System design for a solar powered thermal storage – to obtain reduction of demand side power peaks

ANDERS ANGELTVEIT LIE

SUPERVISOR
Mohan Lal Kolhe
Johan Olav Brakestad

University of Agder, [2019]
Faculty of Technology
Department of Engineering and Science

System design for a solar powered thermal storage - to obtain reduction of demand side power peaks

Universitetet i Agder

Abstract

Demand side management is an efficiency tool to manage the consumption of energy. In this thesis a load controller is developed and used to store self-produced renewable energy as hot water in a domestic hot water heater. There are challenges associated with the grid, which is operating near max capacity. Instead of expanding the grid and make huge investments to handle grid peak periods, the power consumption can be controlled and utilized better. To utilize all of the self-produced energy, an ac controller is installed and monitored from a computer. A sensor for the temperature, a valve controller and information about self-produced solar power are installed for the domestic hot water heater and are set up in a program to drive the system. Information about the grid peak period are used to choose when the heating element is turned on to raise the temperature. The valve is discharging the tank based on a water consumption profile for an average house. The minimum temperature is set to avoid bacteria and avoid affecting the end user. The results show that up to 8.9 kWh is stored as hot water each day which means the grid is reduced with the same amount of energy. The energy is stored during low grid load periods and used in the peak periods to obtain reduction of demand side power peaks. In this setup, PV system has maximum capacity of 1 kW and it could be installed more PV panels to reduce the grid load even more. The test results show that it is possible to reduce the load on grid in peaks between 27.9 to 54.3%, depending on the self-produced power from the PV system. Demand side management has the ability to deliver technical and economic benefits to customers as well as network operators.

Preface

During the education in renewable energy, there have been a huge interest for solar power and the knowledge have been increased a lot. To control a domestic hot water heater and heat the water with self-produced renewable energy to reduce grid load is a big goal.
Professor Mohan Lal Kolhe have been the supervisor and the author want to express gratitude for discussions and feedback during the whole thesis. Senior Engineer Johan Olav Brakestad have contributed with discussion to the physical model- and the labview program and ordered the new parts which was needed for the model. The author wants to express a gratitude for this acknowledgement and discussions.

During the autumn, there was also done research together with fellow student Even Kleppevik Skaga. The author also wants to express gratitude for all the research and discussions during this time.

Individual/group Mandatory Declaration

The individual student or group of students is responsible for the use of legal tools, guidelines for using these and rules on source usage. The statement will make the students aware of their responsibilities and the consequences of cheating. Missing statement does not release students from their responsibility.

1.	I/We hereby declare that my/our thesis is my/our own work and that I/We have not used any other sources or have received any other help than mentioned in the thesis.	☒
2.	I/we further declare that this thesis: • has not been used for another exam at another department/university/university college in Norway or abroad; • does not refer to the work of others without it being stated; • does not refer to own previous work without it being stated; • have all the references given in the literature list; • is not a copy, duplicate or copy of another's work or manuscript.	☒
3.	I/we am/are aware that violation of the above is regarded as cheating and may result in cancellation of exams and exclusion from universities and colleges in Norway, see Universitets- og høgskoleloven §§4-7 og 4-8 og Forskrift om eksamen §§ 31.	☒
4.	I/we am/are aware that all submitted theses may be checked for plagiarism.	☒
5.	I/we am/are aware that the University of Agder will deal with all cases where there is suspicion of cheating according to the university's guidelines for dealing with cases of cheating.	☒
6.	I/we have incorporated the rules and guidelines in the use of sources and references on the library's web pages.	☒

Publishing Agreement

Authorization for electronic publishing of the thesis.
Author(s) have copyrights of the thesis. This means, among other things, the exclusive right to make the work available to the general public (Åndsverkloven. §2).
All theses that fulfill the criteria will be registered and published in Brage Aura and on UiA's web pages with author's approval.
Theses that are not public or are confidential will not be published.

I hereby give the University of Agder a free right to
make the task available for electronic publishing: ☒JA ☐NEI

Is the thesis confidential? ☐JA ☒NEI
(confidential agreement must be completed)
- If yes:

Can the thesis be published when the confidentiality period is over? ☐JA ☐NEI

Is the task except for public disclosure? ☐JA ☒NEI
(contains confidential information. see Offl. §13/Fvl. §13)

Table of Contents

List of Figures

List of Tables

Notation

T	Temperature [C]
m	*Mass [kg]*
Q	*Heat loss [W]*
P	*Power [kW]*
E	Energy [kWh]
η	Efficiency [%]
Cv	Spesific heat for water $[\frac{J}{kg*C}]$
l	Liter [L]
I	Current [A]
V	Voltage [V]
t	time [s]
k	Boltzman constant [JK^{-1}]
q	electron electrical charge [C]
L	Inductance [H]
C	Capacitor [F]
w	Angular velocity [rad^{-1}]
ɑ	Delay angle [rad]

