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Modelling and Simulation of Grid Connected Electro-Thermal Microgrid with Utilization of Waste Heat from Power Transformer

Modellering og simulering av nett-tilknyttet elektro-termisk mikronett som utnytter spillvarme fra transformator

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Preface

This work marks the end of my six years as a student. Starting off with a Bachelor's degree in physics at the University of Bergen, including an exchange semester at the University of Iceland in Reykjavik. I am now completing my master's and ready to embark on a professional career armed with a specialization in environmental physics and renewable energy obtained from the Norwegian University of Life Science (NMBU).

Microgrid technology has been in my interest the last few years since I was introduced to the issues and ongoing projects on the island of Utsira. The island is located outside my hometown Haugesund, and has therefore become a natural case study to turn to. For my master's, I therefore wanted to include microgrid technology, and my supervisor came up with the thermal aspect of it. This thesis's overall research question and created model are therefore inspired by the microgrid case at Utsira. However, it must be specified that this work is done by me independently and Utsira has only been an inspirational source, such that the parameters and results don't necessarily fit for the actual case at Utsira.

I would, first of all, like to thank my supervisor, Jagath Sri Lal Senanayaka, who has been a great support during this semester and always welcomed me when having questions and issues with my model. Writing this thesis without any experience within modelling and simulation has been a challenge and my patience has been put to the test, but I am now grateful to have been introduced to Simulink/Simscape and seen the opportunities it can provide.

Furthermore, I would like to thank my fellow students that I have grown close bonds to during these years, in Bergen, Reykjavik, and here in Ås. My time as a student has now come to an end, and I am really looking forward to new challenges and opportunities as an Energy-Trainee for the next two years.

Silje Johannessen Monstad
Ås, 15th of May 2023

Abstract

Microgrid technology is a promising method to overcome technical challenges related to the integration of distributed intermittent renewable energy. However, effective energy storage for maintaining power balance is crucial to obtain independent operation from the utility grid. Electric heating dominates in Norway and heating purposes make up the largest share of households' total energy consumption. Substituting electricity with alternative heating methods could thereby free up electricity within microgrids. Thermal microgrids consist of low-temperature district heating networks and thermal energy storage, and could be such an alternative heating method. Furthermore, it enables better integration of low-temperature sources such as waste heat. Power transformers generate heat from stepping up and down voltage and may be such a waste heat source.

This thesis examines if implementation of thermal microgrids can boost storage capacity and strengthen the reliability of microgrids. In addition, it investigates if heat recovery from a power transformer could be a valuable source for low-temperature district heating. To examine the presented, an electro-thermal microgrid model with both battery and water tank storage has been carried out in Simulink/Simscape, where the main objective was to study power and heat flows. For comparison, a fully electrical model was also created.

Simulation results showed the power transformer could contribute greatly to the district heating network, and together with heat pump technology, the overall system performance was significantly improved compared to electricity heating. The power demand within the microgrid was significantly decreased, improving the time of running self-sufficiently by 12 %. Furthermore, it enabled the electro-thermal microgrid to netto export during the week, economically resulting in a difference of 100 000 NOK. During a grid failure scenario, the electro-thermal microgrid had more available storage capacity as the discharge rate was lower. Especially, the thermal energy storage showed it provided great flexibility and boosted the storage capacity as it could run independently for several hours.

The overall conclusion is that implementation of thermal microgrids will extend storage capacity, improve reliability and resilience, provide flexibility and increase the energy systems' performance. Additionally, power transformers are found to be great contributors to low-temperature district heating. Appropriate planning of their location to easier utilize the heat for other interests should be considered. However, it will be necessary to create the model physically and not only based on power/heat flows for more accurate simulation results.

Norsk Sammendrag

Mikronett teknologi er en lovende metode for å overvinne tekniske utfordringer ved å integrere distribuert variabel fornybar energi. Imidlertid er effektiv energilagring avgjørende for å oppnå uavhengig drift fra strømnettet ved å opprettholde en balansert kraftforsyning. Elektrisk oppvarming dominerer i Norge og oppvarmingsformål utgjør den største andelen av husholdningers energiforbruk. Ved å erstatte elektrisitet som oppvarmingskilde med andre oppvarmingsmetoder kan potensielt effekt frigjøres i mikronettet. Termiske mikronett består av lav-temperatur fjervarmenett og termisk energilarging, og kan være en slik alternativ oppvarmingsmetode. I tillegg gjør et slikt system det enklere å integrere lav-temperatur kilder slik som spillvarme. Krafttransformatorer generere varme ved å transformere opp og ned spenning og kan være en slik spillvarmeressurs.

Denne oppgaven undersøker om implementering av termiske mikronett kan øke largingskapasiteten og styrke påliteligheten til mikronett. I tillegg undersøkes det om varmegjenvinning fra en transformator kan være en verdifull kilde i lav-temperatur fjernvarmenettet. Det er derfor laget en elektro-termisk mikronett modell med batteri- og vanntankslagring som er modellert i Simulink/Simscape, hvor hovedfokuset har vært å studere effekt og varmestrømmer. For sammenligning er det utviklet en hel-elektrisk modell.

Simuleringsresultater viste at transformatoren kunne bidra vesentlig til fjernvarmenettet, og i kombinasjon med varmepumpeteknologi, ble systemytelsen vesentlig forbedret sammenlignet med elektrisk oppvarming. Effektbehovet i mikronettet ble betydelig redusert, og tiden mikronettet kunne operere uavhengig av hovednettet ble forbedret med 12 %. Dessuten var det termiske mikronettet i stand til å netto eksportere til hovednettet, noe som utgjorde en økonomisk differanse på 100 000 NOK gjennom uken. Ved feil på nettet viste det termiske mikronettet at det hadde mer tilgjengelig lagringskapasitet ettersom utladningsraten var lavere. Spesielt bidro termisk energilagring med å øke fleksibilitet og lagringskapasitet da det kunne levere selvstendig i flere timer.

Den overordnede konklusjonen er derfor at implementering av termiske mikronett øker lagringskapasitet, pålitelighet og motstandsdyktighet, fleksibilitet og forbedrer systemytelsen. I tillegg er det funnet at transformatorer kan gi et vesentlig bidrag til lav-temperatur fjernvarmenett. Gjennomtenkt planlegging av deres lokasjon for å lettere kunne utnytte spillvarme til andre interesser burde derfor vurderes. Videre vil det være nødvendig med fysisk modellering og ikke bare ta hensyn til effekt/varmestrømmer for mer nøyaktige resultater.

List of Abbreviations

4GDH Fourth generation district heating.

COP Coefficient of performance.

HEX Heat exchanger.

LTDH Low-temperature district heating.

PT Power Transformer.

PV Photovoltaic.

SoC State of charge.

TES Thermal energy storage.

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1 Introduction

In this chapter, first, the background and motivation of the research are presented. Next, the research questions are stated and put into context by presenting the case study. Lastly, a short overview of the thesis structure is given.

1.1 Background and Motivation

The Paris Agreement, signed in 2015, became a breakthrough for international climate policy. Most of the world's countries made commitments to reduce greenhouse gas emissions, aiming for maximum global warming of 2 °C, but preferably at 1.5 °C compared to pre-industrial levels [1]. The Intergovernmental Panel on Climate Change (IPPC) states in the latest *Summary for Policy Makers (2021)* from the *Climate Change 2021* report

> It is unequivocal that human influence has warmed the atmosphere, ocean, and land [...]. Human-induced climate change is already affecting many weather and climate extremes in every region across the globe (p.4). [2]

Norway has committed to reducing its greenhouse gas emissions by 50 to 55 % by 2030, a crucial step in achieving its low-emission society goal for 2050 [3]. In order to accomplish this, it is imperative to increase investment in renewable energy and enhance electrification efforts. Traditionally, Norway's energy mix has been dominated by adjustable hydropower. As the energy mix diversifies to include renewables such as wind and solar power (PV), we will encounter challenges for the future electricity grid associated with decentralized power production, energy storage, and intermittent production. Energi21[1] highlights "efficient and integrated energy systems", in the report *Strategy 2022*, as one of the focus areas that should be paid special attention to. Further, this is justified by the following: "The power grid, system operation and supply security are key challenges that has to be overcome to succeed with the green transition" (p.5) [4].

Microgrid technology is a promising method for solving many technical challenges related to grid integration of distributed intermittent renewable energy. Furthermore, microgrids help to increase local reliability and resilience [5, 6]. Maintaining the power balance within the electricity grid is crucial and requires energy storage as an essential component in microgrids to ensure reliability, especially with the intermittent nature of decentralized power production. Despite its potential, microgrid technology has had limited usage in practical

[1]National strategy for research, development and commercialisation of new climate-friendly energy technology. It is established by the Ministry of Petroleum and Energy.

applications so far due to high costs of storage systems, etc. Batteries are considered a crucial component in microgrid technology, but are expensive and have generally low capacities for usage on a long term. Battery storage should therefore be complimented by other forms of energy storage systems for increasing the storage capacity. However, microgrids are recognized as one of the key-stones in the future electricity grid and several pilot projects have been implemented in Norway the recent years, such as on the islands Utsira and Senja [7, 8]. The islands share a weak distribution network, and therefore, microgrid technology is an appealing alternative to increasing transmission capacity.

Throughout history, Norway has enjoyed affordable electricity rates thanks to available and inexpensive hydropower. Consequently, the country predominantly relies on electric heating for its heating system and has a smaller proportion of district heating compared to its Scandinavian counterparts. Nonetheless, the building sector is responsible for more than one-third of the final energy consumption worldwide [9], and this is largely due to heating requirements. Research has revealed that in Norwegian households, 80 % of the energy consumed is utilized for heating purposes, with approximately 67 % dedicated to space heating while remaining 13 % is allocated to domestic hot water [10]. Combining this knowledge with the fact that electricity has become a valuable commodity, heat demand could be covered by other, more low-value energy carries resulting in a relieved power system. This would in fact be an advantage for microgrid technology, as the electrical energy storage could be lowered.

District heating could be a solution to cover heat demand and thereby free up electricity within the grid. These systems undergo a transition to so-called fourth-generation district heating (4GDH), which are low-temperature district heating systems (LTDH). District heating with low supply temperatures enables low-temperature sources to better be integrated into the energy system [11]. For the case of microgrids, implementing LTDH and thermal energy storage (TES), which goes under the term *thermal microgrid*, could free up electricity within the microgrid and thereby improve reliability and resilience.

Waste heat occurs commonly as a low-temperature source which could be integrated into LTDH. Until now, there has been no requirement by law that these resources must be utilized, but recently, waste heat recovery from data centers and industry has been paid special attention [12]. However, there is a wider range of systems providing heat as a by-product which have not been discussed to the same degree. Power transformers (PTs) are critical infrastructure and are a part of the electricity grid. From stepping up and down voltage, they generate heat. With further electrification, the role of PTs will remain important, and may, with advantage, be analyzed as waste heat sources.

There have been few projects related to waste heat recovery of PTs. Further, actually few studies covers the topic. In Norway, a pertinent case for this exists at Bergen's Smart City Montana, where an outdated substation on the mountainside necessitates modernization. The propositional solution involves submerging the substation and creating a smart city above it, which captures the heat it generates for district heating [13, 14].

The presented background forms the baseline of this thesis, where the aim is to study how implementation of a thermal microgrid (LTDH and TES) will affect the microgrid operation for a decentralized area with limitation in transmission capacity. For investigating the described, a grid-connected electro-thermal microgrid with utilization of waste heat from a PT is modelled and simulated for in Simulink/Simscape in MATLAB. Further, a relevant case study is used as an inspirational source, namely the island of Utsira.

1.2 Research Questions

The overall research question of this work can be summarized as follows

> Will implementation of thermal microgrids boost storage capacity and strengthen the reliability of microgrids?

Additionally, a secondary question explores a possible low-temperature source for the thermal microgrid

> Could heat recovery from power transformers be a valuable source for the thermal microgrid?

1.3 Case Study

As initially introduced in the background of this thesis, Utsira is one of the islands who has an on-going pilot project related to microgrid technology and smart energy systems. For setting the research questions into context, a short introduction to Utsira is given below:

> Utsira is located outside Haugesund on the west coast of Norway (see Figure 1). The municipality is Norway's smallest based on inhabitants and second smallest by area [15]. The island has marked itself by participating in Norsk Hydro's investment in a hydrogen project from 2002 to 2010 [16]. Two wind turbines were then installed at the island, and since then, the island has been of interest within microgrid technology.
>
> The island has therefore locally renewable energy production from the two wind turbines with an installed capacity of 1.2 MW. The recent years, some PV modules have also been installed. The distribution grid on the island is considered weak and is connected to the utility grid on the mainland through an old and long seacable. The seacable therefore sets limitations for the transmission capacity to the island. However, during the year, the island exports more power to the utility grid than it consumes, but in cases of high electricity demand at winter time and lack of wind power, the grid can experience voltage issues. An old ferry battery has therefore been implemented as voltage support on the island [17]. Nevertheless, the lack of available power makes it difficult to start up any new industries or electrify the island further, e.g. the local ferry [18].
>
> Furthermore, ENOVA[2] has supported the pilot project for smart energy control, microgrids and flexibility markets on the island [7]. In addition, Utsira is highly relevant due to the declared field for offshore wind, Utsira Nord, which is located just outside the island and will cover a lot of the municipality's sea area. The installed capacity of the wind farm is announced to be 1500 MW and the connected substation is proposed to be located on the island [19].

[2]ENOVA is an organization for contributing to energy-use and energy-production conversion in Norway.

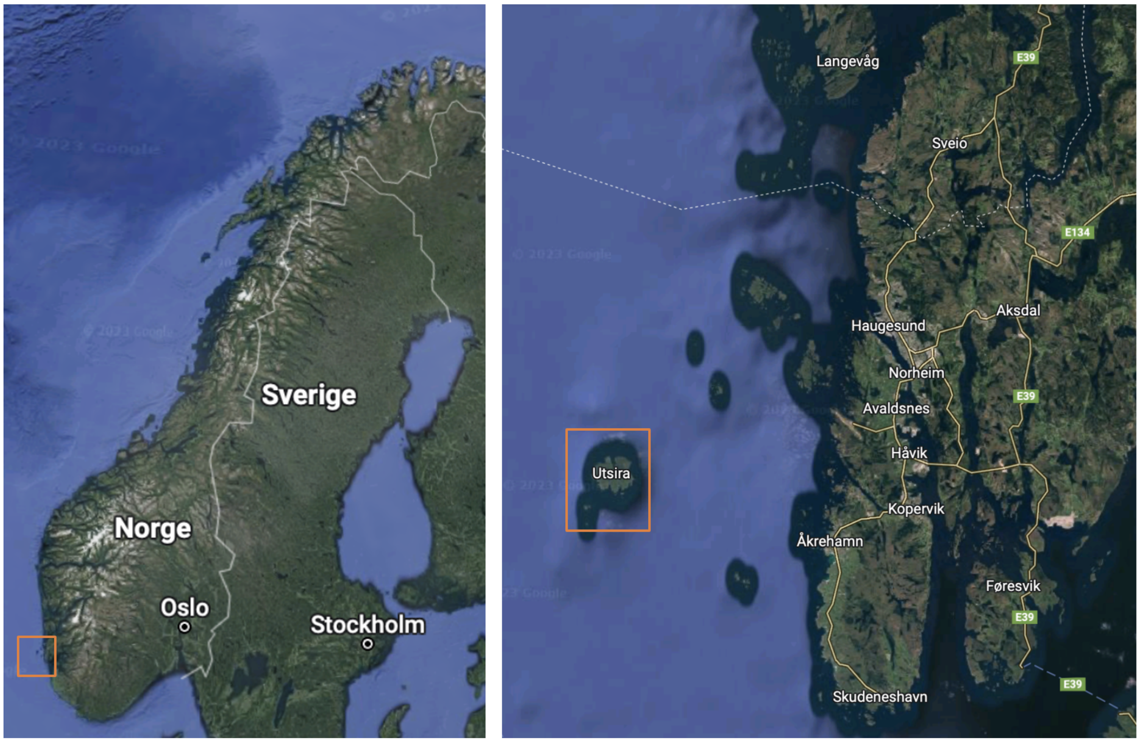

Figure 1: The location of Utsira Island in Norway, at the west coast outside Haugesund.

In other words, Utsira has locally energy production, energy storage, local loads, and a clear connection point to the utility grid, and are therefore closely related to microgrid technology. Furthermore, it has limitations in transmission capacity from the utility grid and it could be interesting to see how the implementation of a thermal microgrid could affect the energy situation on the island. If the new substation in connection to the offshore wind farm gets located on the island, a low-temperature heat source would also be available.

The overall topic of this thesis has been inspired by their case, however, the created model, used parameters, and results are not necessarily consistent with Utsira. For example will a LTDH network be preferable within areas with high heat densities and within low-energy buildings. Therefore, the purposed solution may not be the best suitable solution for Utsira. The case is still used as the aim is to present general findings for a decentralized electricity grid with limitations in utility grid transmission capacity and therefore could be an attractive location for establishing a microgrid, or further, hybrid electro-thermal microgrid technology.

The created and analyzed model in this thesis can be described by the following components:

1. Grid-connection to utility grid
2. Battery storage
3. PV production
4. Wind power production
5. Household consumption
6. Fixed load
7. Thermal energy storage
8. Waste heat from power transformer
9. Heat pump
10. District heating network

1.4 Thesis Structure

The next chapters of this report are organized to present information relevant to the objectives, models, results, and discussion of this thesis. **Chapter 2** provides the definition of a microgrid, followed up by the definition of a thermal microgrid. In addition, theory for heat recovery of PTs is included. **Chapter 3** aims to give a description of the method used, including choice of components and parameters, model description with working principles, and software tool used for modelling. **Chapter 4** includes the results and **Chapter 5** provides the discussion. Finally, **Chapter 6** presents the final conclusion and suggestion to model improvements and further work are included in **Chapter 7**.

