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Modelling Electrical Flexibility from Domestic Water Heaters

Master's thesis in Electric Power Systems
Supervisor: Jayaprakash Rajasekharan
June 2021

Master's thesis

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Abstract

Electric water heaters (EWHs) have gained a lot of attention in academic research because of their excellent thermal capacity, high rated power and fast response time, making them a great source of flexibility to provide grid services, such as load shifting and frequency control. Many researchers have looked into large populations of residential EWHs when studying the flexibility potential, leaving much to be studied on smaller populations, taking into consideration the discreteness of their behaviour. Therefore, the objective of this master thesis is to explore the behaviour and estimate the flexibility potential of a small scale population of EWHs, both on an individual and aggregated level, by using different control and reconnection strategies.

High frequency power and temperature measurements of an EWH at the National smart grid laboratory were used to create different models of an EWH. The simplest model was chosen to simulate the EWHs, since it matched well with the experiments done at the laboratory, with the temperature differing by at most 8%. The model was used together with a water consumption behaviour model to simulate a small population of EWHs, and the flexibility potential was estimated using two different controls techniques: activity and temperature control.

Despite the lack of Norwegian water consumption measurements, the simulated aggregated power profile performed very well with Swedish time-of-use data when comparing it to power measurements from EWHs in Norway. The same trend of morning and afternoon peaks could be observed, and the amplitude of the peaks matched reasonably well.

The aggregation of EWHs has a large potential for load shifting, and up to 7 kWh was successfully shifted to a later time without affecting consumer comfort. The results provide a detailed overview of both the behaviour and flexibility of the individual EWHs, as well as the aggregated flexibility. It is found that the reconnection of the EWHs is critical, and the proposed strategy for reconnection performed excellently by shifting all consumption during one hour without increasing the maximum instantaneous power consumption after reconnection.

The temperature control strategy is preferred over the activity control, since it can shift more energy and still cause smaller peaks in power consumption. In addition, this strategy is less sensitive to errors in predicted hot water usage.

Sammendrag

Elektriske varmtvannsberedere (EVB-er) har fått mye oppmerksomhet i akademiske studier på grunn av deres utmerkede termiske kapasitet, høye effekt og raske responstid. Dette gjør dem til en bra kilde for fleksibilitet til strømnettet, som for eksempel flytting av last og frekvenskontroll. Mange forskere har sett på store populasjoner av EVB-er i husholdninger når de studerer fleksibilitetspotensialet, mens det kan forskes mye mer på mindre populasjoner der man tar hensyn til den diskrete oppførselen til EVB-ene. Derfor vil denne oppgaven utforske oppførselen og estimere fleksibilitetspotensialet til en liten gruppe EVBer, både på et aggregert og individuelt nivå ved å bruke forskjellige kontroll- og gjenkoblingsstrategier.

Høyefrekvens temperatur- og effektmålinger på en EVB på det Nasjonale Smart Grid Laboratoriet har blitt brukt til å lage forskjellige modeller av en EVB. Den enkleste modellen ble valgt for å simulere EVB-en, siden denne passet bra med de målte eksperimentene gjort på laboratoriet, og temperaturen avvek med maksimalt 8%. Modellen ble brukt sammen med en modell som simulerer vannforbruksdata for å lage en liten populasjon av EVB-er, og fleksibilitetspotensialet var estimert ved å bruke to forskjellige kontrollstrategier: aktivitetskontroll og temperaturkontroll.

På tross av mangelen på norske vannforbruksdata traff den simulerte aggregerte effektprofilen, laget med svenske vannforbruksdata, bra sammenliknet med effektmålinger gjort på EVB-er i Norge. De samme morgen- og ettermiddagstoppene ble observert, og amplitudene på lasttoppene stemte bra overens.

Populasjonen av EVB-er har et stort potensial til å flytte lasten sin, og totalt 7 kWh ble flyttet til et annet tidspunkt uten at komforten til forbrukerene ble påvirket. Resultatene gir en detaljert oversikt over oppførselen og fleksibiliteten til den enkelte EVB-en i tillegg til den aggregerte fleksibiliteten. Gjenkoblingen av EVB-ene er kritisk, og den foreslåtte strategien for gjenkobling virket utmerket slik at all last forbrukt en time, kunne bli flyttet uten å forårsake en større effekttopp etter gjenkobling.

Temperaturkontroll er foretrukket over aktivitetskontroll, siden mer last kan flyttes og de maksimale effekttoppene etter gjenkobling er mindre. I tillegg er denne strategien mindre sensitiv til feil i predikert varmtvannsforbruk.

Preface

There are a number of people I want to thank for helping me with my thesis. First of all my supervisor, Jay, for invaluable help and feedback throughout the semester. I also want to thank you for always supporting my ideas and for motivating me. I would also like to thank Eilif Hugo Hansen for the excellent help at the Smart House, and for always brighten up my day with funny stories and providing inside information about hiking in Bergen.

I would like to thank all my friends and family for the love and support this semester. Video coffee breaks, food and flowers at my door, the list is long, and it is highly appreciated. Thank you, we need to catch up when the pandemic allows it.

Finally, I would like to thank my boyfriend, for helping me with writing and for keeping my motivation up, especially in these final weeks. Thank you for sharing the journey at NTNU with me, it would not have been the same without you.

Contents

List of Figures

List of Tables

List of Abbreviations

DHW	Domestic Hot Water
DLC	Direct Load Control
DSM	Demand Side Management
EWH	Electric Water Heater
ICT	Information and Communication Technology
ILC	Indirect Load Control
NVE	Norwegian Water Resources and Energy Directorate
SLM	Stochastic Load Model
TEC	Thermal Equivalent Circuit
ToU	Time-of-Use
TSO	Transmission System Operator

List of Symbols

C	Heat capacity of the water in the tank
C_{el}	Electrical capacitance
C_s	Heat capacity of the water in the tank in the stratification model
C_w	Heat capacity of the wall of the tank
c_w	Specific heat capacity of water
d	Distance
E_{flex}	Energy provided as flexibility by an individual EWH
E_{tot}	Aggregated energy provided as flexibility by the EWHs
I	Current
K_s	Conduction coefficient
m	Mass
$\dot{m}$	Mass flow of hot water
$\dot{m}_{shower}$	Mass flow of water in shower
$\dot{m}_s$	Mass flow in layer s
P_{flex}	Power provided as flexibility by an individual EWH
P_{tot}	Aggregated power provided as flexibility from the EWHs
Q_{conv}	Heat exchange between the layers
Q_{env}	Heat exchange to the environment
Q_{flow}	Heat transfer due to water extraction
Q_h	Power from the heating element
R	Thermal resistance between the wall of the tank and the ambient
R_{el}	Electrical resistance
R_{iw}	Thermal resistance between the water and the wall of the tank
R_s	Thermal resistance between the wall of the tank and the ambient in the stratification model
S	Number of layers in the stratification model
T	Temperature

T_a	Ambient temperature
τ_{cycle}	Period
t_{flex}	Time the individual EWH provide flexibility
t_{heat}	Heating time, which is the time used to heat up from minimum temperature to maximum temperature
T_{in}	Temperature of the inlet water
T_{max}	Maximum temperature
T_{min}	Minimum temperature
T_{out}	Temperature of the outlet water
T_{ref}	The set-point of the tank
t	Time
T_w	Temperature of the wall of the tank
U	Potential
x_{hot}	Fraction of hot water in the shower

1 Introduction

1.1 Background

The world's energy demand is growing, with a projected increase of almost 50% towards 2050 [1]. At the same time, the Paris Agreement is demanding a reduction in green house gas emission to fight global warming [2], and the energy sector, with its large CO2 footprint, must change to fulfill its responsibilities. With this in mind, the focus on integrating clean and efficient energy resources have gained a lot of attention to both meet the growing demand of energy and to substitute carbon intensive resources, such as coal and gas. Therefore, the interest and research on renewables is increasing, and the prices of these sources are declining rapidly [3]. Renewable energy sources will help reduce the carbon footprint of the energy sector, but integrating them into the power system is not straight forward.

A secure operation of the power system requires a constant balance of supply and demand. The intermittency of renewable energy resources, such as solar and wind, adds uncertainty in the day-ahead market, increasing need for reserves. In the traditional power system, the imbalances in supply and demand could be regulated by the transmission system operator (TSO) through reserve markets and ancillary services. However, as renewable energy sources entering the system are largely connected to the distribution grid, the balancing problems are shifted down to distribution level. At the same time, the advancement in Information and Communication Technology (ICT), opens up new frameworks for handling these challenges by including the consumer through demand side flexibility.

Flexibility can be defined as the ability of an energy resource in the power system to respond to variations in generation and demand [4]. On the demand side, flexible resources can help ease the stress on the power system by increasing, reducing or rescheduling their demand. For example, charging an electric vehicle when wind and solar power production is high, or deactivating home appliances in residential households when power lines are overloaded. Demand side flexibility has the potential to provide useful services in the real-time operation of the power system, emphasizing the importance of studying how these sources can be integrated in the system.

1.2 Motivation

Electric water heaters (EWH) are a special type of demand side flexibility resource for many reasons. Primarily, they have widespread availability, appearing in many residential households. They have excellent thermal storage, as the high heat capacity of water allows them to store large amounts of electric energy, and the insulation allows for this energy to be stored until needed. EWHs also have a high rated power, and can be turned on and off in matter of seconds or less.

To estimate the flexibility potential, many studies have looked into different modelling approaches of EWHs to capture the relationship between power and temperature. The main techniques used are simple one mass models, assuming a uniform temperature, and more detailed models considering the stratification of the temperature inside the tank [5],[6]. The more complex stratified models have shown to better describe the temperature inside the tank, at a greater computational cost [7].

Many researchers have investigated the flexibility potential of large aggregated populations of EWHs, along with methods of compensation to encourage participation in demand side flexibility. However, there are numerous sparsely populated places in Norway where aggregating a large population of EWHs can be challenging. Furthermore, the willingness to participate with demand side flexibility of EWHs might be too small to be able to form a large population. With this in mind, more research is needed on the behaviour and the flexibility potential of a small scale population of EWHs. Scaling down results from large populations of EWHs is one option, but this approach smooths out the discrete behaviour of a small population.

To be able to accurately estimate the individual flexibility of the EWHs, a bottom-up approach must be used. This requires high frequency measurements of an EWH to model the temperature and power response, from which a parametric model can be created. Further, water consumption data from residential households is required to model realistic behaviour of EWHs.

1.2.1 Specialization Project autumn 2020

In the specialization project, an EWH was investigated to obtain characteristics of the temperature and power behaviour following different events. High frequency data was collected through experiments on the EWH at the Smart House. The different experiments were:

- studying the EWH without withdrawing water
- deactivating the EWH for different time periods
- showers of different lengths with the EWH activated or deactivated.

The data provided a good understanding of the behaviour of an EWH, such as the heating time during normal operation and after showers. The obtained characteristics can be used to make a parametric model of an EWH.

1.3 Scope of the Thesis

This thesis aims to investigate the flexibility potential of a small aggregated population of EWHs, looking into the behaviour of each individual water heater. To achieve this, the following method is proposed.

First, three different EWH models are presented and parameter fitting is performed, using experimental data from the Smart House. Based on the results, one model is chosen and validated against other experiments at the Smart House.

Next, a domestic water consumption model is used as input data to the EWH model to simulate the power and temperature profiles. The power profiles are added together to simulate an aggregated population of EWHs, and this profile is compared to measured data from a different project.

Lastly, different control strategies are developed to be able to estimate the flexibility potential of the population of EWHs. Different reconnection strategies are also proposed for avoiding new peaks in power consumption after reconnection. The flexibility potential is presented both at an individual and aggregated level with the attributes power, energy and duration.

1.4 Contributions of the Thesis

- High frequency data have been collected from the experiments at the Smart House, providing detailed power and temperature measurements of a single EWH.
- Three EWH models have been implemented and tested to simulate power and temperature profiles, showing that a simple EWH model provided good results, and more complex models did not improve the results significantly. Therefore, the TEC model was chosen to simulate the temperature and power relationship of the EWH.
- A Stochastic Load Model generating water consumption data has been used together with a TEC model to generate power and temperature profiles of an aggregated population of EWHs, and validating this against measured data showed a good match despite the simplifications done in both the model and input data.
- Two different control strategies have been used to estimate the flexibility potential of the EWHs along with different reconnection strategies. The result demonstrated a huge potential for load shifting without creating new power peaks, and still maintaining user comfort. The flexibility of the EWHs is successfully found on both an individual and aggregated level.

1.5 Structure of the Thesis

Chapter 1, *Introduction*, presents the background, motivation, scope and contributions of the master thesis.

Chapter 2, *Literature Review*, reviews the modelling approaches of an EWH and the different domestic hot water consumption models to be able to generate power and temperature profiles of a population of EWHs. Then, the literature on the topics of flexibility services from electric water heaters and their flexibility potential is presented.

Chapter 3, *Theory*, presents general theory, design and operation of an EWH. Then, the theory behind the different EWH models is presented.

Chapter 4, *System Model and Methodology*, goes into detail about the approach used to perform experiments at the Smart House. Then, the implementation of the different EWH models is presented, and further, a population of EWHs is aggregated. Lastly, different control strategies and scenarios for investigating the flexibility are presented.

Chapter 5, *Results*, presents the results of the experiments performed at the Smart House, the parameter fitting of the EWH models, the validation of the TEC model and lastly, the results of the flexibility investigation.

Chapter 6, *Discussion and Further Work*, analyses the main findings of the thesis, along with recommendations for further work on the topic.

Chapter 7, *Conclusion*, provides a summary of the main findings in the report.

2 Literature Review

The literature review is organized as follows:

1. Existing EWH models simulating temperature and power profiles are being reviewed.
2. The water consumption data available is reviewed.
3. The demand side flexibility and its different services and characteristics are reviewed to better understand how to estimate the flexibility potential of EWHs.
4. A comparison table and summary is presented at the end of this chapter to highlight the main gaps in the literature.

2.1 Electric Water Heater Modelling

To be able to estimate the flexibility potential of EWHs, it is useful to have a model that can simulate the relationship between temperature and power. This allows for studying the response following different control strategies. In this section, different modelling approaches for EWHs, used in the literature, are reviewed.

The EWH models reviewed differ in complexity and accuracy. The one mass model, also called single zone model, assumes that the water inside the tank has a uniform temperature [5], [7]-[8]. This model is easy to implement, and has few parameters that needs to be determined. The parameters can be identified through temperature measurements when no hot water is drawn from the tank, but a paper has also looked into estimating the parameters based only on power measurements [5].

Some EWH models include the thermal stratification of the water inside the tank, by either dividing the tank into different thermal zones or slicing the tank into a selected amount of layers [6],[7]. Modelling the stratification of the water provides a better representation of the inner behaviour of the tank. More parameters need to be determined, like the placement of the temperature sensor and the heating element(s), and also the parameters pertaining to heat convection and conduction in the water. Dividing the tank into different thermal zones has been shown to better simulate the temperature behaviour, compared to a one mass model [7].

2.2 Water Consumption Data

The next step after choosing the EWH model and performing the parameter fitting, is finding suitable water consumption data. This section looks into water consumption measurements and models which will be important for simulating realistic behaviour of EWHs.

Different techniques are used to model the hot water consumption data. Some models use standardized load profiles, while others rely on reference load profiles [9]. A standardized load profile takes the average of a measured load profile, often linked together with outdoor temperature, while a reference load profile selects a representative load profile from the measurements [9]. These methods can be useful when modelling a single EWH, but the consumption can stack up when aggregating multiple EWHs, not producing the smooth consumption profile one would expect. When modelling aggregated populations, it is therefore be better to use stochastic behaviour models.

Behaviour models are created by collecting Time-of-Use (ToU) data based on consumer activities [9]-[10]. Information about when the activities start and end is collected and builds the foundation of the model, and a probability distribution is derived. These activities can be registered through consumer survey with time dairies, where the consumers write down their daily activities [11]. By linking probability distributions for activities that requires hot water with the average water consumption for these activities, a stochastic model simulating domestic hot water consumption for a household is created. Behavioural models have been created for Swedish[11], Belgian[10] and German[9] households, among others. No behaviour models based on Norwegian household data are available.

There has been little research about the domestic hot water usage in Norwegian households on an individual level. The project VarmtVann2030 is a collaboration project between building owners, suppliers, SINTEF and NTNU with the aim of increasing the knowledge about domestic hot water (DHW) use in Norway in different types of buildings. The goal of the project is to be able to suggest more energy efficient and environmental friendly solutions for the use of DHW [12]. The project has collected an aggregated DHW consumption profile of 56 apartments in Oslo in 2019, and the results showed that DHW systems can be a significant source of flexibility in Norwegian apartment buildings [13]. Another research has analysed and predicted the hot water consumption data mainly in non-residential buildings in Norway [14].

2.3 Estimating the Flexibility Potential of the Aggregated EWHs

When the EWH model and the input data are in place, the next step will be to investigate the flexibility potential of the EWHs. Therefore, literature regrading flexibility is reviewed, with the purpose of gaining valuable information regarding flexibility. The structure of this section is as follows:

- The concept of demand side flexibility, along with two main control methods, are presented.

- Different characteristics used to estimate the flexibility potential are presented
- Flexible loads and their flexibility services are presented, then narrowing it down to flexibility from residential EWHs
- The idea of a flexibility market is briefly introduced

The reviewed literature will provide valuable information when aggregating the EWHs, trying different control techniques and characteristic the flexibility potential of the population. Further, the reviewing has an aim of revealing possible gaps in the research.

2.3.1 Flexibility

The concept of demand side management (DSM) has gained a lot of attention in academic research. DSM is a term used for the method of managing the power consumption of the consumers, i.e. by reducing, increasing or rescheduling their consumption[15]. The motivation for performing these types of control on the demand side is to provide *flexibility* to the power system. Flexibility can be defined as the ability of a resource to adjust its energy consumption or generation pattern [16]. The potential of the flexibility and what it can be used for is a much discussed topic, and various sources of flexibility is being investigated. Some studies look into storing electricity as thermal energy, while others study look at purely electric sources like plug-in electric vehicles [13],[17].

Since the traditional power system is now rapidly changing, with the advancements in ICT, flexible loads on the demand side are becoming available. Researchers are investigating different control techniques to harness flexibility from the demand side, often divided into two groups, direct load control (DLC) and indirect load control (ILC). In DLC, the consumer allows the system operator to control the load on their behalf, while with ILC the consumer itself decides how the load should respond to a control signal, e.g. a price signal [5]. Having direct control over loads can be a useful tool for a system operator, while for a consumer it can be less tempting to give away the control of their loads. Indirect control, on the other hand, allows consumers to remain in control, but the response of the control signal will be more uncertain for a system operator [18].

2.3.2 Characterizing Flexibility

In order to use flexibility as a solution to the challenges in the power system, it is important to characterize the flexibility available on the demand side. A literature study found that a variety of attributes can be used to define the flexibility of a load, describing its usefulness for a system operator [19]. Some researchers characterised the flexibility by its location in the distribution system, the activation time, duration and direction, i.e. upward or downward regulation, while others characterised it based on delivery time, predictability, time availability and controllability [19]. Another researcher presents the flexibility by means of a flexibility function to present a buildings ability to adjust its energy consumption in response to a price signal, proving to be a useful tool even when the system is not in steady-state [20]. Further, an aggregation system, called Distributed Energy Resource Aggregation System (DERAS), can present the parameters of each individual resource, e.g. the state of the asset and the amount of energy available, which can be beneficial when controlling and monitoring different sources of flexibility [21]. As can be seen, there are numerous ways to characterize the flexibility potential from a flexibility source, and it is therefore important to define the flexibility in terms of its attributes and the type of service it is going to offer.

2.3.3 Flexibility Sources

Different residential loads have been investigated to provide flexibility. Researchers have looked into the possibility of providing flexibility with air conditioners because of their large share of power consumption and regulation possibilities without impacting the comfort of the consumers [22]. Others have looked at the possibility of exploiting the energy storage potential of electric vehicles with the use of vehicle-to-home or vehicle-to-grid charging [17]. Both of these sources of flexibility show promising potential.

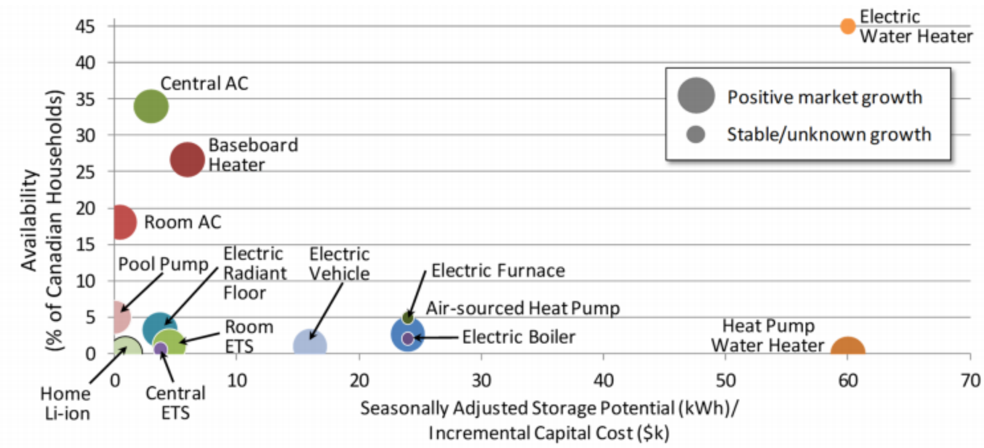

Figure 2.1: Residential flexibility sources and their energy storage potential [23]

Figure 2.1 provides an overview of energy storage system in Canadian residential households, showing that the EWH has the highest storage potential, per incremental capital cost, and also the highest availability [23]. The transmission system operator (TSO) in Norway, Statnett, estimates that there are 2 million EWHs in Norway, and assuming that each of them have a capacity of 2 kW, there is a combined capacity of 4 GW [24]. Thus, there are many EWHs in the Norwegian power system with excellent potential for offering flexibility. Figure 2.2 shows how the EWH also contribute to a significant portion of the total household energy consumption [25], meaning that a large amount of the household energy consumption can be adjusted simply by controlling the water heater.