Abbreviations

AMS	Advanced metering system
AC	Alternating current
DAQ	Data Acquisition
DC	Direct current
DHWH	Domestic hot water heater
kWh	Kilowatt hour
kW	Kilowatt
NI	National-instrument
NOK	Norwegian krone
PF	Power factor
PV	Photovoltaic
PVGIS	Photovoltaic geographical information system
RMS	Root mean square
SCR	Silicon controlled rectifier
STC	Standard test conditions
VAR	Volt ampere requirements

1. Introduction

In Norway, the news often writes about the growing electricity prices and how the power consumption increases. Up to 80% of the consumption in total goes to heating houses. From these 80%, about 15-20% is the water heater [1]. The power consumption varies through the day, and it is in the mornings and evenings the consumption peaks. This means that the powerlines are highly charged in these time intervals. This also applies the water heater. The water consumption is highest in the morning and evening because of showering, cooking, house applications and so on.

Today consumers are paying the electricity bills monthly. The price is being calculated from the average electricity price through the current month. The power meters that was installed in homes earlier, did not have the opportunity to register in which time frame the electricity are being used. You simply report your monthly consumption at the end of each month. To change this, grid operators started installing new “smart” power meters (AMS) in the beginning of 2018. These power meters can measure power consumption in real time. NVEs plan is to start having a price that varies during the day depending on the consumers consumption from year 2021. In the periods of high consumption, such as mornings and evenings, the prices will be higher. This will be done to make people aware of power consumption, and to reduce their consumption during the grid peak hours [2].

The power lines in Norway today are already limited. In periods where the consumption is high, the lines are working on max capacity. If the power consumption keeps increasing, this will result in upgrading requirements on the power lines in the future. This will lead to increased electricity prices caused by increased rent prices. Norway have a tight cooperation with Europe when it comes to electricity. They export and imports electricity to even out the prices. Because Norway has big water reservoirs that can supply more that the whole country, renewable electricity is being sold to other countries in Europe instead of producing with coal-, gas- and nuclear power [3]. In 2018 the electricity prices have been twice the price compared to some months in 2017 [4]. Demand side management is becoming a key ingredient to future power networks. It has the ability to deliver technical and economic benefits to customers as well as network operators [5].

The electricity prices have increased a lot the last few years, at the same time the price for PV systems have decreased [6]. In Norway there are more and more people installing alternative solutions for power production. For a self-produced electricity power plant, Enova is supporting private individuals with between 10000-28750 NOK [7]. In 2018, 837 private individuals were supported, an increase from 146 in 2016 [8]. This implies that PV power plants is more popular and more profitable than before.

There is also a huge increase in electric cars, which has a great influence on the grid. In 2015, 50000 electric cars were registered. In 2016, electrical car number 100000 was registered. In the end of 2018, there was 200192 electrical cars registered [9]. According to NVE, the grid can handle 1500000 electric cars in 2030 if they charge evenly through the day. It is expected to will be 1500000 electric cars in Norway in 2030. There will also be local varies on the grid [10]. Statnett have planned investments for 35-45 billion the next 5 years, and they are planning investments for over 140 billion in the future. This is historically large grid investments [11].

1.1 Background

In recent years, a range of strategies implementing the increase share of renewable energy have been proposed. DHWH provide relatively high nominal power, normally from 2-3 kW and it has storage capacity of 8-15 kWh. A more sophisticate use of DHWH was tested where 35 DHWH was controlled to avoid grid peaks based on real time pricing over 1 year, with the controls they managed to limit the usage in peak periods and the demand side management [2]. Since renewable energy has variable production, it is necessary to design a system which will not affect the end user, without regard to the energy production [12].

Although Norway is in the north, the sun conditions are good. In summertime, the sun lasts for about 20 hours a day. In the winter, the production is reduced due to lack of sun. In fact, the solar radiation in Norway are comparable to counties in central Europe. In figure 1, an estimate of solar electricity generation at UiA for 1 kW installed PV power is shown [13].