This thesis presents the definition of a thermal microgrid based on [20]. They state a thermal microgrid consist of the features of an traditional electrical microgrid, but that the term "thermal" is added for highlighting it also provides thermal services. However, this thesis have used the term **electro-thermal microgrid** model to emphasize it has both an electrical and thermal section. Further, to compare with the traditional electrical microgrid, this will be referred to as the **electrical microgrid** model.

2 Theory

The second chapter provides the relevant theory for this thesis. Firstly, the concept of microgrids is presented, including the definition, recognized advantages and energy storage technologies. Secondly, thermal microgrids are introduced, including theory of LTDH, waste heat, heat pump and TES. Finally, heat recovery from PTs is presented, including transformer losses, waste heat potential and temperature, and system designs for the recovery.

2.1 Microgrid

2.1.1 Definition and Advantages

Microgrid is a relatively new concept and the definitions somehow vary. In 2015, a working group from the International Council on Large Electric Systems (CIGRÈ) went through a variety of formal definitions of microgrid and found two fundamental requirements:

1. The microgrid contains sources and sinks under local control
2. The microgrid can operate either grid-connected or in island mode

Furthermore, the working group defined microgrid by the following

> Microgrids are electricity distribution systems containing loads and distributed energy resources, (such as distributed generators, storage devices and controllable loads) that can be operated in a controlled, coordinated way either while connected to the main power network or while islanded [5].

Another commonly used definition of a microgrid is presented by the U.S. Department of Energy's Microgrid Initiative, defining it as

> [A microgrid is] a group of interconnected loads and distributed energy resources within clearly defined boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island mode (p. 84) [6].

Both definitions include the term distributed energy resources, which by definition can include small-scale fossil fuels, biomass, photovoltaic modules, wind turbines, mini-hydropower, etc. Energy storage can be electrical, electrochemical, mechanical or thermal [5]. These storage technologies are further presented in Section 2.1.2. For smart energy systems, which microgrids will undergo, the concept of controllable loads is also of importance. Within a microgrid, the load variability will be higher compared to utility-scale systems [5], and the ability to disconnect non-critical loads or delay them will be crucial for minimizing the power consumption within the grid. A general illustration of a microgrid setup is given in Figure 2.

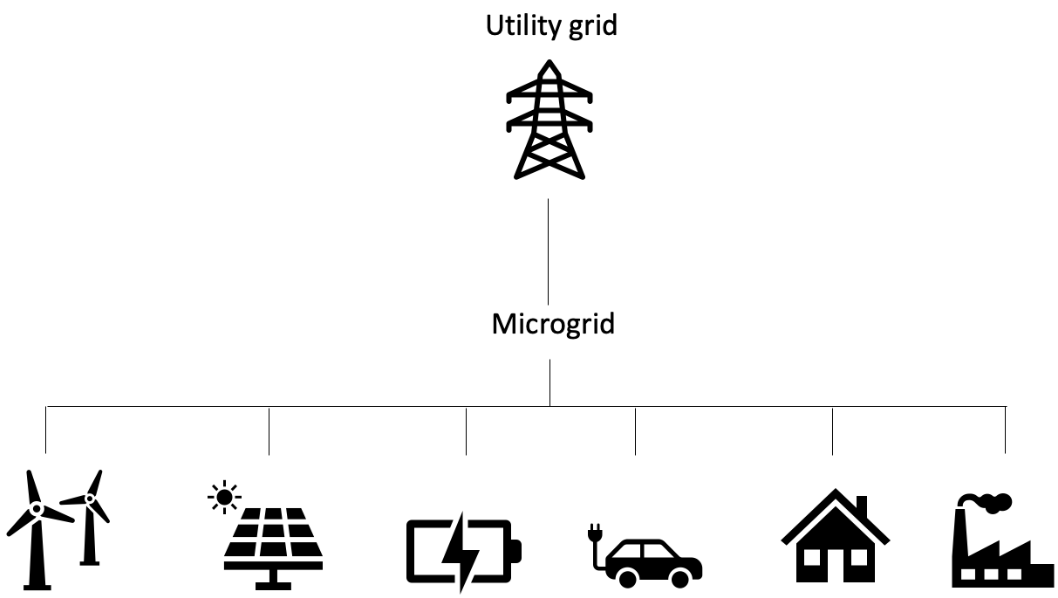

Figure 2: Illustration of typical microgrid with energy generators, energy storage, loads and a clear connection point to the utility grid.

The definition of microgrid does not include any scale of production, load, or storage. Therefore, a minimum time the microgrid should be capable of operating in island mode is not given by definition, but the intent is that it can function for more than just a few minutes [5]. Therefore, the installed energy storage needs to reflect the range of local consumption, as the ability to run independently from the utility grid is one of the main advantages of microgrid technology [5].

Several advantages related to microgrid technology have been identified, such as improved energy efficiency, minimization of energy consumption, reduced environmental impact, improvement of reliability and resilience, and more cost-efficient electricity infrastructure replacement [5, 6]. These findings comes from the fact that microgrids enable energy production to be close to consumption, which will reduce power losses in transmission lines and the need for power lines crossing the country. Furthermore, as they should be able to run independently, the reliability and resilience for locals may be improved. This will be the case when having grid failures or other disturbances, and actually, cyber-attacks and natural disasters have become drivers for microgrid technology the recent years [5]. In addition, controllable loads can provide local flexibility and reduce overall costs as they can be disconnected when having higher power demand or price.

Although the Department of Energy's (U.S) definition of a microgrid is based on electrical boundaries [6], TES can play a role if it impacts the microgrid operation [5]. Thermal microgrids are therefore presented in Section 2.2.

2.1.2 Energy Storage

Sterner and Stadler (2019) defines energy storage as

> An **energy storage** is an energy technology facility for storing energy in the form of internal, potential or kinetic energy. An energy storage preforms three processes: **charging** (loading), **storing** (holding), and **discharging** (unloading). These processes are physically implemented by energy converters (charging and discharging), storing units (holding), and peripherals. A complete facility, including all these components, is called an **energy storage system** (p. 24) [21].

Energy storage within a microgrid can be electrical, electrochemical, mechanical, or thermal [5]. The most important function of energy storage is to provide reliability, as there always has to be power balance within the grid. Renewable energy such as wind and solar are to a strong degree fluctuating, and the need for energy storage to keep balance in the system is therefore higher than for adjustable hydropower or fossil fuels which can be adjusted after the demand. Energy storage are therefore crucial within microgrids. Table 1 presents some commonly used storage techniques and Figure 3 shows capacity and discharge time for the energy storage systems.

Table 1: Overview of possible energy storage techniques.

Storage Technique	Storage Type
Pumped hydro	Mechanical
Flywheel	Mechanical
Battery	Electrochemical
Supercondensator	Electrical
Hydrogen	Chemical
Sensible heat	Thermal
Latent storage	Thermal
Thermochemical	Thermal

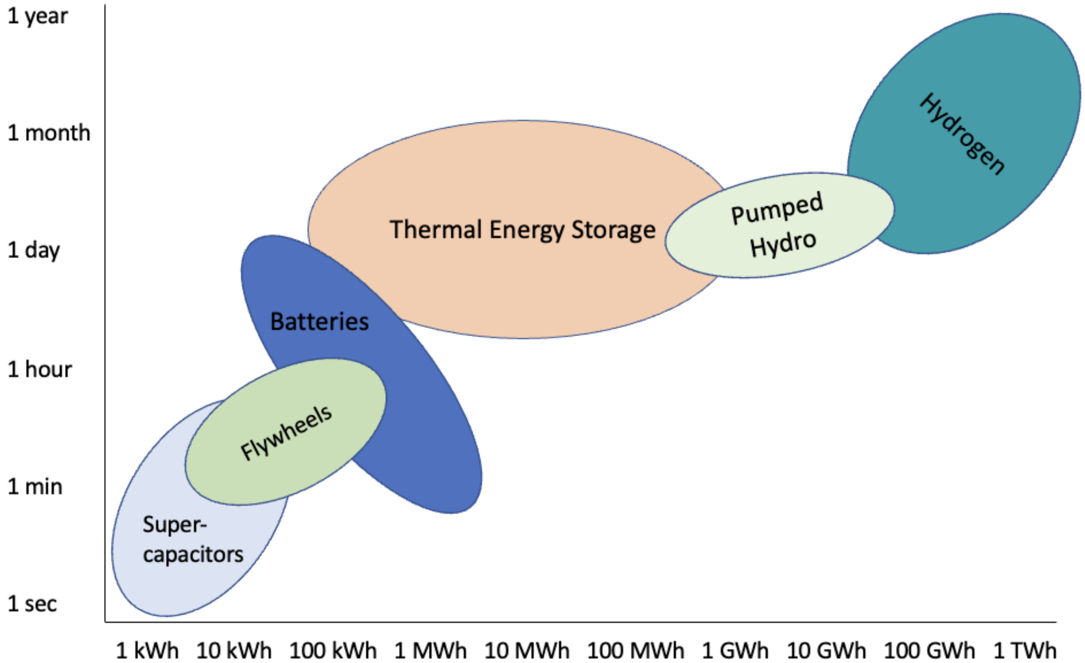

Figure 3: Storage capacity and discharge time for various energy storage technologies. Illustration inspired by [21].

Energy storage systems can be classified as short-term or long-term storage. Short-term includes secondly, minutely, hourly, and daily basis. Most short-term storage systems are designed for hourly or daily storage and are often used for balancing short-term fluctuations in the electricity grid [21]. For long-term, it will be on a weekly, monthly, or seasonal basis, and be used to balance seasonal fluctuations in energy supply due to for example low water levels (hydropower) or high peak demand in cold periods [21].

From Figure 3, the various energy storage systems have different characteristics, whereas super capacitors have low installed capacity and short discharge time. On the other hand, hydrogen storage generally provides high storage capacity and long discharge time.

Choosing storage technology should therefore be based on what function the storage shall provide for the energy system. Batteries will generally have both shorter discharge time and lower installed capacity than TES systems. Depending on which TES system is applied, the storage can last for months [21]. For this thesis, battery and TES will be in focus. Below will a short introduction to battery storage be given, while TES will be covered under the section of thermal microgrids (2.2.5).

A battery is defined as a multiple of electrochemical cells of the same chemistry in a container, where electrical energy can be stored as chemical, and thereby be converted back to electrical energy [22]. The capacity of a battery is the amount of charge that can be withdrawn from a fully charged battery under specific conditions. This number is specified by the manufacturer and usually given in Ampere-hours [Ah] [22], but can also be given in kilo-watt-hours [kWh]. The stored energy is given as

$$E = P * t \tag{1}$$

where E is the stored energy [kWh], P is the power [W] and t is the time [h]. Further, state of charge (SoC) is defines as the fraction of the full capacity still available for further discharge and is given as

$$\text{SoC} = [100 - \%\text{depth-of-discharge}] \tag{2}$$

2.2 Thermal Microgrid

2.2.1 Definition

When searching for the concept of thermal microgrids, it is a lack of papers on the topic. The added term "thermal" into microgrid is used to indicate that the microgrid not only includes the provision of electricity, but also thermal services like hot water, steam, or chilled water. EDF Innovation Lab (2017) defines a thermal microgrid as

> A thermal microgrid utilizes energy efficiency; renewable electricity-powered heat recovery; thermal storage; and, advanced analytics and controls to provide co-optimized power and thermal services to a group of interconnected and controllable energy loads within a defined boundary (p. 11) [20].

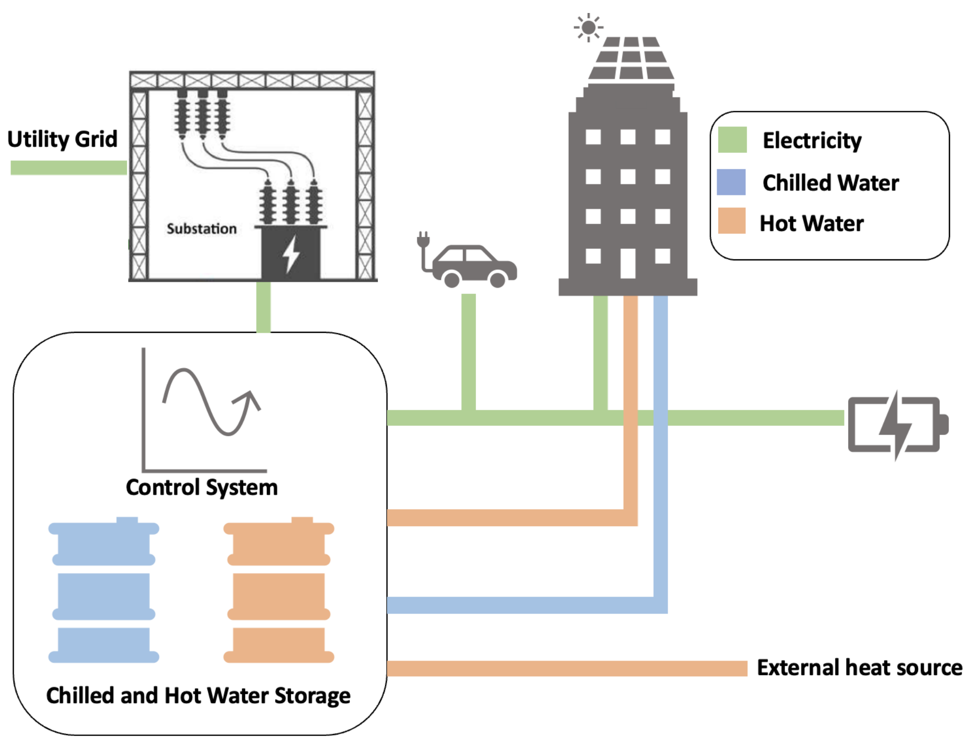

Figure 4: Illustration of the thermal microgrid concept introduced by EDF Innovation Lab [20].

The illustration of the concepts shows an electricity distribution network and a thermal network consisting of a chilled network and a hot water network. The district heating is therefore an essential part of the thermal microgrid, but EDF highlights that the definition also includes the features of a traditional microgrid [20]. The section below gives a short introduction to district heating, or more specific in this case, LTDH.

2.2.2 Low-Temperature District Heating

Before introducing the concept of LTDH, the general district heating term is presented. A district heating network provides heat delivery to consumers through a pipe network of hot/-cold water, and can cover both space heating and domestic hot water use. At the supply side, it is a heat central which can utilize several energy resources like waste management, bioenergy, gas, and waste heat. On the consumer's side, there are installed heat exchangers (HEX) and the buildings are installed with systems for receiving waterborne heat, e.g. radiators/floor heating. Generally, for district heating networks, it is preferable to have short distances between heating central and consumers for lowering heat losses in the pipe-network. According to [23], heat loss of 8 - 15 % of the total heat delivery can be expected in Norway. The temperature drop is dependent on several parameters: temperature levels in the district heating network, ground temperatures, pipe length, mass flow rate, and the heat loss coefficient of the material (insulation) [23].

The *Heat Roadmap Europe* study [24] came to the conclusion that thermal grids will play a crucial role in the redesign of the energy system and the integration of renewable energy and excess heat sources. Modern district heating, or LTDH, are an attractive solution for better integrating renewable energy resources and waste heat, as these heat sources often provide low-temperature outputs, which then can be utilized in the low-temperature network [25].

District heating systems can be categorically separated based on temperature levels, where the first generation of district heating (1GDH) used steam as a heat carrier and were first introduced in the U.S. in the 1880s [25]. 2GDH used pressurized hot water with supply temperature over 100 °C and were common from the 1930s to the 1970s. The third generation of district heating (3GDH) systems were introduced in the 1970s, using pressurized water as the heat carrier, but now with temperatures below 100 °C [25]. Lowering the supply temperature leads to lower grid losses and enables low-temperature sources to contribute to the system. This can be referred to as fourth-generation district heating (4GDH), or as initially introduced, LTDH. The temperature level should in this case be as close to the demand as possible, at a maximum of 60 - 70 °C [11]. For Norway, the majority of district heating networks are of the third generation with supply temperatures of 80 - 90 °C [23]. The findings of [23] shows the heat losses can be lowered by 25 % when decreasing the supply temperature from 80 to 55 °C.

Schmidt et al. [26] presented several successfully implementations of LTDH, concluding the technology is proven to be reliable and market-ready. 15 selected demonstration activities in Europe were analyzed, proving heat sources as solar collectors, heat pumps, combined heat- and power plants, and excess heat from industry, working finely in the low-tempered thermal grid. Temperature combinations (supply/return) were typically 70/40 °C, 65/35 °C, 50/30 °C, etc. [26]. As space heating requires generally low temperatures and domestic hot water requires a range of 50 °C to avoid the risk of legionella bacteria, these low temperature combinations are considered suitable [27].

2.2.3 Waste Heat

Heat occurs naturally as a by-product in several industries, infrastructures, and commercial activities. This heat often enters the surroundings without any further utilization and is thereby defined as waste heat or excess heat.

NEPAS and Norwegian Energy executed in 2009 a comprehensive survey of the utilization of waste heat in the Norwegian industry. The mapping included 63 % of the energy use in the Norwegian industry on the mainland, such as concrete, aluminium, chemical industry, etc. The report concluded with a theoretical potential of waste heat at 19 TWh in 2009 [28, 29]. Furthermore, the report pointed out some barriers to why the utilization of waste heat has had a slow process, like the lack of an external heat-marked and district heating infrastructure. Other factors mentioned are immature technology, capital, lack of economic attractiveness and low awareness or unavailable competence [28].

The quality of the waste heat is dependent on temperature and defines the various possible purposes for utilization. Table 2 presents an overview of output waste heat temperatures and potential purposes for use.

Table 2: Overview of different temperature intervals for waste heat and possible purposes for use. Table from [28].

Temperature	**Potential Purpose**
>140 °C	Electricity production District heating
60 - 140 °C	Electricity production District heating
40 - 60 °C	Low temperature district heating Heat source for heat pump
25 - 40 °C	Heat source for heat pump Fish farming Ground heating

From the Table, LTDH and heat source for heat pump are mentioned for temperature ranges of 40 - 60 °C and 25 - 40 °C, respectively. In other words, a heat pump is commonly used for achieving higher temperatures for utilization in district heating. The basic principles of heat pump technology are given below.

