliability of future studies.

7.5. Future research

This master’s thesis constitutes a pre-operational feasibility study to evaluate the potential value of waste heat from a data center in Stavanger. Including energy and emission savings, as well as environmental and societal impact. Tt would be interesting to compare reflections with the actual observations after full operation of the data center is in motion. This way both assumptions and uncertainties made during this thesis work would be open for evaluation, and possibly utilized for other feasibility studies. It would also be interesting to evaluate the data center during its expected phases of upscaling in the upcoming years. What is the barrier for large scale adoption of waste heat recovery to hybrid solutions of nearby energy grids and district heating systems. Future opportunities include investigations on both sides considering technical limitations now and in the future, but also societal and political persuasions and their effects on adoption. It would also be interesting to gauge the overall acceptance of waste heat utilization both from technical professionals, but also the public. An observation from meetings with key actors in the industry is that researchers and scientists seem to point to a higher degree of public awareness but perhaps others do not and would like more awareness. Waste heat utilization research is not overly abundant and ubiquitous, so it could be an interesting basis for a study on the public engagement and industry adoption of research and innovation. It is also important to mention that technology advancements have already progressed heat capture possibilities, so an evaluation of emerging technology trends within this area of interest could be beneficial for both industry actors but also in the public interest. Addressing the role of waste heat utilization in the broader context of sustainable energy systems and the circular economy can also be relevant for further studies.

8. Conclusion

Digitalization increasingly shapes the daily lives of people worldwide, and data centers play a pivotal role in facilitating this transformative development. Data center operations consume substantial amounts of energy and generate excess waste heat as biproduct. This waste heat may represent a valuable resource contributing to energy efficiency, environmental sustainability, and economic benefits. This thesis examined the potential value of waste heat energy from a data center in Stavanger by assessing factors including proximity to end-users, waste heat quantity and quality, and infrastructure requirements. By harnessing and utilizing recovered waste heat, the dependence on conventional heating systems can be diminished. Resulting in energy conservation, and alleviation of the power grid. This not only aligns with sustainability objectives but also fosters industrial symbiosis through collaborative resource sharing among companies and industries. Such practices extend the life cycle of data centers' power consumption and promote operational efficiency.

Implementing waste heat recovery systems in data centers enhances efficiency, reduces environmental impact, and leads to cost savings. By utilizing modern liquid cooling systems, a significant portion of the IT-power consumption can be captured as heat. Scaling up operations in the future would enable monetization of waste heat, driving economic growth and creating employment opportunities. The broader societal impact of waste heat utilization is valuable. By effectively utilizing waste heat, data centers can reduce operational costs which can lead to economic savings and investment opportunities. The implementation of waste heat utilization systems can also foster the development of new industries and job roles associated with heat recovery technologies, maintenance, and energy system integration.

The most optimal solution for increased value of waste heat from the data center in Stavanger according to the investigation results and insights from discussion would be a hybrid energy grid solution. Including both a low-temperature grid and high-temperature grid to leverage a mixed heat demand profile. The overall investment cost for Green Edge Compute regarding this type of solution is in the magnitude of 47 MNOK. Including liquid cooling equipment for testing, assumed connection costs to nearby heating grid, and later connection to the district heating grid with heat pump facilitation. Embracing waste heat recovery technologies not only benefits data centers but also contributes to broader societal goals of energy conservation, greenhouse gas reduction, and the transition to sustainable and circular economies. Maximizing the value of waste heat fosters a more efficient and sustainable society.

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Appendix

Appendix A. Long form questionnaire for Green Edge Compute data center company

Preparation for meeting with Green Edge Compute delimited to data center in Stavanger.

GENERAL INFO

What is the status of the data center today? Is it still in some kind of planning phase, or has it been set to full operations mode, or somewhere in between?

What is the exact address of the datacenter and is it possible to arrange for a visit for us two to have a look?

What is the general business plan for the data center, especially considering the customer base?

What is the capacity of the data center today? And what is the size, both in terms of area but also considering server density?

Do you have some kind of formulated decision basis that might be relevant for us, which you can disclose and would give us an insight into how you have made choices that in the end put the data center into existence?

Do you have any restrictions concerning data shared with us? If so, the master thesis can be set in quarantine for a certain amount of time to protect your interests.

Is it needed that we sign a non-disclosure agreement?

Do you have other relevant general information that you think we should know about the data center or your thoughts on waste heat utilization?

WASTE HEAT

Do you wish to implement a waste heat utilization solution for your data center?

How far have you come in the process of finding the potential for waste heat utilization? Is it a notion that you want to explore, or do you have testing data and statistical analysis that is pushing towards this path?

What is the driver for why you might want to consider waste heat utilization?

Have you performed a type of analysis of potential end-users for the potential waste heat, or will you try to focus on your own needs in the beginning?

Are end-users nearby possibly considered as your waste heat consumers, which can be connected directly to the data center?

If using waste heat, how much of the waste heat are you planning to use into your own facilities? Would it be feasible to use your own waste heat for facility heating needs?

Have you performed preliminary studies on the theoretical output of waste heat from your data center or others like it before?

Do you have any other reflections on the concept of waste heat or its’ benefits to your organization and data center operations that we should know?

Do you have calculations or measurements on the temperature of waste heat from the data center?

At what temperature can the data center with servers operate under optimally? At what temperature can the data center operate under maximally?

Do you have any analysis results on the optimal temperature for operations and the potential impact on waste heat production potential?

Where does waste heat from cooling down data centers end up if it is not utilized through district heating systems?

SUSTAINABILITY

What have you considered for future growth and demand, and the needed computing power?

Is the data center scalable, both downsizing and upsizing?

What are your main contributors for minimizing carbon footprint?

Have you considered the potential environmental benefits of utilizing waste heat?

Is the potential utilization of waste heat and the indirect reduction of CO_2 emissions calculated when reviewing investment cost (cost-efficiency)?

What are the most important and heavy weighing reasons for your shifts towards greener edge data centers?

What are your main competitive advantages in today’s market?

To be a sustainable source of waste heat, the potential production and potential utilization should be effective, meaning minimization of loss. Is this something you have considered?

How flexible is the potential waste heat production from the data center? Can server activities within the data center be either planned or forecasted, so the waste heat production can coordinate with high demand?

Do you wish to reduce environmental impact in the future? What is the plan to reduce emissions in the future? Is it considered only to use power generated from renewable energy sources?

Have you calculated the data centers emissions depending on the different choices for cooling (air, liquid)? What are the calculated emissions from the data center, considered liquid cooling, measured monthly and yearly?

How many jobs does the new data center generate? What is the calculated BNP for this data center? How do you quantify your contributions to society, the impact and value realization?

POWER

Do you have data for computational power and energy consumption for the data center, quantified in MW? Data of daily, weekly, monthly, and yearly consumption is interesting.

Have you performed calculations for PUE?

What is the data center PUE now? What is the future goal for the PUE?

Have you any considerations for ERF, either potential calculations or general reflections? Do you have exact estimates?

What type of cooling systems do you use for servers now? Have you used air cooling before, if so, what is the decision basis for the transition?

What are the cost differences for the distinct types of cooling systems for your data center in Stavanger, considering size and computing output?

What power output do you need to run the cooling systems? Is the energy needed a substantial part of the datacenter energy consumption?

Do you have any estimates concerning waste heat produced over time, considering peak computing and variation over days, weeks, months, and seasons?