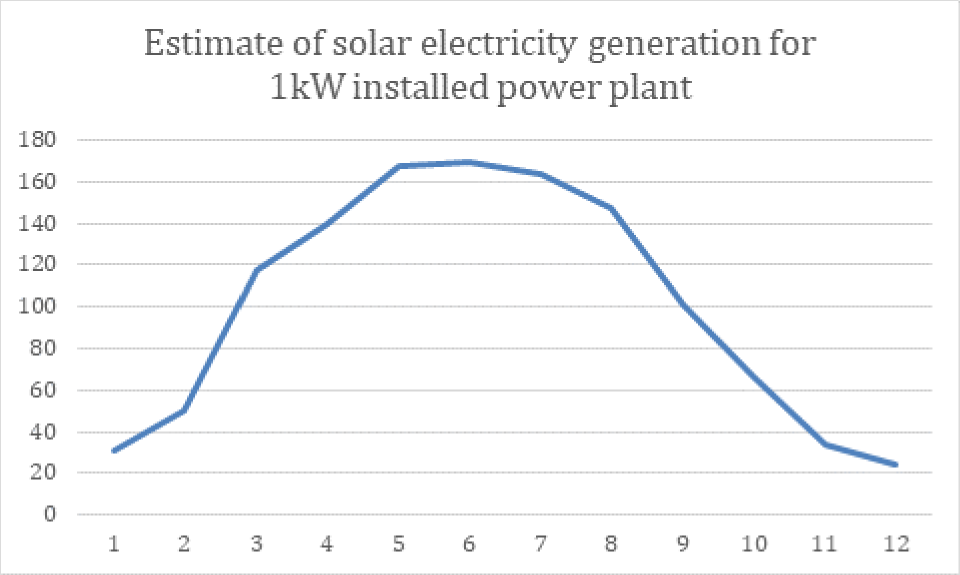


Figure 1 Estimate of solar electricity generation at UiA for 1 kW installed PV power. kWH at y-axis and month at x-axis. Total yearly production of 1220 kWh [13].

By installing a controller for the PV plant and storing the energy as hot water. For a grid connected PV plant, some of the energy may be delivered to the grid in sunny summer days. With an optimized controller the energy will be better utilized. It is possible to use all the energy production instead of delivering it back to the grid. This will reduce the grid peaks in a household which will be economical for private individuals, but also for the environment and grid operators [2].

1.2 NVE

In figure 2, it is shown the electricity prices for January 2019. It consists of three parts; fees, rent and the power price. In total, the price was 1,19 NOK/kWh in January [14].
One reason for the price increasing, is that the consumption is increasing as well. The grid capacity is reaching its max. By expanding, the rent will increase considerably, and the fees will increase as a

result of this. Solar cells and other renewable energies can reduce the grid which will benefit the consumer [14].

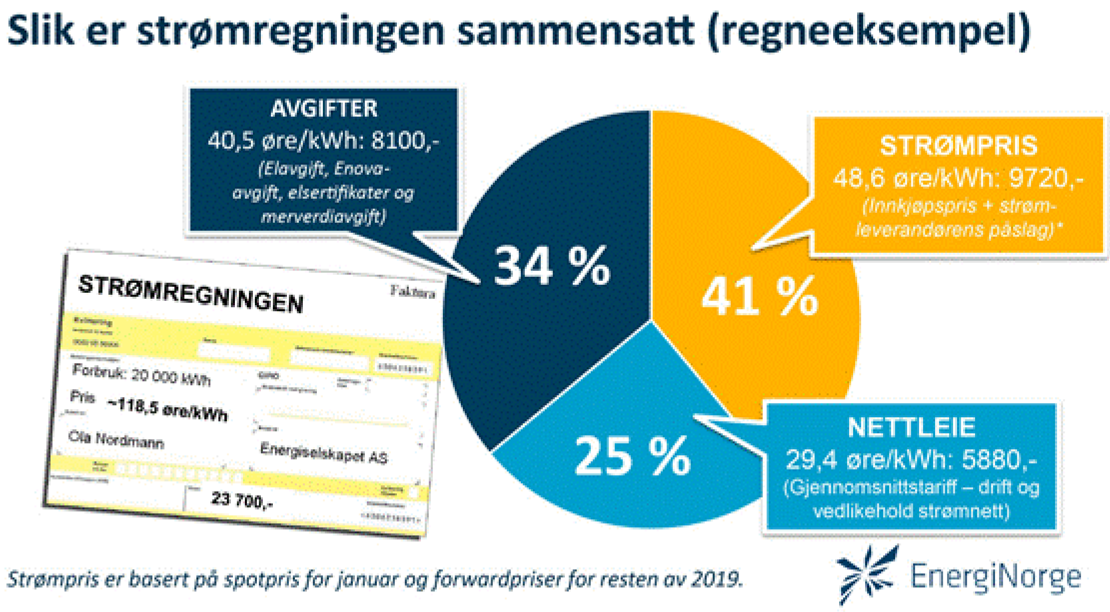


Figure 2 Distribution between price, grid and taxes [14]

1.3 Pluss customer

When connecting a PV system today, the panels connect to an inverter which is connected to the grid. The electricity is first being used in the household, and excess power will be transferred to the grid. The power that's being transferred, can also potentially be delivered to power-companies you make deals with. This way you can get money back for your excess power. The price varies from companies but is about 1 NOK/kWh [7].

1.4 Previous work

A research has been done for a PV system connected to a water heater in the autumn 2018. The system has PV panels with total 1000 W connected to a hot water tank. In the hot water tank, there is installed temperature sensors and a valve controller which can be opened and closed through a digital signal. A program is made with different tests for when the hot water tank heating element is turned on, and when the valve is opened to empty the tank. This physical system with a program was already installed from previously thesis.

In the research project a new system was designed with different tests and some improvements. Due to low PV production and lack of controls for the power delivered to the heating element, the program was based on heating the water outside grid load peaks. It was concluded that more controls need to be implement for better utilization of the PV production. More research about the grid load was also needed and an overview of the grid load peak intervals. Figure 3 shows the results of the research project where the heating element was turned on during the night to raise the temperature and during day when there was PV production. The red graph is the temperature in the tank, and the blue graph shows when the heating element is turned on and off [15].