2.2.4 Heat Pump

Heat pumps increase energy efficiency by converting a share of electrical energy into a higher amount of heat energy. The efficiency factor is called the Coefficient of Performance (COP) and is dependent on the working temperatures. The COP is given by

$$\text{COP} = \frac{Q_H}{W} = \frac{T_H}{T_H - T_C} \tag{3}$$

where Q_H is the heat energy output and W is the electrical energy input. Furthermore, T_H is the temperature of the high-level source, T_C is the temperature of the low-level source, and $(T_H - T_C)$ is the temperature difference between the two temperature levels.

From Equation 3, the COP is dependent on the temperature lift done by the heat pump. Minimizing the temperature lift will therefore result in a higher COP and give increased efficiency for the heat pump. Using waste heat as a source for the heat pump, as purposed in Table 2, can therefore increase the efficiency of the district heating system. Heat pumps are recognized as important for the efficient heating of buildings and have been installed worldwide the recent years [30].

The most commonly used heat pump is the air-to-air heat pump. Other types are water-source heat pump (WSHP), often denoted as a water-to-water heat pump. In addition, it is possible to use an air-to-water heat pump.

2.2.5 Thermal Energy Storage

TES is considered a key technology for enabling optimized system operation of a thermal microgrid [20]. The main function is to balance thermal energy supply and demand, and can increase the amount of heat recovery potential enable electricity load shifting, and improve reliability and resilience by providing service during grid disturbances, etc [20].

There are several options of TES systems, and the technologies can be divided into three main groups: 1) sensible heat storage, 2) latent heat storage, and 3) thermochemical heat storage. The three categories have various maturity of technology and storage capacities. The thermochemical will have highest energy density, but lowest development of technology. The latent heat storage, where heat energy is stored in phase change of a material, has lower energy density but are more developed. Lastly, sensible heat storage is the most common, easy to use, and commercially proven, but also has lowest heat density [21]. Sensible heat storage will be of focus in this thesis.

Possible technologies for sensible heat storage systems are water tanks and underground storage such as borehole heat storage and aquifer heat storage. Water tanks are commonly associated with short-term storage, while the underground storing are considered seasonal storage systems [21]. The most common storage medium to use is water, as it has high specific heat, easy availability, is environmental friendly, and has low costs [21]. The sensible heat storage will therefore be in range of 0 - 100 °C for preventing freezing and boiling.

Sensible heat is the energy required to change the temperature of a substance without phase change. Thermal energy or heat can be stored in a sensible heat storage by

$$Q = mC_P\Delta T \tag{4}$$

where Q is the added or removed heat, m is the mass, C_p is the specific heat and ΔT is the temperature change $(T_2 - T_1)$. Equation 4 can further be derivative to calculate heat flows and mass flow rates.

2.3 Heat Recovery of Power Transformers

PTs play a critical role in the power system by enabling efficient and cost-effective transmission of electricity with minimal voltage drops [31]. In operation, they provide heat loss. The following sections will provide information of how PTs generate heat losses, their waste heat potential and operating temperatures, and lastly, system designs for heat recovery.

2.3.1 Transformer Losses

Generally, when a machine transfers energy from one form to another, there will always be a certain loss that will occur in the machine itself. This causes an increase in temperature and a reduction in efficiency [32]. Transformers are stationary electrical equipment, meaning they have no revolving parts, and therefore only generate electrical losses. However, under normal operation the efficiency may reach 99.5 % for large PTs [32]. I.e., the losses are generally low compared to other machines.

PTs generate both no-load and load losses. The no-load losses include losses from hysteresis and eddy currents, which occur as the primary windings needs to be energized with voltage to prepare for incoming power. Currents in the iron core itself arises and give hysteresis losses. Further, the load losses will be dependent on how much current is flowing in the windings and give ohmic losses [32, 33]. Since the heat loss is dependent on the voltage and current the PT is exposed to, the manufacture sets limits to these values, known as the nominal voltage and nominal current. Furthermore, the power rating, or capacity, is equal to the product of these [32].

2.3.2 Waste Heat Potential and Operating Temperature

There are few studies covering the topic of heat recovery of PTs. However, project SHOES: *Secondary Heat Opportunities from Electrical Substations* and a case study from Denmark contributes to the research field. Both papers conclude heat recovery from PTs has a great potential for contributing to district heating networks [33, 34].

Bowman et al. (2020) gathered manufacturer's nameplate data for varying transformer ratings and derived a kW/kVA losses factor. The total losses factor was estimated to be 0.67 %, where 0.0087 % comes from no-load losses, and the remaining 0.59 % is related to load losses [33]. Assuming 40 % loading and that 80 % was actually recoverable, they estimated a heat potential of 50 kW for a 25 MVA PT [33].

The output temperature from the transformer will decide if the waste heat can be directly utilized in district heating or if a heat pump is necessary to lift the temperature further (see Table 2 for temperature levels and purposes for use). The temperature within a transformer will have a gradient from bottom to top, where higher temperature will be found at top (top oil) and colder levels at bottom (bottom oil) [34]. The operating temperature will be dependent on the transformer loading [32]. Bowman et al. (2020) found an average oil temperature at ranges between 40 - 50 °C, meanwhile Petrovic et al. (2021) found an average top oil temperature of 33.5 °C [34]. However, the PTs were not fully loaded, where the study by Petrovic et al. (2021) assumed an average load of 30 %, resulting in a lower top oil temperature. At rated conditions (nominal voltage and current), the top oil temperature could be up to 105 °C, but the majority of PTs are oversized due to the dependency on service time [34]. According to [32], service life diminishes by half every time the temperature increases by 10 °C.

Petrovic et al. (2021) analyzed if the waste heat potential could be improved by changing the load on the PT or by increasing the operating temperature such that the waste heat could be directly used in to district heating. Doubling the load from 30 % to 60 % increased the waste heat recovery potential significantly [34]. However, when increasing the operating temperature for direct utilization, they found a decrease in potential. The study included district heating network with a supply temperature 80 °C, and therefore the operating temperature were increased to 90 °C, resulting in no need for a heat pump. Thereby, they didn't get to utilize the advantage of heat pump technology.

2.3.3 System Design: Heat Recovery of Power Transformers

To prevent too high temperatures within the PT resulting in reduced efficiency and increased need for service, adequate cooling of the windings and core must be provided [32]. PTs can either be so-called dry, or oil-immersed. Larger PTs are usually immersed in mineral oil and enclosed in a steel tank [32], as oil is a better insulator than air. There are several cooling methods and they are generally chosen based on the PT's need for cooling. For oil-immersed PTs, the oil circulation can be either be induced by pumps (oil-forced cooling) or due to thermal buoyancy (oil-natural). Hot oil reaches the top of the PT and goes into the cooling system, where the cooling system can be so-called air-natural (AN), air-forced (AF), or water-forced (WF). For both air cooling methods, radiators are used, but for air-forced cooling, fans are also included. For larger PTs in the range of megawatts, it is common to apply water-forced cooling, by use of an oil-water HEX [32].

Following are some system designs for waste heat recovery of PTs for usage in district heating networks. For all designs presented, water-forced cooling is assumed. Figure 5 presents a proposed system from [33], where firstly, water-forced cooling is applied, followed by a water-to-water heat pump for lifting the temperature before entering the district heating network.

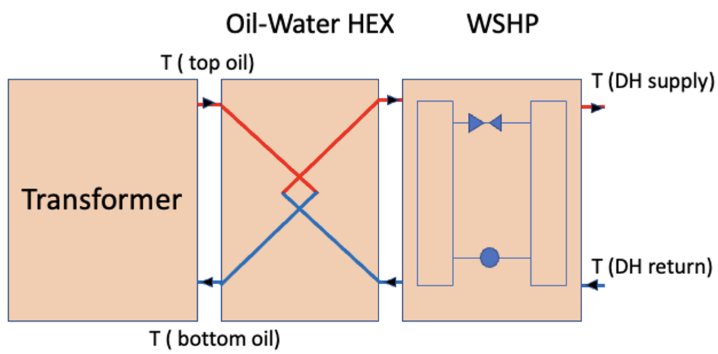

Figure 5: Heat recovery design for PT with oil-to-water HEX and water-to-water heat pump.

If the top oil temperature is higher than the district heating supply temperature, the waste heat can be directly utilized through a HEX. The system design is presented in Figure 6.

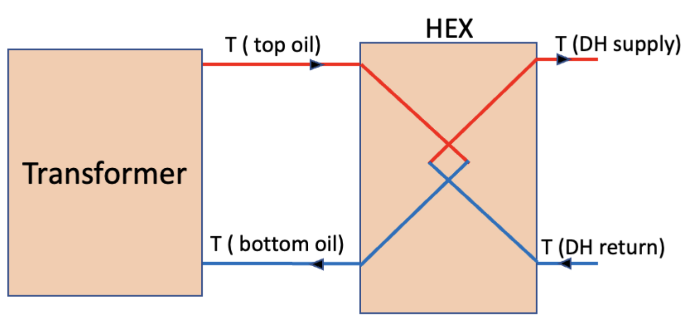

Figure 6: Heat recovery design for PT with heat exhanger for direct utilization.

Thirdly, a system design presented in [34] involves both a heat pump and HEX for increasing efficiency. The design is presented in Figure 7.

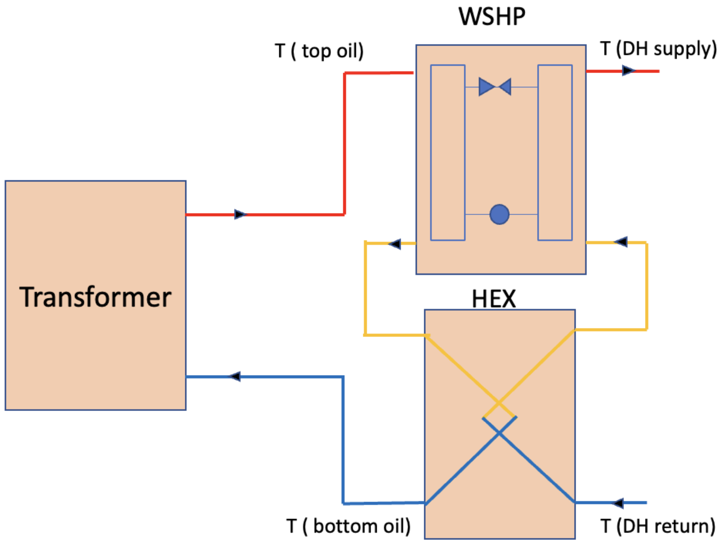

Figure 7: Heat recovery design for PT with heat pump technology in combination with a HEX.

3 Method

Chapter 3 presents the method used for answering the research questions. Firstly, an overview of the main lines is given, thereby the electro-thermal microgrid model is described with its layout, parameters, data input, etc. The comparison model and a constructed grid failure scenario are then presented. Lastly, an introduction to the applied software for modelling and simulation is given.

3.1 Introduction to Methodology

To examine the presented research questions in Section 1.2, the following decisions were made:

1. Create an electro-thermal microgrid model with components of energy generators, loads, electrical energy storage, a PT as a waste heat source, a district heating network, and TES.
2. Set the power balance within the model as focus area. Including energy generation, consumption, and transfer, both electrical and thermal.
3. Model the energy generators and loads as voltage/current sources and sinks.
4. Test the model in normal operation.
5. Test the robustness of the model by constructing grid failure.
6. Compare the electro-thermal microgrid to a fully electrical microgrid model for easier improvement comparison.
7. Include basic economic comparison

Furthermore, Utsira was picked as an inspirational case study. An introduction to the island was given in Section 1.3. Naturally, some of the electro-thermal microgrid model's main components are based on Utsira.

However, there has been no implementation of detailed power electronics as the main focus was on power balance. Furthermore, reactive power has not been included in the study.

3.2 Electro-Thermal Microgrid Model

This section provides information of the created electro-thermal microgrid model. Firstly, the main components are presented, thereby, the system layout and set parameters. Thirdly, the simulation week and data input are given, including the calculation of expected waste heat from a PT. Followed by is the electrical model used for comparison presented, and the constructed grid failure scenario for testing the robustness. Lastly, the used software is introduced.

3.2.1 Choice of Main Components

PV and wind power were selected as energy generators aligning with the energy generators at Utsira. Additionally, battery storage was chosen as the electrical energy storage solution due to its current implementation on the island. The energy model includes a fixed load and a variable load to account for the demands of farms, households, school, commercial building and grocery store located at Utsira.

In terms of thermal considerations, the network had to be designed to accommodate the selected heat waste source, which was PTs. As outlined in Section 2.3.2 of the theory, studies on recovering heat from PTs indicate operating temperatures ranging from 30 - 50 °C [33, 34]. Consequently, the transformer was regarded as a low-temperature source, and the model incorporated heat pump technology for lifting the temperature. For TES system, sensible heat storage was chosen as it is commercially proven and easy to use [21]. Further, as the main object was to study power balance within the electro-thermal microgrid, a short-term storage was considered the best technology, and therefore a water tank was used as storage technology.

3.2.2 System Layout

Figure 8 shows a block diagram of the electro-thermal microgrid model. The image clearly shows the connection point to the utility grid and the division of the electrical and thermal sections of the model. The heat pump and variable load are highlighted, meaning they have both an electrical and thermal function in the model. The heat pump uses electricity and outputs heat energy, while the variable load represents household demand meaning they have both electrical demand and heat demand.

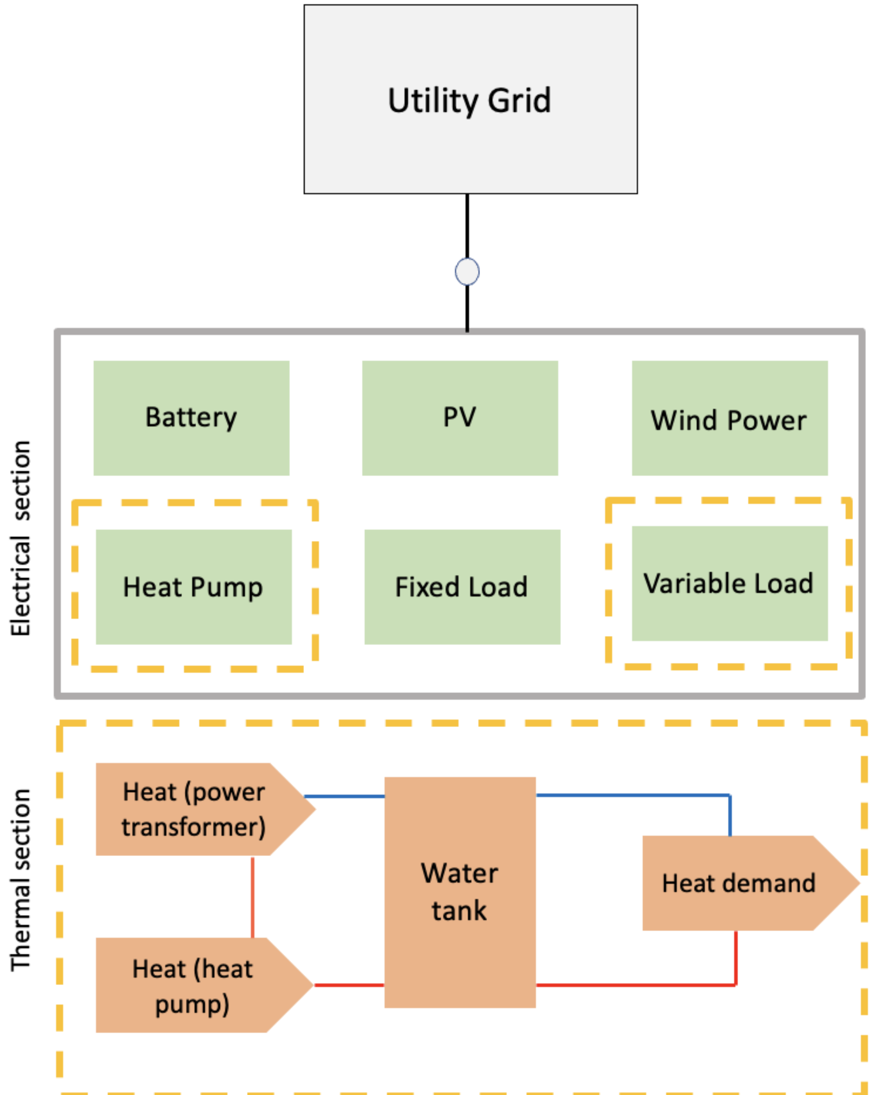

Figure 8: Block diagram of electro-thermal microgrid model.

Later in the text, this model will be referred to as the **electro-thermal microgrid model**. When mainly referring to the LTDH, this is often referred to as the **thermal microgrid**, **thermal network** or **thermal section**.

3.2.3 Working Principles/Control Systems of the Model

General working principles of the electro-thermal microgrid model were set:

1. **Battery charging:** When local renewable energy production from PV and wind power exceeds local consumption, charge the battery with the overshoot before exporting to utility grid.

2. **Utility grid transmission limit:** If delivered power from the utility grid exceeds a set limit, use the battery storage as voltage support.

3. **Return line water heating:** Cold return water from households gets first heat added by the PT, and then additional heat from the heat pump to lift to required supply level.

3.2.4 System Parameters

Table 3 and 4 summarises the set parameter values. Several of the electrical parameters for the model was set such that the total load varied around 1 MW at peak for actually gaining the described case scenario for Utsira, where the implemented battery is needed sometimes as voltage support. The battery capacity was further set to match the local demand and power generation, after the definition of a microgrid, where it is supposed to run independently in island more for more than just a few minutes [5]. The loads on the island were not identified in detail, such that the variable load was based on household demand, even though there are for instance a school, swimming pool, commercial buildings, etc, located on the island[3]. In addition, it was assumed a fixed load which could be controllable of 0.35 MW.

Installed capacity of the wind turbines was set to 1.2 MW, which is actually the case on the island, meanwhile no data was found regarding installed PV modules. These were therefore assumed to be 40 kWp. The transmission capacity limit for the sea cable was assumed to be 1 MW. From the study of [10], it was assumed 20 % of the total variable load was for electrical appliances.

[3]This can be considered an aggregated variable load for all the different loads, but are modelled based on a created household load profile.