Cooling needs for the data center is obvious because of the heat generation from active servers, however what is your energy consumption for general heating needs at the data center?

Do you have a granular and detailed overview of the total energy consumption for the data center, including all constituents contributing to the total consumption and their fraction?

COST AND RISK

What are the risks considered when establishing the data center in Stavanger? What risks were considered acceptable and what risks were considered unacceptable?

Do you own the facilities and the

Do you have any supply chain dependencies that might be relevant to know about?

What are your main supply chain strengths and weaknesses?

Do you have any contingency plans when events occur such as Covid 19? Meaning supply chain resiliency.

Do you have any risk management procedures for evaluating investment opportunities?

Are any decisions made due to potential future incentives from the government?

What reflections do you have concerning current legislation? What do you think the future is for data centers, waste heat and the two together?

Have you made any guiding principles concerning ownership of infrastructure, and who should provide the funds for initial investment of waste heat systems?

What obligations bind the data center to the power supplier considering the delivery of waste heat as a product? More specifically, meaning delivery requirements.

What is the operating and investment cost difference between air cooling and liquid cooling?

What are the initial costs for cooling systems vs. forecasted maintenance costs?

What are the costs for establishing a cooling system?

Where is the interface between the power supplier and the data center?

If you cannot supply this information for the given data center in Stavanger, do you have data from a different data center of the same order?

Do you have any other considerations concerning risk, cost, economic evaluation and investment analysis that might be relevant for us?

Appendix B. Short form questionnaire for Green Edge Compute data center company

Preparation for meeting with Green Edge Compute delimited to data center in Stavanger.

- Hva er strømforbruket for luftkjøling i dag i kWh? Finnes noen estimater på fremtidig forbruk?
- Har dere produktinformasjon for servere som beskriver optimal brukstemperatur?
- Hva er grensesnittet mellom involverte aktører ved etablering og drift av datasenteret?
- Hva er de viktigste årsakene til at dere vurderer investering av væskekjøling?
- I hvilken grad er potensialet for spillvarmeutnyttelse grunnlag for potensiell overgang til væskekjøling?
- Hvilke beregninger har dere gjort i forhold til strømforbruk? PUE, ERF?
- Hvor fleksibel er datakraften dere leverer? Er strømforbruk til kjøling stabil over tid?
- Hva er størrelsesdifferansen mellom datasenteret i Trondheim og Stavanger? Kan tall benyttet fra datasenteret i Trondheim skaleres slik at det kan brukes for datasenteret i Stavanger? Eksempelvis beregning for utslipp.

Appendix C. Questionnaire for SINTEF concerning waste heat and data centers

Preparation for meeting with SINTEF.

Questions concerning GEC One data center in Trondheim:

- Does Green Edge Compute data centers only use renewable energy?
- What were the factors that led to inconclusive test results from GEC One in Trondheim?
- What is the reason for using propylene-glycol in the cooling system instead of water?

General questions about waste heat and data centers:

- How would you describe the current state of the data center industry in terms of its growth, technological advancement, and sustainability practices?
- What do you consider are the main risks and challenges commonly associated with waste heat utilization in the data center industry?
- Are the potential reductions in greenhouse gas emissions resulting from waste heat utilization in data centers significant and sustainable in the long term?
- What are the key considerations and strategies employed by the data center industry to achieve a balance between energy efficiency, operational reliability, and environmental sustainability?
- What economic benefits or cost savings can be realized through the effective utilization of waste heat in data centers?

Appendix D. Data and responses from Green Edge Compute

Notes considering answers from Green Edge Compute regarding short form questions in Appendix B are presented below. Notes from electronic communications are also included and based on responses received 16th of May, 7th of June and 9th of June 2023.

Air-cooling and power consumption

Theoretically it is estimated that if a server needs 1000W of power to operate, air-cooling systems and auxiliary equipment will need approximately half. It will need between 5-600W in addition to the operational power consumption of the server. Utilizing the equation for PUE (1) we get values between 1.5-1.6 for this scenario. As equipment varies a lot, different server types will present with different power needs. Powerful processor(s) and memory capacity will impact the consumption as to need more power generally.

Liquid-cooling investment

The main reasons for investing in liquid-cooling are threefold. Liquid-cooling is in the order of magnitude 1000 times more efficient than air-cooling. Liquid-cooling systems also enable an environment to provide HPC (High Performance Computing), which is not feasible with air-cooling systems. The power consumption need is also much less, and server density is much higher. As liquid cooling more efficiently cools an area, less space is needed for heat dissipation. This enables more tightly fit server unit systems. Additionally, this also provides excess heat energy, that is transported out from the servers in a liquid medium with a large heat capacity. This hot liquid medium will then constitute its own resource and may serve as a heat energy source. Either directly to consumers which make use of the heat energy at its' output temperature, or the temperature may be increased to connect to the district heating grids.

Server equipment

Supply of servers for the data center in Stavanger comes from Dell. Product information sheets provide detailed product information. Generally, the processor(s) in a server unit will generate the most amount of heat energy when operating. The processor server component is produced by Intel, which has optimal operating temperature under 75°C. It is however recommended to keep an air-cooled server below 40°C, as the risk of malfunction and complete loss of function increases. If transition is made from air-cooling to liquid-cooling, it is estimated to be possible to operate under higher temperatures because of more efficient cooling. With a liquid-cooling solution the operating temperature can reach up to 60°C. But since the processor is cooled with a cold plate, it is possible to operate with temperatures up to 90°C inside the processor. Possibly even at higher temperatures than that as well, without the processor taking damage. Intel is not likely to approve usage at these temperatures, which might inform decisions as it can affect lifetime, guarantees and such. Green Edge Compute has tested these scenarios and can confirm these operating temperatures. What is feasible regarding the actual operating temperature when delivering services to customers is not clear at the time being.

Project collaboration

The most common constellation for a data center project according to Green Edge Compute is the following. A company generally builds and owns industrial facilities which then can be rented to other companies. Companies renting such facilities include IT-companies which hold a portfolio of clients. It can also be the specific client companies renting directly. Renters usually cover costs including space, electricity, network connection, cooling, and security to renters. IT-companies operate servers and their own equipment and deliver IT services to clients and may bill some or all the relative costs forward to clients as part of the complete service. If it is the client company renting directly, they need to cover the same costs and can have several business models on how to charge their customers.

Benefits of waste heat utilization

Utilization of waste heat can affect the overall carbon footprint and may provide Green Edge Compute with a competitive advantage concerning a better product considering CO_2. The waste heat utilization impact is not necessarily the most important grounds for transitioning to liquid-cooling systems. But the fact that it will be possible to exploit the bi-product heat energy when transitioning is essential.

Energy efficiency

Green Edge Compute data center PUE is calculated all the way down to 1.03, compared to the market benchmark around 1.5-1.6 as mentioned earlier. If we estimate data center total energy use at 1 MW (1000kW). By using the modern data center model by Green Edge Compute they estimate up to 90% reuse of energy. By using the equation for ERF (3), a value of 0.9 will be the case for this scenario. If we consider the Trondheim data center which the SINTEF Trondheim study investigated [61], Statkraft would be the facilitator for waste heat energy infrastructure. Their role would be similar to the role of Lyse Neo, as they both operate their respective district heating systems. Statkraft has informed GEC that they primarily can make use of the estimated supply of waste heat energy approximately half of the year. They have some decision basis where they cannot utilize this heat in the warmest parts of the year, the summertime. But can utilize this heat during the coldest parts of the year, the wintertime. This implies a factor of 0.45 for ERF, and not 0.9 which was not corrected for seasonal effects.