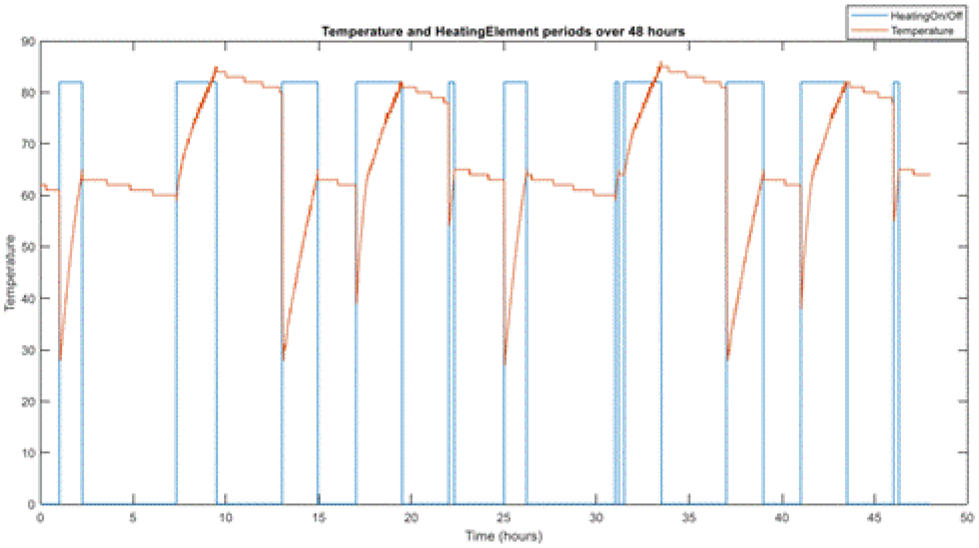


Figure 3 Temperature of the water and heating element turned on/off [15]

As the research project was done in the autumn and winter, it was poor sun conditions. The PV production for 2 days in November is shown in figure 4. There are only a few hours with production and it only reached 180 W.

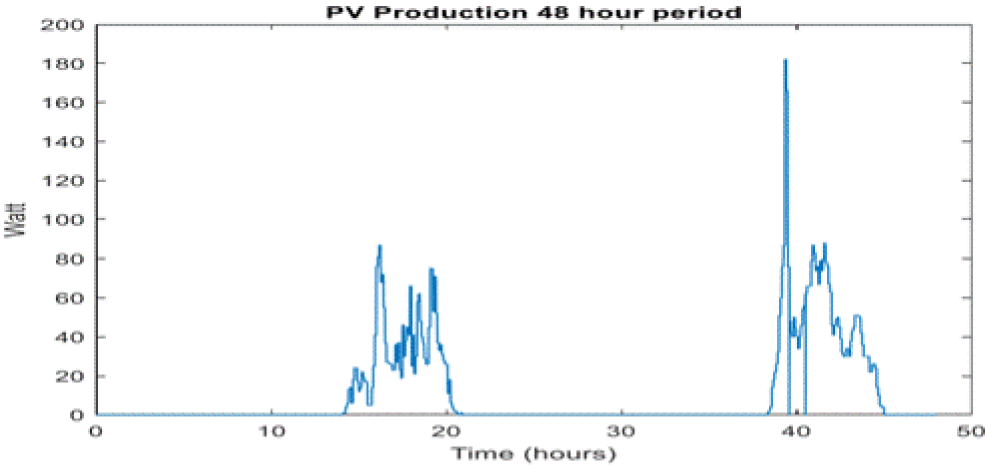


Figure 4 PV production [15].

1.5 Thesis outline

The structure of the thesis is shown in this section.

- **Section 1 – Introduction**
  Section 1 present background and motivation for the thesis. It is also showing previously work and what has been done from previous thesis.
- **Section 2 – Theory**
  Section 2 present theory of the physical parts used in this thesis together with water- and grid profile for an average household.
- **Section 3 – Reasearch question**
  In this section the research question and the problem are presented.
- **Section 4 – Methode**

In section 4 the physical model is presented with installation of new parts. It is also shown how the labview program is set up and the logic behind it.

- **Section 5 – Results**
  Several tests have been done and they are presented in section 5 with some discussion for each test.
- **Section 6 – Discussion and results**
  Section 6 present the results from the tests and some thoughts and reflections about the results.
- **Section 7 – Conclusion**
  In section 7 the conclusion of the thesis is presented.
- **Section 8 – Further work**
  In section 8 further work is presented with suggestion for improvements in the system.
- **Section 9 – List of references**
  In section 9 the references used in the thesis is presented.
- **Section 10 - Appendix**
  In section 10 the appendix is presented. Some details about the program, installation and results are shown.