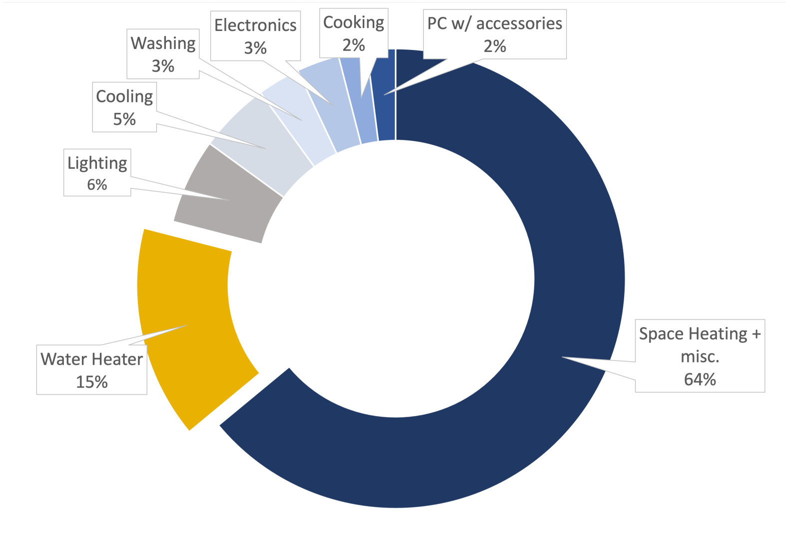

Figure 2.2: Electricity usage in Norwegian households [26]. EWHs stand for 15% of the energy consumption in a residential household, so a large amount of the energy consumption can be adjusted simply by controlling the water heater.

2.3.4 Flexibility from EWHs

Different flexibility services from EWHs have been investigated during the last couple of years. Researchers have looked into the possibility of using EWHs to provide frequency control, since their power consumption can be controlled quickly and frequently [27],[6], though most look into using EWHs for load shifting[5],[6],[13]. The time of power consumption of the EWHs corresponds well to the overall peak demand in the power system, so controlling the operation time of a large population of EWHs can be a great tool for peak shaving [21],[5]. These examples show the versatility of using EWHs for flexibility services.

However, shifting the power consumption of a population of EWHs can cause other problems that need to be addressed, e.g. generating a new consumption peak that exceeds the normal daily peaks. A Norwegian study used measurements of power in a regression model to perform direct load control on residential water heaters, and they found that the average consumption per household increased with 0.28 kWh/h the following hour [28]. A suggestion proposed by a paper to avoid this problem is to organize the population of EWHs into different groups based on their specific characteristics. With this method it is possible to group the EWHs into different clusters based on rated power, occupants in the household or similar consumption profiles. By grouping the EWHs, the system operator can choose to send a control signal to a specific group of EWHs, so that the risk of getting a new consumption peak after providing flexibility services is reduced. The same paper presented a study where 73 residential hot water profiles were grouped into two classes, high consumption and low consumption. The results showed that with this method of clustering it was possible to shift part of the consumption profiles to off-peak hours without causing significantly higher peaks afterwards [6].

Another obstacle of using EWHs for flexibility services is recruiting a large enough number of customers to participate with flexibility. The concern is that the deactivation of the EWHs can cause the consumers to run out of hot water [6]. In a study preformed by the Bonneville Power Administration, 26.5% of the EWHs in the states of Oregon and Washington were enrolled in a flexibility service program, and the consumers were paid different compensations based on their local utility. Control signals were sent to 277 households over a period of 220 days, and 80% of the consumers said that they were satisfied with the program, and 94% of them stated that they would participate in future similar programs [21]. A survey performed in Norway, on the behalf of The Norwegian Water Resources and Energy Directorate (NVE), showed that over the half of the participants were willing to shift their consumption if they were compensated for it [29].

2.3.5 Flexibility Markets

There are multiple studies on how the trading of flexibility might work, and how the participants should get compensated [13],[19],[30]. The project EMPOWER [31] has studied the local energy market design and looked into the possibilities of compensation for the participation with flexibility sources. For direct load control, the concept of a reservation and activation fee is presented, where the participants gets an instant reward for participating with their flexibility source and additional compensation when providing flexibility [30].

To further motivate for participation in the flexibility market, there is indirect compensation as well. If a consumer decides to shift their load consumption from hours with high electricity price to an hour with a lower price, the same amount of energy will cost less. However, a study performed in Norway showed that shifting the consumption of a shared EWH for 56 apartments to low price hours gave a total saving of 8 euros over 23 days [13]. Without other incentives, the difference in electricity price during a day must be larger for making participating with flexibility attractive [13].

Since the flexibility from an individual flexibility source will have little power to negotiate with in a market, aggregating them together is more valuable for a system operator. Therefore having a flexibility operator to harvest these individual resources, and form various flexibility services, can be useful. The flexibility operator will also have the job of trading these services to a market, and will get paid for selling flexibility services. A flexibility operator is proposed so that consumers do not participate individually, due to both the lack of negotiable power, but also the large amount of communication exchange needed to trade flexibility individually [19].

2.4 Summary of Literature Review

After reviewing literature about EWH modelling, water consumption data and the flexibility potential of EWHs, the gaps will be further explored. To show the gaps in the literature, a comparison table, Table 2.1, is made for the main literature studied in this master thesis. The table also shows the focus of this thesis.

As seen from Table 2.1, many of the studies reviewed focus on the flexibility from an aggregated population of EWHs, while a more detailed overview of the individual flexibility from each EWH could be further investigated.

Moreover, the number of the EWHs is high in most of the studies. Since many places in Norway are sparsely populated, aggregating a large population might not be possible. Scaling down the results from a large population will smooth out the discrete behaviour of a small population, so estimating the flexibility of a population of few EWHs is useful.

In the estimation of the flexibility potential in this thesis, different control strategies are proposed, with direct load control by sending deactivation and activation signals to the EWHs. There has been little research based on the control of residential EWHs with the use of an activity control strategy, i.e. controlling the EWHs based on hot water use.

Based on the gaps found in the literature, this thesis aims to investigate the behaviour and estimate the flexibility potential of a small population of EWHs. The flexibility will be presented for the aggregated population of EWHs, as well as the individual EWHs. Therefore, it will be possible to see which EWH that has contributed with flexibility to the power system.

Table 2.1: Comparison of reviewed literature on EWH modelling and flexibility

Article	EWH Model	Input data	Input data origin	Scale	Flexibility service	Aggregated flexibility	Individual flexibility	Control Strategy
[5]	One Mass Model	Power Measurements	Canada	96	Load Shifting	✓	✓ (looks into 1 EWH)	DLC
[7]	Stratification Model and One Mass Model	-	Canada	1	-	-	-	-
[6]	Stratification Model	Measured Hot Water Profiles	Canada	73	Load shifting	✓	-	DLC
[13]	Energy Balance Equation	Measured Flow and Energy Data	Norway	One electric DHW system (56 apartments)	Load Shifting	-	✓ (for all 56 apartments)	DLC, ILC
[21]	One Mass model	Behaviour Model	USA	69 - 100	Load Shifting, Frequency control	✓	-	DLC
[27]	One Mass model	DHW Schedule Generator	USA	22	Frequency Control	✓	-	DLC
[28]	Power in Regression Model	Power Measurements	Norway	475	Load Shifting	✓	Average per household	DLC
[8]	One Mass Model	Behaviour Model (same as [21])	USA	10 000	Load Shifting	✓	-	DLC
Focus of this Thesis:								
	One Mass Model	Behaviour Model	Sweden	12	Load Shifting	✓	✓	DLC

3 Theory

3.1 Electric Water Heaters

Section 3.1.1, regarding the design and functionalities of an EWH, is based on a paper investigating design and operation of EWHs [32].

3.1.1 Design and Functionalities of an EWH

EWHs heat and store water for domestic use in many residential households. They come in different sizes, both in terms of rated power and water capacity of the tank. The tank is insulated, limiting the heat losses to the environment. The inlet and outlet for the water is located at the bottom and top of the tank, respectively. The water is usually heated with restive heating elements, and the numbers of heating elements ranges from one to three. Each heating element is equipped with a thermostat controlling the on and off state of the element. It is normal that only one heating element is heating at a time. The temperature set-point of the tank is normally adjusted manually.

The water heater has a deadband, with upper and lower temperature limits, that triggers the activation and deactivation of the heating element. This prevents frequent switching of the EWH. When cold water flows into the bottom of the tank, warmer water rises to the top of the tank because of the difference in density, causing a thermal stratification in the tank. Due to this stratification, the water at the top of the tank, where the outlet is located, will always have the warmest temperature, also when cold water is flowing into the tank.

Keeping the EWH within the correct temperature range is crucial, both for the comfort of the consumer and to avoid bacterial proliferation. EWHs are exposed to legionella bacteria if certain conditions are not met, which can in worst case cause serious pneumonia with high mortality [33]. The bacterium thrives and flourishes in stationary water with temperatures between 20 to 55°C. According to the Norwegian Institute of Public Health (FHI) the criteria that needs to be fulfilled to avoid legionella in the tank are [34]:

- Good circulation of the water in the tank
- Temperatures above 60°C or below 20°C
- Possibility of maintenance of the tank

3.1.2 Storing Energy in EWHs

EWHs are excellent for storing energy due to the heat capacity of water. Water has a higher heat capacity compared to many other substances, meaning that it stores more energy at a given temperature compared to the same mass of for instance air [35]. This ability lets the EWH store significant amount of electric energy as thermal energy. The water heater can be deactivated for different time periods and still keep the water warm because of the insulation of the tank. It is this strength that will be exploited when offering it as a source of flexibility.

3.2 Electric Water Heater Modelling

3.2.1 Thermal Equivalent Circuit

A thermal system can be modelled as an electrical system using the analogy between them. Table 3.1 presents the analogies between the thermal and electrical systems [36].

Table 3.1: Analogies between thermal and electrical systems

Thermal	**Electrical**
Thermal resistance, R $[W/K]$	Electrical resistance, R_{el} $[\Omega]$
Temperature, T $[K]$	Potential, U $[V]$
Heat transfer, Q $[W]$	Current, $I[A]$
Thermal capacitance, C $[J/K]$	Electrical capacitance, C_{el} $[F]$
Relationship between temperature and heat flow, $\Delta T = Q \cdot R$	Ohm's law, $\Delta U = I \cdot R_{el}$
Relationship between heat flow and change in temperature, $Q = C\frac{dT}{dt}$	Current across capacitor, $I = C\frac{dU}{dt}$

Relating this to an EWH, the water inside the tank has a heat capacity and the insulation of the tank acts as a thermal resistance. The heating element supplies a constant power and can be modelled as a current source in the thermal equivalent circuit. The following equations are used to calculate the theoretical values of the heat capacity and the thermal resistance:

$$C = m \cdot c_w \tag{3.1}$$

where

- m: Mass of water inside the tank
- c_w : Specific heat capacity of water, taken as 4.2 kJ/kg°C. [37]

$$R = \frac{\Delta T}{W} \tag{3.2}$$

where

- W: Rated heat loss of the tank from Table 4.1
- ΔT: Temperature difference between the ambient and the water temperature inside the tank

A Thermal Equivalent Circuit (TEC) can be used to model the thermodynamic processes of an EWH, and the method represents the heat transfer processes by means of an electric circuit [27]. The differential equation used to describe these thermodynamic processes are made by solving the circuit with electric circuit theory. When modelling EWHs, a uniform distribution of the temperature in the tank is assumed, and the model can therefore be categorized as a one mass model. Section 3.2.1 below depicts the TEC model of an EWH.

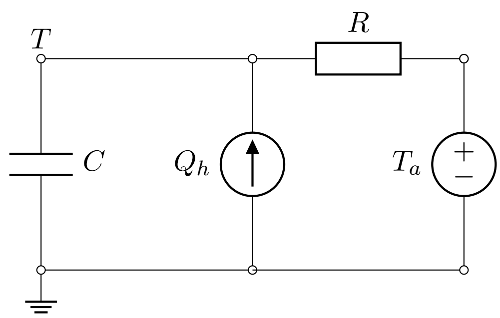

Figure 3.1: TEC with one thermal resistor and one thermal capacitor

Based on this circuit the following differential equation is obtained, describing the thermo-electrical response of the EWH:

$$\frac{dT}{dt} = \frac{\dot{m} \cdot c_w}{C}(T_{in} - T) + \frac{1}{R \cdot C}(T_a - T) + \frac{1}{C} \cdot Q_h) \tag{3.3}$$

where

- T : Temperature of the water in the tank
- C : Heat capacity of the water in the tank
- $\dot{m}$: Mass flow of water
- T_{in} : Inlet temperature of water
- T_a : Ambient temperature outside the tank
- Q_h : Power provided by the heating element

3.2.2 Extended Thermal Equivalent Circuit

The TEC model gives a purely linear temperature response, while the measurements exhibits a more complex response. In an attempt to capture this response an extended TEC model, with two degrees of freedom, is created. The extended TEC model is based on the same thermal equivalent theory as the TEC model presented in Section 3.2.1. The modelling of the EWH follows the same principle as used for a building in a previous study [38], and is not commonly used when modelling EWHs.

In the extended TEC model, the thermal resistance of the water heater is divided into two components, one thermal resistance between the water and the wall and one thermal resistance between the wall and the ambient. The heat capacity of the water heater is also modelled with two heat capacitors, one for the water inside the tank and one for the wall of the tank. Section 3.2.2 shows the circuit and the parameters included in the model.

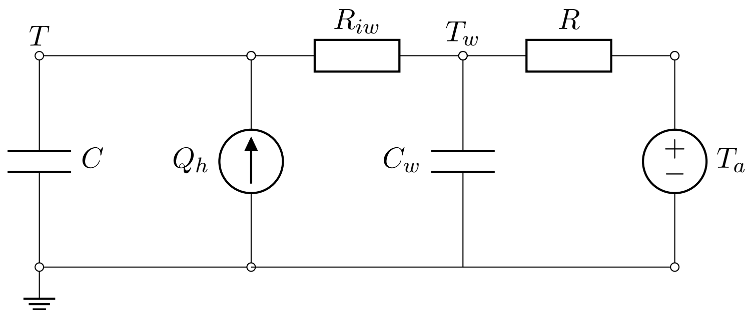

Figure 3.2: TEC with two thermal resistors and two heat thermal capacitors

From this circuit the two following differential equations can be obtained:

$$\frac{dT}{dt} = \frac{\dot{m} \cdot c_w}{C} \cdot (T_{in} - T) + \frac{1}{R_{iw} \cdot C} \cdot (T_w - T) + \frac{1}{C} \cdot Q_h \tag{3.4}$$

$$\frac{dT_w}{dt} = \frac{1}{R_{iw} \cdot C_w} \cdot (T - T_w) + \frac{1}{R \cdot C_w} \cdot (T_a - T_w) \tag{3.5}$$

where

- T : Temperature inside the tank
- $T_{w:}$ Temperature of the wall of the tank
- C : Heat capacity of the water in the tank
- C_w : Heat capacity of the wall of the tank
- R_{iw} : Thermal resistance between the water in the tank and the wall of the tank
- R : Thermal resistance between the wall of the tank and the ambient

3.2.3 Stratification Model

The temperature in an EWH is generally not uniform, as has been assumed in the previous two models. In this model, the stratification of the temperature inside in the tank is considered. The model is based on previous research [6], and is from now on referred to as the stratification model. The stratification model assumes that the water in each layer is perfectly mixed, and by solving the energy balance equation (Equation (3.6)) in each layer, the temperature and power profiles of the tank are calculated.

$$\frac{dT_s}{dt} = \frac{1}{m_s \cdot c_w} \cdot (Q_{env,s} + Q_{conv,s} + Q_{flow,s} + Q_{h,s}) \tag{3.6}$$

where

- T_s : Temperature in layer s
- m_s : Mass of water in layer s
- $Q_{env,s}$: Heat exchange to the environment
- $Q_{conv,s}$: Heat exchange between the layers

- Q_{flow} : Heat transfer due to water extraction
- $Q_{h,s}$: Heat addition from the heating element when activated

The heat exchange to the environment:

$$Q_{env,s} = U_s(T_a - T_s) \tag{3.7}$$

where

- U_s : heat loss coefficient between the layer and the environment

The heat exchange between the layers is calculated with the following equation:

$$Q_{conv,s} = \begin{cases} K_s(T_{s+1} - T_s) & \text{if s=0 (bottom layer)} \\ K_s(T_{s-1} - T_s) & \text{if s=S (top layer)} \\ K_s(T_{s+1} + T_{s-1} - 2T_s) & \text{otherwise} \end{cases} \tag{3.8}$$

where

- K_s : conductivity coefficient between the layers.

Lastly, the heat transfer due to water extraction is calculated with Equation (3.9).

$$Q_{flow,s} = \begin{cases} \dot{m}_s c_w(T_{in} - T_s) & \text{if s=S (top layer)} \\ \dot{m}_s c_w(T_{s-1} - T_s) & \text{otherwise} \end{cases} \tag{3.9}$$

where

- $\dot{m}_s$: Water flow rate
- T_{in} : Water temperature at the inlet

4 System Model and Methodology

Chapter 4 explains the process of modelling the system, and can be divided into five parts:

1. The experiments performed at the Smart House to obtain high-frequency power and temperature measurements.
2. The parameter fitting of the TEC model, extended TEC model and the stratification model.
3. Verification of the chosen EWH model.
4. Creating a population of EWHs.
5. Estimating the flexibility potential of the aggregated EWHs.

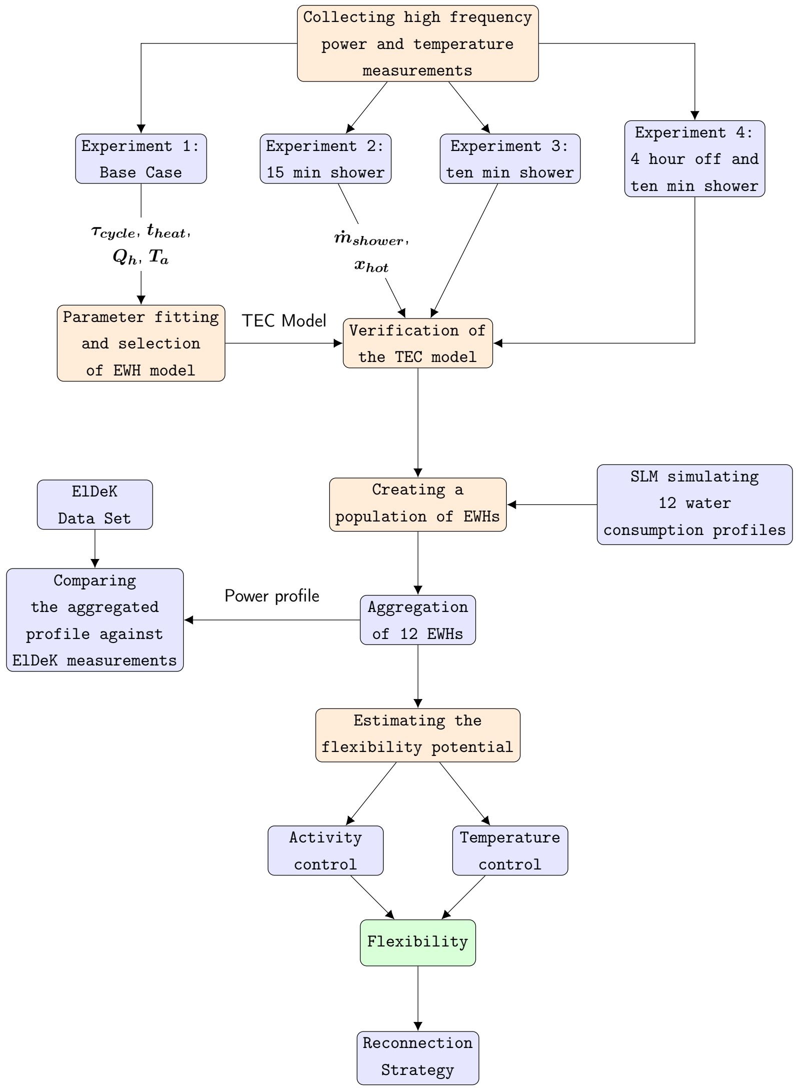

Figure 4.1: Overview of the System Model and Methodology

4.1 Experiments at the Smart House

The National Smart Grid Laboratory, from now on referred to as the Smart House, in Trondheim is operated by NTNU and SINTEF, and enables testing of the smart grids of tomorrow [39]. The Smart House is a two room apartment with all the household interior needed, but also high frequency monitoring of the electric loads in the house. There is an electric water heater installed at the bathroom that supplies hot water to the sink and the shower in the bathroom. The hot water in the kitchen is supplied by a 9 kW tankless water heater.

A control system called Logic Machine 4 (LM4) is installed in the Smart House, allowing to control the on and off state of the water heater and measure the temperature in the tank with 5 minute interval. LM4 sends control signal to a relay in order to activate or deactivate the EWH, and a sensor monitors the temperature of the water in the tank. To access the data a PC is used with an Ethernet cable. A power meter was installed to measure the power drawn by the EWH, and it takes measurements on a 15 second interval. Figure 4.2 gives an overview of the structure of the communication system in the Smart House.

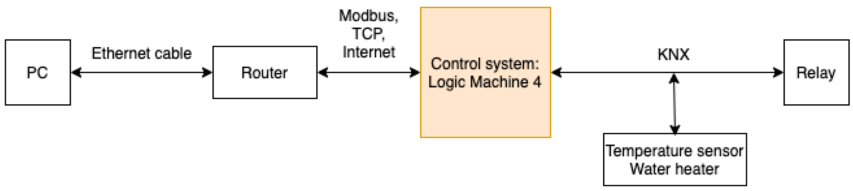

Figure 4.2: The communication system structure of the Smart House [40]

Data from EWH was collected from the Smart House during the specialization project, autumn 2020. Table 4.1 shows the technical data of the water heater in the experiment from the producer OSO Hotwater. The different experiments preformed were:

- Base Case: no hot water consumption.
- Case 1: no hot water consumption during the experiment, but the water heater is deactivated for different time periods, i.e. one, two and four hours.
- Case 2: Ten-minute shower while the water heater is either deactivated or activated.
- Case 3: Five-minute shower while the EWH is activated.

