Utilizing Home Automation Data for Model Creation of a Heat Pump Water Heater System with PV: A Case Study in Norway

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Abstract

Norway continues to advance its commitment to sustainability and carbon neutrality, the integration of renewable energy technologies into residential settings has increased over the past years. Increasing grid connected decentralized pv production

Among these technologies, Air Source Heat Pump Water Heaters (ASHPWH) offer a promising solution for efficient heating. However, the intermittent nature of renewable energy sources and the electrification of the energy system necessitate innovative approaches for energy management. One of the solutions involves controlling the operation of flexible loads to increase the consumption of local production, reduce the reduce reliance on centralized production, and reducing energy waste.

This thesis has researched the potential benefits and challenges of collecting and storing data locally in a an open Home automation solution, and implemented an open time series database for long term data storage and collection.

This thesis has investigated the potential benefits and challenges of using a data-driven approach for day-ahead scheduling of an ASHPWH. This includes the collection and storage of sensor data from a home automation system, and using this data as input to a MILP optimization problem. The creation of a MILP optimization prblem based primarily on sensor data for modelling the system dynamics showed to be an oversimplified approach. This oversimplification resulted in unrealistic outcomes that did not accurately reflect the true dynamics of the system, making it difficult to draw valid conclusions about the model's solutions.

Even though the model results did not not come to any final conclusions about the validityof the strategies for the control of an ASHPHW system .This model can serve as the foundation for developing a more advanced and accurate model in the future The use of MILP is an underestimated approach, but requires better input parameters than what was provided in this model.

Abbreviations

IoT Internet of things

DSO Distribution System Operator

TSO Transmission System Operator

EWH Electric Water Heater

ASHPWH Airsource Heat Pump Water Heater

TES Thermal energy storage

HP Heat Pump

SS Self Sufficiency

SC Self Consumption

DSR Demand Side Repsonse

DSM Demand Side Management

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Chapter 1

Introduction

1.1 Motivation

Norway is committed to sustainable growth in accordance with the Paris agreement, and renewable energy production and low carbon production into the energy system is a central part of that development. With plans and investments to integrate more wind, and solar power into the energy system, follows challenges. These challenges are related to energy management, particularly in decentralized systems where local energy production and consumption need more cohesive integration and optimization. This is the case for remote areas and the increasingly popular smart city projects.

In addition to an increase in renewable energy penetration in the energy system, the future energy demand is expected to increase. The Norwegian Transmission System Operator (TSO), Statnett, does a yearly rapport on the future power system and power market with a focus on the Nordic and Norway in a 5 year time period. According to this report, the Norwegian power consumption is expected to increase with atleast 25 TWh until 2028 in their base scenario. In comparison to their previous report, this increase in power consumption has been shifted to a shorter time frame. The Norwegian energy balance is expected to decrease greatly, and the plans of installing more wind and solar power, without more flexible power plants, creates the expectation of a great decrease in the power balance for both Norway and the Nordic countries. [20]

One of the ways to reduce the necessity of flexible power plants, is to introduce more flexibility in the demand of the end-use sectors, which is called Demand-Side Response (DSR). The total consumption of the end-use sectors disregarding the power production sector, increased by 6.1% from 2022 to 2023, and was 80,7 TWh in 2023, where the consumption of households covers about 50%.[14] Traditionally,this increase imposes a need for upgrades in centralized production and storage, which often involves long-distance transmission, high losses and high costs. However, with the recent developments in smart grid systems, allowing for local energy production and DSR, there are options besides upgrades in centralized production.

Decentralized energy systems with renewable energy have the potential to reduce reliance on centralized energy production. The integration of Internet of Things (IoT) systems with energy monitoring and control can offer more independence and contribute to a sustainable development of the energy system. Households can possibly enhance the efficiency of their energy utilization by integrating control systems, ensuring that their renewable resources are optimally exploited and costs are minimized.

More specifically, space heating is an essential end-service for the Norwegian households and accounted for approx. 70% elecitricity consumption in 2012. [22] and approx 80 % in the recent years . Norway's cold climate demands high energy use for heating, and especially electrical energy is main contributor.However, it is expected that the energy efficiency of Norwegian household will increase in short future. [18]

Heatpumps with a water heater (HPWH) covers the hot water demand for different applications, such as heating systems and domestic hot water usage in households. Despite their high efficiency and potential for energy savings, the widespread adoption of HPWH systems faces challenges, primarily due to their complex integration into existing energy systems [32]. However,According to the Europian Heat Pump Association (EHPA): Norwegian sales of Air to water heat pumps sales grew by 34% in the 2022 and has the largest share of heat pumps per capita [5].

The integration of HPWH systems with renewable energy sources, such as solar production, presents an additional layer of complexity but also opportunities. By effectively managing these integrated systems in a cohesive way, it is possible to maximize the use of renewable energy systems, and reduce reliance on centralized energy production.Therefore, developing control algorithms that can handle the stochastic nature of renewable energy sources and demand-side variability is of interest.

1.2 Scope

This study utilizes an existing energy system in a selected household, referred to as the ”Pilothouse,” as the foundational of configuration of an energy model for analysis. The energy system modeling will be restricted to only incorporate inputs and parameters based on the EWH user manual [37] and actual data measurements, including electrical consumption of the heat pump, PV energy production, outdoor temperature readings, and operating temperatures of the hot water tank.

Initially, the primary objective of this thesis was to investigate how an air source heat pump water heater (ASHPWH) system with a photovoltaic (PV) system can be controlled to optimize cost-effectiveness without compromising the comfort levels of Pilothouse.However, due to limited foreknowledge on the thermal characteristics of the household and thermal modelling techniques, the potential for cost-effectiveness is limited by the accuracy of the thermal behavior predictions for the ASHPWH system. This limited information and necessary approximations resulted in a shifted focus, where the primary objective is to explore how various parameters, thermal coefficients and granularity on input data for the ASHPWH system influence daily costs across different days, each characterized by varying environmental conditions.

Moreover, this research leverages the capabilities of Home Assistant, a versatile home automation platform, to collect and analyze real-time sensor data from the ASHPWH system and other applications. The integration of Home Assistant has enabled the precise monitoring of environmental and operational conditions, enabling approximation and assumptions on parameters for the energy system model.

The design of the energy system's optimization problem will be formulated as a Mixed-Integer Linear Programming (MILP) model using the General Algebraic Modeling System (GAMS). algorithm aimed at enhancing the cost-effectiveness

This study aims to show that optimized control of an ASHPWH system integrated with a PV system, can result in substantial cost savings and increased self sufficiency without compromising the comfort levels of the household across multiple parameters for the ASHPWH system.

Additionally, with DSR Secondly, the results are anticipated to provide general insights into the potential benefits of energy management systems with heating systems particularly in terms of economic efficiency, and sustainable energy usage.

Finally, it is anticipated that this energy optimization model will offer valuable insights and serve as a foundation for day-ahead control of the ASHPWH system in the Pilothouse.

1.3 Structure

The structure of this thesis will include:

Home Automation system: In Pilothouse, an integrated energy monitoring system has been deployed, consisting of both sophisticated hardware components and software algorithms. This IoT system's primary objective, related to this thesis, is to collect and store real time data from sensors.The Pilothouse's Iot system will be examined in detail in architecture, hardware and software components. Chapter (2.1)

Theory: The theoretical framework of this thesis is divided into two parts. The first focuses on the IoT system and data communication, while the second accounts for the thermodynamics and components in a ASHP system, including the solar production.

Data analysis: Data collected from Home assistant will be examined and analyzed. The set of parameters and coefficients for the Energy system model will be defined.

Optimization model: A detailed breakdown of the energy model will be provided. With the fundamental laws and theory in thermodynamics related to the ASHPHW system being explained in a Theory Chapter. 2

Results: the results from the energy model for the selected days and various parameters are presented.

Dsciussion The model's output is discussed in terms of options, possibilities, and validation.

Conclusion and Future work: A conclusion of the thesis and future work is presented.

Chapter 2

State-of-the-Art in Heat pump Optimisation

2.0.1 Flexibility and DSR

Norway's extensive deployment of smart meters and adoption of real-time pricing mechanisms facilitate the practical implementation of DSR at the household level. By 2019, nearly all Norwegian households were equipped with smart meters, enabling detailed energy usage monitoring and management. The widespread availability of dynamic "spot price" contracts allows consumers to respond to hourly fluctuations in electricity prices, which are publicly available through the Nord Pool energy market. The integration of energy flexibility within residential settings primarily involves DSR mechanisms, where energy usage is adjusted in response to external signals such as changes in electricity prices or energy supply conditions.[9]

Some typical DSR strategies include:

Peak shaving: reducing the consumption tops at the highest consumption periods.

Valley filling: Increase the consumption during the lowest consumption periods.

Load shifting: Shift the consumption to different periods.

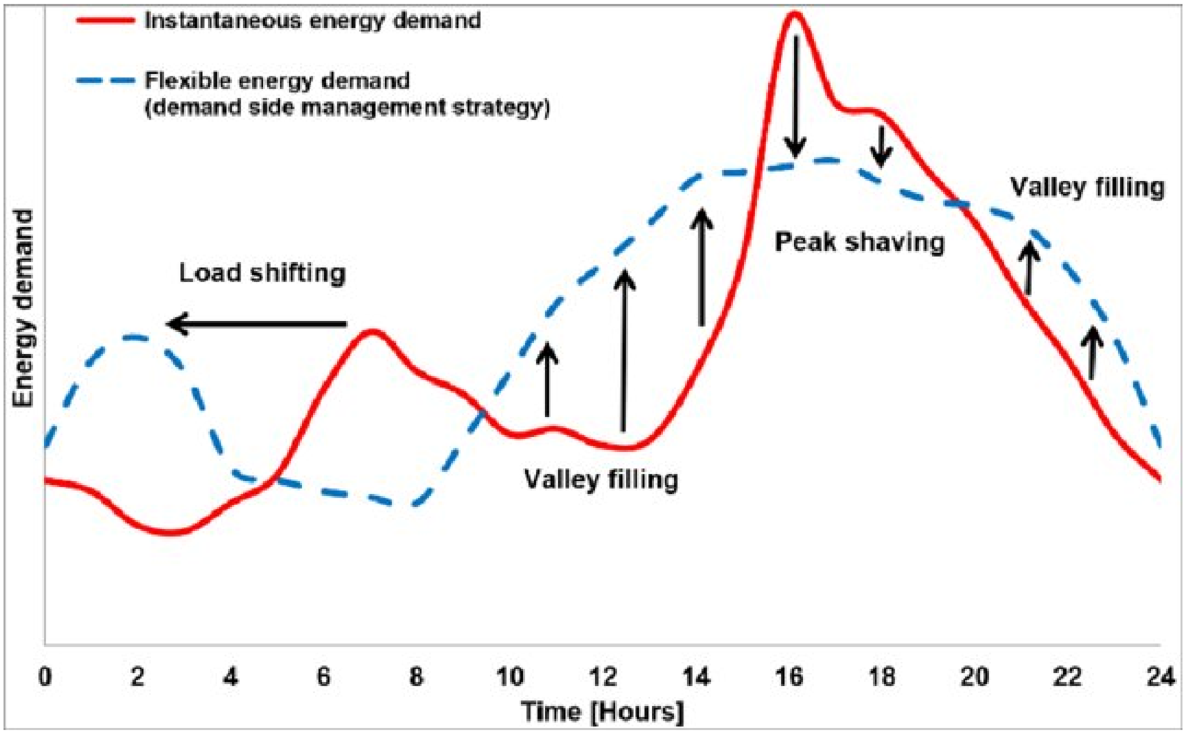


Figure 2.1: Demand side respsonse strategies with peak shaving, valley filling and load shifting, [21]

Demand side response

There are three different types of Demand Side Response (DSR) strategies, Manual DSR, Semi automated DSR and Autmated DSR. Manual DSR involves direct user interference with the component to change operation. Semi automated DSR involves user oversight of a centralized system to initalize strategies automated strategies. Autmated DSR is fully automated where external signals trigger pre-programmed algorithms to activate a DSR strategy.[28]

DSR programs are designed to incentivize users to reduce or shift their electricity use during peak hours, enhancing grid reliability and reducing energy costs. From a utility standpoint, the objective is to reduce overall energy usage and remove the fluctations in the load behavior. For the user, the main objective of DSR is to reduce the overall energy usage, but also to avoid discomfort.[30] Developing comprehensive metrics to assess DSR programs in buildings is challenging due to the complexity of the aspects involved. Currently, the lack of commonly accepted and standardized metrics represents one of the main obstacles to achieving widespread adoption of DSR programs in residential buildings.[28]

Many studies have been conductud on the optimal control of domestic EWH. The EWH optimization of energy efficiency thorugh thermal models, adnvanced control algorithms, user comfort and the prevention of Legionella. [30]. The typical control of an EWH is to use the thermostats to set a target temperature in the tank. This is called thermostat control (TC). Another way to control the EWH, is the use of schedule control (SC). Where the schedule is manully determined based on user comfort and energy efficiency. DSR with ASHPWH focuses on optimizing energy usage by adjusting operation times and strategies to match energy demand with supply, thereby enhancing energy efficiency and reducing costs. Significant benefits of DSR include reducing the frequency of start-stop operations and improving the overall efficiency of ASHP systems. Studies have shown that optimal DSR strategies can lead to substantial energy savings and lower operational costs by managing heat pump operations during peak energy periods[41]

The economic viability of implementing DSR strategies in Norwegian households is influenced by several factors including the variability of electricity prices, the capacity and efficiency of how water tanks, and the specific energy needs of the household. The analysis from [9] indicated that savings from DR are most significant during periods of high price volatility. However, these savings must be weighed against the potential increase in energy losses associated with maintaining larger or hotter water heater storage tanks.

In this thesis, the two dimensions of assessing the DSR strategies in the scenarios, are the economic dimension and technical dimension. The economic dimension looks at the cost associated with a specific flexibilty measure (CF), and can be evaluated by comparing the operational costs resulting from the activation of the DSR xtrategy (OC_{DSR}) with the operational costs of a baseline reference scenario (OC_R). The formula is given by:

$$CF = \frac{OC_{DSR} - OC_R}{OC_R} \times 100\% \tag{2.1}$$

The Available Electric Energy Flexibility (AEEF) measures the variation of the systems electrical energy consumption over the period (τ) in which the flexibility measure is active. Equation 2.2 expresses the AEEF, where the electric power consumption with and without DSR strategies, ($P_{t,DSR}$) and ($P_{t,R}$), respectively.[28]

$$\text{AEEF} = \int_{\tau} (P_{t,DSR} - P_{t,R})\, dt \tag{2.2}$$

2.0.2 Prosumers in Norway

Prosumers in the energy sector refer to entities that produce their own energy while also consuming energy from the grid. The role of prosumers in Norway is shaped by regulatory frameworks that facilitate or constrain their activities. Policies such as net metering, feed-in tariffs, and subsidies for renewable energy installations play an important role. Generally, national energy systems with high level of emissions has driven country policies in the direction to support prosumers. Specifically for Norway who already has a large share of renewable penetration, the main driver for prosumer growth lies in the goal to diversify the the energy sources and enhance the energy security.[39].

However due to the generally low prices in norway, return on investment are delayed[39]. A

2.1 Energy system

2.1.1 Heat pump

The working principle of a heat pump (HP) involves transferring heat from a colder area to a warmer area using energy in the form of electricity. In the sense of air source heat pump (ASHP), the source of energy comes from the outside air, and is transferred to a warmer area, for example indoors, for heating purposes.

There are two main types of ASHP, air to air HPs (AAHPs) and air to water HPs (AWHPs). For an AAHP the refrigerant in the system absorbs heat at low temperatures from the outdoor air in the evaporator, and the compressor then increases the temperature of the refrigerant. The heated refrigerant flows through the condenser, releasing the stored heat into the indoor air.[34]. For an AWHP, the refrigerant is transferred to a heat exchanger which heats up the water in a water based (hydronic) central heating system. These systems requires a compact heat exchanger and a control unit next to the hot water tank [34].

The efficiencies of HPs is called the Coefficience of Performance (COP), and is the main attribute from the technology. It is defined as the ratio between the heat added, and the work required to achieve the heat transfer in the refrigerant, see equation 2.3.

$$COP = \frac{Q_{out}}{W_{in}} \tag{2.3}$$

By assuming that there are no losses in the process, Equation 2.3 can be simplified to Equation 2.4 (Carnot efficiency). where the cop is only dependent on the ratio between the temperature of the refrigerant T_h and the temperature difference between T_h and the ambient air temperature T_c (for ASHPs).This is the highest theoretical efficiency a HP can have.

$$COP = \frac{T_h}{T_h - T_c} \tag{2.4}$$

According to IEA, the COP for a typical HP in househould systems is around 4 [25]. The performance of ASHPs is highly dependent on its operating conditions, particularly the ambient air temperature and the required water temperature for heating, as shown in Equation 2.4.

ASHPs exhibit variable performance efficiency based on the ambient air temperature. The COP of ASHPs, such as the Panasonic T-CAP 9 kW model, demonstrates significant fluctuations with changes in outdoor temperatures. At a moderate outdoor air temperature of +7°C and a water temperature of 35°C, typical for under-floor heating systems, the COP can be as high as 4.6. However, as outdoor temperatures drop to -15°C, the COP dramatically decreases to approximately 2.5.[32]This reduction is due to the increased energy required to extract heat from colder air and the additional defrost cycles that may be needed to maintain efficiency.

The required water temperature for heating applications also significantly impacts the COP of ASHPs. For heating systems that require higher water temperatures, such as radiators needing water heated to 65°C, the COP efficiency further declines. Under the same challenging conditions of -15°C outdoor temperature, the COP for heating water to 65°C can drop to as low as 1.3. This decrease underscores the challenges of using ASHPs in colder climates where higher temperature water is needed.[32]

2.1.2 Electric Water Heater

Electric water heaters (EWH) are common household appliances used to heat water for domestic purposes such as bathing, cooking, and cleaning. The working principle of EWHs is the conversion of electrical energy into thermal energy through a heating element, which is then transferred to water.