2. Theory

2.1 Solar cells

Solar cells or photovoltaic (PV) cells are semiconductor devices that transfer sunlight into electrical current or useable electric power. They were first produced in the 1950s from crystalline silicon with 6% efficiency. Today crystalline silicon remains the dominant PV material and is used all over the world. When PV cells are being tested, they are doing it after standard test conditions (STC). Cell temperature is set to 25 °C, irradiance is 1000 W/m2 and air mass is 1.5 (AM1.5). With this standard it is easy to compare PV modules all over the world [16].

2.1.1 Structure of the solar cell

In the p-n junction solar cell, it is a uniform structure with two active layers. One of the layers is a thin heavily doped top layer emitter, the other one is a thick moderately doped bottom layer/base. The top emitter is about 0.3 to 0.8 µm thick and the bottom base is 100 to 300 µm thick. In the emitter- and base there is opposite dopant species. The emitter is doped n-type with 10^{18} /cm^3 average concentration. The base is doped p-type with 10^{16} /cm^3 uniform concentration. By making a high temperature diffusion from gaseous or liquid source into the base material, the emitter is formed. Surface concentration is steadily decreasing with depth till the n-type dopant concentration is equal to p-type dopant. At this point, the material changes from n-type to p-type. The interface is referred to as metallurgical junction. The p-n junction with electric field built in is formed around the metallurgical junction. The space charge region width is around 1 µm. This is shown in figure 5 [17].

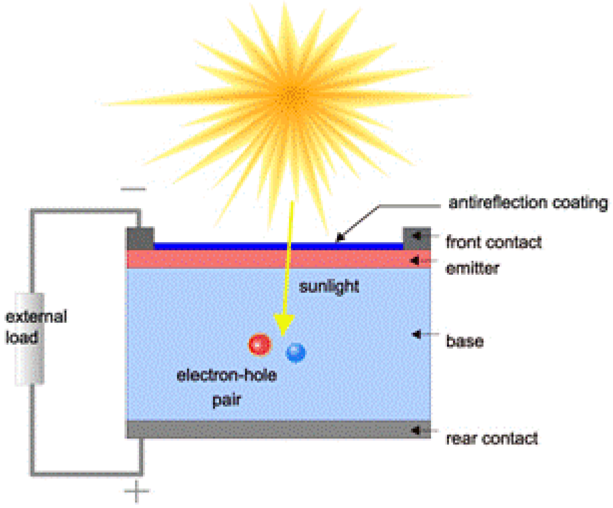


Figure 5 Cross section of the silicon p-n junction solar cell [18].

2.1.2 Equivalent circuit

In figure 6, an equivalent circuit model of a solar cell is shown. The current generator I_s is representing the photogeneration mechanism. The diode is representing the dark recombination current. I_s and I_D are the magnitudes of the currents. The diode and current generator are oriented in opposite directions because diode current detracts from photogenerated current. There are three resistors in the equivalent circuit. R_{sh} is a shunt resistor or any parallel high conductivity paths. These shunts can be on the edges on of the solar cell or through the solar cell. They can be caused by crystal damage, metallization spike through junction or other things. A low R_{sh} will degrade $V_{out.}$ For a good silicon cell R_{sh} should be at least 500 Ω. R_s is representing the series resistance at the metal contact to semiconductor interface and in the top of the semiconductor interface. A high R_s will degrade I_{out} and in a good cell R_s should be less than 0.5 Ω. There can also be a load R_L in series with R_S and V is across this load [16].

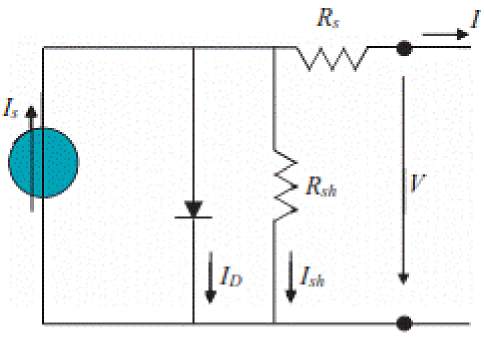


Figure 6 Equivalent circuit model of a solar cell [19].

There are two interesting cases in the equivalent circuit; an open circuit and a short circuit across the load. I_{sc} is the short circuit current if the load is shorted. V_{oc} is the open circuit voltage across diode and generator if the circuit is opened. If R_{sh} is very large and R_s is very small, it will be equal to I_{sc}. For an ideal case, R_{sh} is very large and R_s is very small. The equation for output current is,

$$I = Isc = Is - Id = Is - I0\left(e^{\frac{V}{nVt}} - 1\right) \tag{1}$$

I_0 is the diodes inverse saturation current, V is the voltage, n is the diodes ideality factor, V_T is the thermal voltage which is $V_T = KT/q$ where K is Boltzmann constant, T is absolute temperature and q is electrons electrical charge. I_S is equal to I_{SC} because its ideal case. In figure 7, it is shown the ideal equivalent circuit model [19].