Table 3: Parameters for electrical considerations of the electro-thermal microgrid model.

Electrical Parameters	**Value**
Households	200
Installed capacity PV	40 kWp
Installed capacity wind turbines	1.2 MW
Battery capacity	1.2 MWh
Battery SoC (min, max)	[5, 92] % [4]
Battery rated power	1 MW
Fixed load	0.35 MW
Variable load (min, max)	[0.49, 0.78] MW
Electrical demand of total variable load	20 %
Utility grid transmission capacity	1 MW

For thermal considerations, it was chosen to have a LTDH network with supply temperature of 60 °C. This value could be lower, but as Norway has strict regulations regarding avoiding legionella bacteria, the temperature was considered realistic as the heating network is supposed to cover both space heating and domestic hot water. Further, based on the temperature combinations presented from the successfully LTDH networks [26], several combinations had a temperature drop of 30 °C, so this was assumed also in this work. For the heat pump, the COP was set to 3. This was as if a top oil temperature of 40 °C was assumed, then the COP will be 3 when lifting to 60 °C. The heat demand for the households was set to 80 % of the total variable demand based on the study of [10]. Heat losses from pipe-network and water tank was modelled as aggregated losses. This was set to 10 % based on the study of [23] and was baked into the heat demand in the model.

The size of the transformer will affect the heat loss it will generate [32]. As the installed capacity in the offshore wind farm is announced to be 1500 MW, a large substation is demanded for transforming the incoming power. However, to set the PT consistent with the size of the thermal microgrid, it was chosen to use a 300 MVA PT. The expected waste heat supply from the PT are presented with calculations in Section 3.3.3.

[4] When reaching 5 % SoC the battery is set to be not functional.

Based on the heat demands, supply, and a decided average supply/return temperature of 60/30 °C, the circulation pumps in the network were set to mass flow rates at 4.4 kg/s from Equation 4. For assuming a large system, as 200 households are involved in the district heating, the water tank was assumed with a dimension of 10m x 10 m x 3m.

Table 4: Parameters for thermal considerations of the electro-thermal microgrid model.

Thermal Parameters	**Value**
Supply temperature	60 °C
Return temperature	30 °C
COP	3
Heat loss	10 %
Heat demand of total variable demand	80 %
PT rating	300 MVA
Heat supply PT	0.32 MW
Flowrate consumers side	4.4 kg/s
Flowrate heat supply side	4.4 kg/s
Water tank initial temperature	60 °C
Water tank dimensions	300 m3
Water tank energy capacity	13.95 MWh [5]

For getting an idea of the storage capacity of the chosen storage technologies, small calculations were done. Firstly, the battery,

$$t_{discharge} = \frac{1.2\,MWh}{1\,MW} = 1.2\,hours \tag{5}$$

Secondly, the water tank storage

$$t_{discharge} = \frac{300\,000\,kg}{4.4\,kg/s} = 18.94\,hours \tag{6}$$

[5] With 20 °C as reference level.

3.3 Simulation week and Data Input

To study power flows in the microgrid, it was chosen to simulate for an entire week. The required data for the electro-thermal microgrid model was solar irradiance, wind speed, household load curve, price curve and expected heat supply from the PT. A short presentation of the data material is given in this section.

3.3.1 Simulation Week

The selection of simulation week was influenced by the desire to simulate a high power consumption in the grid. As winter tends to have higher power demands, week 5 (31. January to 6. February) of 2022 was chosen randomly.

3.3.2 Solar Irradiance, Wind Speed, Household Load and Power Price

Solar irradiance was used for generating PV power in the model. Due to lack of available data for Utsira, solar irradiance for Ås, Norway was used. However, since the simulation week falls in early February, solar irradiance is minimal and therefore unlikely to impact the model significantly. The solar irrandiance for Ås was therefore considered sufficient enough for such an initial study. As PV was modelled as a current source, only the estimated power production was essential for the model. It was assumed an overall efficiency of 20 % and a total solar panel area of 200 square meters. Power delivered from PV is given by

$$P_{pv} = \eta * S * A \tag{7}$$

where η is the efficiency, S is the solar irradiance and A is the total area.

Wind speed from a weather station on Utsira was downloaded from [35] for week 5, 2022. The wind power production was calculated from

$$P_{wp} = \frac{1}{2} * C_p * \rho * A * v^3 \tag{8}$$

where C_p is the coefficient of performance, ρ is the density of air, A is the sweiping area and v is the wind speed. The data set included several values of quite high wind speeds, and according to [36], wind turbines deliver a maximum efficiency when reaching 12 - 13 m/s so the high wind speeds were filtered. As the installed capacity was set to 600 kW per turbine, the power output was limited to this value at maximum. Based on a rotor diameter of 40 m [16], the swiping area was set to 1257 m2.

For providing a variable load, it was chosen to download actual consumption data for a price region in Norway (NO1) for week 5 in February. The curve was then scaled down to fit an average household consumption with taking inspiration of a load curve presented by Ericson and Halvorsen (2008, p.48 [37]), as their study provides separate profiles for each month.

The price curve used for the basic economic calculations was downloaded from Nordpool's database [38].

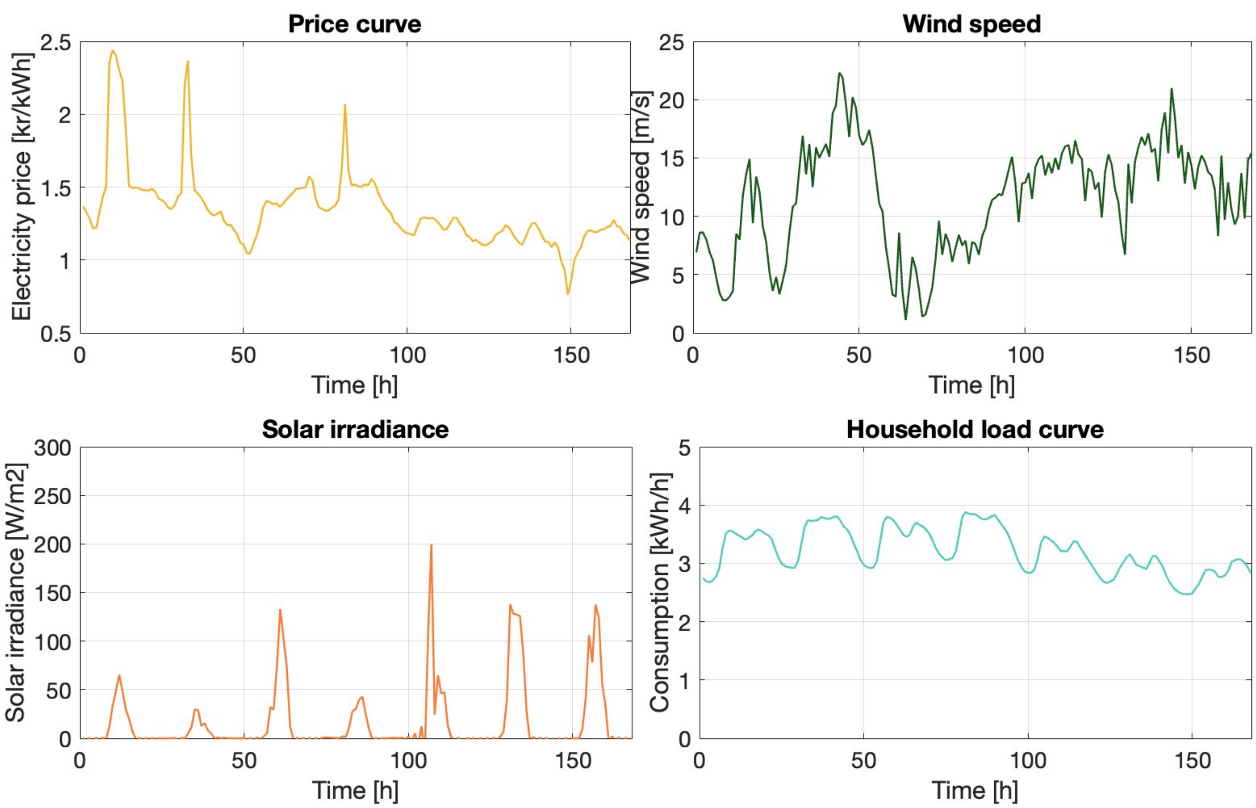

Figure 9: Input data for solar irradiance, wind speed, household load profile and power price.

3.3.3 Heat Supply from Power Transformer

The heat supply input from the PT was based on the heat losses factor presented by Bowman et al. (2020) at 0.67 % [33]. Further, they presented 0.0087 % came from no-load losses and 0.59 % from load-losses. Plotting the losses versus power capacity rating and assuming 40 % load was put on the transformer, gave the linear graph presented in Figure 10. From the graph, a 300 MVA PT will generate 0.8 MW available heat energy with the assumed load. However, the figure includes a curve if only 40 % of this heat is actually recoverable for district heating.

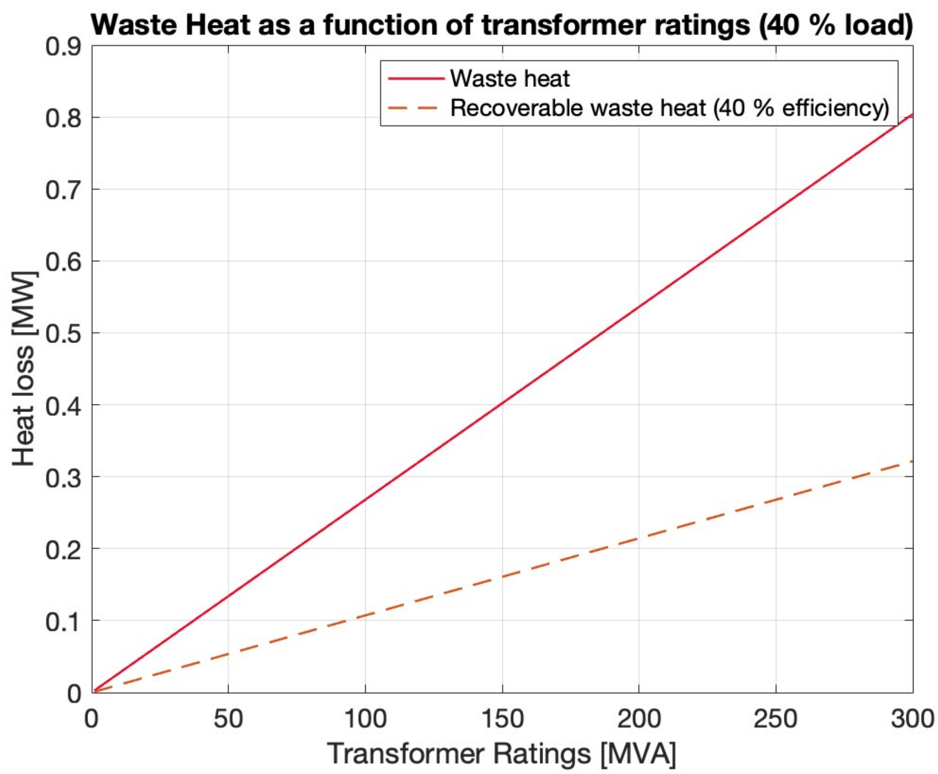

Figure 10: Waste heat as a function of transformer ratings.

In Figure 11, the expected heat loss for a 300 MVA transformer is plotted versus the percentage load. The line ends at 2 MW when having 100 % load on the PT, showing the heat losses increase by the load. In addition, the no-load losses line is included in the plot, showing great potential even when the PT is idling. However, these curves are based on an assumption that 100 % is actually recoverable, and the potential will probably be lower.

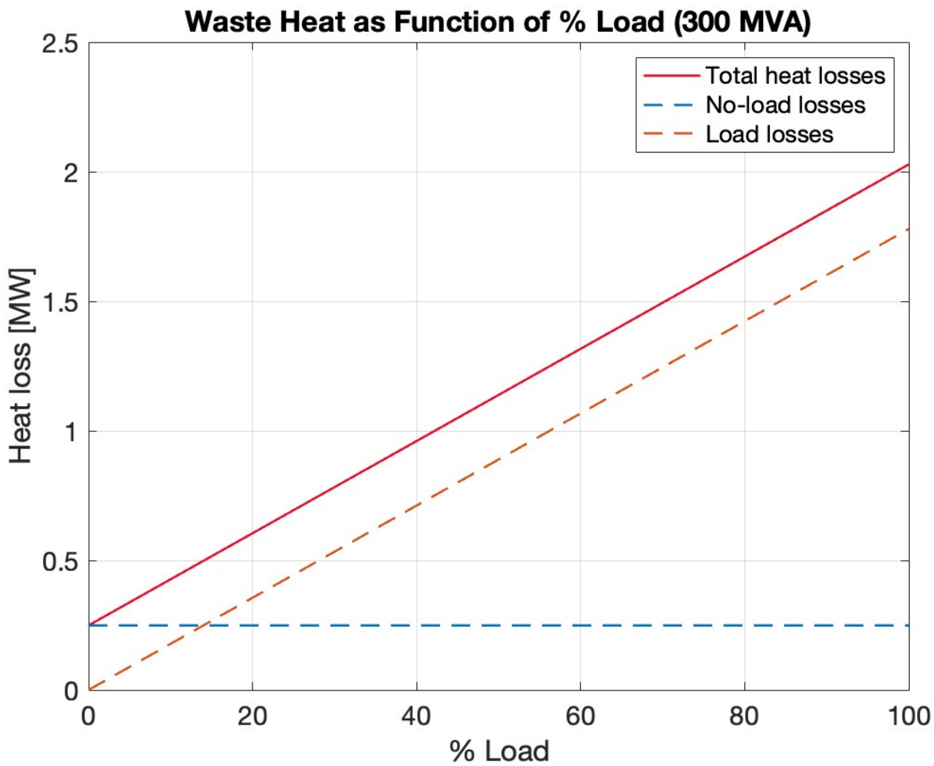

Figure 11: Waste heat for a 300 MVA transformer as a function of loading.

The load-losses dominate the total losses and are the ohmic losses in the windings equal to I^2R. The curves should therefore not be linear, but this was assumed as the only factor taken into account was the capacity rating and the losses factor by [33]. As the theory states, it is common to oversize PTs due to the dependency on lifetime [31]. Bownman et al. (2020) assumed a constant 40 % loading, while Petrovic et al. (2021) assumed 30 %. For this thesis, 40 % constant loading was assumed. Expected heat loss is then given by

$$P_{loss} = 0.67\% * 300\ MVA * 40\% = 0.81MW \tag{9}$$

It would be unrealistic to assume that all of this heat could be provided into the district heating network. The heat would be partly lost in HEXs, pipe-losses, etc. Therefore, it was chosen to assume only 40 % would be actually recoverable. For the 300 MVA PT, available heat is then calculated by

$$P_{recoverable} = P_{loss} * 40\% = 0.32MW \tag{10}$$

This value was set as a constant heat supply from the PT in the model.

3.4 Electrical Model for Comparison

For easier comparing the actual improvement for the microgrid operation by implementing a thermal microgrid, a fully electrical microgrid model was created for comparison only. Figure 12 shows a block diagram of the model, showing it is the same model as the created electro-thermal microgrid model but without the thermal section.

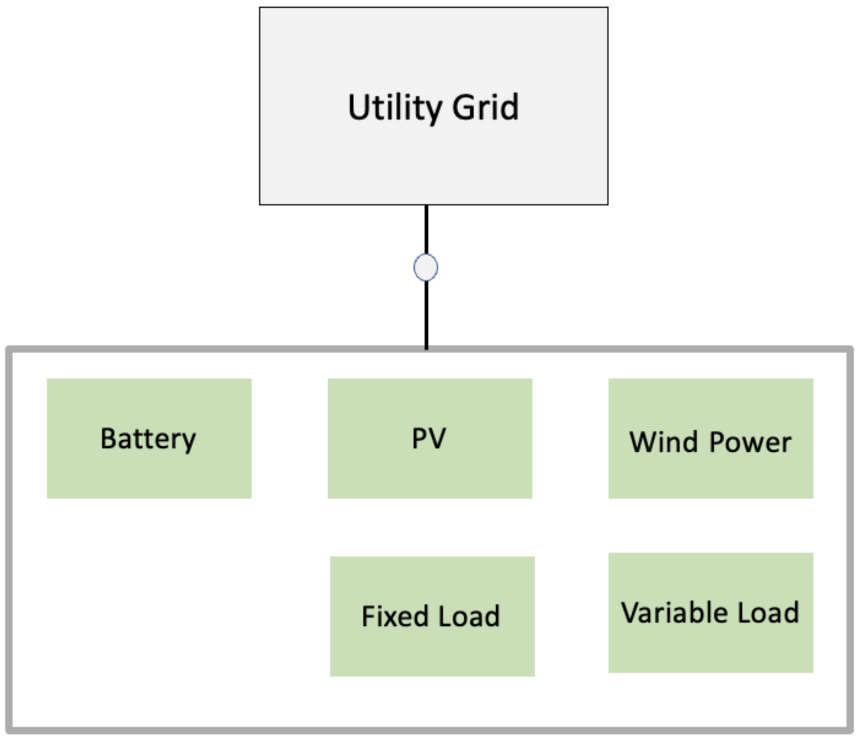

Figure 12: Block diagram of the electrical microgrid model.

The main difference compared to the electro-thermal microgrid model, is that the variable load is now totally electrical, for electrical appliances and assumed electrical heating. For example, if the total variable load demand is at 0.78 MW, this will be covered all by electricity. For the electro-thermal microgrid model, 20 % will be covered by electricity, and 80 % will be heat demand covered by the LTDH network.

Later in the text, this model will be referred to as the **electrical microgrid model**.

3.5 Grid Failure Scenario

To examine the improved robustness of the microgrid by implementing a thermal microgrid, a grid failure scenario was constructed. Scenario details are given below:

1. When entering the third simulation day, there occurs a grid failure and lack of wind power production for two hours.

2. The electro-thermal microgrid goes into island mode, using the battery as voltage support.

3. The fixed load acts as a controllable load and is set down to half its demand through the breakdown.

4. The heat pump for running the district heating network is shut off during the occurrence. The heat demand gets covered by the water tank.

