



# UNIVERSITY OF AGDER

## MAS-500 Renewable Energy

DEMAND SIDE MANAGEMENT OF ELECTRIC WATER HEATER WITH A  
PHOTOVOLTAIC SYSTEM

BY

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MAY 31, 2018

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UNIVERSITY OF AGDER, 2018

FACULTY OF TECHNOLOGY AND SCIENCE

DEPARTMENT OF ENGINEERING

### Abstract

This thesis presents the development of a load controller, which can be used to store self-produced electricity as hot water in a regular electrical water tank. The electricity market today facing challenges towards grid utilisation and consumption during peak hours. To prevent massive investment for the grid operators for upgrading the grid to handle peak hours, a better utilisation is necessary. An expected increase in electricity prices together with a reduction of cost for renewable energy production opens for new solutions to reduce the grid electricity consumption. The problem statement was to design a controller for implementation on a regular electric water heater in a household, with the aim to reduce the grid peaks, and the price of hot water in the household, by increasing the temperature when there was excess electricity available from the photovoltaic system. By using an already existing household appliance, the investment cost of the overall system compared to, i.e. batteries are low. Previous research has focused towards reducing grid consumption during peak hours from a grid operators point of view, and the approach was to use models to predict the water consumption and remotely control the heater. However, recent research has included demand-side management and more precise models. In the thesis, the controller is used for demand-side management, and only require a few modifications to the electric water heater. For estimating water consumption, two profiles are used which is based on average and electricity based water consumption. The controller uses logic and forecast data to set the tank temperature according to expected PV production. During testing, some improvements were made to optimise the controller, but for further increasing the energy storage and cost reduction, additional improvements are necessary. The results show that energy storage would reduce the grid consumption, and reduce the price of electricity between 9-55% per day with grid tariff, depending on the amount of self-produced electricity. However, more experiments and with other water usages is required to confirm the saving potential for grid consumption. Besides, the consumption in high demand periods is reduced by shift the demand from the Electric Water Heater(EWH). This can be further improved by power control of the heating element in the EWH as the results show that without power control, the savings results are inconclusive. Overall, the controller reduces the peaks in the grid and lowers the cost of hot water, but the exact saving is not possible to predict until the new electricity prices structures are available. Nevertheless, the results show that there is possible to store large amounts of energy as hot water, without affecting the user-comfort, with the benefits of reducing grid consumption and peaks.

## Preface

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Thanks for all your encouragement!



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*Marius Christoffersen*

Grimstad, May 31, 2018

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# Contents

<b>Abstract</b>	<b>i</b>
<b>Preface</b>	<b>ii</b>
<b>Individual declaration</b>	<b>iii</b>
<b>Publishing Agreement</b>	<b>iv</b>
<b>List of Figures</b>	<b>ix</b>
<b>List of Tables</b>	<b>xii</b>
<b>Nomenclature</b>	<b>xiii</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Motivation . . . . .	2
1.1.1 Power tariff implementation . . . . .	2
1.1.2 Plus customer . . . . .	3
1.1.3 Elhub . . . . .	4
1.2 Problem Statement . . . . .	5
1.3 Design criteria . . . . .	5
1.4 Report Structure . . . . .	6
<b>2 State of the Art</b>	<b>7</b>
2.1 Load management methods . . . . .	7
2.1.1 Direct load control . . . . .	7
2.1.2 Indirect load control . . . . .	8
2.2 Development of load management control for electric water heaters . . . . .	8
2.3 Load management control of electric water heaters in smart grid . . . . .	9
2.4 Load control models . . . . .	10
2.4.1 Average consumption models . . . . .	10
2.4.2 Water tank modelling . . . . .	11
2.5 Load management control with renewable energy implementation . . . . .	13
<b>3 Method</b>	<b>15</b>
3.1 Method for designing a sufficient controller . . . . .	15
3.2 Experimental constraints and limitations . . . . .	15
3.2.1 Time to develop a sufficient LabView program . . . . .	15
3.2.2 AMS communication . . . . .	16
3.2.3 PV system limitations . . . . .	16
3.2.4 Tank constraints . . . . .	17
3.3 Fundamental water equations . . . . .	17
3.4 Water usage profiles . . . . .	18
3.4.1 Electricity consumption-based water profile . . . . .	18

3.4.2	Average household consumption per resident water profile . . . . .	19
3.4.3	Random consumption water profile . . . . .	19
3.5	Electricity consumption profiles . . . . .	20
3.5.1	Reduce grid peak and cost of water usage profile . . . . .	20
3.5.2	Normal electricity consumption with utilization of PV produced electricity . . .	21
3.6	Data handling . . . . .	22
<b>4</b>	<b>Electric Water Heater Model</b>	<b>23</b>
4.1	Physical model . . . . .	24
4.2	LabView Program . . . . .	26
4.2.1	Main program . . . . .	26
4.2.2	Tank data and control . . . . .	27
4.2.3	Collecting solar data . . . . .	28
<b>5</b>	<b>Developing experiments</b>	<b>29</b>
5.1	Heating . . . . .	30
5.2	Experiment 1: Temperature change in the tank when aiming to reduced grid peak and cost of heating . . . . .	32
5.2.1	Experiment 1a: Without PV produced electricity . . . . .	32
5.2.2	Experiment 1b: With PV produced electricity . . . . .	33
5.2.3	Comparison of experiment 1a and 1b . . . . .	34
5.2.4	Experiment 1c: Water consumption cases independently without any PV electricity	36
5.3	Experiment 2: Temperature change in the tank when using normal electricity consumption	37
5.3.1	Experiment 2a: Without PV produced electricity . . . . .	37
5.3.2	Experiment 2b: With PV produced electricity . . . . .	39
5.3.3	Comparison of experiment 2a and 2b . . . . .	39
5.4	Modifications necessary for the controller based on developing experiments . . . . .	41
<b>6</b>	<b>Controller logic</b>	<b>42</b>
6.1	Weather forecast . . . . .	42
6.2	Temperature control . . . . .	44
<b>7</b>	<b>Experimental results</b>	<b>46</b>
7.1	Average and random consumption with normal electricity consumption . . . . .	47
7.1.1	Days without any PV production . . . . .	52
7.2	Average and random consumption with reducing grid peak and cost electricity consumption	54
7.2.1	Reducing grid peak . . . . .	59
7.2.2	Day without PV production . . . . .	60
<b>8</b>	<b>Discussion and improvements</b>	<b>62</b>
8.1	Discussion . . . . .	62
8.2	Future work . . . . .	65
<b>9</b>	<b>Conclusion</b>	<b>66</b>

<b>Bibliography</b>	<b>68</b>
<b>Appendix A Comparison of renewable energy sources</b>	<b>74</b>
<b>Appendix B Physical model</b>	<b>75</b>
B.1 Sketch of the tank modifications with location of temperature sensors . . . . .	75
B.2 Wiring scheme junction box . . . . .	76
B.3 Wiring scheme DAQ-modules . . . . .	77
<b>Appendix C Physical Setup</b>	<b>78</b>
C.1 Advance Metering System . . . . .	78
C.2 Power Relays . . . . .	78
C.3 Gateway . . . . .	78
C.4 PV system . . . . .	80
C.4.1 Solar panels . . . . .	80
C.4.2 Micro Inverter . . . . .	80
C.4.3 Energy Communication Unit . . . . .	81
C.4.4 Expected PV production based on location . . . . .	81
C.5 Electrical Water Heater . . . . .	83
C.6 Data Acquisition System . . . . .	84
C.7 Computer . . . . .	86
C.8 Temperature Sensors . . . . .	86
C.9 Valve . . . . .	87
C.10 Heat Flux Sensor . . . . .	88
<b>Appendix D LabView</b>	<b>89</b>
D.1 LabView program hierarchy . . . . .	89
D.2 Sections of LabView programs . . . . .	91
D.2.1 Collecting solar cell information program . . . . .	91
D.2.2 Tank data and control program . . . . .	92
D.2.3 Parameters which needs to be set before starting experiment . . . . .	93
<b>Appendix E Parameters</b>	<b>94</b>
E.1 Variables available for measuring in the program . . . . .	94
E.2 Variables used in the program . . . . .	95
E.2.1 PV produced electricity . . . . .	95
E.2.2 Power measurements of the heating element . . . . .	96
<b>Appendix F Average flow calculations</b>	<b>97</b>
<b>Appendix G Price of components</b>	<b>98</b>
<b>Appendix H Data for experiments</b>	<b>100</b>
H.1 Experiment 1 . . . . .	100
H.2 Experiment 2 . . . . .	101

H.3	Data Result experiment 1 . . . . .	103
H.4	Result graphs result experiment 1 . . . . .	104
H.5	Data Result experiment 2 . . . . .	107
H.6	Result graphs result experiment 2 . . . . .	108
<b>Appendix I Additional experiments</b>		<b>111</b>
I.1	Additional experiment 1: Average household and random consumption water profile when reducing grid peak . . . . .	111
I.2	Additional experiment 2: Average household and random consumption water profile with normal electricity consumption . . . . .	114
I.3	Comparison of additional experiments and result experiments . . . . .	117
<b>Appendix J System for selling all self-produced electricity</b>		<b>118</b>

## List of Figures

1.1	Average hourly consumption for a passive house, Skarpnes, Arendal. . . . .	1
1.2	Load management objectives. . . . .	2
1.3	Overview of communication between electricity suppliers and grid operators now and with Elhub . . . . .	4
1.4	Overview of load management control with renewable energy. . . . .	5
2.1	Categorization of load management approaches. . . . .	7
2.2	Comparison the development of water demand . . . . .	11
2.3	Reconstructed daily hot water needs . . . . .	12
2.4	Consumption vs PV-production for a passive house at Skarpnes. . . . .	14
3.1	Example of two discharges calculated from eq 4 . . . . .	18
3.2	Example of valve openings for average consumption per resident water profile . . . . .	19
3.3	Example of valve openings for random water profile . . . . .	20
3.4	Estimation of fluctuating electricity prices during a day . . . . .	21
4.1	Physical setup of the complete system with signal and power layout . . . . .	23
4.2	Picture of the modification done for the tank . . . . .	24
4.3	Picture junction box mounted at the tank . . . . .	25
4.4	Picture of DAQ located at the tank for collect information . . . . .	25
4.5	Print screen of the main HMI . . . . .	26
4.6	Print screen of the tank HMI . . . . .	27
4.7	Print screen of the ECU web interface . . . . .	28
4.8	Print screen of the HMI of solar panels information in LabView . . . . .	28
5.1	Temperature increase based on measured power and rated power delivered compared with actual temperature $T_3$ increase . . . . .	30
5.2	Temperature in the tank with average and electricity based water consumption and no PV production . . . . .	32
5.3	Temperature in the tank with average and electricity based water consumption and PV production . . . . .	33
5.4	PV production and grid consumption for experiment 1 with PV . . . . .	34
5.5	Comparison of 1a and 1b temperatures . . . . .	34
5.6	Comparison of 1a and 1b active heating element . . . . .	36
5.7	Results from the experiment with independently water consumptions profiles . . . . .	37
5.8	Temperature in the tank with average and electricity based water consumption with no PV electricity and normal electricity consumption . . . . .	38
5.9	Temperature in the tank with PV electricity and normal electricity consumption . . . . .	39
5.10	PV production and grid consumption for experiment 2b with PV . . . . .	40
5.11	Comparison of 2a and 2b temperatures . . . . .	40
6.1	Print screen of the collected weather and start temperatures . . . . .	42
6.2	Flowchart for setting tank temperature . . . . .	43
6.3	Flowchart for temperature control . . . . .	45
7.1	Temperature in the tank, heating element connected and valve opening for result experiment 1 . . . . .	48
7.2	All the temperature in the tank during result experiment 1 . . . . .	48

7.3	PV production during result experiment 1 . . . . .	49
7.4	Tank temperatures, heating and price graphs for 1 day test of result experiment 1 . . .	52
7.5	Temperature in the tank, heating element connected and valve opening for result experiment 2 . . . . .	54
7.6	All the temperature in the tank during result experiment 2 . . . . .	55
7.7	PV production during result experiment 2 . . . . .	56
7.8	Price during experiment and heating element active for result experiment 2 . . . . .	59
7.9	Consumption grid for result experiment 2 . . . . .	60
7.10	Tank temperatures, heating and price graphs for 1 day test of result experiment 2 . . .	60
B.1	Layout of the tank with dimensions . . . . .	75
B.2	Wiring scheme for the junction box placed at the top of the tank . . . . .	76
B.3	Wiring scheme for the cDAQ used . . . . .	77
C.1	AMS from Kamstrup . . . . .	78
C.2	Develco power relay used for power monitoring of PV and heating element . . . . .	79
C.3	Gateway for communication between AMS, relay and computer . . . . .	79
C.4	Picture of one of the solar panels used . . . . .	80
C.5	Micro inverter from APS . . . . .	80
C.6	Energy communication unit from APS . . . . .	81
C.7	Energy and irradiation for the optimum angle for the location of the system . . . . .	81
C.8	Expected production table . . . . .	82
C.9	Actual PV production for April . . . . .	83
C.10	Electrical water heater from CTC . . . . .	83
C.11	Picture of NI cDAQ-9174 . . . . .	84
C.12	Temperature module NI-9216 . . . . .	84
C.13	Voltage system for valve control . . . . .	85
C.14	Flux module NI-9212 . . . . .	85
C.15	Lenovo ThinkCentre M710t . . . . .	86
C.16	PT-100 element as mounted on the inlet . . . . .	87
C.17	Solenoid Valve . . . . .	87
C.18	GreenTeg Flux sensor . . . . .	88
D.1	Print screen of the front panel in LabView . . . . .	89
D.2	The program for collecting solar production information . . . . .	91
D.3	The program tank data and control . . . . .	92
E.1	Presentation of the two measurements which can be used for PV production . . . . .	95
E.2	Presentation of the two measurements which can be used for consumption . . . . .	96
H.1	Tank temperatures and PV graphs for result experiment 1, day 1 . . . . .	104
H.2	Tank temperatures and PV graphs for result experiment 1, day 2 . . . . .	104
H.3	Tank temperatures and PV graphs for result experiment 1, day 3 . . . . .	105
H.4	Tank temperatures and PV graphs for result experiment 1, day 4 . . . . .	105
H.5	Net consumption grid for result experiment 1 . . . . .	106
H.6	Net consumption grid for result experiment 1 . . . . .	106
H.7	Tank temperatures and PV graphs for result experiment 2, day 1 . . . . .	108
H.8	Tank temperatures and PV graphs for result experiment 2, day 2 . . . . .	108

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H.9	Tank temperatures and PV graphs for result experiment 2, day 3 . . . . .	109
H.10	Tank temperatures and PV graphs for result experiment 2, day 4 . . . . .	109
H.11	Tank temperatures for 1-day result experiment 2 . . . . .	110
I.1	Tank temperatures for additional experiment 1 . . . . .	112
I.2	PV production for additional experiment 1 . . . . .	113
I.3	Tank temperatures for additional experiment 2 . . . . .	115
I.4	All tank temperatures for additional experiment 2 . . . . .	115
I.5	PV production for additional experiment 2 . . . . .	117
J.1	Layout of the system in a household for using self-produced electricity . . . . .	118
J.2	Layout of the system in a household for using all or sell self-produced electricity . . . . .	118

## List of Tables

1.1	Examples from NVE with tariffs for calculating grid tariff . . . . .	3
1.2	Design criteria for a controller . . . . .	5
3.1	Electricity prices for the experiment location provided by Agder Energi . . . . .	21
5.1	Parameters which are equal for every experiment . . . . .	29
5.2	Heating time comparison . . . . .	31
5.3	Comparison of key parameters for experiment 1a and 1b . . . . .	35
5.4	Comparison of key parameters for experiment 1c . . . . .	37
5.5	Comparison of key parameters for experiment 2a and 2b . . . . .	41
7.1	Parameters which is equal for all experiments . . . . .	46
7.2	Data from result experiment 1 with with PV stored energy and without storage of PV produced energy . . . . .	50
7.3	Data from result experiment 1 for 24 hour with no PV produced electricity . . . . .	53
7.4	Data from result experiment 2 with with PV stored energy and without storage of PV produced energy . . . . .	58
7.5	Data from result experiment 2 for 24 hours with no PV produced electricity . . . . .	61
A.1	Comparison of renewable energy sources . . . . .	74
D.1	Parameters which needs to be set before experiment . . . . .	93
E.1	List of variables which can be measured with the controller . . . . .	94
F.1	Experiments for calculating system . . . . .	97
G.1	Comparison of price for PV system . . . . .	98
G.2	Price list for controller components . . . . .	99
H.1	Data from experiment 1a without any PV produced electricity . . . . .	100
H.2	Data from experiment 1b with PV produced electricity . . . . .	100
H.3	Data from experiment 2a with no PV produced electricity . . . . .	101
H.4	Data from experiment 2b with PV produced electricity . . . . .	102
H.5	Key data from result experiment 1 per day . . . . .	103
H.6	Comparison of data per day with one day experiment . . . . .	103
H.7	Key data from result experiment 2 per day . . . . .	107
H.8	Comparison of data per day with one day experiment . . . . .	107
I.1	Data from additional experiment 1 . . . . .	112
I.2	Data from additional experiment 2 . . . . .	116

## Nomenclature

### Abbreviations

AMI	Advanced Metering Infrastructure
AMS	Advanced Metering System
BIPV	Building Integrated Photovoltaic
DAQ	Data Acquisition
EWB	Electrical Water Heater
HAN	Home Area Network
HMI	Human Machine Interface
kWh	Kilowatt hour
kWp	Kilowatt peak
NOK	Norwegian kroner
PV	Photovoltaic
PVGIS	Photovoltaic Geographical Information System
UiA	University Of Agder
VAT	Value-added tax

VI Virtual Instrument

ZEB Zero Emission Building

### Symbols

$\dot{Q}$	Heat loss [ $\frac{J}{s}$ ]
$\eta$	Efficiency [ $W$ ]
$A$	Area [ $m^2$ ]
$C$	Cost[ $NOK$ ]
$c_p$	Specific heat for fluid [ $\frac{J}{kg \cdot K}$ ]
$k$	Thermal conductivity of material [ $\frac{W}{m \cdot K}$ ]
$m$	Mass [ $kg$ ]
$Q$	Heat [ $J$ ]
$s$	Material thickness [ $m$ ]
$T$	Temperature [ $K$ ]
$t$	Time [ $s$ ]
$U$	Total heat transfer coefficient [ $\frac{W}{m^2 \cdot K}$ ]

## 1 Introduction

With a continuous increase in both population and electricity appliances, the electricity grid is operating closer to capacity. The grid utilisation is not evenly distributed, but has peaks in the morning and evening. From a grid operators point of view, this is the demand which the grid must be able to handle. For the rest of the day, the grid has a lower demand but has to be dimensioned for the peaks. With this in mind, the operators seek new solutions to reduce the grid demand and/or shift the demand to even out the demand during the day.

Electricity consumption for a day is not evenly distributed. Consumption during peak periods is much higher compared to low demand periods. With an increase in population and households, the peak demand increases, and resulting in the grid operating close to capacity [1]. Figure 1.1 is an example of annual consumption for a low energy household in Skarpnes, Arendal for one day. The peak consumption is 30% higher than the average daily consumption.

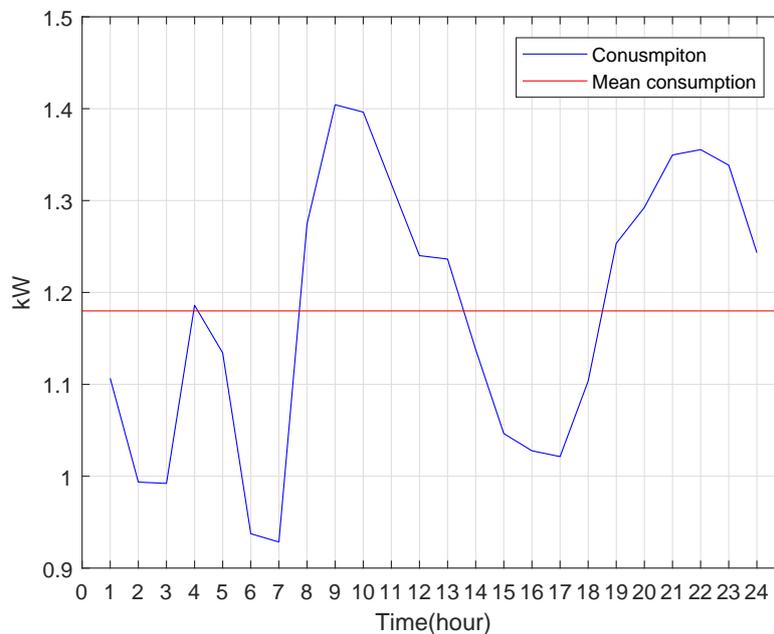


Figure 1.1: Average hourly consumption for a passive house, Skarpnes, Arendal.

Upgrading the grid for handling peak, is an uneconomical approach for the grid operators[1]. To deal with the peak consumptions, load management solutions for shifting the load is more economical. This has resulted in control systems for use with EWH and has been more attractive with the development of new requirements for households regarding energy efficiency. Figure 1.2 illustrates the benefits of load management control based on grid operators and end-user. The best outcome for load management control changes for each goal. A preferable solution for grid operators may be an imperfect solution for the end-user. Nevertheless, with new development and improvements, load management controllers are now able to achieve more of the goals compared to earlier control systems [2].

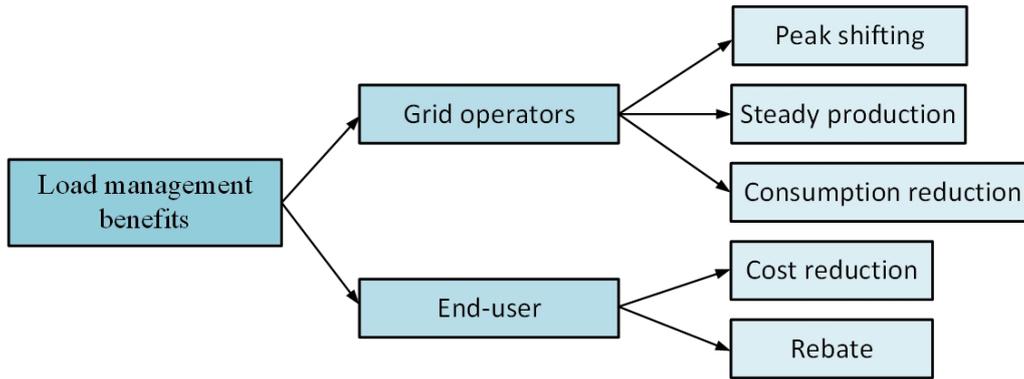


Figure 1.2: Load management objectives.

## 1.1 Motivation

With an increase of household appliances and a higher demand for electricity, the consumption increases. In Norway, the Norwegian transmission operator Statnett estimated in 2005, that the consumption would increase by 1-2 % each year [1]. However, keeping up with the increased electricity demand is expensive. During cold periods with extreme weather, the power grid is operating close to capacity, due to an increase in required house heating. In 2017, StatNett<sup>1</sup> estimated that the cost necessary to improve the grid was in the range of 140 billion Norwegian kroner(NOK)[3]. In a regular household, 15-20% of the electricity is consumed by the EWH[4]. The hot water demand follows the same consumption peaks as the overall electricity demand, with the corresponding peaks during a day [5]. With the expected use of fluctuating electricity prices and new tariffs, which make electricity expensive during high demand periods, renewable energy resources can be implemented, together with control strategies, to reduce the grid demand and therefore electric bill.

A substantial drawback of the use of renewable energy sources is the generation of electricity when the demand is at the lowest, for example in the middle of a warm summer day. By installing a controller to utilise this energy to heat water, the water tank functions as a "blue battery", which holds a large amount of energy as hot water. By utilising the "unused" energy, this can reduce the households energy demand and grid peak consumption. This thesis is a result of a fascination for this subject, and ambition to take advantage of this "unused" potential. Besides, there are new regulations such as new power tariffs and Elhub, that are expected. This addresses the production of renewable energy, from both economic and environmental point of view.

### 1.1.1 Power tariff implementation

In Norway, The Norwegian Water Resources and Energy Directorate(NVE) has presented a power tariff to be implemented together with other regulations regarding AMS. In today's market, the price for electricity paid by a customers includes; consumption, grid tariff, consumption tax(In 2017, 20.73 øre/kWh[6]), VAT(Currently 25% of total amount) and a fee of 1 øre/kWh to Energifondet<sup>2</sup>[8]. In

<sup>1</sup>The system operator in the Norwegian energy system.

<sup>2</sup>Government fund aimed at promoting energy efficiency and environmentally friendly conversion of energy use, and energy production[7]

the consultation presented, NVE introduces four different grid tariffs for consumption calculation for customers. The tariffs are presented in table 1.1 and is the proposed tariffs from NVE[9][10].

Table 1.1: Examples from NVE with tariffs for calculating grid tariff[10]

Model	Fixed Amount	Consumption	Effect-based amount
Circuit breaker size	Yes, differentiated from the customers main circuit breaker[Kr/kWh]	Yes, marginal based[øre/kWh]	No, only differentiated from fixed amount
Measured consumption	Yes, customer depended[Kr]	Yes, marginal based[øre/kWh]	Yes, calculated from peak hour or max consumption for a year, month or day[Kr/kWh]
Expected consumption	Yes, differentiated from customers expectation[Kr/kWh]	Yes, marginal based[øre/kWh]	Yes, estimated by differentiation of the fixed amount and a higher price for use beyond expected consumption[Kr/kWh]
Time of use	Yes, may be differentiated from customer categories[Kr/customer]	Yes, higher when grid is operating close to capacity [øre/kWh]	No, only differentiated from fixed amount

Table 1.1 divides the new proposed tariffs from NVE into four different calculations methods. The first method is to estimate a price based on the *main circuit breaker size* in a household<sup>3</sup>, with an added price, based on consumption. The second proposal is *Measured consumption*, where the fixed amount is based on the customer/household with a consumption price added. Also, there is an effect-based amount where high consumption during peak hours, or if the consumption is higher than the normal/expected per year, month or day, would add to the overall cost of the electricity. *Expected consumption* is for agreements where the customer pays an amount based on expected consumption. Besides, the customer pays for consumption and an effect based price if the composition exceeds expected consumption. The last model is *Time of use*. In this model, there is a fixed amount and a consumption amount which is based on the grid utilisation. Consumption during peak hours is more expensive than low demand periods.

### 1.1.2 Plus customer

In addition to the new power tariff, smart metering offers better service for households which are classified as plus customer. A plus customer is a customer which produced electricity and selling the excess energy to the grid operator. NVE has provided guidelines for households which are classified as plus customer, which limits the output to 100 kW per household. Every facility with a higher output needs to be classified as a supplier of other regulations and tariffs. However, in today's legislation, the operators and electricity suppliers are not obligated to receive the produced electricity from the household, but some offers to buy produced electricity. Agder Energi is currently offering an agreement, paying the price from NordPool<sup>4</sup>, which is referenced as spot price, with an addition of 4 øre/kWh[6]

<sup>3</sup>In Norway, the main circuit breaker size is in the range 40-63A 3-phase in households

<sup>4</sup>Commodity marked of electricity for the European countries

for household produced electricity. A few electricity suppliers, such as LOS[11] and Otovo also offers to pay for customer produced electricity. Otovo is offering to pay 1 kr/kWh for produced electricity as long as the production does not exceed 5000 kWh/year. For production over 5000 kWh/year, Otovo pays the spot price[12].

### 1.1.3 Elhub

Together with the new power tariffs, NVE has instructed StatNett to develop Elhub. The aim for Elhub is to reduce the complexity of communication between electricity supplier, grid operator and end-customer. In the current market, the customer needs to share information with both the grid operator and electricity supplier separate, regarding end-user information, or other changes. Elhub would change this, providing an interface where all the information from both grid operators and electricity suppliers is collected. Besides, Elhub would provide a platform where the customers can share information with third-party for other appliances and areas of applications as illustrated in figure 1.3.

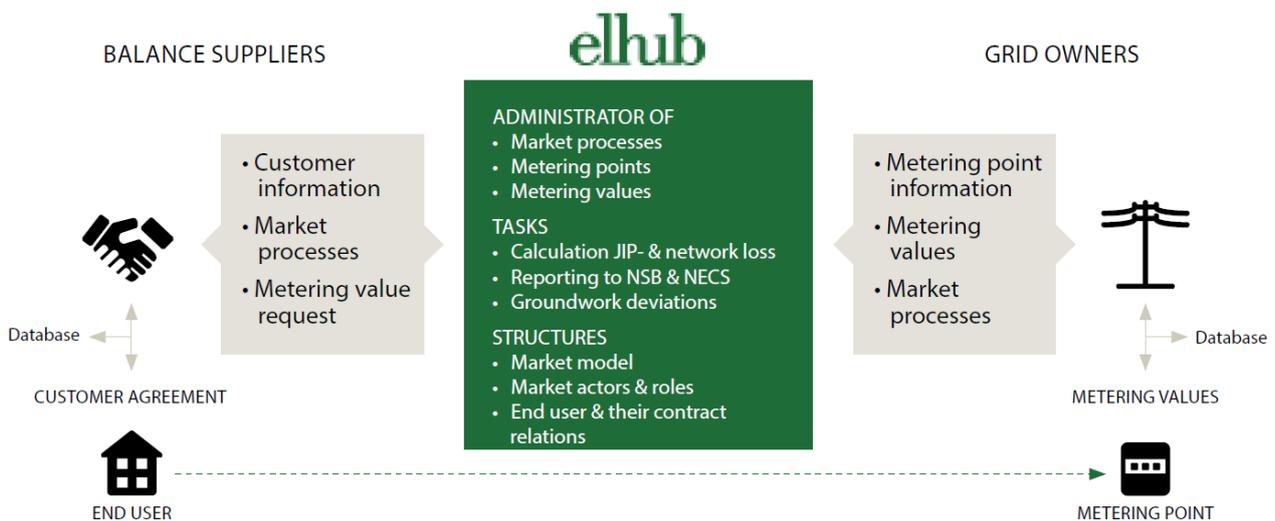


Figure 1.3: Overview of communication between electricity suppliers and grid operators with Elhub[13]

As figure 1.3 illustrates, all the necessary information is stored in a hub where the customer can update, or provide the information with third-party appliances if necessary. Furthermore, the customer has access to all the information at any time and can monitor and change the access to information. Elhub is scheduled to be implemented 18. February 2019, after several delays due to legislation and implementation problems.

## 1.2 Problem Statement

This master thesis presents a controller for use with a regular electric water heater. The main objective is to store energy as hot water produced from a PV system. For doing this, a system needs to be designed to conduct experiments with both water usage and energy production. The system would use information from the renewable energy source ( wind, solar etc.), and compare with the temperature in the water tank. A controller uses this information to start the heating to store energy if it is possible. Controlling the EWH would make it possible to shift the electricity consumption for the EWH, to low peak periods in the grid, and utilise renewable energy produced to use in demand for water periods. Figure 1.4 illustrates how the layout can be explained. Besides, the controller needs to utilise the energy produced more economical than selling the energy to the grid.

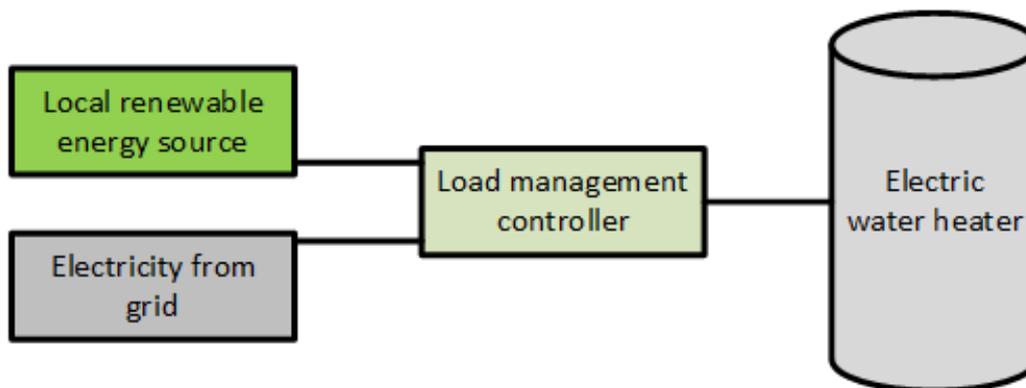


Figure 1.4: Overview of load management control with renewable energy.

The main objectives of this thesis are divided into two main parts. The two tasks to be carried out are:

- Design a controller for implementation on standard hot water tanks.
- Store the energy produced by a PV-system as hot water rather than selling the energy to the grid operator.

## 1.3 Design criteria

A controller needs to be designed for use with a standard EWH. The controller should also communicate with micro-inverters for gathering information of energy from the PV system for storage as hot water. For the development of a controller, there are some criteria and limitations to address.

Table 1.2: Design criteria for a controller

Design Criteria
1. Store produced energy from the renewable energy source as hot water
2. Decrease the electricity consumption from the grid
3. Implement the controller without affecting user-comfort

## 1.4 Report Structure

In this section, a summary for each section in the master thesis is presented. Each section is presented using the following bullet points.

- **Section 1 - Introduction**

This section presents the motivation together with the problem statement. In the end, the main objectives are presented together with the expected outcome and similar limitations.

- **Section 2 - State of the art**

The theory section presented the development of EWH control and methods. First, the control methods are discussed followed by the development of the system. In the end, load management control with renewable energy is elaborated.

- **Section 3 - Method**

Section 3 introduces the method used in this thesis. First constraints and limitations concerning experiments, before an explanation of important equations, are outlined. Furthermore, the water usage profile and electricity consumption profiles are listed.

- **Section 4 - Electric water heating model**

Section 4 presents the electrical water model used for building a controller. First, the physical set-up is presented, before the LabView program is presented with the different sub-programs for collecting and handling data.

- **Section 5 - Developing experiments**

Section 5 includes results from two developing experiments which is necessary to investigate the temperature change in the tank, during different water usage profiles and electricity consumption profiles. The experiment results are used for optimising the controller.

- **Section 6 - Controller Logic**

This section presents the logic responsible for controlling the temperature based on external data. The logic is illustrated and explained while every step is presented.

- **Section 7 - Experimental results**

The section includes two experiments with the logic implemented. The experiments are tested with same water usage profiles, but different electricity consumption profiles

- **Section 8 - Discussion and improvements**

Section 8 includes the discussion of results and the controller, and findings are elaborated with recommendations.

- **Section 9 - Conclusion**

This section includes the conclusion of the thesis.

## 2 State of the Art

In the interest of reducing the grid consumption, there has been extensive research towards load control and demand-side management of households appliances. Being the largest single consumer of electricity, EWH is the most favourable appliances to control when trying to decrease the demands during peak periods. Besides, the EWH functions as energy storage, and have some advantages compared with other energy storage methods as it is available in every household. In this section a description of the development and the current technology for demand site management. First, the different load controls methods is introduced, followed by an explanation of the development of controllers, models developed for EWH is presented. In the end, the load management with renewable energy is elaborated.

### 2.1 Load management methods

As figure 2.1 illustrates, load management control can be divided into two subcategories, direct and indirect. Each method is further divided into categories with different approaches for completing the objective. The approaches are discussed further below.

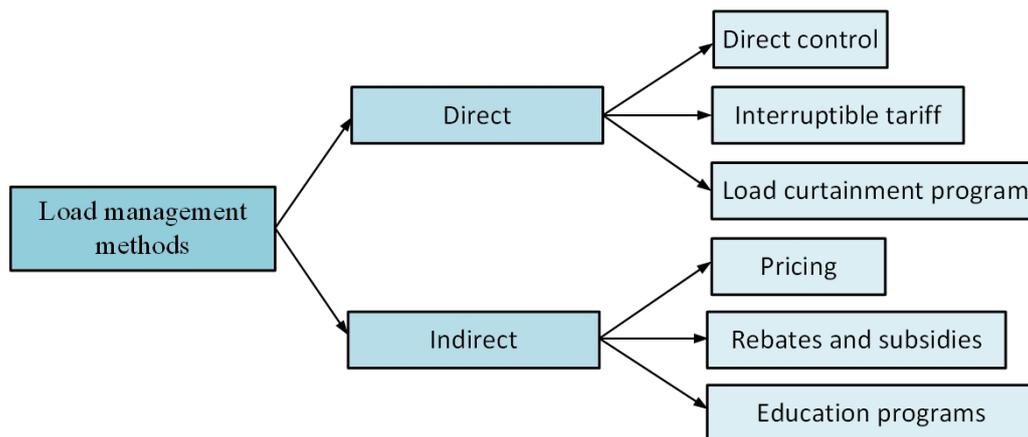


Figure 2.1: Categorization of load management approaches.

#### 2.1.1 Direct load control

*Direct control* is based on grid operators information about utilisation of the grid at any given time. This allows the grid operators to remotely disconnect or reconnect EWH in households to shift the load to off-peak periods [14]. *Interruptible tariff* is an agreement between the end-user and grid operator of an electricity price. This is reserved for large industrial customers with a predictable electricity consumption during each day [15]. *Load curtailment programs* is an offer introduced to the high electricity consuming industry. In Alberta, Canada this is implemented by ESBI Alberta Ltd. (EAL) to every large customer [16]. The customers have to reduce their consumption to a fixed amount. Customers who are failing to do so may be fined. On the other hand, succeeding gives a discount for used electricity [17].

### 2.1.2 Indirect load control

*Indirect control* is based on customers willing to participate in load programs. *Pricing control* is based on changing the electricity prices during the high peak hours. By doing this, the customer reduces the consumption when the grid is operating close to maximum capacity. Rebates and subsidies are given to customers that change/upgrade appliances to reduce the consumption. In Norway, industrial companies and private customers can get subsidies from Enova for changing appliances [18]. *Education programs* are information given to customers towards reducing both the electricity bill and how the change of appliances can reduce the energy consumption [18].

## 2.2 Development of load management control for electric water heaters

During the development of technology, load management control systems extending in both complexity and control parameters, but were still concentrated on reducing peaks and consumption. However, with the introduction of smart grid systems, load management control is used with renewable resources and sophisticated models, to not only reduce load peaks but reduce the overall cost of electricity for the households.