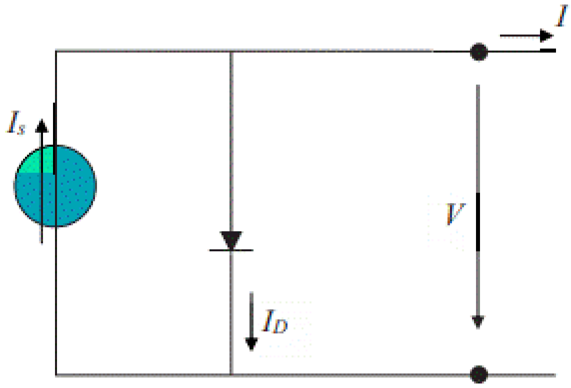


Figure 7 Ideal equivalent circuit model of a solar cell [19].

For open circuit voltage the output current I is zero. The equation is given by,

$$0 = Isc - Id = Isc - I0(e^{\frac{qV}{nkT}} - 1) \tag{2}$$

And the open circuit voltage is given by,

$$Voc = \frac{nkT}{q} * \ln\left[\frac{Isc}{I0} + 1\right] \tag{3}$$

Equation 3 for Voc shows that the open circuit voltage increases as the saturation current decreases. This equation also shows that higher n increases the Voc. For silicon cells $n = E_g = 1.12$ eV which is smaller than example GaAs cells which has $E_g = 1.42$ eV and will have a higher efficiency [20].

In figure 8, a I-V curve for solar cells is shown. The maximum power is given at Imp and Vmp. Efficiency η is the ratio of input- and output power given by,

$$\eta = P_{output}/P_{input}$$
$$\eta = I_{max}V_{max}/P_{input} \tag{4}$$
$$\eta = I_{SC}V_{OC}FF/Pinout$$

Where FF is the fill factor. Fill factor is the squareness of the P_{max} curve [21].

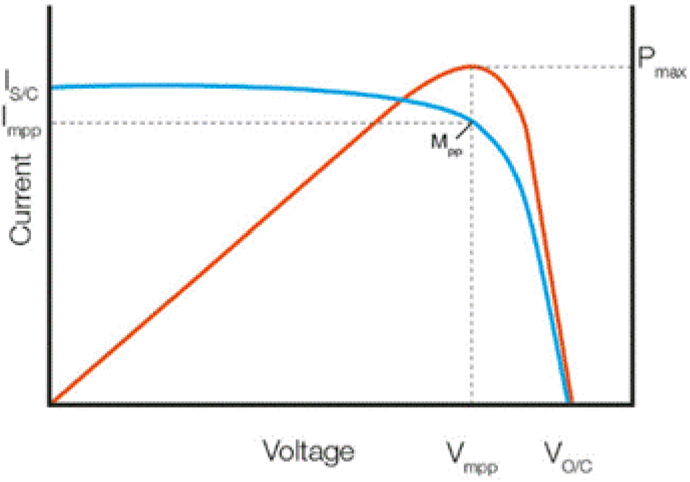


Figure 8 Current vs voltage graph. I-V curve [22].

2.2 Power electronics

Power electronics circuits converts electric power with electronic devices from one form to another. Semiconductor devices is used as switches to function power electronic circuits by controlling or modifying voltage or current. Power electronic application are used in a wide area from high power conversion equipment such as dc transmission and everyday devices such as power supplies to computers or electric screwdrivers. The circuit of the devices varies from milliwatts to megawatts and power electronic are used to control them. The typical conversation where power electronic application is used, is when dc voltage is converted to ac voltage, ac voltage to dc voltage, conversation of an ac power source where amplitude or frequency is changed, or conversation of unregulated dc voltage to regulated dc voltage. In a power electronic application there is a circuit- and control theory, electronics, electromagnetics, heat transfer and microprocessors for controls [23]. An overview of the power electronics interface is shown in figure 9.

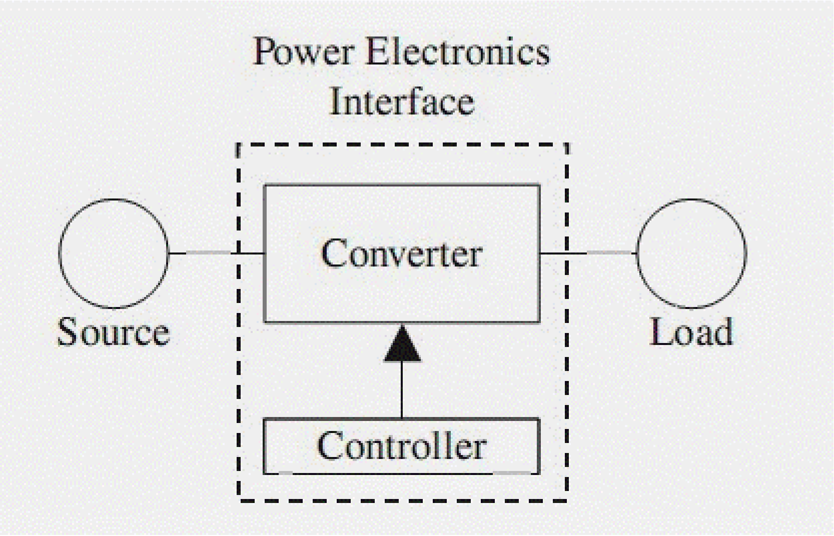


Figure 9 Power electronics interface [24].