The energy of the water inside the tank at a target temperature T_{target} is given by the energy required ΔQ to heat up the mass of water m_{water} from a reference temperature T_{ref}, typically the temperature of the cold water flowing into the tank, see equation 2.5. The required energy to heat up one kg of water with a one degree increase, is called the specific heat capacity of water c_{water}, which is 4.186 $[W/(kg \cdot^{\circ} C)]$ at 20 deg.

$$\Delta Q = (T_{target} - T_{ref}) \cdot m_{water} \cdot c_{water} \tag{2.5}$$

A traditional EWH includes a thermostat that controls the temperature of the water by switching the heating element on and off. It is set to maintain the water at a target temperature. When the water temperature drops below a preset level, the thermostat activates the heating element, and vice versa.

The heat flow of the thermal energy in tank can be described using the 2 law of thermodynamics. The heat will flow from the high temperature water to its surrounding objects with a lower temperature. Thus, the temperature of water inside the tank in a domestic environment will decrease over time, assuming no heat is entering the system, due to heat flow out of the system, see equation 2.6

$$\Delta Q_{water} = Q_{in} - Q_{out} \tag{2.6}$$

Furthermore, the heat transfer rate $Q\prime$ from the tank to its surroundings is then dependent on the surface area A of the tank, the tank's heat transfer coefficient U, and the temperature difference between the water in the tank T_{target} and the ambient air T_{amb}, see.

$$Q\prime = A * U * (T_{target} - T_{amb}) \tag{2.7}$$

Equation 2.5 2.6 2.7 shows that a high temperature on the water in the tank T_{target}, would result in higher losses. Making it desirable to keep the temperature as low as possible, without creating user discomfort.

However, there is not a uniform temperature distribution in the tank. An important physical phenomena in water heater storage tanks is Stratification. The layers of water at different temperatures form due to variations in water density. Stratification ensures that water at different temperature levels remains in distinct layers without significant mixing. This separation is beneficial because it allows for higher temperatures to be maintained at the top of the tank, where hot water is drawn off for use, while cooler water stays at the bottom to be reheated. this phenomena is beneficial in combination with HPs. It allows for HPs to operate more efficiently because the heating element or heat exchanger primarily interacts with the warmer upper layer of water. This reduces the energy required to reach target temperatures compared to a fully mixed tank scenario.[3]

2.1.3 Legionella

Legionella is an important comfort criteria to mention. Legionella is a genus of bacteria that is primarily waterborne and known to cause Legionnaires' disease, a severe form of pneumonia, and Pontiac fever, a milder illness resembling the flu. It mainly exists in natural water systems and man-made water systems. The topic of Legionella prevention is a well researched topic, where the colonization is to be avoided thorugh water-treatment. One of the key criterias of Legionalla growth is the water temperature. The growth and multiplication occurs in the range of 25°C and 42°C. Therefore it is important to polarize the hot and cold water.[27]

According to FHI, temperatures above 50 °C continuously will extinct the bacteria over time. The rate of extinction increases with higher temperatures.[17]. They also state that regrowth can occur relative quickly after rapid temperature increases, and most likely the regrowth occurs due to not thoroughly cleaned systems.

In a central control system, the prevention of Legionalla growth could be implemented by introducing a schedule control. However, due to the short time range of the model, Legionella prevention through water-treatment is not considered.

2.1.4 Air Source Heat Pump Water Heater

An Air Source Heat Pump Water Heater (ASHPWH) is a system in which the water heater is integrated into the hydronic central heating system. As mentioned in... In this setup, the thermal energy is supplied by the ASHP, replacing the electrical energy typically used by a heating element in an Electric Water Heater (EWH). When an ASHP replaces the electrical component of an EWH, it utilizes the heat extracted from the outside air, enhancing the system's energy efficiency compared to traditional EWH systems. The water heater cylinder in an ASHPWH system will be referenced as EWH in this thesis, as the hot water cylinder in Pilothouse is an EWH with internal coils for heat exchange and an electric immersion heater for backup heating.

The configuration of the ASHPHW system in Pilothouse is a standard configuration, see Figure 2.2. The ASHP extracts heat from the external air and uses it to heat water stored in the EWH. The EWH stores hot water for domestic use, ensuring it stays warm for extended periods.

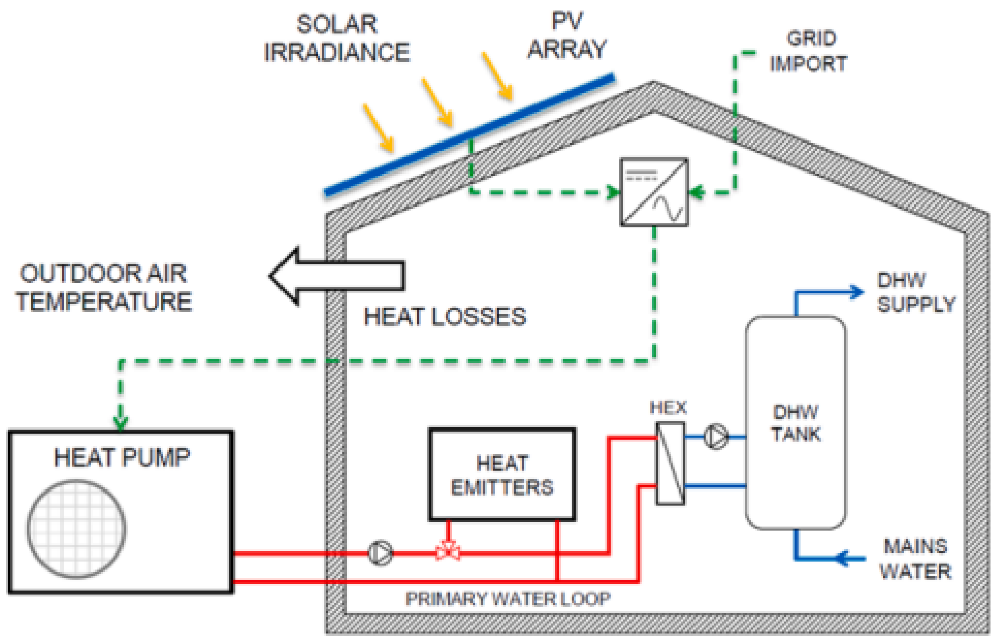


Figure 2.2: Configuration of the energy system in Pilothouse with a HP system coupled with heat emitters and a hot-water cylinder. Retrieved from [26]

The EWH used in Pilothouse is the OSO optima coil (OC) 360 [**noauthor˙varmtvannsbereder˙nodate**]. The relevant dimensions and technical data for this thesis is summarized in Table **??**. It is worth noting that the measured height (1,9 m) of the tank differs from the data sheet provided by the manufactures, but the values from the data are used in the basecase of the model. Moreover, the tank is divided into two sections: the upper section and the lower section. The upper section has a volume of 224 L and the lower section has a volume of 136 L. It is assumed that the heights of the sections are given by the ratio of the respective volume and the total volume of the tank, see Equation 2.8

$$h_{tank} = h_{upper} + h_{lower} \implies h_{tank} = h_{tank} \cdot \frac{V_{upper}}{V_{tank}} + h_{tank} \cdot \frac{V_{lower}}{V_{tank}} \tag{2.8}$$

The control unit regulates the temperature of the water in the lower section by setting minimum and maximum temperature limits. When the ambient temperature falls below -5°C, these limits are set to a minimum of 35°C and a maximum of 45°C. Conversely, when the ambient temperature rises above 18°C, the temperature limits are adjusted to a minimum of 20°C and a maximum of 30°C. For ambient temperatures between -5°C and 18°C, the temperature limits decrease linearly as the ambient temperature increases. This behavior is visualized in Figure 2.3

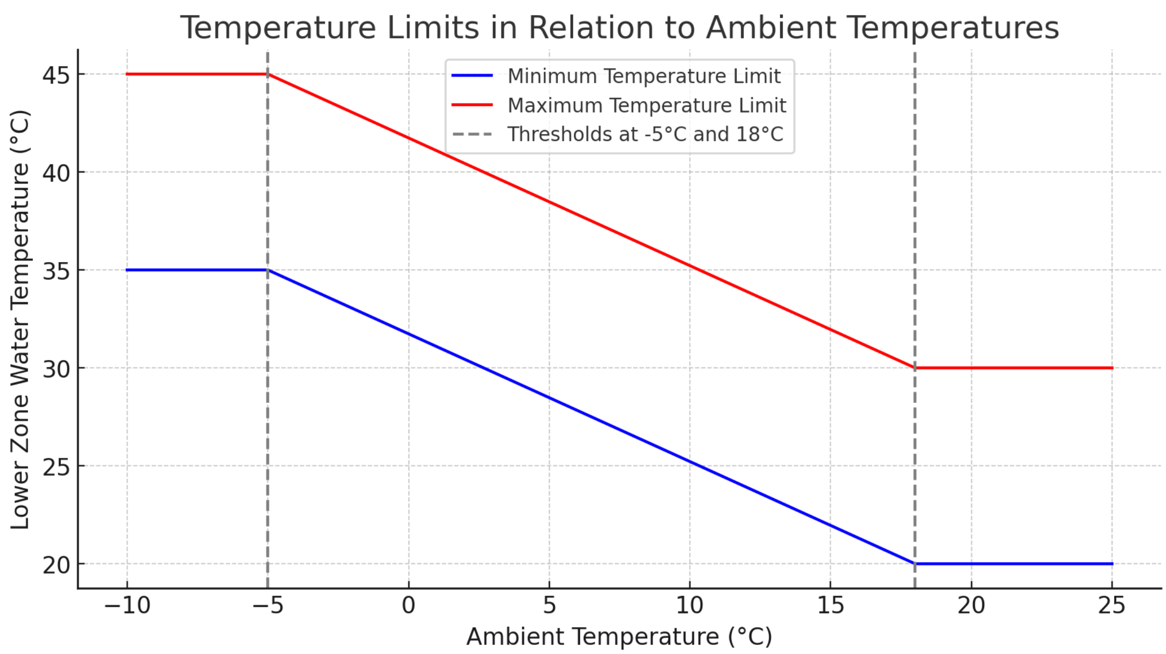


Figure 2.3: Plot of the operating temperature limits for the water in the Lower section in the EWH in Pilothouse

Parameter	**Value**	**unit**
Height	2031	mm
Diameter	595	mm
Volume Upper section	224	L
Volume lower section	136	L

Table 2.1: Dimensions of OSO Optima coil hotwater[37]

2.2 Decentralized PV production

The technical specifications of the PV system in Pilothouse will not be deeply explained, as the main focus of this thesis is on the energy system modelling of Pilothouse. This section will briefly explain the impacts of decentralized production on the grid, and the incentive to increase self sufficiency.

From the view of the DSO, As decentralized PV production increases, one of the most pressing issues that emerges is grid capacity. The IEA PVPS Trends in PV Applications 2023 report highlights that as PV penetration deepens, grid capacity is often strained, leading to grid congestion. This is particularly evident in countries with high PV penetration rates. The decentralized nature of solar PV means power is generated close to the point of consumption, reducing the burden on transmission networks but increasing the complexity of distribution networks.

Decentralized PV systems introduce variability and intermittency in power supply, which can lead to voltage fluctuations and stability issues. To address these challenges, DSO's are increasingly investing in smarter grid solutions and technologies such as advanced metering infrastructure, grid automation, and energy storage systems. The fluctuations in PV output necessitates investment in flexibility options like storage or demand response programs.[15].

The PV system is a 16kWp installation whith an azimuth of 170 °. A 16 kWp PV system is considered a large residential installation. This capacity indicates the peak power that the solar panels can produce under optimal conditions. Depending on the base load of Pilothouse, there is substantial potential for energy self sufficiency during solar production. The azimuth of a PV panel refers to its orientation relative to true north. An azimuth of 170° implies that the panels are facing slightly south of due east. In the context of DSR and energy managment, the key metrics for solar subsystems is the self suffciency and the self consumption. One of the EU target is to increase the self sufficiency of buildings and is an important topic in topics such as energy and micro-grid applications.

$$SC = \frac{S_p}{Solar_e} \tag{2.9}$$

The integration of decentralized renewable energy sources into the grid has notable impacts on grid stability and operation. Increased decentralized energy production penetration, particularly photovoltaic (PV) systems, affects frequency response, power flow, and voltage profiles, necessitating new management strategies to maintain grid reliability and prevent blackouts. The decentralized systems also impact grid losses and power quality, requiring optimized planning for effective integration.

2.3 Heat transfer calculation in buildings

The concept of heat loss in buildings involves understanding how energy is transferred from inside the house to the outside environment, largely impacting the energy efficiency and thermal comfort of the building. Thermal models of a building is difficult to design accurately with limited information about the construction and occupancy pattern. The Thermal performance of Pilothouse is calculated using the proposed approach from Tabatabei et al. in the study *A Data Analysis Technique to Estimate the Thermal Characteristics of a House* from 2017 [35]. Which involves calculating the heat loss rate and heat capacity of a building based on temperature data and energy supplied by a heating system, with the Degree days analysis method. It is worth noting that the method can be sensitive to external factors, such as occupancy patterns and solar radiation as these factors is neglected.

2.3.1 Heat loss rate

The heat loss rate (ϵ), quantifies the rate at which heat is lost from the building per degree of temperature difference between the indoor temperature (T_r) and the ambient temperature (T_amb). This temperature difference over a time period (τ) is called Degree Days DD. This is a tool used to estimate the energy demand for heating or cooling down buildings and is formulated mathematically in Equation (2.10).

$$DD_\tau = \sum_\tau T_r - T_{amb} \Delta t \tag{2.10}$$

"*Aggregating conduction, infiltration and ventilation, the amount of energy lost in a period is a linear function of the amounts of degree days for that period*" - [35] The formula for the heat loss rate can be formulated in a discrete way:

$$\epsilon_\tau = \frac{Q_{r,loss,\tau}}{DD_\tau} \tag{2.11}$$

2.3.2 Heat capacity

The heat capacity of a building C represents the building's ability to store heat. It depends on the mass (m) and specific heat capacity (c) of the materials used in the construction. Higher thermal capacity can mitigate temperature fluctuations, enhancing thermal comfort and reducing the frequency of heating system cycling. Equation 2.5 has a

$$C = mc = \tag{2.12}$$

Smartgrid

2.3.3 Norwegian grid Tariffs

The primary motivation for residential prosumers to invest in local energy production and control systems is the potential to reduce costs associated with their consumption. This section dives into the concepts of grid tariffs specifically for Norway and potential directions for the future.

Grid tariffs

The grid tariffs are the costs and fees associated with the transmission of electricity from production to the end-user. The electricity is transported through the high-voltage transmission network, operated by the TSOs, and the low-voltage transmission Network, operated by the DSOs.[2]. These are separate systems, which therefore have different tariffs associated with them. The costs and tariffs from the DSOs and electricity providers are, in principle, the two sources of costs that end users can control. These tariffs are supposed to reflect the end user's willingness to pay for their electricity and encourage the end user to not use more than is needed.[2] The grid tariffs are set in place to optimize social welfare. Higher electricity consumption than necessary would lead to unnecessary network and production expansion.

A reduction in consumption would lead to overpriced tariffs in order to compensate for the underutilized network. [2]

Specifically for Norway, there are two main components to an end-users electricity bill in today's grid tariffs: a fixed component and an energy component. The fixed component is representative of the capacity needed to supply the end user at all times during that month. It is set by the average of the highest hourly-energy consumption from the grid by the end user over three different days of a month. The fixed component stages can differ depending on the DSO. The fixed component stages from Elvia (DSO in Norway) is represented in Table 2.2.

Stage	Daily Max (kWh per hour)	Cost per Month (kr)
Stage 1	0-2	120
Stage 2	2-5	190
Stage 3	5-10	305
Stage 4	10-15	420
Stage 5	15-20	535

Table 2.2: Fixed Component Pricing Tiers [6]

The energy component is dependent on the amount of energy the end user consumes over a month and at which times the consumption occurs. The energy consumed during the weekend and on the weekdays between 22 and 06 will have a lower fee than between 06 and 22 during the weekdays. In addition, there are monthly variations in the energy component. Elvias time dependent energy components are given in table

Energy Component	Day (¢/kWh)	Night/Weekend (¢/kWh)
Energy Component from January to March	39.59	32.09
Energy Component from April to December	48.25	40.75
(Energy Component excluding taxes)		
Without Taxes	21.16	15.16

Table 2.3: Elvia's Energy Component [6]

Lastly, there are three taxes that contributes to the electricity bill: the Electricity tax, the value added tax (VAT) and the Enova levy. The taxes are provided in table, where the cent

Name	Value	unit
Electricity tax Jan-Mars	9.51	¢/kWh
Electricity tax Apr-Des	16.44	¢/kWh
Enova levy	1.0	¢/kwh
VAT	25	&

Table 2.4: Elecitricy taxes

2.3.4 Electricity support

Electricity support is a financial aid scheme introduced by the Norwegian government to help households cope with high electricity bills. The scheme was initially introduced as a temporary measure in December 2021 in response to a significant increase in electricity prices in Norway. The purpose of the electricity support is to reduce the financial burden on households during periods of extraordinarily high electricity prices. In 2022 and 2023 the Norwegian government paid 32.6 and approx 9.6 million kroners to Norwegian households,respectively. [7]

Today, electricity support is given to households when the hourly spot price is above 73 ¢/kWh. During these hours, the government supports with 90% of the spot price above this threshold, excluding VAT. [7]

2.4 Communication protocols

2.4.1 Zigbee

Zigbee is a wireless communication standard designed for low-power, short-range, and low-data-rate applications. It is often used in home automation and IoT devices to enable communication between different devices within a network. The technological principles behind the characteristics of the zigbee protocol is not explained in detail, however, some of the principles will be explained to show the advantages of its use in home automation and control.