The methods used for communication with EWHs varies. Each way has advantages and disadvantages, concerning communication, reaction time, availability etc. In 1979, Detroit Edison Company (DEC) published a study with control of EWH. The control method was a time clock with no communication. All the clocks were preprogrammed before installing in households. The aim was to reduce the load peak in the grid. This type of control was based entirely on collected information of grid utilisation and information of average heat water usage [19]. Smith et al. presented findings later in the 1980s, where the control method was radio signals combined with power line carrier [20]. Using radio signal instead of a time clock, gave the grid operators direct control of water tank connected. This allowed operators to change the intervals for remote shut-down.

In 1985, Carolina Power and Light Company (CPLC), presented a study which focused on the practical approach to load control of water heaters. CPLC used an average daily diversified load demand for hot water demand with 15 minutes intervals [5]. A similar approach was made by Bischke and Sella [21], still with statistics as background for controlling. However, the controller focused more towards reducing peaks in the grid, instead of minimise electricity consumption overall. Both studies used different pre-timed intervals to decrease the peak-loads and had less focus towards customer advantages.

With an increase in load management control by grid operators, Schulte et al. presented an article in 1983, which pointed out that grid operators looked at load management tools offered to them, emphasised the importance of coordination between operators and end-user, to ensure a good customer acceptance [14]. Gustafson later supported this in 1993, when he argued that for the effectiveness towards load management from an engineering model point of view [22]. He concluded that in addition to heat water demand, inlet/outlet temperature and ambient temperature of the tank was required parameters in order to establish a controller, that maintains the customer needs successfully. Work done by Orphelin and Adnot in 1999, introduced the usage of load curves and compared the curves with actual consumption in every household to optimise load management control [23].

The work which was presented by Nehrir et al. in 2007 introduced a new approach for reducing the power demand for EWH. Changing the resistance in the heating element, by switching operating voltage, cut the required power input. The switching was achieved without affecting the customer [24]. To use this configuration, the EWH needs to be re-designed with two heating elements with different resistance. The change in operating voltage was briefly mentioned in the research presented by Ericson in 2007 [25]. However, Ericson pointed out the size of the element in conventional hot water tanks are different. In the US, a standard heating element has a rated power of 4.5 kW [23], compared to a typical Norwegian element, which has an estimated power of 2 kW. Ericson concluded that disconnecting the heaters during the day, depending on user patterns, is the most desirable solution for a reduction in electricity consumption [25]. However, to also take into account user needs, smart grid system implementation may be required.

In 2007, Paull et al. published an article introducing electric water heater model for a multi-objective demand side management program. The model was a controller which used individual user patterns for hot water and compared it to the information from the grid operators regarding load demand on the grid. By correlating the data, the controller estimated the best time for shut down [26]. The research presented by Paull et al. can be seen as the beginning of the development of smart grid implementation of domestic water heaters.

### 2.3 Load management control of electric water heaters in smart grid

To ensure optimum load control management of electric water heaters, real-time information on grid utilisation, in combination with user needs to be investigated. Advance metering system (AMS), provide information to the operators about the real-time use of electricity in a household. In Norway, the Norwegian Water Resources and Energy Directorate (NVE), has decided that AMS has to be installed in every home by the end of 2018 [27]. Du and Lu published in 2010 a paper describing an algorithm for use in thermostatically controlled households with AMS. The model used pricing and consumption forecast, can be available with AMS implementation. The result was an algorithm for use with independent user patterns and comfort settings [28].

Building on the work by Du and Lu, Vanthourout et al. published in 2012 an article, introducing a smart, hot water buffer. Vanthourout et al. presented a general interface that used the state of charge<sup>5</sup> in the tank, compared it to the estimated hot water usage, and calculated the necessity of heating time [29]. In a study published in 2017, Al-jabery et al. introduced a controller that used an action-dependent heuristic dynamic programming (ADHDP) [2]. This is an algorithm of approximate dynamic programming and does not require an explicit model of a system that is to be controlled [30]. This is the first time dynamic programming techniques were used for monitoring EWH. In the results, an annual saving between 102 and 453 \$ per year, for a four-person household is estimated [2].

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<sup>5</sup>Percentage of max energy available

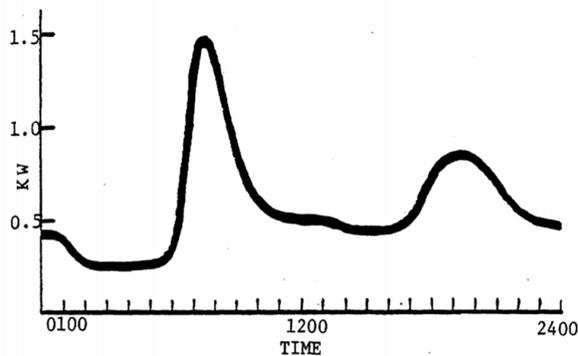
## 2.4 Load control models

In pursuance of improving the controller, the development of accurate models is essential. By using different models, a prediction of consumption would increase the benefits of installing a controller. Besides, hot water for households is necessary for user comfort. For a model, it is crucial to predicting the consumption to ensure always to have hot water available. If this fails, it can lead to a situation where a household is without hot water for more extended periods, as the water needs time to heat. This is the most significant drawback for storing energy in a water tank. For a battery storage system, if emptied the grid provides electricity immediately if necessary. As the technology has improved, the models have become more complicated. The models range from Detroit Edison Company with average water demand[19], towards more advanced controls with dynamic programming to build control models[2].

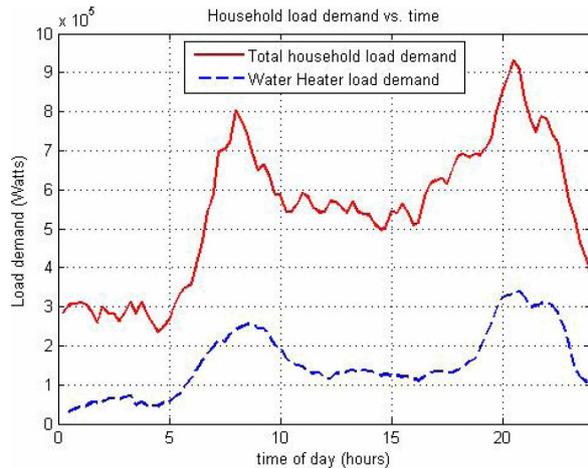
### 2.4.1 Average consumption models

The least complex and most straightforward load control model is using average water usage statistics. When Detroit Edison Company started researching load reduction in the early 1970's, there were no previous research to build on, or technology developed. The solution was to use an average water consumption data and set a maximum shut-down period of 4 hours[19]. Building on the model presented by Detroit Edison Company, Carolina Power & Light Company improved the model towards a more practical design. As shown in figure 2.2a, the demand curve had two peaks and was the same peaks when compared with the electricity consumption. The results were a load curve which overlay with the peaks for grid consumption.

The benefits of using a demand curve are the prediction of when the consumption would increase and decrease. With this information, CPLC could shift the loads for a specific number of EWHs. For the study, a total of 200 water heaters was controlled, but the study showed that the experiments could be scaled up to 200,000 heaters to increase the peak reduction[5]. The benefits of using average consumption make it easy to remotely disconnect or connect the water heaters. A drawback of the models is the lack of individually consumption patterns. If a household has an unusual consumption pattern, it could result in lack of hot water available when needed. Figure 2.2 shows the development of water demand models based on electricity consumption, where figure 2.2a is from article published in 1985, as the figure 2.2b is from 2010. The figures show that there are some differences when comparing the peaks. Nevertheless, it occurs at the same time of day for both cases.



(a) Typical daily diversified water demand in winter[5, Fig 1.]



(b) Average temperature and water heater load simulation for the uncontrolled system[31, Fig 2.]

Figure 2.2: Comparison the development of water demand

### 2.4.2 Water tank modelling

Another approach to creating load and consumption models is to use water tank modelling. The objective is to estimate how the hot water demand affects the temperature change in the tank. This section covers the mathematical models which have been presented for use with hot water storage. Mathematical models for hot water usage is commonly based on optimisation approaches. When using optimisation, computer power is essential for solving the problems in reasonable time. This can be seen in articles published. Earlier models are based on smaller and less complicated models, while state of the art models are more complex and requires significantly larger computing capacity. Another approach is to develop mathematical expressions for EWH to estimate both consumption and time intervals. In this thesis, only models developed and used for hot water is presented.

#### Optimisation models

In pursuance of developing more accurate models, Laurent et al. introduced a model which used a column generation method to achieve optimal load management. *Column generation method* is used to solve significant optimisation problems by dividing the problem into one master problem, and multiple subproblems. Still, when the article was presented, the model was based on a uniform tank temperature, and the model was developed for maximal electric load peak reduction[32]. The authors concluded that the model could be improved to increase the reduction of a model which include stratification<sup>6</sup> and temperature in the tank.

Another model was presented by Sepulveda et al. in 2010 where the method was *particle swarm optimisation*. The optimisation is developed from how bird moves. In short, it can be described as particles which move through a multi-dimensional space, where the position and speed information is registered, where the best movement and location is the solution after the last iteration. The method was used and modified to minimise the peak demand and increase the temperature in the tank over a

<sup>6</sup>Stratification is water layered with different temperature, because of the difference in density of water based on temperature. This happens naturally in a tank.

period of 24 hours. This model had a substantial advantage compared with the model presented by Laurent et al. due to the implementation of tank temperature, which increased the user comfort[33]. This model has later been used to optimise control of price-based demand [34] and improve the user comfort in control of EWH[31].

When Al-jabery et al. presented an article in 2017 where the controller was developed by using action-dependent heuristic dynamic programming (ADHDP), it had never been used to optimise an EWH. By using Q-learning<sup>7</sup>, the model minimised the energy consumed, reduced load peaks in the grid and achieved optimal customer satisfaction. The article concluded that using machine learning technique can be used to achieve both cost savings and has environmental benefits[2].

Besides, there are several other optimisation models developed. Pipattanasomporn et al. introduced in 2012 a home energy management algorithm for more widespread use in households. This is a control for all the appliances in the household[35]. With all the developed optimisation models researched, Gandhi et al. published an overview of different optimisation models[36]. In the article, Ghandi et al. concluded that more and better models would be developed and will become more realistic.

### Mathematical expressions

Mathematical expressions have also been developed to describe the consumption of hot water. In 1999 Oprhelin introduced a mathematical method for reconstructing the load curves for hot water usage. The expression for the model was developed by combining the stochastic model presented by Mortensen and Haggerty published in 1981[37], and the physically based model by Ihara and Schweppe published in 1988[38]. Figure 2.3 shows the graphical output of the expression for consumption during 24 hours. The model was tested with one study in France and Italy where the conclusion was that in France the model would increase the demand while in Italy the model would decrease the demand. This showed that expression might not be the optimal solution for different water usage profiles[23].

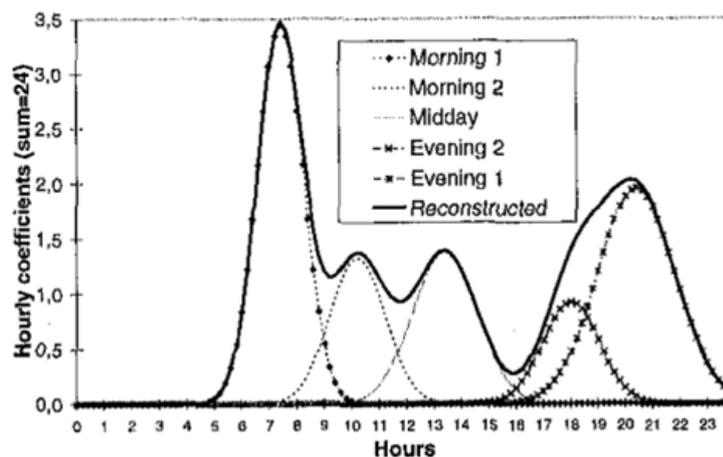


Figure 2.3: Reconstructed daily hot water needs [23, Fig 5.]

<sup>7</sup>Learning technique which is used in machine learning to solve stochastic transitions

In pursuance of better models, Xu et al. introduced a model in 2014 which was developed by experimental data. A regular EWH with two heating elements was modified to compare actual temperatures with calculated values. The model was developed to model a tank with uniform temperature or a tank with stratification. The model was validated with over 240 hours of experimental data, and the conclusion was that the developed equation was a good benchmark for testing direct management controls[39]. A similar approach was made in the article presented by Sinha et al. in 2017. The results showed that difference between uniform temperature model and stratification model is 0.3% if the thermal energy is used for input/output. On the other hand, if focusing towards temperature, layers of water and flow rate, the stratification model is considerable more accurate[40].

## 2.5 Load management control with renewable energy implementation

Load management control with renewable energy is a new approach compared with previous research. Renewable energy can be used in addition to the grid to reduce the demand for grid electricity. A list of available renewable energy sources, with pros and cons, is presented in appendix A. For a household it is solar and wind power which is the most preferable, which has its disadvantage due to unpredictable production. In 2008, Biaou and Bernier published an article focusing on total hot water production with use of renewable energy, primarily solar and ground heating. The results showed that this was achievable, but an electricity backup is necessary [41]. This illustrates that a total supply of electricity from renewable resources is difficult. As illustrated in figure 2.4 the consumption and PV generated has peaks which not corresponds. The highest PV production occurs when the consumption is low.

To utilise the energy produced from PV systems without selling it first, an energy storage system is required. The storage system would store the produced energy and supply it when the demand is increased. An EWH can be used as energy storage. Using appliances which are present in almost every household in Norway, every house can have it own "blue battery". With the technology available today, this can be controlled by a smartphone or with larger control units. As of today, the variety of available solutions are ranging from plug-in-modules [42] to advanced systems for entire households [43]. The drawbacks of these technologies are lack of communication possibilities when implementing renewable energy resources.

However, there are systems in use for load management control with use of renewable energy, in combination with other energy reduction methods. Outside Arendal in Norway, an area with ZEB is tested. ZEB produce all its energy, and the net consumption for a year of energy is zero. This is accomplished by selling excess energy to the grid operator, and repurchase it when the consumption exceeds production [44]. From an EWH point of view, this system can be further developed. For the system in Skarpnes, the PV is used when it is available. However, by storing this energy in an EWH, the energy can be used when the electricity peak occurs later when the PV is not available.

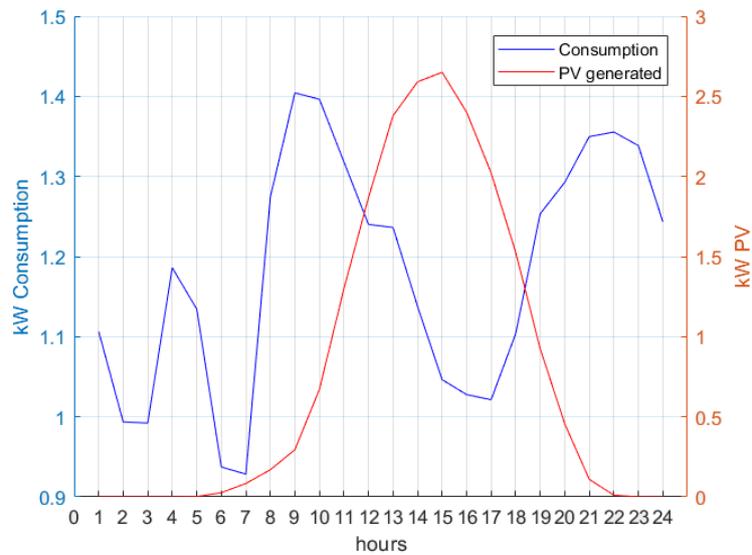


Figure 2.4: Consumption vs PV-production for a passive house at Skarpnes.

On the other hand, figure 2.4 emphasises another problem, which may occur if the energy produced from renewable energy sources which are becoming more conventional for households to invest in. The prices for PV-systems have and is conditioning to decrease, meaning that there is seen an increase in the last years of households which now has installed solar cells. According to MultiConsult the combined capacity for the installed solar energy systems in Norway by the end of 2017, is now exceeding 45 MWp[45]. This raises for the challenge of creating new peaks in the grid. As the solar systems are increasing in capacity, the output is increasing as well, which means the correspondence between used and produced electricity increases. All of this electricity is produced at the same time in one area, and the grid needs to handle a new peak of receiving produced electricity. Energy storage would reduce the new peak as the energy produced is stored, instead of sent to the grid.

### 3 Method

This section covers the method used for designing a sufficient model, for developing a controller. The controller can either be designed with the use of a mathematical or a physical model. For this thesis, the physical model is used, and section 3.2 presents the constraints and limitations of which are present for experimenting. Section 3.3 introduces the fundamental equations necessary for developing the water usage profiles. Water profiles are necessary for getting comparable results across experiments. In section 3.4 the water-based profiles are presented, and in section 3.5, the different electricity consumption profiles are presented.

#### 3.1 Method for designing a sufficient controller

To design a sufficient controller, it is essential to examine the behaviours and change of temperature in the tank during discharges and heating. In this thesis, the approach is to test the controller with different water usage and consumption profiles with and without PV stored energy. Some experiments with short time-span should be executed first, to see the temperature behaviour in the tank, before the logic for the controller is designed. This would provide information towards how the behaviour changes with different water usage and with storing of PV produced energy. When an acceptable controller is developed with a corresponding logic of temperature control, the controller should be tested with random water profile to test the behaviour when the demand is uneven.

In this thesis, there is no development or use of mathematical models for temperature estimations. The justification for not implementing any temperature estimation is based on the physical model which needs to be designed. Besides, when running experiments, the water demand is higher than what is expected for a tank of this size. The approach would reduce the overall energy storage capabilities as the system needs to be designed for high consumption each day. However, by designing for large water consumption every time, the complexity of the system is reduced.

#### 3.2 Experimental constraints and limitations

In this section, the constraints for experiments is presented. Due to time-consuming experiments, there are some limitations which need to be addressed before experimenting. The constraints have a direct impact towards the amount of data, and the result of the control design.

##### 3.2.1 Time to develop a sufficient LabView program

To design a controller, it is necessary to modify a water tank to get temperature and consumption information. When running experiments, there is not possible to decrease the overall experimental time. For comparing different situations and profiles, a considerable number of tests is required. Whereas the idea for each profile is quite easy, it is time-consuming developing the profile in LabView, and to assure that it functions according to the description. Besides, there are different components which need to be modified to communicate with LabView.

### 3.2.2 AMS communication

In Norway, there is no grid operator which delivers AMS with communication module as standard to customers. The justification for this is the consultation presented by NVE mentioned in section 1.1.1. Until it is stated how the new electricity tariffs are going to be, the operators await the interface between customer and AMS. As of today, every AMS system installed in households is delivered without any communication unit. Also, there are numerous parts of the AMI system which need to be decided before the AMS communication is available for the household.

NVE has overall responsibility for the AMI, but it is The Norwegian Data Inspectorate (Datatilsynet) which is responsible for ensuring the security of personal data. They pointed out that the new and extensive data acquisition, which the AMS technology offers, may conflict with the personal data regulations. Datatilsynet has concluded that the only information the grid operator can collect without any extended agreement from the customer, is the data which is relevant for determining the correct price for delivered power[46]. If the operators want to collect information about consumption in a shorter interval, e.g. time-based consumption, an exclusive agreement is needed. Hourly consumption may be necessary for individual agreements where the customer's price is deepened over time of use as in table 1.1 model 4.

All the AMS installed in Norway uses the HAN interface. Every AMS is delivered without the communication unit. However, every household in Norway may request this unit, which the operator should deliver and activate for free. The data from the unit is not encrypted, as a result of that activating the interface is not mandatory. The information which the customer can access is live consumption, voltage quality and time-based consumption. This can quickly be further developed to work with mobile applications and other smart system components[47].

### 3.2.3 PV system limitations

For this system, there is a PV mounted on the roof of UiA, located in Grimstad, Norway with a peak of 1 kW. This is only 50% of the output of the heating element which has a fixed output. In the program, there must be set a minimum production before the heating element is enabled. If that value is lower than the rated power of the element, grid-electricity needs to be used. Due to the low output of the PV system, every time the element is on, it would use grid-electricity. This has to be accounted for to ensure that the net-consumption from the grid is documented.

In pursuance of storing the PV produced energy as hot water, the system is not able to be self-sufficient with only PV. To justify the output of the available PV system, the output is amplified to 2 kW in the program. Doubling the production would not have any impact on the rest of the controller, as the essential information from the PV, mainly when the system is producing electricity, remains unaffected.

Another limitation of the PV system is the angle at which the panels are mounted. At UiA, the panels are installed to a pre-fabricated frame which tilts the angle of the panels to 40 degrees. According to the PVGIS, the optimum angle is 44 degrees[48], see appendix C.4.4.

### 3.2.4 Tank constraints

To get sufficient data from the experiments, the heating element needs to be controlled. This needs some considerations towards protection of the element itself and the environment. The controller needs to prevent the tank from overheating as the internal thermostat may be disconnected. Besides, an interlock needs to be designed to ensure that the element is prevented from reconnecting to fast after disconnections. Also, it is important to prevent the temperature in the tank to decrease too low to prevent the growth of legionella bacteria. The bacteria survive in water which has a lower temperature than  $60^{\circ}\text{C}$  and has an ideal condition in temperatures between  $20 - 45^{\circ}\text{C}$ . To ensure that there is no bacteria growth in the tank, the lowest temperature in the tank should not decrease below  $60^{\circ}\text{C}$  for longer periods[49].

### 3.3 Fundamental water equations

When discussing energy stored in a water tank, it is referred to energy in water which has a given temperature. By adding energy to the water, temperature increases and the potential energy stored increases. The overall energy in a tank with fluid, according to the law of conservation is,

$$Q_{\text{total}} = Q_{\text{added}} - Q_{\text{removed}}, \quad (1)$$

where  $Q_{\text{added}}$  is the added energy (J) and  $Q_{\text{removed}}$  is the energy (J) removed from the tank. The added energy is referred to as the energy added by the heating element. Accordingly, the energy out of the tank is heat loss to the environment and discharges from the tank. The energy in a fluid ( $Q_{\text{fluid}}$ ) follows a thermodynamic formula and is described as

$$Q_{\text{fluid}} = m \cdot c_{p,\text{fluid}} \cdot \Delta T, \quad (2)$$

where  $m$  is the amount of fluid (kg),  $c_{p,\text{fluid}}$  is the specific heat for fluid ( $\frac{\text{J}}{\text{kg}\cdot\text{K}}$ ) and  $\Delta T$  is the change in temperature (K). Equation 2 is used for defining the energy in and out when using water. Also, the energy in the tank is depended on the heat loss from the tank to the environment. The energy loss for a tank is depended on the size and the temperature of both the fluid and environment. The rate of heat loss, or conductive heat transfer(Fourier's Law) and can be expressed as,

$$\dot{Q} = U \cdot A \cdot \Delta T = \frac{k}{s} \cdot A \cdot \Delta T, \quad (3)$$

where  $\dot{Q}$  is the heat loss ( $W = \frac{J}{s}$ ),  $U$  is the total heat transfer coefficient( $\frac{W}{m^2\cdot K}$ ),  $k$  is the thermal conductivity of material( $\frac{W}{m\cdot K}$ ),  $s$  is the thickness of the material(m),  $A$  is the area of the tank ( $m^2$ ) and  $\Delta T$  is the temperature difference (K) between the water and environment.

Equation 2 and 3 is important equations for use with a hot water storage. For designing a functional controller, both the energy in the tank, as well as the energy loss (heat) to the environments need to be considered. A regular household tank is not designed for collecting this information and would need extensive modifications. Especially the heat loss is difficult to calculate as the manufacturer of the chosen tank does not have any information regarding the heat loss rate,  $\dot{Q}$ . An approach to calculating the heat loss is to measure the flux through the wall of the tank. The flux ( $W/m^2$ )with reference to

equation 3 is known as the total heat transfer coefficient  $U(\frac{W}{m^2 \cdot K})$ . In this thesis, the tank would be used regularly for adding cold water and discharge hot water daily. With this in mind, heat loss is not addressed for designing the controller.

### 3.4 Water usage profiles

For designing an acceptable controller, different water usage profiles needs to be as comparable to actual consumptions as possible. Creating user profiles for every situation and households are challenging. For this thesis, three water profiles, and two consumption based profiles are developed and tested. All the profiles can be run simultaneously at any given time.

#### 3.4.1 Electricity consumption-based water profile

Considering that EWH uses approximately 20% of the total electricity consumption in a household, a water profile is developed from the overall electricity consumption. Using consumption statistics to estimate water usage is a good representation of water usage for a household. Using the figure 2.2 as a reference, it can be seen that considerable use of water in the morning and the evening occurs. This would be the outcome of this water profile as well. For estimating the hot water from the tank, average electricity consumption for a house in Norway is used. According to NVE, an average Norwegian EWH has an electricity consumption of 2600 kWh/year[50], which is 7.12 kWh/day and accordingly with two discharges each day 3.56 kWh/discharge, henceforward referenced as  $P_{case,1}$ . By using equation 2 an expression for the amount of discharge based on temperatures can be expressed as,

$$m_{case,1} = \frac{P_{case,1} \cdot 3.6 \cdot 10^3}{c_{p,water} \cdot (T_{tank} - T_{inlet})}, \quad (4)$$

where  $P_{case,1}$  is the power consumption for the discharge(kWh),  $c_{p,water}$  is the specific heat for water at  $20^\circ C$  ( $\frac{J}{kg \cdot K}$ ),  $T_{tank}$  is the tank temperature (K) and  $T_{inlet}$  is the inlet temperature (K).The expression ensures that the right amount of water is discharged depending on the temperature in the tank and inlet. Figure 3.1 illustrates an example of two discharges calculated with the equation 4.

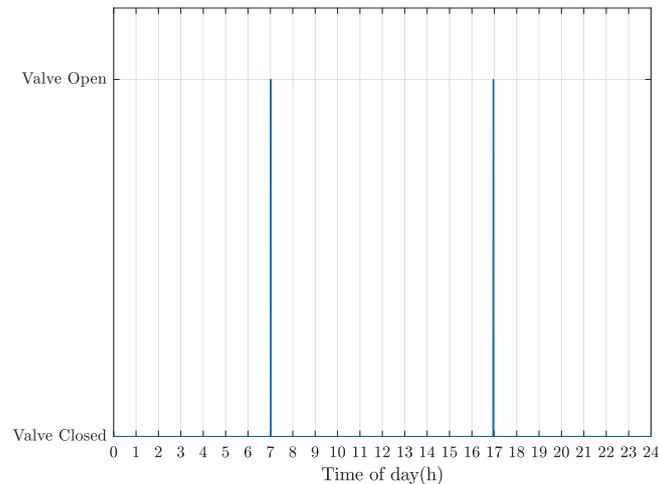


Figure 3.1: Example of two discharges calculated from eq 4

### 3.4.2 Average household consumption per resident water profile

As reported by Statistics Norway, an average resident in Norway used 190 liters/day in 2016[51]. Originating from this information, a water profile may be composed. 190 liters is total water consumption which includes both hot and cold water for any water consumption in a community. An article written for Statnett in 2005, presented a hot water consumption only of 100 liters/day [52]. Using the information from the article and Statistics Norway, there can be approximated that 120 of 190 litres is hot water for shower, hand wash etc. in a household, per capita. The remaining 70 liters is for other water demands such as toilets and other households appliances(Dishwasher, washing machine, i.e.). From this, and using equation 2 an expression for the profile is,

$$m_{h,water} = \frac{120 \text{ kg} \cdot n \cdot (T_{use} - T_{in})}{(T_{tank} - T_{in}) \cdot N}, \quad (5)$$

where  $m_{h,water}$  is the amount of water discharged(kg),  $n$  is the number of persons the tank supplies with water, and  $N$  is the number of discharges during the day. This profile allows the consumption to be based on a number of persons, and change in temperature in the tank and inlet is considered. in figure 3.2, the average consumption during a day for four people and five valve openings is illustrated as an example.

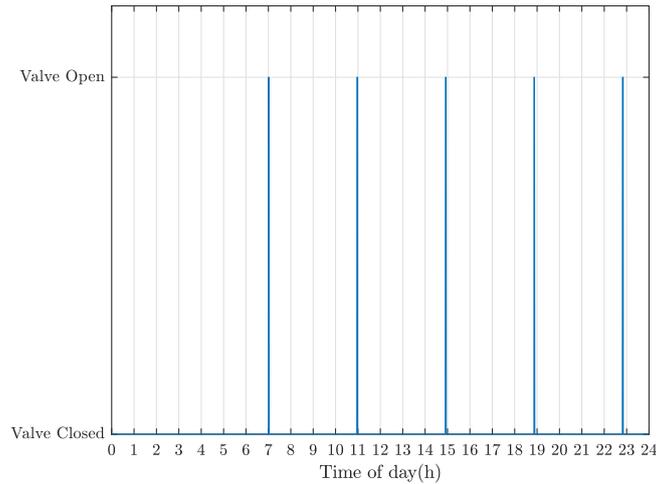
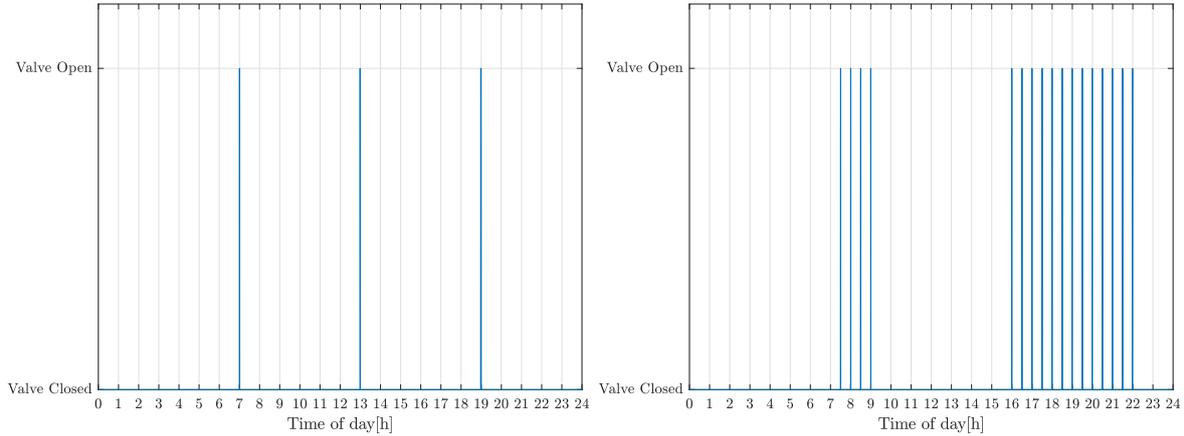


Figure 3.2: Example of valve openings for average consumption per resident water profile

### 3.4.3 Random consumption water profile

Regardless of the number of water profile designed, a profile for every situation and household is not possible to test. To ensure a most fitting controller, a random consumption profile will test the controller. In this profile, the consumption is not known and is decided by selecting a random valve opening time. Activating this profile will illustrate if a controller is capable of uneven water demand. The profile can be divided into two consumption profiles, where one frequently has valve openings with small discharges, and one has more massive discharges but less frequent. Examples of valve openings during one day are illustrated in figure 3.3.



(a) Three large random discharges during one day (b) Multiple small random discharges during one day

Figure 3.3: Example of valve openings for random water profile

### 3.5 Electricity consumption profiles

With the expected implementation of fluctuating electricity prices, it is necessary to introduce consumption profiles to reduce the overall price for electricity. For this thesis, two consumption profiles are presented. For all cases, the user-comfort is the restriction. In a case where the temperature in the tank is too low, the heating would start until the temperature is at the lowest temperature acceptable. As for the water profiles, all the consumption profiles can be run simultaneously at any given time.

#### 3.5.1 Reduce grid peak and cost of water usage profile

As figure 2.2b illustrates that the load demand at the grid has two peaks during the day. For the designing, this controller, an approach for relocating the grid demand from EWH to low demand periods can be reviewed. For this profile, the intention is to shift the load from the heater during different water profiles and overall reduce the cost of water usage. The electricity price is presented in figure 3.4 and it is based on that electricity consumption during peak periods is significantly more expensive than other times. To do so, the profile corresponds to the "Time of use" model presented in table 1.1. Also, to minimise the price, this also functions as to move the consumption to low-demand periods of the grid. Besides, this has to be accomplished without affecting the user-comfort for the household.

Figure 3.4 shows how the price of electricity may change during the day. The change of prices changes following the total household load demand presented in figure 2.2b, which shows low demand during the night and high demand in the morning and evening. In the middle of the day, there is a slightly higher demand than during the night. The substantial price difference is high but is selected to have a significant impact on consumption during high demand periods. Overall there is an expectation of a considerable increase in the electricity price in 2018 [53].

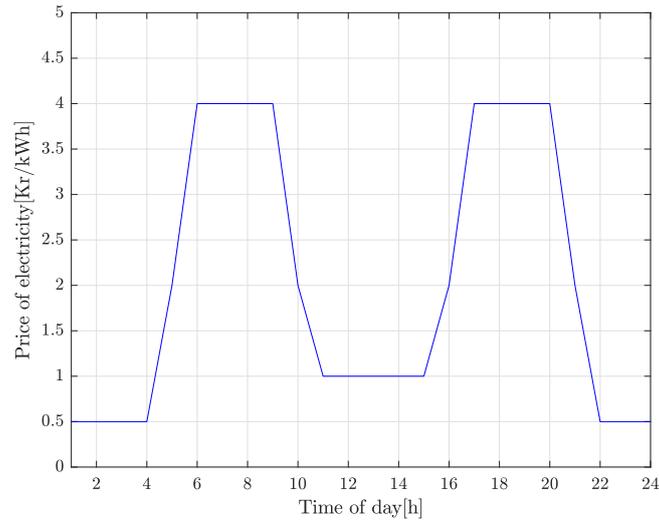


Figure 3.4: Estimation of fluctuating electricity prices during a day

### 3.5.2 Normal electricity consumption with utilization of PV produced electricity

For this profile, the grid consumption should be reduced to a minimum. This is done by utilising all the PV energy available and deliver electricity from the grid to EWH to ensure user comfort. The consumption which is based on the electricity prices today. The different price agreement is explained under in table 3.1. Also, the presented prices are also compared with the agreement from Otovo, explained in section 1.1.2.

Table 3.1: Electricity prices for the experiment location provided by Agder Energi[6]

Description	Fixed Amount [Kr]	Consumption [øre/kWh]	Power tariff summer [øre/kW/month]	Power tariff winter [øre/kW/month]
Grid tariff	162.5	50.1		
Grid tariff season				
Summer(May-Oct)	162.5	38.55		
Winter(Nov-April)		56.35		
Grid tariff without installed AMS	37.5	50.10		
Grid tariff power	65.5	25.88	44.58	133.75
Grid tariff power season				
Summer(May-Oct)	65.5	25.06	44.58	133.75
Winter(Nov-April)		26.71		

### 3.6 Data handling

For each experiment carried out, it is necessary to separate the essential data for comparison between the experiments. This is done by collecting specific data for each experiment for comparison. The main data for comparison is the price for the electricity used during the experiment. For calculating the price of the experiment, the prices presented in table 3.1 is used. The different price tariffs are depending on which agreement the customer wants to use. For a household, the most common is the grid tariff, but all the tariffs are available for every customer. Also, the energy in the tank is compared, because this affects the required added energy for the next day.

For calculating cost  $C_{\text{experiment}}$  (kr) off experiment with the different price agreements in table 3.1, the following formula is used:

$$C_{\text{experiment}} = C_{\text{fixed}} + C_{\text{consumption}} + C_{\text{power,summer}} + C_{\text{power,winter}} - (C_{\text{price,PV}} \cdot E_{\text{produced}}), \quad (6)$$

where  $C_{\text{fixed}}$  is the fixed amount(kr) part(when used for price calculations, the fixed amount is recalculated to daily basis),  $C_{\text{consumption}}$  is the consumption(øre/kWh) part,  $C_{\text{power,summer}}$  is the power tariff summer part (øre/kWh),  $C_{\text{power,winter}}$  is the power tariff winter part (øre/kWh) and  $C_{\text{price,PV}}$  is the price for sold PV electricity(Kr) and  $E_{\text{produced}}$  is the amount of produced PV electricity(kWh).

Another comparison variable is the energy in the tank. The energy is calculated using the the setup presented in section 4.1 and can be calculated using the following formula,

$$Q_{\text{tank}} = m \cdot c_{p,\text{fluid}} \cdot \frac{(T_1 - T_6) + (T_2 - T_6) + (T_3 - T_6)}{3}, \quad (7)$$

where  $m$  is the amount of water(kg),  $c_{p,\text{fluid}}$  is the specific heat for fluid ( $\frac{J}{kg \cdot K}$ ) and  $T_1, T_2, T_3$  is the temperature in different sections of the tank(K) and  $T_6$  is the outside temperature(K).

## 4 Electric Water Heater Model

This section presents the model used for experiments necessary to design a functional controller. In section 4.1 the physical model is presented with a description of modifications done to the heater. Section 4.2 covers the developed LabView program used for control. Figure 4.1 illustrates a layout of the system. All components used, are described in appendix C.