2.2.1 Inverter

Inverters used for PV systems converts dc power to ac power. An inverter can be connected to single phase utility grid or three phase utility grids. The switching cycle is shown in figure 10. There are two switching power poles where the inductance if the low pass filet is establishing the current ports of the two power poles [25].

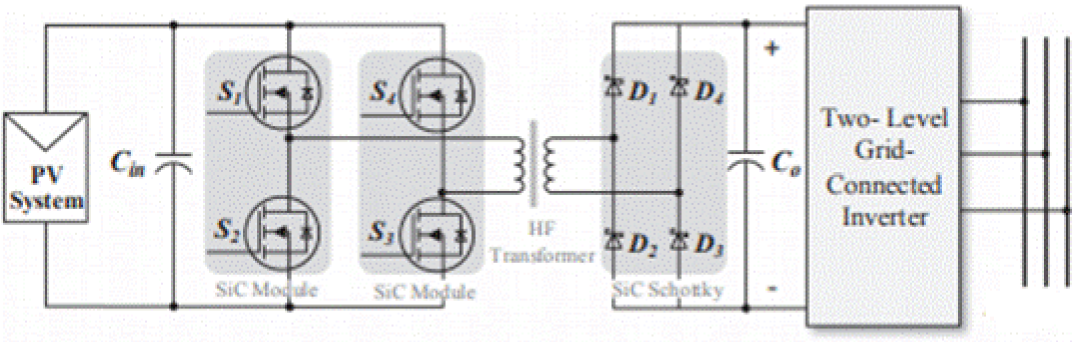


Figure 10 DC/AC converter [26].

The switching cycle average voltage is being synchronised as shown in figure 11.

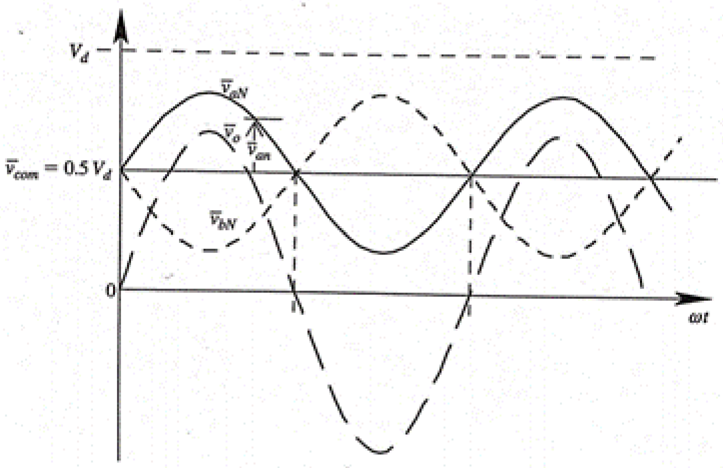


Figure 11 Switching cycle average voltage for single phase inverter [25].

This switching cycle average voltage can be calculated from,

$$\tilde{v}_0 = V_0 \sin (w_1 t) \tag{5}$$

And the common mode power supply can be calculated from,

$$\tilde{v}_{com} = \frac{Vd}{2} \tag{6}$$

From figure 11, the output pole voltage with respect to hypothetical neutral n can be calculated,

$$\tilde{v}_{an} = \frac{\tilde{v}0}{2} \text{ and } \tilde{v}_{bn} = -\frac{\tilde{v}0}{2} \tag{7}$$

And the switching cycle average voltage are,

$$\tilde{v}_{aN} = \frac{Vd}{2} + \frac{\tilde{v}0}{2} \text{ and } \tilde{v}_{bN} = \frac{Vd}{2} - \frac{\tilde{v}0}{2} \tag{8}$$

On the dc side to calculate the switching cycle average current, the ac side current is assumed sinusoidal and lagging between the output ac voltage $\tilde{v}_0(t) = V_0 \sin (wt)$ with angle ϕ,

$$\bar{\iota}_0(t) = I_0 \sin (wt - \phi) \tag{9}$$

The ripple is assumed zero in the output current, then the output power can be calculated from the average output voltage and average output current,

$$P_o = \tilde{v}_o \, \bar{\iota}_o \tag{10}$$

If the inverter is assumed lossless the average input current can be calculated by equating the input power to the average power,

$$\bar{\iota}_d = \tilde{v}_o \, \bar{I}_o * \frac{1}{Vd} = \tilde{V} \, \bar{I} * \frac{1}{Vd} \sin (wt - \phi) = 0.5 \, \tilde{V} \, \bar{I} * \frac{1}{Vd} \cos (\phi) - 0.55 \, \tilde{V} \, \bar{I} * \frac{1}{Vd} \cos (2wt - \phi) \tag{11}$$

Equation 11 shows that the switching cycle average current has a dc component $\bar{I}$ which is responsible for the power transferred to the ac side of the inverter [26].