Table 4.1: Technical data of the EWH in the Smart House[41]

Product code	S 300 - 3kW/1x230V
Capacity, persons	5.5 persons
Capacity	281 liters
Factory thermostat setting	75°C
Time heating cold water to $65°C$	7.2 hours
Heat loss	86 W
Heating elements	1

Repetition of the Experiments Performed at the Smart House, Autumn 2020

One additional experiment was planned to be performed at the Smart House during the spring 2021 to get water temperature measurements and the flow rate of the shower. While doing this experiment it was discovered that the heating time and period of the EWH had changed, and it was therefore decided that some of the experiments should be redone. The obtained characteristics (Table A.1 and Table A.2) from the Smart House, autumn 2020, will not be used in the parameter fitting of the EWH models. Instead, characteristics from the new measurements are used.

4.1.1 Experiment 1: Base Case

In experiment 1, the heating time, period and power of the EWH is measured, without any hot water withdrawal. The ambient temperature of the room will also be measured. The average value of the heating time and the period will be used to perform the parameter fitting, and the average power will be used as the power of the heating element in the EWH models.

4.1.2 Experiment 2: 15 Minute Shower

After having measured the heating time, period and power of the EWH, the purpose of experiment 2 is to obtain the inlet and outlet water temperatures, as well as the flow rate of the water in the shower.

The water flow rate is measured with the use of a bucket, with marks for every liter, and a timer. A 15 minute shower will be taken with maximal flow rate, and the water consumption will be measured three times. While measuring the water consumption with the bucket, a thermometer will be used to measure the outlet temperature in the shower and the inlet temperature in the sink. The temperature inside and outside the tank is monitored by the control system, LM4, which provides temperature measurements every 5 minute. The power drawn by the EWH is measured every 15 seconds interval with a power meter.

To calculate the amount of hot water from the tank used in the shower, the following relationship is utilized:

$$x_{hot} \cdot T_{ref} + (1 - x_{hot}) \cdot T_{in} = T_{out} \tag{4.1}$$

- x_{hot}: Fraction of hot water from the tank
- T_{ref}: Set temperature of the tank
- T_{in}: Temperature of the inlet water
- T_{out}: Temperature of the outlet water in the shower

4.1.3 Experiment 3: Ten Minute Shower

An experiment with a ten minute shower is performed so that the chosen EWH model can be tested against measurements with shower data.

4.1.4 Experiment 4: Four Hours off and a Ten Minute Shower

Lastly, an experiment with a ten minute shower will be performed with the EWH deactivated. That means that the EWH will not heat the water when the temperature drops below the minimum temperature. The experiment will be simulated and compared with the chosen EWH model. The reason for testing this is because this is a scenario that can happen when the EWH is providing flexibility; consumers might use the shower while the EWH is deactivated.

4.1.5 Summary of the Experiments at the Smart House - Spring 2021

Table 4.2 provides an overview and the purpose of each of the experiments. In addition to collecting temperature and power profiles, some parameters used in the modelling are obtained.

Table 4.2: Experiments at the Smart House - spring 2021

Name	Experiment	Purpose	Obtained Parameters
Experiment 1: Base case	Measure the average heating time, average period and average power, and the average ambient room temperature.	To perform the parameter fitting of the three EWH models	t_{heat}, τ_{cycle}, Q_h, T_a
Experiment 2: 15 minute shower	15 minute shower at maximal flow rate. Measuring the inlet and outlet water temperature, and the flow rate of the shower.	Simulating shower events equal to the showers performed at the Smart House	T_{in}, $\dot{m}_{shower}$, x_{hot}, T_{out}
Experiment 3: ten minute shower	ten minute shower with a maximal flow rate	To test the chosen EWH model	-
Experiment 4: deactivating EWH and ten minute shower	The EWH is deactivated for four hours and a ten minute shower is taken while the the tank is deactivated	To test the chosen EWH model	-

4.2 Electric Water Heater Modelling

This section is structured as follows for each of the EWH models:

1. The algorithm for the EWH model is presented.
2. The method of parameter fitting is explained, based on the obtained parameters from the base case.
3. One of the models is chosen and the method of validating this model against shower experiments is explained.

4.2.1 Thermal Equivalent Circuit Model

The first model is the TEC model. It is implemented in Python and provides temperature and power profiles of a single EWH. The differential equation, Equation (3.3), is solved numerically with Euler's method.

$$T_{k+1} = T_k + \Delta t \cdot \left[\frac{\dot{m} \cdot c_w}{C}(T - T_k) + \frac{1}{R \cdot C}(T_a - T_k) + \frac{1}{C} \cdot Q_h \right] \tag{4.2}$$

Algorithm 1 shows how the TEC model is implemented.

Algorithm 1: TEC Model

Result: Returns time series of temperatures and power

for *Each time step* **do**
  if *Temperature is above 69.8 degrees* **then**
    Turn off the heating element;
  else if *Temperature is below 67.3 degrees* **then**
    Turn on the heating element;
  else
    The heating element stays in the previous state;
  end
  Calculate the temperature with Equation (4.2)
end

Parameter fitting of the TEC Model

The values of R and C needs to be determined with a parameter fitting, based on the measurements in the base case experiment at the Smart House. The parameter fitting is done with the use of a quick and simple optimization algorithm.

Since the main goal is to recreate the measurements done at the Smart House, the values of R and C are adjusted so that the heating time and the heating period from the model gets as close as possible to the measurements.

An algorithm is used to calculate the heating time and period for different values of R and C. The pair of R and C that provides the solution closest to the period and the heating time from the base case will be used in the TEC model. The chosen parameters are presented in Table 4.3. The results from the optimisation is presented in Section 5.2.1.

Table 4.3: Parameters used in the TEC model in Python

Parameter	Value	Unit	Description
T_{in}	5.9	°C	Inlet water temperature
T_a	24	°C	Ambient temperature outside the tank
T_{ref}	75	°C	Set-point of the tank
Q_h	2.89	kW	Power rating of the heating element
R	286.58	°C/kW	Thermal resistance
C	0,171	kWh/°C	Heat capacity

4.2.2 Extended Thermal Equivalent Circuit Model

The algorithm to calculate the power and the temperature with the extended TEC model is similar to Algorithm 1, but in addition to the temperature of the water in the tank, the temperature of the wall is also calculated. Euler's method is used to solve the two differential equations Equation (3.5) and Equation (3.4) the same way as performed with the TEC model.

The extended TEC model contains one additional heat capacity and thermal resistance compared to the simpler TEC model. Since the values of R_{wa} and C_{wall} are not known a similar optimisation, as presented in Section 4.2.1, will be preformed to determine these values.

Parameter fitting of the extended TEC Model

There are four parameters that need to be determined in the extended TEC Model. The additional parameters makes the computation much more costly, hence the optimisation is preformed in multiple iterations.

The starting values of C and R are based on the theoretical values calculated with Equation (3.1) and Equation (3.2), and C_w and R_{iw} are assumed to be smaller because the heat capacity of the wall should be less than the heat capacity of the water in the tank. The same goes for the thermal resistance between the water and the wall of the tank, compared to the thermal resistance between the wall and the ambient air.

The resulting heating time and period are normalized using the measured values, and then the distance between the simulated and measured values are calculated with Equation (4.3):

$$d = \sqrt{(\frac{t_{heat_s}}{t_{heat_m}} - 1)^2 + (\frac{\tau_{cycle_s}}{\tau_{cycle_m}} - 1)^2} \tag{4.3}$$

where subscripts s and m indicate simulated and measured values, respectively.

The 12 combinations with the smallest distance are investigated to find new ranges of the parameters for the next iteration. This is shown in the result, Section 5.2.2 and in the appendix, Table A.6 to Table A.8.

The final heat capacities and thermal resistances, with the smallest distance in the crude optimization results, are used to simulate experiment 2 from the Smart House, shown in Section 5.2.2. All the parameters used in the extended TEC model to simulate the base case is shown in the Appendix, Table A.10.

4.2.3 Stratification Model

Euler's method is also used to solve the Equation (3.6) when the Stratification model is implemented in Python.

$$T_{k+1,s} = T_{k,s} + \Delta t \cdot \left[\frac{1}{(m \cdot c_w)} \cdot (Q_{env,s} + Q_{conv,s} + Q_{flow,s} + Q_{h,s}) \right] \tag{4.4}$$

The stratification model has some extra parameters that needs to be decided compare to the two TEC models. The number of layers in the model is set to be equal to 10, and each layer is equal in volume. The reason for choosing 10 is because having more layers in the model did not improve the accuracy of the model greatly, but the computational time increased. Although the computational time improved with the use of fewer layers, the results showed less agreement with the measurement data. Algorithm 2 shows how the stratification model works.

Algorithm 2: Stratification Model

Result: Returns a list of temperatures and a list of power

```
for Each time step do
    for Each layer s do
        Calculate Q_env, Q_conv and Q_flow (presented in Section 3.2.3);
        if s is the heating element layer then
            if Temperature is above 69.8 degrees then
                Turn off the heating element;
            else if Temperature is below 67.3 degrees then
                Turn on the heating element;
            else
                The heating element stays in the previous state;
            end
        Calculate the temperature in the layer with Equation (4.4)
    end
end
```

Parameter Fitting of the Stratification Model

The stratification model has multiple values that needs to be determined. The heating element and the temperature sensor needs to be placed in a layer in the stratification model. The heating element should be near the bottom at the tank, according to the data sheet and the general theory about EWHs, and the temperature sensor is assumed to be in the layer above the heating element. The information about the whereabouts of the temperature sensor in the EWH at the Smart House is lacking, but could have improved the credibility of the model. Thus, the heating sensor is placed in layer three and the temperature sensor is set in layer four by trial and error method to match the base case obtained through experiment 1 at the Smart House. It is the temperature in layer four that will be plotted in the results.

The value of the heat capacity and the thermal resistance is obtained through trial and error to match the heating time and the period obtained through experiment 1. The reason for not running an optimization, as for the TEC model and extended TEC model, is because the stratification model is much more computationally costly and has more unknown parameters.

The parameters used in the stratification model to simulate the base case in experiment 2 can be found in the Appendix, Table A.12.

4.3 Verification of the TEC Model

The TEC model will be chosen as the model to simulate a population of EWHs. After simulating the base case with all the EWH models, it was seen that the TEC model matches very well with the measured data, and this model also has less unknown parameters compared to the two other EWH models.

To further test the accuracy of the TEC model, the experiments at the Smart House containing showers will also be simulated with the EWH model.

To be able to simulate showers, the two constants, $\dot{m}$ and c_w in Equation (3.3), need to be determined.

To find the value of $\dot{m}$, the parameters, x_{hot} and $\dot{m}_{shower}$, from experiment 2 at the Smart House is used together with the following equation:

$$\dot{m} = \dot{m}_{shower} \cdot x_{hot} \tag{4.5}$$

Instead of using the theoretical heat capacity of water, a value of 2.34 kJ/kg is used instead since this gave a better fit to the measurement data after trial and error.

Table 4.4 presents the final parameters of the TEC model.

Table 4.4: Parameters used in the TEC model

Parameter	Value	Unit
T_a	24	°C
T_{in}	5.9	°C
T_{max}	69.8	°C
T_{min}	67.3	°C
T_{start}	69.8 - 67.3	°C
$\dot{m}_{shower}$	8.9	kg/min
x_{hot}	0.49	-
R	286.58	$°C/kW$
C	0,171	$kWh/°C$
Q_h	2.89	kW
$\dot{m}$	4.36	kg/min
c_w	2.34	$kJ/kg°C$

4.4 Generating Power and Temperature Profiles with Hot Water Consumption Data

The EWH model has been chosen and the parameters have been determined. The next step is to generate a population of EWHs to get water consumption data. This section is structured as follows:

1. The available behaviour models are briefly discussed, and one is chosen.
2. The procedure of creating a population of EWHs is presented.
3. The Norwegian data set, ElDeK, containing power measurements of 12 EWHs, used for validation, is presented in detail.

4.4.1 Available Hot Water Consumption Data Sets

To be able to create a realistic power consumption profile of an aggregated population of EWHs, residential hot water consumption data is needed. Ideally, a hot water consumption model based on measurements in Norway would be chosen, but as this is not available, a foreign model has to be used. Behaviour models have been found using measurements from Belgian, German, American and Swedish households. It is assumed that Norwegian hot water consumption habits are similar to Swedish, due to the physical and cultural proximity, so the Swedish behaviour model is chosen.

4.4.2 Stochastic Load Model

The stochastic load model (SLM) constructs load profiles for household electricity and hot water based on ToU data-modelling [11]. It uses a Time-of-Use data called TU-SCB-1996, as the main input, which is a survey performed by Statistics Sweden in 1996. The parameters for each of the appliances in the household are estimates of standard power and run-time for electrical appliances obtain through object testing [11]. The other four data sets were used for validation and comparing the output of the model with measurements. Table 4.5 provides an overview of the five data sets.

Table 4.5: Overview of the data sets used to make and validate the Stochastic Load Model [11]

Name	Period	Resolution	Description	Collection Method	Function
TU-SCB-1996	August to December 1996	5-min intervals (some 1-min intervals)	ToU by Statistics Sweden (SCB). Pilot survey.	The participants wrote diaries about their activities	Create behaviour model
TU/EL-SEA-2006	Autumn of 2006	ToU data: 1-min intervals. Electricity consumption: 10-min intervals (average)	ToU survey and electricity use	Measurements	Validate the model against actual measurements
EL-SEA-2007	2005 - 2007	1-h averages based on 10-min means.	Household electricity (individual appliance level)	Measurements	To compare the electricity part of the model with average load curves on population level
HW-MDH-2006	2005 - 2006	Hourly measurements	Aggregate measured load data for hot water and electricity	Measurements	Calculate average load curves for comparison to the modelled load profiles
HW-SEA-2007	October 2006 and June 2007	Mainly 10-min intervals and some 1-min intervals	Measurements of water demand at different taps	Measurements	Hot water output from the model is compared with this data set

In the main data set, TU-SCB-1996, the people are in between ten to 97 years old, and the households are composed of couples, singles etc. The settings of the households vary between rural and urban. The data set contains 431 persons in 169 households, and only activities performed at home are included. The ToU data are recorded at 5-min interval.

Using this model, behaviour data is simulated in MATLAB, with households containing a random number of occupants. The load profiles are constructed with the energy/water consumption parameters for each of the appliances, giving load profiles of both water consumption and electricity consumption for each unit in each of the households over a year. Only the water consumption from showers will be used in this thesis.

After the publication of the paper, the water consumption profiles have been updated. Showers are modelled with a constant flow rate of 10 l/min for 4 minutes.

4.4.3 Creating the Population of EWHs

The next step is now to create the aggregation of EWHs. The flow chart in Figure 4.3 illustrates how the SLM and the TEC model will be used to simulate an aggregation of EWHs.

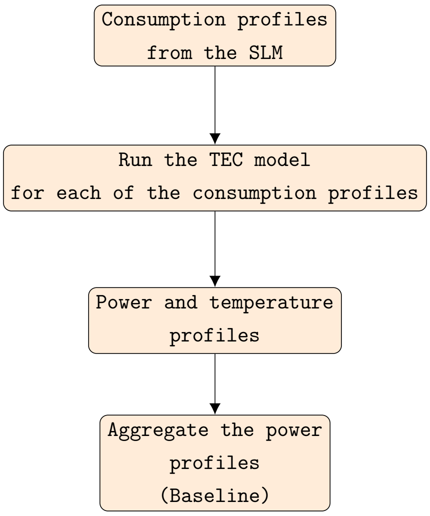

Figure 4.3: Flow chart illustrating how to generate the power and temperature profiles with the SLM, and then aggregate the power profiles

First, the consumption profiles will be made with the SLM. Since the population of EWHs will be small, the SLM is set to generate 12 consumption profiles. The reason for choosing exactly 12 EWHs is because a small population is wanted, and the data set, ElDeK, used for validation, contains measurements of 12 different EWHs. The 12 consumption profiles from SLM, generated for an arbitrary weekday, is presented in Figure 4.4, and the and the number of occupants in each household can be found in Table A.13. These 12 consumption profiles will be used throughout this thesis.

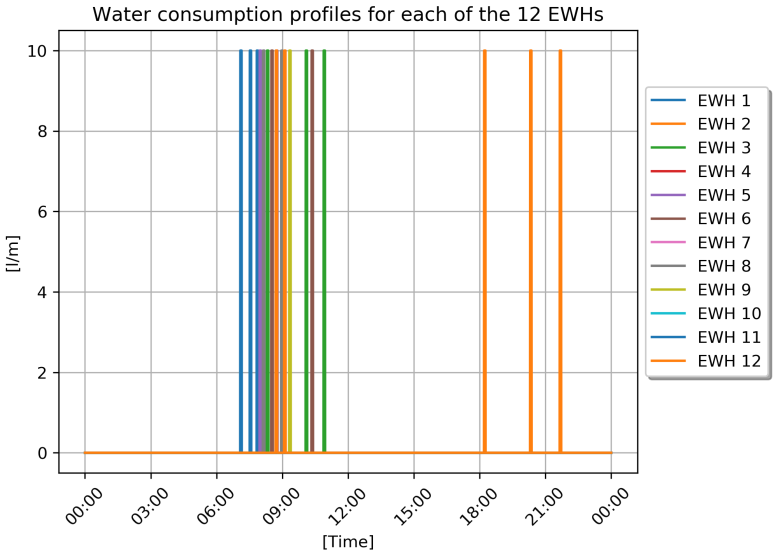

Figure 4.4: Water consumption for 12 EWH generated by the SLM. Each shower has a constant flow rate and duration of 4 minutes

The shower consumption profile from SLM contains both hot and cold water, while only hot water consumption is wanted in the EWH model. Since the hot water flow in the shower at the Smart House is already defined in the model, only the time of the events in the SLM profiles are needed. Hence, the showers are modelled with a constant hot water consumption of 4.4 l/min, as was calculated with Equation (4.5).

The EWHs used to simulate the power and temperature profiles are all equal, but the input data generated by the SLM provides differences in the power and temperature profiles due to the different numbers of occupants and the stochastic behaviour of the model. The start temperatures and the state of the EWH are chosen randomly. After running the TEC model with each of the water consumption profiles, the resulting power profiles are aggregated together, which will be referred to as the baseline.

4.4.4 ElDeK - Electricity Demand Knowledge

Having created a baseline of 12 EWHs, the next step is to validate this baseline against measurements. First, the measurement data set, ElDeK, is presented.

The purpose of the ElDeK project is to "increase the knowledge concerning the electricity demand for end-users such as household customers" [26]. The data set consists of power measurements from 12 different EWHs in Norway. The resolution of the measurements are at 1 minute intervals, and each EWH provides approximately two weeks of measurements. Table 4.6 gives an overview of the data set. The 12 power consumption profiles from ElDeK, chosen from the same weekday as the water consumption profiles from SLM, are aggregated and compared to the baseline.

Table 4.6: Overview of the ElDeK data set

Number of EWH	12
Rated power	1.5 - 3 kW
Household composition	Unknown
Year	2010-2012
Resolution	1 min interval
Days of measurements per EWH	23 - 34 days
Location	Norway

4.5 Estimating the Flexibility Potential of the Aggregated EWHs

To estimate the flexibility potential of the EWHs, two different control strategies are made, activity control and temperature control. These control strategies will be tested on the 12 EWHs, the first requiring knowledge about shower activities and second using the temperature of the tank. Four scenarios are made for the activity control, and two scenarios for the temperature control. Since a bottom up approach is used when generating the population of EWHs, is it possible to investigate the individual flexibility potential from each of the EWHs, as well as the combined flexibility potential.

Different scenarios will be made and the resulting power profile is compared to the baseline to estimate the flexibility potential of the 12 EWHs. The flexibility will be categorized based on three attributes presented in Table 4.7. Flexibility will be requested from 8-9 a.m. in all scenarios, aiming to reduce peak load.

Table 4.7: Flexibility attributes

Parameter	Unit	Description
P_{flex}	kW	The reduction in power by the EWH
E_{flex}	kWh	The reduction in consumed energy by the EWH
t_{flex}	min	The time providing flexibility
P_{tot}	kW	Reduction in maximum instantaneous power consumption
E_{tot}	kWh	The total reduction in consumed energy

In addition, the EWHs are categorized on whether they have been reserved or activated. If an EWH is controlled it is considered as reserved, and if it reduces or increases its consumption during the requested hour, it is considered as activated. This indicates what fee the flexibility operator has to pay for the flexibility, as discussed in Section 2.3.5.

4.5.1 Activity Control - Shower Activities

This control strategy uses the knowledge about when the showers happen to control the population of EWHs. Various scenarios are tested, with and without a reconnection strategy.

Scenario 1 - Turning off all the EWHs

In scenario 1, all the EWHs will be deactivated. After being disconnected for one hour, all the EWHs will be reconnected at the same time. The flow chart in Figure 4.5 shows how the control strategy works.

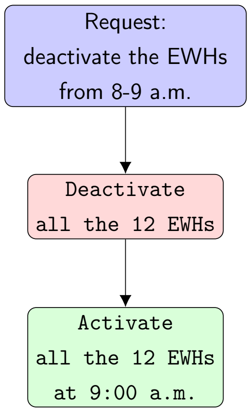

Figure 4.5: Flow chart illustrating the activity control strategy - scenario 1

Scenario 2 - Turning off the EWHs without Shower Activities

In the second scenario, only the EWHs without any shower activities during the requested hour is deactivated. The control strategy checks if there are any showers planned during the requested hour before disconnecting the EWHs. After being disconnected for one hour, all the disconnected EWHs are activated at the same time. Figure 4.6 shows the control strategy.