One of the main advantages of Zigbee is its high reliability characteristics. Its reliability is linked to its data packaging, transmitting and mesh networking. The data is packed in a Frame Checksum(FCS),which is a mechanism used in data communication to detect errors in a transmitted frame of data. When the receiving device receives the frame, it also calculates the checksum using the same algorithm. If the calculated checksum matches the received checksum, it indicates that the data is likely intact. However, if there is a mismatch, it suggests that the data may have been corrupted during transmission, and the receiver may request a re-transmission of the data. the re-transmission occurs up to 3 times, before an error occurs.

Another reliable mechanism zigbee uses is the Carrier Sense Multiple Access Collision Avoidance (CSMA-CA). Zigbee listens for a clear channel before transmitting to avoid data corruption caused by simultaneous transmissions.

In the event that a device is out of radio range to a end device in the network. The mesh network ensures that the data is transmitted through the use of other nodes in the network. This is done automatically, and is updated for frequently in the case of route failure due to interference. [10]

In addition to the reliabile data transmitting, the zigbee protocol is low power consuming. Due to its small data exchange rate, the zigbee devices are able to last an entire shelf life of a AA alkaline battery. The devices in a zigbee network is not constantly in contact with the network, but remains on the network in a stand-by mode, and does therefore not consume unnecessary power. [10].

The positioning of Zigbee in figure **??** encapsulates its niche as a low-power, low-data-rate technology with moderate range. Zigbee's design philosophy emphasizes simplicity and power efficiency, which enables it to support a network of devices that can communicate effectively with low power consumption. It is particularly favored in applications such as smart homes, industrial automation, and consumer electronics, where a mesh network can ensure reliability even if individual links fail.

Zigbee Green Power

Zigbee Green Power is a central component of the Zigbee PRO feature set, specifically designed to accommodate ultra-low-power devices within the Internet of Things (IoT) and smart home environments. This technology enables devices like sensors and switches to operate on minimal energy, which can even be harvested from ambient sources such as light, vibration, or temperature changes. The significance of Zigbee Green Power lies in its ability to maintain connectivity and functionality while using very little power, making it ideal for applications where energy efficiency is essential.

2.4.2 MQTT

MQTT is a client-server publish/subscribe messaging protocol designed for lightweight communication in IoT systems. Originating in 1999 for monitoring oil pipelines over satellite networks, MQTT facilitates efficient data transmission even under limited bandwidth or unreliable networks. Its lightweight nature minimizes power consumption, making it suitable for IoT, mobile or remote sensors.

It operates on a broker-client model where the broker manages network connections and distribution of messages. Clients, which can be publishers or subscribers, interact through the broker, significantly simplifying message routing and network design.The protocol supports different levels of Quality of Service (QoS) to guarantee message delivery under varying network conditions.

Model design of Hybrid Energy systems

When it comes to model design of energy systems, there is a need to simplify the complexity and make assumptions about the system. However, simplifying one part of a system, can impact another part of the system, making it important to understand the system's dynamics. Therefore, it is an emphasis to model the relationships between the components of the system, rather than model the components with high level of details.

One of the simplest designs of a energy system is assuming a linear relationship between the system componenents, called Linear programming (LP). Linear Programming (LP) optimization is a method to achieve the best outcome in a mathematical model whose requirements are represented by linear relationships in decision variables and constraints. It is a technique used to optimize an objective function, subject to linear equality and inequality constraints. The optimization can either be a maximization or a minimization of the objective function. Mixed integer linear programming (MILP) is an extension of LP which combines the integer programming (IP) and LP. This design keeps the model linear, but not continues, as integer and/or binary variables are introduced. The non continuity results in more complexity and computational load for the optimization solver.[11]

Chapter 3

Enabling envornment

3.1 Home Control System: Setup and configuration

The IoT system architecture utilizises various components and technologies for data management and device control. The setup incorporates a combination of hardware and software technologies designed to monitor and control home automation devices. The data flow is illustrated in Figure 3.1.

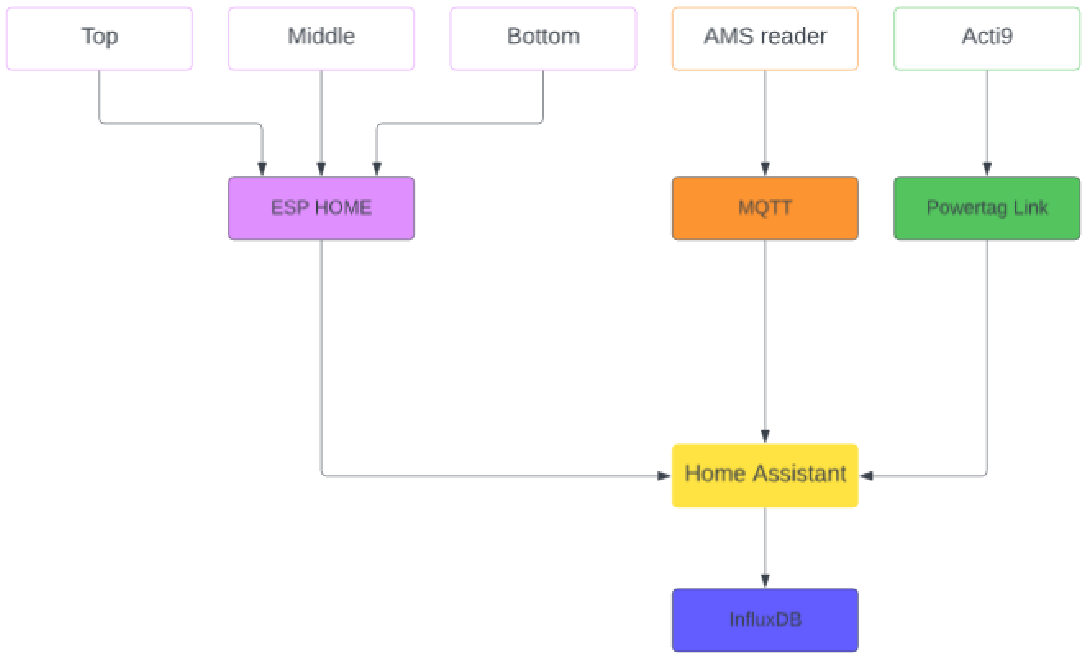


Figure 3.1: Flow-chart of data flow in system

3.2 Hardware

The three temperature sensors, Dallas DS18B20, are interfaced with an ESP8266 microcontroller, which is configured using ESPHome—a firmware that integrates with Home Assistant for device management. The AMS reader connects to the HAN (Home Area Network) port on the AMS meter, transmitting real-time data to Home Assistant using the TCP/IP protocol via the MQTT integration. Additionally, the Acti 9 power tags are connected to a PAS 600 server panel, which in turn is linked to HA through the Powertag Link Gateway integration. A list of all the hardware components are listed in Table 3.1

Table 3.1: IoT System Hardware Components

Component	Purpose	Manufacturer/Model
Microcontroller	Collect and transmit temperautre data to HA, and control operation of HP through ESPHome integration.	ESP8266
Temperature Sensors	Collects temperature data from the lower and upper zone of EWH	DS18B20
Relay	Controls the power supply to ASHP	Luxor 4-gate
Powertags	Measures real-time energy consumption data from circuits in the system.	Schenider acti9
Panel server	Collects the circuit metrics recorded from the powertags and acts as a gateway with the Home assistant integration "Ecostrucure Powertag link gateway"	PAS-600.
AMS reader	Collects the AMS meter metrics and communicates with the MQTT integration in HA.	AMSleser.no

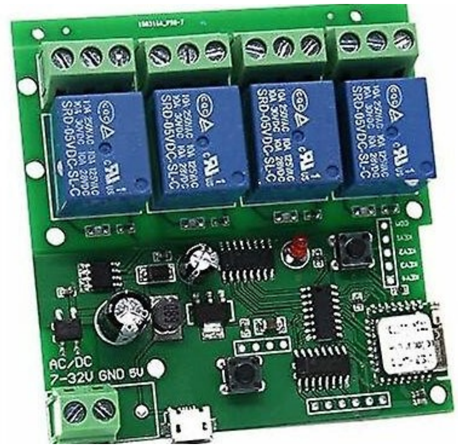
Temperature sensors in EWH

The placement of the three temperature sensors is strategically selected in the EWH.

- **Middle Sensor**
  - **Location:** 170 cm from the bottom of the tank.
  - **Purpose:** Measures the hot water in the upper section of the EWH.

- **Top Sensor**
  - **Location:** 140 cm from the bottom of the tank.
  - **Purpose:** Measures the colder water in the upper section of the EWH.
- **Bottom Sensor**
  - **Location:** 50 cm from the bottom of the tank.
  - **Purpose:** Measures the water temperature in the lower section of the EWH.

(a) DS18B20 Temperature sensor

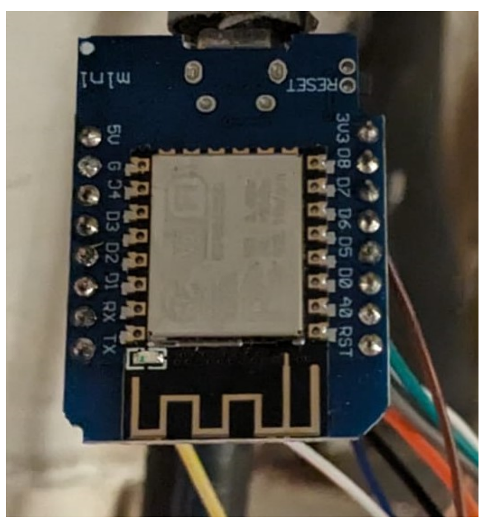


(b) Luxor Relay: 4-gates

(c) EcoStruxure Panel Server: PAS-600

[29]

(d) Acti 9 - PowerTag - 1P+N



(e) Esp8266 microcontroller

Figure 3.2: Pictures of the Hardware components in the IoT system of Pilothouse

3.2.1 Schneider hardware and software

The main sensors for consumption readings in Pilothouse are the acti 9 power tags connected to a pas 600 panel server.

EcoStruxure Panel Server and Acti 9 powertags

The EcoStruxure Panel Server is a part of Schneider Electric's EcoStruxure Building Operation, an integrated platform that provides centralized monitoring and control over building systems, including energy management. The Panel Server acts as a gateway that aggregates data from various sensors and systems, enabling intelligent automation and analytics. In the context of a home energy system, the Panel Server serves as the central component that connects all the electrical devices and sensors in an Schneider ecosystem, see Figure 3.3.In order to fully integrate the Schneiders Powertag ecosystem into Home assistant, the Ecostruxure Powertag link gateway integration in Home assistant is used.

Acti 9 power tags

Acti 9 PowerTags are wireless energy sensors designed to enhance electrical distribution through real-time monitoring and measurements. They are compact, wireless sensors that attach directly to circuit breakers. Some of the technical data include:

- Voltage monitoring range up to 480 V AC
- Current measurement capabilities from 40A to 630A
- Energy accuracy of Class 1 as per IEC standards

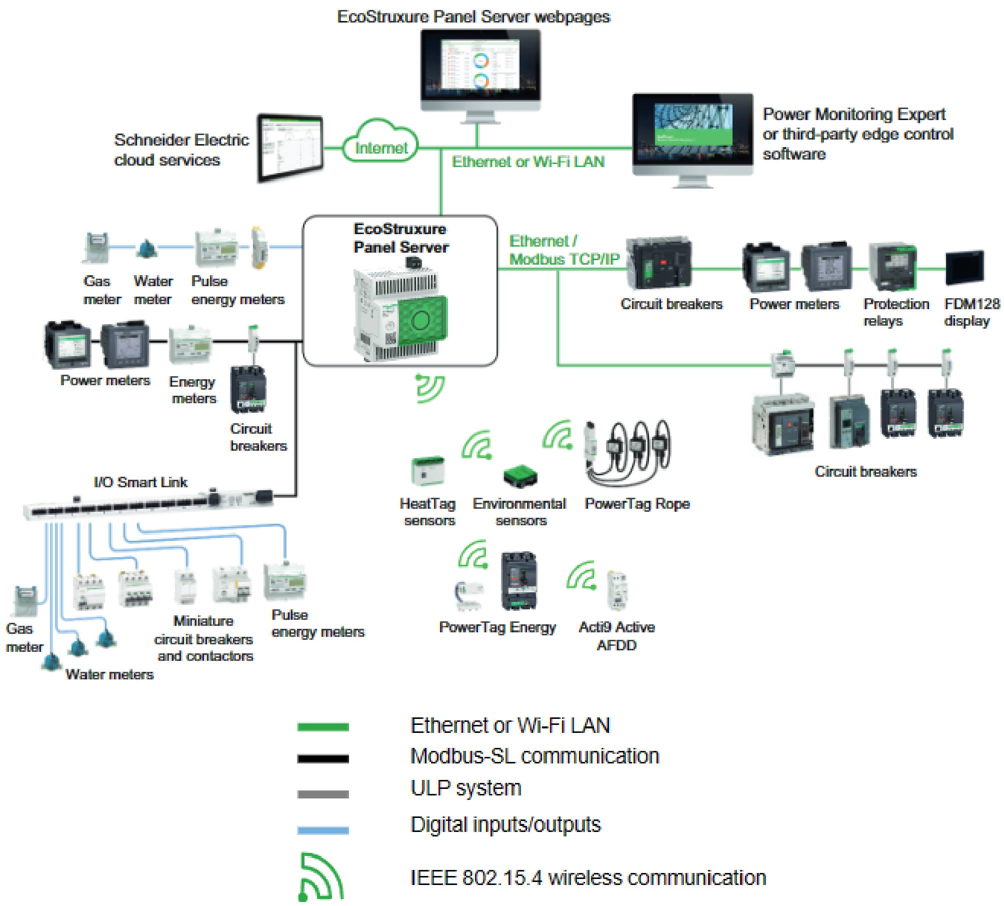


Figure 3.3: Typical architecture of Schneider system, retrieved from [4]

3.3 Home Assistant

Home Assistant (HA) is an open-source platform developed for the purpose of controlling and automating smart home devices. And is the selected open solution for home automation in Pilothouse. The platform supports over 1800 integrations, which fascilitates communication between devices and the HA system.[23] Integrations are softwares which allows HA to connect to other softwares and platforms, such as ESP and MQTT.[1]

When compared to third party applications, which is usually offered by the automation equipment manufacturers, an open solution offers advantages such as centralized control of the devices, continues development of automation solutions with different devices from different manufactureres, and eliminates the threat of unhautorized access by a third party.[23]

One of HA's primary advantages, i lies in its ability to integrate various smart devices from different manufacturers into a single, cohesive system.

3.3.1 Challenges of integrating ZGP into Home Assitant

The intended setup of the IoT system in involved integrating Elko PowerTags and the Conbee 3 gateway device as the primary hardware components for energy consumption measurements. The Elko PowerTags were chosen for their ability to monitor energy usage efficiently with the ZGP protocol, while the Conbee 3, a popular Zigbee gateway, was intended to facilitate communication between the sensors and HA. Despite the promising IoT capabilities, we encountered significant challenges during the integration phase with HA. The primary issue were related to compatibility between ZGP devices and HA. ZGB devices has limited support and development within the HA ecosystem, were the primary solution is to introducing a proxy Zigbee device, which could communicate with HA on behalf of the ZGP device.[36] Therefore implementation of Zigbee devices was disregarded, and the Schneider Ecostruxure eco-system with modbus was introduced.

3.4 Data collection and Storage

Initially the data collection and storage of Pilothouse's IoT system was to be stored locally on the Raspberry Pi to enhance the security and privacy of the system. Due to shortcomings in the creation of automated python scripts for data storage in Home assistant, InfluxDB was selected as intermediate for collecting and storing data for the long term.

InfluxDB, developed by InfluxData, is an open-source time-series database designed specifically to handle time-stamped data with high efficiency and speed. Its architecture enables rapid high-availability storage and retrieval of data. InfluxDB's architecture is optimized for time series data, which is characterized by sequential, time-stamped entries. Unlike traditional databases that treat time as a secondary attribute, InfluxDB optimizes data storage around time-stamped data. Each data point consists of time, a measurement name, and key-value pairs known as fields and tags. Fields are used to store the values associated with the data point, whereas tags are used to store metadata that indexes for fast querying.

More over, InfluxDB supports Transport Layer Security (TLS) to encrypt data in transit.