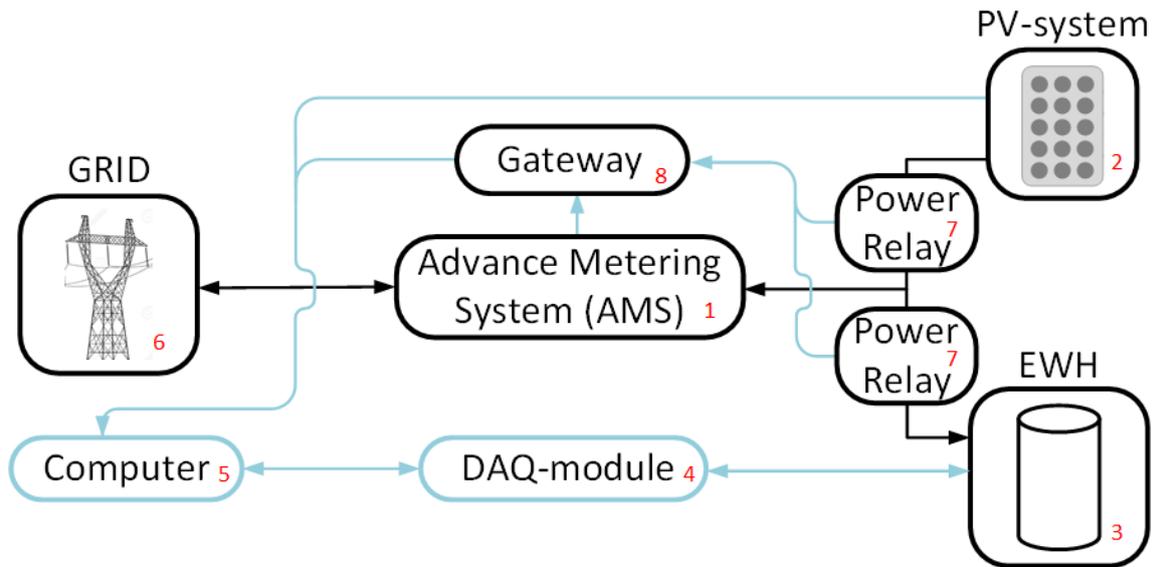


Figure 4.1: Physical setup of the complete system with signal and power layout

1. The advanced metering system is the standard measuring unit which is now being installed in every household in Norway.
2. The PV-system has a peak production of 1 kW and is installed at the roof of University in Agder's facility in Grimstad, Norway.
3. The EWH has a capacity of 190 liters and a 1.95 kW heating element, suitable for a household with four people.
4. The DAQ-module is communicating with EWH(2) for temperatures and controlling the heating element.
5. The computer is used for collecting data from the gateway regarding net consumption for the system, and in combination with the DAQ-module controlling the EWH.
6. The grid supplies the system with 230 volts and receives electricity from the PV(2).
7. The power relays are used for comparing the information from the EWH(3) and PV(2) system regarding power consumption and producing.
8. The gateway collects information from the AMS(1) and the relays(7) and sends it to the computer.

## 4.1 Physical model

This section covers the experimental setup. Figure 4.2 shows a picture of the system with the position of temperature sensors. Exact measures concerning distances and placement of sensors are presented in appendix B.1, and includes a sketch of the tank. The tank is modified with three sensors located at different heights to see temperature difference. Besides, there is a temperature sensor located on the wall outside the tank to measure the surrounding temperature. The outlet is controlled by a valve to simulate water usage. The computer controls the heating element.



Figure 4.2: Picture of the modification done for the tank

From the figure 4.2 it can be observed that there is a flexible tube connected to the base of the tank and a drain located on the wall. The tube is required because a pressure valve which opens if the pressure in the tank exceeds 8 bar. This valve is provided by the manufacturer and recommended to install close to a drain, as the valve may open at any time.

At the top of the tank, there is mounted a junction box for collecting all the wiring from the tank. The wiring scheme can be seen in appendix B. The junction box is equipped with two switches for the two relays inside, accordingly for valve and heating element. Figure 4.3 is a close up of the switches. Appendix B.2 includes the wiring scheme in the box.

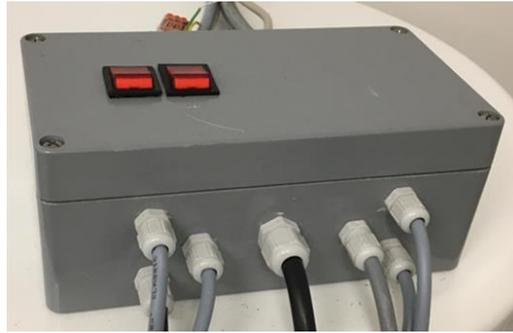


Figure 4.3: Picture junction box mounted at the tank

For collecting the measurements and controlling the tank, the DAQ module with the power supply is placed to the side of the tank. From the module, a USB-cable is connected to the computer for communication with the LabView program. Figure 4.4 shows the DAQ and voltage power supply. The connections are done in correspondence with the wiring scheme in appendix B.3.

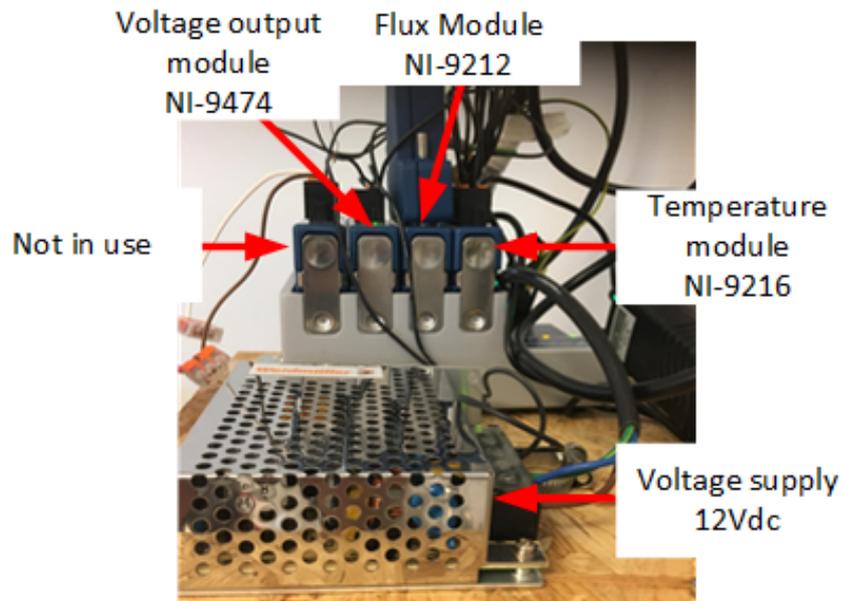


Figure 4.4: Picture of DAQ located at the tank for collect information

## 4.2 LabView Program

This section covers the development of the program. For software LabView 2017 is used, together with a cDAQ from National Instruments (all components is listed in appendix C). The program henceforward references as the VI, is divided into small sub-programs, named subVI to reduce the complexity of the program and for reducing the time for debugging. First, in this section, the overall functionality of the program is presented followed by a presentation of the to main subVI's with an explanation of functionality. For hierarchy presentation of the complete program, see appendix D.1. A layout of each block program is presented in appendix D.2. In addition, the variables which the controller may use is listed in appendix E.2, table E.1.

### 4.2.1 Main program

The main program is built up of two subVI's further described in the following sections in addition to the water profile and consumption profiles described in 3.4 and 3.5. The user selects the temperatures in the tank and which profile to use using the HMI showed in figure 4.5. The different parameters which need to be set are described in appendix E.1, table E.1. When the program starts, a check of PV production is done, and if available, the maximum temperature in the tank is increased to store the produced electricity as hot water.

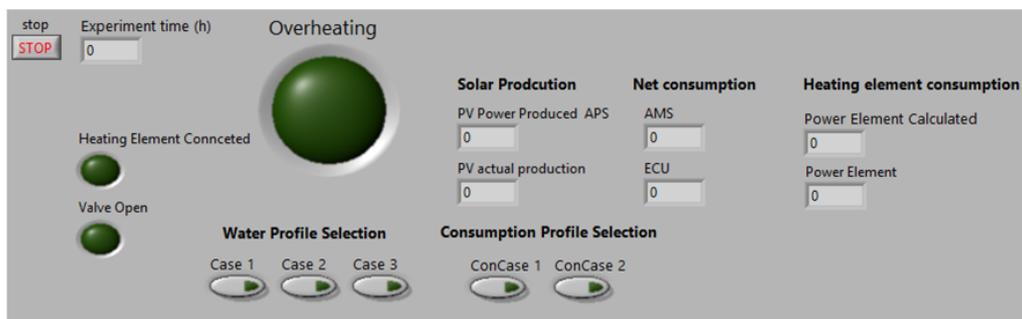


Figure 4.5: Print screen of the main HMI

#### 4.2.2 Tank data and control

As seen in figure 4.2 the tank has been modified with temperature sensors and valve control and is the main part of the program. As mentioned in section 3.2.4, the heating element is disconnected from the thermostat inside the tank. To maintain the function of preventing overheating the water to a dangerous temperature, a safety switch is implemented in the program. The switch disconnects the element power and opens the valve if the temperature is rising over  $100^{\circ}\text{C}$ . This is done independently of any other sequences or commands executed. For protecting the element, there is implemented a delay time of 1 hour which prevents the heating element from reconnecting after it has been turned off. The VI for the tank is presented in appendix D.2.2.

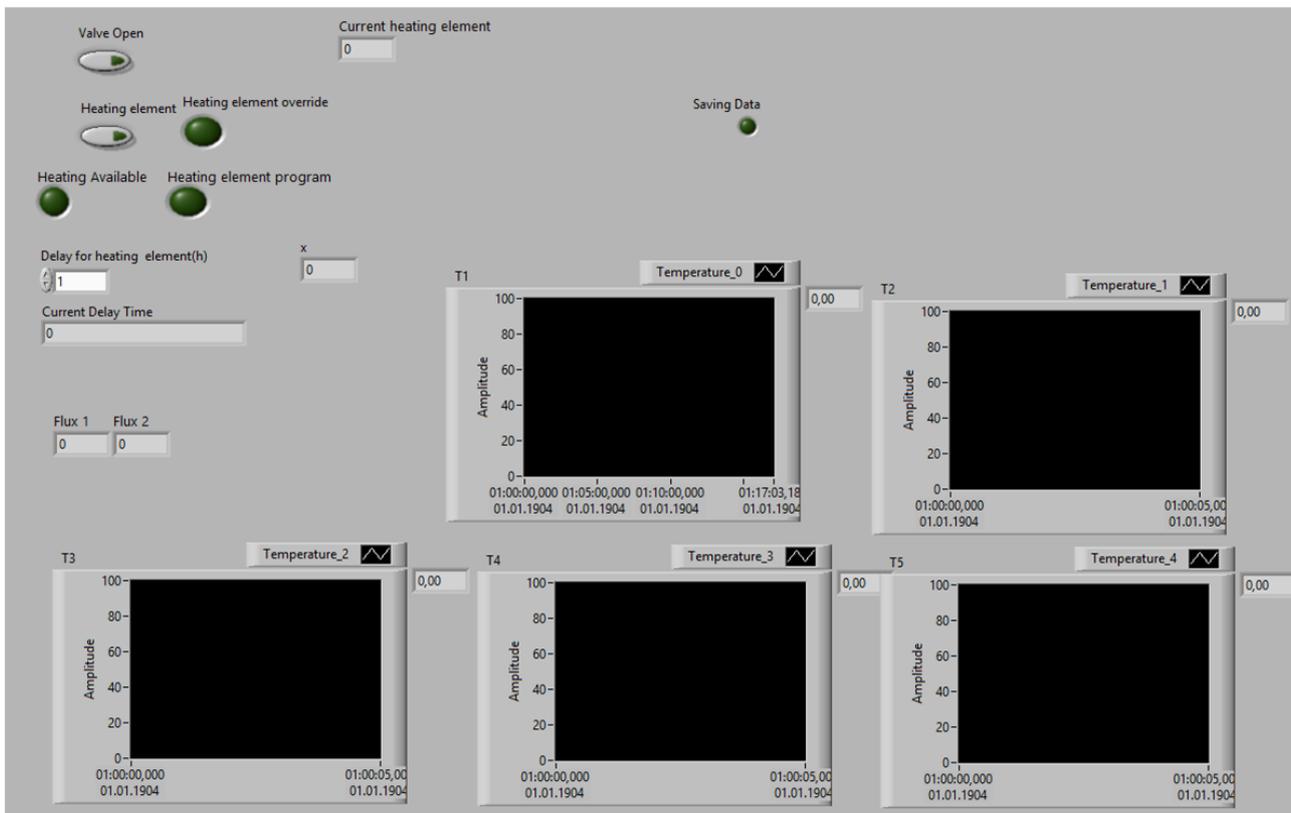
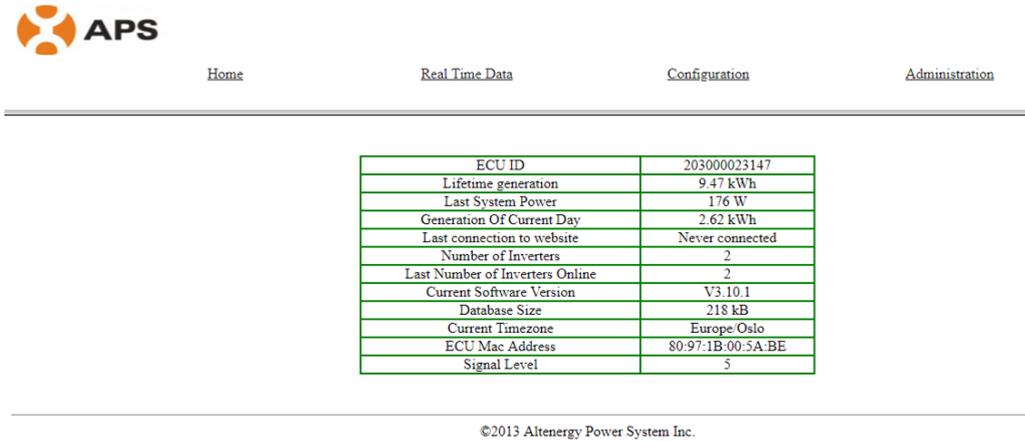


Figure 4.6: Print screen of the tank HMI

An HMI for the tank shown in figure 4.6. This gives the operator an overview at any time with temperature in the tank, inlet and outlet. Also, the HMI includes an override of both heating element and valve. Besides, the time the heating element has been disconnected is shown in seconds.

### 4.2.3 Collecting solar data

For collecting the information from the ECU, a VI is designed to scrape the webpage interface from the ECU seen in figure 4.7. This is updated automatic and provide information about each panels production, temperature, voltage and frequency.



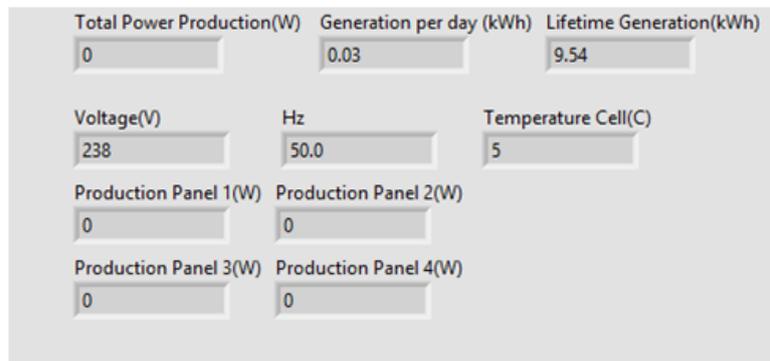
The screenshot shows the APS web interface with a navigation menu (Home, Real Time Data, Configuration, Administration) and a table of system statistics. The table is as follows:

ECU ID	20300023147
Lifetime generation	9.47 kWh
Last System Power	176 W
Generation Of Current Day	2.62 kWh
Last connection to website	Never connected
Number of Inverters	2
Last Number of Inverters Online	2
Current Software Version	V3.10.1
Database Size	218 kB
Current Timezone	Europe/Oslo
ECU Mac Address	80:97:1B:00:5A:BE
Signal Level	5

©2013 Altenergy Power System Inc.

Figure 4.7: Print screen of the ECU web interface

When scraping a webpage, all the formatting from the page is included in the information. In LabView, the scraped information is sent through a series of blocks to remove any unwanted formatting information, as a print screen in appendix D.2.1 illustrates. For every iteration of the program, all the information possessed is stored in a log file for easy access. Also, an HMI is created to give a visual presentation of current information from the solar panels. The HMI is shown in figure 4.8



The screenshot shows the HMI interface with the following data:

Total Power Production(W)	Generation per day (kWh)	Lifetime Generation(kWh)
0	0.03	9.54
Voltage(V)	Hz	Temperature Cell(C)
238	50.0	5
Production Panel 1(W)	Production Panel 2(W)	
0	0	
Production Panel 3(W)	Production Panel 4(W)	
0	0	

Figure 4.8: Print screen of the HMI of solar panels information in LabView

In addition to the ECU production information, the power relay also logs the production of electricity. This is done to compare the measured production with actual production, and the expected production from the site, which is explained in appendix C.4.4.

## 5 Developing experiments

This section covers the experiments done for modification and further developing the controller. For each experiment, the results are analysed and used in following experiments. A total of 3 experiments, where two of the experiments includes a sub-experiment is executed. As presented in 4.2, there are parameters which need to be set for each experiment. Nevertheless, in both experiments expect the heating experiment presented in section 5.1, many of the parameters are constant and is shown in table 5.1. The description of each parameter is explained in appendix D.2.3. Each experiment is carried out twice to compare situations with both with and without PV production where this is required. Each experiment is started with a tank temperature of  $60^{\circ}C$ . The experiments which are executed are 24 hours experiments. The information collected from these experiments is used to develop and improve the controller for more extensive experiments. All the data used for comparison is listed in appendix H. For all experiments, the tank temperature is referenced as the temperature sensor  $T_1$ . Besides, the price of the experiments is calculated for comparison with further experiments.

Table 5.1: Parameters which are equal for every experiment

Parameter name in VI	Value
Length of experiment	24 Hours
Experiment start temperature in tank	$60^{\circ}C$
End temperature tank grid	$70^{\circ}C$
Low temp tank	$66^{\circ}C$
Delay for heating element	1 Hour
End temperature PV	$90^{\circ}C$
Min PV prod for heating(ECU)	400 W
Delay time	1 Second
Critical max temperature	$100^{\circ}C$
Critical Low	$60^{\circ}C$
System flow	$0.37 \frac{l}{s}$
Temp water usage	$38^{\circ}C$

As table 5.1 illustrates, the information about PV production in the experiments is collected from the ECU. The reason is to reduce the number of components needed by the controller. As mention in 4.2.3, the information is gathered from the web interface produced by the ECU.

## 5.1 Heating

In the interest of validating the added energy from the heating element corresponds with the increase of energy in the water, a heating experiment is performed. Also, the experiment provides information about the efficiency of the tank. First, the tank is filled with cold water by opening the valve for 10 minutes, before the experiments start. During the experiment, the power consumption to the tank is measured for calculations. First, the estimated heating time  $t_{\text{heat}}$  is calculated using equation 2 and the rated power of the element.

$$t_{\text{heat}} = \frac{Q_{\text{heat}}}{P_{\text{element}}} = \frac{m \cdot c_{p,\text{water}} \cdot \Delta T}{P_{\text{element}}}, \quad (8)$$

where  $P_{\text{element}}$  is the rated power of heating element (kW) and  $c_{p,\text{water}}$  is the specific heat for water. As the temperature increases,  $c_{p,\text{water}}$  would change. However, the change is approximately  $0.006 \left(\frac{\text{kJ}}{\text{kg}\cdot\text{K}}\right)$  for the temperature range  $10 - 80^\circ\text{C}$ , and is therefore neglected. The specific heat for  $20^\circ\text{C}$  is used for this calculation. The start temperature (cold tank) for the test is measured to be  $7^\circ\text{C}$  at the height of the  $T_3$  sensor. End temperature in the tank is set to be  $80^\circ\text{C}$ .

$$t_{\text{heat}} = \frac{194 \text{ kg} \cdot 4.18 \frac{\text{kJ}}{\text{kg}\cdot\text{K}} \cdot (354\text{K} - 280\text{K})}{1.95 \text{ kW}} = 30773 \text{ s} \approx 8.54 \text{ hours}. \quad (9)$$

This is the theoretical heating time and is compared with the actual heating time and rated heating time in figure 5.1.

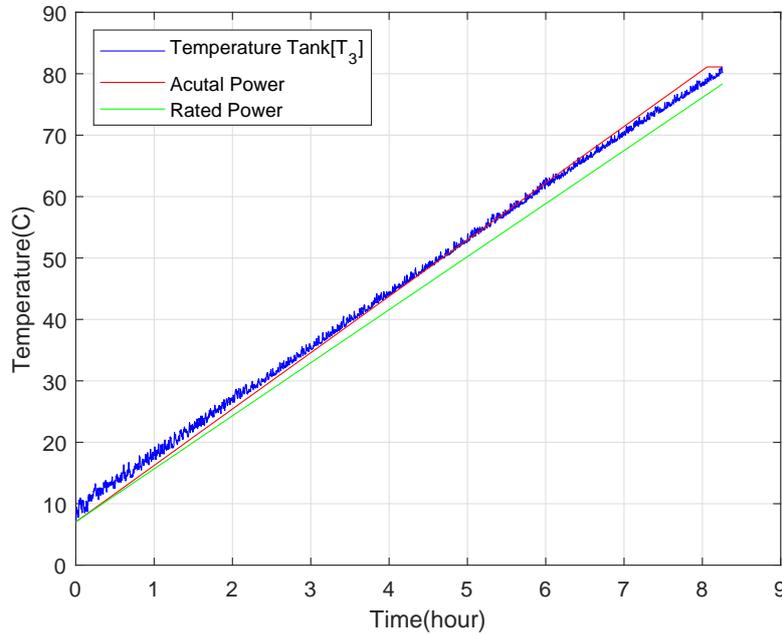


Figure 5.1: Temperature increase based on measured power and rated power delivered compared with actual temperature  $T_3$  increase

As seen in figure 5.1 the heating time to  $80^{\circ}\text{C}$  degrees can be seen to be 29690 seconds or 8.24 hours. This is lower than the heating time calculated in equation 9, and is not possible. However, looking at the heating time based on actual power<sup>8</sup>, it shows that the heating time is longer. From the data which measures the power sent to the tank, there is a higher power sent to the element, compared with the rated power.

As illustrated in figure 5.1, comparing the actual temperature increase with the expected with rated power, and with actual power shows some unlikeness. Table 5.2 list the actual heating times illustrated in figure 5.1.

Table 5.2: Heating time comparison

Heating time in seconds	
Actual power	29012 seconds
Actual heating time	29690 seconds
Rated Power	30773 seconds

It is seen that the heating time based on delivered power is lower than the actual heating time, which can be explained due to losses in the system. Based on the heating times, a thermal efficiency,  $\eta_{th}$  for the system is calculated:

$$\eta_{th} = \frac{29012 \text{ s}}{29690 \text{ s}} = 0.98 \quad (10)$$

The losses from the efficiency calculations are 0.022 and can be explained by heat loss to the environment.

---

<sup>8</sup>The power of the element varies with time due to change in grid voltage and is calculated every iteration during the experiment

## 5.2 Experiment 1: Temperature change in the tank when aiming to reduced grid peak and cost of heating

In this experiment, the average consumption water profile introduced in section 3.4.1 and 3.4.2 is executed with the consumption case presented in 3.5.1. The purpose of combining these cases is to investigate if the EWH can be disconnected for the whole time between the grid peak in the morning and evening with a large discharge. As figure 3.4 illustrates this would result in only using electricity in low-cost periods during the night. For this experiment, the discharged is for a four-person household with four dischargers per day.

### 5.2.1 Experiment 1a: Without PV produced electricity

Figure 5.2 illustrates the temperature change during the experiment time with the valve openings and heating element illustrated. The heating element and valve opening is multiplied with respectively 50 and 4 to illustrate when the heating is activated, and the valve is open.

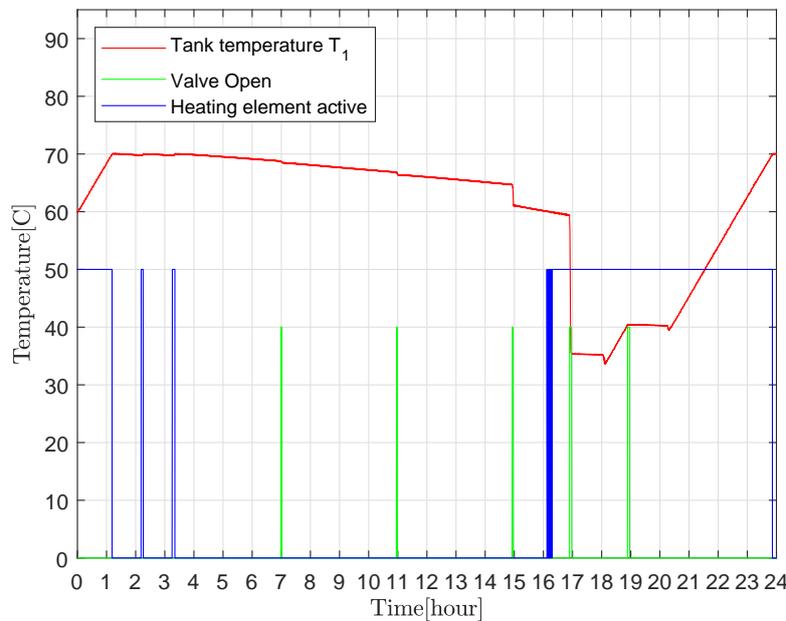


Figure 5.2: Temperature in the tank with average and electricity based water consumption and no PV production

From the figure 5.2 it is outlined how the temperature in the top of the tank is changed. When the experiment starts, the element is connected to the tank temperature of  $70^{\circ}\text{C}$  is reached. The element is then disconnected twice for 1 hour before it is reconnected to keep the temperature at  $70^{\circ}\text{C}$  when the price is low. During the day and the next two discharges, the temperature is decreased, with the only minor effect of each discharge. When the third discharge occurs, the temperature drops approximately  $2^{\circ}\text{C}$  to  $60^{\circ}\text{C}$ . At this point, the temperature is close to the absolute minimum acceptable temperature in the tank and crosses the temperature when the valve opens. Because of the minimum temperature is reached, the element is reconnected to keep the temperature over  $60^{\circ}\text{C}$ .

For the next two discharges, the temperature is below accepted temperature, and the heating element

is active for the rest of the time and manages to increase the temperature of the tank to  $70^{\circ}\text{C}$  before the experiment ends. The necessary experiment data is listed in appendix H.1, table H.1.

### 5.2.2 Experiment 1b: With PV produced electricity

The experiment is then repeated with PV produced electricity. Figure 5.3 illustrates the temperature change during the experiment time with the valve openings and heating element illustrated. The heating element and valve opening is multiplied with respectively 50 and 40 to illustrate when the heating is activated, and the valve is open.

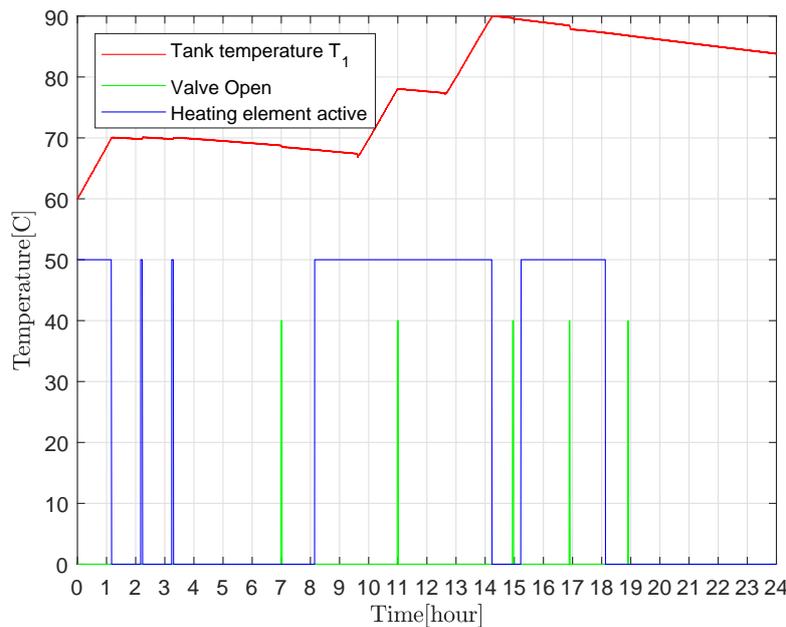


Figure 5.3: Temperature in the tank with average and electricity based water consumption and PV production

Figure 5.3 illustrates the temperature during the experiment. From the start temperature of  $60^{\circ}\text{C}$  the element connects and increases the temperature to  $70^{\circ}\text{C}$ . The element remains off until one hour after the first valve opening. Du the PV production is above 400 W, the heating element is reconnected after one hour. As the production continuous, the temperature increases with some discontinuance due to valve openings during the day. At approximately 14:00 the element disconnects as the maximum temperature of the tank is reached at  $90^{\circ}\text{C}$ . Shortly after, the valve opens and the temperature decreases while there is still solar production. Because of the delay time for reconnection is one hour, the element remains switched off even though the temperature falls below  $90^{\circ}\text{C}$ . As soon as the delay time is passed, the element reconnects and is on until the PV produces less than the required 400 W. The end temperature in the tank when the experiment stops is  $86^{\circ}\text{C}$ .

Figure 5.4a illustrates the electricity used from PV production during the experiment. It can be seen that a large amount of the produced electricity is sent to the tank. Further on, figure 5.4b shows the consumption of electricity from the grid during the experiment. The necessary experiment data for this experiment is presented in appendix H.1, table H.2. The amount of PV utilised for heating can be calculated from the information provided in table H.2,

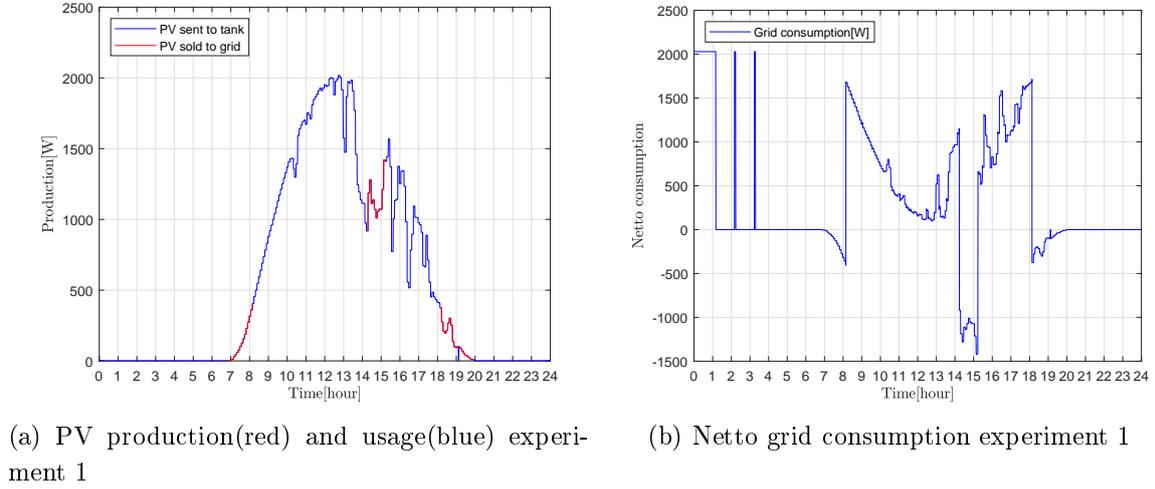


Figure 5.4: PV production and grid consumption for experiment 1 with PV

$$\eta_{PV,ex1} = \frac{11.5 \text{ kWh}}{13 \text{ kWh}} = 0.88 \quad (11)$$

### 5.2.3 Comparison of experiment 1a and 1b

In this section, a comparison of experiment 1a and 1b is presented. The purpose of comparison is to illustrate the consumption profile effect on the tank if there is no PV produced for 24 hours. Figure 5.5 illustrates the temperature  $T_1$ ,  $T_2$  and  $T_3$  during the experiments. When comparing the two graphs,

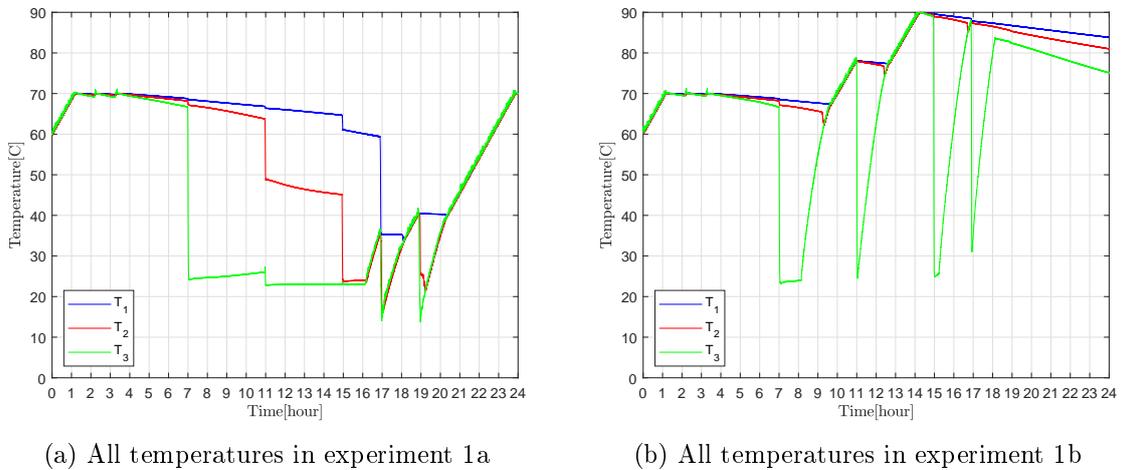


Figure 5.5: Comparison of 1a and 1b temperatures

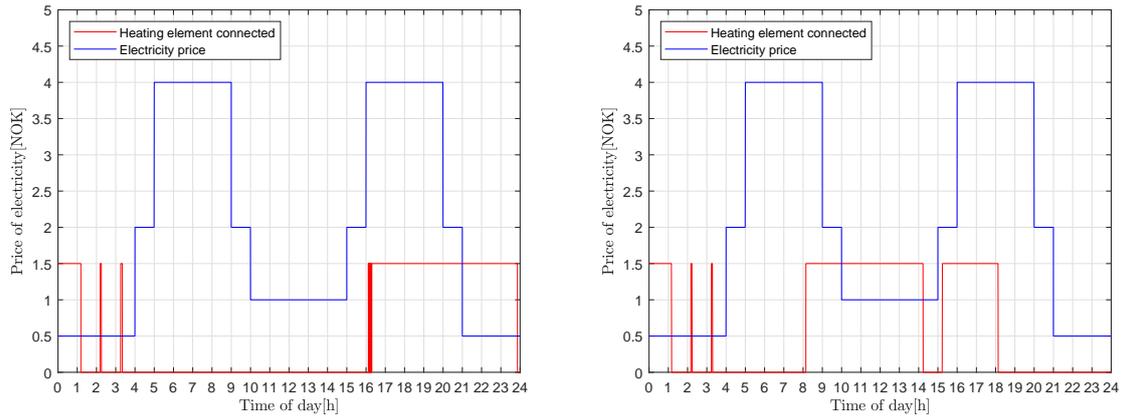
it is seen that the first 6 hours are equal. After the first valve opening, stratification occurs due to the cold water from the inlet in 1a. As for experiment 1b there is also added cold water, but for this case, the PV is producing which connects the heating element and reduces the stratification by heating the added water. For every upcoming valve opening the  $T_1$  decreases for 1a, while it slows down the increase in 1b. As the figure 5.5a shows, the minimum temperature acceptable is reached for 1a and the system is not able to deliver the required outlet temperature, as for the figure 5.5b, where there is sufficient hot water available through the experiment. For both the experiments, the essential comparable segments is presented in table 5.3. The energy in the tank is calculated using equation 7, and the price is calculated using equation 6. For experiment 1b the price of the experiment is calculated twice, first with the use of PV and second with only grid electricity.

Table 5.3: Comparison of key parameters for experiment 1a and 1b

Description	Experiment 1a	Experiment 1b	Unit
Start energy tank	27,582	27.750	kJ
End energy tank	35,776	43,909	kJ
Lowest temperature tank[ $T_1$ ]	35	60	Celsius
End temperature tank[ $T_1$ ]	70	83	Celsius
Electricity consumption all	19	21.5	kWh
Electricity consumption grid	19	10	kWh
Price used electricity	40	21/42.5	NOK
Total exchange of water	315	172	Liters

From table 5.3, the data collected from the two experiments have only minor changes in start energy in the tank, when the experiment starts, which corresponds with the start temperature for both situations is equal at  $60^\circ$ . The end temperature is affecting the energy in the tank, which shows that there is more stored energy in the experiment 1b compared with 1a, when concentrating towards the electricity consumption, it can be seen that for 1b there are two different grid consumptions. The first is the actual consumption due to PV production, while the second is grid electricity solely. Still, the heating element behaviour in 1b is more economical than 1a. This is illustrated in figure 5.6, which illustrating when the heating element is connected, and the price during the period.

Another interesting detail for the comparison is the lowest tank temperature for each experiment, as mention earlier, the temperature should never decrease below  $60^\circ$  due this is the lowest acceptable tank temperature. For a developing point of view, the controller needs to prevent the temperature to decrease below  $60^\circ$  when there is an expected discharge occurring.



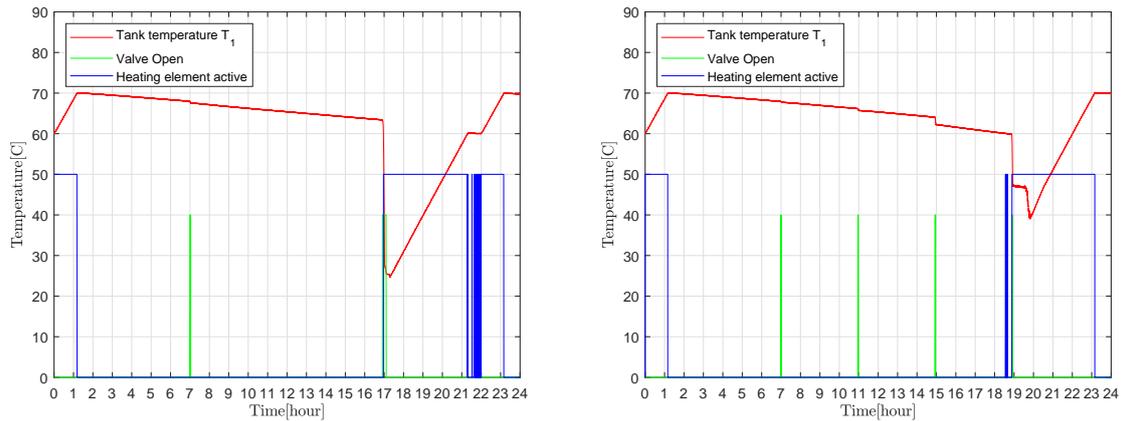
(a) Heating element connected experiment 1a      (b) Heating element connected experiment 1b

Figure 5.6: Comparison of 1a and 1b active heating element

In addition, the amount of water which has been exchanged for each experiment is interesting. In 1a a total of 315 liters is exchanged, where for 1b it is only 172 liters. The discharge amount is based on energy discharge. If the temperature difference between the tank and inlet is low, a more substantial amount of water needs to be discharged, to meet the energy discharge requirement. The valve opening time for both cases is calculated instantly when the valve is programmed to open.