3.6 Software Tool for Modelling and Simulation

The model was modelled in Simulink/Simscape in MATLAB. A short introduction of the software tool follows. Simulink is a block diagram environment for graphical simulation and model-based design. It provides a graphical editor, customizable block libraries, and solvers for modelling and simulating dynamic systems. It is integrated with MATLAB, which makes it possible to incorporate the two and export simulation results to MATLAB for further analysis [39]. Simscape is within the Simulink environment, enabling the user to make physical systems.

The electrical part of the electro-thermal microgrid was modelled in Simulink, while the thermal parts were modelled using Simscape library. The connection point between the two libraries were the heat pump. The electro-thermal microgrid model is presented in Figure 21 and 25 in Appendix A. A small description of the method of modelling is provided. Further, for implementing the control systems, MATLAB function blocks were applied. These are also presented in Appendix A. For analyzing and presenting the results, the simulation data were exported to Workspace in MATLAB. All the presented results are only by basic calculations, however the small analysis of time duration in island mode is attached in Appendix B.

4 Results

This chapter provides the results from the modelling and simulation of the electro-thermal microgrid. When studying power flows in the model, the electrical model is used for comparison. Firstly, results from normal operating conditions are presented, and secondly, results from the constructed grid failure scenario are given.

4.1 Normal Operation: Battery as Voltage Support

This section presents the results of the simulation for normal operation where the battery is used as voltage support. Firstly, power flows and SOC levels of the battery are presented, including results for time as self-sufficient and operating costs. Secondly, heat flows and temperature profiles are presented.

4.1.1 Power Flows

Simulation of the electro-thermal microgrid showed the power flows as presented in the upper plot of Figure 13. For comparison, power flows for the electrical microgrid model is also included in the lower plot of the figure.

Positive value indicates the component acts as a source to the microgrid, while negative values indicates it works as a sink. For the utility grid this means the microgrid is importing power when the value is positive, while the microgrid exports to the utility grid when having negative values.

Both plots show wind power dominates as the energy generator, while PV can actually be negligible as the other flows are in ranges of megawatts. Further, the fixed load is set to constant and is similar for both models. The main difference of the two plots have its root in the variable load curve. For the electro-thermal microgrid, only demand for electrical appliances is included in the power flow for variable load. The rest of the variable load demand will be related to heating purposes covered by the district heating network, and the only electrical power flow measurement for this is thereby for the heat pump, which actually is measured to be lower than the demand for electrical appliances in the electro-thermal microgrid. This results in a generally lower local power demand within the microgrid.

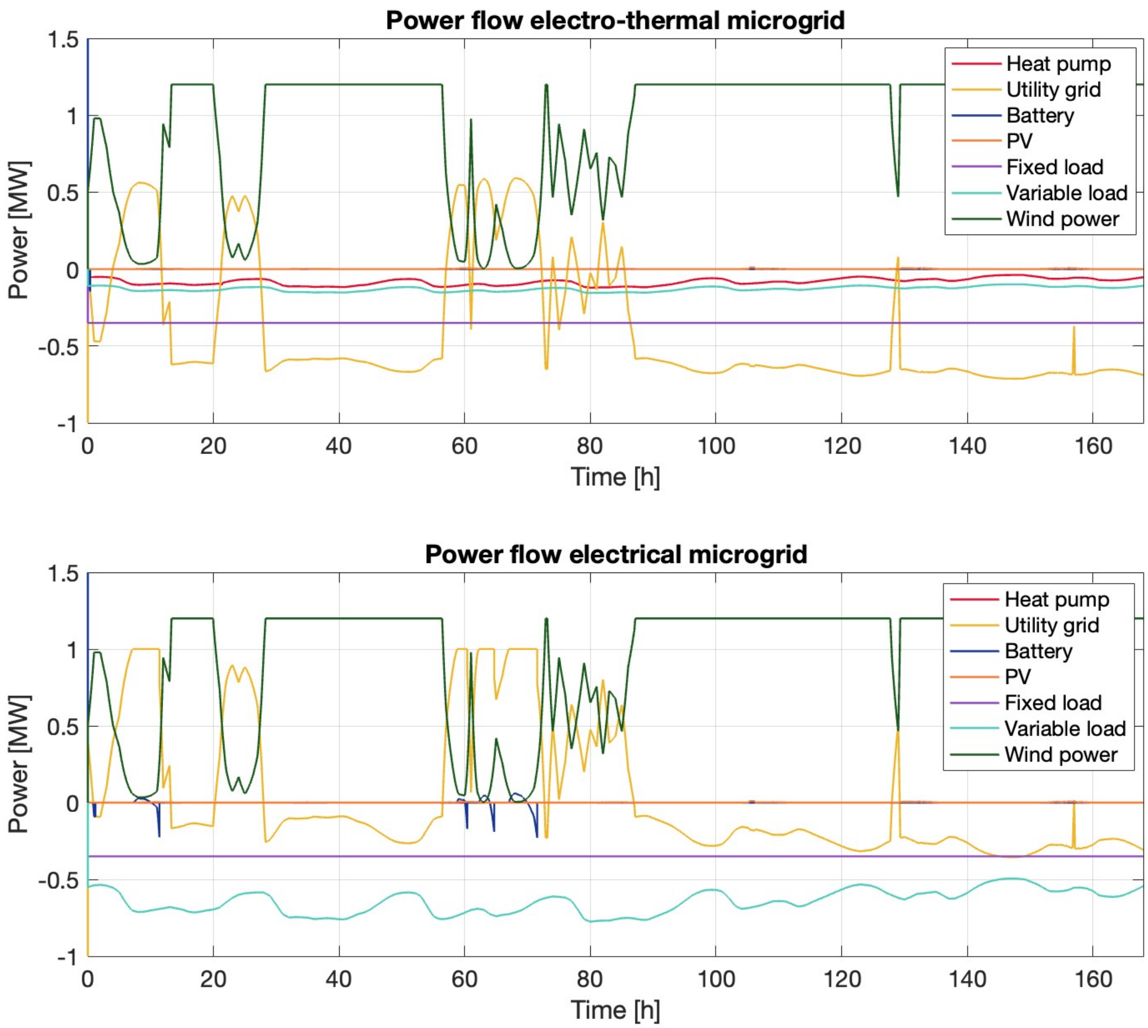

Figure 13: Power flow for electro-thermal microgrid and fully electrical microgrid model.

The local power consumption affect the microgrids' ability to export to the utility grid. The power flows are shown to be generally lower when importing, and higher when exporting for the electro-thermal microgrid compared to the electrical microgrid.

Studying the power flows closely, the two models differ in the use of the battery storage under normal operation. For the electrical model it is shown the battery is needed as voltage support four times during the simulation week. This occurs in cases when the utility grid import exceeds the transmission limit capacity of 1 MW. For these occurrences, it can be seen this happens when wind power production drops significantly. However, for the electro-thermal microgrid, the battery is not needed as voltage support during the week.

The SoC levels for the two models are presented in Figure 14.

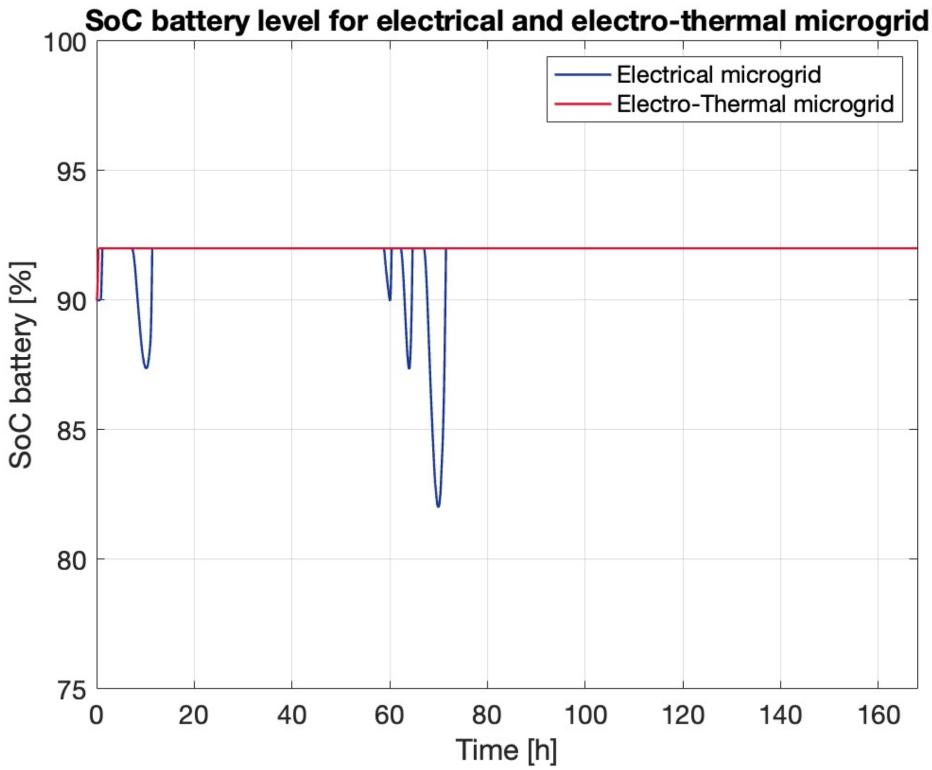

Figure 14: SoC battery level for the electrical and electro-thermal model.

For both models the battery charges initially to the maximum SoC level at 92 %. For the electro-thermal microgrid, the level stays at 92 %, while for the electrical microgrid it drops four times at a maximum down to around 82 %.

To explore the results further, Table 5 provides data for the operating time as self-sufficient, the total variable load energy demand, netto import and total costs during the week.

Table 5: Comparison of the electrical and electro-thermal simulation.

	Electrical Microgrid	**Electro-Thermal Microgrid**
Time as self-sufficient	70.4 %	82.3 %
Total variable load	108.3 MWh	35.5 MWh
Netto import from utility grid	6.6 MWh	- 66.2 MWh
Netto costs	18 663 NOK	- 80 170 NOK

The time the models operates independently from the utility grid is generally high for both as the wind power production usually covers the local demand. However, the electro-thermal microgrid improves the time of running self-sufficiently by 12 %, meaning almost 20 hours during the week. The increased independence can be seen as a result of the lowered energy demand for the variable load for the two models, with 108.3 MWh for the electrical model and a total of 35.5 MWh for the electro-thermal microgrid. This is a total reduction of 67.2 %. Furthermore, this results in a netto need for import from the utility grid for the electrical model, while the electro-thermal microgrid actually netto exports. The difference is significant, and results in almost an economical difference of 100 000 NOK during the week.

4.1.2 Heat Flows and Temperature Profiles

Figure 15 shows the heat flows for the district heating system under normal operation.

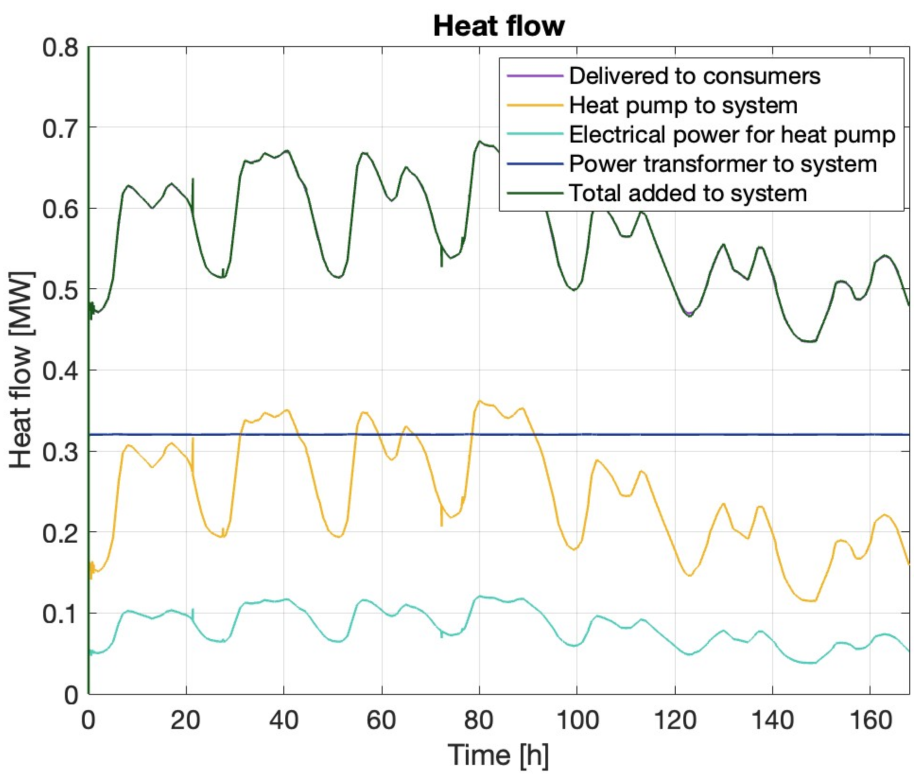

Figure 15: Heat flow/Electrical power for the electro-thermal microgrid over the simulation week.

The heat delivered to consumers and the total heat added to the district heating systems overlaps, varying between 0.5 MW and 0.7 MW. The heat flow plot shows the constant heat provided by the PT at 0.32 MW and the additional heat provided by the heat pump for covering the demand. The electrical power for running the heat pump is also included, showing the electricity for running the system is significantly lower then the applied heat.

Figure 16 shows the temperature profiles during the normal operation. It shows a constant supply temperature of 60 °C and that the water tank holds the same temperature. Further, the temperature level after the heat added by the heat pump overlaps with these temperatures. The return line after the consumers have had a temperature drop of around 30 °C, varying around 30 °C depending on the heat demand of the consumers. Further, the heat supply from the PT provides a constant temperature lift. Thereby, the temperature lift by the heat pump varies for gaining the set supply temperature of 60 °C.

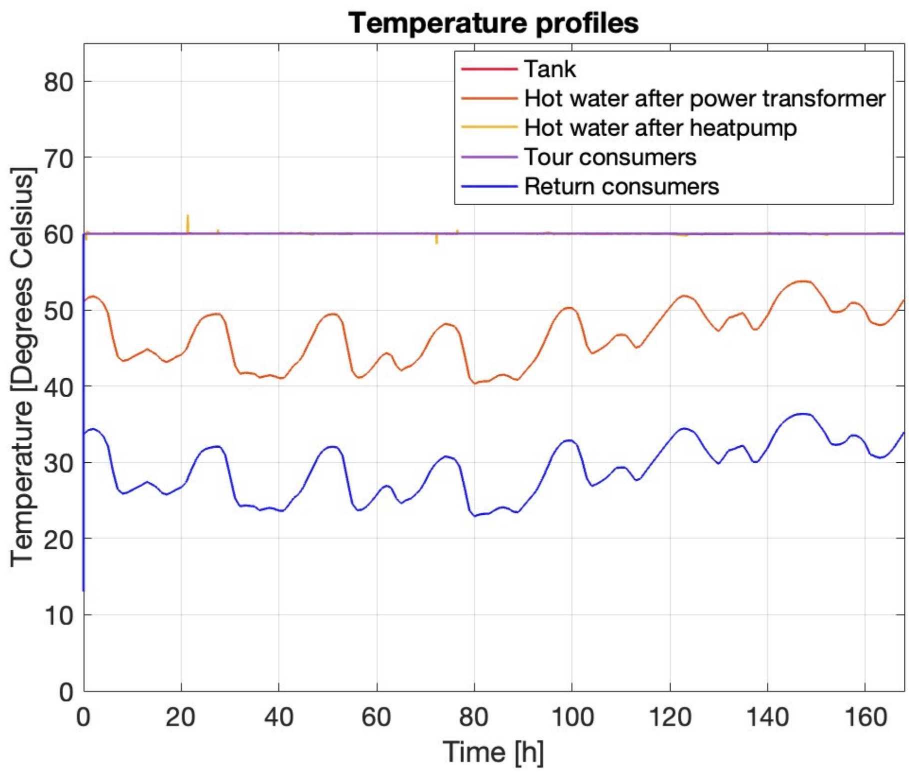

Figure 16: Temperature profiles for the electro-thermal microgrid.

Figure 17 provides a plot for studying the actual temperature lifts done by the PT and heat pump in the model. The plot shows the PT lifts the temperature of the cold return water by approximately 17.5 °C, while the heat pump has to cover up for the variations in heat demand, varying from around 6 to 20 °C.

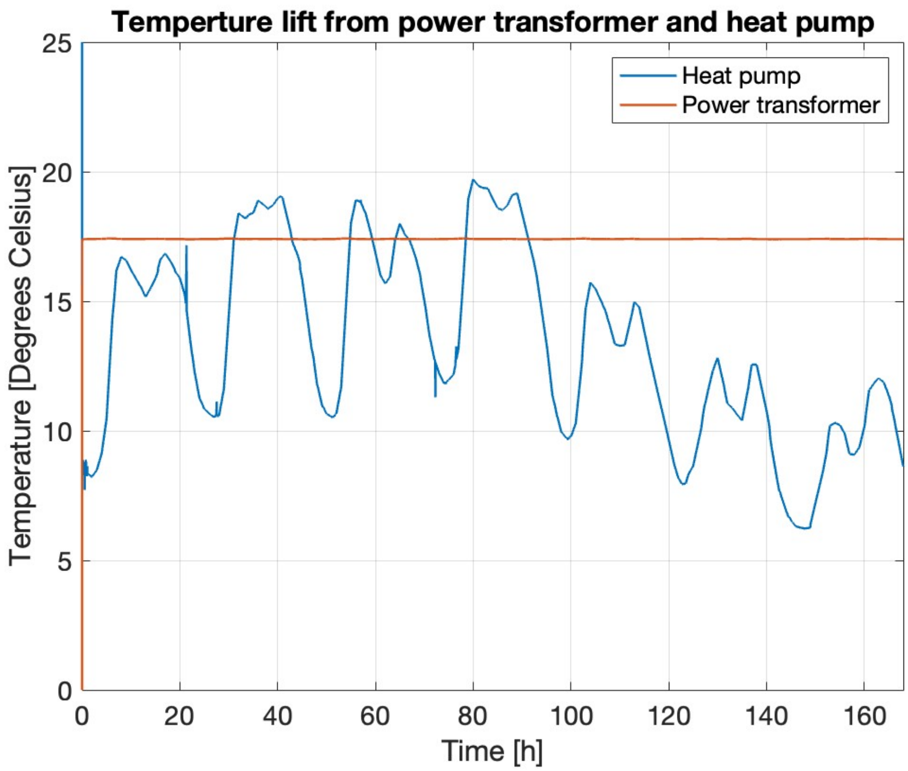

Figure 17: Temperature lift of the return water for PT and heat pump in the model.