This ensures that data transferred between clients and the InfluxDB server is secure from eavesdropping and tampering. [16]

Chapter 4

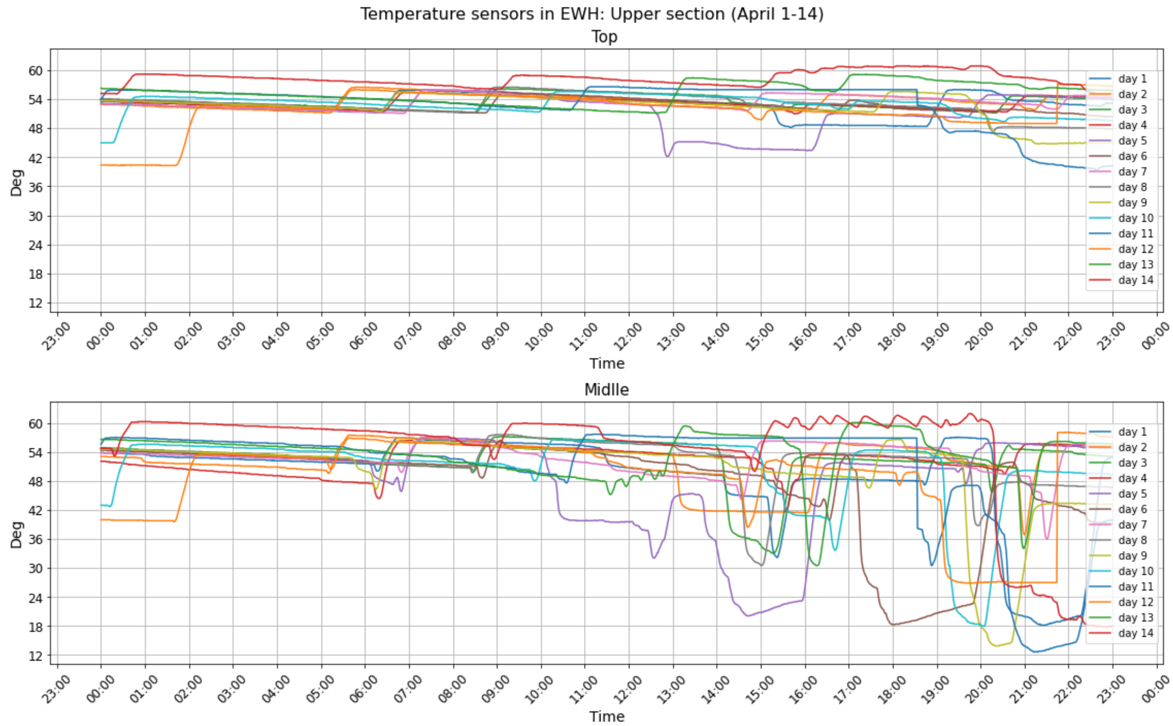
Methodology

4.1 Data analysis

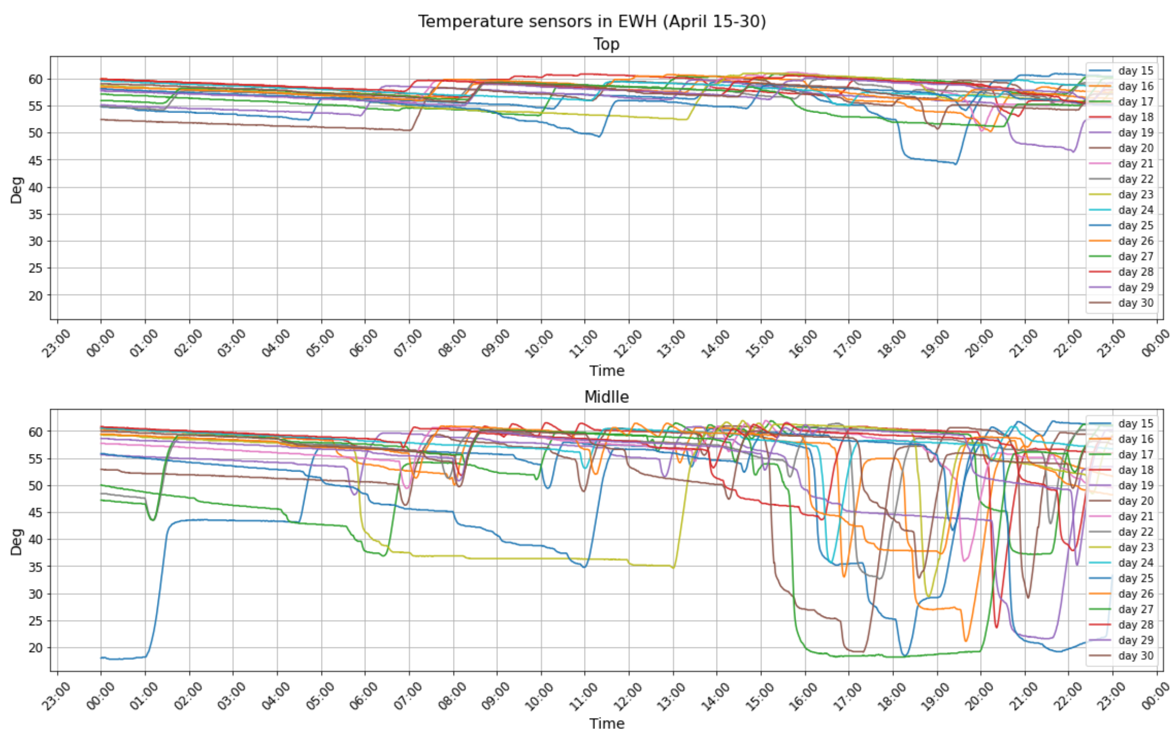
4.2 Domestic hot water

To analyze the energy management scenarios for the Electric Water Heater (EWH), the domestic hot water(DHW) demand over a day is synthenticaly created. The dataset aims to provide a simplified, but realistic daily consumption patterns of hot water, influenced by typical household activities such as showering and tapwater. The DHW demand profile has been based on the temperature readings of the upper zone over a month, see figure 4.1

The DHW demand in pilothouse often peaks during mornings and evenings when occupants prepare for work or school and then again when they return home. The two temperature sensors in the upper zone clearly shows the occurance of stratification. The top water does not go below a temperature of approx 40 °C, while the middle temperature drops below 20 °C for several days. However, the temperature readings can not be directly connected to the amount of energy being drawn from the tank, due to stratification.



(a) First half of month: Day 1-14



(b) Second half of month: Day 15-30

Figure 4.1: Plots of Temperature values of the sensors in the upper section of the EWH, ”Top” and ”Middle”, in 15 min resolution every day over the month April in 2024. Divided into 2 halfs: subfigure 4.1a and subfigure 4.1b

.

A simplified dataset is created focusing on energy use, where most the activities occurs between the hours 7-8 and 17-22. The simulation incorporates 2 appliances: a shower demanding water at 40 degrees for 15 minutes, and 50 degree Indoor tap/spray faucet for durations of 15,10 and 5 minutes. These activities are the primary contributors to the DHW demand in the model.

The calculation uses typical values for volumetric flow rates of water in domestic hot water fixtures [24], see Table **??**. With the volumetric flow and duration to the respective fixtures, a reference temperature of 10 degrees and the density of water being approx 1 kg per L; the thermal energy for each fixture is calculated using Equation 2.5:

Appliance	Thermal energy demand	Duration
Shower battery	6 kWh	15 min
Indoor tap/spray faucet	2.8 kWh	5 min
Indoor tap/spray faucet	5.6 kWh	10 min

Table 4.1: Calculated DHW energy demand for three typical appliances: Shower, washer and dishwasher

Fixtures	**Cold Water (l/s)**	**Hot Water (l/s)**
Drinking fountains	0.05	—
Toilet flush	0.1	—
Washbasin taps	0.1	0.1
Bidet taps	0.1	0.2
Indoor tap/spray faucet	0.2	0.2
Utility sink tap	0.2	0.2
Sink and utility tap in workshops	0.2	0.2
Shower battery	0.2	0.2
Household washing machine	0.2	0.2
Dishwasher in households	—	0.3
Bathtub tap	0.3	0.3
Garden tap	0.4	—
Flush valve for urinals	0.4	—
Flush valve for toilets	1.3	—

Table 4.2: Standard Water Flow Rates for Various Outlets

Time	7-7:15	7:30-7:45	17-17:05	18-18:15	19-19:10	20-20:15	22-22:15	
Shower [kWh]	6.0	6.0	-	6.0	-	6.0	6.0	
Fauset [kWh]	-	-	2.8	-	5.6	-	-	-

Table 4.3: Table of the synthetic DHW demand used in all model cases

dishwasher and washing machine is not connected to EWH in norway.

4.3 Hot water tank

Thermal Performance Analysis

The analysis of finding the heat coefficients for the lower and upper section of the tank, and (DD) for Pilothouse was conducted using data from April 19, 2024 during the hours of 5 PM and 8 PM,Figure **??**, a period when the heat pump was deactivated and the lower outlet valve was shut. As a result, the estimated heat losses for the sections are primarily due to the temperature difference between the sections and the surrounding temperature. The calculation of the heat transfer coefficients for the upper and lower section includes the thermal gradiant for both sections within the given time. The heat loss for each section is calculated using Equation (2.5). The thermal gradient is approximated to be the temperature difference between the average temperature of the section over the given time and the ambient temperature in the room of the tank (20 °C). The heat loss , see Equation (2.5) is divided by the amount of time, in seconds. Lastly, Equation (2.7) is used the find the heat transfer coefficients for the sections.

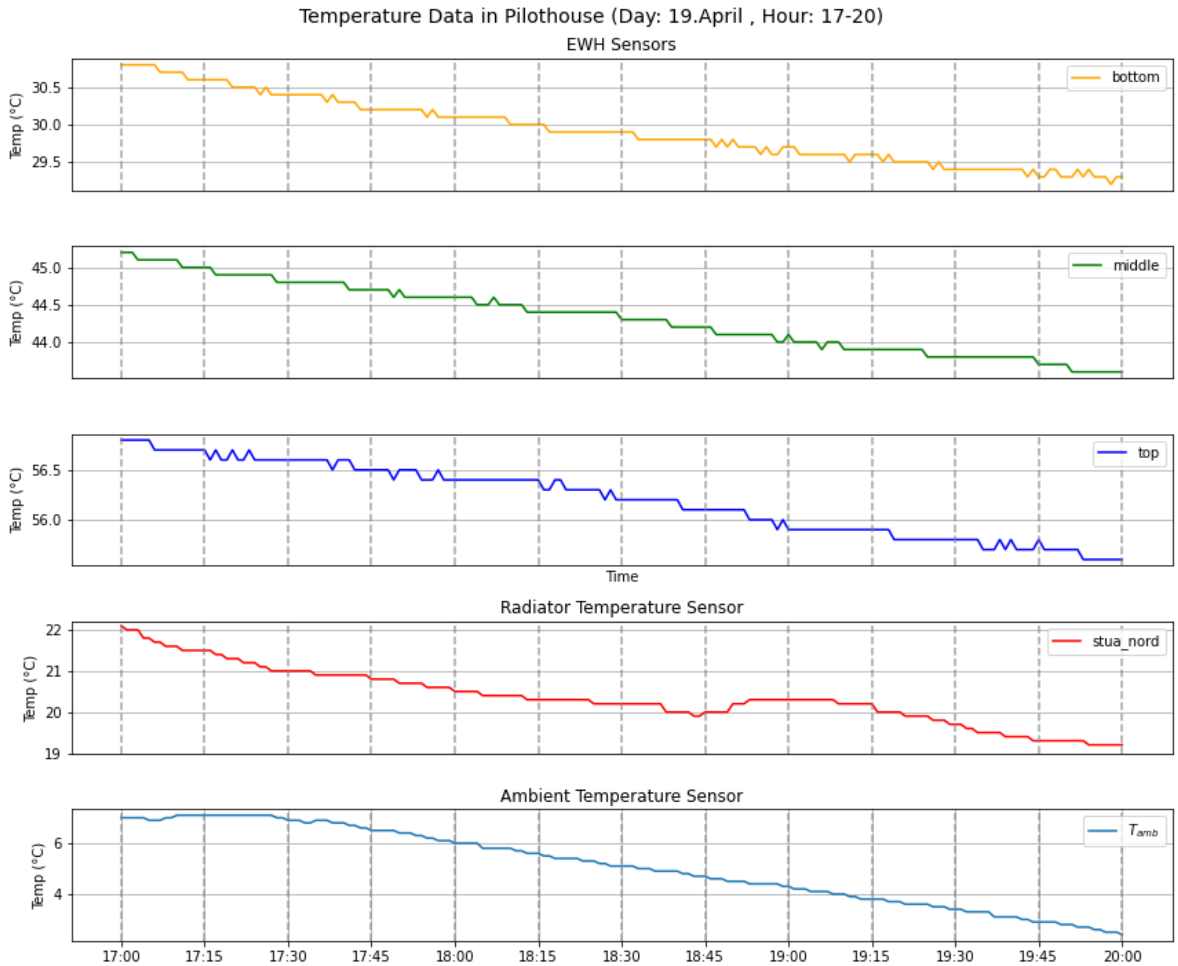


Figure 4.2: Temperature sensor data of the EWH sensors, Radiator sensor and the Ambient Temperature sensor in Pilothouse from 19.04.2024 from 17:00 to 20:00

The thermal performance of the house has been calculated using the temperature sensor data of "$Stua\_nord$", the ambient temperature T_amb and the temperature of the lower section T_l from 18.April 11:00-13:00.The sensor "$Stua\_nord$" is located in the north side of the living room in Pilothouse, and represents the room temperature T_r in the calculation of the thermal characteristics of Pilothouse. The results from the calculations is given in Table 4.4 Figure 4.3 shows the data from the mentioned sensors during this period. In addition, the operational flow of the radiators in Pilothouse is included in the figure to illustrate that they were non-operational during this period, indicating minimal circulation in the hydronic heating system.

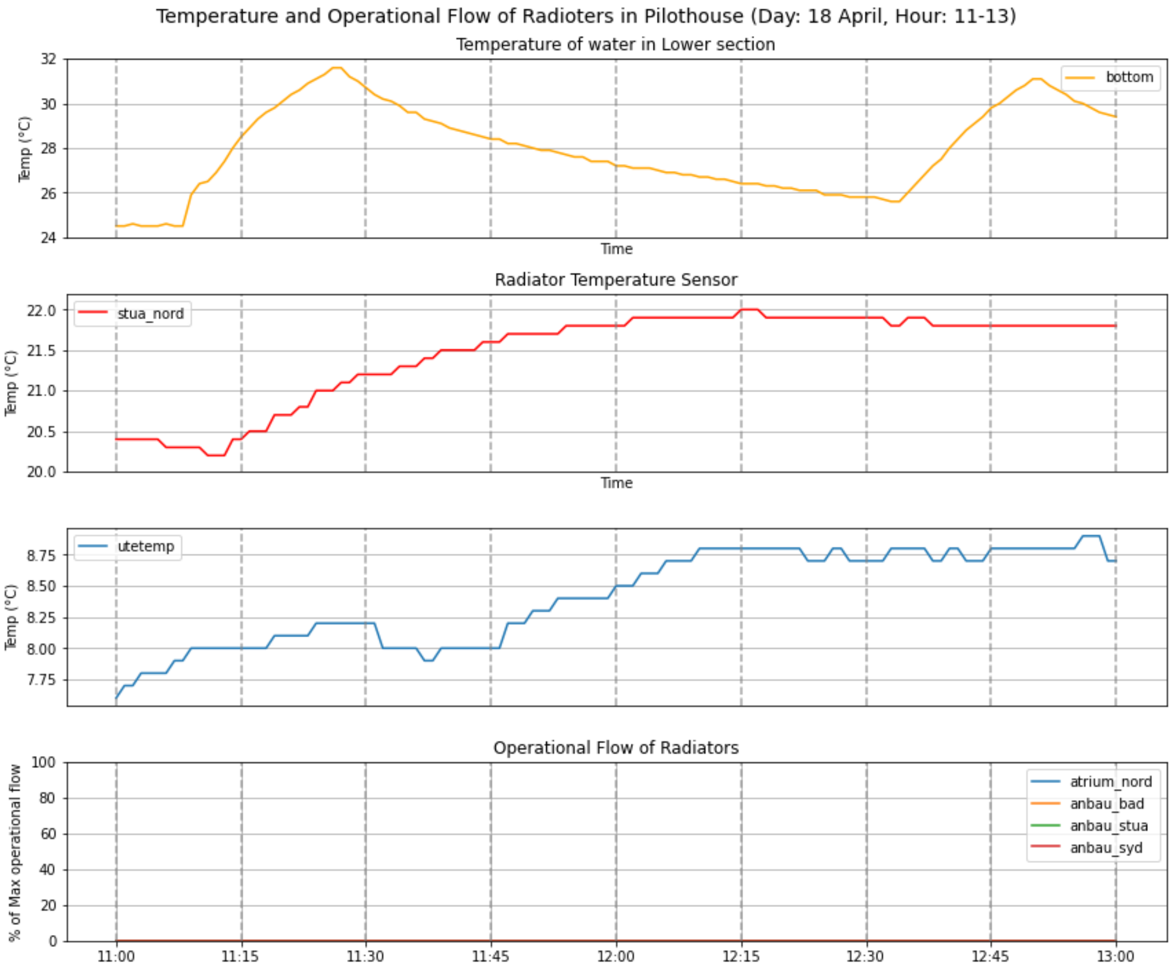


Figure 4.3: Temperature data from the lower section of the EWH, radiator and ambient temperature sensor, and the operational flow of the Radiators in Piolthouse 18.04.2024 from 11:00 to 13:00

Thermal charactersitcs of house	**value**	**Unit**
μ	3/16	-
ϵ	-100	$Wh/°C$
C_r	525	$Wh/°C$
Heat transfer coefficients	**Value**	**Unit**
u_l	5.2	$Wh/(m^2 \cdot^\circ C)$
u_u	1.1	$Wh/(m^2 \cdot^\circ C)$
$Q_{l,out}$	900	Wh

Table 4.4: Table of calculated Thermal characteristics of Room and EWH, (April 18 and 19

4.4 Selected days

There are selected three distinct days for the energy model to operate under different external conditions. Specifcally, the selection of days is based on ambient temperature,spot price and solar production over the month of April, where the each day represents a scenario. The scenarios are shown in a Table 4.5 as an ordinal scale, and the real data is displayed in Figure 4.4.

Criteria	**Scenario 1** (Day5)	**Scenario 2** (Day 18)	**Scenario 3** (Day 20)
Ambient Temperature	Low	Medium	Medium
Spot-Prices	Medium	High	Medium
Solar Production	Medium	High	High

Table 4.5: Selected days based on outside temperature, price, and solar production in an ordinal scale.