### 5.2.4 Experiment 1c: Water consumption cases independently without any PV electricity

Based on the experience from the experiment 1a in section 5.2.1 it is seen that during the day, the temperature in the tank drops below acceptable temperature before all the discharges are executed. Building on this, two more experiments related to the selected water consumption profile is executed separately. The objective of dividing the two water profiles to investigate if the separate cases can be executed with the electricity consumption profile for one day where PV is unavailable. The result for both water profile is illustrated in figure 5.7. As figure 5.7 reveals, there is not possible to run either of the water consumption profiles during a day without PV production storage and the heating element connected. For figure 5.7a it is seen that the temperature in the tank is approximately  $64^{\circ}C$  when the valve is opened the second time. This corresponds to the temperature drop which occurs in figure 5.2. After this drop, there is no hot water available for the rest of the day. For the average consumption profile, there is hot water available until the fourth valve opening. The critical parameters for the experiment are listed in table 5.4, and shows that there are large exchanges of water due to a low temperature when the valve opens. Again, there is to low temperature in the tank during the experiment, which means that with the current program, neither of the water consumption profiles can be executed with one day without any PV produced energy.



(a) Temperature in the tank with electricity based water consumption (b) Temperature in the tank with average based water consumption

Figure 5.7: Results from the experiment with independently water consumptions profiles

Table 5.4: Comparison of key parameters for experiment 1c

Description	Electricity based water consumption	Average based water consumption	Unit
Start energy tank	27,322	28,643	kJ
End energy tank	34,369	35,447	kJ
Lowest temperature tank[ $T_1$ ]	24	39	Celsius
End temperature tank[ $T_1$ ]	70	70	Celsius
Electricity consumption grid	14	11	kWh
Price used electricity	32	17	NOK
Total exchange of water	324	160	Liters

### 5.3 Experiment 2: Temperature change in the tank when using normal electricity consumption

In this experiment, the same water consumption profiles used in experiment 1 is retested with normal electricity consumption. Building on the results of experiment 1, this experiment includes an electricity consumption which allows the use of grid-produced electricity during the day. First, the experiment is executed without PV, and then again during a day where there is available PV electricity. For this experiment, the price of the experiment is calculated using the tariffs presented in table 3.1.

#### 5.3.1 Experiment 2a: Without PV produced electricity

For experiment 2a, the normal electricity consumption is tested with the average and electricity consumption based water profiles. Figure 5.8 illustrates the temperature change in the tank during the day, with valve openings and heating element connection times.

As figure 5.8 outlines, the temperature increase in the start of the experiment is similar to the other test executed in the experiment in section 5.2. For the first valve opening the heating element remains

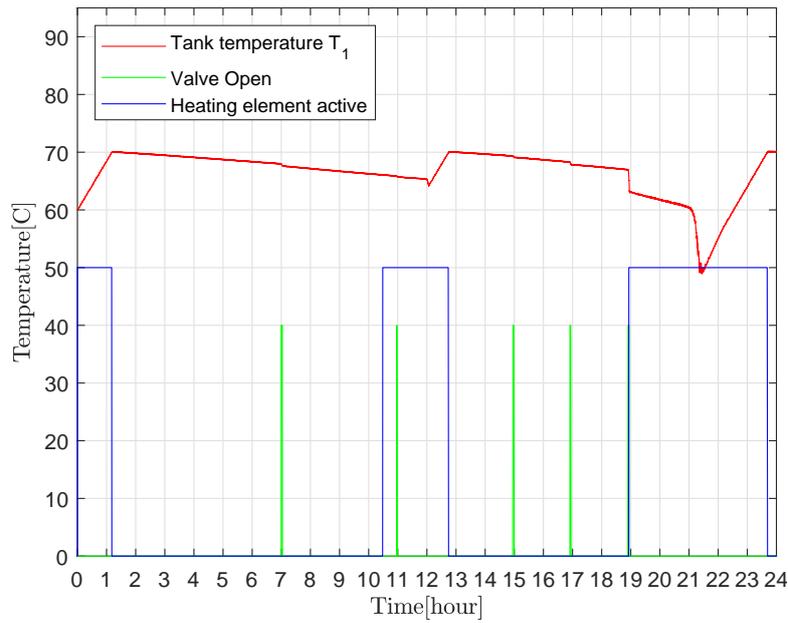


Figure 5.8: Temperature in the tank with average and electricity based water consumption with no PV electricity and normal electricity consumption

disconnected until right before the second valve opening. At this time, the tank temperature is under  $66^{\circ}C$ , and the element is connected during the second valve opening and remains connected for two hours. For the next two valve openings, the element is disconnected and opens when the valve is opened for the third time. Regardless of the element is heating, the temperature decreases down to  $50^{\circ}C$ . The element is connected for almost 5 hours, and the end temperature of  $70^{\circ}C$  is reached just minutes before the experiment is ended. Calculated and collected data is presented in table H.3 appendix H.2.

### 5.3.2 Experiment 2b: With PV produced electricity

The experiment is run once more, but this time, the controller uses PV produced electricity together with the grid electricity. Figure 5.9 illustrates the temperature change during the experiment time with the valve openings and heating element illustrated. As in previous experiments, the heating element and valve opening is multiplied with respectively 50 and 40 to illustrate when the heating is activated, and the valve is open.

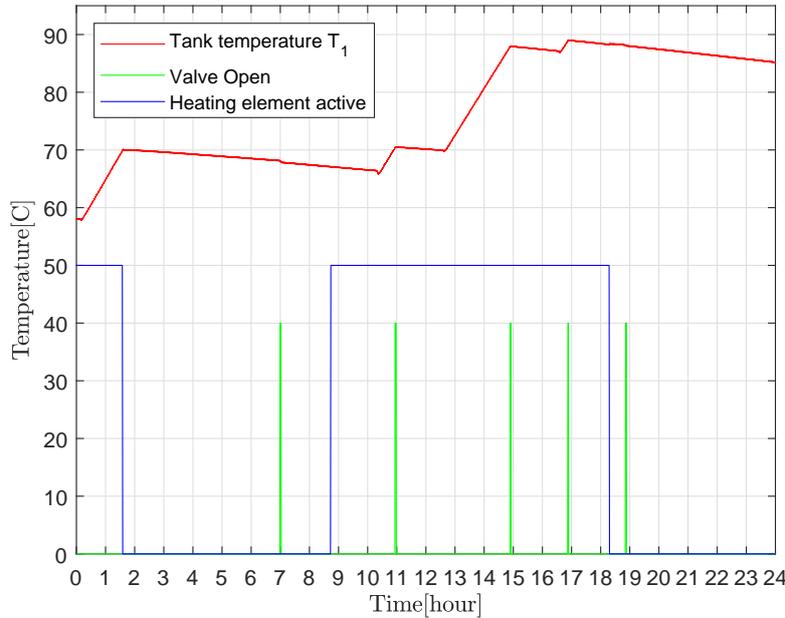


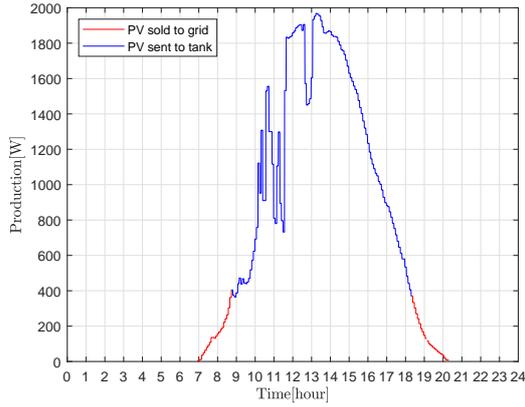
Figure 5.9: Temperature in the tank with PV electricity and normal electricity consumption

It is seen from figure 5.9 it can be seen that the element is disconnected during the first discharge, and is connected at approximately 09:00 due to sufficient PV production. For the rest of the day, the element is connected and increases the temperature with only minor decreases due to valve openings. As the temperature never reaches  $90^{\circ}\text{C}$ , the element is connected for over 9 hours for as long as there is PV electricity produced. When the experiment is stopped, the temperature in the tank is  $85^{\circ}\text{C}$ . Figure 5.10 illustrates both the PV production (a) and grid consumption (b) for experiment. Figure 5.10a illustrates that all the energy which is available for the tank is used to increase the temperature in the tank. All the data from the experiment is listed in appendix H.2 in table H.4. From the table, the amount of PV utilised for heating can be calculated:

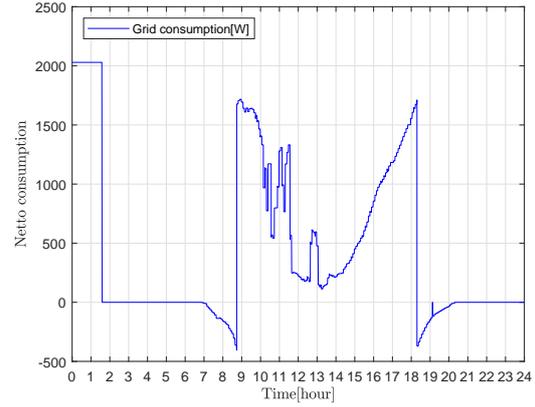
$$\eta_{pv,ex2} = \frac{5.9 \text{ kWh}}{6.2 \text{ kWh}} = 0.95 \quad (12)$$

### 5.3.3 Comparison of experiment 2a and 2b

As for experiment 1, experiment 2a and 2b have to be compared to see how the difference temperatures in the tanks develops during each experiment. Figure 5.11 illustrates the temperature  $T_1$ ,  $T_2$  and  $T_3$  during the experiments.

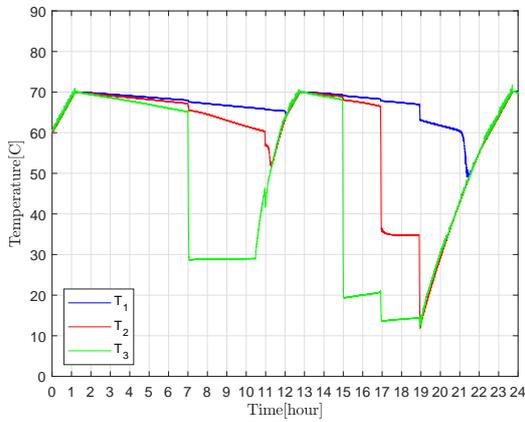


(a) PV production (red) and usage (blue) experiment 2b

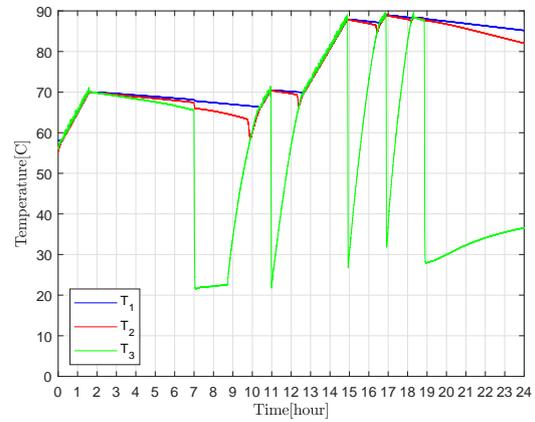


(b) Netto grid consumption experiment 2b

Figure 5.10: PV production and grid consumption for experiment 2b with PV



(a) All temperatures in experiment 2a



(b) All temperatures in experiment 2b

Figure 5.11: Comparison of 2a and 2b temperatures

When comparing the two experiments in figure 5.11 it is seen that there is similarity until the second valve opening. For experiment 2a, a small stop of increase of  $T_3$ . For 2b the temperature drops rapidly because the heating element has been activated and heated the water around the  $T_3$  sensor. For both cases the valve is open, but for experiment 1a the valve is not open long enough to decrease the  $T_3$  noticeable. For the rest of experiment 1b the element is connected, and for 2a the element is disconnected every time the temperature exceeds  $70^\circ C$ . When the last valve opening occurs, the temperature in 2a is decreasing to under acceptable temperature, as for 2b there is only minor decrease. For both the experiments, the essential comparable segments is presented in table 5.5.

As the table 5.5 shows, there are some key parameters which seems a little bit far-fetched. Studying the end energy for both experiments, the experiment without any PV electricity has greater energy at the end regardless of lower end temperature. The explanation is that the heating element has heating all the water to  $70^\circ C$ , as for the 2b, the  $T_3$  temperature is considerably lower than the highest temperature  $T_1$ .

Table 5.5: Comparison of key parameters for experiment 2a and 2b

Description	Experiment 2a	Experiment 2b	Unit
Start energy tank	24,254	23.940	kJ
End energy tank	35,072	32.642	kJ
Lowest temperature tank [ $T_1$ ]	49	58	Celsius
End temperature tank [ $T_1$ ]	70	85	Celsius
Electricity consumption all	17	23	kWh
Electricity consumption grid	17	12	kWh
Price used electricity grid tariff	9	6	NOK
Total exchange of water	230	213	Liters

#### 5.4 Modifications necessary for the controller based on developing experiments

The experiments have illustrated some significant drawbacks for the controller concerning the temperature behaviour in the tank for all the experiments. As the experiments show, there can be substantial temperature differences inside the tank from top to bottom. With this in mind, using the sensor located highest  $T_1$  may not be ideal, when seeing how different the temperature layers are in the tank. Besides, heating during the night only is not sufficient to keep the temperature above the minimum acceptable temperature.

Focusing on the primary goal for this controller, storing PV produced electricity as hot water, the tank temperature has a maximum which needs to be respected. If the maximum temperature is reached, and the system still producing, the electricity is sold to the grid, which is not a preferred solution. A way to prevent this for any discharges and production situation needs to be implemented.

## 6 Controller logic

This section introduces the logic for the controller concerning temperature control and controlling the heating element. The controller logic is the essential part of any controller and is responsible for utilising all the collected information ensuring optimal control. First, the PV logic and weather forecast logic is explained. In the end, the temperature logic is presented. For an explanation of which parameters used for the logic, see appendix E.2.

### 6.1 Weather forecast

Based on the developing experiment presented in section 5, the start temperature in the tank is important. Setting the temperature too low results in not enough hot water through the day, and setting it to high prevents all the PV produced energy to be stored in the tank. To solve this issue, the program is designed to use weather data to estimate what the optimal temperature in the tank should be when the day begins. The goal is to store all the PV produced electricity in the tank, by selecting the best temperature for each day by using weather forecast data. For collecting the weather data, the webpage for the long-term forecast for Grimstad is scraped from yr, which is a Norwegian weather service[54]. In LabView, the essential information about expected weather is sorted and converted into a temperature which the water in the tank should be heated to when the day begins. Figure 6.1 shows the HMI of the estimated weather for the experiment periods for the next four days.

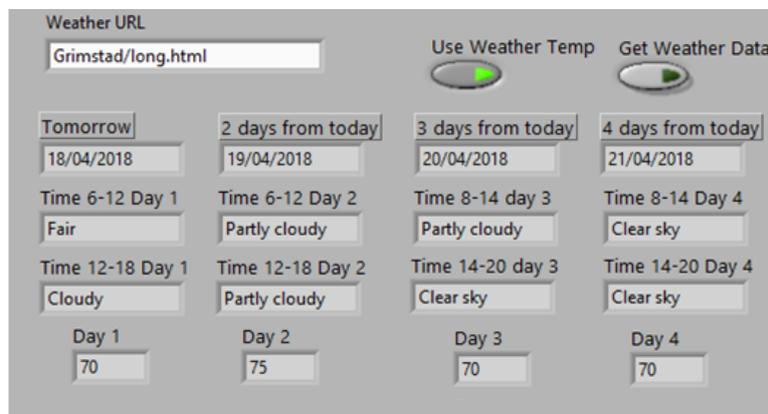


Figure 6.1: Print screen of the collected weather and start temperatures

The logic which the operates as is illustrated as a flowchart in figure 6.2. When the program starts, the webpage is scraped, and the program initiates a search for the symbols name matching the clear sky, fair, partly cloudy or cloudy. If there is a match, the program continues to set the tank temperature corresponding to the name. If there are no matches, the program assumes that there would be no PV production and sets the temperature to  $80^{\circ}C$ . The lowest tank temperature is set to be  $70^{\circ}C$ , as a result of the early vale openings, to ensure available hot water for morning use. The program logic is executed twice for each day, as the webpage splits the forecast to morning and afternoon forecast, and sends the lowest start temperature, to the temperature controller. The logic updates the forecast one time each day, 5 minutes for the day ends, or it can be updated manually by using the "Get Weather Data"-switch shown in figure 6.1.

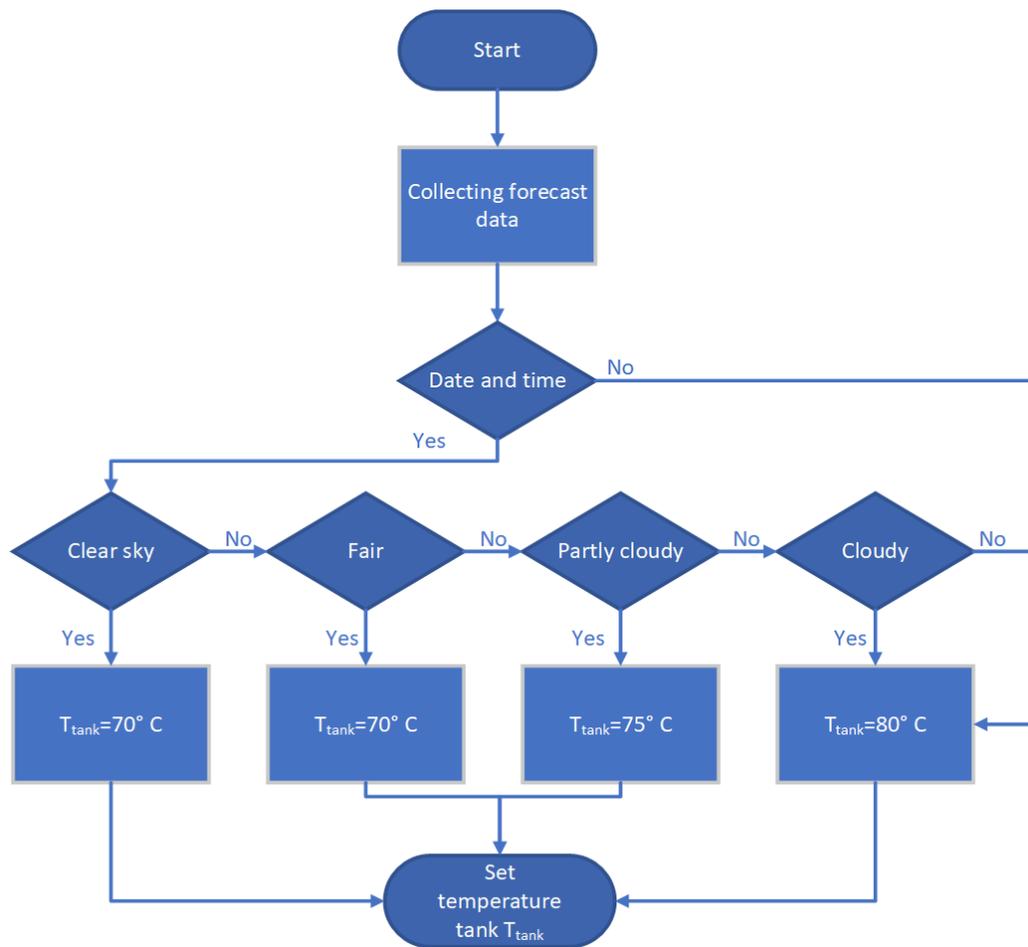


Figure 6.2: Flowchart for setting tank temperature

## 6.2 Temperature control

The temperature logic is an essential part of the controller logic. The logic is responsible for always keep hot water available, and still have low enough temperature for the PV produced energy to be stored. The main aspect of the program is not visible in any HMI, due to there is a large amount of parameter reading and comparison which is not of any interest to the user. The logic used for controlling the temperature in the tank is presented in figure 6.3, and can be divided into three parts each has its function. The logic is executed for every iteration. In addition to the temperature logic, there is a small logic which scans the  $T_1$  sensor at the top of the tank. If the temperature exceeds the maximum allowed temperature, the heating element is disconnected and the valve opens.

When the program executes, the first step is to check if the PV production exceeds 200 W. If there is sufficient production, the tank temperature is set to  $95^{\circ}\text{C}$ . The temperature is set based on previous experiments and needs to be further tested to ensure that it is sufficient to store all the produced energy. If there is not enough production, the tank temperature is set to be the output of the forecast logic presented in section 6.1, which has been adjusted to the weather forecast.

The second step in the logic is controlling the heating element. The temperature  $T_{\text{tank}}$  is first compared with the  $T_{\text{min}}$ . If  $T_{\text{tank}}$  is lower than  $T_{\text{min}}$ , the heating begins immediately. When  $T_{\text{tank}}$  has increased, the availability of electricity is checked, which is dependent on the selected electricity consumption profile presented in 3.5. If the selected profile denies electricity consumption, the program returns to check PV production. In the next step the  $T_2$  sensor in the tank is compared to check if  $T_2$  is higher compared with  $T_{\text{tank}}$ . If the conditions are false, the heating element starts and the program goes back to check for PV. For true condition, the logic continues to check if the heating element is active. If the element is not active, the program returns to check for PV.

When the program has accomplished step one and two, the tank has reached the foreseen temperature. In step three, the heating element is disconnected, and a timer is initiated. Further on, the timer is checked to see if the time has exceeded 3600 seconds(1 hour) if the condition is false, the logic checks if the tank temperature is higher than the minimum acceptable temperature. As long as this is true and the timer is below 1 hour, the program loops. When the timer condition is true, the program goes back to check for PV.

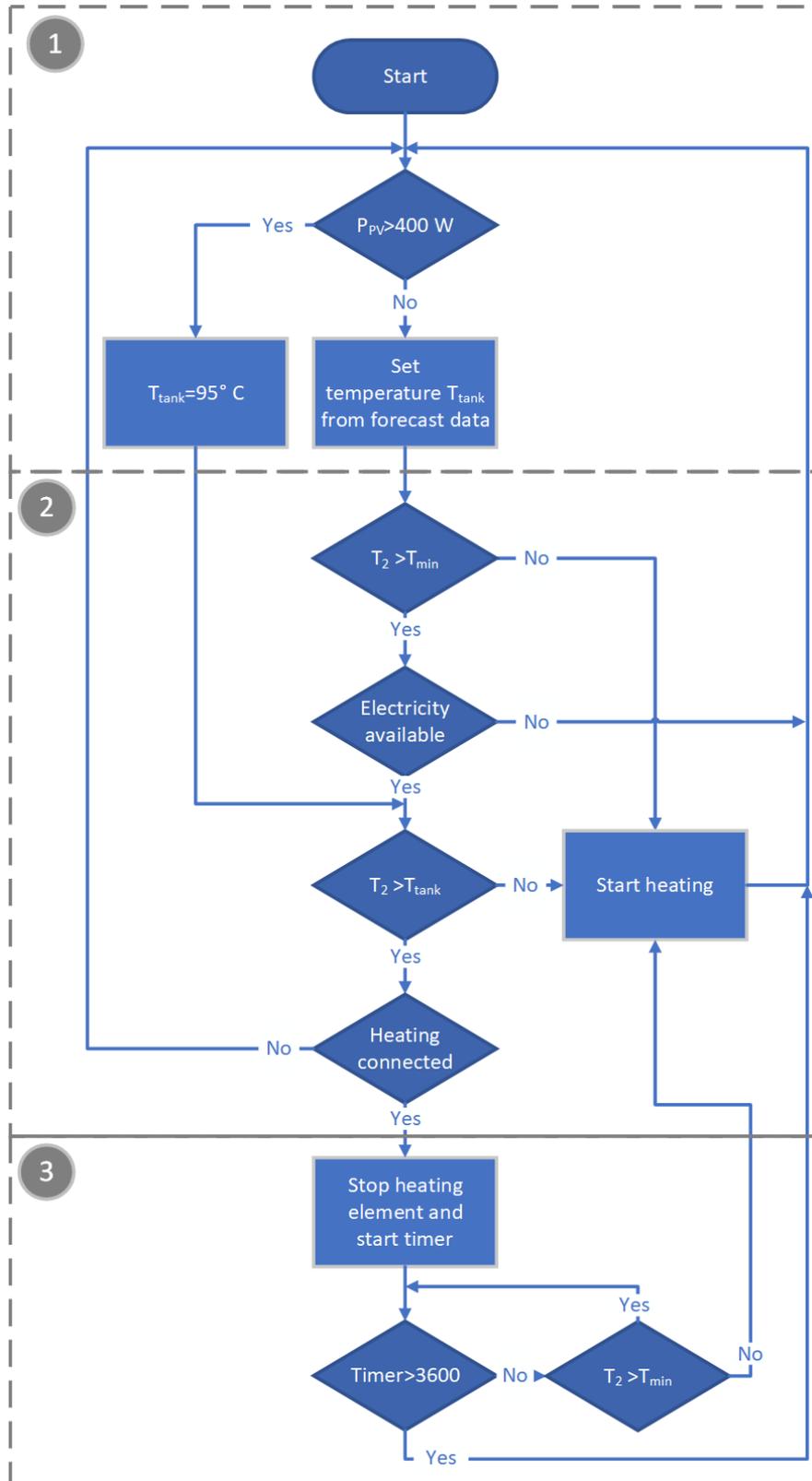


Figure 6.3: Flowchart for temperature control

## 7 Experimental results

This section introduces the resulting experiment for testing the controller ability to store PV produced energy as hot water. The controller is also tested with both electricity consumption profiles. The experiments are run for 96 hours to cover both days with appropriate PV production, and days with minimal production. The first experiment is with regular electricity consumption, and the second is with grid peak reduction consumption. Both the experiments has electricity consumption based water profile, and random water usage profile. The two water consumption profiles would exceed a normal water demand but are selected to test the temperature change when adding energy due to PV production. The water exchange is set up with the electricity consumption based water profile executes two dischargers during the day. The discharges are at 07:00 and 17:00. The random consumption profile executes every hour between 07:00-09:00, and 17:00-22:00.

The parameters in table 7.1 is equal for both the experiments. The experiment prices are entirely based on electricity consumption and do not take in to account the price of PV system or other components required. For a description of the investments cost of installing the controller, see appendix G. In addition to the two experiments presented in this section, two additional experiments are presented in appendix I. The addition experiments are with a different water consumption profiles which exchanges water more dispersed during the day.

Table 7.1: Parameters which is equal for all experiments

Parameter name in VI	Value	Unit
Length of experiment	96	Hours
Low temp tank	66	Celsius
Delay for heating element	1	Hour
End temperature PV	95	Celsius
Min PV production for heating	400	Watt
Price sold electricity	0.34	NOK/kWh
Delay time	1	Second
Critical max temperature	100	Celsius
Critical Low	60	Celsius
System flow	0.39	kg/s

## 7.1 Average and random consumption with normal electricity consumption

First experiments are executed with normal electricity production. For this experiment, the electricity price is constant during the day. The purpose for selecting this electricity profile is to investigate the controllers' abilities in today's price market, and comparing it with the different price agreements presented in table 3.1 in section 3.5.2. Also, the temperature settings, which is based on forecast weather is also reviewed. Figure 7.1 illustrates the tank temperature  $T_1$ , henceforward referenced as  $T_{\text{tank}}$ , heating element active and valve opening. Heating element active and valve opening is multiplied with 50 for 40 for illustrations purposes. The data collected for the experiment per day is presented in appendix H.3 table H.5. For 24 hours graphs, PV produced and stored and consumption, see appendix H.4, figures H.1-H.6.

As figure 7.1 illustrates, the experiments start with a tank temperature of  $60^\circ$ , From the weather data, the tank temperature is set to  $80^\circ$ , due to expectations of low PV electricity production. During the day, the tank temperature is decreasing due to valve openings, until there is enough PV production to activate the heating element and increase the temperature. As the valve opens, there is a small drop in tank temperature, until the third to last valve opening occurs. At this point, the heating element is connected, but the temperature decreases with approximately  $17^\circ C$  during the opening. This occurs again at the second to last before the temperature starts to increase. At the last valve opening, the temperature is  $55^\circ C$  and only levelling out during the opening, before it increases further.

For day two, the tank temperature is set to  $75^\circ C$  due to expectations of some PV production. The heating element is connected 08:00, after two valve openings, due to the low temperature at the location of  $T_2$ , see figure 7.2. At 08:30, the PV is producing sufficient to activate the heating element and increase the tank temperature. During the day, the element is connected until approximately 14:00 when the maximum temperature in the tank is reached. The PV production is still high, but the element is switched off. After 1 hour, the element is reconnected, but due to no valve openings, the element is only active for one hour before it reaches maximum temperature, regardless of the occurring valve openings. This happens once more at 17:30, but the element is only activated for a short period due to lack of PV production. The element remains off until  $T_2$  is under  $66^\circ C$  and the element is connected again. At this time, the tank temperature is  $89^\circ C$ , but the temperature in the lowest area of the tank.  $T_3$  is only  $22^\circ C$ , see figure 7.2. The element remains connected the rest of the day.

When the third day begins, the tank temperature is higher, than the temperature set based on the weather forecast. Because of expectations of significant PV production, the tank temperature is set to be  $70^\circ C$ , which is lower than the actual temperature in the tank. As figure 7.1 presents, the heating element is not active until there is sufficient PV production to increase the tank temperature. The heating element remains active until the maximum temperature is reached, and disconnects for one hour before it is reactivated. It is seen that the tank temperature drops considerably during the two last valve openings, but can deliver water with acceptable temperature. After the last valve opening, the temperature continues to decrease. The decreasing temperature does not affect the household as there are no more valve openings during the day.

For day four, the tank temperature is set to  $70^{\circ}\text{C}$ , due to the expectation of PV produced electricity. When the first valve opening occurs, the heating element is activated, due to low temperature. As the PV production increases, the element remains active until the maximum temperature is reached. The heating element is then disconnected for one hour before it is reactivated. At this time, the valve has opened and increases the time the element is connected due to the decrease of the temperature lower in the tank seen in figure 7.2. At 18:00 the PV production is too low, and the element deactivates. After the last valve opening at 21:00, the temperature  $T_2$  is decreasing under  $66^{\circ}\text{C}$ , which activates the element again. The temperature in the tank is  $85^{\circ}\text{C}$ .

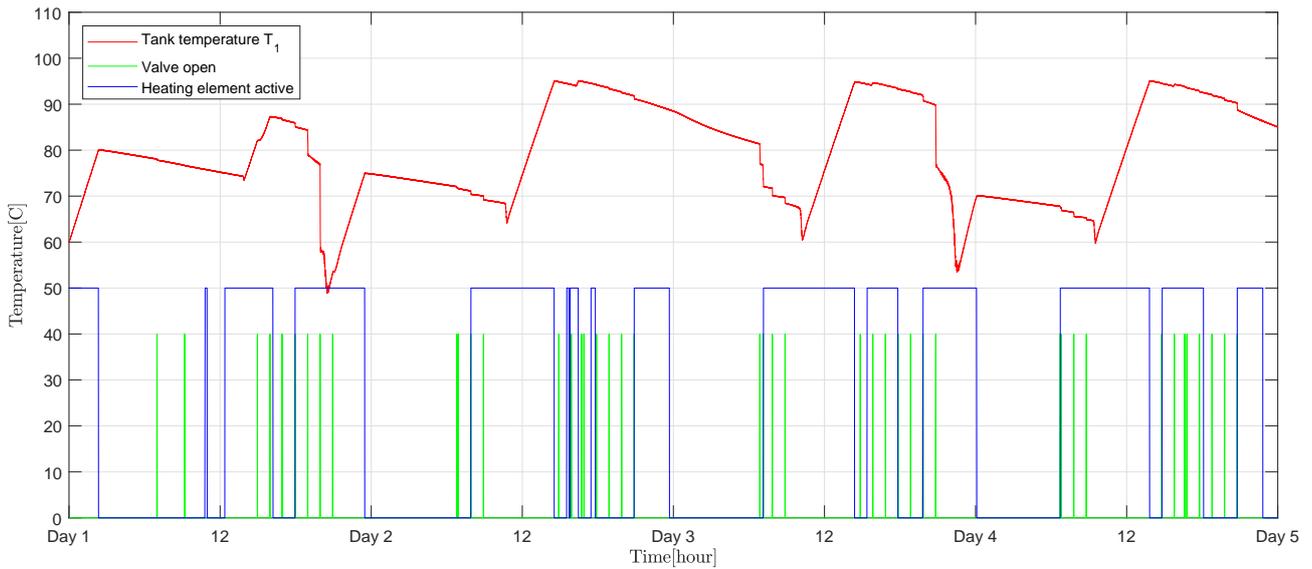


Figure 7.1: Temperature in the tank, heating element connected and valve opening for result experiment 1

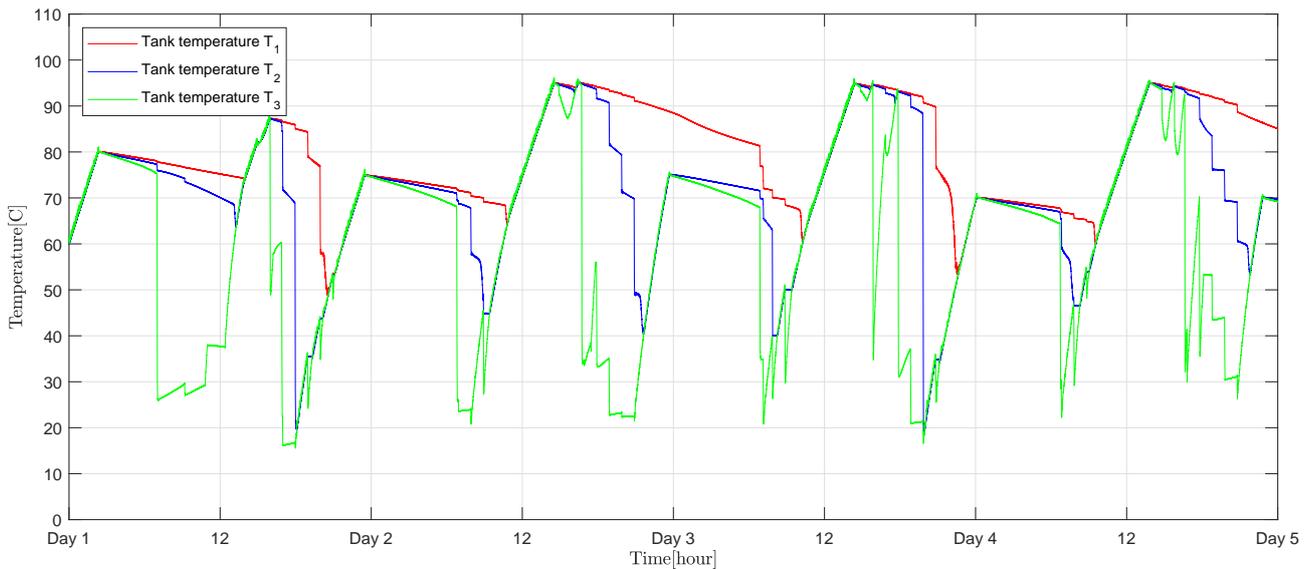


Figure 7.2: All the temperature in the tank during result experiment 1

The PV production is monitored and is shown in figure 7.3 for the whole experiment period. From figure 7.3, it is seen that for the first day, the logic does not start to store until the production exceeds 400 W. This occurs for a short period around 11:00, but the continuous storage does not take place until 12:30. For the rest of the day, all of the produced energy is stored until approximately 16:30, when the production is below 400 W. Later in the day, the element is active due to low temperature in the tank, which explains the energy storage from 18:00.

For day two, the energy storage begins at 08:00, due to low tank temperature. The energy storage continuous until the maximum temperature is reached at 14:30. As seen in figure 7.3, there is still a significant production of electricity, and the electricity is sold to the grid for the next hour until the element is activated again for a short period. At 17:30, the element is reactivated for a short period until the production falls below 400 W.

For day 3 and 4, the storing pattern is equal for both days. The energy storage begins after the first valve opening, due to low temperature. During the day, the storage continuous until the maximum temperature is reached and the element is disconnected. After 1 hour, the element is reconnected until the production decreases below 400 W.