Table 6 gives the total heat supplied to the district heating network from the PT and heat pump. In total, the PT covers 56.41 % of the demand, while the heat pump covers 43.49 %, and totally delivered heat to the system is at 95.28 MWh/week.

Table 6: Total heat energy delivered to the electro-thermal microgrid.

Source	**Heat Supplied**	**% Supplied**
PT	53.75 MWh/week	56.41 %
Heat pump	41.53 MWh/week	43.59 %
Total heat to system	**95.28 MWh/week**	**100 %**

Table 7 compares the total heat supplied to the district heating network by the PT and heat pump, with the electricity used to run the heat pump. The improved system performance is found to be 688 % compared to electricity heating, due to available heat waste and heat pump technology.

Table 7: Electricity used for heat pump compared with heat supplied to district heating system.

Electricity Use Heat Pump	Heat Supplied	Improved Performance
13.84 MWh/week	95.28 MWh/week	688 %

4.2 Grid Failure: Microgrid in Island Mode

This section presents the results of the simulation for the constructed grid failure scenario. Firstly, it examines the power flows and SoC levels of the battery. Secondly, heat flows and temperatures during the failure are presented. Lastly, the energy storage discharge times are given.

4.2.1 Power Flows

In Figure 18, the power flows during the simulated grid failure scenario are displayed. The time axis has been adjusted to focus on the period leading up to, during, and just after the event.

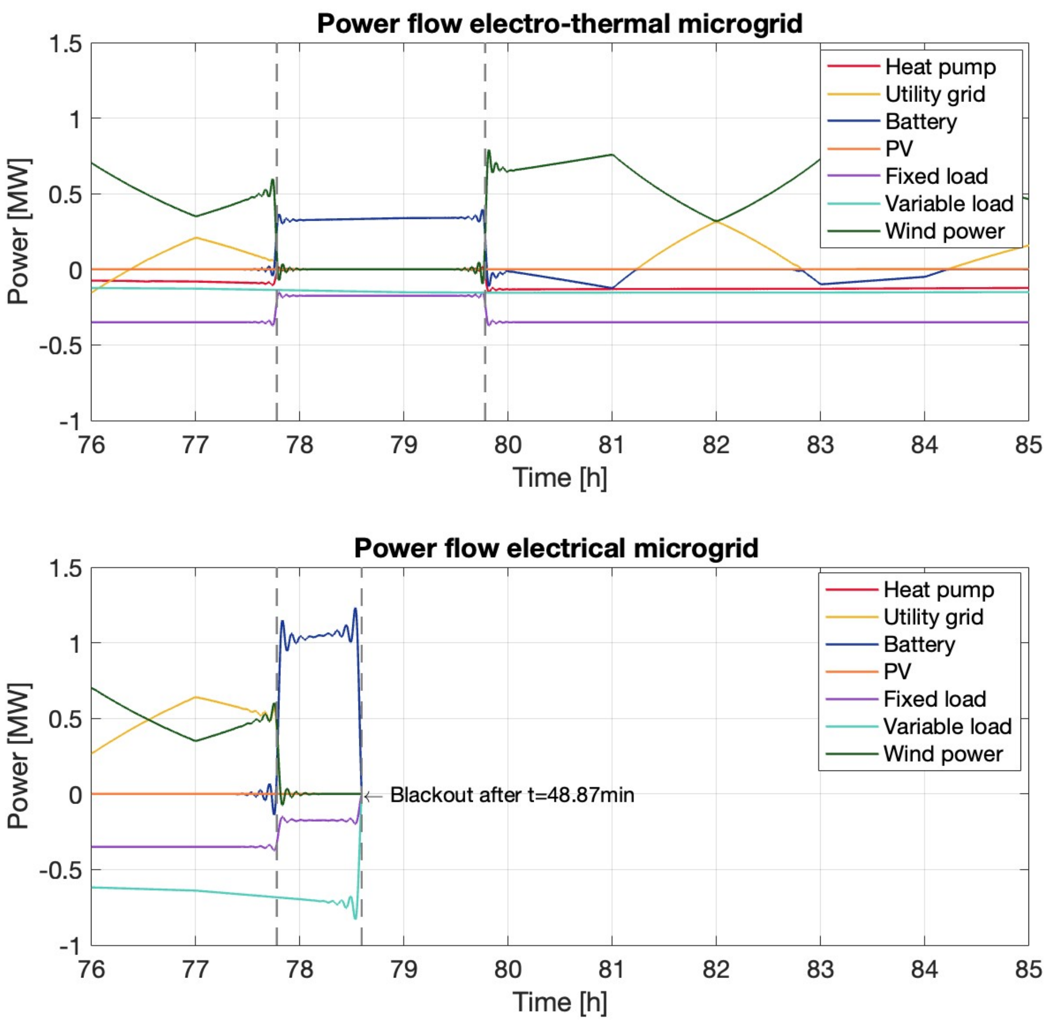

Figure 18: Power flow during grid failure and lack of wind power.

The power flows illustrate that both the utility grid power and wind power production are completely lost, dropping to zero in the diagram. The fixed load is reduced by half during the event, and the batteries are activated to support both models while the microgrid operates in island mode. The electrical microgrid's battery is depleted after approximately 49 minutes. In contrast, the electro-thermal microgrid's power flows indicate that its battery is able to sustain all demand for the entire two-hour grid failure period and return to normal operation afterward.

Figure 19 displays the SoC levels, showing the electrical microgrid model runs out of battery capacity when running in island mode, reaching a minimum SoC level of 5 %. However, the electro-thermal microgrid enables to operate fully through the occurrence, dropping down to a SoC level of approximately 30 %. When wind power production runs normally again, the battery charges relatively fast up to the maximum SoC level of 92 %.

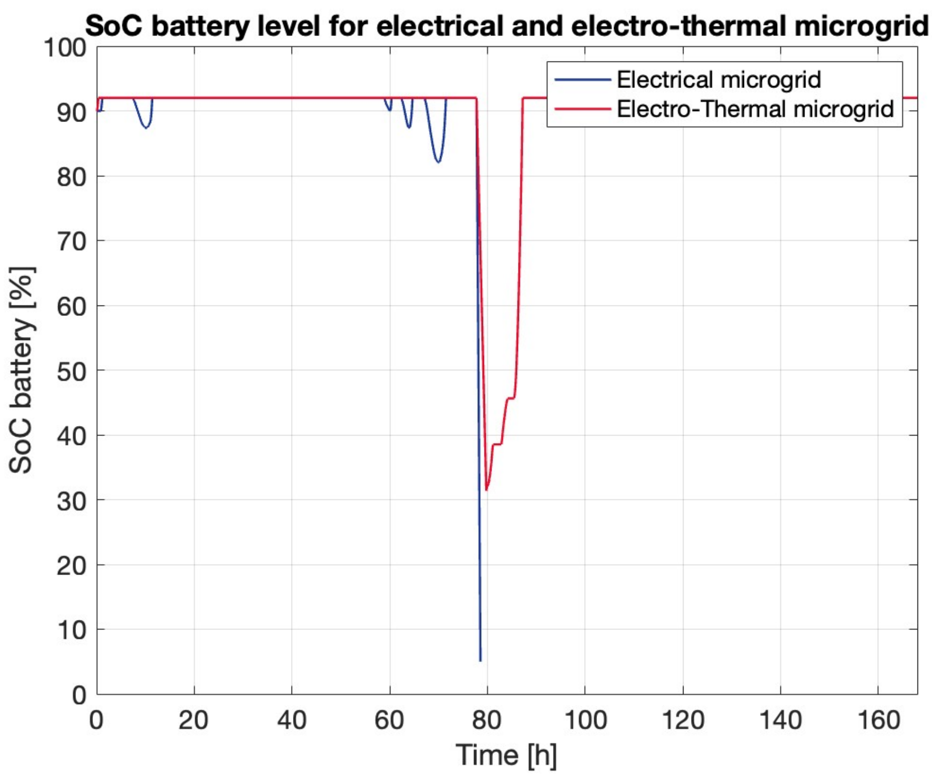

Figure 19: SoC battery level for the electrical and electro-thermal model during grid failure.

4.2.2 Heat Flows and Temperature Profiles

Figure 20 shows the heat flows and temperature profiles during the occurrence. During the grid failure, the heat pump was disconnected such that there was no heat supply to the district heating network. However, the water tank and thereby supply temperature only got a small drop before raising when heat was supplied after the two hours. From the heat flow plot, it can be seen an overshoot of heat delivered compared to the system straightly after the occurrence, for actually raising the tank temperature again. In other words, the water tank seams to be robust even when having grid failure.

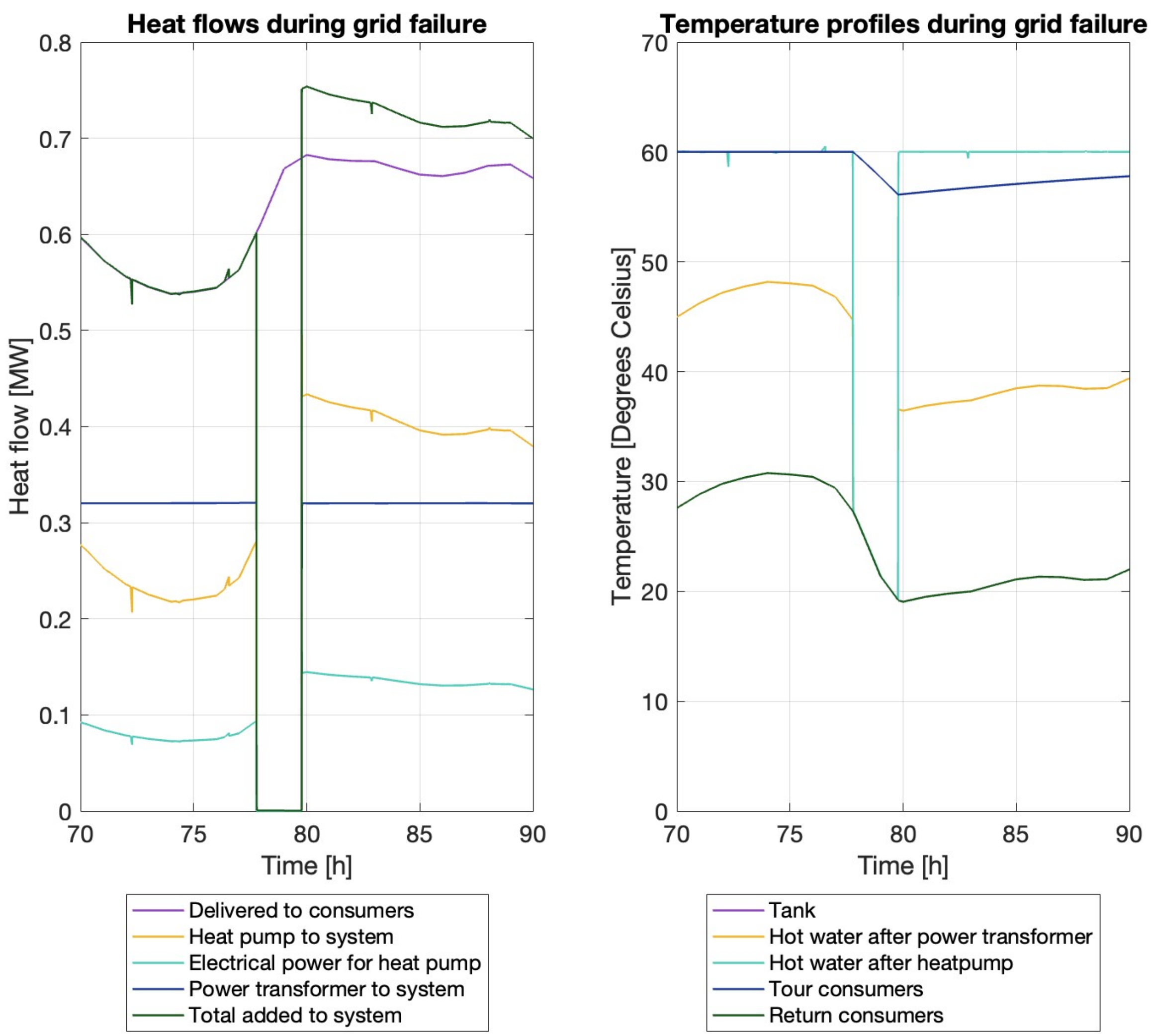

Figure 20: Heat flow and temperature profiles during the grid failure.

4.2.3 Discharge Times

For the electro-thermal microgrid model, the battery and water tank were able to deliver the demand throughout the grid failure occurrence. For further testing their robustness, it was simulated until they also got fully discharged. Table 8 summarizes the discharge times in the two different models.

Table 8: Simulated discharge times for the electrical model versus the electro-thermal microgrid model.

Model	**Storage**	**Simulated discharge time**
Electrical Microgrid	Battery	49 minutes
Electro-thermal microgrid	Battery	2 hours, 50 minutes
	Water tank	34 hours, 27 minutes

Compared to the electrical microgrid model, the battery in the electro-thermal model can run almost two hours longer before dropping to the minimum SoC level. For the thermal energy storage, the simulation shows the water tank can cover the heat demand for almost 34.5 hours.

5 Discussion

Chapter 5 provides a discussion of the findings from this work. Firstly, the storage capacity and robustness are discussed. Secondly, the PT as a source for district heating is discussed. Lastly, a general discussion of the findings is provided.

5.1 Storage Capacity and Robustness

The simulation results for normal operation showed a significant reduced power demand within the electro-thermal microgrid model compared to the electrical model. Additionally to the actual increased energy storage capacity, where the electro-thermal microgrid model has both battery (1.2 MWh) and water tank (13.95 MWh), the installed battery capacity in the model can be considered as higher with respect to the range of normal local consumption. This is due to a higher discharge time. This gives a clear advantage to the electro-thermal microgrid model, especially since the transmission capacity from the utility grid to the area is limited. In cases of unexpected high power demands in combination with lack of wind power production, will the electro-thermal microgrid model be more likely to handle the stress and complement the utility grid. Furthermore, as the intent of microgrids is to be able to run independently, the time as running self-sufficiently was improved for the electro-thermal microgrid model rather than the electrical.

The constructed grid failure scenario confirmed that the reliability was improved for the electro-thermal microgrid model. The electrical model had blackout after 49 minutes as the battery ran out due to the high discharge rate. For the electro-thermal microgrid model, in addition to having generally lower electricity demand, it could utilize the flexibility the water tank provides and disconnect the heat pump, and thereby even lower the electricity demand within the microgrid during the failure. This resulted in an even lower discharge rate for the battery, and thereby it was able to cover all electricity demand during the occurrence. When checking how long the battery could cover demand, it was found it had a discharge time of 2 hours and 50 minutes, i.e. more than two hours difference from the electrical model. Furthermore, the water tank could deliver heat demand for one and a half day, confirming the great flexibility is provides to the microgrid. Thereby, the findings indicate the electro-thermal microgrid model provides more reliability and resilience.

The simulated battery discharge time in the electrical microgrid model was lower than the theoretically calculated. This is due to that the SoC level was at its maximum (92 %) when the occurrence happened, and the simulation was stopped when it reached the absolute minimum of 5 %. Therefore, the total installed capacity was not used fully. Testing the discharge time of the water tank without any heat supply could cover the demand for 34.5 hours. Comparing this to the theoretical discharge time of 18.94 hours, it is a big difference. This is as the theoretical value is calculated based on delivering constantly 60 °C. However, for the simulation, the cold return line goes back to the water tank and gives a slightly lower average tank temperature which then is set as the supply temperature. For how long the water tank actually could cover the heat demand should have been analyzed further, and a minimum required supply temperature should be set, as this value is based on sending out lower temperatures than 60 °C. However, both discharge times are quite high and this indicated the tank dimensions could be designed smaller if needed. This should be considered in order of how available the heat source will be during the year.

5.2 Power Transformer as a Source for District Heating

Table 6 showed the PT was able to supply 56.41 % of the total heat added to the system. The heat provided therefore reduces the required electricity demand for running the heat pump for the district heating system. Furthermore, the peak heat demand during the simulation week was at 0.62 MW, and the PT was set to deliver 0.32 MW, which indicates the PT is a valuable source for the district heating network. In addition, a 300 MVA transformer will generate a significant amount of no-load losses as examined in Section 3.3.3. For this large of a transformer, the no-load losses will be estimated to be 0.25 MW, such that only by no-load losses, it could actually cover 40 % of the peak heat for 200 households.

It was assumed that 40 % of the waste heat generated by the transformer actually was recoverable. In the research done by Bowman et al. (2020), they assumed 80 % was recoverable, which may indicate the set percentage in this work is an understatement. An assumption of 80 % would generate 0.65 MW, i.e. a doubling of the accessible heat. Over the whole week, this would result in a total of 109.2 MWh of heat supplied, and would actually cover the total heat demand for the households over the week, based on heat flows. However, the recoverable heat amount will depend on various factors such as the efficiency of the cooling system and HEX, but these components were not modelled physically.

Theory states the heat loss from PTs is dependent on the loading [32]. In this thesis, the heat supply was set to be constant over the whole week. These variations in loading should have been taken into account. For the case study of Utsira, the PT will be in connection to an offshore wind farm, and the generated heat loss will therefore be dependent on the wind speed at the field. This point is discussed in a more general aspect in Section 5.3.