Stability of waste heat recovery

The computing power delivered from Green Edge Compute is 100% stable. It is estimated that they will never go above 70% of capacity, and in periods it will drop to approximately 40%. The plan is to use liquid-cooling systems, and not air-cooling systems, which uses liquid medium in the form of water solution. The input temperature of the cooling system will be approximately 30°C.

Testing data from Trondheim

There are similarities between the two data centers Trondheim and Stavanger, which entails the possibility of using some of the testing data for rough estimates. There are however differences between equipment, and it is preferred that testing data from the data center Stavanger is used to inform decision making. Temperature measurements on the water solution in the liquid-cooling systems in real-time is possible. Assuming this will include both the input and the output for the cooling liquid. The load on the system will need to be simulated for the Stavanger data center. This includes measurements of power consumption for all electrical circuits the data center is leveraging to power operational activities. This setup will enable accurate data which is reportable and testable. From these datasets it will be possible to calculate needed metrics for future considerations.

Estimated specifications for Stavanger

The data center in Stavanger will only have access to approximately 40 m^2 of server space to start with, but there is another room in the same building where there have been data center operations before. This additional room is approximately 200 m^2. As for the data center capacity we estimate a maximum capacity at 4 MW, but ordinary operations will be at 2 MW. There is no upper limit for how many servers we can operate. At GEC One in Trondheim, we have 2 racks in total, not entirely filled with servers yet. Main operations include computing, storage, and network. Our collaborating partners at CGI will easily be able to fill more racks with their additional equipment. Our operating platform is based on Dell's PowerFlex system, a platform with APIs for all the biggest applications and databases.

GE data center needs

The need for appropriate operations space is important, and will usually be around 1-200 m^2, meaning space enough for about 20-40 racks. When it comes to power needs for future data centers, we try to secure a high enough maximum capacity to be able to scale operations without having to apply for operation extensions. A 4 MW total maximum capacity would be ideal for our data centers, but it is important to note that we start in the small ranges of perhaps 1-200 kW. Regarding the actual power consumption, it is very hard to estimate without close monitoring, as it changes frequently. Variations will naturally occur between day and night, but also between seasons. Other time periods of power demand changes include weekends, holidays, and mid-summer. The demand for power is dictated by the IT-equipment, which in turn is directly related to computing, storage, and network needs of consumers. People affect power consumption. But people are also somewhat predictable, at least concerning general assumptions on working hours and demand changes over time. This is particularly true if the equipment is virtual, however with dedicated equipment this will not be possible. As this type of equipment is dedicated to specific customers.

Temperature aspects

The outside temperature variations both concerning day and night, but also seasonal changes will not affect the IT-equipment. This is because we use liquid cooling systems with stabilized inlet and outlet temperatures. The output will however be dependent on the demand for integrated energy grids, like that for GEC One in Trondheim. Meaning that in the warmest part of the year, the summertime, it is likely that we must emit waste heat to air of water. This is because of lack of consumers. In the coldest part of the year, in the wintertime, output can be delivered into district heating systems, as screening have shown in Trondheim. If there are some consumers that need heat energy all year around, like swimming pools or private households using hot water, we would be able to utilize the waste heat energy to a larger extent.

GEC One in Trondheim

Regarding the GEC One data center in Trondheim, we have space for approximately 20 racks, but we currently operate 2 racks. We scale equipment with the increasing number of customers, and the scenario in the SINTEF study depicts a possible future at full capacity. The actual case is a downscaled version. When we talk about racks, these are modules able to store approximately 80-100 servers according to our current structure design. The solution we use today at GEC One is produced by Intel and contains 4 servers per 2U. The racks we have are graded as 48U racks, meaning that it can theoretically hold 96 servers in total. The real case scenario is a bit different, as the rack needs to contain auxiliary equipment too, including rack switches. The realistic number at full capacity is probably nearer to 80 servers.

CGI partnership

As for the data center in Stavanger we have partnered with CGI, which will be able to scale up operations according to their needs. At the start we will probably start with 1 rack at half capacity, so the total server amount would initially be about 40 servers. After that CGI can add their equipment. We will also be able to fill up racks and servers in relation to increased demand over time.

Dell system

We currently use Dell PowerFlex software for operations and APIs enabling the connection to other major platforms including Windows, SQL, RedHat Openshift, Google, Azure, AWS and more. The result being delivery of a local cloud which reflects the current data center needs, because of distances. Clients wish to have their data as near as possible without having to service it themselves in their own facilities.

PowerEdge

The PowerEdge hardware from Dell is a server series we will utilize to enable cooling solutions from Cool IT. It is not an immersion type cooling system, but a cold-plate cooling system. Immersion cooling solutions does not use rack based server structure, which has its pros and cons regarding our operations. The major advantage by utilizing the solution we have planned includes close collaboration with Dell and Cool IT and is not an OEM product, meaning not an original product.

Appendix E. Meeting minutes, data, and responses from Lyse Neo

Part I. Responses to GEC long form questionnaire

Notes considering comments from Lyse Neo regarding questions from Appendix A sent to Green Edge Compute data center are presented below. Responses received 14th of May 2023.

Information concerning data center in Stavanger

The data center in Bjergsted near Stavanger city center operates with air-cooling of server racks at current times. Their exact address is Veritasveien 25. Green Edge Compute and CGI are formulating plans on how to implement liquid cooling systems but remains without decision analysis conclusion currently. Investment needs to do realistic testing is in the order of magnitude 10 MNOK and depending on equipment give waste heat in the order of magnitude 100 kW. These are loosely based numbers with basis from meetings with Green Edge Compute.

Testcase in Trondheim data center

GEC’s data center in Sluppen near Trondheim is fully operational with liquid cooling systems. The operating power consumption for these systems are in the order of magnitude < 1 MW, which subsequently created waste heat energy. Their cooperation company is Statkraft, which operates a district heating system. The relatively small amount of waste heat energy available has determined that there is currently not enough to gain by connecting the data center to the district heating grids. The SINTEF Trondheim study provides a lot of data concerning this case. A future testing proposition can possibly be made for the Stavanger data center by using the facilities in Trondheim, but clarification is needed before considering this possibility.

Sources of knowledge and data

The SINTEF study on the Trondheim data center provides data basis from GEC. Knowledge on the feasibility of waste heat energy utilization lies primarily at Lyse Neo for the data center in Stavanger.

Areas of focus

The primary area of focus is the output temperatures from the future liquid cooling systems. How high can the temperature levels be before it affects performance and lifetime of equipment? How low can the temperature levels be for our delivery of waste heat energy to potential consumers? Higher temperature of waste heat energy output provides a larger utility. The possibility to deliver low temperature waste heat energy to consumers broadens the span of potential areas of utilization. What are the feasible scenarios with and without need for temperature boosting using heat pumps? What are the possibilities of adjusting temperature levels with heat pump systems? Another interesting area of focus is the delivery criteria and demands for heat energy by liquid medium to consumers. Drinking water needs temperatures of a certain range to ensure against Legionella bacteria, are there other ways of mitigating this issue? What is the actual legislation concerning drinking water and Legionella? Can UV treatment or Chlorine treatment become an alternative? Other countries operate under less strict recommendations.