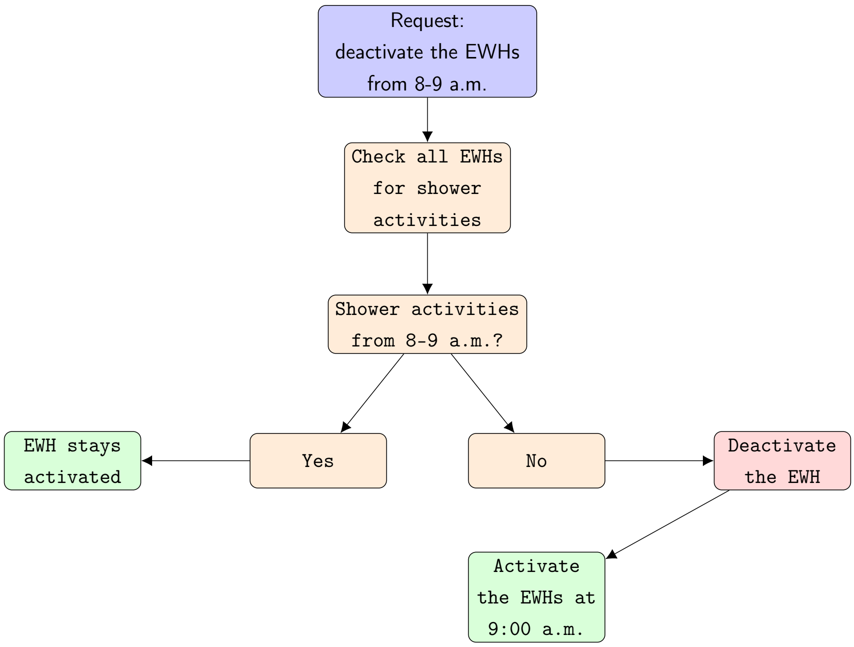

Figure 4.6: Flow chart illustrating the activity control strategy - scenario 2

Scenario 3 - Turning off the EWHs without Showers and using a Reconnection strategy

In scenario 3, a reconnection strategy is implemented when activating the EWHs. All EWHs that do not have shower during the request time are deactivated for one hour. The EWHs that have planned showers the hour after the deactivation are reconnected immediately, while the EWHs that do not have planned showers the hour after stay disconnected an additional 60-90 minutes. The reason for delaying the reconnection is to avoid new power peaks after having provided flexibility to the system. The flow chart in Figure 4.7 shows how the control strategy in scenario 2 is extended to include a reconnection strategy.

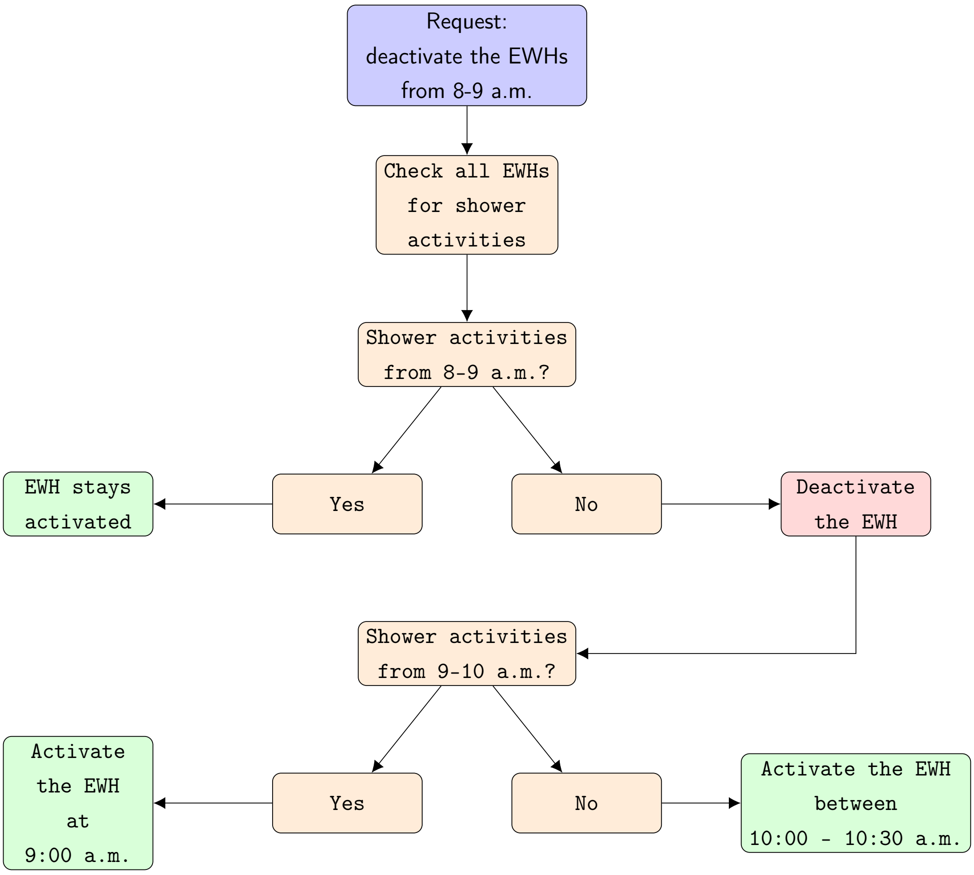

Figure 4.7: Flow chart illustrating the activity control and reconnection strategy - scenario 3

Scenario 4 - Turning off the EWHs without shower activities and having a extended reconnecting strategy

The reconnection strategy is further extended in scenario 4. The EWHs that have shower activities after the request time are reconnected at a random time stretching from 0-20 minutes after the requested hour. The EWHs that have showers within one hour after the requested hour stay disconnected for 30-50 minutes, while the EWHs that have showers two hours after the request stay disconnected for 60-90 minutes.

Figure 4.8 shows a flow chart of the control and reconnection strategy in scenario 4. The flow chart shows how each of the 12 EWH are monitored based on their shower activities and then reconnected accordingly. The activity control checks each of the EWH for planned shower activities and decides when the EWHs should be reconnected based on the activities.

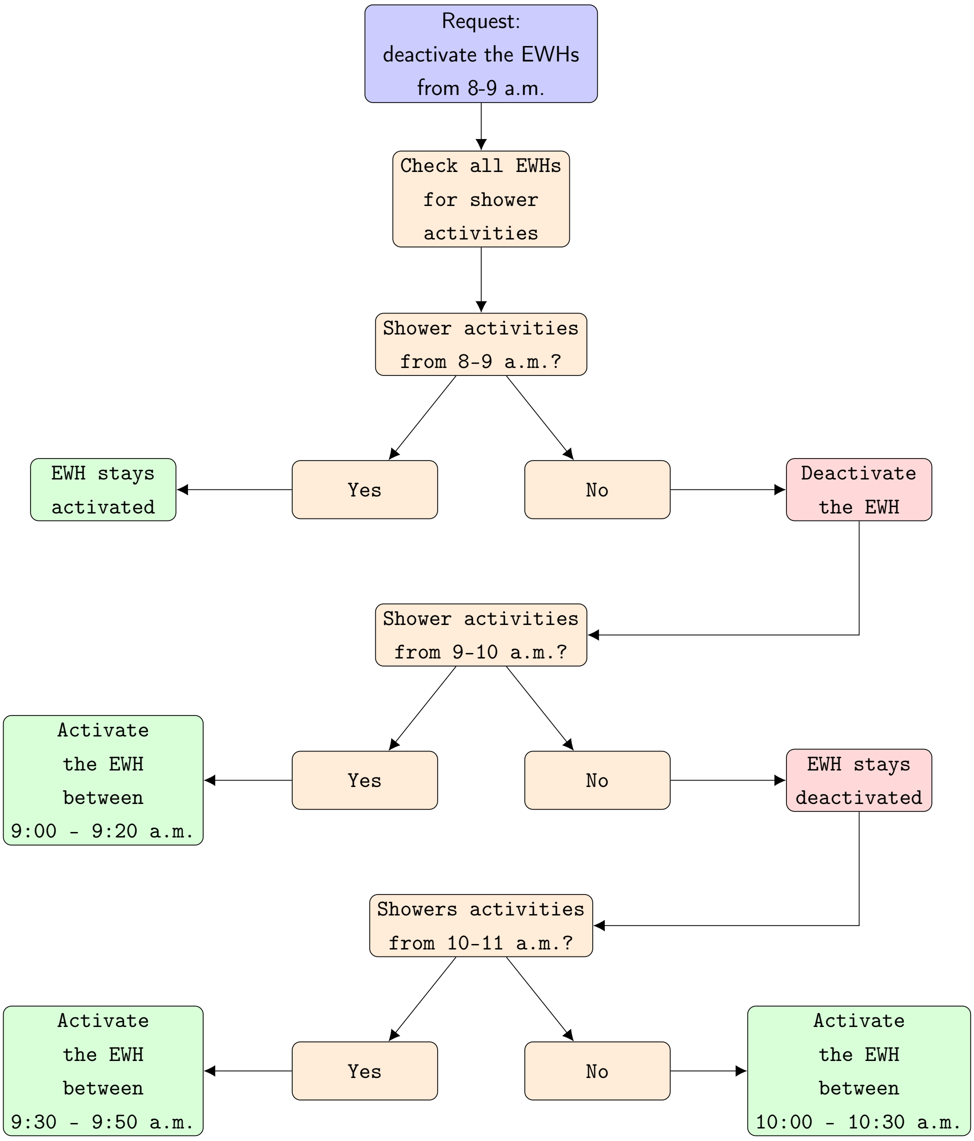

Figure 4.8: Flow chart illustrating the activity control and reconnection strategy - scenario 4

Overview of the scenarios with activity control

A summery of the different control and reconnection strategies of the EWHs is presented in Table 4.8.

Table 4.8: Control and reconnection strategies based on shower activities

Scenario	Duration of the request	Control strategy	Reconnection strategy
1	1 hour	Deactivating all the EWHs	None
2	1 hour	Deactivating the EWHs without planned showers	None
3	1 hour	Deactivating the EWHs without planned showers	Delay the reconnection for some of the EWHs with 1 hour based on the planned showers
4	1 hour	Deactivating the EWHs without planned showers	Reconnect the EWHs at different times, and delay the reconnection for some EWHs with 1-2 hours based on the planned showers

4.5.2 Temperature Control

A control strategy using the temperature of the tanks is implemented and tested with two different scenarios. Both of the scenarios have a reconnection strategy that ensures that no more than three EWHs are allowed to reconnect at the same time after the requested time for flexibility. To decide which EWHs are allowed to reconnect, the temperatures of the tanks are monitored and sorted from the coldest to the hottest, and the tanks with the lowest temperatures are allowed to heat first.

Scenario 1 - Turn off all EWHs and reconnection strategy

In the first scenario, all the EWHs are disconnected during the requested time. After the requested hour is over, the reconnection strategy starts. Three EWHs are allowed to reconnect at the same time, and the temperature of the tanks are sorted to find out which EWHs are coldest.

Scenario 2 - Limiting Power Consumption and Using a Reconnection Strategy

In the second scenario, it is possible to set a limit on power consumption during the requested hour. After the requested flexibility time, a reconnection strategy, equal to the one in scenario 1, starts. Only three EWHs are allowed to reconnect at the same time, and the tank with the coldest temperature are allowed to heating first. The reason for having a constraint on how many EWHs that can reconnect at the same time is for avoiding new power peaks when the EWHs are reconnected.

Overview of the Scenarios with Temperature Control

Section 4.5.2 provides an overview of the two scenarios tested with the temperature control.

Table 4.9: Control and reconnection strategies with temperature control

Scenario	Duration of the request	Control strategy	Reconnection strategy
1	1 hour	Deactivating all the EWHs	Reconnect no more than 3 EWH at the same time
2	1 hour	Set a limit on power consumption	Reconnect no more than 3 EWHs at the same time and activate the EWHs with the lowest temperature first

5 Results

5.1 Experiments at the Smart House

The experiments at the Smart House were redone because of the difference in the heating time and period discovered. Each of the experiment required a day to perform, so that the behaviour of the tank before and after the experiment could be monitored.

5.1.1 Experiment 1: Base Case

The temperature and power profiles of the EWH in steady-state is presented in Figure 5.1. No water was drawn from the tank.

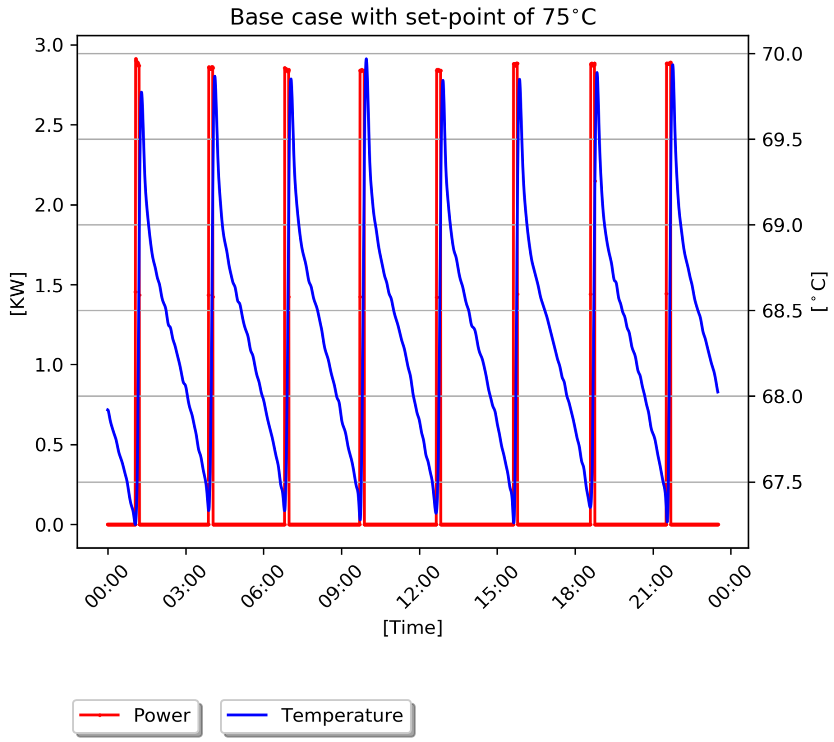

Figure 5.1: Temperature and power profile - experiment 1

The average heating time and period of the EWH is 9.5 and 175.2 minutes, respectively. Further, the average maximum and minimum temperatures are 69.9°C and 67.3°C, which is used as the deadband in the EWH models. The average power is measured to be 2.89 kW, and is used as the rated power of the heating element. Moreover, the average temperature in the bathroom this day was measured to be 24°C, which is used as the ambient temperature in the EWH models.

Table 5.1: Results of experiment 1: Base Case

Temperature	Value	Description
τ_{cycle}	175.25 min	Average period
t_{heat}	9.56 min	Average heating time
T_{max}	69.87°C	Average maximum temperature
T_{min}	67.25°C	Average minimum temperature
Q_h	2.89 kW	Average power
T_a	24°C	Ambient temperature

Comparing the parameters of autumn 2020 and spring 2021

The measurements at the Smart House in the specialization project [40] differed from the measurements at the Smart House done during spring 2021. In Table 5.2, the heating time and period in the specialization project, autumn 2020, are compared with the new measurements at the Smart House, spring 2021.

Table 5.2: Measurements from the Smart House: autumn 2020 vs spring 2021

Name	Autumn 2020	Spring 2021	Difference	Description
τ_{cycle}	195.65 min	175.25 min	10.88 %	The average period
t_{heat}	11.05 min	9.56 min	13.48 %	The average heating time
t_{heat}/τ_{cycle}	5.65 %	5.46 %	3.36 %	The fraction of time spent on heating

It can be observed that even though the heating time and period differed by 11% and 13 %, respectively, the EWH uses 5% of its period on heating in both the cases.

5.1.2 Experiment 2: 15 Minute Shower

Figure 5.2 shows the temperature and power measurements of the experiment with the 15 minute shower performed. The inlet temperature, measured in the sink, was 5.9°C, and the temperature of the outlet water in the shower was measured to be 40°C. The minimum temperature after the shower is 60.2°C, and the heating time right after the shower is 72 minutes.

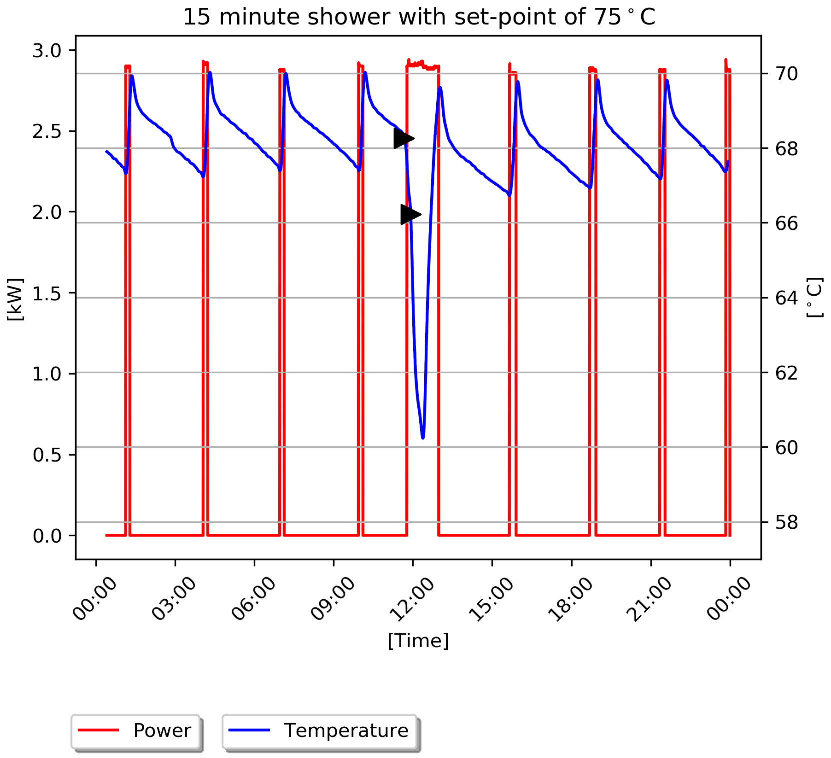

Figure 5.2: Temperature and power profile - 15 minute shower. Triangles indicate the start and end of the shower.

During the 15 minute shower the water flow rate is measured three times, and the results are shown in Table 5.3.

Table 5.3: Water consumption - 15 minute shower

Measurement	Time [m]	Water [L]	Water Consumption [l/min]
1	1.00	8.8	8.8
2	1.09	9.8	8.9
3	1.12	10.0	8.9

The shower uses on average 8.9 l/min of water, and the fraction of hot water is calculated with Equation (4.1). All the results obtained in this experiment is summarized in Section 5.1.2.

Table 5.4: Results of experiment 2: 15 minute shower

Temperature	Value	Description
T_{in}	5.9°C	Inlet water temperature
T_{out}	40°C	Outlet water temperature
$\dot{m}_{shower}$	8.9 kg/min	Mass flow
x_{hot}	0.49	Hot water fraction

5.1.3 Experiment 3: Ten Minute Shower

Figure 5.3 shows the result of the ten minute shower taken at the Smart House.

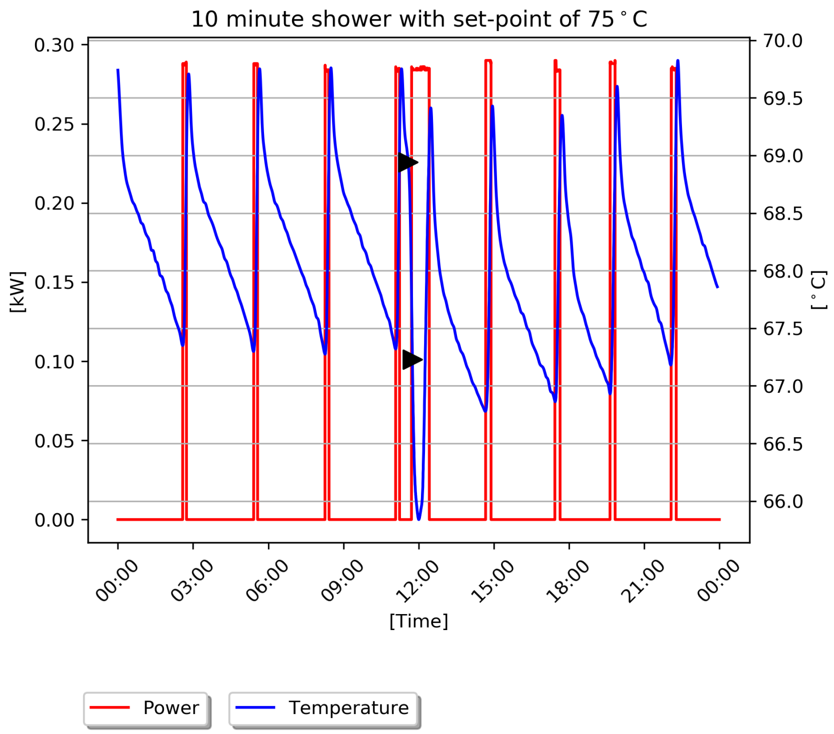

Figure 5.3: Temperature and power profile - experiment 3. The triangles indicate the start and stop of the shower.

The minimum temperature after the shower is right below 66°C, and it can be observed how the shower influences the temperature cycle afterwards. The EWH uses 42.3 minutes to heat the water after the shower.

5.1.4 Experiment 4: Deactivating EWH and Ten Minute Shower

The EWH is deactivated for four hours and a ten minute shower is taken in between. The minimum temperature is 60.1°C, and the maximum temperature right after the activation signal is remarkably lower than the maximum temperature at steady-state. The EWH uses 44.6 minutes to heat the water after getting the reconnection signal.