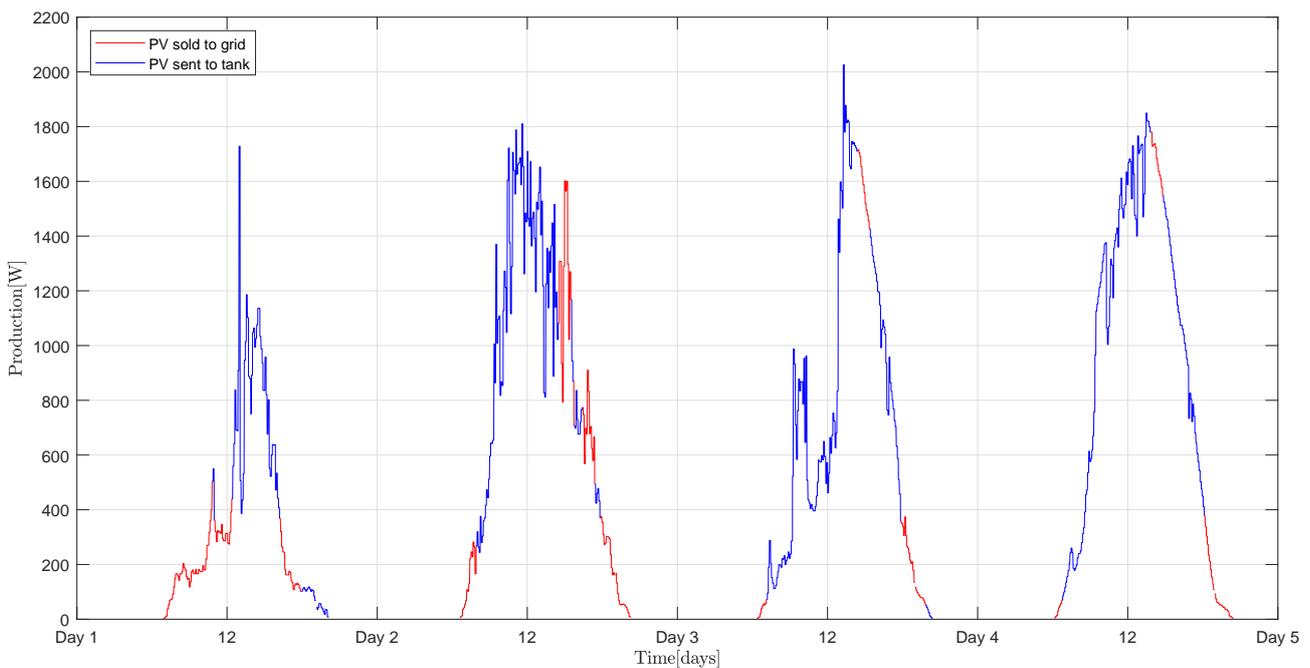


Figure 7.3: PV production during result experiment 1

The energy in the tank is calculated using equation 2 and is executed for the experiment start and end. For calculating the price of the experiment, the first calculation is based on selling all the PV and only use grid consumption<sup>9</sup>, see appendix J. The second price is calculated based on utilising as much PV as possible. Both the prices are calculated using equation 6, and the energy using equation 7. Besides, the worst case price is calculated using the fluctuating price shown in figure 3.4. The data is presented in table 7.2 with the lowest price highlighted in green and highest in red.

Table 7.2: Data from result experiment 1 with with PV stored energy and without storage of PV produced energy

Description	Without PV	With PV	Unit
Start energy tank	18,181	18,181	kJ
End energy tank	38,980	38,980	kJ
Lowest temperature tank [ $T_1$ ]	48	48	Celsius
End temperature tank [ $T_1$ ]	80	80	Celsius
PV produced electricity	38	38	kWh
Electricity consumption all	100	100	kWh
PV produced electricity stored in tank	0	30	kWh
PV produced electricity sold	38	8	kWh
Electricity consumption grid	100	70	kWh
Price used electricity Worst Case	168	127	NOK
Price used electricity grid tariff	37	32	NOK
Price used electricity grid tariff season Summer/Winter	70/177	56/131	NOK
Price used electricity with no AMS	83	64	NOK
Price used electricity grid tariff power Summer/Winter	58/157	47/109	NOK
Price used electricity grid tariff power season Summer/Winter	57/148	46/110	NOK
Price used electricity Otovo grid tariff PV electricity buying price [1 kr/kWh]	12	27	NOK
Total exchange of water	1,102	1,102	Liters

<sup>9</sup>Requires that the PV system is connected to a separate AMS

From table 7.2 it is seen that the total exchange of water for the experiment period is 1,102 liters. By using equation 1 at the point where the energy in hot water from the tank, is mixed with the energy from cold water, the following relation is given,

$$Q_{\text{discharged}} = Q_{\text{use}}, \quad (13)$$

where  $Q_{\text{discharged}}$  is calculated by adding all the energy discharged during the experiment using the following equation:

$$Q_{\text{discharged}} = \sum_{n=1}^{34560} (T_5 - T_{\text{cold,water}}) \cdot \text{valve} \cdot \text{flow} \cdot c_{p,\text{water}}, \quad (14)$$

where  $T_5$  is the outlet temperature from the tank(K),  $T_{\text{cold,water}}$  is the cold water set to 283 K, valve is the valve position (1 if open, 0 if closed), flow is the system flow (0,36 kg/s) and  $c_{p,\text{water}}$  is 4200  $\frac{J}{\text{kg}\cdot\text{K}}$ . This gives the discharged energy:

$$Q_{\text{discharged}} = 3.0456 \cdot 10^8 J. \quad (15)$$

The amount off usable water, can be calculated. For the calculations, the water temperature for a shower, hand wash etc. is 38°C. The cold water temperature is set to be 10°C.

$$Q_{\text{discharged}} = Q_{\text{use}}$$

$$Q_{\text{discharged}} = m_{\text{use}} \cdot c_{p,\text{water}} \cdot \Delta T_{\text{use}}$$

$$3.0456 \cdot 10^8 J = m_{\text{use}} \cdot 4200 \frac{J}{\text{kg}\cdot\text{K}} \cdot (311 K - 283 K) \quad (16)$$

$$m_{\text{use}} = 2589.8 \text{ kg} \Rightarrow 647 \text{ kg/day}.$$

Equation 16 states the the tank delivers 647 kg/day of water with a temperature of 38°C. With an estimated consumption per capita of 120 liters/day explained in 3.4.2. The tank is capable of accommodating a household of 5 persons during the experiment time.

Table 7.2 shows the total produced PV is 38 kWh. By using the information from PVGIS in appendix C.4.4, the conventional PV production for the experiment is calculated:

$$P_{\text{expected}} = 4.24 \text{ kWh/day} \cdot 2 \cdot 4 \text{ days} = 33.92 \text{ kWh} \approx 34 \text{ kWh}, \quad (17)$$

This illustrates that the system produced 4 kWh more than the estimation from PVGIS. However, the data from PVGIS is based on average production. Further on the utilisation of the PV produced energy is calculated. From the table 7.2 the total produced and the PV stored is acquired, and the utilisation of PV for final experiment 1 is then calculated to be

$$\eta_{\text{pv,ResultExperiment 1}} = \frac{30 \text{ kWh}}{38 \text{ kWh}} = 0.79. \quad (18)$$

As table 7.2 illustrates, the price of the experiment varies between the different pricing agreements. The price of the experiment varies between 12 NOK and 177 NOK for not any storage, and between 27 and 131 for storage. It is seen that the lowest experiment price is the agreement Otovo presents with paying 1 NOK/kWh. For all other price agreements, storing PV produced electricity as hot water has a lower cost than selling it directly and repurchasing it. For a presentation of how this is achievable, see appendix J. Overall the data from the experiment in table 7.2 shows that there is a reduction in cost by 15% for the period with the grid tariff prices is used, which is the agreement for most households.

### 7.1.1 Days without any PV production

As figure 7.3 present that during the four day period, there is PV produced energy stored in the tank every day. To test the controller for days without any PV production, the experiment is run for 24 hours where the energy storage logic is deactivated as well as the forecast. If the controller can keep the required temperature during the discharges, this confirms the controller’s ability to adapt to situations where there is no PV production. The tank temperature and heating element active is presented in figure 7.4a. The heating element multiplied with 2.4 for illustrations purposes. All the temperatures in the tank during the experiment is seen in figure 7.4b. For price and heating element graph, see appendix H.4, figure H.6.

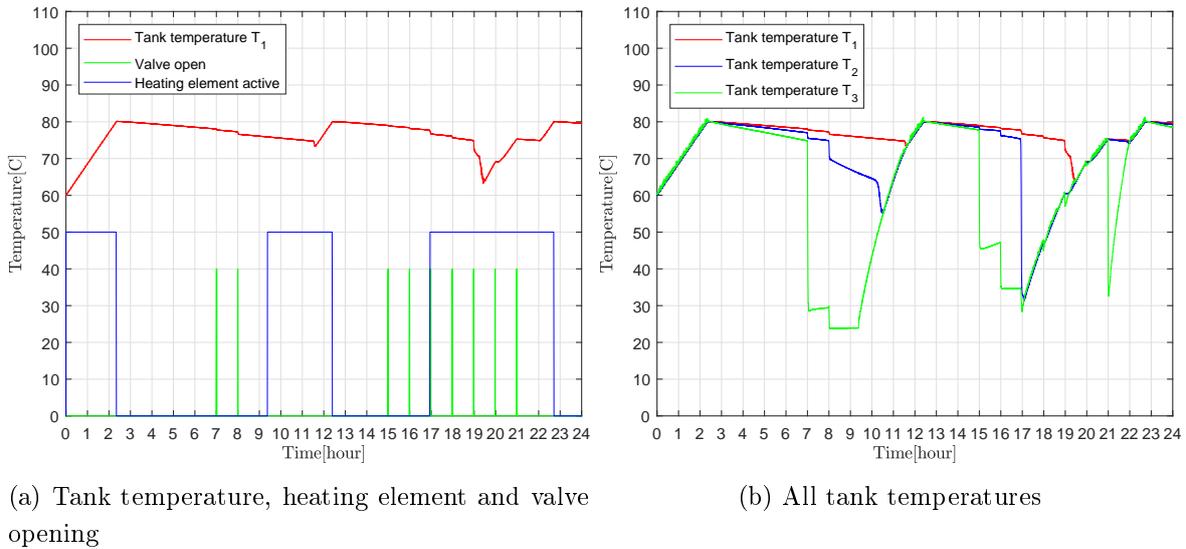


Figure 7.4: Tank temperatures, heating and price graphs for 1 day test of result experiment 1

When the experiment starts, the tank temperature is  $60^{\circ}C$ . The heating element is activated, and increase the tank temperature to  $80^{\circ}C$ . During the first valve openings, the tank temperature only experiences small change. When looking at figure 7.4b, the temperature in the lower regions is more affected by the valve openings as expected. Around 09:00, the temperature  $T_2$  is under  $66^{\circ}C$ , and the heating element is activated. When the next valve openings occur at 15:00, the temperature is high, and the element is first activated when the valve opens for the third time in the afternoon. At the end of the experiment, the tank temperature is  $80^{\circ}C$ .

The table 7.5 shows that the lowest tank temperature during the 24 hour period is  $60^{\circ}C$ ., which is when the experiment starts. During the day, the lowest temperature is at 19:30, when the temperature is  $64^{\circ}C$ . As presented in table 7.3, the experiment price has a substantial difference, depended on how it is calculated. The price varies between 40 NOK in the worst case and 11 NOK for regular electricity price. However, during the day the logic can deliver acceptable temperature at every valve opening. This makes the controller logic acceptable for use at days with no PV produced electricity. For price comparison with the 4-day experiment, see appendix H.3, table H.6.

Table 7.3: Data from result experiment 1 for 24 hour with no PV produced electricity

Description	Value	Unit
Start energy tank	28,581	kJ
End energy tank	43,911	kJ
Lowest temperature tank[ $T_1$ ]	60	Celsius
End temperature tank[ $T_1$ ]	79	Celsius
Electricity consumption all	23	kWh
Price used electricity worst case	40	NOK
Price used electricity grid tariff	11	NOK
Total exchange of water	247	Liters
Total amount usable water	528	Liters

## 7.2 Average and random consumption with reducing grid peak and cost electricity consumption

For this experiment, the electricity consumption profile selected is designed to reduce the peak in the grid by increasing the price for electricity in high demand periods. The reason for using the selected electricity consumption profile is that the controller may accomplish two main task simultaneously. As the price of electricity is high during high demand periods, the controller would avoid using the heating element unless if there is PV available or the tank temperature is too low. As for result experiment 1, the temperature settings based on weather is reviewed in addition to the temperature change in the tank. Figure 7.7 illustrates the tank temperature  $T_1$ , henceforward referenced as  $T_{\text{tank}}$ , heating element active and valve opening. As for previous experiments, the heating element active and valve opening is multiplied with 50 for 40 for illustrations purposes. The data collected for the experiment per day is presented in appendix H.5 table H.7. For 24 hours graphs, PV produced and stored, see appendix H.6, figures H.7-H.10.

For the first day, figure 7.7 illustrates that when the experiment begins, the temperature in the tank is  $60^\circ\text{C}$ . According to the weather forecast, there is good weather for PV production which results in tank temperature setting of  $70^\circ\text{C}$ . After the first valve opening for the day, the temperature in the lower part of the tank is decreasing to  $25^\circ\text{C}$ , see figure 7.6. After the second opening, the middle temperature decreases as well, but at 08:30, there is sufficient PV production to start the heating element. During the day the tank temperature is increased until 14:00 when it reaches its maximum temperature. Further on, the element is disconnected for one hour and is activated for a short period before the PV production has a short under minimum production. The heating element is activated again at 22:00 when the electricity price is low and remains active for the rest of the day.

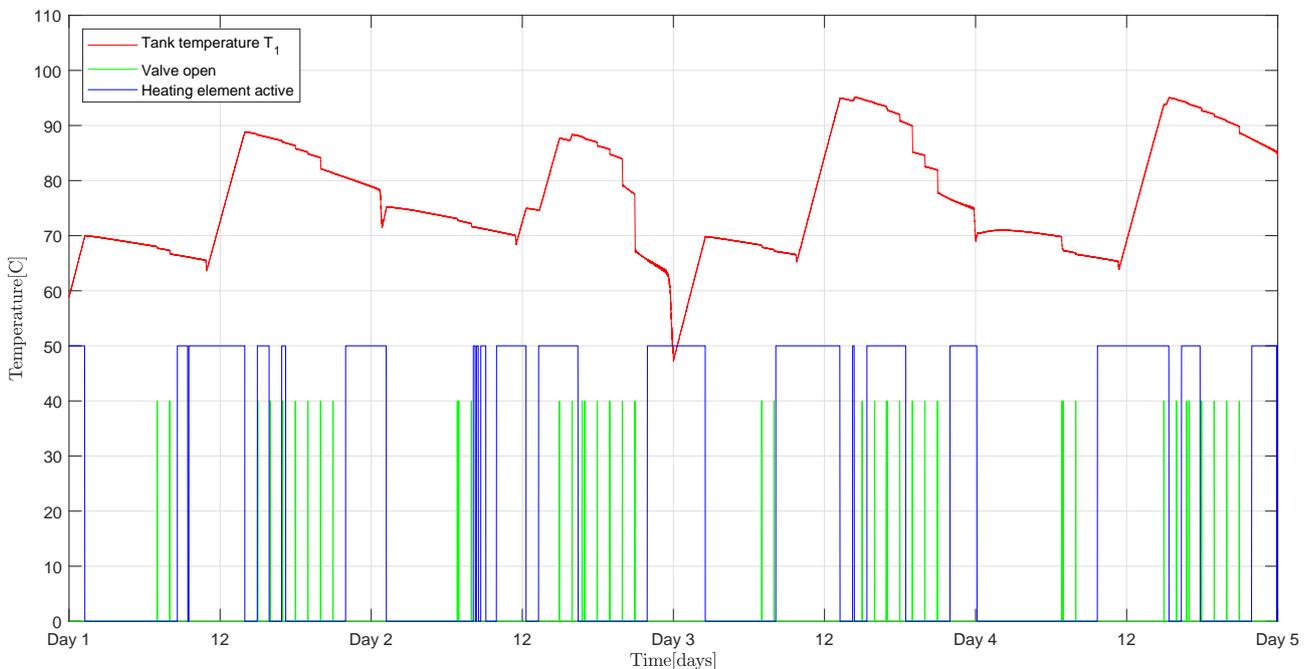


Figure 7.5: Temperature in the tank, heating element connected and valve opening for result experiment 2

Due to an expectation of some PV production, the tank temperature is set to  $75^{\circ}\text{C}$  for day 2. After the first valve openings, the heating element is active due to PV production. However, the amount of production varies due to clouds, which results in the short burst of the heating element being activated/deactivated. At 10:00, the production increases and the element is active until 12:30, when there is another drop in production. The element is disconnected for one hour and is reactivated 13:30. Due to valve openings starts at 15:00 and continuous throughout the day, the tank temperature drops. At 16:30, the PV production declines under 400 W, and the heating element deactivates until 22:00. After 22:00 the temperature drops to the lowest temperature for the whole experiment of  $47^{\circ}\text{C}$ . However, this is after the water consumption for the day is completed, and therefore the temperature drop is of less concern.

As day 3 begins, the heating element is connected due to the low temperature from day 2. The tank temperature is set to  $70^{\circ}\text{C}$  due to expectations of high PV production. For the first valve openings, the temperature is decreasing until 09:30, when the production of PV is sufficient, and the heating element is activated. During the day, the production increases and when the maximum temperature in the tank is reached, the production is over 2 kW. The element is deactivated for one hour and then activated again, only to be active for a short period before the maximum temperature is reached again. During the next hour, there are valve openings which decreased the tank temperature which allows more PV produced energy stored in the tank during the remaining hours of PV production. At 22:00 the element reconnects due to low electricity price and remains active until the end of the day.

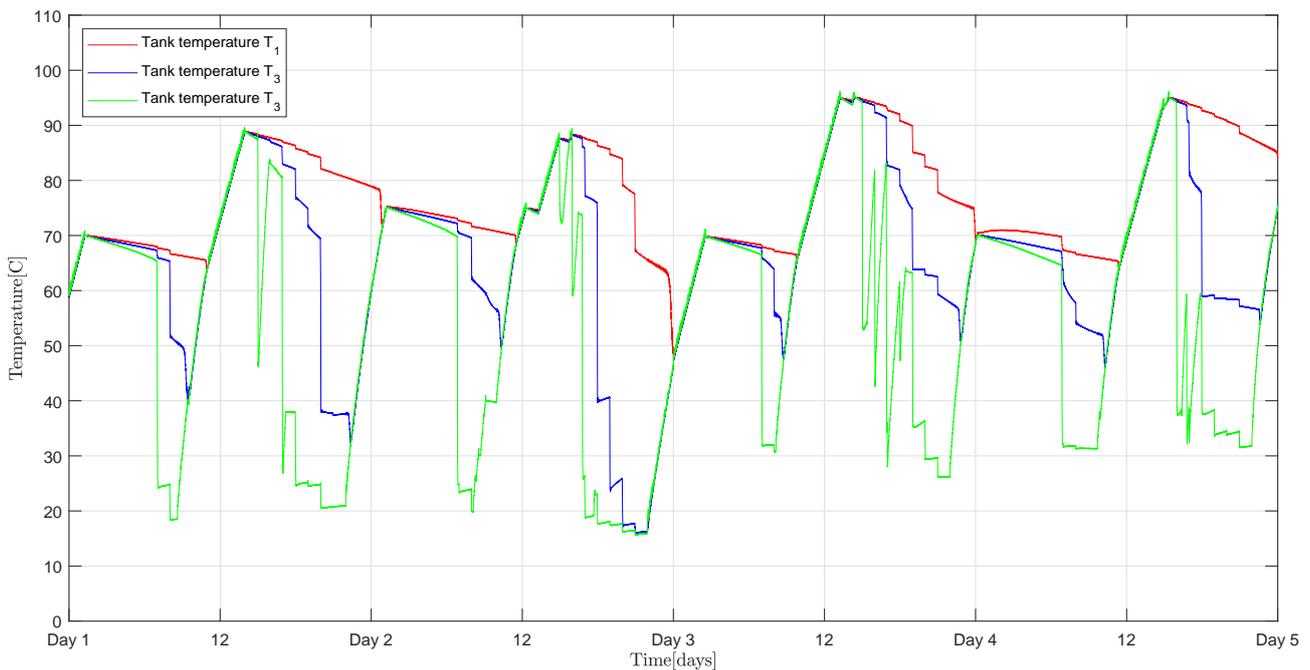


Figure 7.6: All the temperature in the tank during result experiment 2

When day 4 begins, the temperature in the tank is set to  $70^{\circ}\text{C}$ , and the heating element is disconnected. The tank temperature is still increasing due to some residual heat from the heating element. At the time of the first valve opening for the day, the tank temperature drops  $2^{\circ}\text{C}$ . During the following valve openings, there are not any sudden drops in the tank temperature. The electricity production exceeds  $400\text{ W}$  at  $09:30$ , and the heating element is activated. The element remains connected until  $15:30$  when the maximum temperature in the tank is reached. During the next hour, there is one valve opening, which allows the heating element to be reactivated after the off period. The energy storage continuous until the production decreases under  $400\text{ W}$ . At  $22:00$ , the element activates to heat the lower parts of the tank. At the end of the experiment, the tank temperature is  $79^{\circ}\text{C}$ .

Figure 7.5 the PV production for during the experiment period. In appendix H.5, the production is divided into 24-hour graphs for all the days. At the first day, the PV system starts producing at  $06:00$ . However, due to the logic requires the production of minimum  $400\text{ W}$ , the heating element is not activated until  $08:30$ . During the next hour, the production is fluctuating due to clouds preventing the sun from hitting the panels. After  $12:00$  there are clouds which makes the production fluctuating even more. At  $14:00$  the maximum temperature of the tank is reached. The next hours, the production is fluctuating between  $230\text{ W}$  and  $1800\text{ W}$ , until  $19:00$  when the productions steadily decrease.

For day two, the hours between  $06:00$  and  $10:30$  is fluctuating around  $400\text{ W}$ , which results in the element being activated, and deactivated three times before it is deactivated until  $10:00$ . At this time the production increases to a level where the fluctuating is well above  $400\text{ W}$ . At  $12:30$  there is a sudden drop in production which the logic deactivates the element for one hour. During the hour the production increases to almost  $2\text{ kW}$ , which all is sent to the grid. At  $18:00$  the production is over  $400\text{ W}$  only for a short period where the controller does not activate the element.

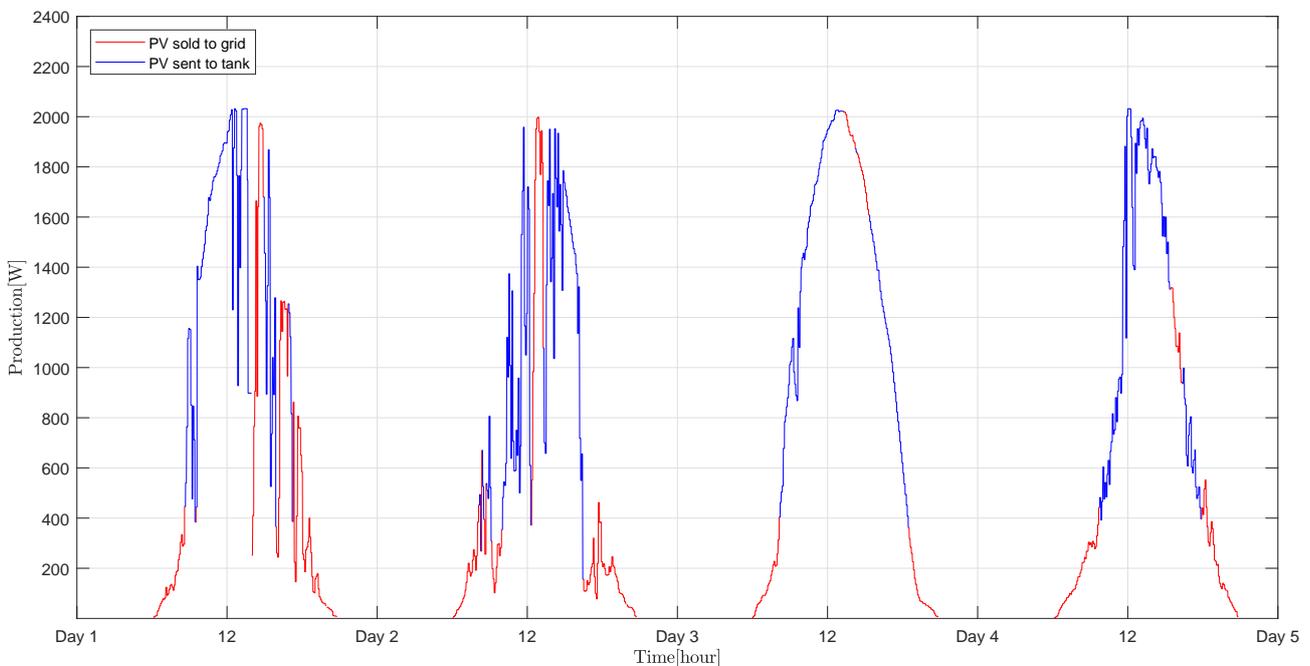


Figure 7.7: PV production during result experiment 2

For day three, the production is estimated to be steady due, to forecast prediction clear and sun for the entire day. The PV production exceeds 400 W at 08:00, and the element activates. As the production increases, the element remains active until 13:00 when the logic deactivates the element due to maximum temperature in the tank is reached. After one hour the element is active for a short period before the maximum temperature is reached once more. When the element is reactivated at 15:00, it remains active until the production is under 400 W at 18:30.

For the last the day of the experiment, the forecast is partly cloudy, the energy storage begins at 10:00, and continue through the day until 15:30 when the maximum temperature is reached. After one hour, the element re-activates and continues to heat until the production decreases 400 W around 18:00. After 30 minutes, the production exceeds 400 W, but the element is prevented from disconnecting due to the logic.

When calculating price, this is executed for all the different pricing agreements although the logic is designed for worst case pricing described in section 3.5.1. The prices are calculated using equation 6, and the energy using equation 7. The data is presented in table 7.4 with the lowest price highlighted in green and highest in red.

As table 7.4 presents, the overall experiment price varies between the different price agreements. The prices vary between -7 and 145 NOK for selling all the PV electricity, and 11/87 NOK for storing. A price which stands out is the Otovo agreement. For this experiment, the price of the experiment is -7 NOK. In other words, the household would earn 7 NOK by selling all the produced PV electricity, and then re-buying it back to heat water, for a presentation of how this is achievable, see appendix J. The important price in this experiment is the worst case price, due to the controller focus of not use electricity during high demand periods. Table 7.4 shows that there is a difference in price of 80% for the experiment without and with PV. For all price agreements except Otovo, storing PV produced electricity as hot water has a lower cost than selling it directly and repurchasing it.

From equation 17, it is shown that the expected production for a four day period at the location is 34 kWh. As the data from the experiment presented in table 7.4, it is seen that the total produced PV is 49 kWh. From the 49 kWh, 36 kWh was stored in the tank as energy. That gives a utilisation of PV for the experiment calculated to be:

$$\eta_{pv,ResultExperiment2} = \frac{36 \text{ kWh}}{49 \text{ kWh}} = 0.74. \quad (19)$$

As from the first result experiment, the amount of usable water during the experiment periods is calculated. During the experiment, a total of 990 liters is exchanged. By using equation 14 to calculate the energy discharged, and equation 16 for the amount of usable water. First, the discharged energy is calculated:

$$Q_{discharged} = 2.6863 \cdot 10^8 \text{ J}. \quad (20)$$

Table 7.4: Data from result experiment 2 with with PV stored energy and without storage of PV produced energy

Description	Without PV	With PV	Unit
Start energy tank	27,194	27,194	kJ
End energy tank	41,759	41,759	kJ
Lowest temperature tank [ $T_1$ ]	47	47	Celsius
End temperature tank [ $T_1$ ]	79	79	Celsius
PV produced electricity	49	49	kWh
Electricity consumption all	85	85	kWh
PV produced electricity stored in tank	0	36	kWh
PV produced electricity sold	36	13	kWh
Electricity consumption grid	85	49	kWh
Price used electricity Worst Case	106	59	NOK
Price used electricity grid tariff	26	18	NOK
Price used electricity grid tariff season Summer/Winter	54/145	36/87	NOK
Price used electricity with no AMS	65	42	NOK
Price used electricity grid tariff power Summer/Winter	43/119	30/72	NOK
Price used electricity grid tariff power season Summer/Winter	43/120	29/73	NOK
Price used electricity Otovo grid tariff PV electricity buying price [1 kr/kWh]	-7	11	NOK
Total exchange of water	990	990	Liters

Further on, the amount which discharged water from the tank provides to the household as usable water can be calculated for experiment 2. The constant temperatures of usage and cold water are equal to previous calculations, accordingly  $38^\circ C$  for usage water, and  $10^\circ C$  for cold water.

$$\begin{aligned}
 Q_{\text{discharged}} &= Q_{\text{use}} \\
 Q_{\text{discharged}} &= m_{\text{use}} \cdot c_{p,\text{water}} \cdot \Delta T_{\text{use}} \\
 m_{\text{use}} &= 2284.3 \text{ kg} \Rightarrow 571 \text{ kg/day}.
 \end{aligned}
 \tag{21}$$

Equation 21 states the the tank delivers 571 kg/day of water with a temperature of  $38^\circ C$ . With an estimated consumption per capita of 120 liters/day explained in 3.4.2. The tank is capable of accommodating a household of 4 persons during the experiment time.

### 7.2.1 Reducing grid peak

One particular objective for the controller is to reduce the grid peak by controlling the heating element. Figure 7.8 presents the electricity price during the experiment time and an illustration when the heating element is connected (the heating element indication is multiplied with 2.4 for illustrations purposes).

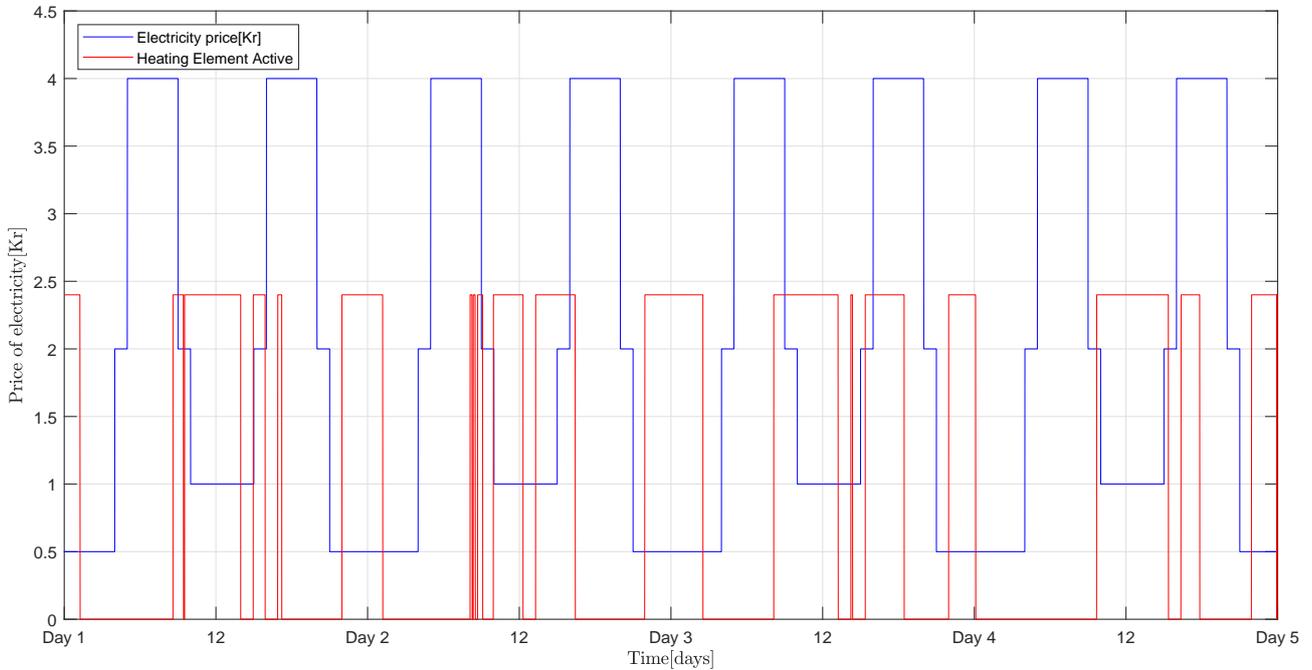


Figure 7.8: Price during experiment and heating element active for result experiment 2

As seen in figure 7.8, the heating element is most active when the electricity price is low. For the situations where the element is connected during high price periods, the element is activated due to PV production. Without any exceptions, the heating element is connected during the night when the grid capacity and electricity price is low. However, due to the output of the PV system is lower than the elements power, the system uses grid electricity when the logic activates the heating element based on PV production. Nevertheless, as figure 7.9 represents, the grid consumption is reduced during the peak periods due to PV production.

Another situation which is interesting in figure 7.9 is the situation which occurs when the heating element is disconnected due to maximum temperature reached, and the PV production still produces electricity. This results in a new peak on the grid, taking place every day during the experiment period. Nevertheless, the goal of reducing the consumption during high demand period by controlling the heating element is achieved.

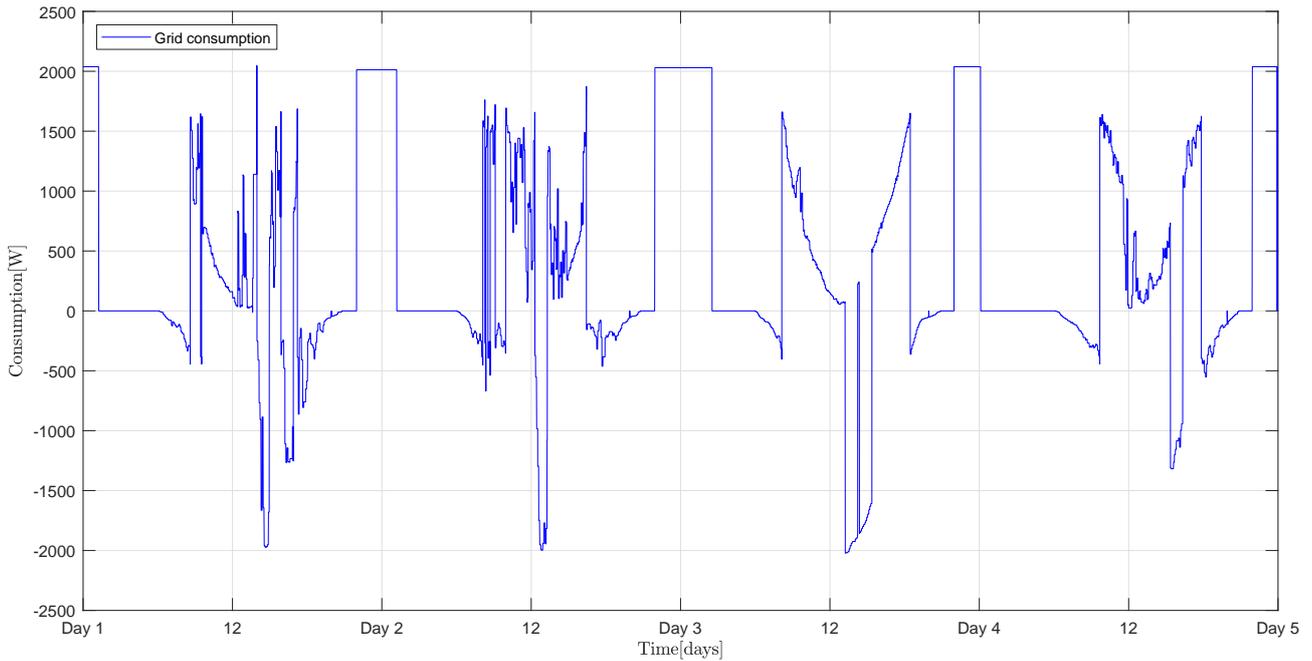
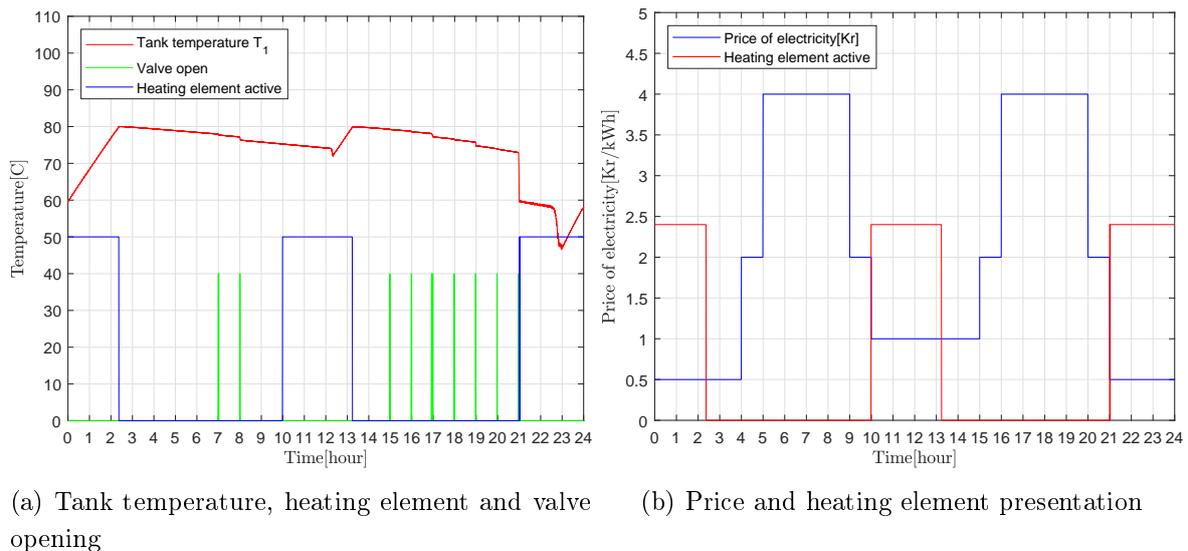


Figure 7.9: Consumption grid for result experiment 2

### 7.2.2 Day without PV production

As figure 7.5 illustrates, every day during the 4-day experiment where there was no PV produced electricity to be stored. With this in mind, the experiment is run once more for 24 hours, when the energy storage logic is deactivated as well as the forecast. The result is a tank temperature of  $80^{\circ}\text{C}$  and is illustrated in figure 7.10a. Figure 7.10b shows the price of electricity and a presentation when the heating element is active. For graphical presentation of all the temperatures in the tank, see appendix H.5, figure H.11. For price comparison with the 4-day experiment, see appendix H.5, table H.8.



(a) Tank temperature, heating element and valve opening

(b) Price and heating element presentation

Figure 7.10: Tank temperatures, heating and price graphs for 1 day test of result experiment 2

As illustrated in figure 7.10a, the tank temperature is set to  $80^{\circ}\text{C}$ , and the element is active for the first two hours to reach the tank temperature. At 07:00 is it two following valve openings, and the next valve opening occurs at 08:00. During the first valve openings, the heating element remains off until the electricity price, showed in figure 7.10b, decreasing down to 1 NOK/kWh. The element remains active until the tank temperature is reached. During the next valve openings, the element is not active until the last valve opening at 21:00. At this time, the electricity price is at 1 NOK/kWh, and the element activates. The tank temperature continues to decrease, but there are no more valve openings. Table 7.5 presents the key data from the experiment.