Benefits for the data center

Implementation of waste heat energy utilization systems may provide many benefits to the data center. More sustainable operations may result in increased competitive advantage. This may become their license to operate in the future. The data center will primarily focus on their delivery of services and Lyse Neo will take the thermic responsibility if waste heat utilization systems are established. Business models will need to be developed for this business case. The system will possibly include a low-temperature transportation grid if no district heating is currently installed in feasible locations. Increasing the output temperature to match district heating temperature using heat pump systems is also a possibility. This would enable the connection to district heating grids where this is feasible. The first part of this process concerns the removal of excess heat, the second part of this process concerns heat utilization. Important to note that the excess heat today is going into the air, water or into the ground for dissipation. The business model at the starting phase would probably not include payment for utilization of waste heat energy from the data center. The point being to keep this energy source option desirable. Very interesting to investigate the temperature level on output waste heat energy, and possible locations where this waste heat energy holds value further along the supply chain.

Part II. Technical and economic evaluation on the potential use of heat pumps

Notes considering technical and economic basis from Lyse Neo and heat pump supplier are presented below. Knowledge basis concerns the potential for a heat pump system in conjunction with waste heat utilization from the data center, and its' possible connection to the district heating system. Responses received 22nd of May.

Existing district heating system in Stavanger

The district heating grids in Stavanger consists of many smaller heat energy grids with the size magnitude of 0.5-1.5 MW of heat energy. As Lyse Neo is shifting their operations towards a lower carbon footprint (decarbonizing), energy system modifications are needed. A combination solution they are investigating includes a heat pump system for base load with locally produces biogas for peak load. Current systems for base load include gas boilers, assumed to consist primarily of natural gas which is very hydrocarbon rich.

Heat pump system

To investigate a future solution based on heat pumps, several queries were made from Lyse Neo to supplier. Inquiries included sizes, cost (NOK / kW), area need, and performance (SCOP). The scenario in question is a stand-alone air to water heat pump system with the capacity of unloading the current gas boilers. Supplier informed on the area need, which was approximately 17 or 29 m^2 for the evaporator components of the heat pump system, which is assumed to be the most area consuming. Depending on the models, 4-6 are installed for the different areas. Prices depend on a multitude of variables, including the need for prefabrication or not on delivery. Without installation or supply the price range between 4-4.5 MNOK / MW. Another scenario concerns two machines with the capacity of 1.5 MW with input temperature 50-55°C and output temperature 80-85°C. The approximate price per machine is estimated around 2.37 MNOK, which in total is approximately 4.75 MNOK with currency exchange rate EUR to NOK from May 2023. These estimates do not include installation and additional equipment needed.

Integration with district heating grid

Based on the information from heat pump supplier, Lyse Neo constructed a hypothetical scenario. A solution consisting of a two-machine heat pump system (2 x 1 MW) with possible integration with the liquid-cooling system of the data center in Stavanger. The temperature level magnitude of waste heat integration lies in the interval of 30-60°C. Which means that the output of the waste heat energy source, in this case a modern data center with liquid cooling needs to have output temperatures above 30°C. Preferably closer to 60°C to not exert more energy than necessary for elevating the waste heat energy temperature. The heat pumps themselves have a cost around 2500 NOK / kW, and with a pi-factor surcharge (x 3.14) and estimate of 8000 NOK / kW may be feasible for the entirety of the heat pump system. With the capacity of 2 MW (2 x 1 MW), the total price would be approximately 16 MNOK everything included concerning installation and additional equipment.

Part III. Comments on SINTEF Trondheim study

Notes considering comments from Lyse Neo regarding the SINTEF study on Green Edge Computes' data center in Trondheim are presented below [61]. *Responses received 14th of March.*

Context in Norway for waste heat utilization

The SINTEF study refers to the Energy Act from the Norwegian Government, more specifically article 14.5 concerning the proposal for waste heat utilization requirement. If this is the future, key metrics like ERF will play a bigger role in the time to come.

Waste heat output temperatures

According to the SINTEF study liquid-cooling systems enable a higher potential output temperature of waste heat from the data center. Exit temperature from servers with processors can be up to 80°C. What is necessary to achieve these output temperatures? If the temperature when exiting the data center is stable at approximately 70°C a direct connection to the district heating grid may be possible. The overall value of this solution must be evaluated against the investment costs and future potential.

Data center operations

The SINTEF study should be used for comparison when considering the data center in Stavanger. The data center in Trondheim is called Green Edge Compute One, with area of 135 m^2, capacity of 1 MW and approximately 10 server-racks. Future aspirations are to increase capacity to 2 MW and approximately 20 server-racks. The liquid-cooling system in use at Trondheim data center "One" consists of a propylene-glycol coolant medium. Why is glycol used in this context? If there is no danger of freezing, would not water be a better coolant medium in this case?

Data center testing

Testing on the data center in Stavanger is necessary to uncover operational metrics as it functions with the current equipment. Pilot testing results for the Trondheim data center were inconclusive according to the SINTEF study. As Green Edge Compute has data centers in other locations with similar equipment setup, testing was possible at other these locations to provide equipment test data.

Sustainability

The SINTEF study underlines the fact that the data center industry has not yet implemented comprehensive best practices for sustainability. Key metrics like ERF and others might supplement the mostly used PUE in future evaluations to encompass the environmental impact of data center establishment and operations.

Waste heat energy recovery

From the simple schematics of the data center system in the SINTEF study, there seems to be some excess heat leaking from the liquid-cooling system. Meaning that some heat energy will pass into the air bypassing the liquid-cooling system. As the heat exchange with air constitutes a loss in value, it would be interesting to evaluate how much energy that is in effect lost in this pathway. As heat energy recovery is only feasible for liquid-cooling systems in this context, heat leakage to the ambient air can be viewed as lost energy. If we assume that this is a closed system, and use the capture rate which SINTEF refers to, approximately 4% of the heat energy would need to be dissipated by the air-cooling system. What is the value of lost heat in this scenario? For the case of 2 MW power consumption, 80 kW would be handled by the air-cooling system from server waste heat. Auxiliary equipment is estimated to produce approximately 118 kW, resulting in 198 kW that goes into the ambient air.

Waste heat energy temperatures

Because of lacking test data for the data center in Trondheim, the SINTEF study based their operational temperature data on numbers from cooling system supplier. Capture rates used were 96%, with corresponding input temperature of 39.3°C and output temperature of 46.6°C. An interesting area of investigation would be to evaluate different variants of this setup. What would the effects be for lower temperatures and higher temperatures? Since Lyse Neo can provide free cooling options for certain areas it is possible to lower the coolant input temperature for cooling, would temperatures <39.3°C be of value in this context? Possible issues with lower temperatures can be condensation.

Analysis assumptions

For the evaluation of lost heat energy to the air-cooling system, power consumption for this system is negligible, and is omitted in SINTEF evaluations which can be applied to the Stavanger data center as well.

Heat pump system scenario

The SINTEF study focus includes heat pump systems in the interface between the data center and the district heating system, enabling temperature elevation so that the waste heat pathway into the district heating grid is feasible. Another aspect which is interesting in the case of the data center in Stavanger is direct connection to potential consumers, perhaps with a connection to the district heating system additionally. Focus areas on this case would be largely on the temperature ranges of the waste heat energy output. A parallel scenario to the one presented in the SINTEF study would be a direct heat energy supply grid locally in the area around the data center in Bjergsted. What are the utilization possibility and benefits for direct waste heat energy supply without using heat pumps? Important to evaluate different cases with and without heat pump system integration for temperature elevation. What effects will different waste heat temperature levels have? What is the value for different heat pump systems, and what is the cost benefit picture with and without integration?