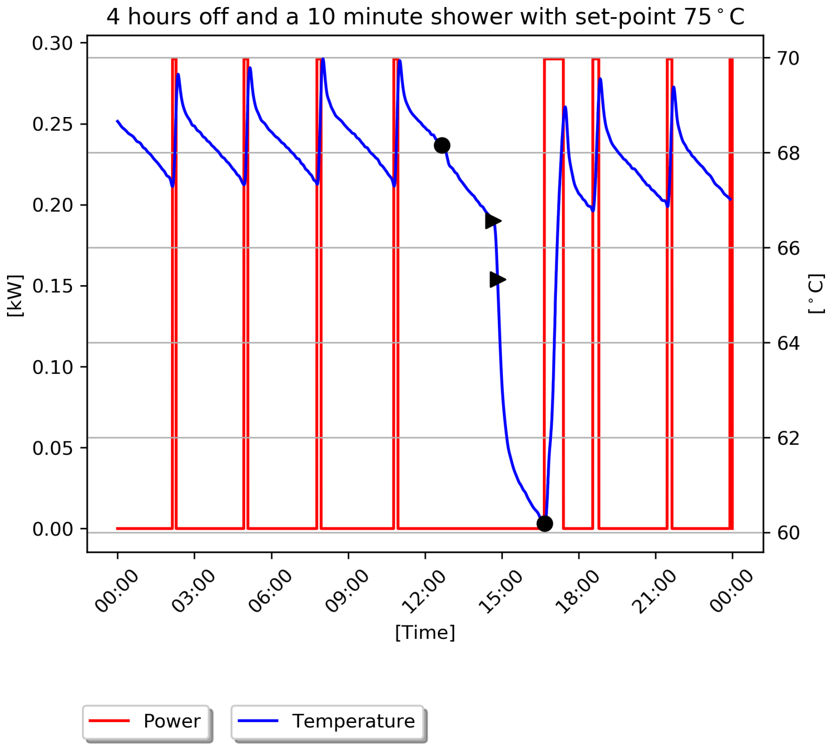

Figure 5.4: Temperature and power profile - experiment 4. The triangles indicate the start and stop of the shower. The circle indicate the deactivation and activation signal.

5.2 Electric Water Heater Modelling

5.2.1 Parameter Fitting of the TEC model

The results from the base case experiment is used to find the best suited values of the thermal resistance and the heat capacity in the TEC Model. The procedure of the optimization is described in Section 4.2.1 and the result is shown in Figure 5.5. It can be observed that for increasing values of R the period increases, and for increasing values of C the heating time increases. The red mark indicates the measured values for the period and heating time which is 175.2 minutes and 9.5 minutes respectively. Each blue dot is the resulting heating time and period of a pair of R and C. All values of R and C, and their resulting period and heating time, are presented in Table A.3

and Table A.4 in the Appendix.

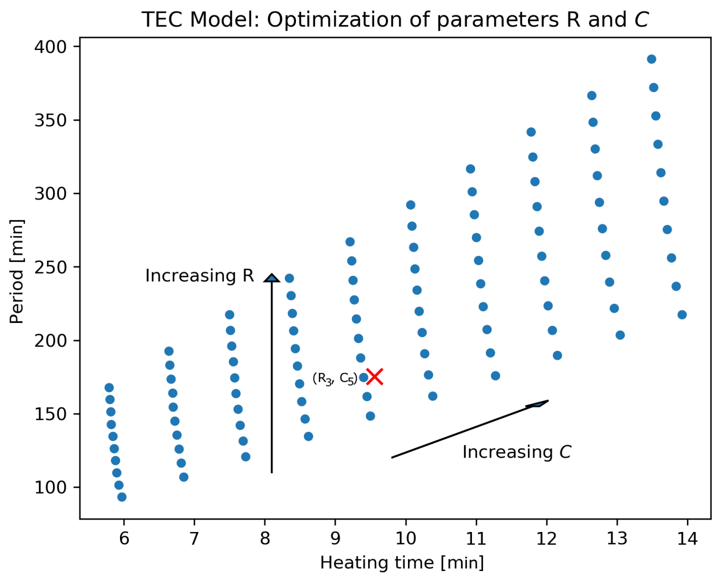

Figure 5.5: Result of the optimization for determining the optimal values of R and C. Each blue point represents the heating time and period of a pair of R and C. The red mark indicates the measured values of the heating time and the period based on the measurements from the base case.

The optimization provided a solution that gives a heating time of 9.5 minutes and period of 176.5 minutes, with R equal 286.6 $°C/kW$ and C equal 0,17 $kWh/°C$. These values will be used in the TEC model in this thesis. Figure 5.6 and Figure 5.7 show the TEC model compared with the measurements from the base case.

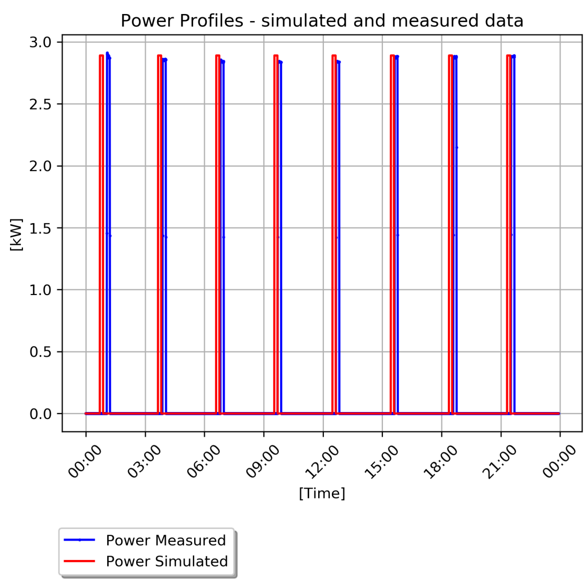

Figure 5.6: Power profiles of the simulated and measured data

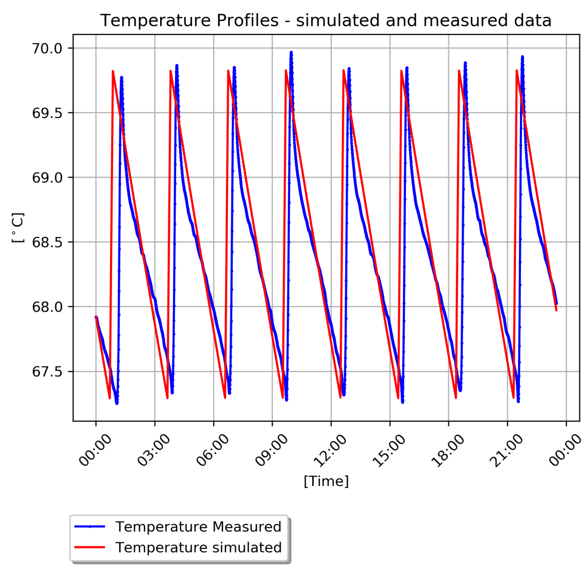

Figure 5.7: Temperature profiles of the simulated and measured data

5.2.2 Parameter Fitting of the Extended TEC Model

As described in the modelling section, three iterations have been performed with different ranges for the values of C, R, C_w and R_{iw}. The tables with the results are shown in Appendix A.2.2. The extended TEC Model does not seem to improve the power and temperature plots considerably. The variables C_w and R_{iw} seem to have very little impact on the result.

The simulation of the base case, along with the parameters from the optimization, can be found in the Appendix, Figure A.1 and Table A.9. The parameters chosen for the extended TEC model are highlighted in Table A.8 in the Appendix. The heating time and period of the extended TEC model are 176.4 minutes and 9.5 minutes, respectively, and matches well with the measurements from the Smart House. To better show the difference of the two EWH models, the base case of the extended TEC model and the simpler TEC model are plotted together in Figure 5.8. The initial conditions of the extended TEC model creates a delay, and therefore the model does not fit the measurements as well as the simpler TEC model.

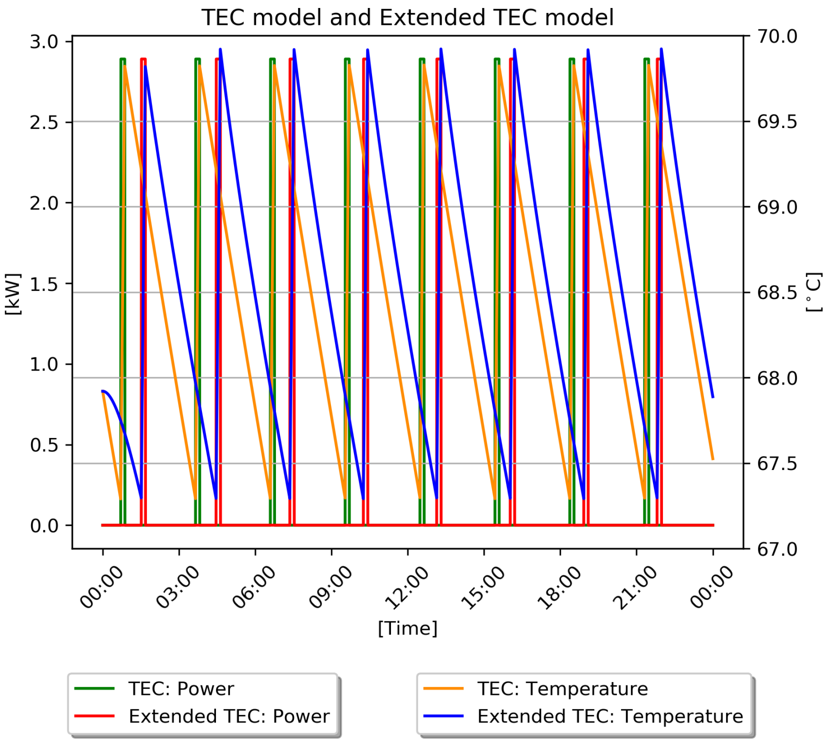

Figure 5.8: Comparing the temperature and power profiles of the TEC and extended TEC Models

5.2.3 Parameter Fitting of the Stratification Model

After trial and error, the thermal resistance and the heat capacity of the stratification model is determined and presented in Table A.11 in the Appendix. Section 5.1.1 shows the base case simulated with the stratification model.

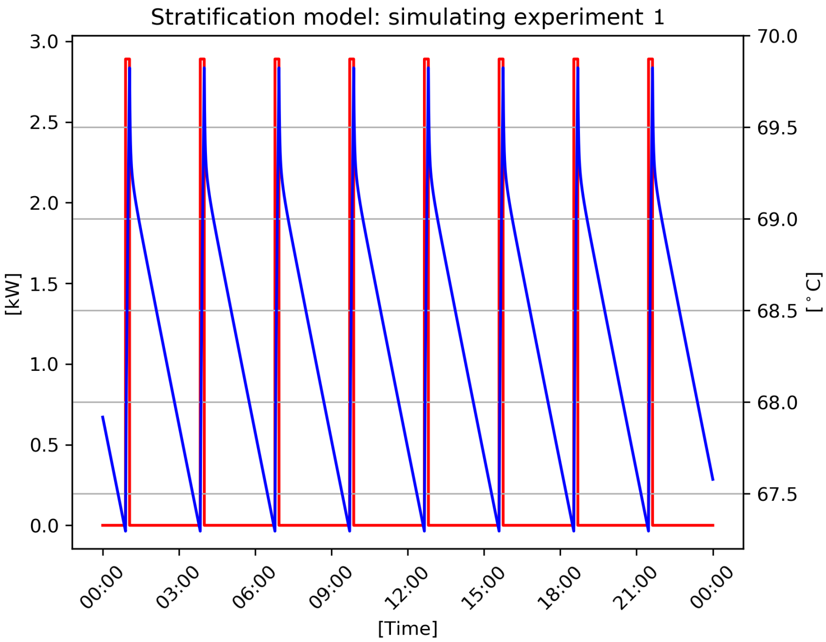

Figure 5.9: Stratification model simulating the temperature and power profile of the base case

The stratification model provides a profile with a period of 176.3 minutes and a heating time of 9.5 minutes, fitting very well with the measurements from the base case. The stratification model also simulates the same rapid decrease in temperature after heating as observed in the base case measurements. Nevertheless, the stratification model is very sensitive of the placement of the heating element and temperature sensor, shifting it by only one layer affects the temperature plots significantly.

5.3 Verification of the TEC Model

The TEC model is chosen as the model for simulating the temperature and power profiles of an EWH. The reason is because that it provides a satisfactory base case profile, and it has less uncertain parameters compared to the extended TEC model and stratification model. To test the accuracy of the model, all the experiment with shower events are simulated with the TEC model, and the power and temperature profiles are compared with the measurements from the Smart House.

5.3.1 TEC Model: Simulating Experiment 2 - 15 Minute Shower

Experiment 2 is simulated with the TEC model and compared with the measurements in Figure 5.10 and Figure 5.11.

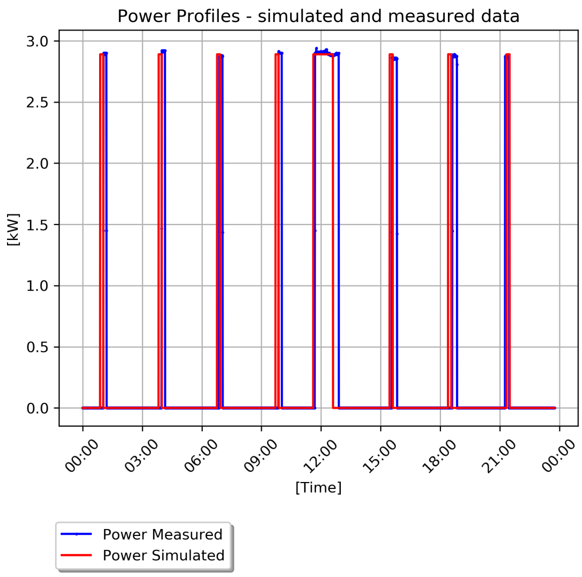

Figure 5.10: Power profiles of the simulated and measured data

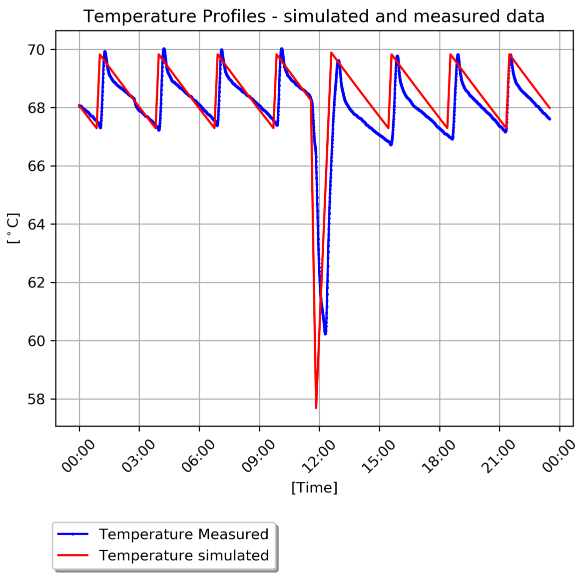

Figure 5.11: Temperature profiles of the simulated and measured data

The power profile of the TEC model fits well to the measurement data from the Smart House. Comparing the two minimum temperatures in Figure 5.11 gives a difference of 2°C, which is a great result. The trend of the temperature profile from the TEC model and the measured data correlates well before the shower, but the shower influences the measured temperature afterwards and the TEC model does not recreate this response. The simulated power profile is still quite accurate.

5.3.2 TEC Model: Simulating Experiment 3 - Ten Minute Shower

The comparison of the simulated and measured profiles for experiment 3 is shown in Figure 5.12 and Figure 5.13. It is seen that the simulated data lags the measured data and does not reach maximum temperature before the shower starts. This causes a mismatch between the simulated and measured data.

Regardless of this, the heating time after the showers matches well with the simulated and measured data. The minimum temperature after the shower is 5°C lower in the simulated data compared to the measured data.

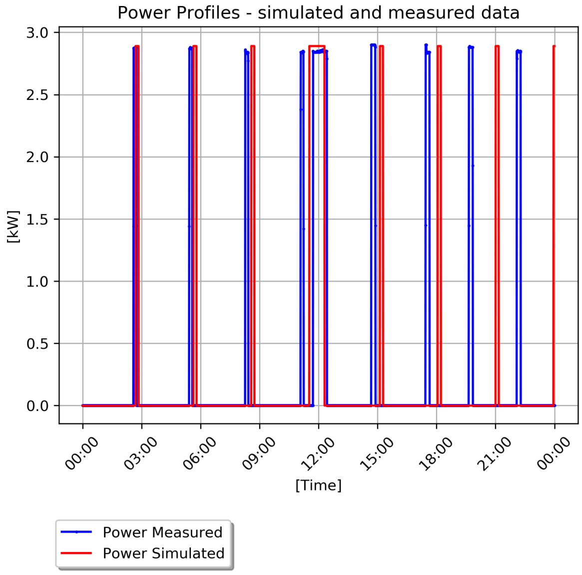

Figure 5.12: Power profiles of the simulated and measured data

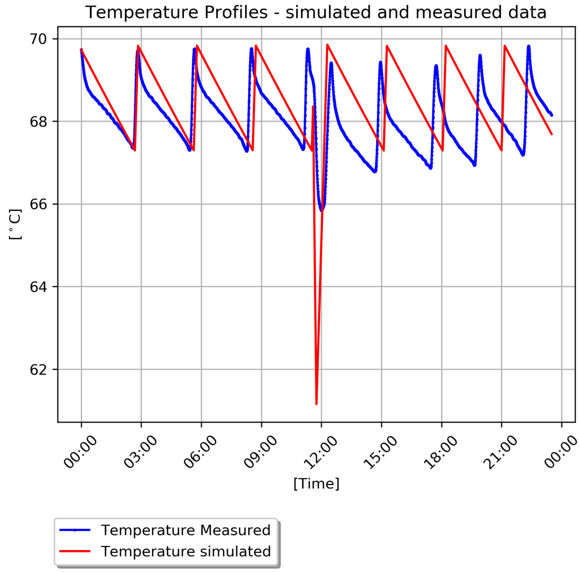

Figure 5.13: Temperature profiles of the simulated and measured data

5.3.3 TEC Model: Simulating Experiment 4 - Four Hours off and Ten Minute Shower

The initial temperature response does not match well between the simulated and measured profiles, as seen in Figure 5.15. However, the heating time after the reconnection of the EWH in Figure 5.14 matches well. The measured data does not heat back to maximum steady-state temperature after being deactivated for four hours, and this greatly affect the period afterwards. This response is not recreated by the TEC model. The minimum temperature during the deactivation time is 4°C lower in the simulated data compared to the measurements.

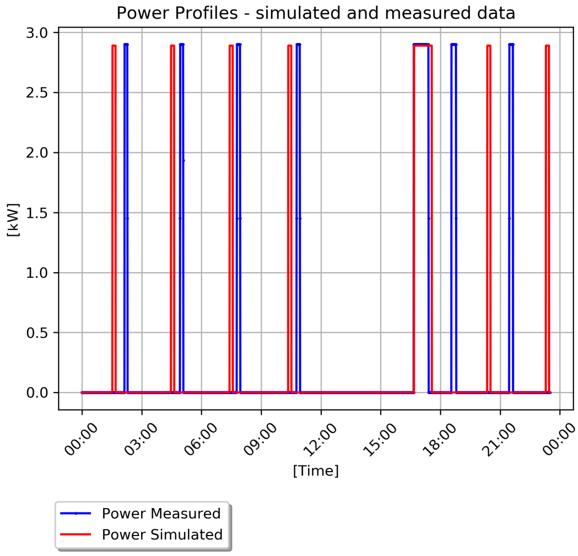

Figure 5.14: Power profiles of the simulated and measured data

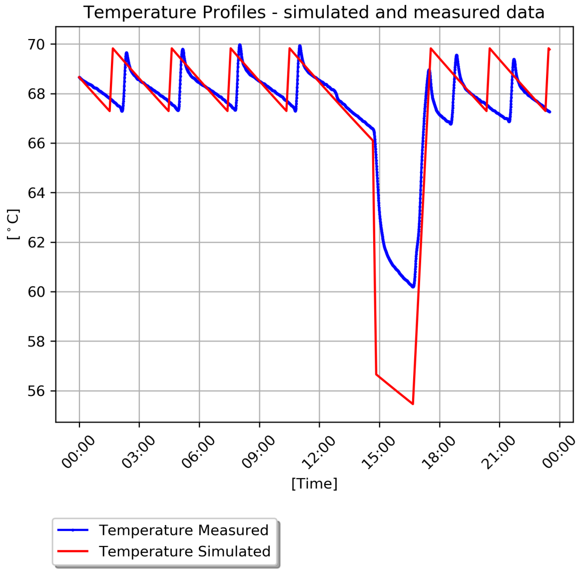

Figure 5.15: Temperature profiles of the simulated and measured data

5.4 Generating Power and Temperature Profiles with Consumption Data

After having chosen and verified the EWH model, this section presents the results of the aggregated population of EWHs.

5.5 Creating the Population of EWHs

Figure 5.16 shows the resulting temperature profiles of the 12 EWHs simulated with the TEC model using the consumption profiles from SLM.

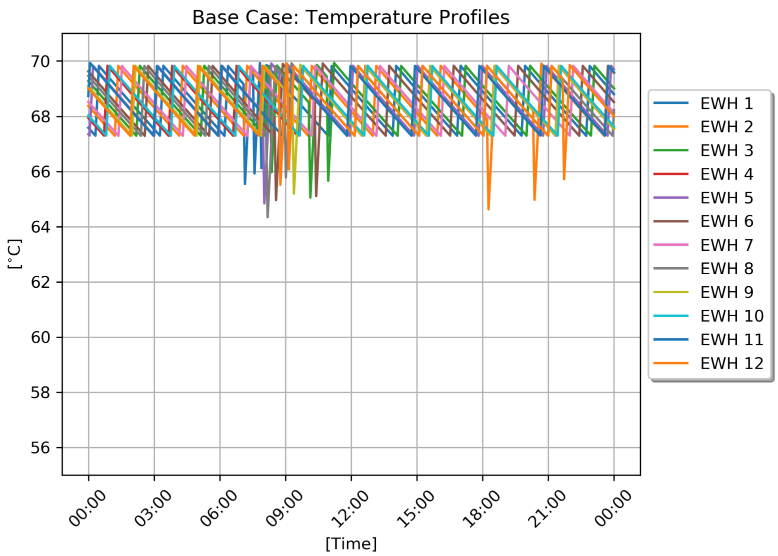

Figure 5.16: The temperature profiles of the population of 12 EWHs

The power profiles generated by the TEC model are added together to form the aggregated power profile, called the baseline, shown in Figure 5.17.