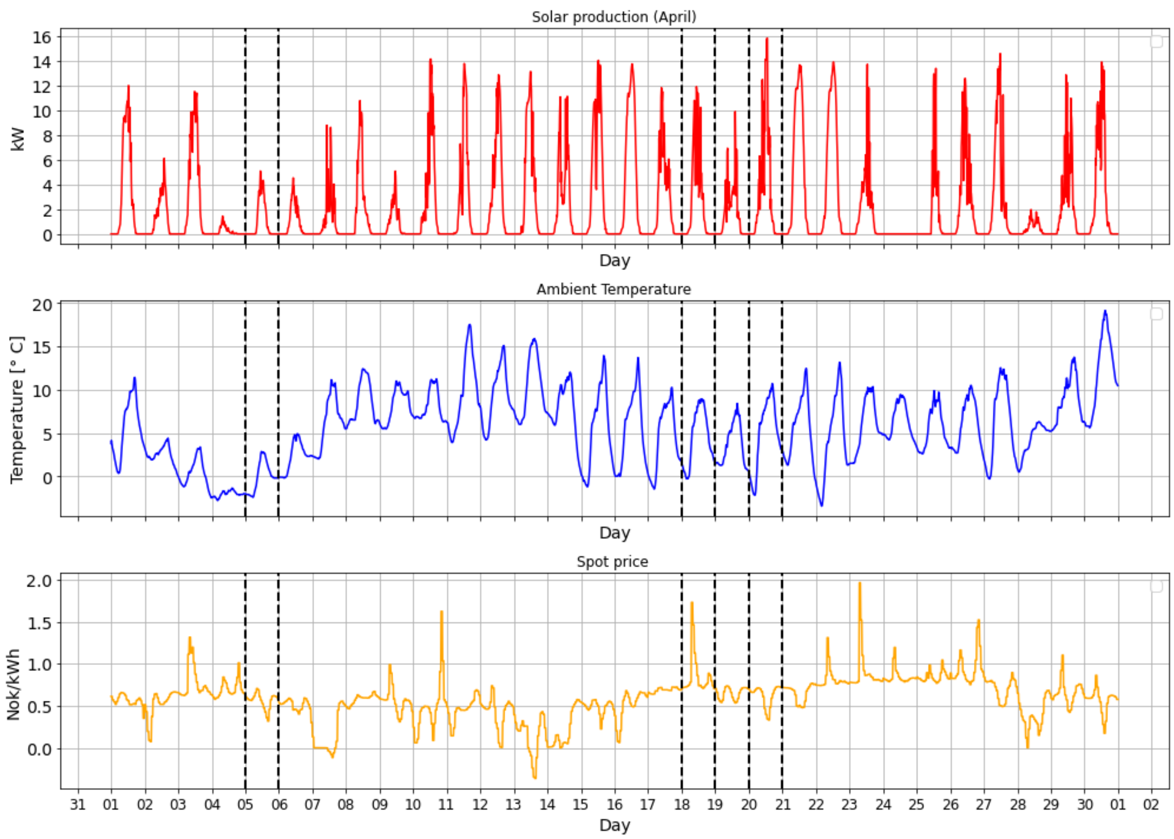


Figure 4.4: Solar production, Ambient temperature and Spot-prices over the month of April in 15 min resolution. Selected days for scenario selection is shown with dark strip lines.

Chapter 5

Optimization Model

5.1 Initial Model setup

The initial setup of the energy system model was approached as a linear programming (LP) problem, structured to manage operations at a high temporal resolution. The chosen granularity was a 15-minute interval, allowing the model to reflect more precise fluctuations in energy demand and supply over the course of a month, in comparion to an hourly resolution. However, during simulations in Pyomo, it was clear that the resulting operation of the HP was non reflective of Pilothouse's HP operation. In order to properly model the operational behavior of the HP in Pilothouse, the HP model was reformulated to use binary variables, reformulating the problem from a LP problem to a MIP problem.

The shift from LP to MIP introduced increased computational intensity due to the necessity to solve integer variables. To manage this increase in computational load, the decision was made to reduce the temporal scope of the model from a month to a single day. This reduction retains the essential dynamics and decision-making processes within the energy system without the computational burden that a full-month model would entail. Although the reduction of operating points decreased the computation load, there were still computational challenges. These challenges lead to a transition of the modeling environment from Pyomo with a glpk solver to GAMS with a Gams/Cplex solver, with an academic license. The Cplex solver is designed to solve complex and large problems efficiently, MIP-problems included, through the use of complex algorithms.[**noauthor˙cplex˙nodate**].

Initially, a comparison between 1-minute, 5-minute, and 15-minute resolutions was planned. However, as the resolution increased, the model's flexibility to adjust the descision variables decreased. Due to numerous changes in the heating system design, the final model was unable to find feasible solutions for the HP scheduling for the 15 min resolution, leaving only the comparison of 1 and 5 min resolution. The final model showed impractical solutions at 1 min resolutions with rapid cycling, which is why the resulting schedule control of the ASHPHW model are not presented in the results section.

5.2 Current Model Setup

Although the relatively simple mathematical model is solved using GAMS with a CPLEX solver, the adoption of a MIP approach caused unnecessary computational time in order to to find the global optimal solution.

Some of the simulations of the energy model used a CPU time of over 1 hour without finding the optimal solution. The simulations has been run on a Computer with a AMD Ryzen 7 5800HS processor (3.20GHz), with 16GB RAM 8 cores and 16 logical processors. Compared to a low-energy-consuming Raspberry Pi 4 model B with maximum 4 GB RAM and 4 cores without the capability of multi threading, these CPU times are unrealistic. This highlights the need for simple energy models when using model predictive control of a HP locally on a Raspberry Pi. Alternatively, external systems can be used to perform complex optimization algorithms and then upload the scheduling to Home Assistant.

Pallento et al. prvoided a comprehensive review of the development, assessment, and optimization of DSR programs in residential buildings, focusing on energy flexibility and smart grid integration[28]. One of the key highlights is the potential success of obtaining optimal solutions with a heuristic approach over a short time frame. However, special attention is needed on the objective function and stop criteria in order to not get misleading results.

Figure 5.1 shows the process log during simulation of Day 5 with strategy 1, where the CPLEX solver created a nodefile size of approx 4.7 GB of RAM, meaning that the intermediate solutions and nodes are being stored on the short term memory of the Computer. In comparison to a Rasberry Pi

```
Process Log
 26946424 25596503      428.8295   201       445.0487      415.2782 1.59e+08    6.69%
 27097245 25753840      418.6641   229       445.0487      415.2786 1.60e+08    6.69%
 27311592 25960562      430.3423   243       445.0487      415.2792 1.61e+08    6.69%
 27521181 26151017      442.3704   217       445.0487      415.2799 1.63e+08    6.69%
                                                         Cuts: 38
Elapsed time = 9611.11 sec. (8294703.84 ticks, tree = 27451.26 MB)
Nodefile size = 25401.21 MB (4419.10 MB after compression)
 27724422 26341646      421.1793   229       445.0487      415.2805 1.64e+08    6.69%
 27920779 26523031      419.1132   199       445.0487      415.2813 1.66e+08    6.69%
 28113251 26728136      440.0907   232       445.0487      415.2820 1.67e+08    6.69%
 28308061 26914156      418.0985   238       445.0487      415.2828 1.69e+08    6.69%
 28437504 27022642      442.4487   235       445.0487      415.2832 1.70e+08    6.69%
 28628247 27204758      418.2615   238       445.0487      415.2841 1.71e+08    6.69%
 28814868 27385834      421.6804   195       445.0487      415.2849 1.73e+08    6.69%
 29003049 27566201      428.4347   241       445.0487      415.2859 1.74e+08    6.69%
 29098782 27671842      420.0888   212       445.0487      415.2864 1.75e+08    6.69%
 29290189 27851465      419.2366   217       445.0487      415.2874 1.76e+08    6.69%
Elapsed time = 10068.86 sec. (8447292.51 ticks, tree = 29252.27 MB)
Nodefile size = 27203.27 MB (4714.90 MB after compression)
 29481838 28042547      425.0523   212       445.0487      415.2885 1.78e+08    6.69%
                                                         Cuts: 35
 29668646 28220819      418.7300   200       445.0487      415.2897 1.79e+08    6.69%
```

Figure 5.1: Process log from Cplex solver during simulation of strategy 1 for day 5

The priority of the model design is to minimize the models complexity and computational intensity despite reaching suboptimal solutions. Therefore, a strategic decision is made to let the solver stop searching for the global optimal solution when the current solution is within an acceptable % of the best known solution. This function is implemented using the *OptCR* option in the CPLEX [8]. The stop percentage is not fixed for all simulations but vary based on experienced computational intensity; 2% to 5%.

5.2.1 Working principle of Model

Moreover, the working principle of the model is to receive some input data and output an operating schedule of the ASHPHW as shown in Figure 5.2. The input datasets for each selected day in these model simulations are:

1. Historic day-ahead spot prices retrieved from Entsoe
2. Synthetic data of DHW demand

3. Pilothouse's sensor data on the ambient temperature

4. Electrical consumption of Pilothouse, which exclude the HP consumption

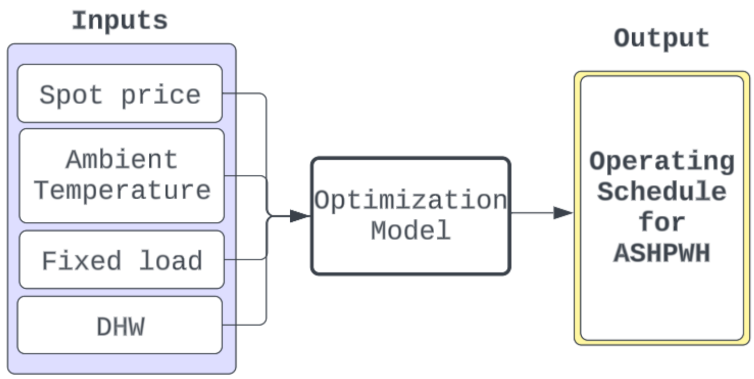


Figure 5.2: Information flow of the Model

5.2.2 HP model

There are several ways to model the HP's operational behavior, and several studies has been conducted on this topic. The behavior can be known by the model before simulation, treating it as an exogenous variable, or it could be found by the model, treating it as an endogenous variable. In order to keep the model linear, the COP and a nominal electrical capacity of the HP was chosen to be known by the model before simulation, treating the heat output from the HP as an endogenous variable. Verhelst et al. [38] suggest the usage of a pre calculated COP, by selecting a target value for the HP's refrigerant at the output T_H and known values of the source temperature T_C, making it temperature dependent and linear. Heinen et al. [13] suggests assuming a linear relationship between the COP and the T_C, where measurements and emperical data determines the slope.

The approach suggested by Heinen was selected for this HP model. However, the calculation of the slope was disregarded as result of limited information about the heat output from the HP in Pilothouse Thus, the HP in Pilothouse is modelled to have two nominal electrical capacities with their respective COPs, where each capacity and COP correspond to the power consumption and efficiency during operation at elevated temperature differences and lower temperature differences. This behavior is shown in Figure 5.3.

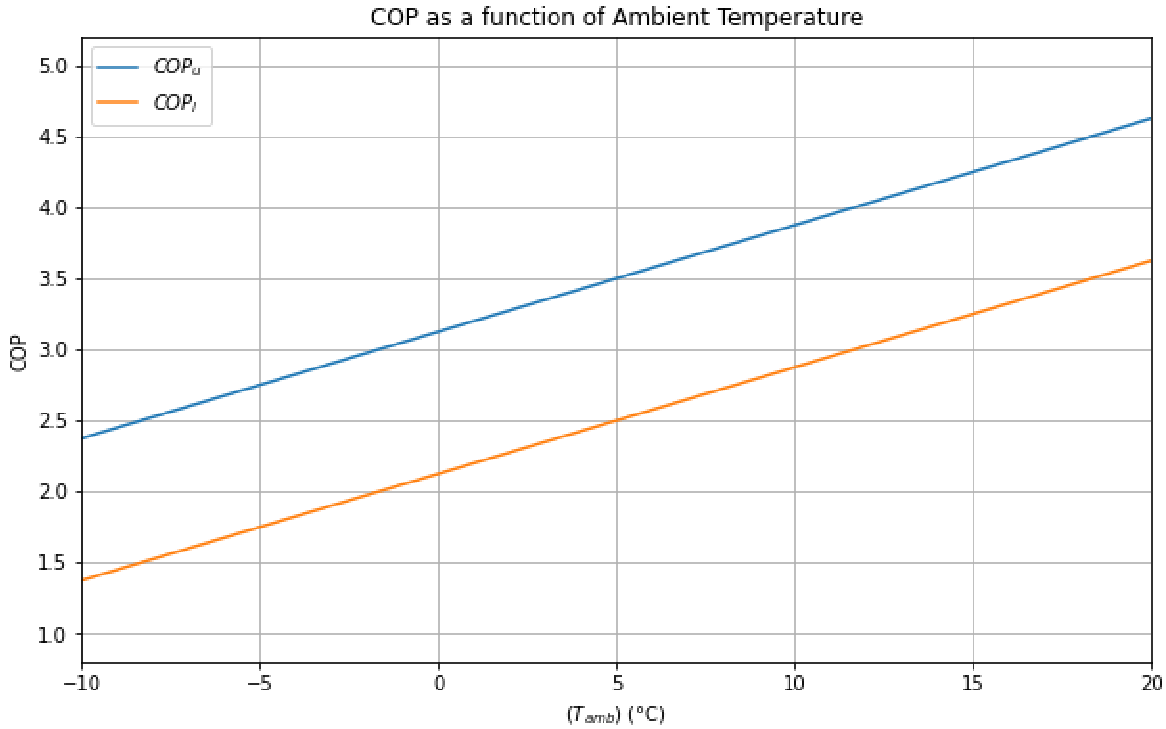


Figure 5.3: Modelled COP for elevated temperature differences COP_u and lower temperature differences COP_l as a function of Ambient Temperature

5.2.3 EWH model

There are 2 main models that used for modelling the behavior of an EWH. The simplest model is the one node model,also known as the simplfied storage model, where the tank is assumed to have a uniform temperature of water in the tank.[33]

The other model is a two node model,also known as a simple stratified model, where the water temperature in the tank is not uniform but rather divided into hot a cold water. This model is more accurate during partial depletion stages when the tank contains both hot and cold water. The temperatures are then divided into to comprtments,where each compartment is assumed to have a uniform temperature. The model calculates the height of the hot water compartment, and with that, the available energy in the entire tank. The switching between one-node and two-node models depends on the state of the water tank.[31] BY applying multiple compartments the model becomes a multi zone model.

This thesis has utilized a simplified storage model of the EWH for the energy system model, as it a simplified but a valid approach for the purpose of DSR. For the purpose of operation optimization, the mass of the water in the tank is usually known by the model previous to the simulation. For design optimization, the mass is considered a decision variable as it is directly connected to the size of the tank. [19]

The tank is modelled as a Thermal energy storage (TES), where the volumetric flow of water in and out of the tank has not been taken into account.

5.3 Energy system

The system is limited to the energy flow between the power supply cable from the distribution grid and the PV system to the DHW demand, internal energy in the room, and the electrical energy consumption from the appliances in Pilothouse. Specifically for the electrical subsystem, the supply of electrical energy comes from two sources: The energy utilization from the PV system S and the imported energy from the grid I, while the overproduced energy from the PV system E is exported to the grid. The electrical energy demand is consisting of three components, the HP's lower HP_l and upper HP_u consumption, and the remaining consumption of Pilothouse L, that is not supplying the HP.

The internal energy in the upper section of the tank Z_u with the temperature T_u is supplied by the maximum heat the HP can provide Q_{u_in} which is set by the HP's electrical consumption during elevated temperature differences HP_u multiplied by a linear COP factor . HP_u is controlled by the binary variable α_u and set by a constant consumption during rapid heating $P_{HP,u}$. It is the same operation for the internal energy in the lower section, where the constant consumption during normal heating is used $P_{HP,l}$.

The internal energy of the upper section of the EWH Z_r

The internal energy of the room Z_r with the temperature T_r is dependent on the heat from the heating system $Q_{r,in}$ and the heat loss from the room to the outside. A visualization of the models heat flow is presented in Figure 5.4.

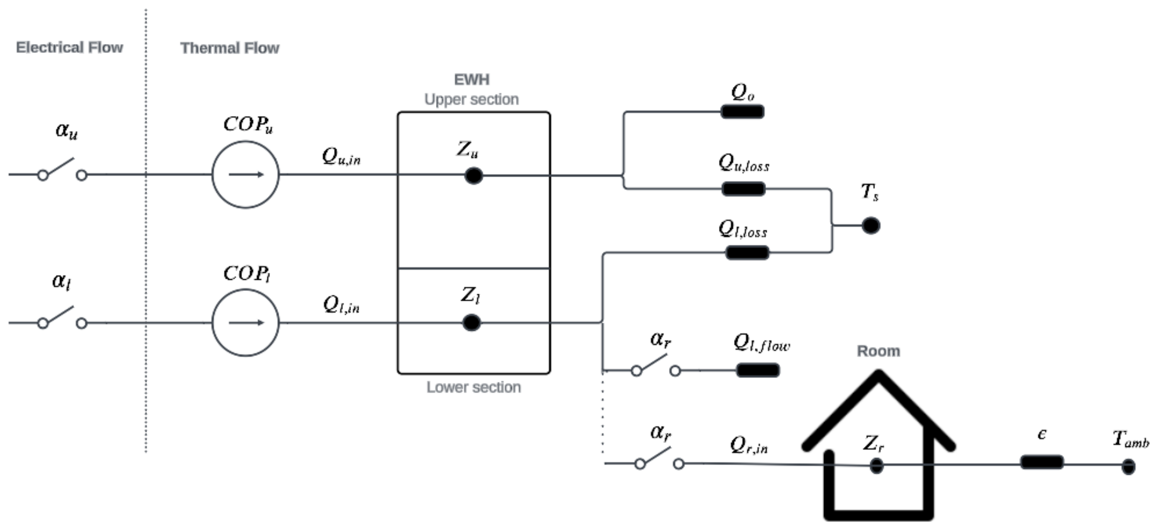


Figure 5.4: Thermal energy flow in system

5.3.1 Scenarios

In the first strategy, the EWH operates independently of other domestic loads. This baseline strategy assesses the performance of the EWH under typical usage patterns without any integration or interaction with other energy loads. The primary focus is on evaluating the EWH's capability to maintain a steady supply of hot water based solely on its internal settings and controls, such as thermostat adjustments and heating cycles.