Low-temperature energy grid

When evaluating the possibility of a low-temperature energy grid utilizing waste heat energy directly from the data center, it is important to note the cost benefits of not implementing a heat pump system. Cost estimations for the scenario with heat pump system may give a better understanding of the benefits of not implementing a heat pump system. What are the associated costs regarding a heat pump system? What is the development cost of establishing a low temperature heat energy grid locally around the area of the data center in Stavanger? What is the cost of establishing a local heating grid with the possibility of connecting it to the district heating grid? What is the cost of connecting it to the district heating grid? There are several accompanying reasonings that also contribute to why it is beneficial to avoid a heat pump system. Especially considering the load coverage, meaning that there is value to avoid using heat pumps for the main load. This is particularly true when the usage time is shorter. Also, it is important to note the calculations for heat pump materials and resource utilization mentioned in the SINTEF study.

Free cooling system

Waste heat utilization is dependent on an efficient cooling system. A constant supply of coolant at the appropriate temperature is vital to uphold the system homeostasis. The concept regarding waste heat utilization from the data center in Stavanger will include free cooling from the local fjord. Free cooling is possible from the Gandsfjord in Rogaland where the fjords keep a constant 8°C approximately 120 meters from the surface. This environmental phenomenon makes it possible to harness it as a renewable source for cooling. As seen in Figure 32 a low-cost high yield cooling system is conceptualized for the data center in Stavanger [77].

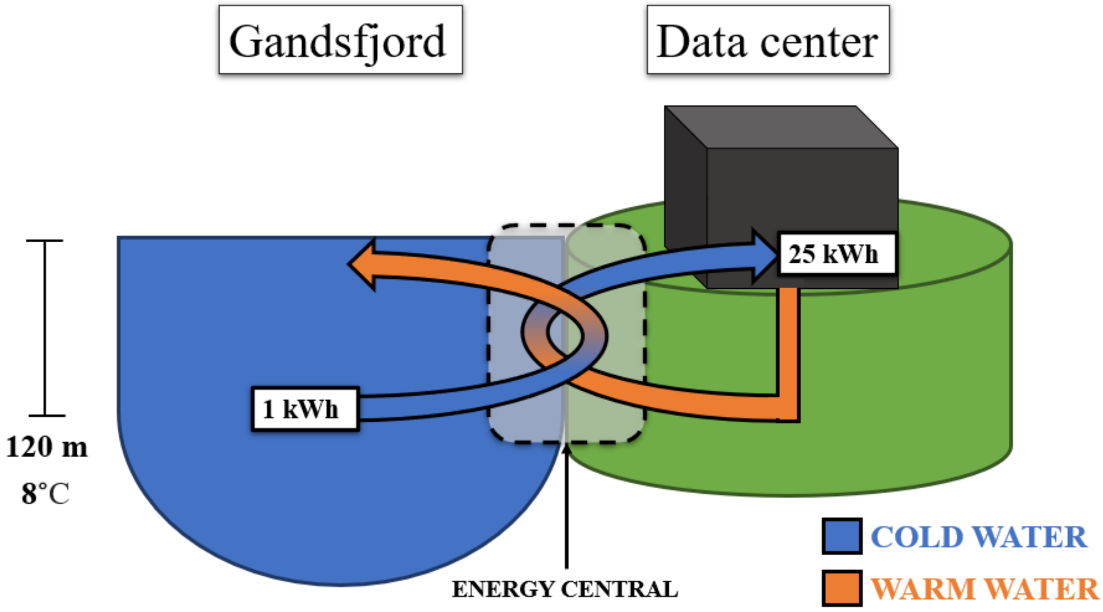


Figure 32 – Free cooling from Gandsfjord in Rogaland.

For 1 kWh in energy cost an estimated 25 kWh of cooling is gained. Cold seawater draws heat energy from fresh water in the energy central unit.

Systematical overview

It is important to conceptualize and visualize a system overview considering the main scenario for waste heat utilization. Meaning a low-temperature nearby heating grid supplied from the data center in Stavanger without the need for heat pumps.

Efficiency metrics

There exist many possible metrics to evaluate the efficiency of a data center. PUE values are commonly used in the industry. Interesting to see the differences in efficiency metrics between existing data centers and new modern data centers as Green Edge Compute develops. There is no standard reference for PUE, but the SINTEF study assumes an average PUE-value of 1.2 based on a calculated 1.17 from a data collection. They also report large variations especially considering IT power consumption and cooling power consumption. Since Lyse Neo is expected to provide free cooling from the Gandsfjord, how will this affect the PUE-value for the data center in Stavanger? As the most inconsistent power consumption variable within data centers compared in the SINTEF study is in fact the cooling power consumption it emphasizes the investigation need here.

Nearby heating grid

A separate district heating grid located in proximity to the waste heat producer is a possible way to distribute and supply waste heat energy to consumers nearby. This will affect the efficiency factor ERF positively. Interesting to compare direct connection to district heating and a nearby heating grid. Nearby heating grids do not generally have free cooling, but will this be possible in the future? Nearby heating grid with free cooling would be a very good combination of technologies for the main scenario of this thesis.

Part IV. Meeting minutes

Notes from meetings and communications with Lyse Neo are presented below. Meeting dates include 14.10.22, 19.12.22, 12.01.23, 22.02.23, and 31.05.23.

Waste heat energy value

Waste heat energy recovered from the data center can be distributed directly for some distance without disruption. For delivery at longer distances, intervention and boosting of the waste heat energy temperature is needed to provide the same temperature range. This radius or feasible distance would be interesting to investigate to find optimum and possible corporate actors willing to connect to a direct supply grid. The value of the recovered waste heat will determine the usage potential. The usage potential will depend on the output temperature. Is it possible to push the temperature to the 70°C temperature level where Legionella bacteria does not proliferate? Is it more feasible to do this by increasing the output temperature from the data center by increasing the operating temperature, or by boosting the temperature with a heat pump system? Tap water delivery criteria is over 50% of the energy usage.

Duration curves

An energy duration curve including district heating with heat energy from incineration at Forus Energigjenvinning, including waste heat and including biogas will have a certain shape. Some energy sources will provide the main load, and some the peak load. Energy sources have different durations and different utilities. For energy sources that have a long duration and can be used the whole year around, higher development costs may be accepted. For energy sources that have a shorter duration, the investment cost magnitude will be decisive. In the two scenarios which are interesting for the waste heat from the data center in Stavanger, one concerns a nearby heating grid, and one concerns connection to the high-temperature district heating grid by utilizing a heat pump system. A nearby heating grid will be an investment that provides effect all year around and can be matched with consumers with needs in the capacity range supplied by the data center. In the case with district heating connection, the grid will have seasonal demands. Here the waste heat energy may only serve as peak load at specific seasonal times of demand. Investment costs will in this scenario determine to a higher degree the feasibility of waste heat utilization. For short energy duration cheap sources are generally utilized, which is not assumed to correspond to waste heat from the data center.