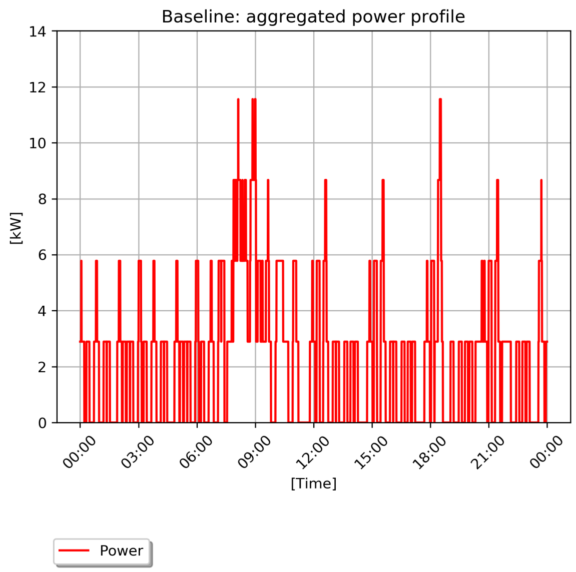

Figure 5.17: Aggregated power profile of 12 EWHs simulated with the SLM and TEC model

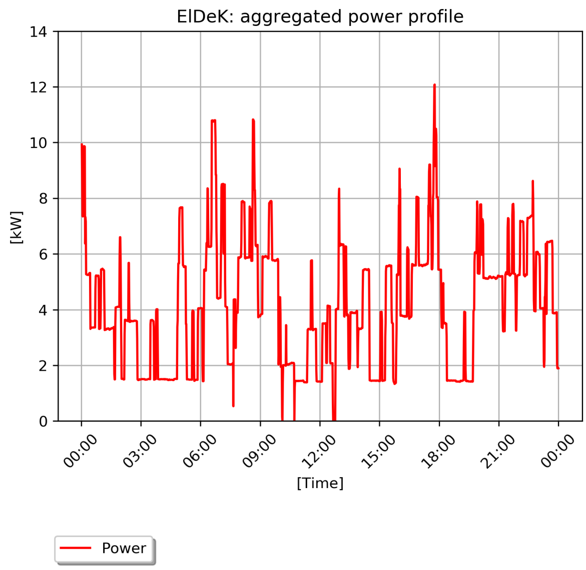

Figure 5.18: Aggregated power profile of 12 EWH from the ElDeK data set

Figure 5.18 presents the aggregated power profile of the 12 EWHs from the ElDeK data set. In the simulated profile, the highest power peaks of 11.6 kW can be found in between 7-10 a.m. and at 6 p.m., and the same morning and afternoon peaks can be observed in the measured data, with similar amplitudes.

5.6 Estimating the Flexibility Potential of the Aggregated EWHs

With the obtained baseline profile, the flexibility potential of the 12 EWHs can be estimated by using the two control strategies, activity and temperature control. As explained in the Chapter 4, *System Model and Methodology*, the requested flexibility hour is from 8-9 a.m. in all the scenarios, with the purpose of reducing the morning peak load.

5.6.1 Activity Control - Shower Activities

Energy Consumption in the Baseline - an Hourly Overview

Figure 5.19 shows the baseline obtained earlier, and Figure 5.20 presents the energy consumption in the baseline on an hourly basis. The red bars indicates the energy used by the EWHs to heat the water after showers, while the green bars are energy used on regular heating times. The purpose of indicating the energy use by the EWHs for showers and regular heating is to better illustrate how the activity control works.

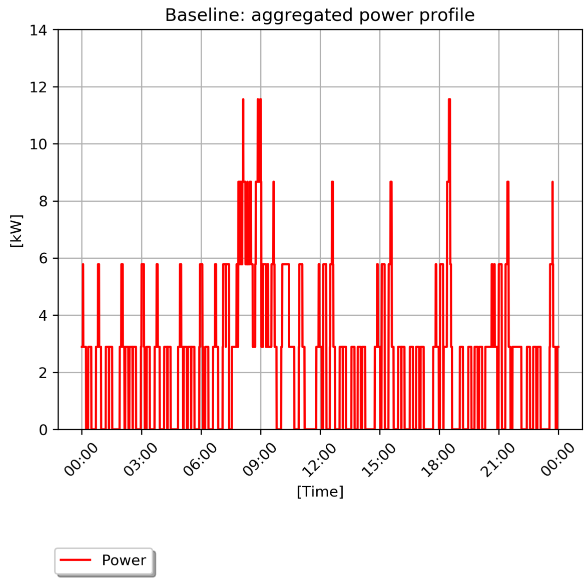

Figure 5.19: Baseline power profile of the 12 EWHs

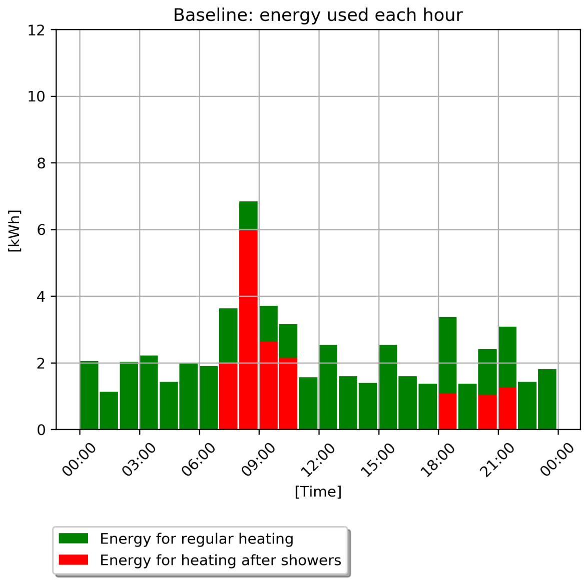

Figure 5.20: Energy per hour of the baseline power profile

Scenario 1 - Turning off all the EWHs

All EWHs are disconnected from 8-9 a.m., and Figure 5.21 and Figure 5.22 show the resulting power and energy profiles.

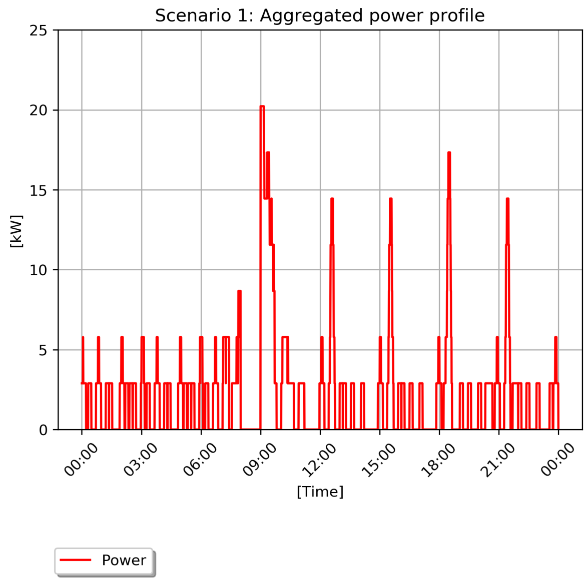

Figure 5.21: Activity Control - scenario 1, aggregated power profile

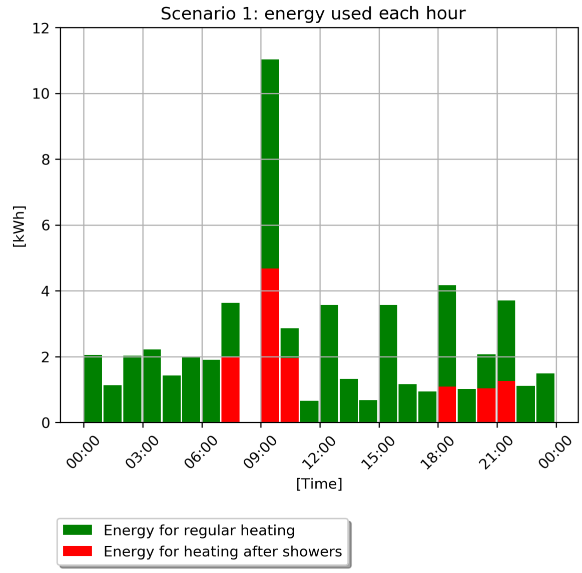

Figure 5.22: Activity Control - scenario 1, energy used each hour

The deactivation of the 12 EWHs during the requested hour causes a new instantaneous power peak of 20.2 kW at 9 a.m, corresponding to seven EWHs heating at the same time. There are also new additional peaks throughout the day of 14.5 kW and 17.3 kW, meaning that five and six EWHs are heating at the same time, respectively. The high power peaks is an unfortunate scenario. The energy consumption between 9-10 a.m. is much higher than the baseline, since all consumption was shifted to this hour.

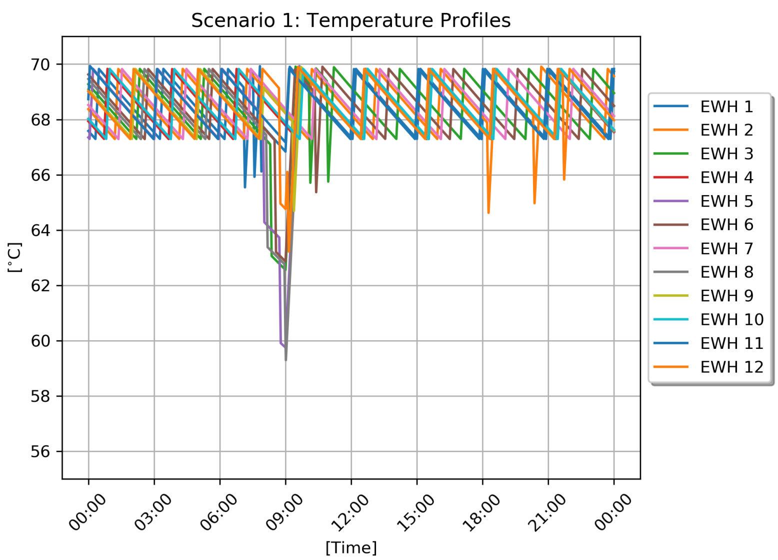

Figure 5.23: Temperature profiles of the 12 EWHs in scenario 1

Figure 5.23 shows the temperatures of the 12 EWHs. The temperature of EWH 5 and 8 drops down to around 60°C, because they have have shower activities while being deactivated.

Table 5.5 shows the amount of flexibility provided by the individual EWHs during the requested hour. The columns with reservation and activation fees illustrates how the consumer can been compensated for providing flexibility the requested hour in a hypothetical flexibility market. All the EWHs would receive a reservation fee, but only the EWHs reducing their consumption would also get an activation fee.

Table 5.5: The flexibility provided by the individual EWHs in scenario 1

EWH	**Power** (P_{flex})	**Energy** (E_{flex})	**Time** (t_{flex})	**Reservation fee**	**Activation fee**
1	2.89 kW	0.39 kW	60 min	✓	✓
2	0	0	60 min	✓	-
3	2.89 kW	1.23 kW	60 min	✓	✓
4	0	0	60 min	✓	-
5	2.89 kW	1.71 kWh	60 min	✓	✓
6	2.89 kW	1.20 kW	60 min	✓	✓
7	0	0	60 min	✓	-
8	2.89 kW	1.20 kWh	60 min	✓	✓
9	2.89 kW	0.12 kWh	60 min	✓	✓
10	0	0	60 min	✓	-
11	2.89 kW	0.41 kWh	60 min	✓	✓
12	2.89 kW	0.77 kWh	60 min	✓	✓

The aggregated population of EWHs have reduced the total power by 11.6 kW and the energy by 7 kWh during the requested hour, compared to the baseline, as presented in Table 5.6.

Table 5.6: The flexibility provided by the aggregated population of 12 EWHs in scenario 1

Number of EWHs	**Power** (P_{tot})	**Energy** (E_{tot})
12	11.56 kW	7.03 kWh

Scenario 2: Turning off the EWH without Shower Activities

In scenario 2, the EWHs that have shower activities during the requested hour stay active. Figure 5.24 and Figure 5.25 shows the aggregated power and energy profile, respectively.

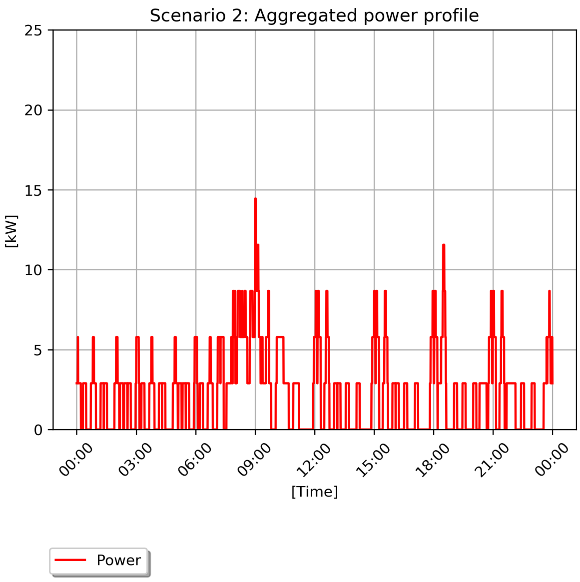

Figure 5.24: Activity Control - scenario 2, aggregated power profile

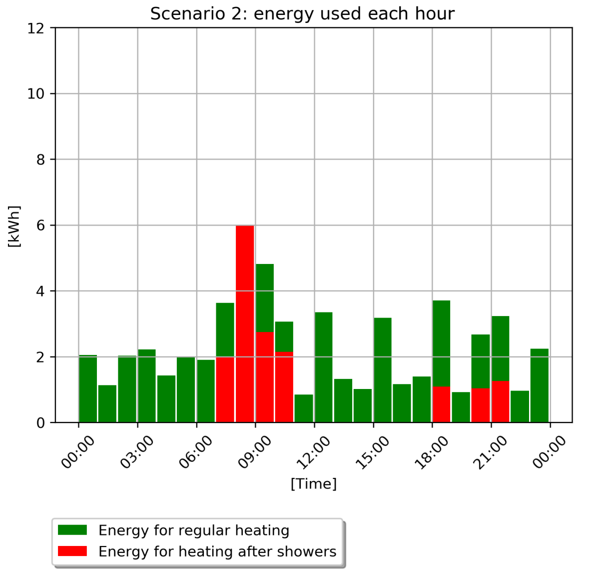

Figure 5.25: Activity Control - scenario 2, energy used each hour

The power peak at 9 a.m. is now much smaller, compared to scenario 1. In Figure 5.24 the new instantaneous power peak 14.5 kW, which is still larger than the maximum baseline power peak of 11.6 kW. Figure 5.25 shows the energy profile of scenario 2, and it is possible to see how only the EWHs without showers are shifted away from 8-9 a.m., leaving the red bars with shower activities.

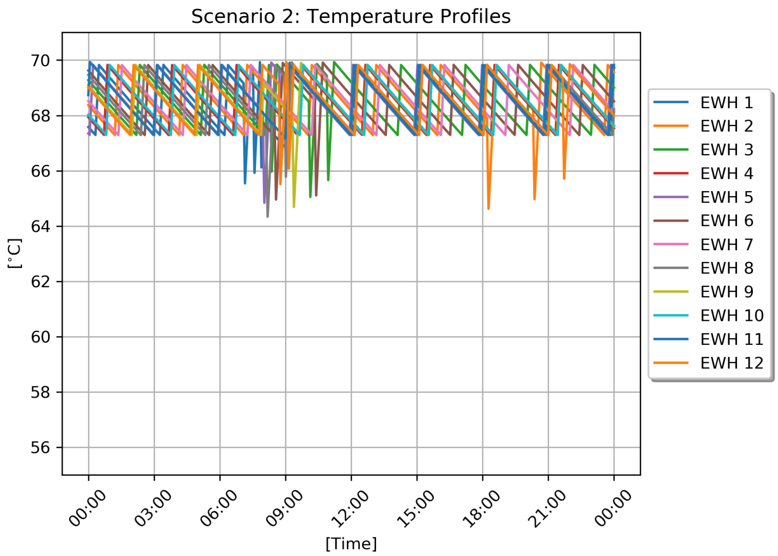

Figure 5.26: Temperature profiles of the 12 EWHs in scenario 2

Figure 5.26 shows how the temperature of EWH 5 and 8 are 4°C higher than in scenario 1, because they were active during the requested hour.

In Table 5.7 there are five EWHs that do not provide flexibility because they have shower activities scheduled the requested hour. These EWH are therefore not getting reservation or activation fees since they are not available for providing flexibility.

Table 5.7: The flexibility provided by the individual EWHs in scenario 2

EWH	**Power** (P_{flex})	**Energy** (E_{flex})	**Time** (t_{flex})	**Reservation fee**	**Activation fee**
1	2.89 kW	0.39 kW	60 min	✓	✓
2	0	0	60 min	✓	-
3	0	0	0	-	-
4	0	0	60 min	✓	-
5	0	0	0	-	-
6	0	0	0	-	-
7	0	0	60 min	✓	-
8	0	0	0	-	-
9	2.89 kW	0.12 kWh	60 min	✓	✓
10	0	0	60 min	✓	-
11	2.89 kW	0.41 kWh	60 min	✓	✓
12	0	0	0	-	-

The total energy shifted by the 12 EWH is 0.9 kWh, and the power peak in the requested hour is reduced with 2.89 kW compared to the baseline. This result is presented in Table 5.8.

Table 5.8: The flexibility provided by the aggregated population of 12 EWHs in scenario 2 from 8-9 a.m.

Number of EWHs	**Power** (P_{tot})	**Energy** (E_{tot})
12	2.89 kW	0.92 kWh

Scenario 3 - Turning off the EWHs without Showers and Using a Reconnecting Strategy

In scenario 3, only the EWHs without showers are deactivated from 8-9 a.m. For the purpose of avoiding new instantaneous power peaks, a reconnection strategy is used as presented in Section 4.5.1. The EWHs that do not have showers the following hour, after the requested time, stay deactivated for another 60-90 minutes.

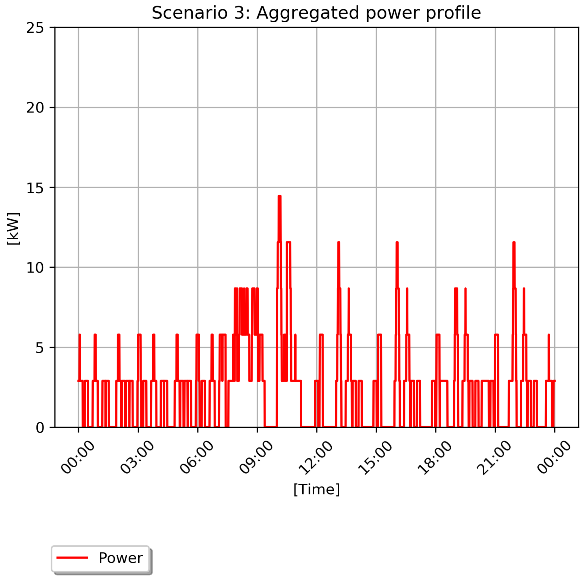

Figure 5.27: Activity Control - scenario 3, aggregated power profile

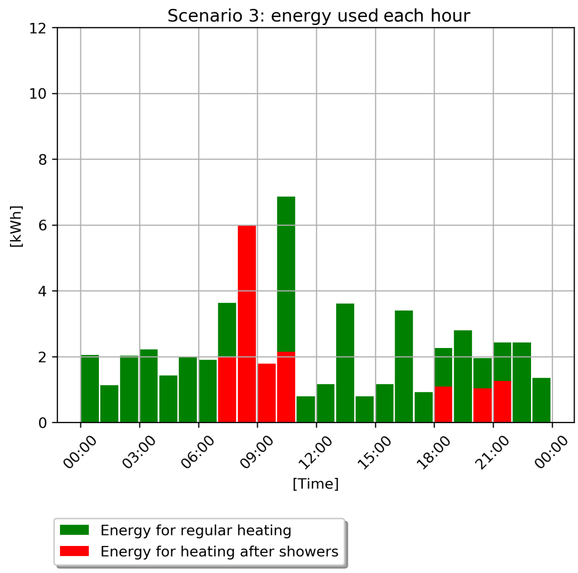

Figure 5.28: Activity Control - scenario 3, energy used each hour

In Figure 5.27, the power peak during the requested hour is reduced with 2.89 kW, and the instantaneous power peak at 9 a.m. is the same as in scenario 2, 11.6 kW. It seems like four EWH have started to synchronize after reconnection, since a periodic power peak of 11.6 kW can be seen in the plot. It is observed in the energy plot, Figure 5.28, that only the red bars are left from 8-10 a.m.

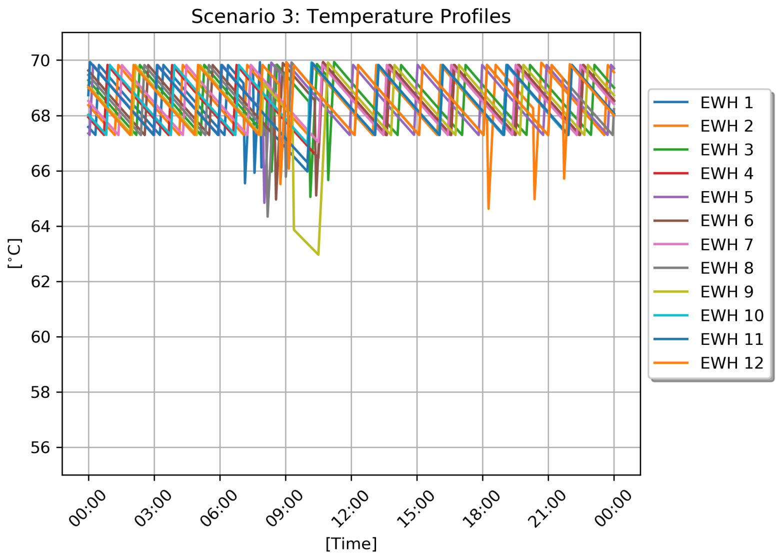

Figure 5.29: Temperature profiles of the 12 EWHs in scenario 3

Figure 5.29 shows the temperature profiles of the EWHs, and Table 5.9 presents an overview of the individual flexibility provided by the EWHs.