Table 7.5: Data from result experiment 2 for 24 hours with no PV produced electricity

Description	Value	Unit
Start energy tank	28,856	kJ
End energy tank	27,096	kJ
Lowest temperature tank[ $T_1$ ]	47	Celsius
End temperature tank[ $T_1$ ]	58	Celsius
Electricity consumption all	18	kWh
Price used electricity worst case	12	NOK
Price used electricity grid tariff	9	NOK
Total exchange of water	241	Liters
Total amount usable water	519	Liters

The table 7.5 shows that the lowest tank temperature during the 24 hour period is  $47^{\circ}\text{C}$ . This is occurring after the second valve opening and is therefore negligible. At the end of the experiment period, the heating element is active and can increase the temperature to  $58^{\circ}\text{C}$  before the end. During the day, the logic can deliver acceptable temperature at every valve opening. This makes the controller acceptable for use at days with no PV produced electricity.

## 8 Discussion and improvements

This section presents the discussion and suggestion to improvements to optimise the controller further. First, the economic potential is discussed followed by the development. Further on, results are discussed and compared with previous work. In the end, some further improvements are listed based on the elaboration done in the discussion part.

### 8.1 Discussion

#### Economical potential

One of the main objective for this thesis was to store self-produced energy which again would decrease the grid consumption and decrease the cost of hot water usage. By designing a controller the heating element is activated when the production of electricity from the renewable energy source begins. The experiments has shown that there is beneficial to store the self-produced electricity rather than use all necessary electricity from the grid. The first experiment presented a savings off 15% when using today's pricing agreement for a 4-day period. The second experiment which was run to reduce grid peaks and consumption during high periods shows a saving of 80% when using worst-case pricing for a 4-day period. However, the saving is calculated using the same experiments which is set up for PV utilisation, meaning that all the settings and control is based on energy storage. In addition, PV production is not equal for any day which affect the actual saving.

Supplementary to the 4-days experiments, there was executed two 24 hours experiments without any energy storage. When comparing the price for this experiment with the day by day data from the 4-day experiment, it is seen that the saving is between 9-55% per day with grid tariff, depending on the amount of self-produced electricity. For grid reduction consumption experiment, the difference between the one day experiment showed that there was only day one which lower price than the one day experiment. This can be justified due to the PV system output is not fixed compared to the heating element which is fixed. For actual saving in this case, the experiment the system needs to be re-tested with a variable heating element input, ensuring no grid use when the logic has activated the heating element du to PV production.

By installing a controller for energy storage, there is benefits for the grid operators. From a grid operators point of view, the controller would decrease the overall grid consumption for a household by utilising self-produced electricity. I addition to energy storage, by combining the controller with logic to shift the demand to low-demand periods in the grid, the benefits for grid operators increases even more. The results in this thesis illustrates that with temperature logic, there is possible to move the electricity demand. The economic potential for the grid operators is not addressed in this thesis, but as mention in the introduction, there a billion investment required if the peaks continuous to increase. Another asset is the reduction of new grid peaks which occurs if there is large PV systems in an area. Storing the produced energy instead of selling to the grid reduces the grid demand during periods with high PV production.

In addition, there is benefits for the households. The main benefit is the reduction of grid electricity which reduces the price of hot water usage. In addition, the expected new tariffs may increase the saving further, as one of the suggestion introduces "time of use" as a tariff. Together with the new tariffs, there is an expectancy of overall increase of electricity price in Norway which makes the benefits larger.

### **Controller logic and communication**

One of the design criteria was to reduce the grid consumption without affecting the user-comfort. Previously presented research focuses on reducing grid peak by managing multiple water heaters remotely or locally. This has lead to intensive and complex load control models, ranging from average consumption to mathematical and optimisation models. In this thesis, the grid peak and consumption is decreased without any load model, only using average and electricity based, and a random water demand profiles. The controller in this thesis differs from previous research by increasing the temperature using "free" energy from renewable sources. By using renewable energy, the grid consumption decreases and the controller is not depended on any consumption patterns, as the controller is designed to a high consumption pattern which exceeds normal use. However, the tank is not used as a household tank, which may affect the results presented in the thesis. Although, the results show that the controller reduces the peaks in the grid without affecting the user-comfort, there is necessary to test the controller in an actual household for verification.

During the design of the controller and the logic, there are some difficulties concerning too low tank temperature and the logic for different situations. To ensure that energy storage in the tank is possible, the temperature in the tank needs to be varied to ensure as much energy storage as possible. The solution is to use forecast data, and adjust the temperature with information from the forecast each day. This is a more straightforward approach compared to estimate water usage with different water consumption profiles. However, this increases the electricity consumption overall, if the water demand for the day is low. If the demand is low, a substantial amount of the used grid electricity is not required. This can be solved by developing a simulated water tank to predict the temperature change in the tank, based on actual water exchange.

Due to the water consumption profiles is based on energy in water, there are no specific benchmarks to address regarding water usage. Besides, the choice of using a random water consumption profile makes the direct comparison of water usage between experiments difficult. Also, the flow is based on average measured flow, which may change due to other water usages in the region and building. Another restriction has been the inlet temperature of water. As the temperature of the inlet water also is depended on other water usages in the building, the temperature varies. This has a direct impact on energy storage and water consumption. Low inlet temperature gives higher energy storage capabilities. High inlet temperature gives low energy storage but is better for water discharge as the average temperature in the tank is higher. However, change in inlet temperature is equal for a regular household as well. Nevertheless, one of the design criteria is not to affect the user-comfort. From a household point of view, the shortage is of greater concern, than the situations where there is an excessive amount of hot water. When comparing the exchanged water with the manufacturer's estimation of the tank is sufficient for a 4-person household, the amount of water exchanged during

the final experiments, is in the higher regions of what to expect of a tank with this capacity.

For the main task of storing PV produced electricity, the results illustrate some shortcomings. During the day, the maximum temperature in the tank is reached, while there is still acceptable production for storage. The reason is how the heating element is controlled. As the presentation of the system explained, the element is controlled by a relay. With the relay, there is not possible to control the power sent to the tank beyond an on/off command. In other words, the consumption from the element is divided between the grid and the solar system. If the PV production is high enough to begin storage but lower than the power of the element, grid electricity use used. To only use PV produced electricity, the element needs to be used with a power controller. A power controller can regulate the power sent to the heating element, based on the production from the PV system. This would make the controller able to store all the produced energy in the tank, as the element would be limited and not heat with full power when the production is lower. With power control implemented, a new series of experiments are necessary to confirm the settings regarding predetermining tank temperature and PV production.

To be able to use the controller with standard water tank without serious modification has been important throughout the design and experiment process. During the developing experiments, the controller demonstrated the referenced temperature in the tank is essential. By using the temperature measured in the middle of the tank, better temperature control was achieved, compared to using the sensor at the top. The logic is set to use the middle-temperature sensor when controlling the temperature during the final experiments. By only using one sensor in the tank, the modifications required for a standard tank is minimised. However, for further development, the possibilities of implementing an internal temperature sensor, by removing the standard thermostat should be investigated.

From the results, the different experimental prices are presented based on the grid consumption. Both the final experiments has price calculations for utilising the majority of the self-produced electricity or sell all to the grid operator for repurchasing it. The price for the experiment varies, depending on the chosen pricing agreements. There is almost without exception, a better solution to store as much produced electricity than selling it. The only exception is the Otovo agreement, which included a high price for the self-produced electricity. As mention, the agreement with Otovo is limited to production up to 5000 kWh/year. How this agreement would change when the new tariffs are implemented is not known. However, using the controller for achieving grid peak reduction criteria is still fulfilled, independent of which pricing agreement used.

The implementation of AMS communicating through the HAN-interface has introduced some drawbacks which need to be improved for ensuring an optimal controller. In this thesis, the AMS has only been used for reading the net consumption from the grid. Based on the interface, there is a large amount of information which should be available but is not used for this controller. The reason is the interface and software installed in the gateway. From the manufacturer, the gateway was not prepared for reading more than the net consumption from the AMS. For further developed, more of the data from the AMS should be researched and implemented in the controller.

When looking at the overall cost for a household by installing a controller, some issues may be addressed. The controller needs to monitor the tank temperature which require some modifications.

However, the modifications are small and only include a temperature sensor. If more experiments were executed to improve the controller, there is a possibility to increase savings and decrease the pay-back time of the controller.

## 8.2 Future work

Due to the time consumed regarding building a physical model, there are some experiments which were not executed, which requires long experiment time. The experiments are time-consuming, and if an error occurs, the complete experiment fails. With this in mind, and the issues elaborated in the discussion section, the following implementations and improvements are presented using the following bullet points:

- Conduct experiments for more extended periods of time with different water consumption.
- Compare experiments with only grid electricity for longer periods.
- Implement the controller to an actual household for periods to get real data regarding water consumption.
- Modify the tank by switching the internal thermostat with a temperature sensor.
- Create a simulated tank to predict temperature change based on water exchanged for more accurate temperature setting.
- Change the relay to power control to increase the utilisation of PV produced electricity.
- Improve the communications between the PV system, and weather forecast to better estimate the tank temperature for each day.
- Improve the communications between the controller and the AMS.
- Create a system with PV production and controller with as small investments as possible.
- Include the controller to a larger system with more price and grid reduction solutions.

## 9 Conclusion

The objective of this thesis was to develop a controller for storing electricity produced from a photovoltaic system in a regular household water heater. The controller should store as much electricity as possible as energy by increasing the temperature when the PV system produced electricity. The encouragement for doing energy storage is related to the implementation of AMS and new tariffs for electricity prices in Norway. Besides, the price of components for installing systems for producing electricity in a household is decreasing.

Previous research done on controlling EWH is based on reducing the peaks in the grid by shutting down the heaters remotely based on grid utilisation information. Further on, the recently presented research has presented advance mathematical models to optimise the shut-down time for the EWH without affecting user-comfort. The consumption models which has been developed and used has undergone only minor changes and has the similar peaks as the grid utilisation. However, the denominator for the research published in the complexity of estimating water consumption in advance. This has lead to algorithms used as learning the consumption for different households, improving the shut-down periods.

The approach for this thesis was to use different water and electricity consumption profiles. By increasing the temperature in the tank when there is electricity production, the produced energy is stored in the tank. During the first experiments, it was discovered that the tank temperature settings needed to be changed to increase the utilisation of energy storage, and prevent the tank temperature from becoming too low. This was done by using logic for estimating expected PV produced electricity from the weather forecast. This improved the tank temperature which the results showed that the controller was able to meet the requirement of having usable water available. For storing self-produced electricity, there were only small changes. This was related to the controlling of the heating element, which for further developed needs to be controlled with a power controller instead of a relay. Installing a power relay would also help in reducing the new peaks occurring when the electricity is sold.

The results show that the grid consumption during peak hours is decreased by controlling the EWH. Regardless of the water demand is evenly distributed during the day, or if the demand is high during grid peak hours, the controller manages to keep sufficient temperature in the tank to manage the demands. The overall grid consumptions are also reduced due to energy storage from the PV system. It is seen that the selected tank temperature settings need more developed for optimising the storage, as there is excessive hot water after some days, which affect the energy storage capability. Also, the results show that the controller can reduce the grid consumption without any PV system.

From an economic point of view, the controller has benefits both for the grid operators and household. The operators benefit from the reduction of overall consumption, and the controller ability to shift the load to low-demand periods. In a household, the amount of saving is depended on which pricing agreement the household uses. For today's pricing agreement with constant price, the results show a saving of 18% compared to only use grid electricity and sell the PV separately. For "time of use" agreements which makes consumption during peak hours significantly higher, the saving inconclusive due to lack of power control for the heating element. It is important to emphasise that for the

experiments done in this thesis, the controller is set-up to enable energy storage which enables the heating element when it is PV production. For actual saving, the controller should be retested with the new tariffs which have been out in consultation, and with storage logic deactivated. Nevertheless, for a regular pricing agreement, there is more economical to store PV produced electricity than selling it. For pricing agreements which gives the household a high price for self-produced electricity, there is more economical to sell and re-buy, but this requires additional components to be installed.

During development of the controller, there have been many available sensors for use in the design process. As the controller has improved, a reduction of required components and sensors for the tank has been necessary for the system to work. For the end controller, there is only necessary with one temperature sensor located in the middle of the tank for temperature control. To reduce the modifications necessary, the sensor can be fitted, replacing the thermostat. However, it is important to emphasise that the sensor should be placed in the middle of the tank.

The results demonstrated a controller which can store electricity as hot water in a regular water tank. During the test periods, there was above average PV production which affected the results. Due to lack of power control of the heating element, the overall grid reduction still can be improved, as the difference between the output from the PV system and the input of the heating element, was covered by grid electricity. Further development should include retesting the same experiments, with power control.

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## Appendix A Comparison of renewable energy sources

All information in table A.1 is based on the information collected from references [55], [56] and [57]. Other energy sources such as ground heating(Geothermal), natural gas, tides, fusion is also available but suffers from large drawbacks which makes them not fitted for household purposes.

Table A.1: Comparison of renewable energy sources

Source	Advantages	Disadvantages
Solar Power	<ul style="list-style-type: none"> <li>- Low maintenance</li> <li>- "Unlimited" source</li> <li>- Long lifetime &gt;20 years</li> <li>- Installed anywhere</li> <li>- Silent</li> </ul>	<ul style="list-style-type: none"> <li>- High investment</li> <li>- Uneven production due to sunlight</li> <li>- Use of non-renewable materials for construction</li> <li>- Needs energy storage or other additional power source</li> </ul>
Wind Energy	<ul style="list-style-type: none"> <li>- High output</li> <li>- Simple installation</li> <li>- Long lifetime &gt;25 years</li> <li>- No emission</li> </ul>	<ul style="list-style-type: none"> <li>- Extensive use of land</li> <li>- High investment</li> <li>- Moving parts which increase the maintenance</li> <li>- Noise during high wind</li> </ul>
Hydro-power	<ul style="list-style-type: none"> <li>- Adjustable production</li> <li>- Large output</li> <li>- No emission</li> <li>- Reliable</li> <li>- Long lifetime &gt;30 years</li> </ul>	<ul style="list-style-type: none"> <li>- Expensive</li> <li>- Extremely high maintenance</li> <li>- Geographical depended</li> <li>- Remote areas</li> <li>- Requires dams</li> </ul>

## Appendix B Physical model

### B.1 Sketch of the tank modifications with location of temperature sensors

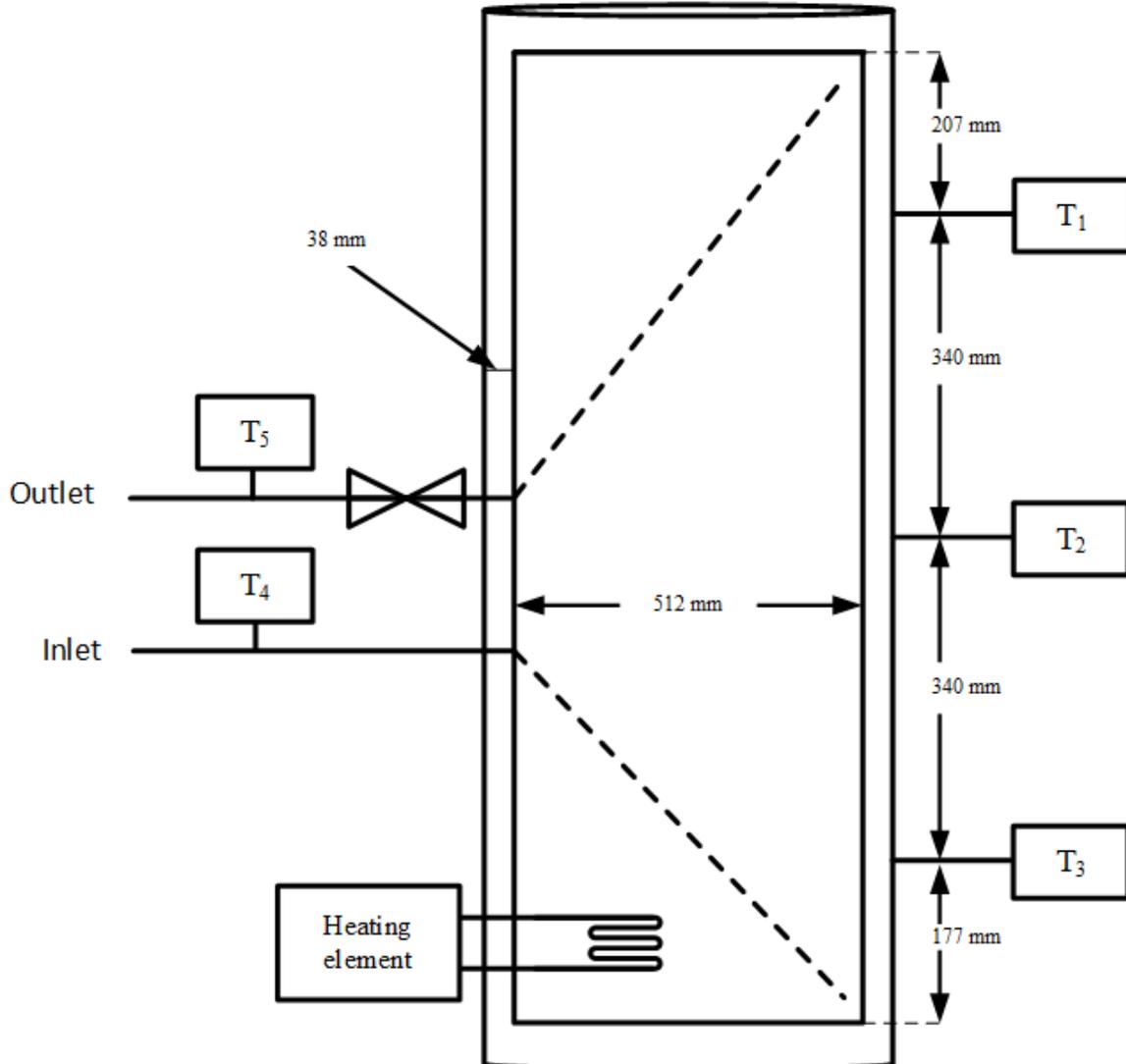


Figure B.1: Layout of the tank with dimensions

**B.2 Wiring scheme junction box**

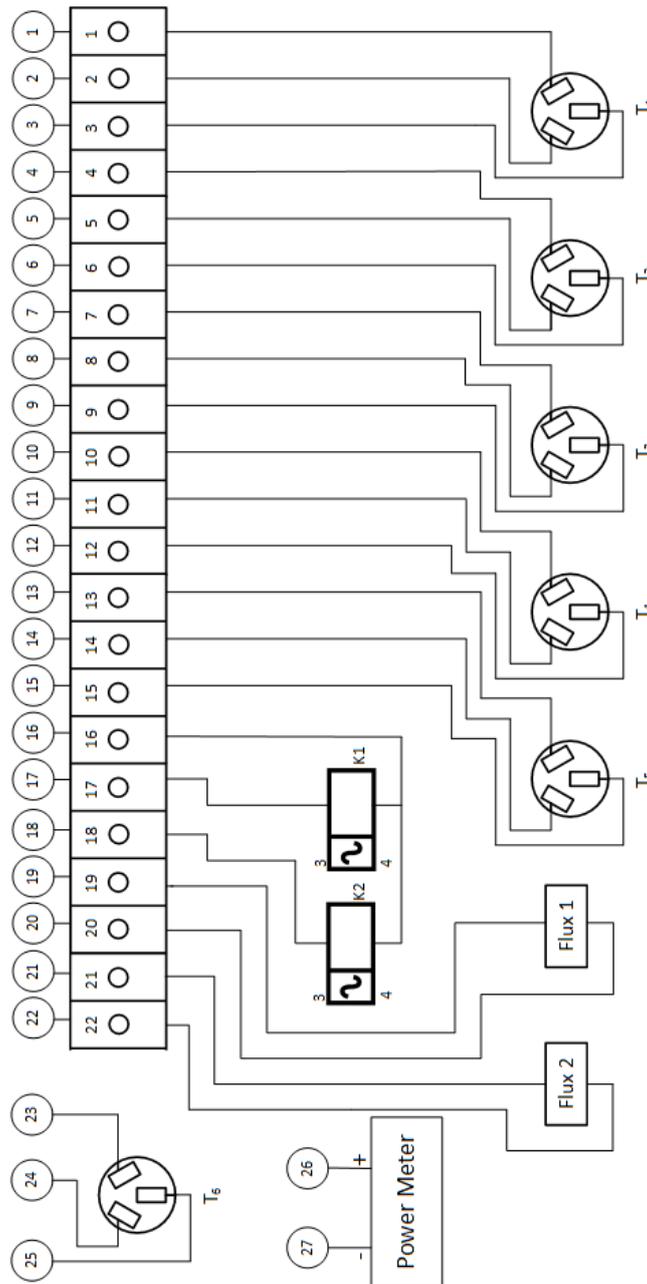


Figure B.2: Wiring scheme for the junction box placed at the top of the tank

### B.3 Wiring scheme DAQ-modules

## cDAQ

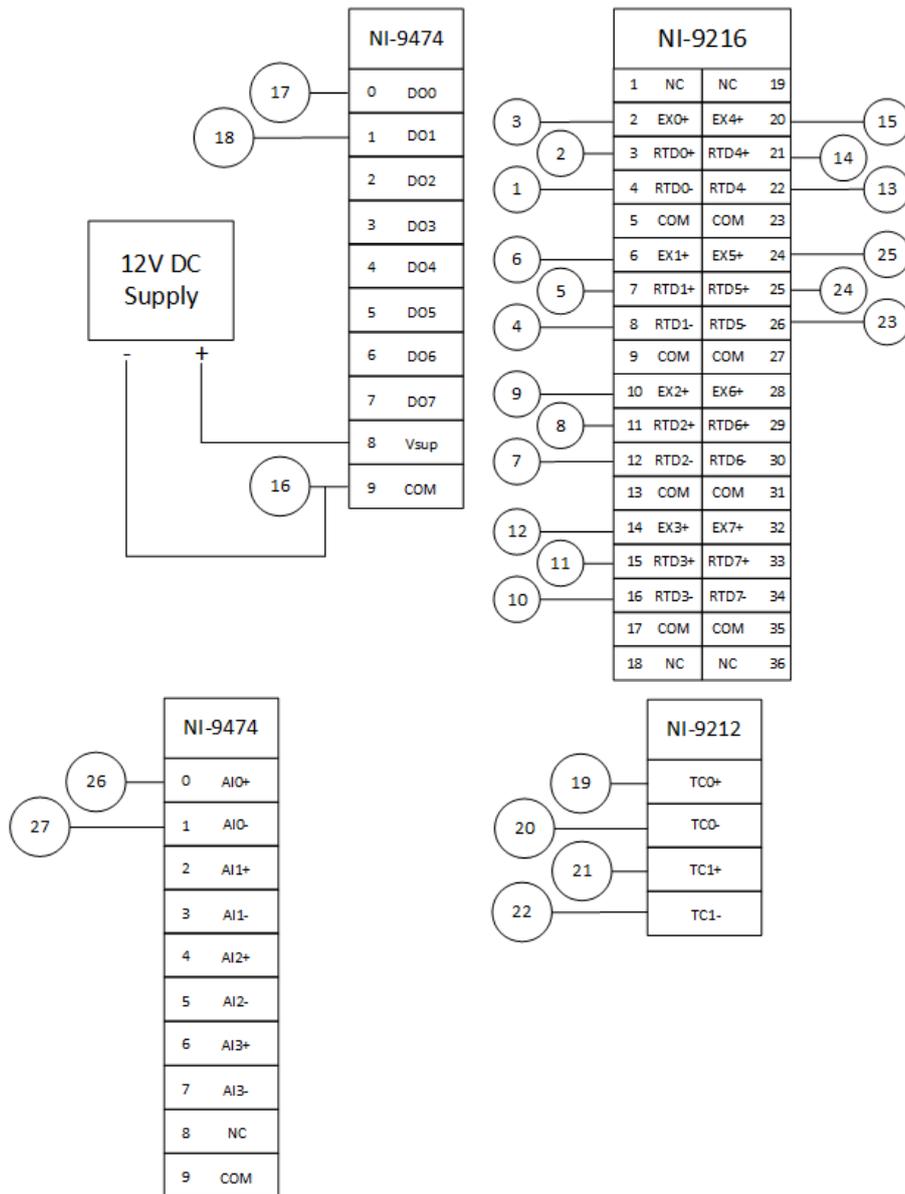


Figure B.3: Wiring scheme for the cDAQ used

## Appendix C Physical Setup

The setup is written and developed in collaboration with A.R Hval as part of a his master thesis at UiA.[58]. In this appendix the system components for making the physical system and conducting experiments. The information for each component is presented in a compressed form, and the information is collected for the manufacturer of each component.

### C.1 Advance Metering System

The advanced metering system, AMS is manufactured by Kamstrup and is a 3-phase model. This unit can provide both the customer and grid-operator with information about voltage, events and load profiles. Besides, the unit supports the most common communications interfaces and is ready to use with Home Area Management, HAN-interface[59]. From NVEs description of the HAN-interface, the information from the AMS should include instant power demand, power (active/reactive), current, voltage, energy(active/reactive) and time stamp[47].



Figure C.1: AMS from Kamstrup[59]

### C.2 Power Relays

The system is installed with two separate power relays delivered by E2U. The reason for the relays is to monitor the consumption by the heating element, and the production from the PV system. The data is used for comparing with other collected data. Figure C.2 shows one of the relays used. The relays communicate with the gateway using ZigBee communication protocols. In addition to power monitoring, the relays may be used as switches if connected to a cloud service.

### C.3 Gateway

The gateway is used for communicating with the relays using Zigbee interface. In this system, the gateway is used to communicate with the AMS using the communication port. For communicating



## C.4 PV system

In this appendix the PV system used is presented. Appendix C.4.1 covers the solar panels used, appendix C.4.2 describes the micro inverters and appendix C.4.3 explains the energy communication unit used.

### C.4.1 Solar panels

REC group manufactures the solar panels used. For this system, four panels are mounted on the roof at UiA Campus Grimstad, Norway. Combined, the panels has a max peak of 1000W, 250W each[62]. Each panel has an efficiency of 16.7%. Figure C.4 shows on the panels mounted.



Figure C.4: Picture of one of the solar panels used

### C.4.2 Micro Inverter

In this system there are two micro inverters named YC500A are mounted underneath the solar panels. Each inverter has a maximum output of 500 W and can accommodate 2 PV modules up to 365 W each. Figure C.5 is a picture of the inverter. [63]



Figure C.5: Micro inverter from APS[63]

### C.4.3 Energy Communication Unit

The APS ECU(Energy Communication Unit) is a user-friendly gateway for the inverters. The ECU provides easy access data for all the connected panels with individual statistics of temperature, voltage and production. In this system, the unit communicates with a computer, using an ethernet cable[64] with updates on changes of production every 5 minutes.



Figure C.6: Energy communication unit from APS[65]

### C.4.4 Expected PV production based on location

The location for position of the solar panels is  $58^{\circ}20'3''$ North,  $8^{\circ}34'36''$ East. By using the PVGIS provided by the European Commission, the expected production and optimum angle is collected and displayed in figure C.7.

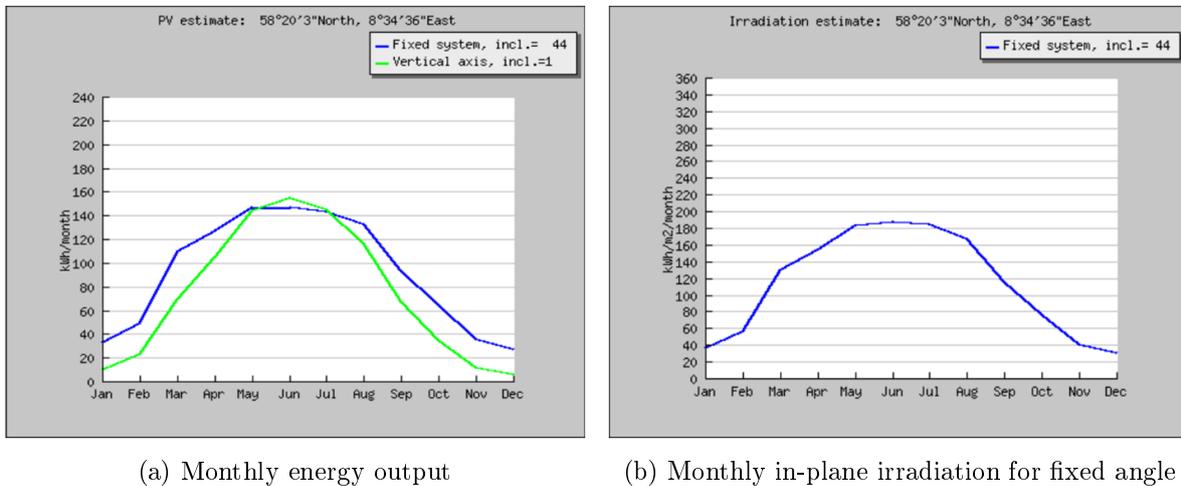


Figure C.7: Energy and irradiation for the optimum angle for the location of the system[48]

From the graph, a figure of tables can be collected and is showed in figure C.8.

Fixed system: inclination=44 deg., orientation=-1 deg. (optimum)				
Month	Ed	Em	Hd	Hm
Jan	1.05	32.5	1.18	36.6
Feb	1.75	49.1	1.99	55.7
Mar	3.54	110	4.17	129
Apr	4.24	127	5.13	154
May	4.73	147	5.91	183
Jun	4.90	147	6.23	187
Jul	4.63	143	5.93	184
Aug	4.26	132	5.41	168
Sep	3.10	93.0	3.84	115
Oct	2.06	64.0	2.46	76.3
Nov	1.18	35.3	1.35	40.5
Dec	0.88	27.1	0.98	30.5
Year	3.03	92.3	3.73	113
Total for year		1110		1360

(a) Fixed system production

Vertical axis tracking system inclination=1°				
Month	Ed	Em	Hd	Hm
Jan	0.30	9.32	0.46	14.1
Feb	0.81	22.7	1.03	28.8
Mar	2.22	68.9	2.66	82.4
Apr	3.48	104	4.14	124
May	4.63	144	5.64	175
Jun	5.14	154	6.37	191
Jul	4.69	145	5.87	182
Aug	3.74	116	4.66	144
Sep	2.23	67.0	2.77	83.2
Oct	1.11	34.4	1.42	44.0
Nov	0.39	11.6	0.56	16.9
Dec	0.19	5.84	0.32	9.91
Year	2.42	73.6	3.00	91.3
Total for year		883		1100

(b) Vertical axis production

Figure C.8: Excepted production table[48]

Where

*Ed*: Average daily electricity production from the given system (1kWp) (*kWh*)

*Em*: Average monthly electricity production from the given system (1kWp) (*kWh*)

*Hd*: Average daily sum of global irradiation per square meter received by the modules of the given system (1kWp)(*kWh/m<sup>2</sup>*)

*Hm*: Average sum of global irradiation per square meter received by the modules of the given system (1 kWp) (*kWh/m<sup>2</sup>*)

The estimated production can be compared with the actual production presented in figure C.9, which shows the production for each day in April. The combined production for the system in April is 133 kWh, which is 5 kWh higher than the expected production. The difference of 5 kWh shows that the service from PVGIS is a good approximation for the cite.

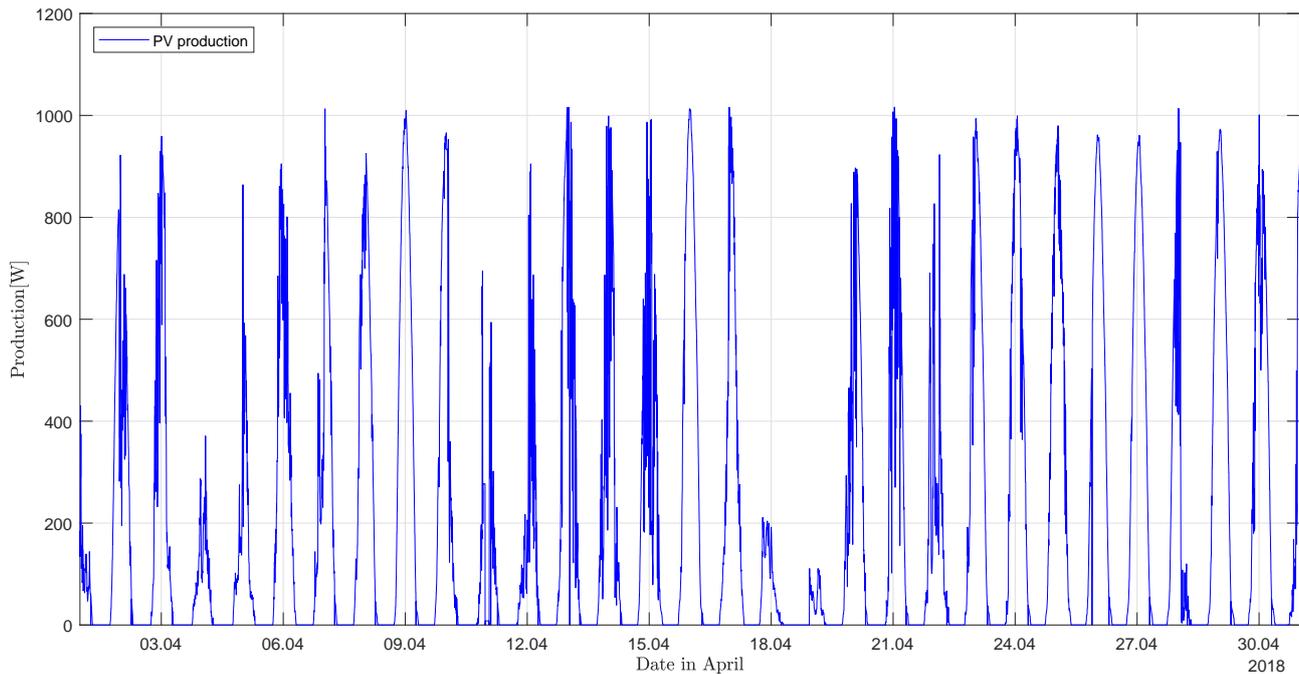


Figure C.9: Actual PV production for April

### C.5 Electrical Water Heater

The electrical water heater used is a FerroTerm 200-s which with a rated capacity of 194 litres. This tank is delivered with a heating element with a rated power of 1.95 kW and is controlled with a solid state relay. Compared to others manufactures CTC has thicker isolation to reduce heat loss to the environment. Also, the heating element is tilted to ensure heating all the way from the bottom of the tank[66].



Figure C.10: Electrical water heater from CTC[66]

## C.6 Data Acquisition System

The data acquisition system has four modules which are arranged in a USB chassis. All the components are from National instruments and are described in detail further below.

### USB-Chassis

National Instruments has developed a compact USB-chassis for use with different of the modules available. For this system an NI cDAQ-9174, 4-slots chassis is used which communicating with the computer using USB. The chassis is capable of fast measuring and has high resolution[67]. Figure C.11 shows the module.



Figure C.11: Picture of NI cDAQ-9174[67]

### Temperature Module

For collecting information from the temperature devices, a temperature module named NI-9216 from National Instruments is used. This module is designed for use with RTD and is compatible with both 3-wire and 4-wire connections. In this system,, 3-wire is used[68]. Figure C.12 presents the module used.



Figure C.12: Temperature module NI-9216[68]

### Voltage output module

For controlling the valve in the system, a voltage module named NI-9474 is used, illustrated in figure C.13a. This is a voltage output module which works with a wide range of components. For creating controlling signal to control the system relays for valve and heating element control. A 12V DC power supply is used, showed in figure C.13b.



(a) Voltage input module NI-9474[69]



(b) 12v DC power supply for valve controller[70]

Figure C.13: Voltage system for valve control

### Flux Module

For measuring flux in the system, a temperature module is used. National Instruments has a module called NI-9212 which is designed for thermocouple temperature sensors. In this system, it is used to measure the proportional heat flux from the tank[71].



Figure C.14: Flux module NI-9212[71]

## C.7 Computer

The computer used is a Lenovo ThinkCentre M710t. The processor used is an Intel Core i5 and is ideal for use with measurements. The computer is located at UiA and is only used for these experiments [72].



Figure C.15: Lenovo ThinkCentre M710t [72]

## C.8 Temperature Sensors

There are five temperature sensors connected to the tank. Three that measure the temperature inside at different heights. Also, a sensor measuring the inlet water temperature, and one measure the outlet temperature. Finally, a PT-100 element is installed outside the tank to measure the room temperature. All the sensors are resistance temperature detectors (RTD) PT100-elements. The sensor is based on the resistance being  $100 \Omega$  at  $T = 0^\circ C$ . Variation in resistance is a function of temperature, approximately  $0.39 \Omega/1^\circ C$  [73]. The connection of PT100-elements varies between 2,3 and 4-wire connection. A 2-wire connection requires calibration due to resistance in the cables. In 3-wire connection, the extra wire functions as a calibration for line resistance, as long as the three wires have the same resistance. For a 4-wire connection, the error from the line resistance is eliminated. This is the most accurate method but is expensive compared to 3-wire systems. In this experiment the type of the connection is 3-wire.



Figure C.16: PT-100 element as mounted on the inlet[74]

## C.9 Valve

The valve used to control the water use by regulating the water discharge is a solenoid valve. By applying a voltage through the solenoid, the valve opens or close depending on the configuration. The valve used in this experiment is a normally closed (NC) valve, which means the valve only opens when a voltage is applied. To control the valve a solid state relay (SSR) is used. The relay makes it possible to use the low voltage signal to control large current systems.



Figure C.17: Solinoid Valve[75]

### C.10 Heat Flux Sensor

The heat flux sensors used is from greenTEG and of the type gSkin-XM. Two heat flux sensors are used mounted on the outside of the tank at the same height as two of the temperature sensors. That way the temperature inside the tank and in the room can be used as reference temperatures for the sensors. The sensor outputs a voltage to the NI-module, and the voltage can then be used to calculate the heat flux in  $W/m^2$  as,

$$\phi = \frac{U}{S},$$

where  $\phi$  is the heat flux,  $U$  is the voltage and  $S$  is the total sensitivity given as,

$$S = S_o + \left( \frac{T_h - T_c}{2} - T_0 \right) S_c,$$

where  $S_o$  is the sensitivity at calibration temperature,  $T_h$  and  $T_c$  is the temperature on the hot and cold side of the wall respectively,  $T_0$  is the calibration temperature and  $S_c$  is the linear correction factor.