The second strategy introduces a fixed load parameter, where the EWH is expected to operate in conjunction with a consistent and predictable external load. The objective here is to determine how well the EWH adapts to external demands in the overall home energy system, and whether its operation is compromised or enhanced under controlled load conditions.

Expanding on the two first strategys, we introduce a relaxation on the constraint for the upper bound for the upper temperature. This strategy lets the model increase the temperature in the tank during solar production. This strategy aims to see how effective it is to increase the temperature in the tank. The increase in potential increase in temperature would increase the losses in the upper section and increase the temperature in the lower section. However, this increase in losses is neglected, simplifying the increase in upper section losses to be equal to the heat increase in the lower section.

strategy 1: EWH as a seperate system strategy 2: Ewh with a fixed load strategy 3: EWh with increased potential for solar consumption

5.3.2 Sets

Set Name	Description	range
t	minute Time periods	$[0, 24 \cdot f]$
h	hourly Time periods	[0,24]

5.3.3 Parameters and Variables

Variable	Description	Value	Unit
f	Frequency factor dependent on the minute resolution	[4,12,60]	-
a	Linear slope for the operating temperature limits of T_l between -5 °C and 18 °C	$-\frac{15}{23}$	-
P_{max}	Maximum energy that can be imported from the grid	$15/f$	kWh
$P_{HP,u}$	Energy consumption of HP_u	$4.5/f$	kWh
$P_{HP,l}$	Energy consumption of HP_l	$2.5/f$	kWh
COP	Efficiency of electrical energy to thermal energy	200	%
η	Efficency of heat transfer from heating system to room	80	%
c_w	Heat capacity of water	1.16	$Wh/kg \cdot K$
c_a	heat capacity of air at 20 deg and 1 atm	0.279	$Wh/kg \cdot K$
ρ_a	Density of air around room temp	1.225	kg/m^3
m_u	Mass of water in the upper section	240	kg
m_l	Mass of water in the lower section	120	kg
$T_{u,min}$	Minimum water temperature allowed in upper section	40	°C
$T_{l,min}$	Minimum water temperature allowed in lower section	25	°C
$T_{r,min}$	Minimum room temperature allowed	20	°C
$T_{u,max}$	Maximum water temperature allowed in upper section	65	°C
$T_{l,max}$	Maximum water temperature allowed in lower section	35	°C
$T_{r,max}$	Maximum room temperature allowed	22	°C
$T_{u,max,s}$	Maximum water temperature allowed in upper section during solar production	90	°C
T_{ref}	reference temperature of the water inflow of tank	40	°C
T_s	Ambient temperature of the EWH	20	°C
$Q_{r,in,max}$	Maximum heat that can flow into to room	1000	Wh

Table 5.1: Scalars in Energy System Model

Table 5.2: Parameters in Energy System Model

Parameter	Description	Value	Unit
SP_t	Solar production	-	kWh
L_t	Load which is fixed	-	kWh
$C_{sp,h}$	Spot price from Entsoe	-	$¢/kWh$
$C_{e,h}$	Energy component of import from Elvia (April) with taxes	Table 2.3	$¢/kWh$
mva	25% Vat	Table 2.4	$\%$
$C_{p,h}$	Energy component of export from Elvia		$¢/kWh$
C_a	Surcharge from electricity provider	5.00	$¢/kW$
s_t	Heat consumption from shower	Table 4.3	kWh
f_t	Heat consumption from fauset	Table 4.3	kWh
$Q_{o,t}$	Energy consumption representing DHW	-	kWh
$T_{amb,t}$	Ambient temperature of the room	-	kWh

Table 5.3: Decision Variables in Energy System Model

Variable	Description	Unit
C_D	Daily operational cost	NOK
I_h	Amount of energy imported from the grid	kWh
E_h	Amount of energy exported to the grid	kWh
I_t	Power imported from the grid	kWh
E_t	Power exported to the grid	kWh
S_t	Solar PV utilization	kWh
$HP_{u,t}$	Energy consumption of HP with elevated temperature difference	kWh
$HP_{l,t}$	Energy consumption of HP with decreased temperature difference	kWh
$Q_{l,in,t}$	Heat transfer from HP into the lower section of EWH	kWh
$Q_{u,in,t}$	Heat transfer From HP to the upper section of EWH	kWh
$Q_{r,in,t}$	Heat into the room	kWh
$Q_{l,loss,t}$	Heat transfer from the lower section to the storage room of the EWH	kWh
$Q_{u,loss,t}$	Heat transfer from the upper section to the storage room of the EWH	kWh
$Q_{r,loss,t}$	Heat transfer from Room to ambient environment	kWh
$Z_{l,t}$	Internal energy of the room	kWh
$Z_{u,t}$	Internal energy in upper section of EWH	kWh
$Z_{r,t}$	Internal energy in lower section of EWH	kWh
$T_{l,t}$	Temperature of the water in the lower section of EWH	°C
$T_{u,t}$	Temperature of the water in the upper section of EWH	°C
$T_{r,t}$	Temperature of the air in the room	°C
λ_u	Slack variable for the upper temperature	°C

Binary variable	Description
$\alpha_{u,t}$	Controls On/Off setting for HP_u
$\alpha_{l,t}$	Controls On/Off setting for HP_l
$\alpha_{r,t}$	Controls On/Off setting for hydronic heating system

5.3.4 Objective function

The objective function is designed to minimize daily costs associated with energy usage. In addition, the temperature of the water in the upper section is constrained with a slack variable to allow the temperature to be below the lower limit, see equation 5.3.5. However, this variable must be penalized for choosing high values, it has therefore been integrated into the objective function.

$$
\begin{aligned}
\text{Minimize}(C_D) = &\sum_h I_h \cdot (C_{e,h} + (C_p + C_{sp,h}) \cdot (1 + mva)) - E_h \cdot (C_{sp,h} + C_a) \\
&+ \sum_t \lambda_u / f
\end{aligned}
\tag{5.1}
$$

$$
\text{Minimize}(I_h) = \sum_h I_h + \sum_t \lambda_u / f \tag{5.2}
$$

5.3.5 Constraints

Equation 5.3 represents the electrical energy balance of the system. It ensures that the sum of imported energy and solar energy at any time t meets or exceeds the total demand from the fixed load and the consumption to the HP supplying the lower and upper sections of the EWH.

$$
I_t + S_t \geq L_t + HP_{l,t} + HP_{u,t} \tag{5.3}
$$

Equation 5.4 is the maximum amount of energy the system can import from the grid.

$$
I_t \leq P_{max} \tag{5.4}
$$

Equation 5.5 defines the exported energy as the difference between solar production and the solar power utilized, indicating how much excess solar power is sent back to the grid.

$$
E_t = SP_t - S_t \tag{5.5}
$$

Equation 5.6 Ensures that the utilized solar energy does not exceed the amount of solar production.

$$
S_t \leq solar\_prod_t \tag{5.6}
$$

Equation 5.7, 5.8 models the energy consumption of the HP during the two temperature setpoints, respectevly. Equation 5.9 models the NAND logic, where the model is constrained to select either one of the two operating settings, but not both.

$$HP_{l,t} = P_{HP,min} \cdot \alpha_{l,t} \tag{5.7}$$

$$HP_{u,t} = P_{HP,max} \cdot \alpha_{u,t} \tag{5.8}$$

$$\alpha_{l,t} + \alpha_{u,t} \leq 1 \tag{5.9}$$

$$Q_{l,in,t} = COP_{l,t} \cdot HP_{l,t} \tag{5.10}$$

$$Q_{u,in,t} = \begin{cases} 0 & , \forall t \in \{Q_{o,t} > 0\} \\ COP_{u,t} \cdot HP_t^u & , \forall t \notin \{Q_{o,t} = 0\} \end{cases} \tag{5.11}$$

The heat losses for the lower and upper section in the EWH, and for the room is based on Equation 2.7, and is given in Equation 5.12,5.13 and 5.14, respectively.

$$Q_{l,loss,t} = U_l \cdot A_l \cdot (T_{l,t} - T_{amb,t}) \tag{5.12}$$

$$Q_{u,loss,t} = U_u \cdot A_u \cdot (T_{u,t} - T_{amb,t}) \tag{5.13}$$

$$Q_{r,loss,t} = \epsilon \cdot [(T_{r,t} - (T_{amb,t}) \tag{5.14}$$

The heat flow of the energy system is, see Figure 5.4, is reflected in Equation 5.15,5.16 and 5.17. The heat balance of the lower section is connected to the room temperature through the binary variable ($\alpha_{r,t}$). Where the calculated loss of energy in the lower section is mainly contributed due to the water flow in the hydronic heating system ($Q_{l,flow}$). Equation 5.18 enables the model to apply heat into the room.

$$Z_{l,t} = \begin{cases} \frac{Z_{l,min}+Z_{l,max}}{2} & ,t = 0, \\ Z_{l,(t-1)} - \Delta T_l \cdot (m_l \cdot c_w) + Q_{l,in,t} - Q_{l,flow}\dot{\alpha}_{r_t} & ,t > 0 \end{cases} \tag{5.15}$$

$$Z_{u,t} = \begin{cases} \frac{Z_{u,min}+Z_{u_max}}{2} & ,t = 0, \\ (Z_{u,(t-1)} - \Delta T_u \cdot (m_u \cdot c_w) + Q_{u,in,t} - Q_{o,t}) & ,t > 0 \end{cases} \tag{5.16}$$

$$Z_{r,t} = \begin{cases} \frac{Z_{r,min}+Z_{r,max}}{2} & ,t = 0, \\ Z_{r,(t-1)} + Q_{r,in,t} - Q_{r,loss,t} & ,t > 0 \end{cases} \tag{5.17}$$

$$Q_{r,in,t} \leq Q_{r,in,t,max} \cdot \alpha_{r,t} \tag{5.18}$$

The output temperatures of the model are set to be within predefined limits and they are initialized to be the average of these limits. AS mentioned, the upper slack variable λ_u allows the temperature of the water in the upper section to be below the predefined limits, Equation (5.3.5), however the variable is restricted to not go below the inlet water temperature T_{ref} in Equation (5.21).

$$\begin{cases} T_{l,min5} \leq T_{l,t} \leq T_{l,max5}, & T_{amb,t} < 5°C \\ T_{l,min5} - a \cdot T_{amb,t} \leq T_{l,t} \leq T_{l,max5} - a \cdot T_{amb,t}, 5°C \leq & T_{amb,t} \leq 18°C \\ T_{l,min18} \leq T_{l,t} \leq T_{l,max18}, & T_{amb,t} < 18°C \end{cases} \tag{5.19}$$

$$\begin{cases} T_{u,min} - \lambda_u \leq T_{u,t} \leq T_{u,max} & ,SP_t = 0 \\ T_{u,min} - \lambda_u \leq T_{u,t} \leq T_{sol} & ,SP_t > 0 \end{cases} \tag{5.20}$$

$$\lambda_u \leq T_{u,min} - T_{ref} \tag{5.21}$$

$$T_{r,min} \leq T_r \leq T_{r,max} \tag{5.22}$$

Chapter 6

Results and discussion

6.1 Simulations of selected days

This section presents the simulations of the operation of the Air Source Heat Pump Water Heater (ASHPWH) system for three days, utilizing three operational strategies. The primary aim of this analysis is to assess the applicability of the model and analyze how different inputs effects the models operational performance of the ASHPWH system. The abbriviations used specifically for this section in is given in Table 6.1

Abbreviations	**Description**
S1	Strategy 1
S2	Strategy 2
S3	Strategy 3
Objective	Minimization objective for the model optimization
Costs	Operating costs of the ASHPHW
Total Costs	Pilothouses daily electricity costs

Table 6.1: Abbreviations used in figures and results

Scenario 1 is a day with low ambient temperature and medium production. which means that during this day, the heating system of pilothouse was fully operating in order to maintain room temperature. Figure 6.1 and 6.2 shows the operation of the HP for heating up the water in lower section of the tank during this day for all three strategies at 5 minutes, where the objective is to reduce the amount of imported energy from the grid and total costs respectively. Firstly, the results indicates that the model wants to drive the temperatures this their minimal bounds, reducing the amount of losses. Additionally, it is observed that the heating operation of the HP is not activate for any particularly periods of high ambient temperatures.This indicates that demand for heating is to great for the model to prioritize certain hours for activation. However, the room temperature for all strategies are increased to the upper bounds before and after 12:00, but are kept at the lower bound most of the time. By comparing the two plots, one can see that there is no particalur scheduling difference. For the lower tank temperature, the maximum increase occurs around 05:00 and 14:00 for all three strategies. which allows the model to not heat up the temperature before the DMH demand has past.

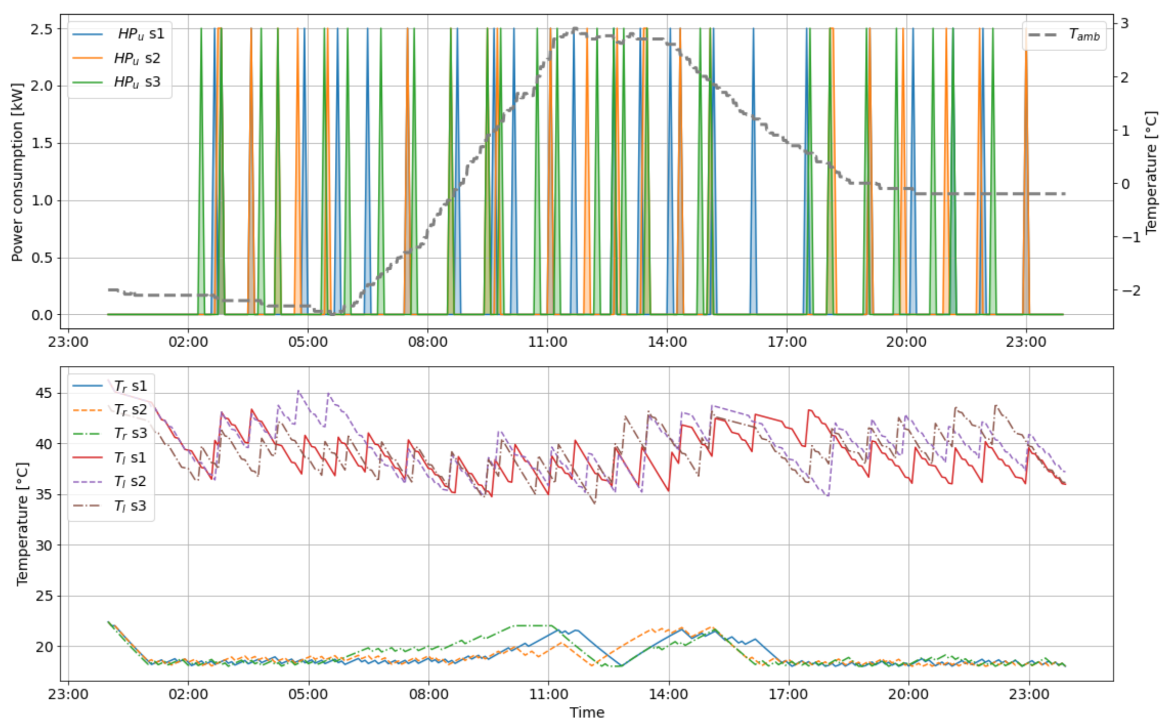


Figure 6.1: Model results of day the lower HP operation for day 5 for all strategies with the objective to reduce import

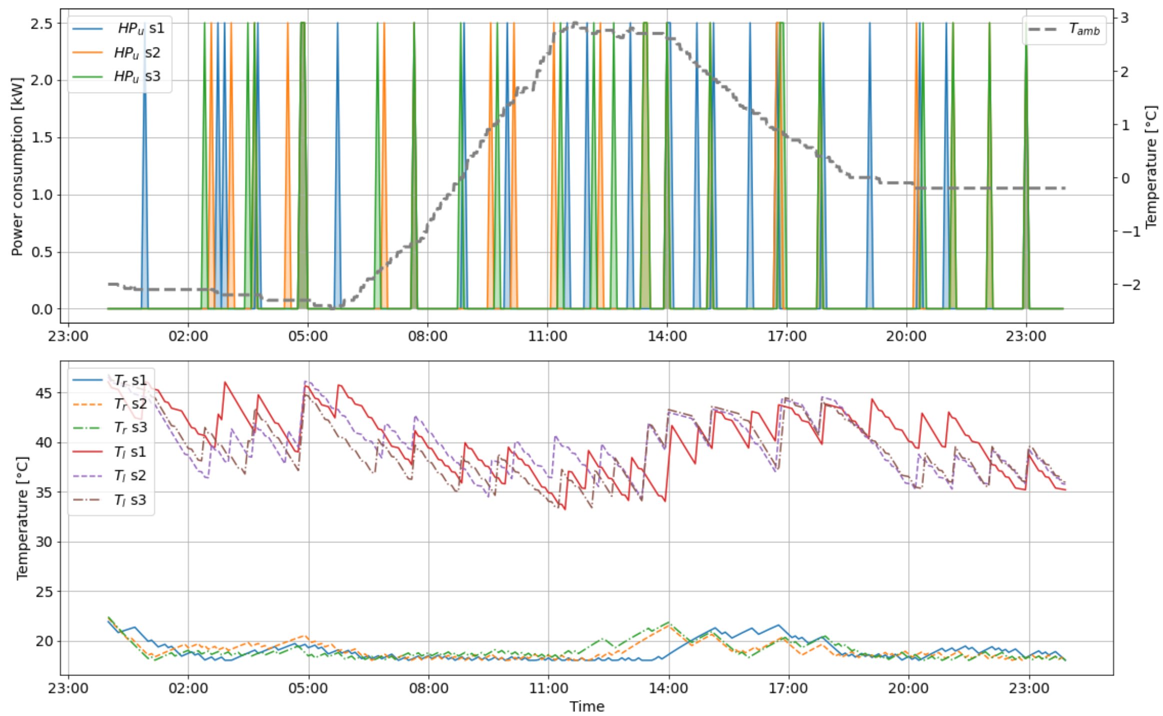


Figure 6.2: Model results of the lower HP operation for day 5 for all strategies with the objective to reduce costs

The temperature of the water in the upper section is not increasing before the first DHW event occurs for all three strategies. The same pattern is shown for strategy 1 and 2 between hour 10 and 16 where the DHW operation is not activated, leading to minimal HP activation.This indicates that the DHW demand is prioritized over maximum heat output on the HP. Additionally,the impact of the slack variable is shown in the temperature behavior. The temperature only goes beneath the lower bound when DHW events occurs.