Table 5.9: The flexibility provided by the individual EWHs in scenario 3

EWH	**Power** (P_{flex})	**Energy** (E_{flex})	**Time** (t_{flex})	**Reservation fee**	**Activation fee**
1	2.89 kW	0.39 kW	60 min	✓	-
2	0	0	60 min	✓	-
3	0	0	0	-	-
4	0	0	60 min	✓	-
5	0	0	0	-	-
6	0	0	0	-	-
7	0	0	60 min	✓	-
8	0	0	0	-	-
9	2.89 kW	0.12 kWh	60 min	✓	✓
10	0	0	60 min	✓	-
11	2.89 kW	0.41 kWh	60 min	✓	✓
12	0	0	0	-	-

The aggregated flexibility is the same as in scenario 2. The biggest difference is that the power peak at 9 a.m. is less than in scenario 2, due to the reconnection strategy. The reconnection strategy causes new problems that needs to be addressed. Since the EWHs are controlled for an additional 60-90 minutes they provide additional flexibility that was not requested. The additional flexibility, lasting from 9 a.m. to 10:30 a.m., can be found in the Appendix, Table A.14.

Table 5.10: The flexibility provided by the aggregated population of 12 EWHs in scenario 3 from 8-9 a.m.

Number of EWHs	**Power** (P_{tot})	**Energy** (E_{tot})
12	2.89 kW	0.92 kWh

Scenario 4 - Turning off the EWHs without Shower Activities and Using an Extended Reconnecting Strategy

Figure 5.30 shows the resulting aggregated power profile with the extended reconnection strategy. The reconnection strategy are explained in detail in Section 4.5.1. Like in scenario 2 and 3 only the EWHs that do not have planed shower activities from 8-9 a.m. are deactivated. The power peak between 8-9 a.m. is reduced with 2.89 kW, and there is no instantaneous power peak when the reconnection starts at 9 a.m. The highest instantaneous power consumption is now the same as in the baseline. Figure 5.31 provides an overview of the energy each hour, and Figure 5.32 shows the 12 temperature profiles of the EWHs.

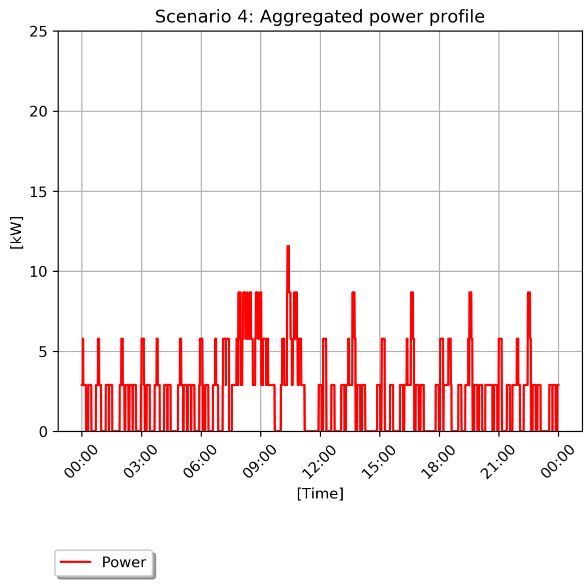

Figure 5.30: Activity Control - scenario 4, aggregated power profile

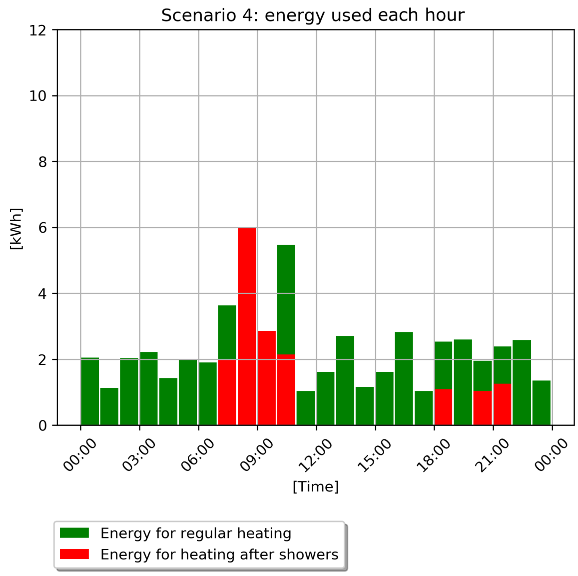

Figure 5.31: Activity Control - scenario 4, Energy used each hour

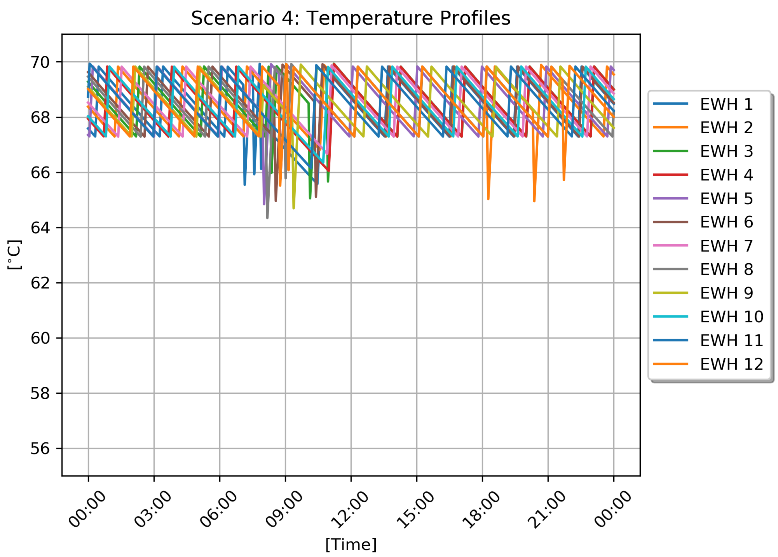

Figure 5.32: Temperature profiles of the 12 EWHs in scenario 4

The flexibility provided individually, Table 5.11 and aggregated, Table 5.12, are the same as in scenario 2 and 3. The differences between these cases can best be observed in the power profiles and the additional flexibility that the reconnection strategy causes, which is found in the Appendix, Table A.15.

Table 5.11: The flexibility provided by the individual EWH in scenario 4

EWH	**Power** (P_{flex})	**Energy** (E_{flex})	**Time** (t_{flex})	**Reservation fee**	**Activation fee**
1	2.89 kW	0.39 kW	60 min	✓	✓
2	0	0	60 min	✓	-
3	0	0	0	-	-
4	0	0	60 min	✓	-
5	0	0	0	-	-
6	0	0	0	-	-
7	0	0	60 min	✓	-
8	0	0	0	-	-
9	2.89 kW	0.12 kWh	60 min	✓	✓
10	0	0	60 min	✓	-
11	2.89 kW	0.41 kWh	60 min	✓	✓
12	0	0	0	-	-

Table 5.12: The flexibility provided by the aggregated population of 12 EWHs in scenario 4 from 8-9 a.m.

Number of EWHs	**Power** (P_{tot})	**Energy** (E_{tot})
12	2.89 kW	0.92 kWh

5.6.2 Temperature Control

Since the shower activities are not used to control the EWH in this control strategy there are no red bars in the energy plots.

Scenario 1 - Turning off all the EWHs and using a Reconnection Strategy

In the first scenario, all the EWHs are deactivated from 8-9 a.m. Then a reconnection strategy starts at 9 a.m. to avoid new power peaks. Three EWHs are allowed to heat at the same time, starting with the tanks with the lowest temperatures. Figure 5.33 presents the aggregated power profile from scenario 1.

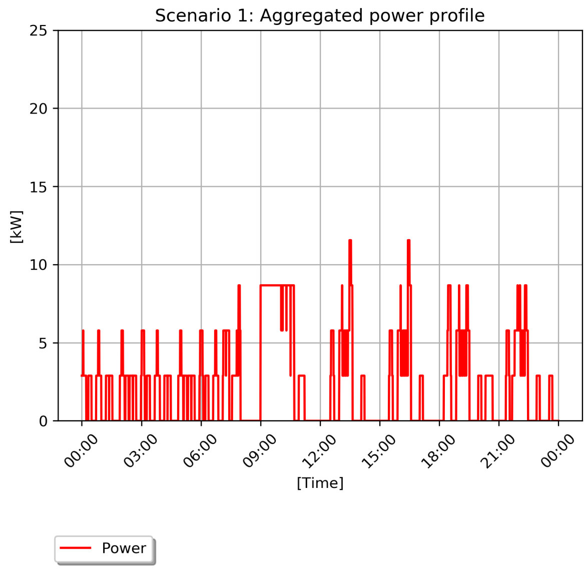

Figure 5.33: Temperature control - scenario 1, aggregated power profile

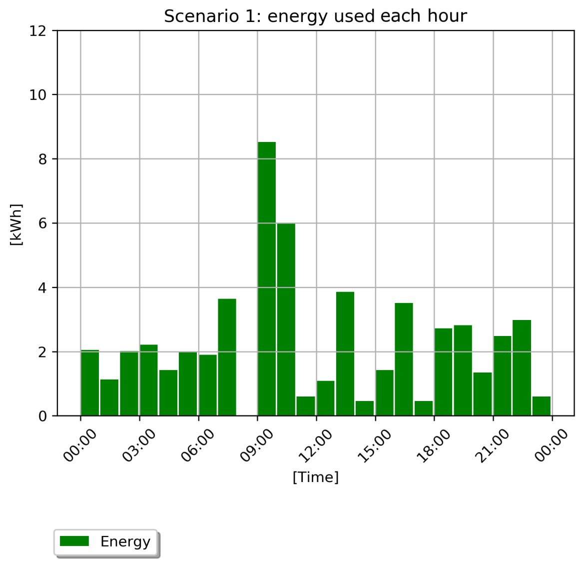

Figure 5.34: Temperature control - scenario 1, energy used each hour

After being deactivated for an hour, the reconnection strategy starts. Since three EWHs are heating at the same time until all the 12 EWHs have been reheated, a constant power consumption can be observed from 9-10:30 a.m. Some of the EWHs are synchronized after being controlled, but the effect is not as severe as in activity control - scenario 1. The temperature profiles of the 12 EWHs can be seen in Figure 5.35.

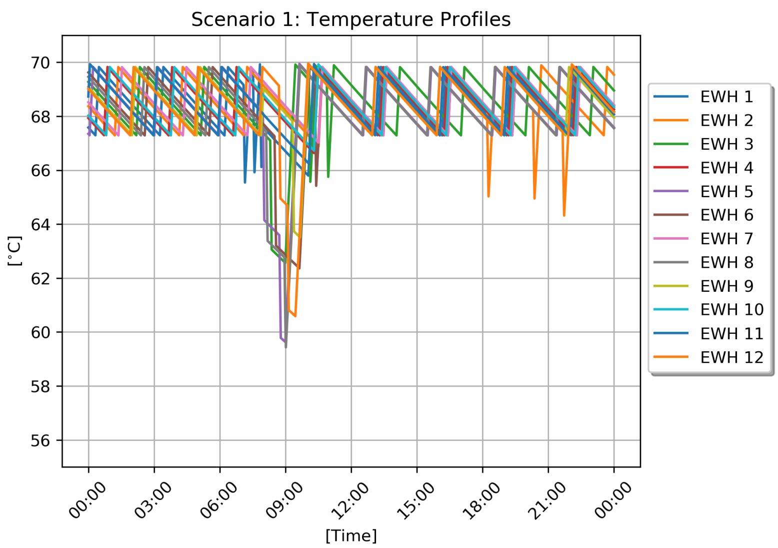

Figure 5.35: Temperature control, temperature profiles of the 12 EWHs, scenario 1

Table 5.13: Temperature control: flexibility from the individual EWHs in scenario 1

EWH	**Power** (P_{flex})	**Energy** (E_{flex})	**Time** (t_{flex})	**Reservation fee**	**Activation fee**
1	2.89 kW	0.39 kW	60 min	✓	✓
2	0	0	60 min	✓	-
3	2.89 kW	1.23 kWh	60 min	✓	✓
4	0	0	60 min	✓	-
5	2.89 kW	1.71 kWh	60 min	✓	✓
6	2.89 kW	1.20 kWh	60 min	✓	✓
7	0	0	60 min	✓	-
8	2.89 kW	1.20 kWh	60 min	✓	-
9	2.89 kW	0.12 kWh	60 min	✓	✓
10	0	0	60 min	✓	-
11	2.89 kW	0.41 kWh	60 min	✓	✓
12	2.89 kW	0.77 kWh	60 min	✓	✓

The individual and aggregated flexibility seen in Table 5.13 and Table 5.14 are the same as in activity control - scenario 1. The additional flexibility caused by the reconnection strategy is presented the Appendix, Table A.16.

Table 5.14: Temperature control: the flexibility provided by the aggregated population of 12 EWHs in scenario 1 from 8-9 a.m.

Number of EWHs	**Power** (P_{tot})	**Energy** (E_{tot})
12	2.89 kW	7.03 kWh

Scenario 2 - Limiting Power Consumption and Using a Reconnection Strategy

The last scenario considers a limit on the maximum power consumption allowed during the requested hour. The limit is set to 3 kW, meaning that only one EWH can be active at a time.

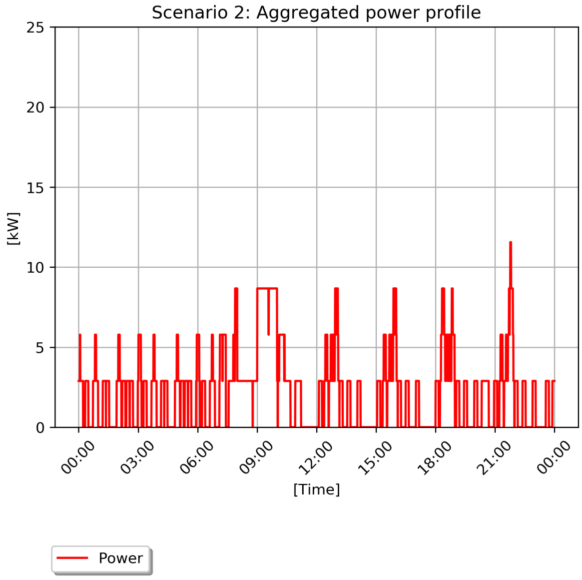

Figure 5.36: Temperature Control - scenario 2, aggregated power profile

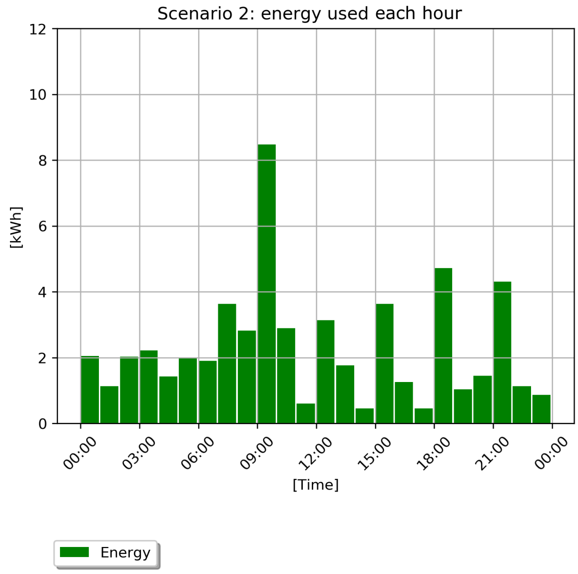

Figure 5.37: Temperature Control - scenario 2, energy used each hour

Figure 5.36 shows how the power peak from 8-9 a.m. is reduced to 8.7 kW. After providing the flexibility, the reconnection strategy allows three EWHs to heat at the same time, starting with the coldest tanks. Figure 5.38 shows the temperature for all the EWHs. The same synchronization problem is seen in this scenario, and the maximum instantaneous power peak is the same as in temperature control - scenario 1.

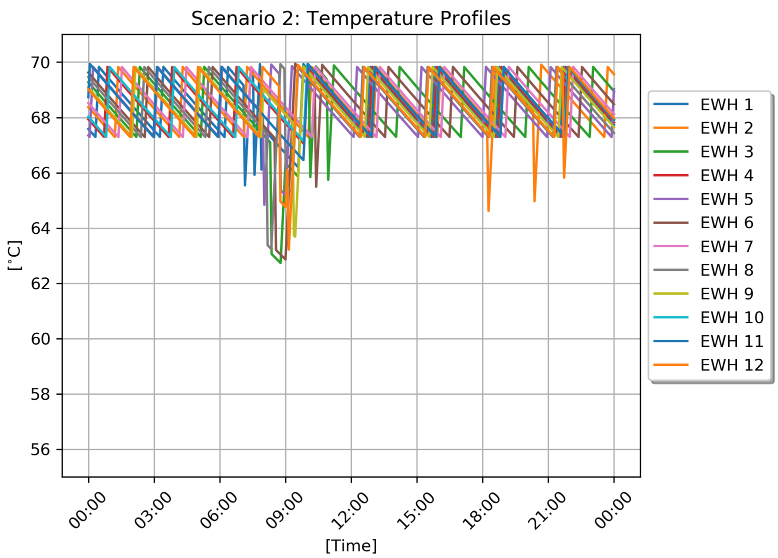

Figure 5.38: Temperature profiles in scenario 3 of the 12 EWHs

Table 5.15 presents the individual flexibility delivered by the 12 EWHs.

Table 5.15: Temperature control: flexibility from the individual EWHs in scenario 2

EWH	Power (P_{flex})	Energy (E_{flex})	Time (t_{flex})	Reservation fee	Activation fee
1	2.89 kW	0.39 kWh	60 min	✓	✓
2	0	0	60 min	✓	-
3	2.89 kW	0.60 kWh	60 min	✓	✓
4	0	0	60 min	✓	-
5	2.89 kW	0.67 kWh	60 min	✓	✓
6	2.89 kW	1.20 kWh	60 min	✓	✓
7	0	0	60 min	✓	-
8	0	0	60 min	✓	-
9	2.89 kW	0.12 kWh	60 min	✓	✓
10	0	0	60 min	✓	-
11	2.89 kW	0.41 kWh	60 min	✓	✓
12	2.89 kW	0.77 kWh	60 min	✓	✓

Further, the total aggregated flexibility can be seen in Table 5.16, where during the requested hour the total power and energy were reduced by 8.7 kW and 4.2 kWh, respectively. The additional flexibility caused by the reconnection strategy are presented in the Appendix, Table A.17..

Table 5.16: Temperature Control: the flexibility provided by the aggregated population of 12 EWHs in scenario 1 from 8-9 a.m.

Number of EWHs	Power (P_{tot})	Energy (E_{tot})
12	8.57 kW	4.16 kWh

6 Discussion and Further Work

6.1 Discussion

6.1.1 Experiments at the Smart House

The experiments preformed at the Smart House Autumn 2020 had to be redone due to the noticeable difference in period and heating time. When comparing the measurements done at the Smart house autumn 2020 and spring 2021, they differed in the period and the heating time by 10.9% and 13.5%, respectively, while the fraction of time spent on heating only differed by 3.4%. It would be interesting to check if this difference is due to seasonal changes. The measurements are done with no water withdrawal, so the inlet and outlet water temperature is not expected to have any impact on the heating time and period.

6.1.2 Electric Water Heater Modelling

The parameter fitting of the EWH models, with the experiments from the Smart House, showed some interesting results. The thermal resistance and heat capacity in the TEC model differ significantly compared to the calculated value of heat capacity, Equation (3.1), and the power loss stated in the data sheet, seen in Table 6.1. This is expected due to the assumption that the temperature in the tank is uniform.

Table 6.1: Comparison of modelled and calculated heat capacity and data sheet heat loss

	TEC model	**Calculated/Data Sheet Value**	**Difference**
Heat Capacity	171 Wh/°C	326 Wh/°C	48%
Heat loss	178 W	86 W	107%

The output of the three EWH models examined in this thesis all matched well with the measurements from the Smart House. The additional thermal resistance and heat capacity of the extended TEC model did not improve the simulation of the EWH noticeably, and when performing the parameter fitting the two additional parameters seemed to have little effect. The stratification model performed better at simulating the behaviour of the temperature, especially the rapid decrease after heating, but this model is very sensitive to the placement of the heating element and temperature sensor. Furthermore, the temperature is only verified at one point in the tank. Having more measurement points to verify against would help in the parameter fitting.

6.1.3 Verification of the TEC model

When simulating shower events, the temperature profile of the TEC model differed at most 5°C, or 8%, compared to the measurements, which is acceptable. The temperature response of the tank after shower events were not accurately captured by the model, due to the complex inner behaviour of the tank. Still, the TEC model captures the behaviour of the tank well enough for the purpose of this thesis.

6.1.4 Generating Power and Temperature Profiles with Hot Water Consumption Data

Behaviour models have shown to be a good way of estimating the power profile of an EWH, since the power used by the EWH is closely related to the hot water consumption activities. The Stochastic Load Model (SLM), used as input data when generating the population of EWHs, has Swedish ToU data from 1996. The method used to collect the data is diary entries, where the participants had to write down their own activities every day. The data is old, and the method may be prone to errors, but the data has been verified using numerous other more recent sources. Still, there might be differences between Norwegians and Swedes when it comes to shower habits. A survey conducted in Norway found that 70% of Norwegians use more than 5 minutes in the shower, while SLM uses a duration of only 4 minutes [42]. Having access to Norwegian hot water consumption data could have improved the results.

The aggregated power profile of the EWHs have been compared with the measurements in ElDeK data set. The general morning and afternoon power peaks in the simulation correspond well with the measurements of the 12 EWHs in the data set, and also the maximum peak differ by only 3.7%. The amplitudes of the other peaks also matches reasonably well. The general trend in the simulated data set differ from the measured data, and the cause of this might be because the ElDeK data sets consists of different types of EWHs and also contains the total usage of hot water in the households. Nevertheless, the proposed model performed very well considering the fact that old Swedish data had to be used.

6.1.5 Estimating the Flexibility Potential of the Aggregated EWHs

The result from exploring the flexibility potential showed that there is a large potential in load shifting with the EWHs. The temperature of the tanks, in all scenarios, stayed above 59°C, showing that user comfort has not been affected. A total of 7 kWh used between 8-9 a.m. has been successfully shifted to a later time, without increasing the maximum instantaneous power consumption.