Figure C.18: GreenTeg Flux sensor[76]

## Appendix D LabView

This section includes the different parts of the LabView controller. First, the hierarchy is presented followed by the two main sections of the program. In the end, the parameters which need to be set is presented.

### D.1 LabView program hierarchy

When opening the program in LabView, the HMI showed in figure D.1 is presented. Located in at the top, four environments are available: Overview, tank control, solar cells, misc and cases. Further on, each hierarchy is explained in a text with a description of what is included in each tab.



Figure D.1: Print screen of the front panel in LabView

### Overview

The overview is the main HMI and provides an overview of the controller during the experiment. In this tab, the length of the experiment, End temperature in the tank for grid consumption, lower temperature tank and the critical low temperature is set. Besides, the water profile and consumption profile is selected. Three lights present if the heating element is connected, valve open and if the tank is overheating. In addition, graphical presentation of PV production, Power consumption(relay and calculated), temperatures( $T_1 - T_5$ ) and grid consumption(AMS and relay). The temperature outside the tank is also shown.

## Tank Control

The second tab is named tank control and includes the data from the tank. Under this tab, two switches are available for override the valve and heating element. Besides, the delay time for the heating element is controlled under this tab. There is a graphical presentation of all tank, inlet and outlet temperatures. There is also a numerical presentation of the estimated time left for heating to the set tank temperature. A light also indicates if the tank temperature is to low.

## Solar Cells

In the third tab named solar cells, the information from the solar system presented in section 4.2.3 is presented. Also, the web address for scraping both the individual parameters and combined production from the system is set in this tab. This is also the tab where the minimum production is set which activates the heating element, and end temperature in the tank when using PV produced electricity, is also set in this tab.

## Misc

Under the misc tab the delay time for each iteration is set, together with the critical temperature for the program to force open the valve and disconnect the heating element. In this tab, the selection of using tank temperature based on the forecast, or using the grid temperature is selected. The weather forecast for the next days is also presented her with the button to manual get weather data. For collecting forecast and the information from the relays, there are to fields which the user sets the address to the location(Grimstad) and gateway(IP-address). A graphical presentation of the outside tank temperature is also seen in this tab.

## Cases

In the last tab, the cases parameters are set. Here the time between valve openings and other parameters for each case is selected. A field for time to midnight is also available for setting the number of hours to midnight. There is also a field for setting the start delay for the cases. For further development, there is also programmed in additional cases for testing both for electricity consumption and water profiles.

## D.2 Sections of LabView programs

This appendix includes the different subVI designed to make the controller for this thesis.

### D.2.1 Collecting solar cell information program

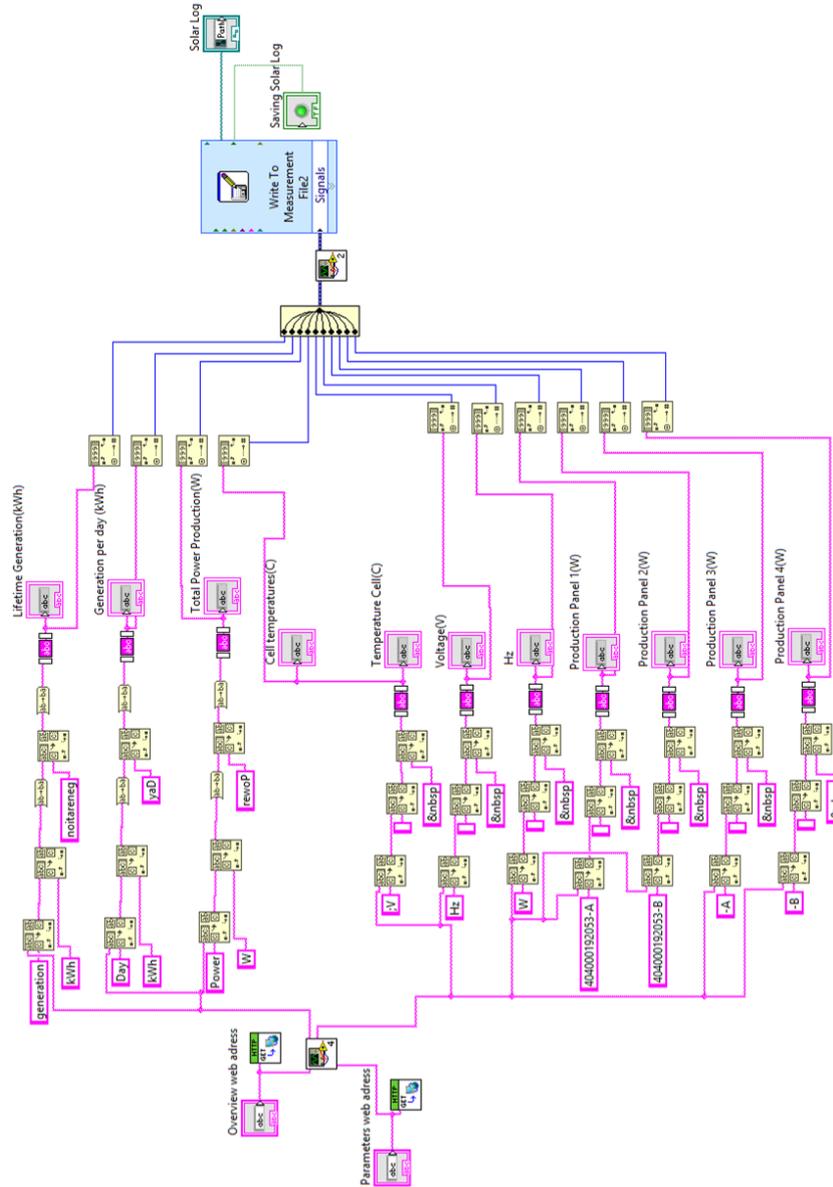


Figure D.2: The program for collecting solar production information

D.2.2 Tank data and control program

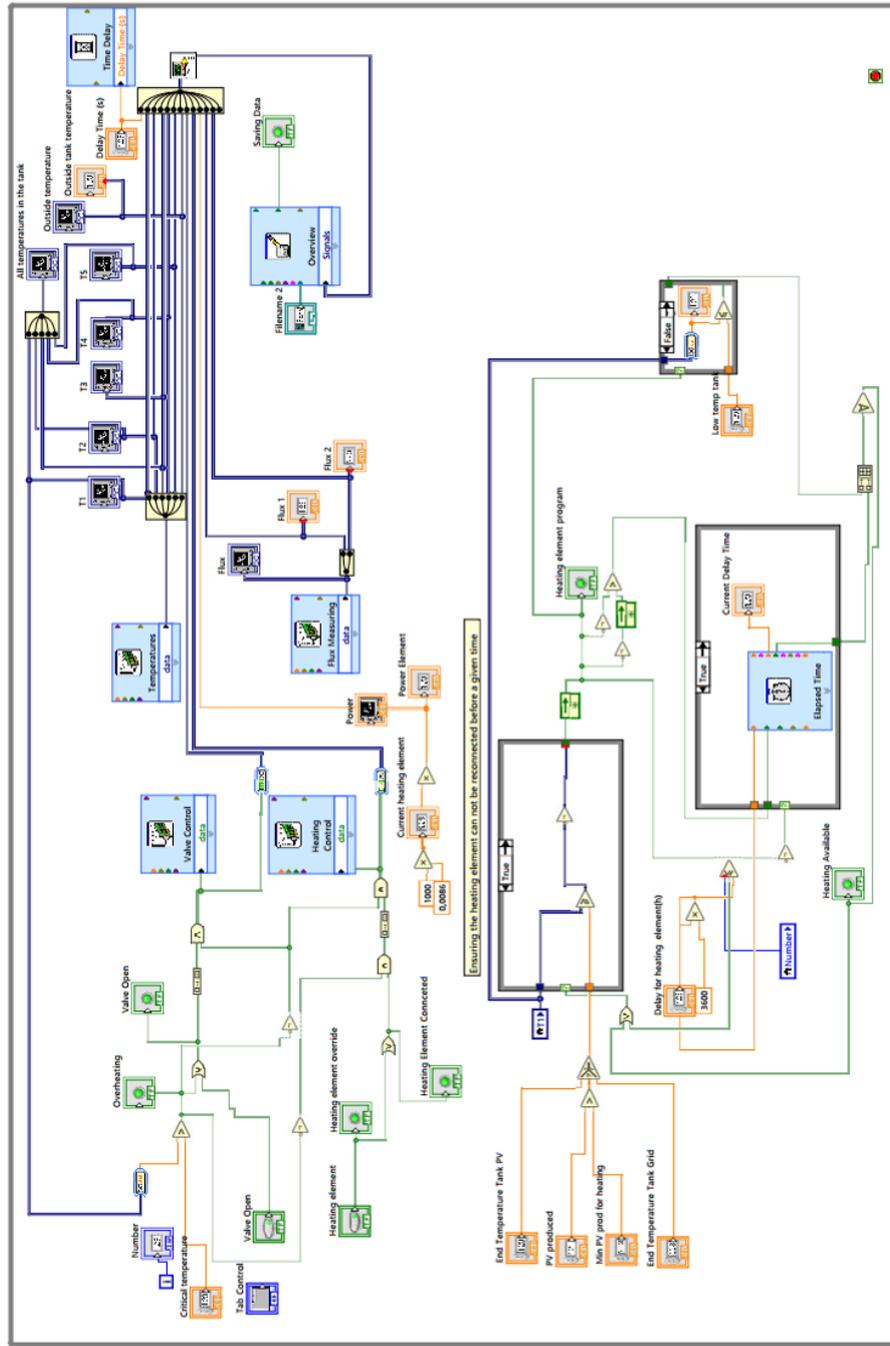


Figure D.3: The program tank data and control

### D.2.3 Parameters which needs to be set before starting experiment

Table D.1: Parameters which needs to be set before experiment

Parameter name in VI	Description
Length of experiment	Set the total experiment time in hours
End temperature tank grid	Setting the end temperature when the electricity is from the grid
Low temp tank	Setting the lowest temperature after heating in the tank before the heating element is connected
Delay for heating element	Setting the time in hours before the heating element is reconnected after disconnection.
End temperature PV	Setting the end temperature when the PV system producing
Min PV prod for heating	Setting the lowest production from the PV system required to heat the tank
Parameters web address	Web address for scraping the parameters from the PV system
Overview web address	Web address for scraping the overview from the PV system
Gateway web address	Web address for collecting JSON-string from gateway
Delay time	Time per iteration in seconds
Critical temperature	Setting the absolute maximum temperature in the tank before the heating element is disconnected and valve opens
Critical Low	The temperature which the program bypasses the consumption profile selected to increase the temperature in the tank
Water profile selection	Selecting which water profile to use
Consumption profile selection	Selecting which consumption profile to use
System flow	Setting the system flow (In this experiment always 0,39 l/s)
Start delay cases	Setting the time in hours before the cases begins
Temp water usage	Setting the temperature of water to the household after mixing in the faucet (Only valid for cases which needs the temperature for use)
Time between valve opening (Case 1-5)	Setting the time between each discharge executes in each case
Total amount case 5	Setting the amount discharged with the temperature of the "temp water usage"

## Appendix E Parameters

In this appendix, the parameters available which can be obtained from the program is presented. Also, the selection of parameters used in the experiments is elucidated.

### E.1 Variables available for measuring in the program

Table E.1: List of variables which can be measured with the controller

Name	Description
Temperature $T_1$	Temperature sensor located at the top of the tank
Temperature $T_2$	Temperature sensor located at middle of the tank
Temperature $T_3$	Temperature sensor located at the bottom of the tank
Temperature $T_4$	Temperature sensor located inlet at the tank
Temperature $T_5$	Temperature sensor located at the outlet of the tank
Temperature $T_6$	Temperature sensor located at wall to log room temperature
Valve	Valve position open/close
Heating	Heating element on/off
PV relay	Logging combined PV production using a relay
Heating element	Logging power sent heating element using a relay
AMS consumption	Logging net consumption from the AMS
Flux 1	Measuring flux through tank wall at the top of the tank
Flux 2	Measuring flux through tank wall at the bottom of the tank
PV ECU	Logging combined PV production information from the ECU
Production panel 1	Logging off production of panel 1
Production panel 2	Logging off production of panel 2
Production panel 3	Logging off production of panel 3
Production panel 4	Logging off production of panel 4
Hertz	Logging off the grid frequency
Voltage	Logging of grid voltage
Cell temperatures	Logging of cell temperatures
Generation per day	Logging of produced PV per day
Total generation	Logging of lifetime PV production

## E.2 Variables used in the program

In this appendix, the explanation and elaboration for selecting the parameters used in the controller. First, the PV production is discussed and compared with the available measurements methods. The last section covers the same approach towards the heating element.

### E.2.1 PV produced electricity

For measuring and document the produced electricity from the PV system, the system has two independent methods. The first is collecting the information about production from the ECU communicates with the panels through the power cable. The second is to use a power relay which is connected between panels and the AMS. Figure E.1 illustrates two hours of production and the difference between the two measuring methods.

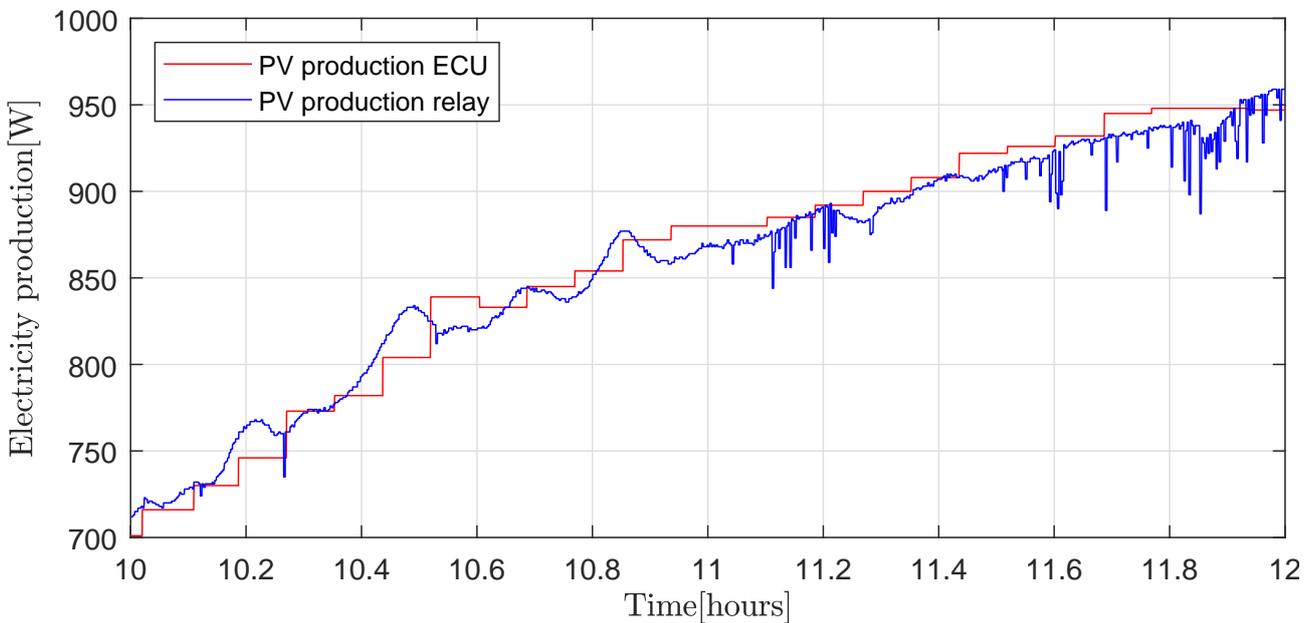


Figure E.1: Presentation of the two measurements which can be used for PV production

As figure E.1 presents, there is some difference between the two measuring methods. The ECU system, as described in appendix C.4.3 refreshes every five minutes. For the relay, the refreshing time is 10 seconds, which gives a more fluctuating graph. The different between the two in a 96-hour experiment is approximately 6%. When considering the low difference of 6%, the PV production information the controller uses is from the ECU. This is done to reduce the fluctuation in the amount required to activate the heating element. This would increase the minimum time for the heating element to the same interval the ECU updates.

## E.2.2 Power measurements of the heating element

As for the PV, there are two methods available for measuring the power consumption for the heating element. The first is a computation done by using the measured voltage done by the ECU and multiply the voltage with current. The current is set to be 8.6A, which is an average over a series of experiments. The second is to use a power relay which is connected between AMS and the heating element. Figure E.2 illustrates two hours of consumption and the difference between the two measuring methods.

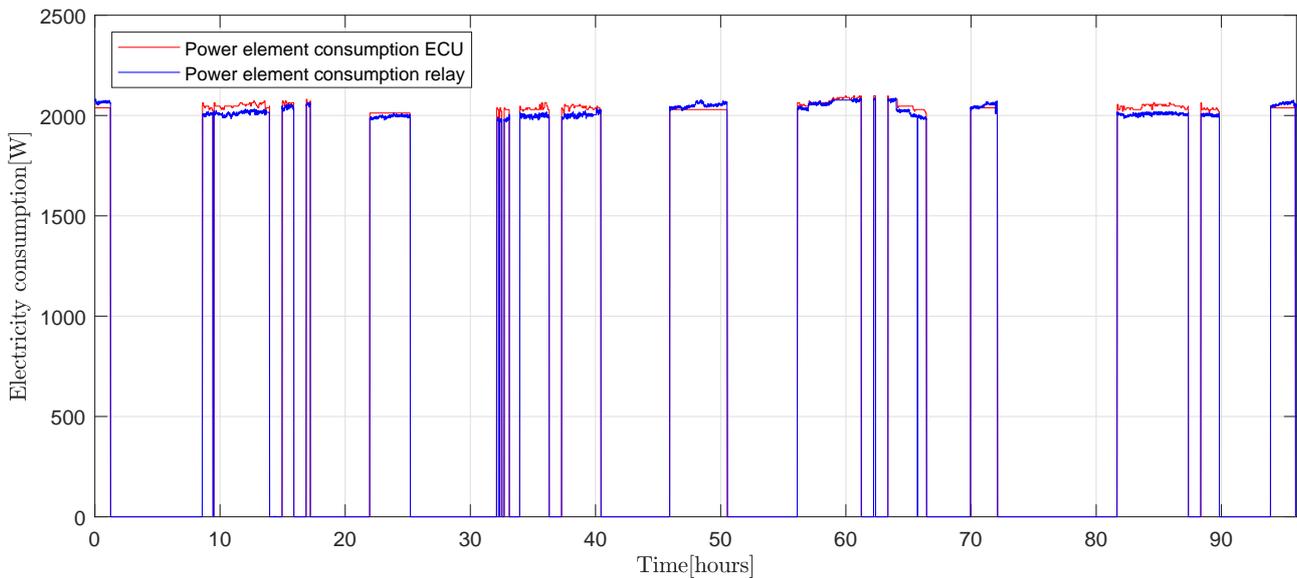


Figure E.2: Presentation of the two measurements which can be used for consumption

Figure E.2 presents the difference between the two measuring methods. By using the ECU and calculations for measuring consumption, the consumption is a little higher compared with relay consumption. As the consumption calculated is done with ECU information, the consumption is updated every 5 minutes. For the relay, the refreshing time is 10 seconds. The difference between the two methods is in a 96-hour experiment is approximately 1%. As the difference is only 1%, the heating element consumption is calculated by using the average every 5 minutes, which is the same interval the ECU updates, 5 minutes.

## Appendix F Average flow calculations

The setup is written and developed in collaboration with A.R Hval as part of a his master thesis at UiA.[58]. The flow-rate is found by opening and closing the valve at a controlled time interval of 3 seconds and measuring the water discharge from the tank. The average is calculated to be 0.36 liters/s. However, this may not be the correct for all the discharges due to other water usages at the university.

Table F.1: Experiments for calculating system

<b>Opening time valve = 3 seconds</b>		
Test 1	1.055	Liter
Test 2	1.091	Liter
Test 3	1.081	Liter
Test 4	1.1	Liter
Test 5	1.096	Liter
Test 6	1.08	Liter
Test 7	1.068	Liter
Test 8	1.084	Liter
Test 9	1.069	Liter
Test 10	1.08	Liter
<b>Average flow</b>	0.36	Liters/second

## Appendix G Price of components

The overall price of the experiments is calculated in this appendix using prices available for a regular customer. It is important to keep in mind that prices changes with rebates and overall reduction of development and construction cost. There are numerous suppliers of complete solar production systems and prices varies between which supplier selected. Also, the system installed for designing this controller has a rated capacity of 1 kWp, as for the experiments the output is doubled to meet the required input from the heating element. Another cost for the controller and its components is limited to physical equipped for instance computer and sensors. All prices are based on the components required for the final controller to functions as described in logic section 6. Strictly speaking, the expenses for designing the controller which includes LabView, experiment tank and National instruments components, are not included in the controller price. All prices are collected 12.05.2018 and may change.

### PV system

A complete PV system contains solar panels, inverters and communication unit. The prices include all the necessary components, but installation costs are not part of the price. All prices are calculated to price for two kWp system. Although systems which are part of a larger installation package is converted to 2 kWp system price. All prices is included with ENOVA subsidies for installing a system.

Table G.1: Comparison of price for PV system

Supplier	Size of package [kWp]	Price package[NOK]	Price for 2 kWp [NOK]
Smart Energi[77]	3	54 500	36 333
Solcellespesialisten[78]	2.1	45,900	40,857
Otovo*	2.7	45,649	33,814
<b>Average price</b>			<b>37,001</b>

\* Otovo prices solar system with installation cost and bases price of the selected roof area for the household. The price is changing due to the design of the roof.

As table G.1 presents the average price for installing a PV system is 37,000 NOK. In addition to the PV system, some components are necessary for installing the controller. The components are listed in table G.2, which presents an example of how the controller can be designed with as few components as possible.

Table G.2: Price list for controller components

Name	Description	Manufacturer	Price [NOK]
Raspberry Pi 3 starter kit	Small computer with components for installing the logic	Raspberry Pi	779
Temperature sensor	PT100 element for installing in the tank by removing thermostat	RS Components	320
USB DAQ	DAQ for communicating with relay and temperature sensor	National Instruments	3,405
Relay	Relay for controlling the heating element	Kudom	199
<b>Total</b>			<b>4,703</b>

The total price for components to build a controller is 4,703. The components used in table G.2 is only a suggestion. There are possible to get components to a lower price, and the price presented in this thesis is only an example of necessary components.

## Appendix H Data for experiments

In this appendix the data regarding energy, price etc. is listed for each experiment.

### H.1 Experiment 1

Table H.1: Data from experiment 1a without any PV produced electricity

Description	Value	Unit
Calculated start energy tank	27,582	kJ
Calculated end energy tank	35,733	kJ
Lowest temperature tank[ $T_1$ ]	30	Celsius
End temperature tank[ $T_1$ ]	70	Celsius
Electricity consumption	19	kWh
Price used electricity	40	NOK
Total exchange of water	315	Liters

Table H.2: Data from experiment 1b with PV produced electricity

Description	Value	Unit
Calculated start energy tank	27,750	kJ
Calculated end energy tank	43,909	kJ
Lowest temperature tank[ $T_1$ ]	60	Celsius
End temperature tank[ $T_1$ ]	83	Celsius
Electricity consumption	21.5	kWh
Price used electricity	21	NOK
Price without PV electricity	42	NOK
PV produced	13.5	kWh
PV used	11.5	kWh
Total exchange of water	172	Liters

## H.2 Experiment 2

Table H.3: Data from experiment 2a with no PV produced electricity

Description	Value	Unit
Start energy tank	24,254	kJ
End energy tank	35,072	kJ
Lowest temperature tank[ $T_1$ ]	49	Celsius
End temperature tank[ $T_1$ ]	70	Celsius
Electricity consumption all	17	kWh
Price used electricity Worst Case	22	NOK
Price used electricity Grid Tariff	9	NOK
Price used electricity Grid tariff season Summer /Winter	14/32	NOK
Price used electricity No AMS	16	NOK
Price used electricity Grid tariff power Summer /Winter	22/28	NOK
Price used electricity Grid tariff power season Summer /Winter	12/27	NOK
Total exchange of water	230	Liters

Table H.4: Data from experiment 2b with PV produced electricity

Description	Without PV	With PV	Unit
Start energy tank	23,940	23,940	kJ
End energy tank	32,642	32,642	kJ
Lowest temperature tank[ $T_1$ ]	58	58	Celsius
End temperature tank[ $T_1$ ]	85	85	Celsius
Electricity consumption all	23	23	kWh
Electricity consumption grid	23	12	kWh
Price used electricity Worst Case	37	22	NOK
Price used electricity Grid tariff	7	5.50	NOK
Price used electricity Grid tariff season Summer/Winter	15/40	14.5/37	NOK
Price used electricity No AMS	18	15.50	NOK
Price used electricity Grid tariff power Summer/Winter	12/33	13/33.50	NOK
Price used electricity Grid tariff power season Summer/Winter	13/33	13/33.50	NOK
Price used electricity Otovo	-0.50	5	NOK
Total exchange of water	213	213	Liters

### H.3 Data Result experiment 1

Table H.5: Key data from result experiment 1 per day

Description	Day 1	Day 2	Day 3	Day 4	Unit
Weather forecast	Cloudy	Partly cloudy	Fair	Clear	
Start energy tank	18,181	38,203	42,512	34,579	kJ
End energy tank	38,203	42,512	34,579	38,923	kJ
Lowest temperature tank[ $T_1$ ]	49	64	53	60	Celsius
End temperature tank[ $T_1$ ]	75	88	69	85	Celsius
Electricity consumption all	24	22	28	26	kWh
Electricity consumption grid	21	13	21	15	kWh
Price used electricity worst case	32	22	37	36	NOK
Price used electricity grid tariff	10	6	10	6	NOK
Energy storage utilisation	70.8	76.5	74.5	84.5	Percent

Table H.6: Comparison of data per day with one day experiment

Description	Price used electricity worst case		Price used electricity grid tariff	
	Price	Difference	Price	Difference
Day 1	32	-20%	10	-9%
Day 2	22	-45%	6	-45%
Day 3	37	-7.5%	10	-9%
Day 4	36	-10%	7	-36%

### H.4 Result graphs result experiment 1

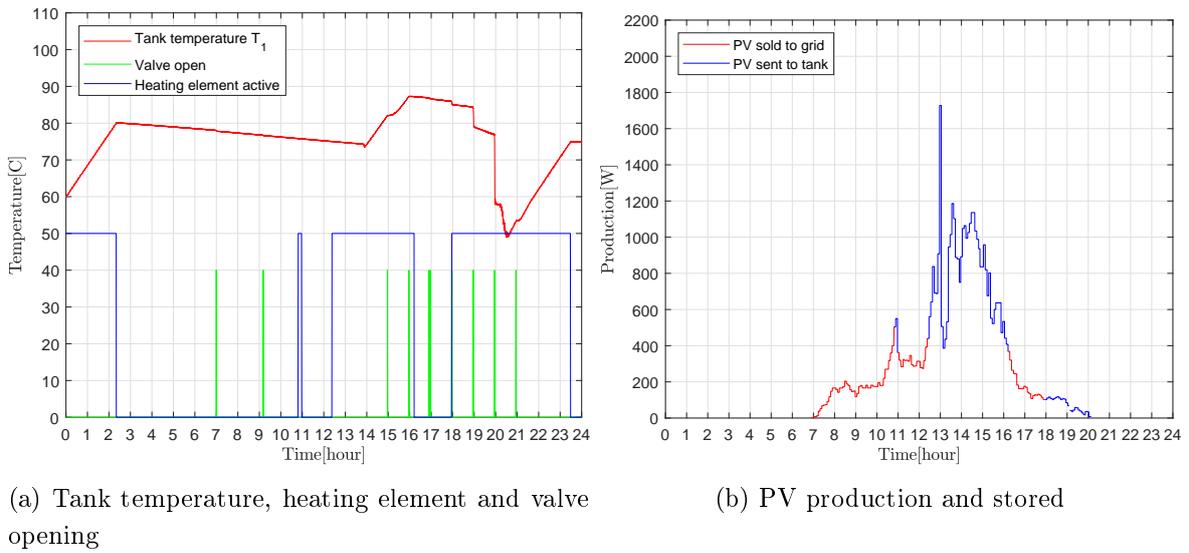


Figure H.1: Tank temperatures and PV graphs for result experiment 1, day 1

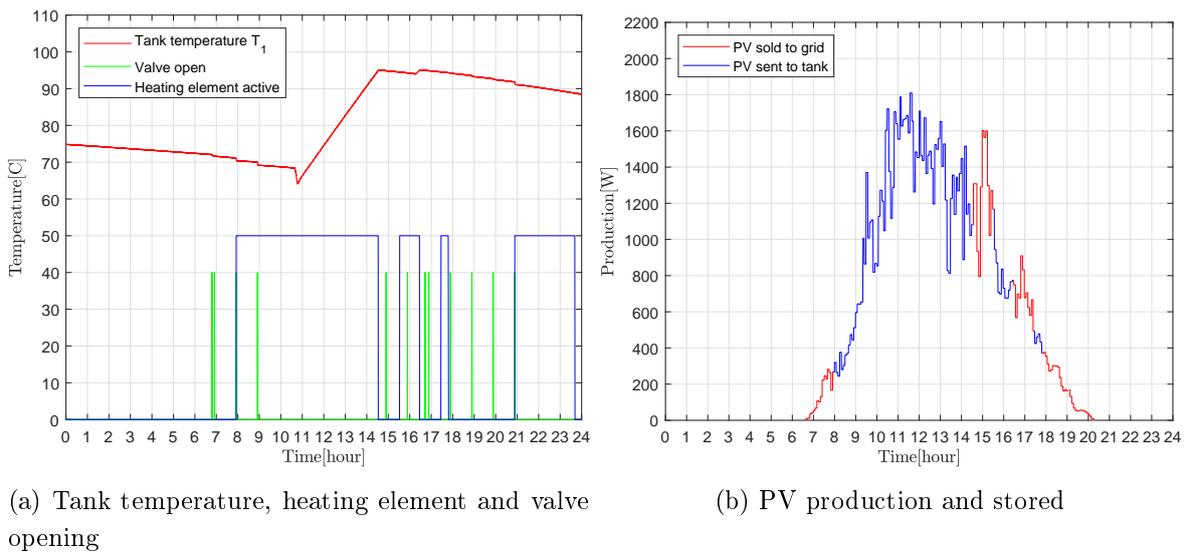
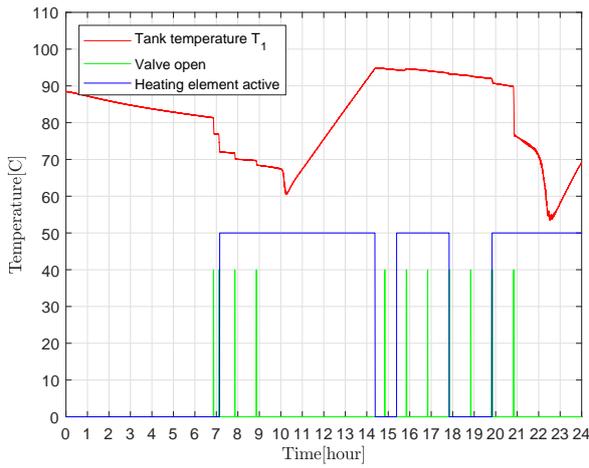
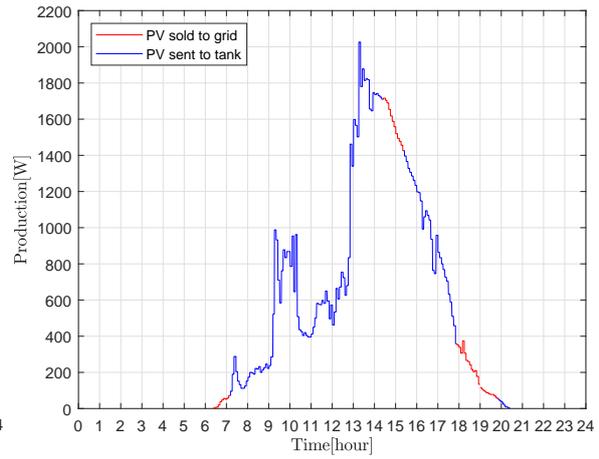


Figure H.2: Tank temperatures and PV graphs for result experiment 1, day 2

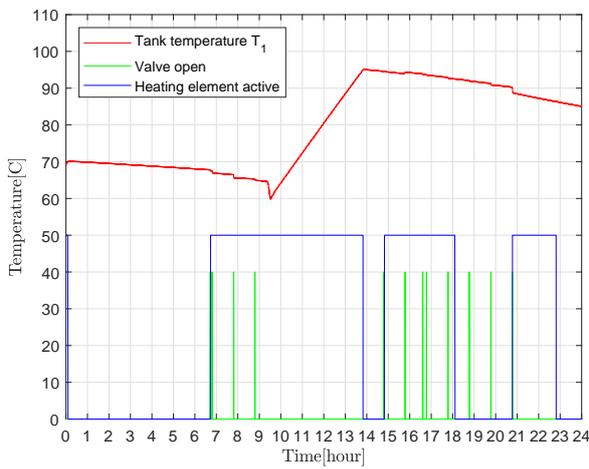


(a) Tank temperature, heating element and valve opening

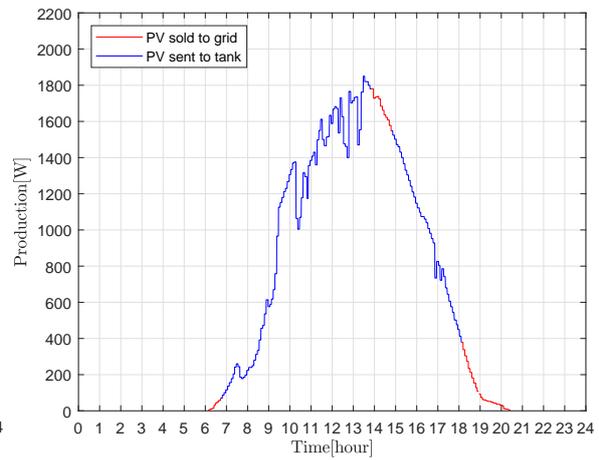


(b) PV production and stored

Figure H.3: Tank temperatures and PV graphs for result experiment 1, day 3



(a) Tank temperature, heating element and valve opening



(b) PV production and stored

Figure H.4: Tank temperatures and PV graphs for result experiment 1, day 4

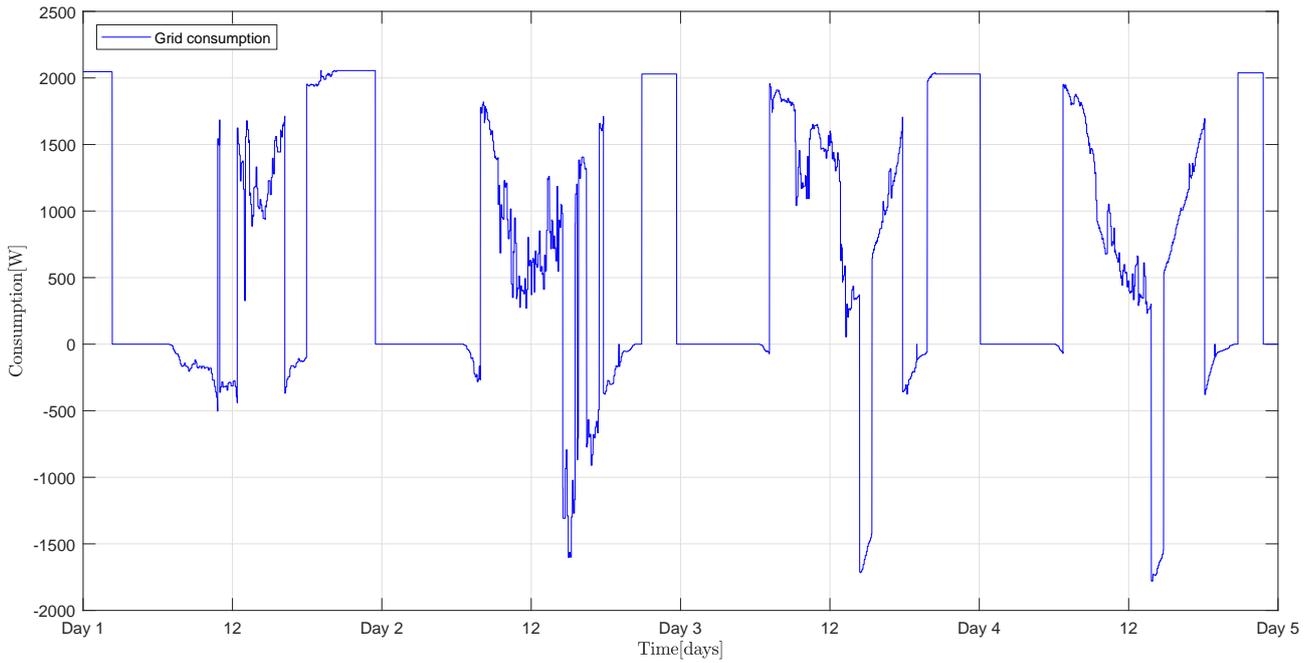


Figure H.5: Net consumption grid for result experiment 1

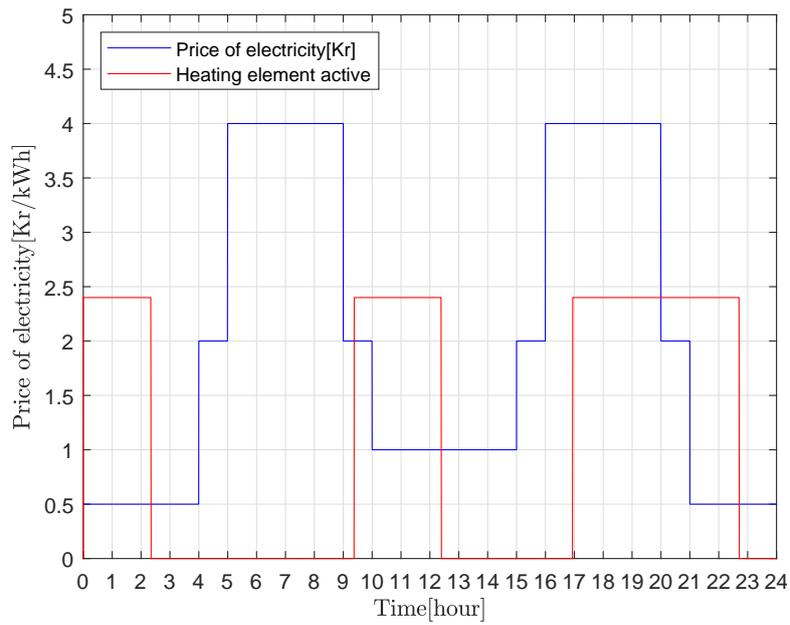


Figure H.6: Net consumption grid for result experiment 1

## H.5 Data Result experiment 2

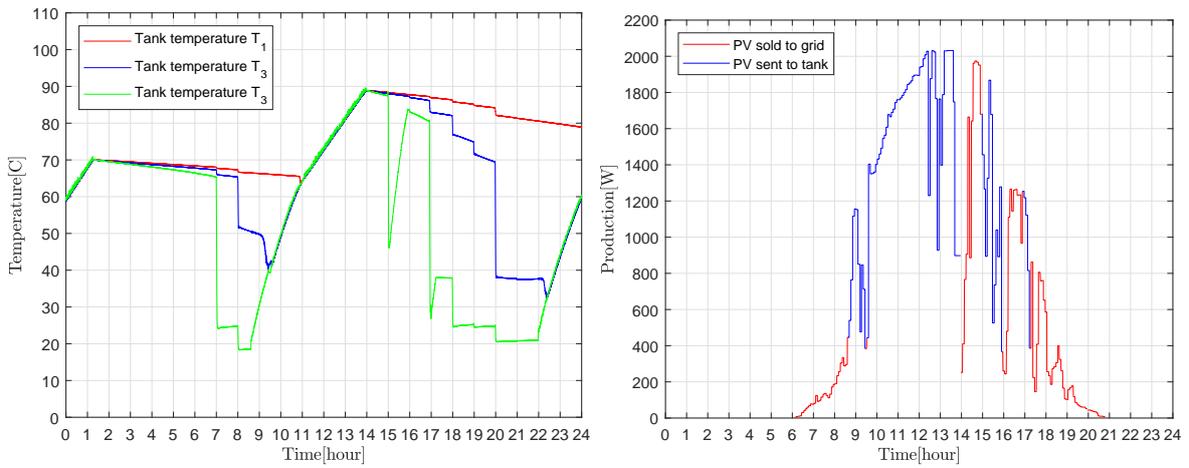
Table H.7: Key data from result experiment 2 per day