Table 7 showed the system performance improved by 688 % by implementing waste heat recovery from the PT in combination with heat pump technology, compared to electricity heating. The reason for the high improvement is the great amount of heat the PT provides, but also as heat pump technology is an efficient heating method as it delivers more heat than the electricity it requires for running. In this thesis, the COP was set to a constant of 3. However, the COP is dependent on the temperature lift and could therefore differ if the top oil temperature was taken into account instead of heat flows. Petrovic et al. (2021) used a constant COP of 4 in their work, and if this was assumed in this thesis, the system's improved performance would be even greater.

Figure 17 showed the temperature lift of the cold return water the PT and heat pump provided. This work has focused on heat flows and not the physical modelling with temperatures. Physically, the transformer will be a heat source for the heat pump and not lift the temperature separately. It would therefore be more accurate to add the assumed top oil-temperature which would be the temperature source for the heat pump. The discussion of using heat flows as method is further presented in the chapter of further research (Section 7).

It must be mentioned that the only measured electricity used for running the district heating network is the heat pump. Realistically, there will be a certain electricity use for running the other circulating pumps in the thermal network, but a fair assumption is to say this electricity use is baked into the COP value.

5.3 General Discussion

The findings from this work has shown that heat recovery from PTs could contribute greatly to LTDH networks and especially for large PTs. Unfortunately, the location of these large PTs is often far from heat densities. With an increasing electricity demand, PTs will remain an important and critical part of the infrastructure and more of them will come. Appropriate planning of their location and/or, if possible, coordinating with other interests which requires heat, will make the utilization more attractive and easier. As shown in Table 2, waste heat could be used for other purposes than only district heating. Fish farming is a great industry in Norway and requires low-temperature heating. Locating such industry nearby PTs could contribute to efficiently utilization of our resources.

Furthermore, Figure 10 showed there is also good potential for waste heat recovery for smaller PTs than the examined in this work. These are often located in urban areas and could also be great contributors to LTDH networks in cities. However, the cooling method sets guidelines for how effective and easy the heat recovery for district heating is. Generally, PTs with less installed capacity have radiator-cooling [34]. For easier coupling to district heating systems, these could be considered applying water-forced cooling, or as an alternative, use an air-to-water HEX or heat pump.

Petrovic et al. (2021) highlighted two methods for increasing the waste heat recovery potential for PTs. This could be done by reducing the flow rate of the circulating pumps for the oil cooling of the PT, or by adding more percentage of load. For the latter, this could be done by avoiding oversizing of the PT, resulting in a higher percentage load. Reducing the installed capacity would also be cost-effective. Comparing the service life to the benefits of higher top oil temperatures which easier can be utilized in district heating, may lead to an argument against oversizing of PTs.

In this thesis, the assumed heat supply from the PT was set to be constant. Realistically, this will vary throughout the day, week, month, and season, depending on the incoming load on the PT. At Utsira, the PT will be in connection to the offshore wind farm and therefore will the loading be dependent on the wind speed at the field. Generally, there will be higher wind power production at night time. The water tank therefore gives great flexibility to the electro-thermal microgrid as the heat pump can be shut off during daytime when the power price tends to be higher. However, analyzing the the incoming load profile on the PT could be a good indicator for choosing TES technology. For instance, if the load profile is significantly reduced in wintertime, seasonal energy storage (long-term) could be a better option than a water tank (short-term), etc.

Petrovic et al. (2021) analysed the national potential for waste heat recovery in Denmark and concluded the potential may not had a significant impact on a national level, but could play a vital role in local electricity grids [34]. The findings of this work have showed the heat recovery can improve the microgrid's performance in several ways, such as reduced electricity demand, increased overall system performance, and making it more flexible and robust. In Norway, with its many islands and small districts located amidst mountains and fjords, transmission capacity is often limited. Extending transmission capacity in the electricity grid is costly and area-demanding. Therefore, implementing electro-thermal microgrids that utilizes local waste heat resources may increase the independence in these regions, and reduce the need for transmission lines or seacable upgrades. As a results, electro-thermal microgrids can potentially lessen the overall environmental impact and be a cost-effective solution.

The simulation results showed both models operated self-sufficiently most of the time during the week. This is due to the two wind turbines with a total installed capacity of 1.2 MW, which are the main source of renewable energy production within the microgrid. In most cases, the wind power production is sufficient enough to cover all the local demands. Further, the definition of a microgrid does not state what scale the energy production must be in, but as the wind power dominates to such a degree, the PV production could be negligible in the simulations. However, PVs are considered an important source within microgrids together with other small-scale renewable energy sources.

Economically, it was found a great economic advantage with the electro-thermal microgrid model compared to the electrical. During the week, the results gave a difference of almost 100 000 NOK. This was as the electro-thermal microgrid was able to export a higher amount to the utility grid due to the internal lowered power demand. The economically perspective was not examined further, but it could be interesting to add the financial gain of the flexibility the electro-thermal microgrid provides as the heat pump can be shut of during high power prices. In addition, investment costs could be included, where this would be higher for the electro-thermal microgrid as pipe-network is generally expensive, as well as the need for upgrading the household systems to be able to receive waterborne heat.

This work has focused on low-temperatures for the heating network. These are quite new systems, but [26] states they are commercially proven and reliable. However, the systems in Norway today are generally of the third-generation with higher supply temperatures (80 - 90 °C) [23]. If such a system was considered, the electricity use for the heat pump would be higher, as the required temperature lift would increase. The integration of the low-temperature source would then be less effective. Furthermore, it would result in higher heat losses and the overall increased system performance would be lower than estimated in this work.

6 Conclusion

The aim of this work has been to study how the implementation of an electro-thermal microgrid can improve the robustness of the traditional electrical microgrid. Further, it was examined if waste heat recovery from a 300 MVA PT could contribute as a valuable heat source to the low-temperature-district heating network. The main focus was studying power balances, and therefore, an electro-thermal microgrid model was modelled and simulated for in Simulink/Simscape. The model was checked under normal operating conditions and a constructed grid failure scenario for testing its robustness. Further, the results were compared with a fully electrical model.

It was found a great potential for heat recovery from PTs, and especially with these high capacity ratings. Furthermore, by supplying the heat to the LTDH network, it showed the PT could contribute significantly. Based on estimated heat supply and demand, it was found the PT could cover 56.41 % of the heat demand for the 200 households. Furthermore, the results showed the PT and heat pump increased the system performance by 688 %.

Comparing the electro-thermal microgrid model to the electrical, the results showed a significant reduction in electricity demand within the grid. This results in several advantages. Firstly, the electro-thermal microgrid model was able to netto export to the utility grid, while the electrical microgrid model had to netto import during the week. Economically, this made a difference of almost 100 000 NOK in total. In addition, due to the significantly lowered electricity demand, the battery had a longer discharge time during grid failure compared to the electrical model, with two hours of difference. Furthermore, the simulation results showed the water tank could cover the heat demand for one and a half day without heat supplied to the network. This indicates the electro-thermal microgrid provides great flexibility.

These findings leads to the conclusion that electro-thermal microgrids boost storage capacity, will free up electricity demand, and thereby improve the reliability and resilience of the microgrid. In addition, it provides great flexibility, which may be utilized to run the network cost-effectively. Furthermore, the overall energy system performance will be improved. These findings gives good arguments for considering electro-thermal microgrid technology, and especially, for decentralized areas with limitations in transmission capacity. Appropriate planning of waste heat sources, such as PTs, could contribute greatly to make the area more independent from the utility grid.

7 Further Research

The applied method for this thesis was to study power and heat flows. By physical modelling, with including expected heat source temperature level, temperature demand, heat exchangers, detailed heat pump, pipe-length network, etc, the model would be more accurate. One of the system designs for heat recovery of transformers should therefore have been chosen and modelled physically. However, this was an initial study and the method can be considered sufficient enough. Even though this thesis focuses on heat and not temperature for the PT, based on other studies, it is within an acceptable range for all the temperature profiles when simulating for the district heating network.

Further improvements could be to analyse the loading on the PT, and for the case study, an easy improvement would be to set it proportional to the wind speed at the offshore wind farm. By physical modelling based on temperature levels, the COP should also become a variable based on the required temperature lift. The COP would then be higher with higher loading on the PT.

For the input data, several possible improvements could have been done to make the model more accurate. First of all, a more precise household load profile should be used. The loads on the island of Utsira should further be analyzed in detail, and possible controllable loads should have been identified. Furthermore, solar irradiance for the island should be used and actual wind power production data. For the electrical part, the model could be improved by including detailed power electronics, electrical grid losses and reactive power.

Furthermore, as mentioned in the discussion section, a more detailed economic analysis should be provided to draw a conclusion based on economic advantage with the thermal microgrid model.

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A Simulink/Simscape Model

Figure 21 shows an overview of the model with the electrical components.

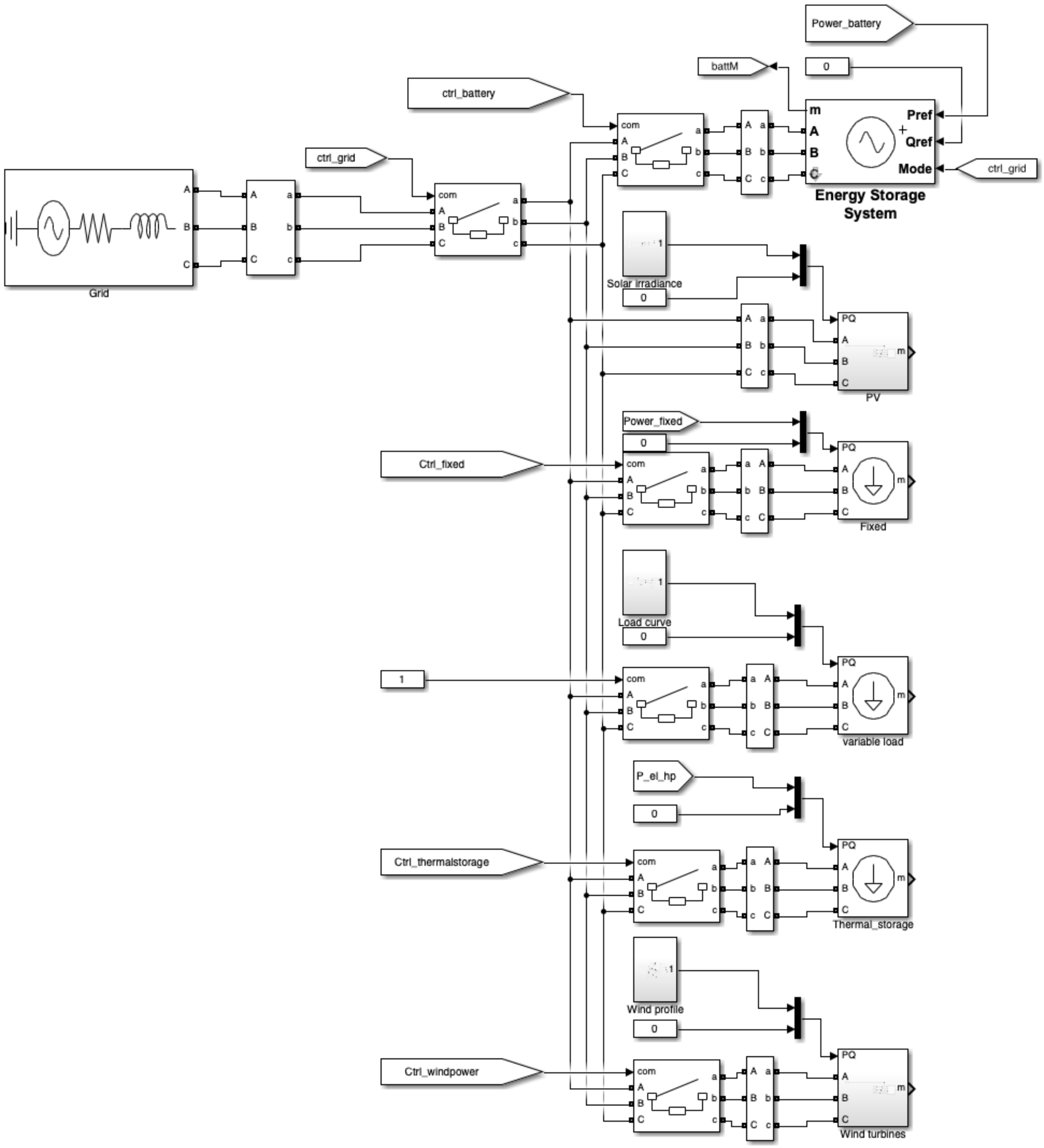

Figure 21: The created model in Simulink showing the electrical part of the microgrid.

The utility grid is connected to the microgrid, consisting of an energy storage system (battery), PV, fixed (load), variable load, thermal storage (heat pump) and the wind turbines. For all the components, except the PV, a breaker is included for enabling to disconnect the load.

For the variable load it is modelled by using a current-source block, which has input arguments for active and reactive power. At this input signal, the reactive is set to zero, while "Load curve" is the input signal to active power. Inside the load curve subsystem, the household load profile is picked up from workspace, and multiplied with the number of households. For the electro-thermal microgrid model, the load profile is then separated based on electrical appliances demand and heat demand. The electrical demand is here sent further as input argument to the variable load block. See Figure 22. For the other blocks, the similar method is applied. For the thermal storage current block, a variable is used as input argument (P_el_hp), which is estimated in the Simscape environment together with the thermal side of the microgrid model. The heat pump therefore acts as a connection point between the electrical and thermal side.

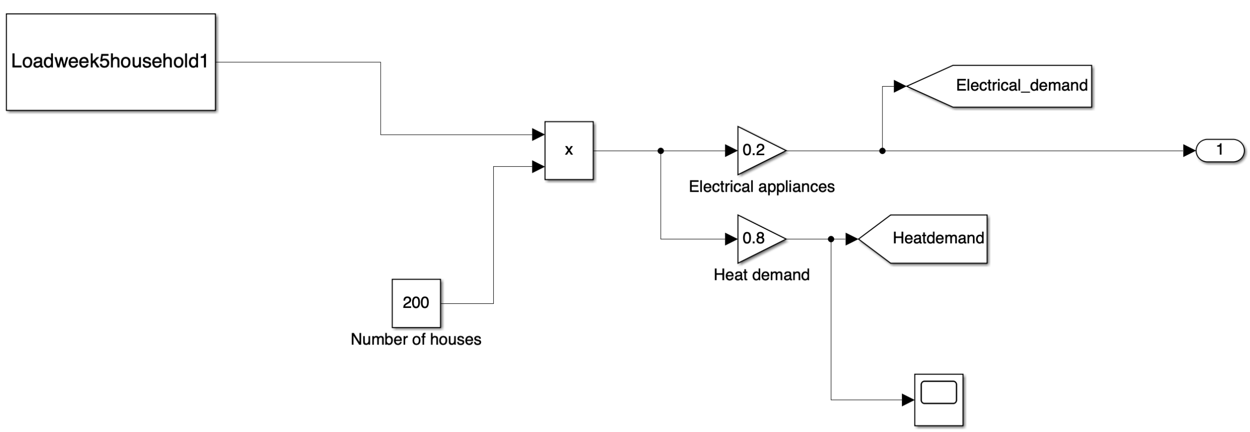

Figure 22: Modelling input argument for the variable load.

Figure 23 shows the MATLAB function implemented for setting the power argument for the battery (charging or discharging). The code inside follows.

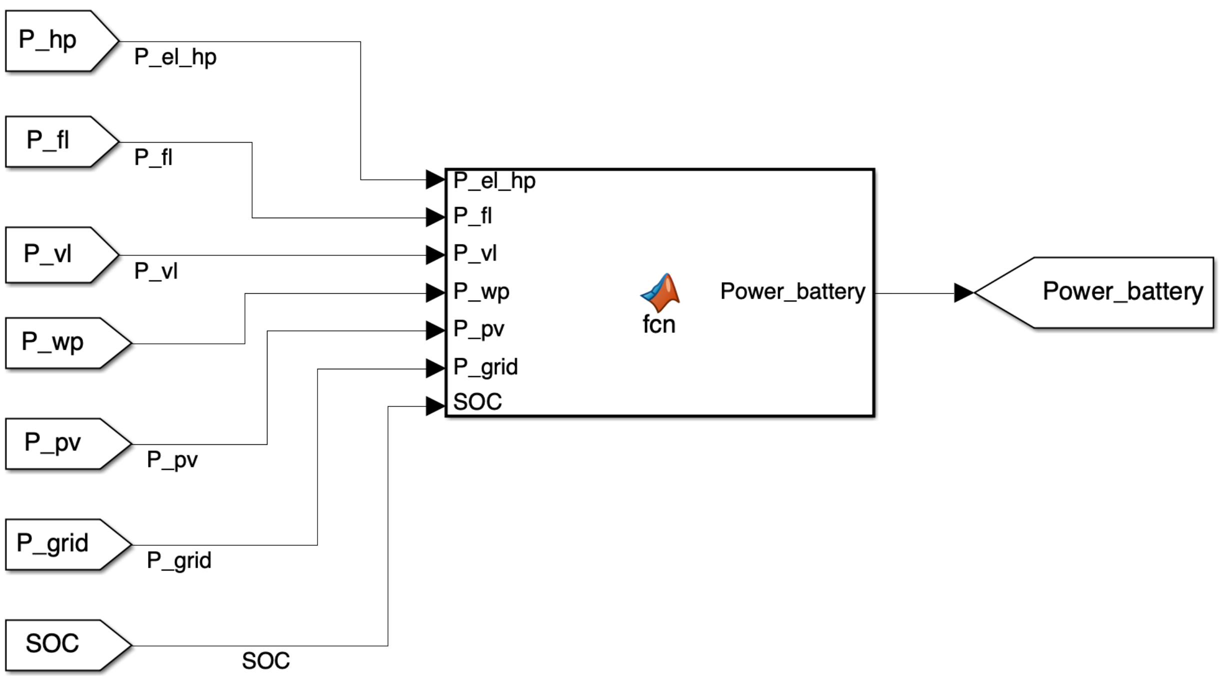

Figure 23: MATLAB function block for setting the battery power.

```
function Power_battery = fcn(P_el_hp, P_fl, P_vl, P_wp, P_pv,
    P_grid, SOC)

Power_battery1 = 0;
Seacablemax = 1e6;

internal_balance = P_el_hp + P_fl + P_vl + P_wp + P_pv;


if internal_balance > 0
    Power_battery1 = internal_balance * (-1);
end


if P_grid > Seacablemax
    Power_battery1 = (internal_balance * -1) - Seacablemax;
```

```
end

if SOC > 95
    Power_battery1 = 0;
end


Power_battery = Power_battery1;
```

Furthermore, another MATLAB function block was mainly created for taking care of the grid failure scenario, but also sets the fixed load parameter. See Figure 24 for the block, and the code is followed below.