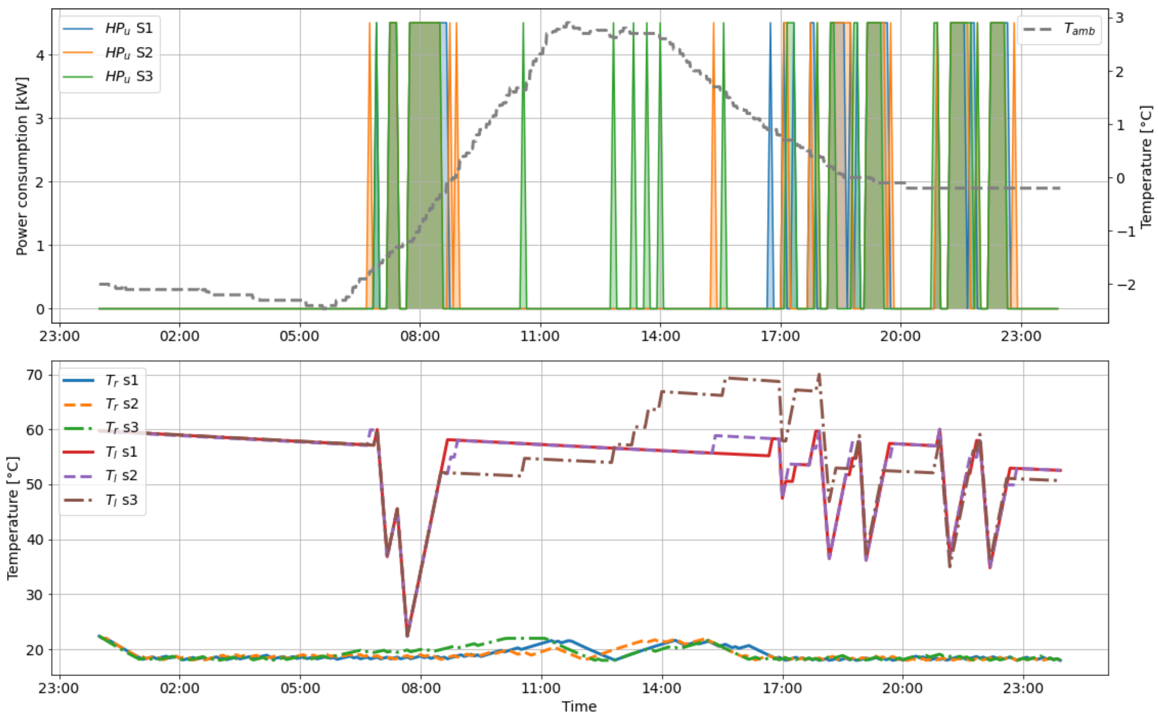


Figure 6.3: Model results of the upper HP operation for day 5 for all strategies with the objective to reduce import

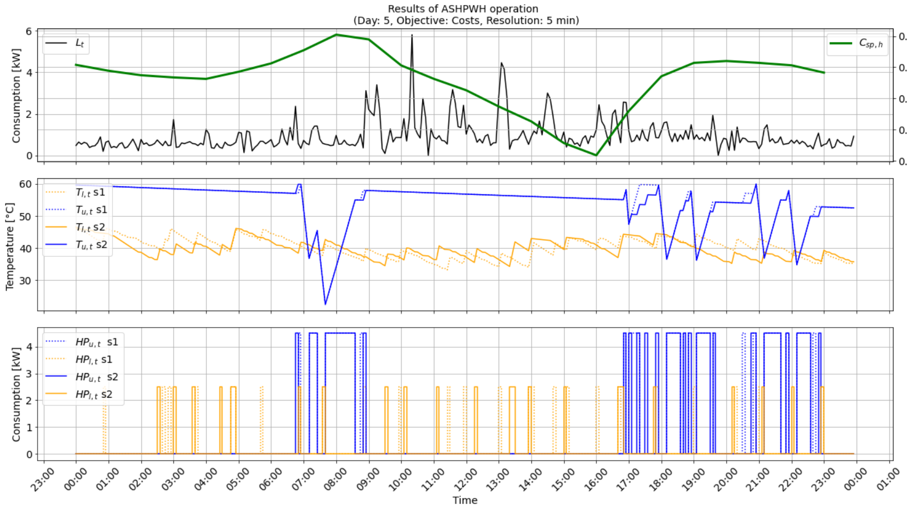
6.1.1 Operation Comparison between the strategies

Strategy 1 and 2

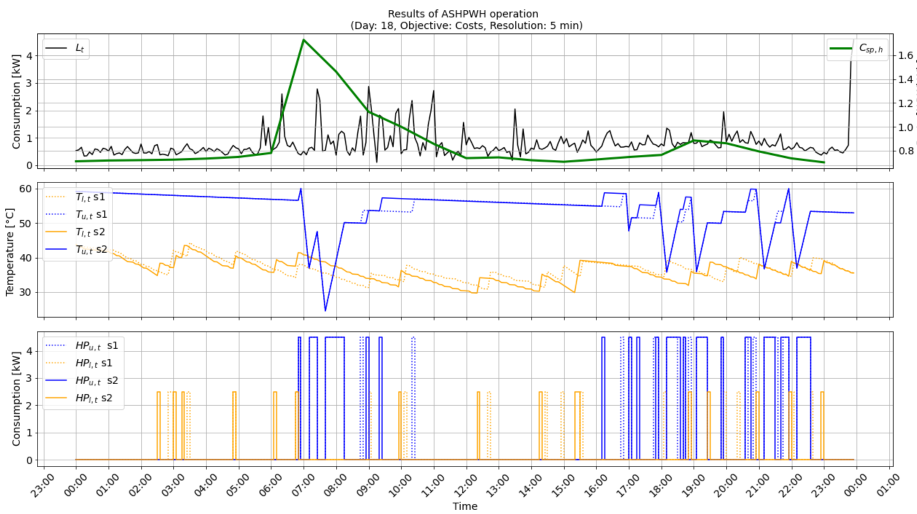
S1 and S2 have similar variable bounds, but the model has the information about the remaining electrical consumption of Pilothouse. Figure 6.4a shows the resulting schedule operation of the ASHPWH for the two strategies of day 5 with the fixed load (L) in the subplot above. The results shows that S1 and S2 has similar behavior in the heating of the upper tank. The greatest difference occurs between 17:00 and 18:00 where the temperature in the upper tank increases continuously over the hour, while strategy 2 heats the water to the same temperature but with three cyclings. The lower temperature changes its operation in accordance with high peaks periods. Between the hours of 11-12,13-14 and 16-17 there occurs power peaks in the fixed load, which introduces an earlier and later heating operation of the water in the section, respectively. There is not alot of flexibility for the model to adjust the operating schedule for the ASHPWH after 18:00, as the increase in DHW demand forces the heating schedule for the lower section to occur between the heating of the upper section.

Figure 6.4b shows the resulting schedule operation of the ASHPWH for the two strategies of day 18. The operating schedule for heating the water in the upper tank is again, not varying to a significant amount. Due to the temperature increase from day 5 to 18, the model does now have more freedom to find the minimal costs for S1 and total cost for S2, as the heat loss of the room is smaller.However, the DHW demand is again the greatest factor for determining the heating schedule for the upper section. For the lower section schedule, the amount of heating cycles is reduced with approx 25%, where the reduction occurs between 09:00 to 19:00.

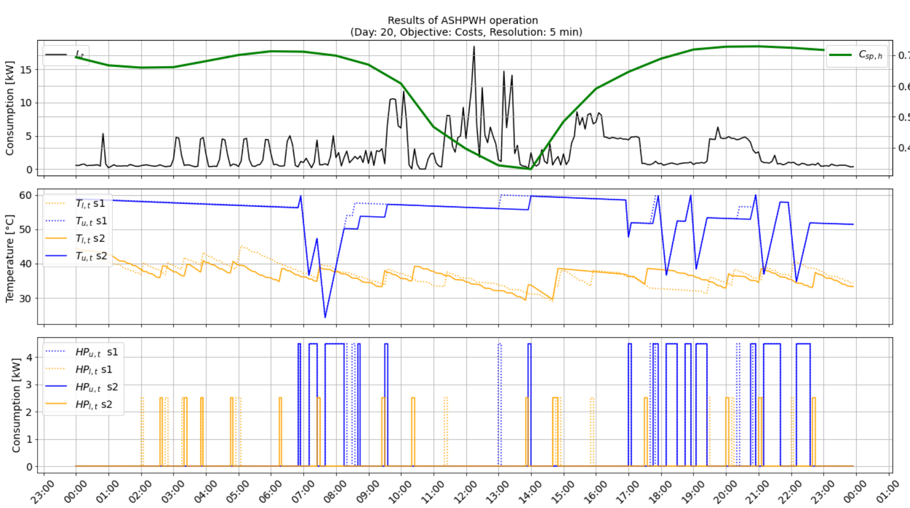
Day 20 shows similar results to day 18 and day 5, see Figure 6.4b. The model shifts the times of heating in accordance with increased load peaks. For S2 the HP is completely turned off between the 10:30 and 14:00. Additionally, the number of heating cycles between the hours of 09-19 is also reduced by 25% compared to day 5.



(a) Results of schedule control of ASHPWH with strategy 1 and 2 with objective to reduce costs for day 5



(b) Results of schedule control of ASHPWH with strategy 1 and 2 with objective to reduce costs for day 18



(c) Results of schedule control of ASHPWH with strategy 1 and 2 with objective to reduce costs for day 20

Strategy 2 and 3

The difference between S2 and S3 is the relaxation of the upper bound for the water temperature in the upper section during solar production. The objective of this simulation is to see if the model would change its operation for the different days based on its optimization objective. Figure 6.5 and 6.6 shows the comparison of S2 and S3 for day 18 for the two objective functions. As expected, the model increases the upper section water temperature to the upper bound before the DHW events occurs. The model reduces the sum of the slack variable and shifts some of the electrical HP consumption to times where there is excess solar production, reducing the amount import energy from the grid.

The temperature increase occurring before the first DHW event, shows the sensitivity of the model. By operating in this way, the HP is highly reliant on the prediction accuracy of the DHW demand. Additionally there is a risk of utilizing unnecessary solar production, which otherwise could reduce the total costs of the system by exporting it to the grid. The temperature of the the lower section water is also fluctuating alot more when the objective is to minimize import. The model chooses to heat up the water to 40 degrees between 11:00 and 14:00 for S3 even though the amount of import does not increase,

The amount of energy that is shifted from the period outside the relaxation to the period with relaxation, is the same as the energy required to heat up the water. The amount of energy is shifted is approx 1 kWh. This is equal for day 5 and 18 regardless of objective function except for day 20, where the solar production stops in the middle of the heating cycle of the HP, resulting in only 0.7 kwh being shifted.

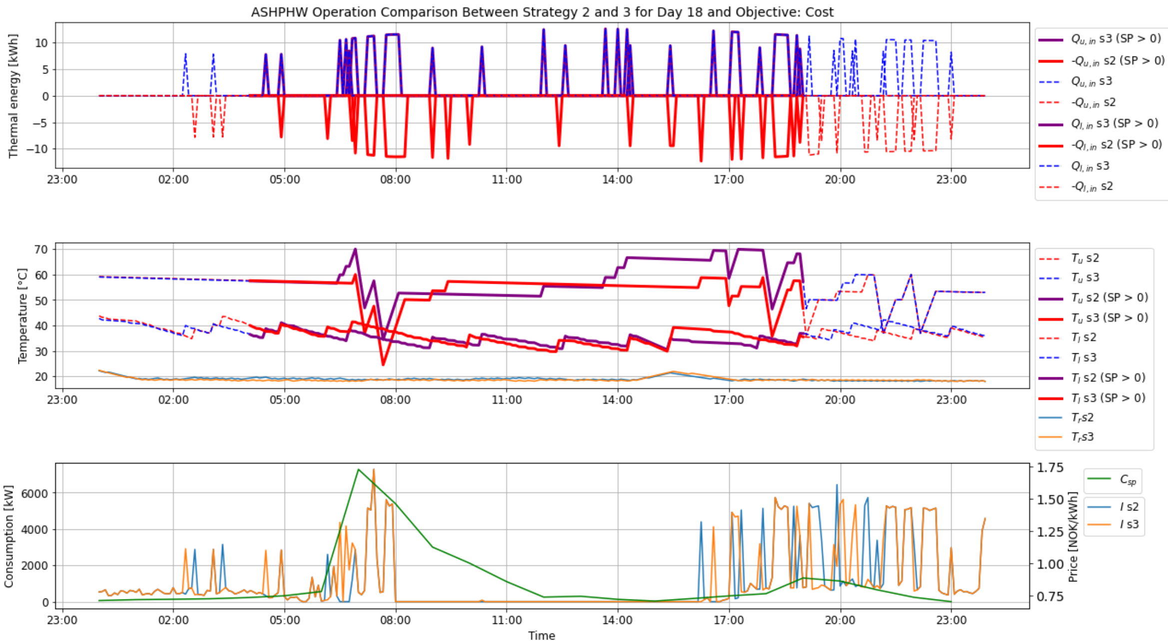


Figure 6.5: ASHPHW operation comparison Between Strategy 2 and 3 for day 18 with the objective to minimize total costs. The thick colored lines represents the times the relaxation of the upper bound occurs.

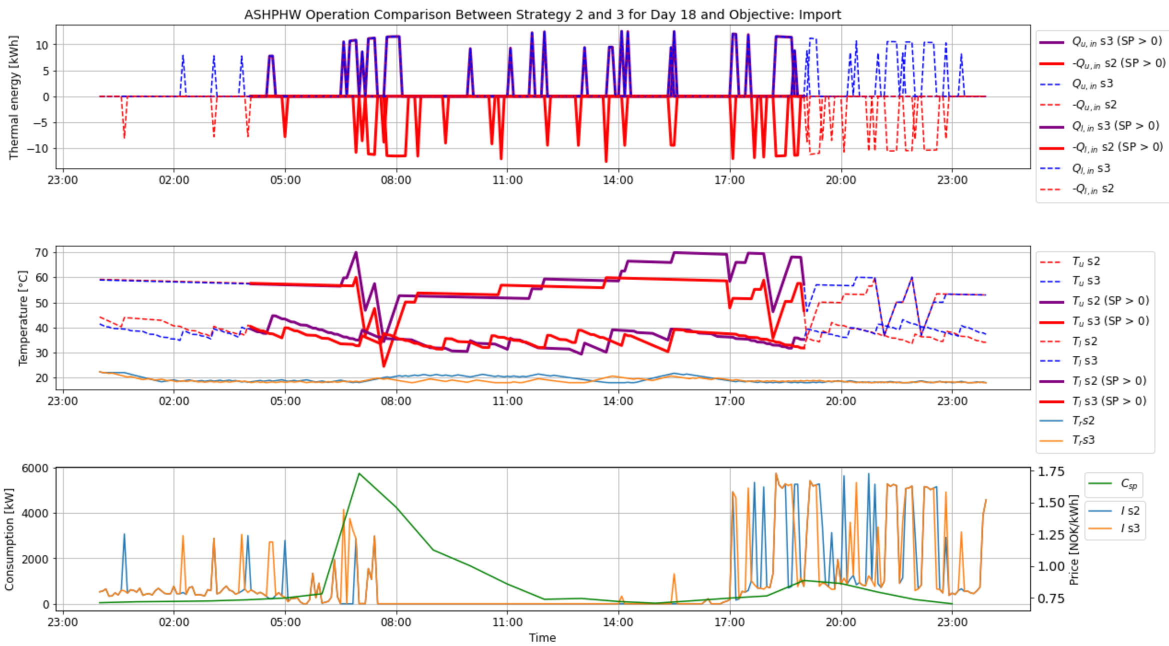


Figure 6.6: ASHPHW operation comparison Between Strategy 2 and 3 for day 18 with the objective to minimize import energy. The thick colored lines represents the times the relaxation of the upper bound occurs. The bottom subplot shows the amount of import the model chooses to use.

6.1.2 Strategies and time resolutions

The metrics that is used in the comparison of the strategies is the total costs of the system, self sufficiency and the self consumption of solar. The results are presented in this section as a comparison between the different simulated granularities and the strategies for all days and both objectives. Figure 6.8, 6.9 and 6.7 shows the resulting total cost, self-sufficiency and self-consumption of the simulations respectively.

S1 is not comparable with s2 and s3 with the metrics mentioned, due to the inclusion of the fixed load. The strategy is in this metric comparison only to visualize the effects of including a fixed load and the magnitude of the HP consumption.

The total system costs for the different days and resolution varies in magnitude and in behavior for all scenarios and objectives, see figure 6.7. Day 5 has the most amount of costs at 36 NOK for with 5 min resolution for day with the objective to reduce costs. With the objective function to reduce import, the costs adds up to 35 NOK. The operational behavior of the two solutions is similar.The difference is most likely due to the models acceptability to allow sub optimal solutions.