District heating grid connectivity

When considering a newly developed nearby heating grid, it is feasible to consider enabling a connection to the existing high-temperature district heating grid. This has been done before and is possible, but is it technically and economically a good solution?

Appendix F. Future Energy Hub seminar notes

Notes from Future Energy Hub seminar workshop 6 – a smart and flexible solution for low temperature district heating system. Presentation created by Prof. Raoof Gholami (UiS). Seminar date was 1st of February 2023.

EU climate neutral by 2050

An action plan for the EU to be climate neutral is provided through the European Green Deal. The European Green Deal sets out a roadmap for policy measures, legislative actions, and financial instruments to drive the necessary changes for climate-neutral and sustainable future in the EU. It reflects the EU´s commitment to global climate action and serves as a model for other regions and countries striving to achieve their climate goals.

Heating- and cooling systems

Half of the energy in Europe is consumed for heating and cooling. Most of this demand is covered by fossil fuels. Of the heat demand in Europe, 10% is supplied by district heating systems currently.

Waste heat

Along with heating and cooling systems there is waste heat in different scales as excess heat from industrial processes. Different industries release waste heat from cooling systems, air compression, ventilation etc. The quantity of the total waste heat potential is unknown.

Applications

Waste heat can be utilized if it has a sufficient temperature that matches the temperature need of potential consumers. To be able to feed this energy to an existing heat grid like district heating grids, a temperature of approximately 90°C is needed for an even transition without boosting the temperature. Waste heat is a low-grade energy form and loses quality if transported for longer distances. Neighboring companies or buildings are interesting for external use.

Waste heat in EU

In England the main waste heat emitter is electricity generation which is responsible for 82% of the waste heat. The main emitters in France are food and beverage production, pulp and paper production, and basic chemicals production. The largest waste heat emitter in France is food and beverage production with 30%.

Waste heat in Norway

Differs from EU as its primary emitters are manyfold, with wood processing, iron production and chemical industry as the major emitters. These three constitute approximately 68% of waste heat emission in Norway.

Temperature of waste heat energy

Large amounts of waste heat in Rogaland, in the south of Norway. With temperatures ranging from 25°C to 140°C. Approximately 74% is in the range of 40°C to 60°C, which compared to the base temperature of the district heating grid is a low temperature level. Many large industry emitters are located outside major cities, far away from communities. The consequence of this is the fact that transportation is difficult for a low-grade heat energy medium.

Local waste heat emitter

IVAR produces waste heat energy from hot water sections, with an output temperature of 40°C. Their business case for recovery of heat from treated wastewater is noted with a potential with large risk, small complexity, and big profitability.

Data center as emitter

More and more need for data center services, and from their cooling systems waste heat is generated. The output temperature ranges from 20°C to 60°C currently. Two interesting data centers near Stavanger is Green Mountain and Green Edge Compute. Green Mountain data center has an output of about 20°C. The collaboration Kalberg data center has an output of approximately 60°C. Green Edge Compute data center is testing the optimal load for their cooling systems and can possibly archive higher temperatures than 60°C with liquid cooling.

Connection to district heating grids

Low-temperature waste heat energy from industrial emitters needs a temperature boost to be able to supply into existing district heating grids. Two primary heat pump types are interesting, absorption heat pumps and CO_2 heat pumps. Evaluations of this type of integration with waste heat sources are not yet finalized.

Low temperature system

A separate low-temperature district heating system, without using heat pumps for boosting, is possible if there exist consumers that can make use of a lower temperature heat energy which differs from the energy provided by existing high-temperature district heating grids. This type of grid will limit the number of users and will need a constant supply of waste heat. Limit for direct domestic hot water production is approximately 60°C, for direct space heating around 30°C, and for direct cooling the limit is at 20°C. Interesting to see these factors in relation to the evolving district heating systems, and new implementation enables new function and connections.

Heat storage

Heat storage may be useful for low-grade energy storage. Seasonal storage options may be pitting heat storage, borehole storage, and aquifer storage. The most interesting for Norway is borehole storage, and aquifer storage. There is also a momentum in EU generally for use of seasonal heat storage.

System overview

A smart low-temperature district heating system is a solution that waste heat emitters may connect to. This solution holds complexity and main challenges include variable temperatures.

Appendix G. Meeting minutes, research organization SINTEF

Notes from meeting with SINTEF 30.05.2023.

The participant provided insights and responses to various questions related to waste heat energy from data centers. In the meeting it was addressed topics such as the use of renewable energy, metrics for efficiency measurement, the choice of cooling systems, current state of data center industry, risks and challenges associated with waste heat utilization and strategies for achieving a balance between energy efficiency, operational reliability, and environmental sustainability. Economics benefits and cost savings of effective waste heat utilization were also discussed. Additional points were made regarding the utilization of existing infrastructure, temperature considerations and proposed regulatory changes in the industry.

The PUE metric is widely recognized in the industry. A data center can have a low PUE despite dumping waste heat into the environment. Another commonly used metric is ERF, which accounts for energy that is reused.

Propylene-glycol can be used in the system instead of water. Alternative substances like propylene-glycol are used when there is a risk of freezing or boiling. The choice depends on the substance heat transfer capabilities. This is related to heat transfer requirements.

The high energy demand of data centers and the competition for power was highlighted when discussing the current state of the data center industry in terms of its growth, technological advancement, and sustainability practices. There is ongoing discussion about building more renewable energy production to support data centers is, but conflicts arise regarding the allocation of resources. Questions have been raised about whether all data centers should be allowed in Norway and if their presence should serve a greater societal purpose beyond specific applications like TikTok. The energy-intensive nature of Bitcoin mining was also mentioned. Significant growth is predicted for data centers, with considerations for cloud-based solutions and the transition from air-cooling to liquid-based cooling to improve efficiency and to allow high-performance data centers with a larger cooling demand.

The two key challenges regarding risks and challenges associated with waste heat utilization in the data center industry are business-related and temperature challenges. The business-related challenge in utilizing waste heat is an issue due to necessary collaboration with two parties such as the data center and a district heating system. The delivery of waste heat to the district heating system is not always guaranteed due to the vulnerability of waste heat production. The main technological challenge is the low temperature. Location of the data center and the temperature output of waste heat are common factors affecting waste heat utilization.

The importance of building robust and sustainable data centers is a strategy to achieve balance between energy efficiency, operational reliability, and environmental sustainability. Utilizing waste heat is seen as a competitive advantage and a selling point. Large data centers typically have diesel generators for backup power. Establishing data centers in Norway can help the need for such generator due to the stable and safe power supply.

Economic advantages of selling waste heat to a district heating system, providing additional revenue streams for data centers are benefits from effective utilization of waste heat in data centers.

There is proposed amendment to the law of energy that would require a cost-benefit analysis for establishing large data centers, although utilization is not currently mandated.

Locating data centers in cities solves the issue concerning infrastructure and contributes to not disturb uncultivated land. This also has an environmental matter.

Appendix H. Meeting minutes, power supplier Statkraft

Notes from meeting with Statkraft Varme 02.06.2023.

Statkraft is a supplier of district heating and an active participant in energy buying and selling. They are currently harnessing waste heat from various primary sources. One of their major waste heat sources is incineration plants which a dominant role in their operations.