There are large differences in the flexibility provided by each individual EWH. In activity control - scenario 1, four EWHs contribute with 76% of the total flexibility. The same is observed in the temperature control - scenario 1. The differences are mainly due to the fact that these EWHs have more shower activities during the requested hour. This explains why the more advanced activity control strategies, which excludes EWHs with shower events, are less efficient in load shifting compared to the temperature control strategies. The temperature control strategy should be preferred over the activity control, shifting the same amount of load as activity control - scenario 1, but with far smaller instantaneous power consumption after reconnection.

The reconnection strategies proved to be able to reduce the power peaks, compared to the scenarios without it. Regardless, there is a clear effect of synchronization of the EWHs after being reconnected, but this is likely exaggerated due to the EWHs all being identical. There is still a downside with the reconnection strategies, as they all require the EWHs to be controlled for a longer time. This could cause higher costs for the system operator. Ideally, the additional flexibility provided during the reconnection time can still be useful by the system operator.

Another cost increasing factor, due to the control methods presented in this thesis, is paying a reservation fee for EWHs that are not active during the requested time. The control strategy could be improved to avoid reserving EWHs with no effect on the load shifting.

The control strategies are based on knowing the water consumption profiles, which in reality need to be predicted. Imprecision in the predicted hot water consumption will consequently lead to imprecision in the predicted flexibility potential, and potentially affect user comfort. The temperature control strategy is less affected since this strategy can control on real-time temperature measurements, if available. The activity control is highly correlated to the use of hot water, so a good prediction is a requirement for this control to work.

The last scenario is constructed in such a way that it is only possible to request a limit on power consumption, instead of an amount of energy shifted. The proposed control strategies are not developed for meeting a specific flexibility demand such as providing 5 kWh of flexibility from 8-9 am. The control strategies could be improved by being able to request an amount of flexibility and then start by disconnecting the active EWHs with the highest temperature.

6.2 Recommendations for Further Work

The recommendations for further work are based on the discussion in Chapter 6 and the simplifications and assumptions done in the thesis.

- **Investigate if there are seasonal effects on the EWHs:** The change in heating time and period is quite large. It would be interesting to check if this is due to some seasonal effects.

- **Improve the EWH model:** If the placement of the temperature sensor and heating element of the EWH at the Smart House could be established, it would be interesting to check whether the stratification model performs better in terms of capturing the behaviours after showers.

- **Make a population of different types of EWHs:** The proposed one mass model can be generalized and used to simulate a variety of different EWHs, possibly avoiding the synchronization problem.

- **Model Norwegian hot water consumption:** Large discrepancies have been found between shower behaviour in the stochastic load model and Norwegian statistics, highlighting the need for Norwegian domestic hot water consumption data.

- **Further develop the control and reconnection strategies:** The control strategy can be improved by requesting an amount of flexibility rather than a number of EWHs, starting with disconnecting the active tanks with the highest temperatures.

7 Conclusion

In this thesis, the flexibility potential of a small population of EWHs has been investigated, both at an individual and aggregated level, with the use of an EWH model combined with two different control strategies through various scenarios.

After having investigated the different EWH models, the TEC model was determined to be the best suited for estimating the flexibility potential of the aggregation of EWHs, fitting the measurement data well. The temperature simulated with the TEC model differed at most 8% compared to the measurements from the Smart House.

The aggregated power profile of the population of EWHs corresponded well with the measurements from the ElDeK data set, despite the lack of Norwegian hot water consumption data. Morning and afternoon peaks were observed in both the power profiles, and moreover, the maximum peak differed by only 3.7%.

In the estimation of the flexibility potential, the overall result showed that the EWHs performed great for load shifting. The total load of 7 kWh during one hour was shifted to a later time, without causing higher power consumption peaks. A problem of synchronization of the EWHs was noticed, likely due to the EWHs being identical. Still, the proposed strategy for reconnecting the EWHs performed well.

The temperature control strategy performs better than the activity control as it can offer more flexibility with smaller power peaks after reconnection, compared to the activity control strategies. This control method is also less sensitive to errors in hot water consumption predictions since it can control based on real-time temperature measurements.

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A Appendix

A.1 Experiments at the Smart House

A.1.1 Characteristics of the EWH at the Smart House - Autumn 2020

The characteristics were obtained through the specialisation project preformed autumn 2020 [40], and further information regarding the parameters can be found there.

Table A.1 shows the characteristics of the EWH at the Smart House with a set-point temperature of 75°C.

Table A.1: The characteristics of the EWH with set-point of 75°C

	E_{heat} [kWh]	t_{heat} [min]	τ_{cycle} [min]	T_{up} [$°C$]	T_{down} [$°C$]	T_{min} [$°C$]	T_{max} [$°C$]	T_{up}/t_{heat} [$°C/min$]	T_{down}/t_{cool} [$°C/min$]	t_{heat}/τ_{cycle} [%]
Base case	0.529	11.052	195.645	2.818	2.826	66.423	69.475	0.255	0.015	5.649
Case 1: 1 hour	0.653	13.567	209.150	3.173	3.341	67.160	70.501	0.234	0.017	6.487
Case 1: 2 hours	0.824	17.283	186.833	4.354	2.728	66.709	69.437	0.252	0.016	9.251
Case 1: 4 hours	1.010	21.333	183.217	5.338	2.879	66.496	69.375	0.250	0.018	11.644
Case 2: ten-min shower water heater: on	2.102	44.317	226.300	2.719	2.914	66.030	68.943	0.061	0.016	19.583
Case 2: ten-min shower water heater: off	2.612	54.767	208.200	5.846	2.996	66.058	69.054	0.107	0.020	26.305
Case 3: five-min shower	0.784	16.083	201.567	2.774	3.053	66.072	69.125	0.172	0.016	7.979

Table A.2 shows the characteristics of the EWH at the Smart House with a set-point temperature of 85°C.

Table A.2: The characteristics of the EWH with set-point of 85°C

	E_{heat} [kWh]	t_{heat} [min]	τ_{cycle} [min]	T_{up} [°C]	T_{down} [°C]	T_{min} [°C]	T_{max} [°C]	T_{up}/t_{heat} [°C/min]	T_{down}/t_{cool} [°C/min]	t_{heat}/τ_{cycle} [%]
Base case	1.299	26.946	376.567	6.129	6.141	75.685	81.960	0.227	0.018	7.156
Case 1: 1 hour	1.390	29.550	362.033	6.645	6.427	75.945	82.372	0.225	0.019	8.162
Case 1: 2 hours	1.339	27.850	405.217	6.179	6.174	75.764	81.939	0.222	0.016	6.873
Case 1: 4 hours	1.268	26.783	416.533	6.419	6.582	76.628	83.106	0.240	0.017	6.430
Case 2: ten-min shower water heater: on	3.346	70.333	409.350	6.608	5.592	77.110	82.702	0.094	0.016	17.182
Case 2: ten-min shower water heater: off	3.043	63.950	392.933	6.231	5.542	77.039	82.581	0.097	0.017	16.275
Case 3: five-min shower	1.655	34.633	288.950	6.393	5.361	76.780	82.160	0.185	0.021	11.986

A.2 Electric Water Heater Modelling

A.2.1 Parameter Fitting of the TEC Model

In Table A.3 and Table A.4, the units of R and C are given in ° C/kW and ° kWmin/° C, respectively, while the periods and heating times are given in minutes.

Table A.3: Values of R and C and their corresponding period

C \ R	240.73	263.66	286.58	309.51	332.44	355.36	378.29	401.22	424.14	447.07
6.44	93.25	101.45	109.72	118.09	126.41	134.66	142.86	151.26	159.63	167.96
7.4	107.00	116.51	126.08	135.56	144.96	154.49	164.21	173.65	183.02	192.63
8.35	120.75	131.56	142.25	153.04	163.72	174.56	185.32	196.03	206.69	217.57
9.31	134.65	146.61	158.44	170.51	182.49	194.39	206.44	218.43	230.36	242.23
10.26	148.40	161.67	174.80	187.99	201.25	214.44	227.55	240.82	254.03	267.18
11.22	162.15	176.56	190.98	205.45	219.81	234.28	248.66	263.21	277.69	292.13
12.17	176.04	191.62	207.34	222.93	238.58	254.34	270.01	285.60	301.10	316.79
13.13	189.79	206.67	223.52	240.40	257.34	274.17	291.12	307.98	324.76	341.73
14.08	203.69	221.72	239.70	257.87	275.90	294.01	312.23	330.37	348.43	366.68
15.04	217.43	236.78	256.06	275.35	294.66	314.06	333.34	352.77	372.10	391.35

Table A.4: Values of R and C and their corresponding heating time

C \ R	240.73	263.66	286.58	309.51	332.44	355.36	378.29	401.22	424.14	447.07
6.44	5.97	5.93	5.90	5.88	5.86	5.84	5.82	5.81	5.80	5.79
7.4	6.85	6.81	6.78	6.75	6.72	6.70	6.69	6.67	6.65	6.64
8.35	7.73	7.69	7.65	7.62	7.59	7.57	7.55	7.53	7.51	7.50
9.31	8.62	8.57	8.52	8.49	8.46	8.43	8.41	8.39	8.37	8.35
10.26	9.50	9.45	9.40	9.36	9.33	9.30	9.27	9.25	9.23	9.21
11.22	10.38	10.32	10.27	10.23	10.19	10.16	10.13	10.11	10.09	10.07
12.17	11.27	11.20	11.15	11.10	11.06	11.03	11.00	10.97	10.94	10.92
13.13	12.15	12.08	12.02	11.97	11.93	11.89	11.86	11.83	11.80	11.78
14.08	13.04	12.96	12.89	12.84	12.79	12.75	12.72	12.69	12.66	12.64
15.04	13.92	13.84	13.77	13.71	13.66	13.62	13.58	13.55	13.52	13.49

Table A.5 the resulting thermal resistance and heat capacity of the optimization of the TEC model.

Table A.5: The values of R and C, from the optimization, used in the TEC model

Parameter	**Value**	**Unit**	**Description**
R	286.58	°C/kW	Thermal resistance
C	10.26	kWmin/°C	Heat capacity of the water in the tank

Figure A.1 shows the extended TEC model simulating the base case.

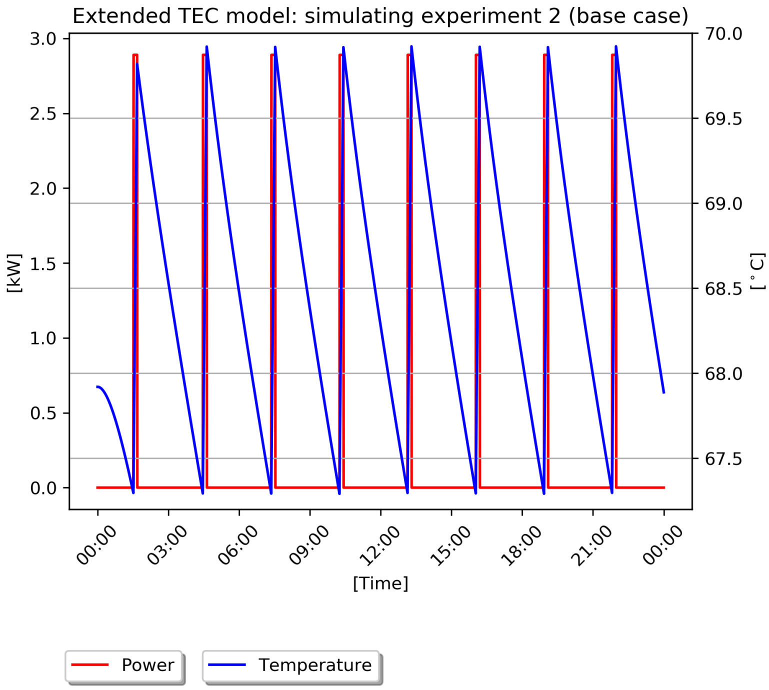

Figure A.1: Extended TEC model simulating the temperature and power profile from the base case

A.2.2 Parameter Fitting of the Extended TEC Model

Table A.6: Parameter fitting of the Extended TEC: Iteration 1

C	R_{iw}	C_w	R	Cycle	t_{heat}	τ_{cycle}	Distance
11.26	5.93	0.20	340.98	6.00	10.40	234.12	0.35
11.26	5.93	0.64	340.98	6.00	10.60	238.72	0.38
11.26	19.27	0.20	340.98	6.00	10.30	240.92	0.39
11.26	5.93	1.08	340.98	6.00	10.70	241.12	0.40
11.26	19.27	0.64	340.98	6.00	10.40	243.32	0.40
11.26	19.27	1.08	340.98	6.00	10.40	243.72	0.40
11.26	19.27	1.52	340.98	6.00	10.40	244.32	0.41
11.26	19.27	1.96	340.98	6.00	10.40	245.02	0.41
11.26	5.93	1.52	340.98	6.00	10.80	243.52	0.41
11.26	5.93	1.96	340.98	6.00	10.80	243.62	0.42
11.26	32.62	0.20	340.98	6.00	10.30	249.72	0.44
11.26	32.62	0.64	340.98	6.00	10.30	250.12	0.44

Table A.7: Parameter fitting of the Extended TEC: Iteration 2

C	R_{iw}	C_w	R	Cycle	t_{heat}	τ_{cycle}	Distance
10.08	55.20	0.57	228.20	8.00	9.30	172.71	0.02
10.08	42.59	1.39	228.20	9.00	9.30	171.21	0.03
10.08	55.20	0.16	228.20	9.00	9.30	171.11	0.03
10.08	55.20	0.98	228.20	8.00	9.20	175.31	0.03
10.08	42.59	1.80	228.20	9.00	9.20	174.01	0.03
10.08	55.20	1.39	228.20	8.00	9.20	180.81	0.05
10.08	42.59	0.98	228.20	9.00	9.30	167.31	0.05
10.08	42.59	0.16	228.20	9.00	9.40	165.11	0.06
10.08	42.59	0.57	228.20	9.00	9.30	164.41	0.06
10.08	29.97	1.80	228.20	9.00	9.30	162.71	0.07
10.08	55.20	1.80	228.20	8.00	9.20	186.91	0.08
10.08	29.97	1.39	228.20	9.00	9.30	160.01	0.09

Table A.8: Parameter fitting of the Extended TEC: Iteration 3

C	R_{iw}	C_w	R	Cycle	t_{heat}	τ_{cycle}	Distance
10.32	**34.56**	**2.16**	**232.50**	**8.00**	**9.50**	**176.41**	**0.01**
10.32	45.12	1.14	232.50	8.00	9.50	176.81	0.01
10.32	45.12	0.64	232.50	8.00	9.50	172.61	0.01
10.32	55.68	0.13	232.50	8.00	9.50	177.61	0.01
10.32	45.12	0.13	232.50	9.00	9.60	172.91	0.02
10.32	34.56	1.65	232.50	9.00	9.50	172.01	0.02
10.32	66.24	1.65	182.40	9.00	9.40	171.61	0.02
10.32	55.68	0.64	232.50	8.00	9.50	179.91	0.03
10.32	66.24	2.16	182.40	9.00	9.40	180.41	0.03
10.32	55.68	2.16	182.40	9.00	9.40	169.31	0.03
10.32	34.56	1.14	232.50	9.00	9.50	168.21	0.04
10.32	45.12	1.65	232.50	8.00	9.50	182.51	0.04

Table A.9 shows the parameters used in the extended TEC model used to simulate the base case.

Table A.9: The values of C, R, C_w and R_{iw}, from the optimization, used in the extended TEC model

Parameter	**Value**	**Unit**	**Description**
C	10.32	kWmin/°C	Heat capacity of the water in the tank
R	232.5	°C/kW	Thermal resistance between the wall of the tank and the ambient
C_w	0.128	kWmin/°C	Heat capacity of the wall of the tank
R_{iw}	50.74	°C/kW	Thermal resistance between the water and wall of the tank

Table A.10 shows the parameters of the extended TEC model used to simulate the base case.

Table A.10: Parameters used in the extended TEC model

Parameter	Value	Unit	Description
T_{ref}	75	°C	Set-point of the tank
Q_h	2.89	kW	Power rating of the heating element
T_{in}	11	°C	Inlet water temperature
C	10.32	kWmin/°C	Heat capacity of the water in the tank
R	232.5	°C/kW	Thermal resistance between the wall of the tank and the ambient
C_w	0.128	kWmin/°C	Heat capacity of the tank's wall
R_{iw}	50.74	°C/kW	Thermal resistance between the water and the wall of the tank

A.2.3 Parameter Fitting of the Stratification Model

Table A.11 shows the results of the trial and error of R_s and C_s.

Table A.11: Result of the trial and error of the thermal resistance and heat capacity in the stratification model

Temperature	Value	Description
R_s	879.31 °C/kW	Thermal resistance
C_s	13.26 kWmin/°C	Heat capacity

Table A.12 shows the parameters of the stratification model used to simulate the base case.

Table A.12: Parameters used in the stratification model

Parameter	Value	Unit	Description
T_a	24	°C	Ambient temperature outside the tank
T_{in}	5.9	°C	Temperature of the inlet water
T_{ref}	75	°C	Set-point of the temperature sensor
Q_h	2.89	kW	Power from the heating element as in base case
S	10	-	The number of layers in the model
K_s	2	-	The convection coefficient
m	281/10	kg	The size of the tank divided by the number of layers
R_s	879.31	°C/kW	Thermal resistance
C_s	13.26	kWmin/°C	Heat capacity

A.3 Generating Power and Temperature Profiles with Hot Water Consumption Data

A.3.1 Stochastic Load Model

Table A.13 shows the number of occupants in the data set simulated with the SLM.

Table A.13: Number of occupants in the 12 different households

Apartment number	Number of occupants
1	3
2	2
3	3
4	1
5	2
6	1
7	1
8	2
9	2
10	2
11	1
12	2

A.4 Exploring the Flexibility Potential of the Aggregated EWHs

A.4.1 Activity Control - Shower Activities

Scenario 3 - Turning off the EWHs without Showers and Having a Reconnecting Strategy

Table A.14 shows the additional flexibility caused by the reconnection strategy in the activity control, scenario 3.

Table A.14: Scenario 3: the additional flexibility due to reconnection strategy,

EWH	**Power** (P_{flex})	**Energy** (E_{flex})	**Time** (t_{flex})
1	0	0	60 min
2	0	0	60 min
3	0	0	0
4	2.89 kW	0.46 kWh	90 min
5	0	0	0
6	0	0	0
7	2.89 kW	0.46 kW	90 min
8	0	0	0
9	0	0	0
10	2.89 kW	0.46 kWh	60 min
11	2.89 kW	0.05 kWh	60 min
12	0	0	0

Scenario 4 - turning off the EWHs without shower activities and having an extended reconnecting strategy

Table A.15 shows the additional flexibility caused by the reconnection strategy in the activity control, scenario 4.

Table A.15: Scenario 4: the additional flexibility due to reconnection strategy

EWH	**Power** (P_{flex})	**Energy** (E_{flex})	**Time** (t_{flex})
1	0	0	88 min
2	0	0.46	95 min
3	0	0	0
4	2.89 kW	0.46 kW	119 min
5	0	0	0
6	0	0	0
7	2.89 kW	0.46 kW	115 min
8	0	0	0
9	0	0	4 min
10	2.89 kW	0.46 kWh	104 min
11	2.89 kW	0.05 kWh	71 min
12	0	0	0

A.4.2 Temperature Control

Scenario 1 - Turning off all the EWH and reconnection control

Table A.16 shows the additional flexibility provided by the reconnection strategy in secnario 1. The negative energy means that the EWHs uses energy that were not planned to be used compared to the baseline, since the reconnection strategy forces the EWHs to go into a heating cycle.

Table A.16: Temperature control: additional flexibility due to the reconnection strategy in scenario 1 from 9:00-10:30 a.m.

EWH	**Power** (P_{flex})	**Energy** (E_{flex})	**Time** (t_{flex})
1	2.89 kW	-0.75 kW	90 min
2	2.86 kW	0.46 kWh	90 min
3	2.89 kW	-1.18 kWh	90 min
4	2.89 kW	-0.10 kWh	90 min
5	2.89 kW	-1.73 kWh	90 min
6	2.89 kW	-1.20 kWh	90 min
7	2.89 kW	0.46 kWh	90 min
8	2.89 kW	-1.16 kWh	90 min
9	2.89 kW	-0.19 kWh	90 min
10	2.89 kW	-0.10 kWh	90 min
11	2.89 kW	-0.60 kWh	90 min
12	2.89 kW	-0.81 kWh	90 min

Scenario 2 - request and reconnection control

Table A.17 shows the additional flexibility provided by the reconnection strategy in secnario 2. The negative energy means that the EWHs uses energy that were not planned to be used compared to the baseline, since the reconnection strategy forces the EWHs to go into a heating cycle.

Table A.17: Temperature control: additional flexibility due to the reconnection strategy in scenario 2 from 9-10 a.m.

EWH	**Power** (P_{flex})	**Energy** (E_{flex})	**Time** (t_{flex})
1	2.89 kW	-0.67 kW	60 min
2	0	0	60 min
3	2.89 kW	-0.75 kWh	60 min
4	2.89 kW	-0.02 kWh	60 min
5	2.89 kW	-0.72 kWh	60 min
6	2.89 kW	-1.28 kWh	60 min
7	0	0	60 min
8	2.89 kW	-0.02 kWh	60 min
9	2.89 kW	-0.14 kWh	60 min
10	2.89 kW	-0.02 kWh	60 min
11	2.89 kW	-0.46 kWh	60 min
12	2.89 kW	-0.77 kWh	60 min

A.5 Additional Information

A.5.1 Overview of the Data Sets Used in the Thesis

Table A.18: Overview of the different data sets

Name	**Year**	**Location**	**Collection Method**	**Type of data**	**Level of detail**
NTNU Smart House	2020	Norway	Measurements	Temperature and power	Individual EWH
Multiple data sets - Stochastic Load Model - Table 4.5	1996 - 2007	Sweden	Diaries and measurements	ToU, power and hot water	Individual household
ElDeK	2010 - 2012	Norway	Measurements	Power	Individual EWH

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