The results indicate that the 1 min model is able to produce more cost effective solutions for all strategies with both objectives. Indicating that the 1 min resolution model can find better suboptimal solutions than the 5 min resolution model. However, the operational scheduling of the 1 min resolution includes rapid cycling of the HP, letting the model find temperature solutions which are close to the lower bounds. These solutions are not applicable, as rapid cycling would reduce energy efficiency and be detrimental for the HP.[12]

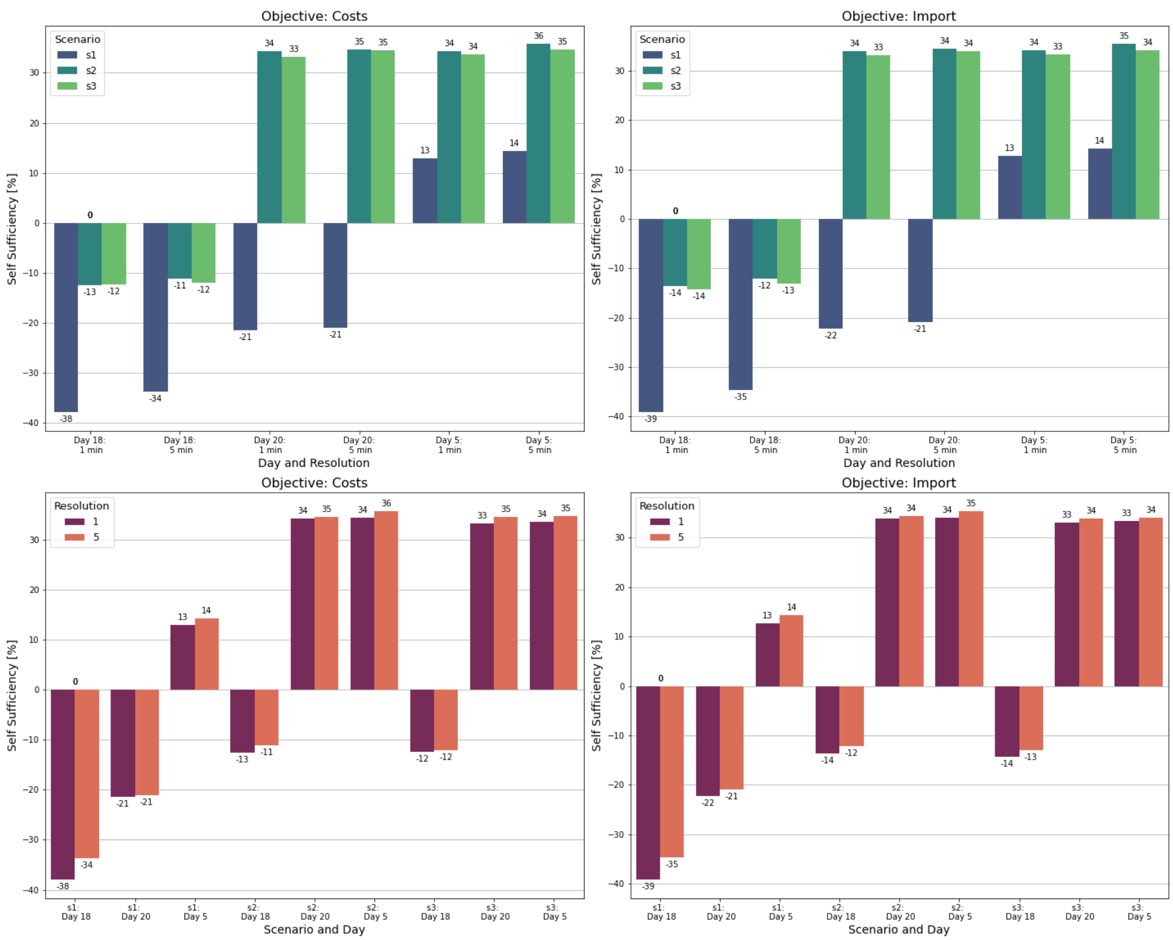


Figure 6.7: Total costs comparison between days and strategies for different resolutions

The SC and SS results for each day does not include s1 as it is a misleading result without L. The results suggests that the greatest increase in SC occurs on day 5, when the lowest amount of solar is produced.By using s3, the model is able to increase the solar utilization with 5% more than with s2 on day 5. The SC for day 18 and 20 is around 22% and 50% for both scenarios with minimizing import, and around 29% and 51% when minimizing for costs.

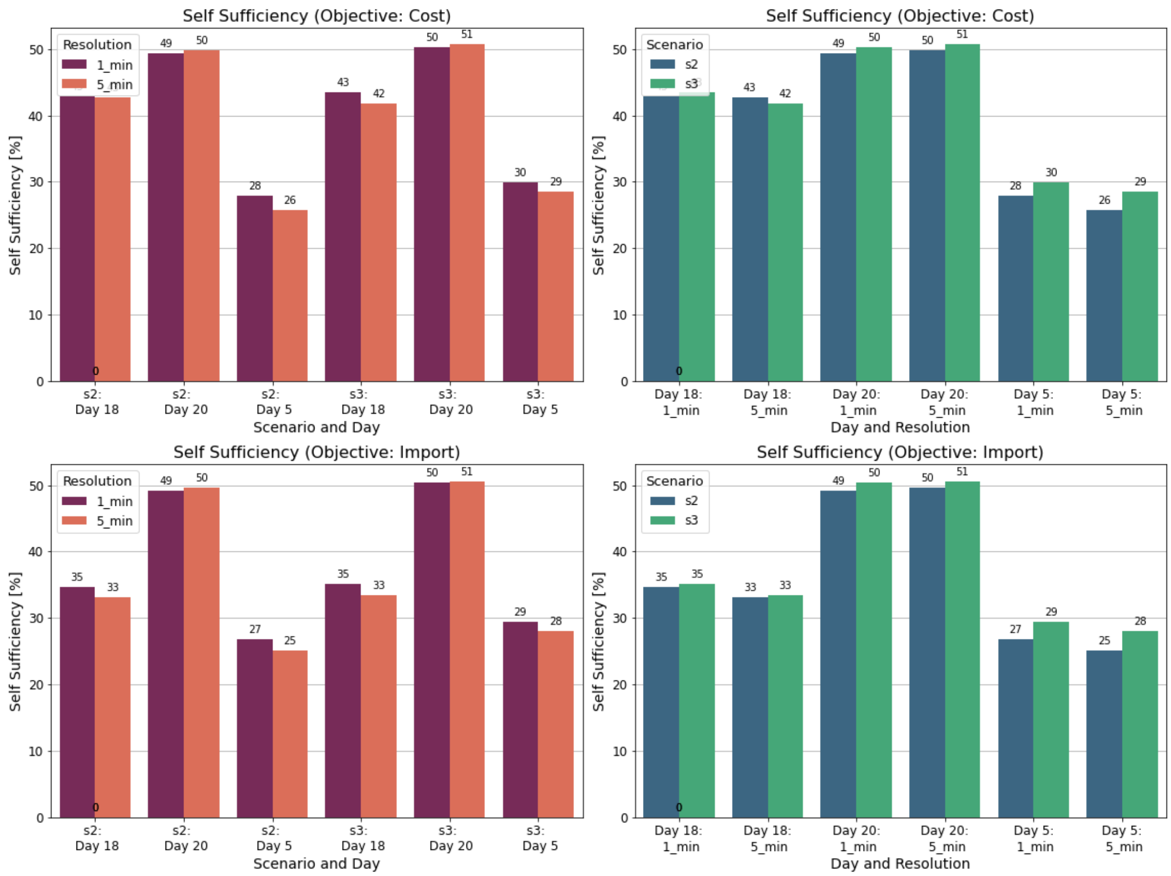


Figure 6.8: SS comparison between day and strategies for different resolutions

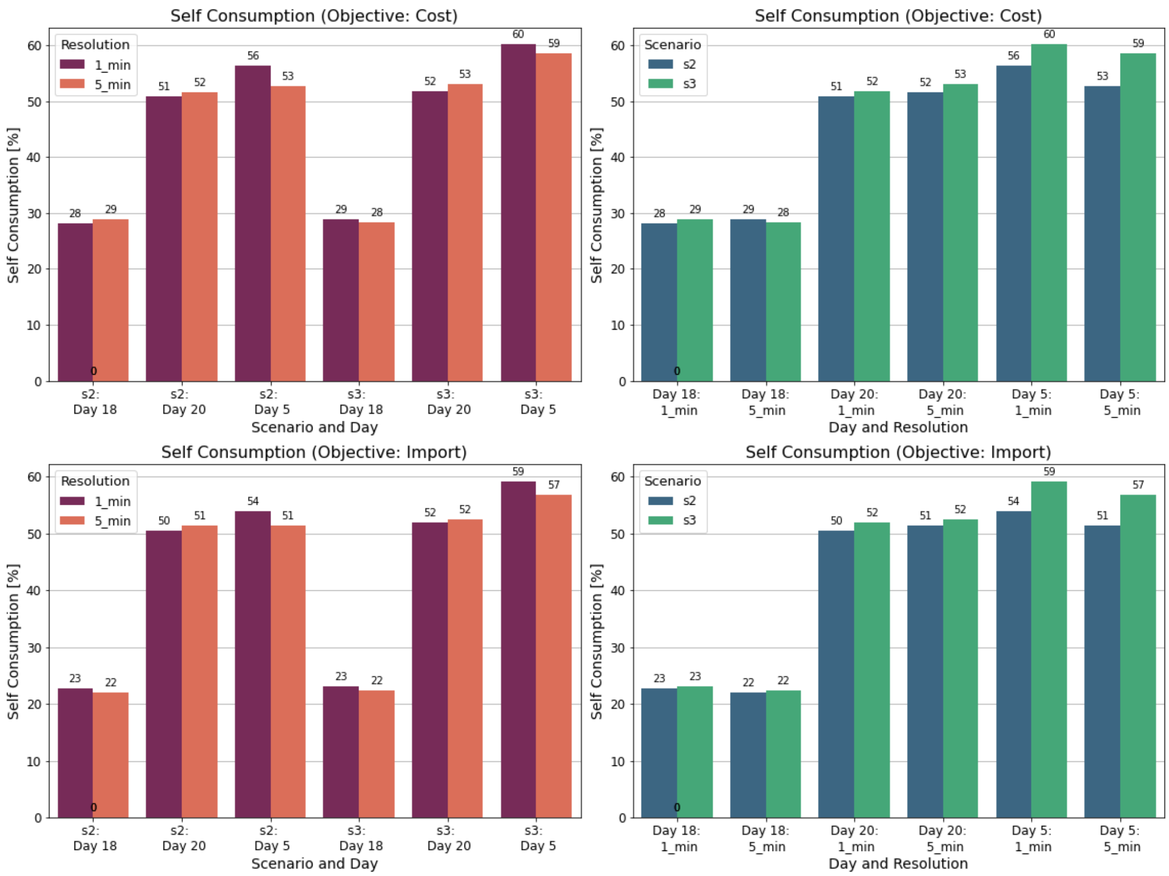


Figure 6.9: SC comparison between day and strategies for different resolutions

Figure 6.10 illustrates the resulting costs associated with the operation of the HP for each day and each strategy for both objectives. The costs shown are not the operational costs derived from the objective function, but rather the estimated costs of each HP operation without the use of solar power and only import power. On Day 20, the daily operational costs are minimal for both objectives across all strategies, amounting to approximately 25 NOK. which was expected based on the

The costs on day 18 increases with 3 NOK compared to day 20 for both objectives, and indicates that is able to . For the total costs

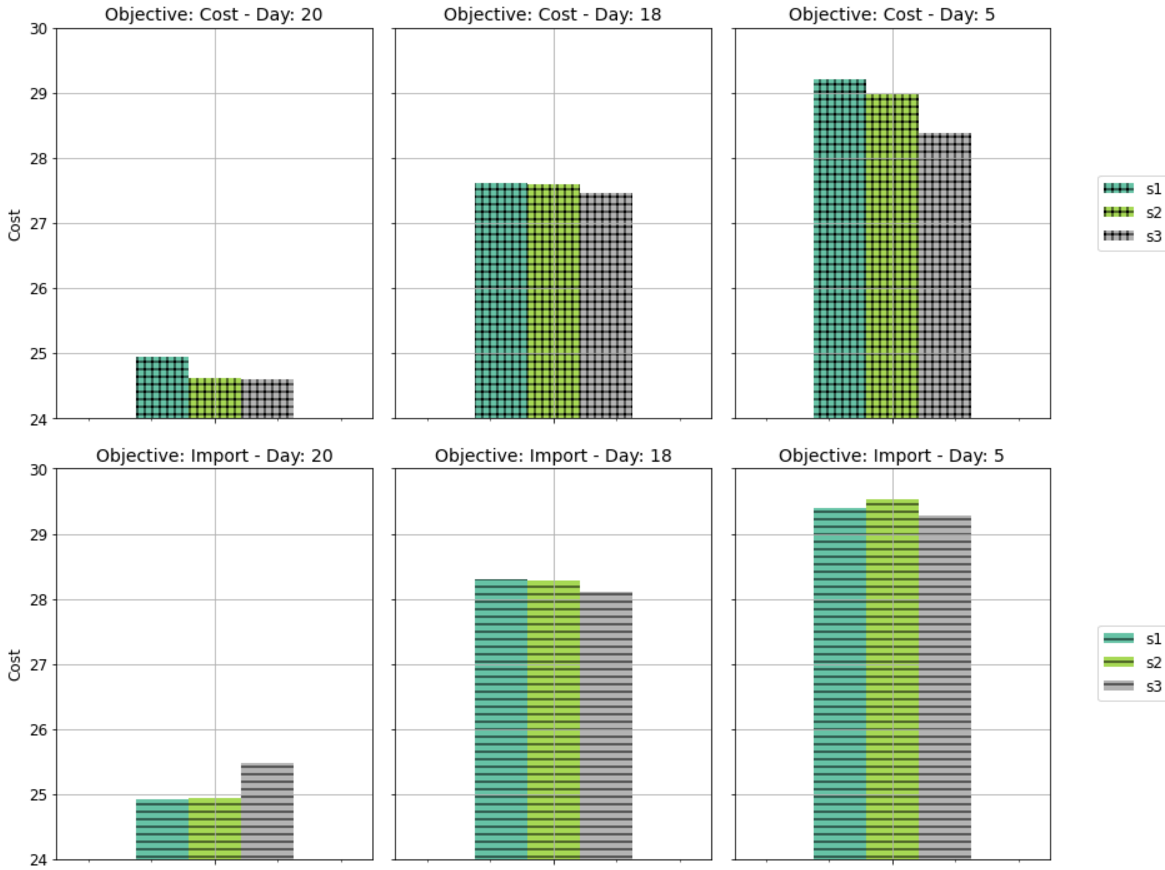


Figure 6.10: Costs of HP operation for day 5, 18 and 20 for all three strategies

Chapter 7

Conclusion and Future work

This thesis has investigated a home automation system in Norway, called Pilothouse, focusing on the collection, storage, and utilization of data to facilitate future scheduling control of a ASHPWH system through a MILP model. The study aimed to explore how sensor data could be used to develop an energy system model with limited information about the system's technical and thermal characteristics.

The first phase involved the collection and long term storage of sensor data. This required delving into the Home Assistant software, research its functionalities and possibilities for local data storage, and experiencing the challenges of installing and connecting recently launched IoT Devices from different home automation equipment manufactures.

Once all the data was available, a data analysis was conducted to get a sense of the energy systems dynamics. The degree days approach was applied to a limited dataset to characterize the house's thermal properties. This involved calculating the thermal capacity and heat loss rate of the house, which were then used in an MILP formulation of the energy system model.

The model results showed that the operation of the ASHPWH for elevated temperature differences was highly dependent on the DHW demand. The created DHW demand profile lead to similar behavior for the water in the upper section of the EWH for all strategies regardless of the day. Indicating that probalistic DHW demand profiles of Pilothouse should be created. Studies focusing on the impact of different DHW demand profiles on the performance of solar-combi systems, including heating systems, through physical modelling tools have emphasized the importance of using realistic daily DHW demand profiles in energy simulations and demonstrated that the use of simplistic and constant WHD demand profiles could lead to inaccurate conclusions.[40]

The transition of Modelling environment was motivated by the need for an environment capable of handling the increased complexity of the MILP formulation of the problem. However, from a practical standpoint, integrating a Python-based open-source optimization modelling language, such as pyomo, into the Home Assistant environment would be more straightforward. Since Home Assistant is built on Python, it naturally supports Python scripts, making it a more optimal option for integration. For pilothouse, it would be more convenient to integrate a Pyomo based model with a comercial solver such as Cplex.

The MILP formulation introduced unexpected complexity in the simulations, leading to simplifications of the heating system. This oversimplification resulted in unrealistic outcomes that did not accurately reflect the true dynamics of the system, making it difficult to draw valid conclusions about the model's solutions. However, the results showed that the HP schedule changed based on external signals from the fixed load. The fixed load, as well as the DHW demand, were created without any uncertainty, leaving the model sensitive to variations.

Even though the model results did not not come to any final conclusions about the validity of the strategies for the control of an ASHPHW system .This model can serve as the foundation for developing a more advanced and accurate model in the futureṪhe use of MILP is an underestimated approach, but requires better input parameters than what was provided in this model.

In conclusion, while the current model faced challenges and produced some unrealistic results due to oversimplifications, it provides a starting point for more detailed and accurate future models. Enhancements in input parameters and the incorporation of realistic DHW demand profiles can improve the model's validity. The insights gained from this study highlights the challenges of basing an energy system primarily on sensor data and the requirement of modelling the thermal system with greater detail.

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