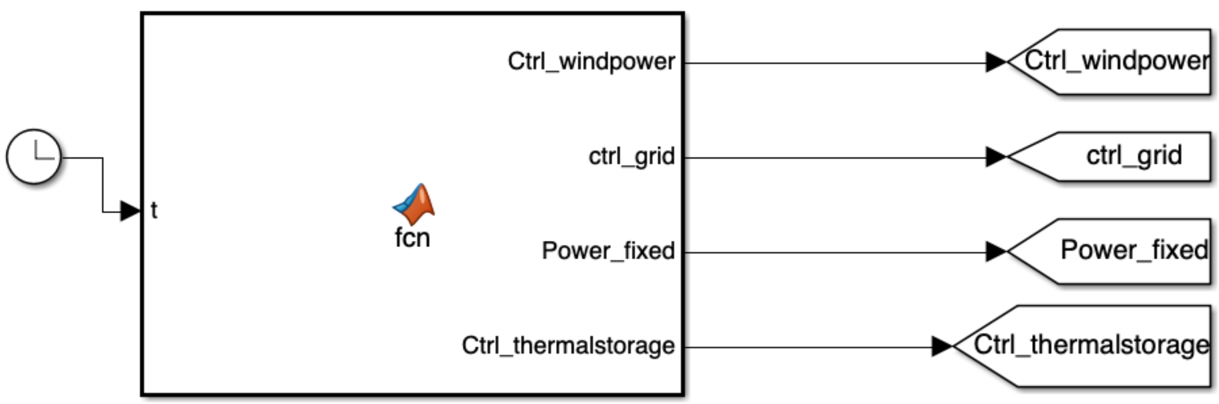

Figure 24: MATLAB function block for grid failure scenario.

```
function [Ctrl_windpower, ctrl_grid, Power_fixed,
   Ctrl_thermalstorage] = fcn(t)

Ctrl_windpower = 1;
ctrl_grid = 1;
Ctrl_thermalstorage = 1;

Power_fixed1 = 0.35e6;

% Grid failure and no wind power production for two hours
%if t > 2.8e5 %&& t < (2.8e5 +2*3600)
%    Ctrl_windpower = 0; % No wind power production
%    ctrl_grid = 0; % Grild failure
%    Power_fixed1 = Power_fixed1/2; % Disconnects non-critical
   loads
%end

Power_fixed = Power_fixed1;
```

Figure 25 shows the model in Simscape. The heat pump is modelled as a heat flow source, providing heat to the district heating system. Further, the hot water enters the water tank. On the other side, there is a loop for the consumers. The heat demand for the consumers is also modelled as a heat flow source with input argument picked up from the varible made in Figure 22. Further its added a 10 % for taken heat losses into account. From there, the cold water goes back again, and on the other side gets heat supplied from the power transformer, and then additionally from the heat pump again.

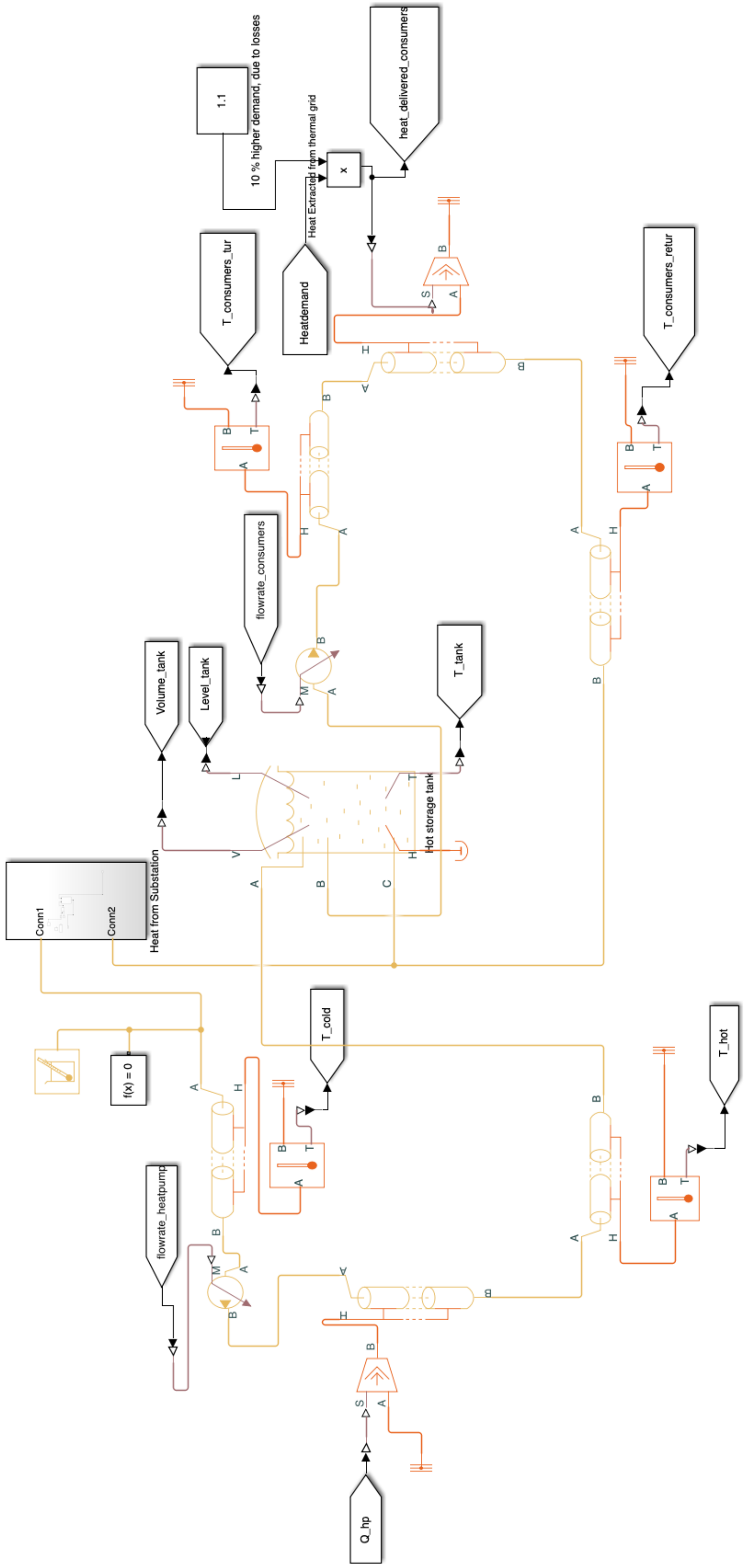

Figure 25: Simscape model of the low-temperature district heating network.

The overview of the Simscape model shows the incoming heat flow from the heat pump (Q_hp) (see Figure 27 for its calculation in the model). This value is calculated from the required heat lift, where then the electricity use for the heat pump is calculated (P_el_hp). The MATLAB function block in Figure 26 shows the input arguments and output variables. The code inside is presented below the figure.

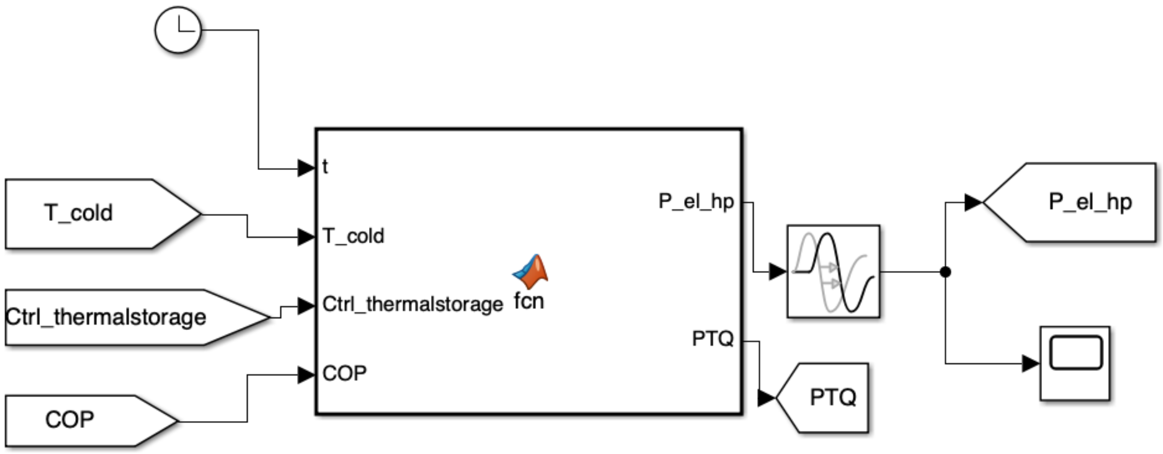

Figure 26: MATLAB function block for calculating heat supplied from heat pump and electricity use.

```matlab
function [P_el_hp, PTQ]  = fcn(t, T_cold, Ctrl_thermalstorage,
    COP)

Ctrl_thermalstorage = 1; % Breaker for heat pump
P_el_hp_1 = 170000; % Start value
flowrate_heatpump = 4.4;

PTQ = 0.32e6; % Constant heat supply from power transformer


% Heat energy from heat pump for lifting to 60 degrees
T_hot_ideal = 333.15;
Q = flowrate_heatpump * 4184 * (T_hot_ideal - T_cold);


% Grid failure scenario - disconnect heat pump
```

```
%if t > 2.8e5 && t < (2.8e5 +2*3600)
%         P_el_hp_1 = 0;
%         PTQ = 0;
%else
%     P_el_hp_1 = Q/COP;
%end



% Ordinary code - calculate electricity use for heat pump
if Ctrl_thermalstorage == 0
    P_el_hp_1 = 0;
else
    P_el_hp_1 = Q/COP;
end

P_el_hp = P_el_hp_1;
```

Figure 27 shows how the variable heat flow Q_hp variable is set back as input argument to the model.

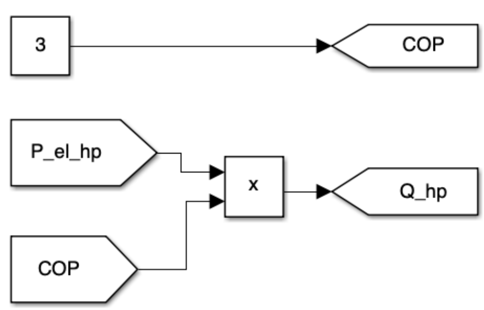

Figure 27: Modelling: heat supplid by heat pump

Figure 28 shows how the heat supply is modelled from the power transformer. The heat supplied is from a variable, PTQ, for being able to shut it off during the grid failure scenario.

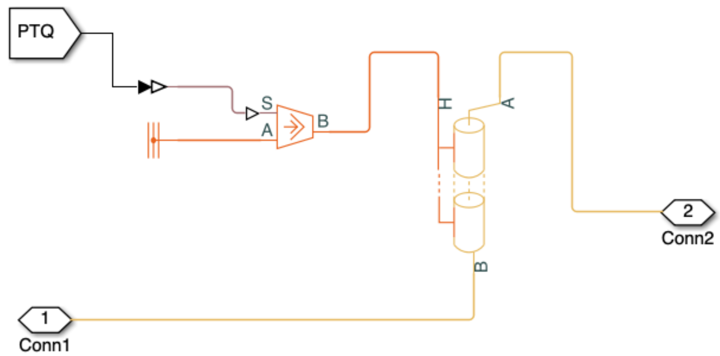

Figure 28: Modelling of heat supply from power transformer.

For showing how the simulation was presented within the modelling program, Figure 29 shows an overview of how the variables were put in to so-called SCOPES for checking the simulation results continuously when simulating. This was also done for the electrical side of the microgrid, for studying the power balance etc.

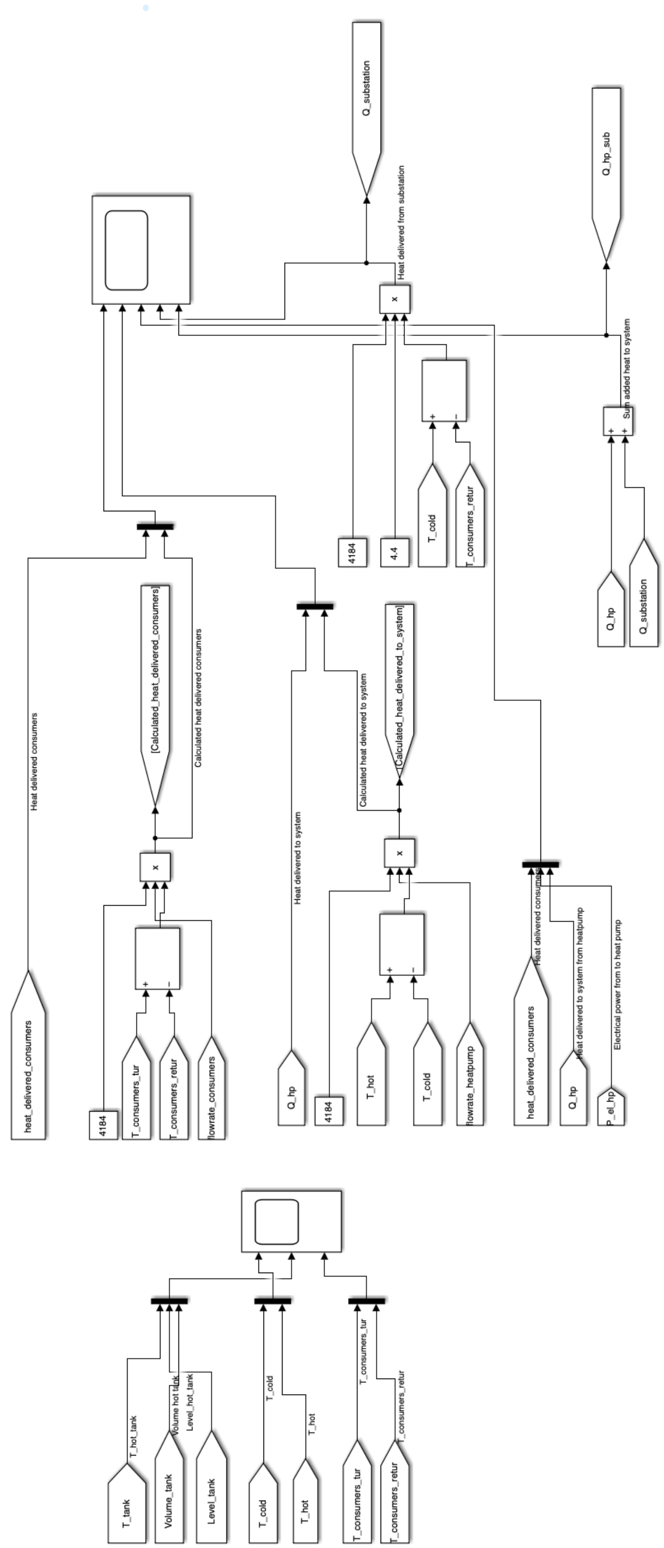

Figure 29: Overview of some of the SCOPES.

Furthermore, for sending the results out to Workspace in MATLAB they were put to an out.workspace variable. See Figure 30 for an example.

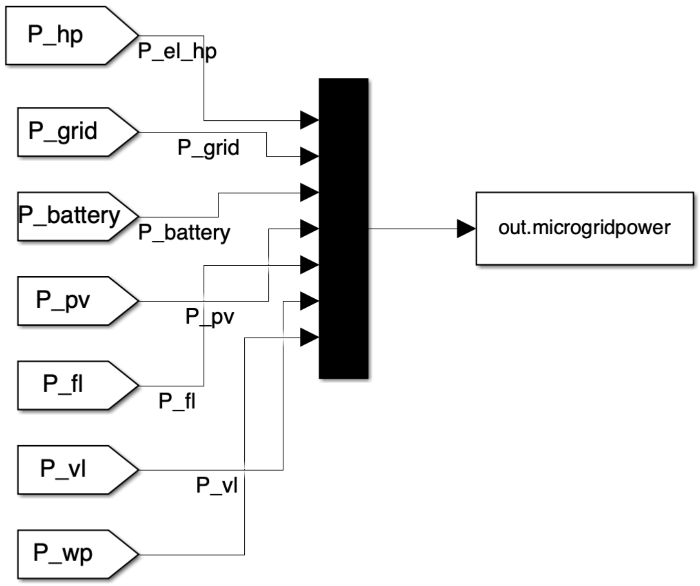

Figure 30: Example of how varibles were sent to workspace in MATLAB.

B Normal Operation Calculations

```
%% Island mode analysis

powerbattery_time = out.microgridpower.Time;
powerbattery_data = out.microgridpower.Data;

[powerbattery_sec, timebattsec] = resample(powerbattery_data, powerbattery_time, 1); % Secondly
[powerbattery_h, timebatth] = resample(powerbattery_sec, timebattsec, 168/604800);

priceweek5 = Priceweek5(:,2);

% Theoretical time in island mode
powergrid = powerbattery_h(:,2);

```

```
islandmode_battery_hours = 0;
for power=1:length(powergrid)
    if powergrid(power) <= 0
        islandmode_battery_hours =islandmode_battery_hours+1;
    else
        continue
    end
end

total_hours = length(powergrid);
time_island_battery = (islandmode_battery_hours/total_hours)*100; %[%]


% Total Costs
Costs =(powergrid/1000) .* priceweek5;
TotalCosts_batterymode = sum(Costs);

% Netto exported
Netto_export_batterymode =sum(powergrid);

% Total energy for household demand (variable load)
powervariable = powerbattery_h(:,6);
sum_variable_battery = sum(powervariable);
```

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