Description	Day 1	Day 2	Day 3	Day 4	Unit
Weather forecast	Fair	Partly cloudy	Clear	Fair	
Start energy tank	27,194	32,805	17,479	34,597	kJ
End energy tank	32,805	17,479	34,597	41,745	kJ
Lowest temperature tank[ $T_1$ ]	65	47	47	64	Celsius
End temperature tank[ $T_1$ ]	79	49	70	84	Celsius
Electricity consumption all	20	20	26	19	kWh
Electricity consumption grid	11	12	16	10	kWh
Price used electricity worst case	10	13	22	14	NOK
Price used electricity grid tariff	4	5	6	5	NOK
Energy storage utilisation	73.6	73.3	74.5	79.1	Percent

Table H.8: Comparison of data per day with one day experiment

Description	Price used electricity worst case		Price used electricity grid tariff	
	Price	Difference	Price	Difference
Day 1	10	-16%	4	-55%
Day 2	13	8.3%	5	-44%
Day 3	22	83%	6	-33%
Day 4	14	17%	5	-44%

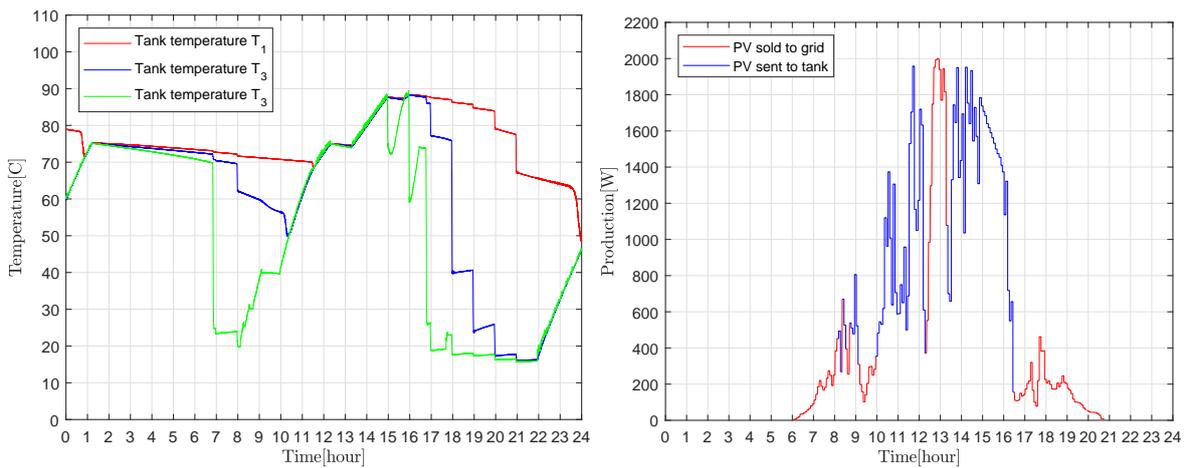
### H.6 Result graphs result experiment 2



(a) Tank temperature, heating element and valve opening

(b) PV production and stored

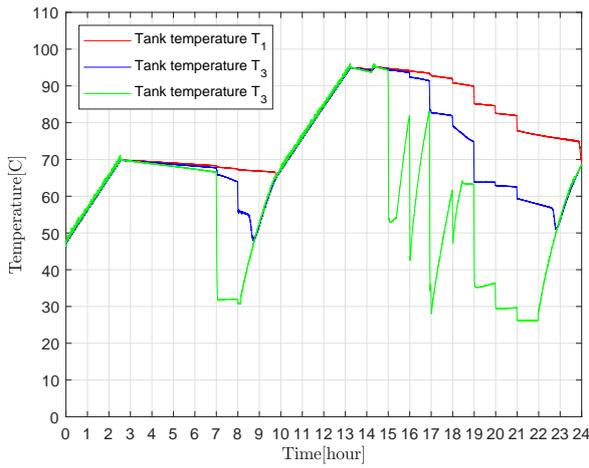
Figure H.7: Tank temperatures and PV graphs for result experiment 2, day 1



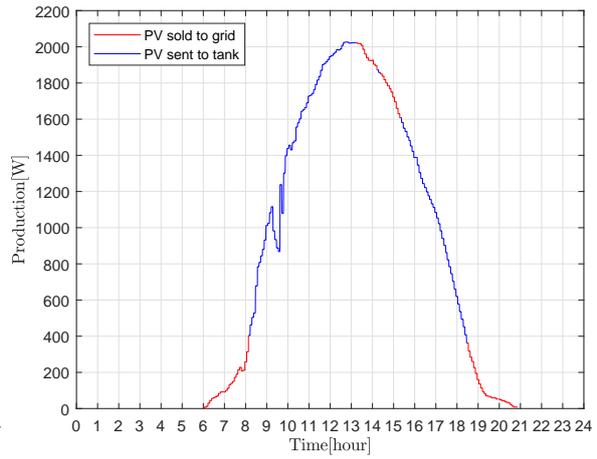
(a) Tank temperature, heating element and valve opening

(b) PV production and stored

Figure H.8: Tank temperatures and PV graphs for result experiment 2, day 2

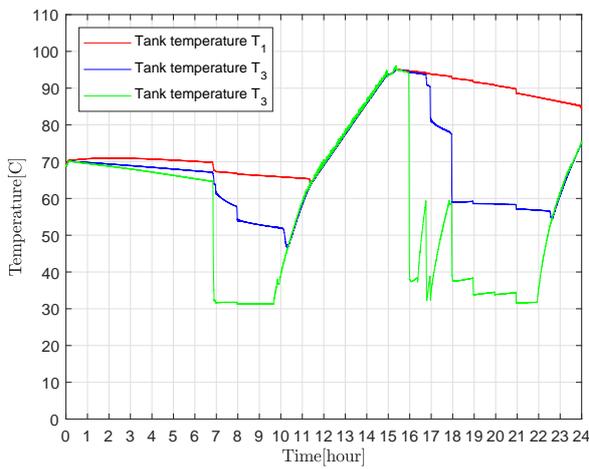


(a) Tank temperature, heating element and valve opening

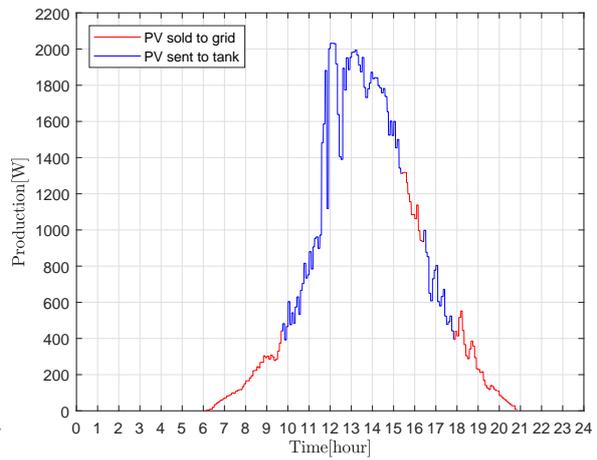


(b) PV production and stored

Figure H.9: Tank temperatures and PV graphs for result experiment 2, day 3



(a) Tank temperature, heating element and valve opening



(b) PV production and stored

Figure H.10: Tank temperatures and PV graphs for result experiment 2, day 4

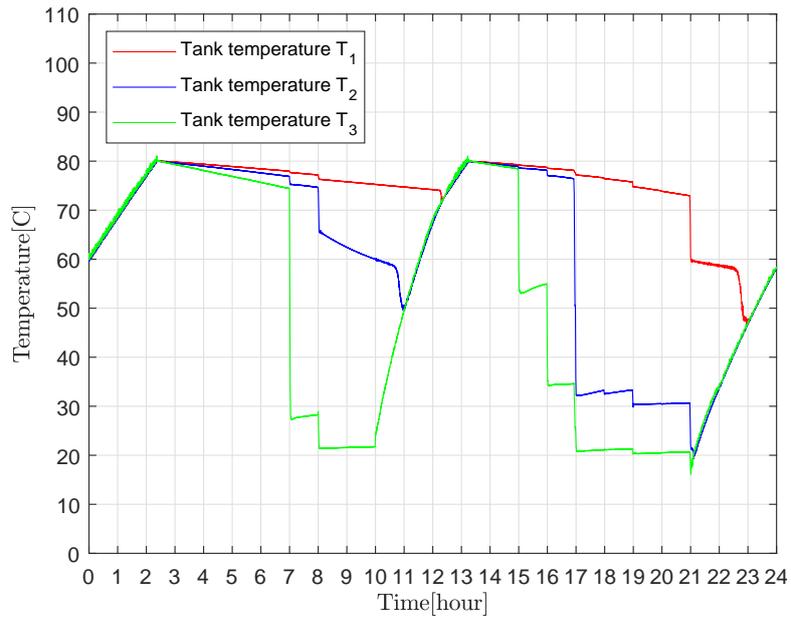


Figure H.11: Tank temperatures for 1-day result experiment 2

## Appendix I Additional experiments

The experiments presented in this appendix is done besides the main result experiments. The length of the experiments is three days (72 hours) and is executed to test the controller's ability towards more spread water exchange during the day. Both the experiments confirm the controller ability in addition to the results experiments. The average water consumption profile is set to distribute the consumption by opening the valve every 3 hours between 07:00 and 22:00 in a four-person household. Besides the random water profile opens every hour in the intervals 07:00-09:00 and 15:00-22:00. The experiments are not as extensively discussed as the result experiments, but findings which are important is pointed out. All the parameters which are used are equal to the result experiments in section 7.

### I.1 Additional experiment 1: Average household and random consumption water profile when reducing grid peak

The first additional experiment is executed with the reducing grid peak electricity profile. During the first day, the tank temperature is set to  $70^{\circ}\text{C}$ . The tank temperature, valve openings, and heating element active is illustrated in figure I.1. The heating element active and valve opening is multiplied with 50 for 40 for illustrations purposes. For day 1, the heating element is activated due to PV production after the first valve opening approximately at 08:00. During the next valve openings, the heating element remains active until the PV production decreases at approximately 13:00. This affects the rest of the valve openings, and the temperature is decreasing for every valve opening. After the last valve opening for the day, the tank temperature drops down to  $45^{\circ}\text{C}$ , and decrease further down to  $33^{\circ}\text{C}$  after it has levelled out.

For day two the tank temperature is set to  $70^{\circ}\text{C}$ . For this day, the PV production is high during the day which allows the tank temperature to reach the maximum at approximately 16:00. The high utilisation of PV is based on valve openings during the day, which decreases the temperature in the lower regions of the tank. After one hour, the element is reactivated and remains on until the PV production falls below 400 W. After the last valve opening for the day, the tank temperature is  $60^{\circ}\text{C}$ , and the element activates at 22:00.

The last day of the experiment begins as the previous days with one valve opening before the heating element is activated due to high PV production. From 08:00 to 09:30, the production fluctuates around 400 W until 10:30 when the production increase and the element remain active until the maximum tank temperature is reached around 13:00. Right after the element is switched off, a valve opening occurs. After 1 hour, the element is reactivated and remains active until the PV production decrease below 400 W at approximately 18:30. During the next valve openings, the tank temperature decreases and at 22:00 the heating element activates to increase the temperature.

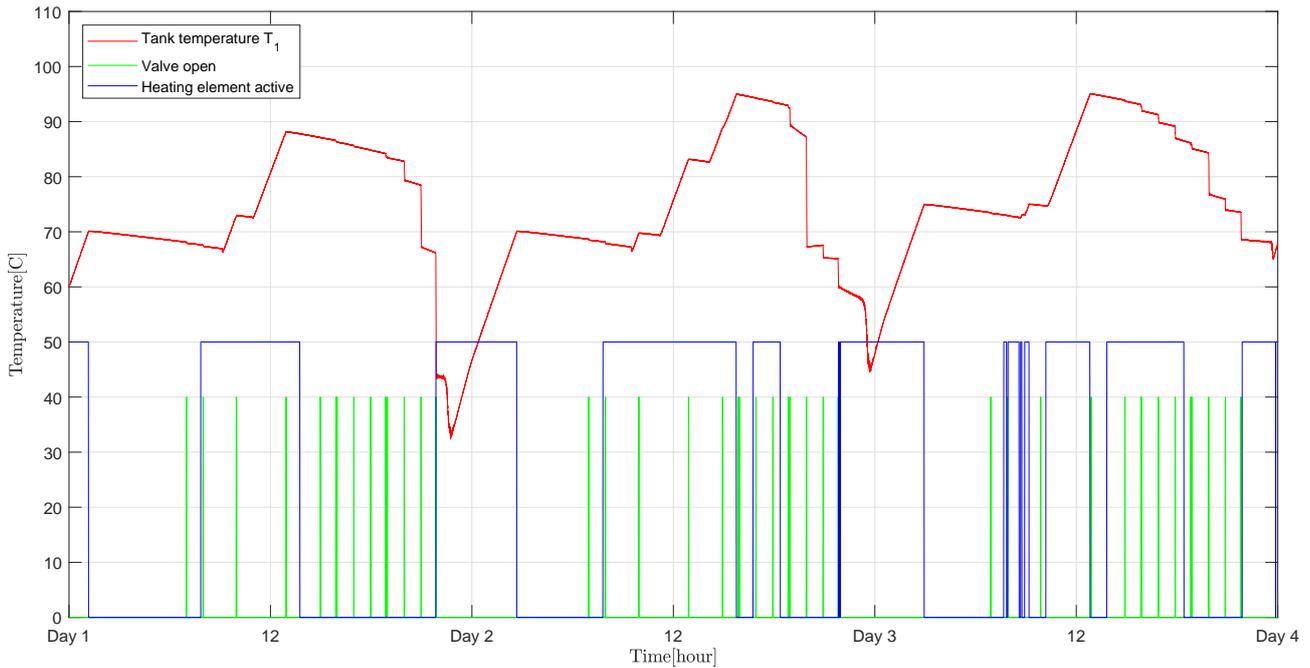


Figure I.1: Tank temperatures for additional experiment 1

Table I.1 presents the main data for addition experiment 1. The amount of usable water is calculated using the same approach as described in previous experiment. The table present that the total amount of usable water is 719 liters per day which meet the requirements for a four-person household. Also, it is seen that 32 of the total electricity consumption is from PV produced electricity, which gives a utilisation of 85 percent.

Table I.1: Data from additional experiment 1

Description	Value	Unit
Start energy tank	27,115	kJ
End energy tank	32,661	kJ
Lowest temperature tank [ $T_1$ ]	33	Celsius
End temperature tank [ $T_1$ ]	67	Celsius
PV produced electricity	37	kWh
PV electricity utilisation	0.85	
Electricity consumption all	76	kWh
Electricity consumption grid	44	kWh
Price used electricity worst case	60	NOK
Price used electricity grid tariff	20	NOK
Total exchange of water	935	Liters
Total amount usable water	719	Liters/day

Figure I.2 presents the PV production during the experiment. For the first day, there is fluctuating production in the middle of the day, before the productions drop and are low rest of the day. The fluctuating of production is high enough to keep the heating element active and store energy. From the forecast for the first day, there is expected high production, but as figure I.2 illustrates, the production is not as high as expected due to clouds.

For day two there is a continuous production which follows the conventional production for a PV system. During the day, the production increase until 12:00, when the production slowly decrease as the day goes by. The utilisation of PV produced energy is similar to other experiments where the maximum temperature in the tank is reached when there is still a high production.

The last day of the experiment has similar fluctuation as the first day. However, for this day, the fluctuation is around the amount where the element is activated, which results in an unusual situation. At around 09:00, the production has a low fluctuation which the controller recognises and disconnects the element. Be that as it may, the logic which changes the end temperature of the tank when the production is high enough does not recognise the increase of production of PV due to the low change. The result is that the controller assumes that the end temperature of the tank which should be  $95^{\circ}\text{C}$  due to PV production, is set to be  $70^{\circ}\text{C}$ , which is lower than the actual tank temperature. This initiates the delay time of the element of 1 hour. As the PV production increases the element is not active until the delay time of 1 hour is completed. The rest of the day is similar to the other days when the maximum temperature of the tank is reached, and the element is deactivated for one hour before reactivated.

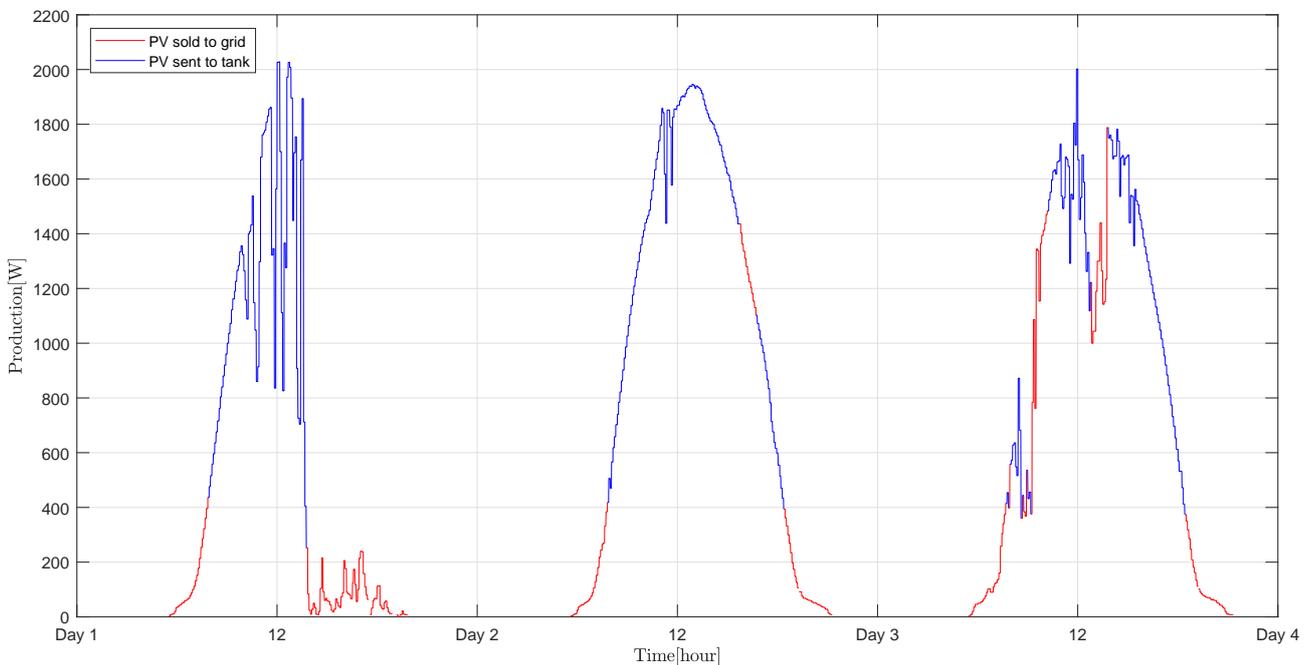


Figure I.2: PV production for additional experiment 1

As seen in figure I.1, the controller can manage multiple discharges during the day while storing produced electricity as energy. If comparing the results in this appendix with the results in section 7,

it is seen that the storage of energy is better for this experiment. This is due to the valve openings occurring every third hour which decrease the lower tank temperature as cold water is exchanged. However, the water demand for this experiment is not equal to a household, as it is rare that there is an even distributed water usage during the day. Nevertheless, the controller can manage water demand which stands out from regular water usage.

## **I.2 Additional experiment 2: Average household and random consumption water profile with normal electricity consumption**

The second additional experiment is executed with regular electricity consumption. For the first day, the tank temperature is set to  $70^{\circ}\text{C}$  as the forecast predicts good weather for PV production. The tank temperature, valve openings, and heating element active is illustrated in figure I.3. The heating element active and valve opening is multiplied with 50 for 40 for illustrations purposes. The tank temperature when the experiment begins is  $60^{\circ}\text{C}$ , and the heating element activates for one hour to increase the temperature. After the first valve opening at 07:00, the heating element activates as the tank temperature in the lower regions decrease under  $66^{\circ}\text{C}$ , see figure I.4. As the PV production increases, the heating element remains active during the day and due to valve openings, the maximum temperature is not reached. At 18:30, the production is below 400 W and the element disconnect. The element reconnects during the last valve opening for the day and remains connected for the rest of the day.

For day two, the element is not active until the first valve opening because of high tank temperature from the previous day. At 07:00, the heating elements activate as the temperature in the lower tank is decreasing. The element remains active until 15:00 as the PV production is over 400 W from 08:30. As the temperature increases, the valve openings allows the energy storage to continue until 15:00 when the maximum temperature in the tank is reached. After the one hour of deactivation has passed, the element reconnects and remains active until the production falls under 400 W. For the next valve openings, the element remains deactivated until 21:00 when the element activates due to low tank temperature in the lower regions.

As day three begins, the tank temperature is  $70^{\circ}\text{C}$ , which is the tank temperature due to expected PV production. The element is activated at 08:00 after the first valve opening due to sufficient PV production. During the day, the element remains active until the production of electricity decreases below 400 W, at 17:00. Due to the high temperature in the tank, the element remains deactivated throughout some valve openings. At 21:00 the element is activated for 2 hours and the end temperature in the tank at the end of the experiment is  $74^{\circ}\text{C}$ .

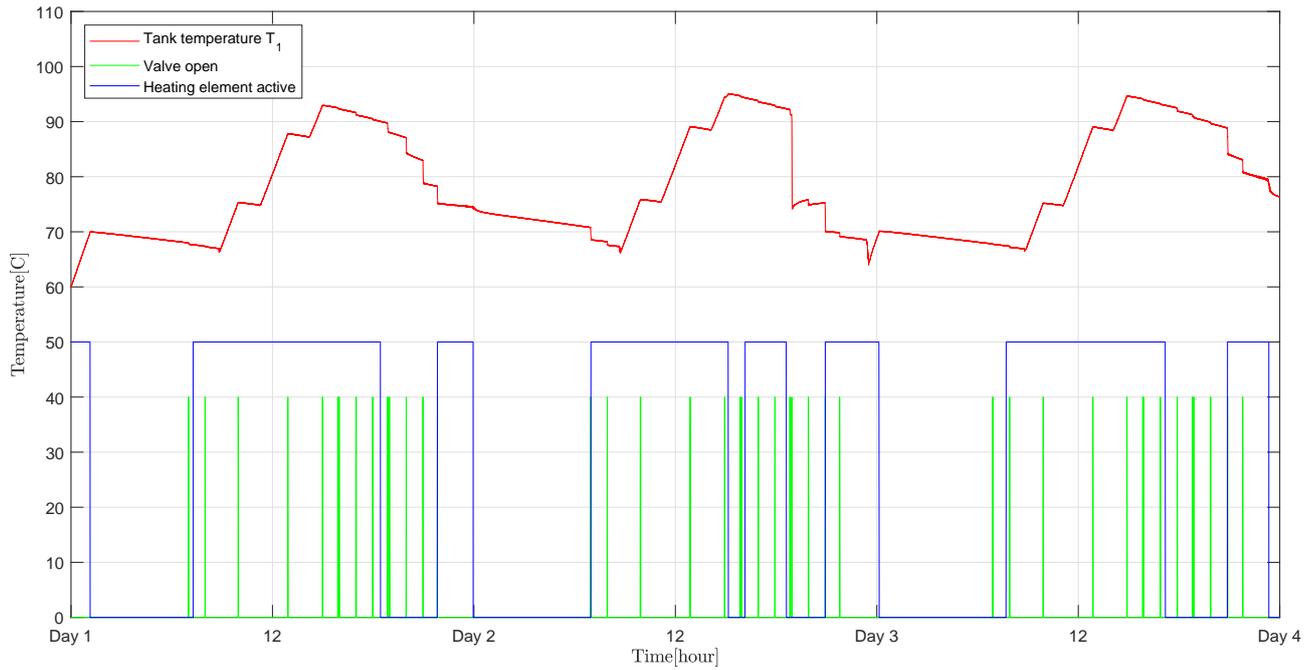


Figure I.3: Tank temperatures for additional experiment 2

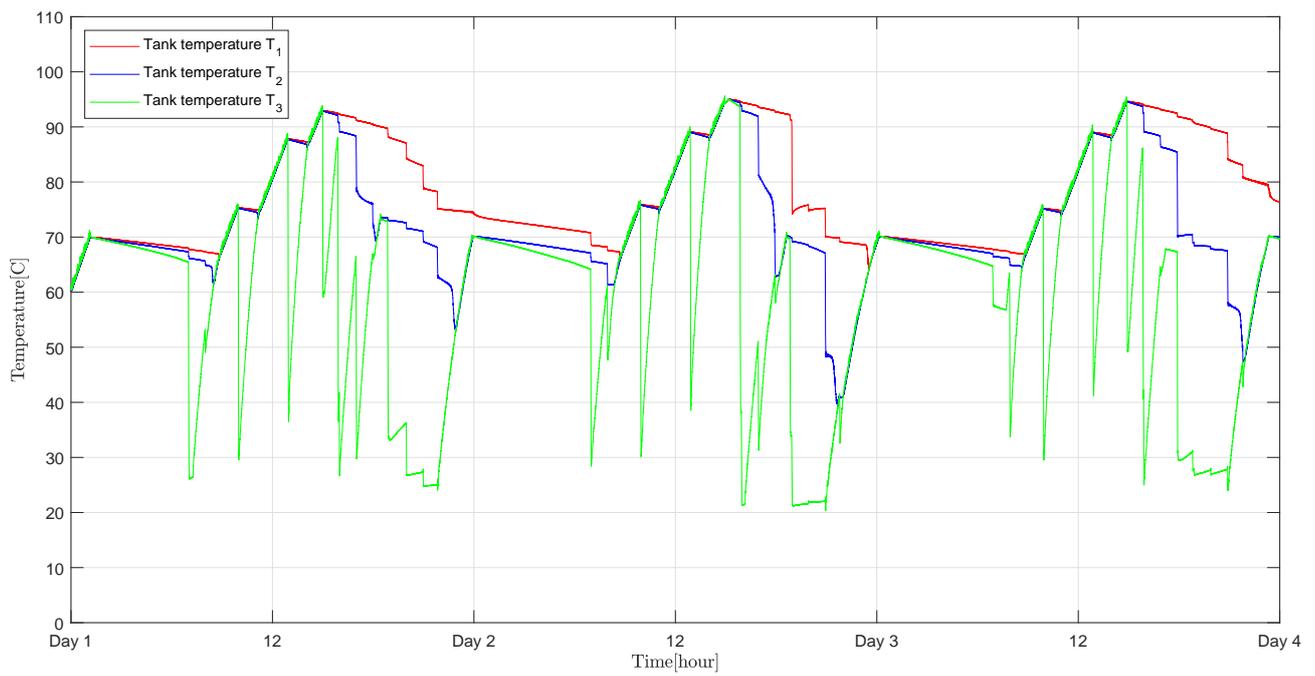


Figure I.4: All tank temperatures for additional experiment 2

The critical data from additional experiment 2 is listed in table I.2. The amount of usable water is calculated using the same approach as previous experiment. The table present that the total amount of usable water is 777 litres per day which meet the requirements for a four-person household. Also, it is seen that 41 kWh of the total electricity consumption is from PV produced electricity, which gives a utilisation of 92 percent.

Table I.2: Data from additional experiment 2

Description	Value	Unit
Start energy tank	26,465	kJ
End energy tank	35,540	kJ
Lowest temperature tank $[T_1]$	60	Celsius
End temperature tank $[T_1]$	74	Celsius
PV produced electricity	44	kWh
PV electricity utilisation	0.92	
Electricity consumption all	82	kWh
Electricity consumption grid	41	kWh
Price used electricity worst case	78	NOK
Price used electricity grid tariff	19	NOK
Total exchange of water	975	Liters
Total amount usable water	777	Liters/day

Figure I.5 shows the PV production during the experiment. For the first day, there is expected an adequate amount of electricity production. When the logic activates the heating element, the production is under 400 W, but the temperature in the tank is low. For the whole day, the element is active which allows all the production over 400 W is stored. Figure I.5 shows that there is a steady production in addition to discharges which allows the significant amount of energy storage.

Day two has the same shape as day one when looking at the production. However, for day two, the maximum temperature in the tank is reached which deactivates the element at 15:00. During the next hours, there is no storage, but the production is still high. When the element is reactivated, the production continues for the rest of the day until the production is below 400 W.

For day three, the approach until noon is equal to the previous days. During the afternoon, there is a sudden drop in the production due to a cloud. The logic deactivates the heating element, but the production increases again and for the next hour there is high production. After one hour, the element is activated again and remains active until the production falls under 400 W.

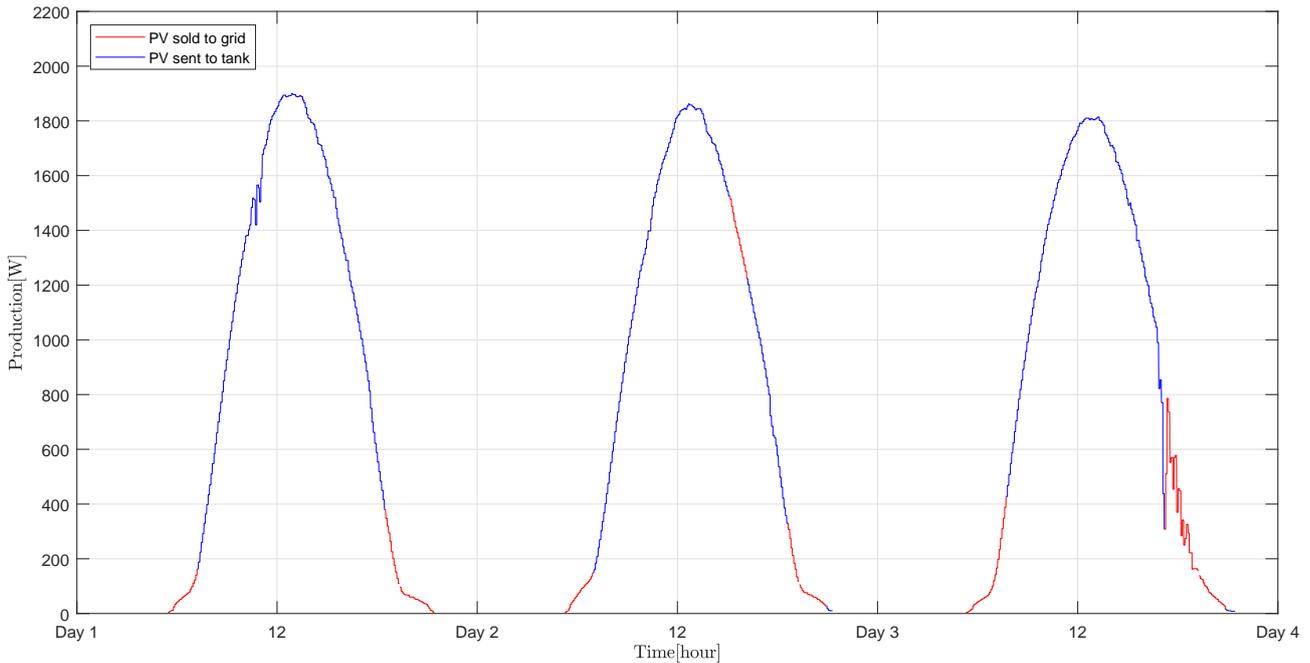


Figure I.5: PV production for additional experiment 2

As seen in figure I.3, the controller is capable of control the heating element and energy storage in a sufficient way. It is worth mention that for this electricity consumption profile, there is always possible to start the heating element independent of production. Nevertheless, during the 72 hours experiment, it is seen that the temperature in the tank is well above acceptable at any time.

### I.3 Comparison of additional experiments and result experiments

The result from the additional experiments points out that the utilisation of PV produced electricity is higher than the results experiments. This is expected as the water consumption profiles for the additional experiments is better suited for energy storage as there are discharges during the whole day. However, the water consumption profile is not an expected water usage pattern in a household. Regardless of the water consumption is rare, the controller can adapt to the consumption pattern. The controller keeps the temperature acceptable both with today's electricity pricing and can reduce the grid peaks as well if that is the primary goal.

## Appendix J System for selling all self-produced electricity

To sell all self-produced electricity, the overall system needs to be modified compared to a regular household. Figure J.1 shows an overview of how a standard system is set up in a household.

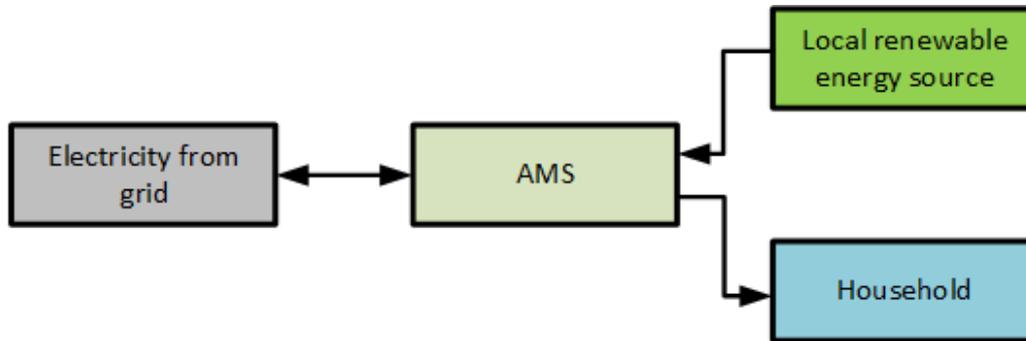


Figure J.1: Layout of the system in a household for using self-produced electricity

In a household, it is common practice to connect the renewable energy source at the consumption side of the AMS and decrease the net consumption from the grid when the source is producing electricity. In this configuration, the self-produced electricity would be used in the household, until the production exceeds the consumption. In other words, there is impossible to sell the produced electricity as long as there is a household demand for electricity.

However, in some situations, it is preferable to sell all the self-produced electricity due to good agreements from the electricity provider. An example of a profitable solution is the Otovo agreements which pay 1 Kr/kWh up to a production of 5000 kWh/year. To maximise the profit of this agreement with a small self-producing system, the set up shown in figure J.2 may be used. Keep in mind that the configuration is for a system where there is unlikely to produce more than 5000 kWh/year.

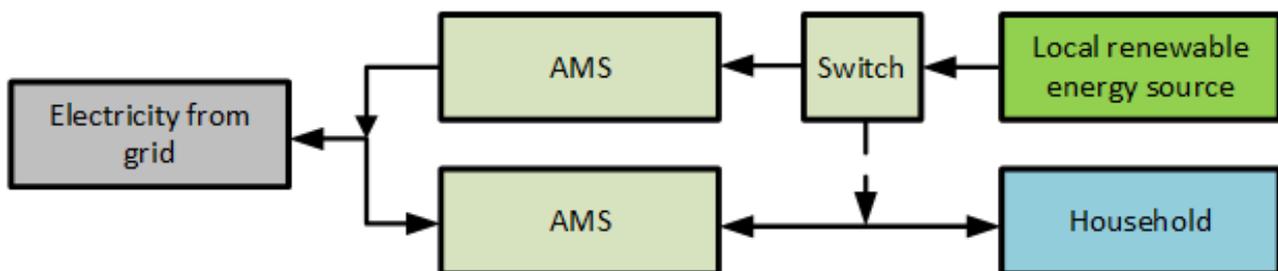


Figure J.2: Layout of the system in a household for using all or sell self-produced electricity

As illustrated in figure J.2 the solution is to install a second AMS and a switch to the original layout. With this configuration, the household could decide if it would use the self-produced electricity, or sell it to the electricity provider. The reason for the second AMS provides information on production amount to the grid. If the household decided to sell all the self-produced electricity, the electricity is sent through the AMS and re-purchased by the household. Nevertheless, it is a more complex system than the standard, but it is achievable.