Waste heat temperatures and considerations

When purchasing waste heat Statkraft has the flexibility to acquire it at temperature ranging from 20-30 ℃ and subsequently raise the temperature themselves by using heat pumps. Alternatively, they can purchase waste heat that has already been elevated to the necessary range of 75-80℃. District heating systems operate at a temperature of 65℃ in Denmark. The high temperatures at the district heating systems in Norway is considered being connected to legionella, output temperature from incineration plants or the historical low electricity prices.

Heat pump systems and commercial availability

Statkraft often takes ownership of the heat pump systems responsible for elevating waste heat temperatures. The availability of commercial heat pumps is increasing, making temperature elevation more straightforward. This advancement not only facilitates waste heat utilization but also enables waste heat produces to enhance the temperature of their output before selling it to district heating distributors.

Risks and benefits of waste heat utilizations from data centers

The risks and benefits associated with utilizing waste heat from data centers depend on the scale of the system being supplied and its reliance on waste heat delivery. Smaller systems are more vulnerable to potential disruptions in waste heat supply, whereas larger systems are less dependent on the availability of waste heat from data centers. The integration of waste heat into district heating networks compares to local heating networks is also a topic of consideration.

Strategy for multiple waste heat sources

To accommodate waste heat from multiple sources Statkraft employees a strategy that involves reducing the necessary temperature. This allows them to efficiently incorporate waste heat from diverse sources into their district heating system. Such strategic planning becomes particularly relevant for future generations of district heating systems.

Coefficient of Performance (COP) considerations

The coefficient of performance should be in the range of 3-3.5 when changing the temperature from 46.6℃ to 65-70℃. This parameter ensures the efficiency and effectiveness of the waste heat utilization process.

Energy load considerations and seasonal value

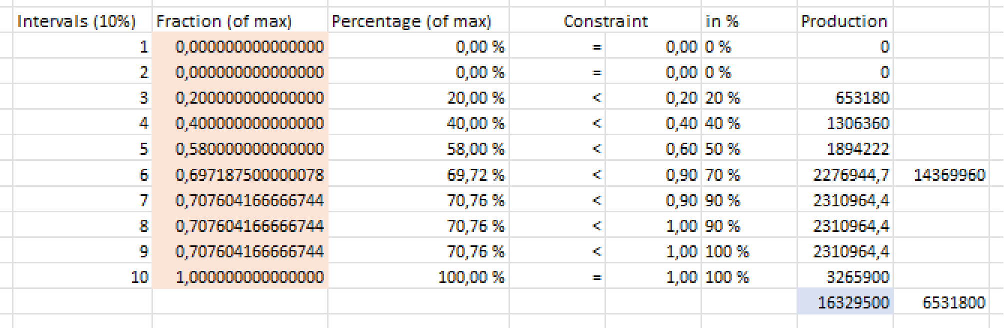
The variation in primary waste heat sources among district heating systems impacts the value of potential waste heat utilization. In both Trondheim and Stavanger waste heat incineration serves as the primary heat source. In Trondheim three waste incineration lines contribute to the base load while peak loads are covered by electrical boilers, gas and fossil fuels. Statkraft is gradually replacing conventional heating methods using fossil fuels to sustainable bio-oil alternatives. Statkraft is gradually replacing conventional heating methods using fossil fuels to sustainable bio-oil alternatives. In Oslo where Gardermoen is the largest recipient, peak loads are met by a heat pump system connected to the Coop organization cooling providing an energy capacity of approximately 25 GWh. In Oslo wood chip firing is turned off during the summer and the waste heat from the heat pumps fulfils the load. In Trondheim, the waste incinerations occur continuously throughout the year ensuring a consistent energy supply. A similar scenario can be observed at Forus Energigjenvinning. During the summer surplus heat is released to air, ground or water as an overflow, while the other energy sources are needed during the winter to meet the peak loads. The location of waste heat producers becomes a crucial factor in determining the most suitable solutions for waste heat utilization. It is advisable to position data centers in areas where there is a demand for waste heat.

Value of waste heat

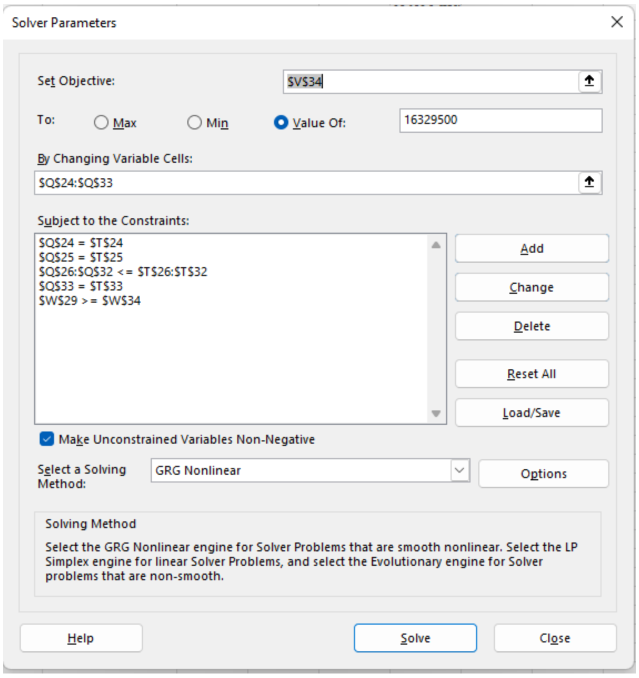
For a district heating system like the one in Oslo where the wood chip firing does not provide a continuous energy supply, waste heat can potentially replace the need in the future if the energy demand is met throughout the year. In Trondheim waste incineration remains a continuous process and the heat energy is available all year around. In the future, if there is an increase or reduction in the waste generation it might lead to a decreased need for incineration. Additional waste heat sources may be required to meet the heat demand. This perspective involves a long-term perspective.

Appendix I. Microsoft Excel Add-In: Solver operations

Simulation of load duration curve for the data center in Stavanger was enabled by leveraging skills learned from Decision Analysis course at UiS during the MSc in Industrial Economics. Solver is a what-if analysis tool often utilized for decision analysis purposes and was leveraged to find appropriate fractions for hourly energy production. The constraints were arbitrarily decided to be able to depict certain phenomena.



Intervals (10%)	Fraction (of max)	Percentage (of max)	Constraint		in %	Production	
1	0,000000000000000	0,00 %	=	0,00	0 %	0	
2	0,000000000000000	0,00 %	=	0,00	0 %	0	
3	0,200000000000000	20,00 %	<	0,20	20 %	653180	
4	0,400000000000000	40,00 %	<	0,40	40 %	1306360	
5	0,580000000000000	58,00 %	<	0,60	50 %	1894222	
6	0,697187500000078	69,72 %	<	0,90	70 %	2276944,7	14369960
7	0,707604166666744	70,76 %	<	0,90	90 %	2310964,4	
8	0,707604166666744	70,76 %	<	1,00	90 %	2310964,4	
9	0,707604166666744	70,76 %	<	1,00	100 %	2310964,4	
10	1,000000000000000	100,00 %	=	1,00	100 %	3265900	
						16329500	6531800



Solver Parameters

Set Objective: $V$34

To: ○ Max ○ Min ● Value Of: 16329500

By Changing Variable Cells: $Q$24:$Q$33

Subject to the Constraints:

$Q$24 = $T$24
$Q$25 = $T$25
$Q$26:$Q$32 <= $T$26:$T$32
$Q$33 = $T$33
$W$29 >= $W$34

☑ Make Unconstrained Variables Non-Negative

Select a Solving Method: GRG Nonlinear

Solving Method

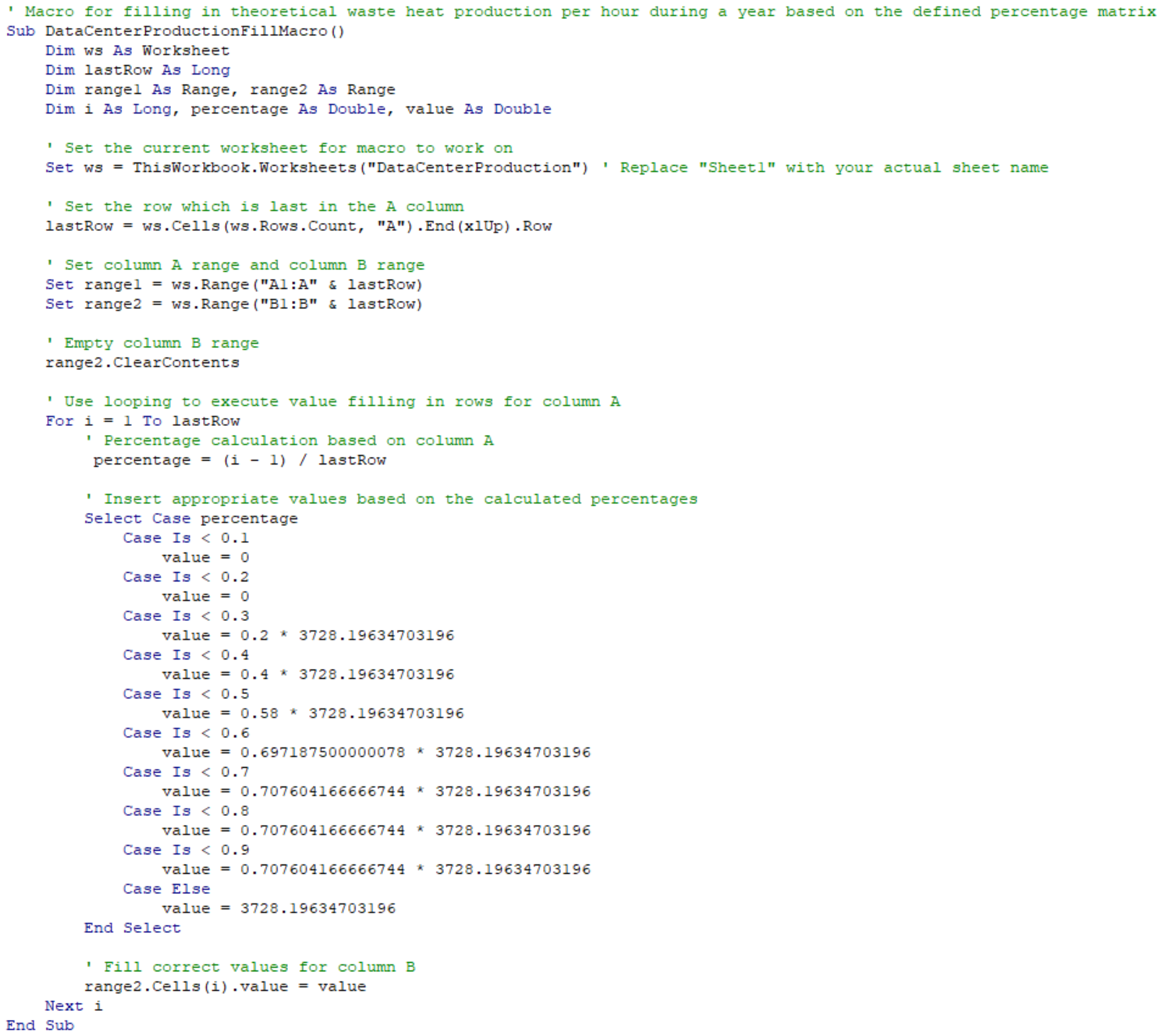
Select the GRG Nonlinear engine for Solver Problems that are smooth nonlinear. Select the LP Simplex engine for linear Solver Problems, and select the Evolutionary engine for Solver problems that are non-smooth.

Figure 33 – Excel screenshot of Solver analysis basis.

Includes a theoretical interval distribution for expected differences in energy production for the data center in Stavanger. Intervals 1 and 2 reflect the warmest months with no supply from the data center to the integrated district heating grid. Intervals 3-6 increase and reflect an increasing supply with decreasing temperatures after the summer. Intervals 7-10 reflect the peak of energy supply from the data center in the coldest months of the year. Bear in mind that this simulation is purely hypothesized and was only created to somewhat indicate trends in the potential supply of waste heat from the data center.

Appendix J. Visual Basic for Applications: Subroutine Macro code segment

Simulation of load duration curve for the data center in Stavanger was enabled by leveraging skills learned from Data Modelling courses at UiS during the MSc in Industrial Economics. Visual Basic for Applications (VBA) in the integrated programming language in Microsoft Excel and can be utilized for larger data modelling tasks. VBA was used to automate input for rows corresponding to all hours during a full year, in total 8760 hours.



```
' Macro for filling in theoretical waste heat production per hour during a year based on the defined percentage matrix
Sub DataCenterProductionFillMacro()
    Dim ws As Worksheet
    Dim lastRow As Long
    Dim range1 As Range, range2 As Range
    Dim i As Long, percentage As Double, value As Double

    ' Set the current worksheet for macro to work on
    Set ws = ThisWorkbook.Worksheets("DataCenterProduction") ' Replace "Sheet1" with your actual sheet name

    ' Set the row which is last in the A column
    lastRow = ws.Cells(ws.Rows.Count, "A").End(xlUp).Row

    ' Set column A range and column B range
    Set range1 = ws.Range("A1:A" & lastRow)
    Set range2 = ws.Range("B1:B" & lastRow)

    ' Empty column B range
    range2.ClearContents

    ' Use looping to execute value filling in rows for column A
    For i = 1 To lastRow
        ' Percentage calculation based on column A
         percentage = (i - 1) / lastRow

        ' Insert appropriate values based on the calculated percentages
        Select Case percentage
            Case Is < 0.1
                value = 0
            Case Is < 0.2
                value = 0
            Case Is < 0.3
                value = 0.2 * 3728.19634703196
            Case Is < 0.4
                value = 0.4 * 3728.19634703196
            Case Is < 0.5
                value = 0.58 * 3728.19634703196
            Case Is < 0.6
                value = 0.697187500000078 * 3728.19634703196
            Case Is < 0.7
                value = 0.707604166666744 * 3728.19634703196
            Case Is < 0.8
                value = 0.707604166666744 * 3728.19634703196
            Case Is < 0.9
                value = 0.707604166666744 * 3728.19634703196
            Case Else
                value = 3728.19634703196
        End Select

        ' Fill correct values for column B
        range2.Cells(i).value = value
    Next i
End Sub
```

Figure 34 – Subroutine Macro code segment.

With purpose to fill in values in each of the theoretical production supply hours of a hypothetical year. Based on the percentage intervals from the Solver analysis, input was automated to insert based on the set intervals. Meaning lower supply half of the year, and larger supply half of the year. According to Green Edge Compute, Statkraft Varme in Trondheim was only able to utilize half of the available heat energy from the data center there. This is the assumption here as well.