2.2.2 SCR thyristors

Thyristors converters were historically used to preform task that now switch mode converters are preforming. Now thyristor converters are typically used in very high-power levels for utility applications. The thyristor converters can be considered as a controlled diode. Like diode, thyristor controllers are available in very high currents and voltages. There are different types of thyristor converters, but Silicon Controlled Rectifiers (SCR) are the most common. These thyristors are 4-layer devices (p-n-p-n) which is shown in figure 12. When a reverse voltage across the thyristor is applied, the current flow is blocked by the junctions pn1 and pn3. When a polarity voltage across the thyristor is applied and the gate terminal is open, the current flow is blocked by the junction pn2 and the thyristor is in a forward blocking state condition. Applying a small positive voltage to the gate when the thyristor is in forward blocking state will supplies a pulse of gate current that latches the thyristor in its on state and the gate current pulse can be removed [25].

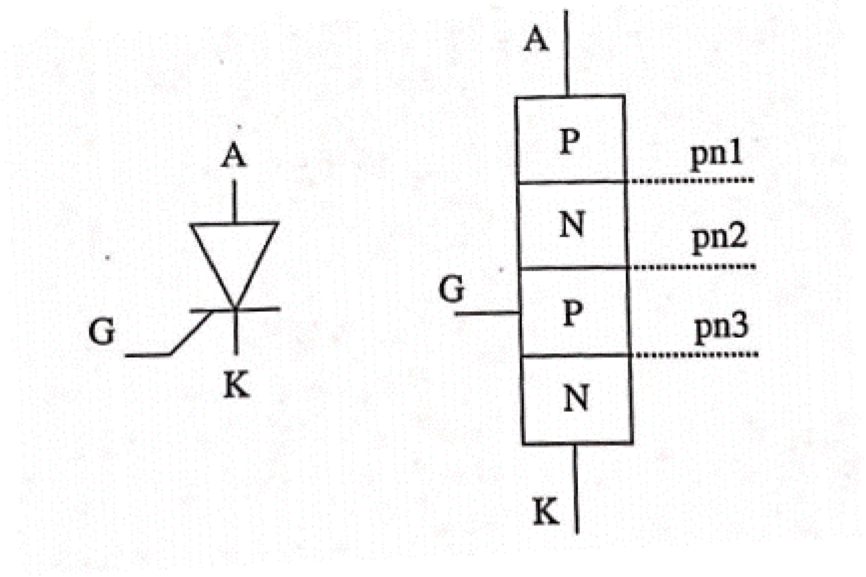


Figure 12 Thyristor symbol to the left and 4-layer devices to the right [25].

A thyristor with an inductance and a resistive load in series is shown in figure 13 (a). At wt=0 the input voltage begins its positive half cycle and if this was a diode the current would start to flow. Thyristors is controllable and the start of conduction can be delayed with an angle α. There is normally a small loss of voltage across the thyristor of 1 to 2 volts which we idealize as zero. v_d is equal to v_s in figure 13 (b) and v_d is shown with darker waveform. The current i_s is equal to v_d/R. Since the current cant reverse through the thyristor, it is zero at wt=π and until the gate pulse is applied in the next cycle. There is some delay in the current i_s because of the inductance. The average load voltage value V_d is shown with the dotted line in figure 13 (b) [27].

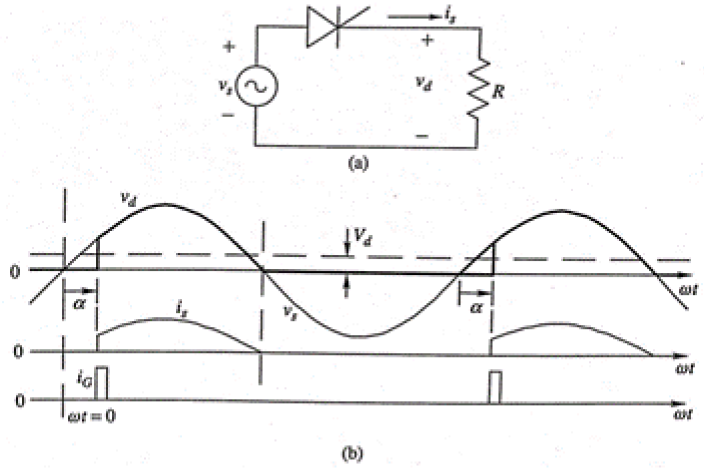


Figure 13 Thyristor circuit with inductance and resistive load in series with waveforms [25].

The average load voltage V_d can be calculated with the formula,

$$Vd = \frac{1}{2\pi}\int_{\alpha}^{\pi} Vs\sin(wt) * d(wt) = \frac{Vs}{2\pi}\ (1 + \cos\ ) \tag{12}$$

Where Vs is peak of the input ac voltage.

2.2.3 Single phase, phase-controlled thyristors

In figure 14 (a), a full bridge phase-controlled converter is shown. This converter is for controlling rectifications of the single-phase utility voltage. To easier understand the principle it is redraw without the inductance in the figure 14 (b). I_d is representing the load on the dc side.

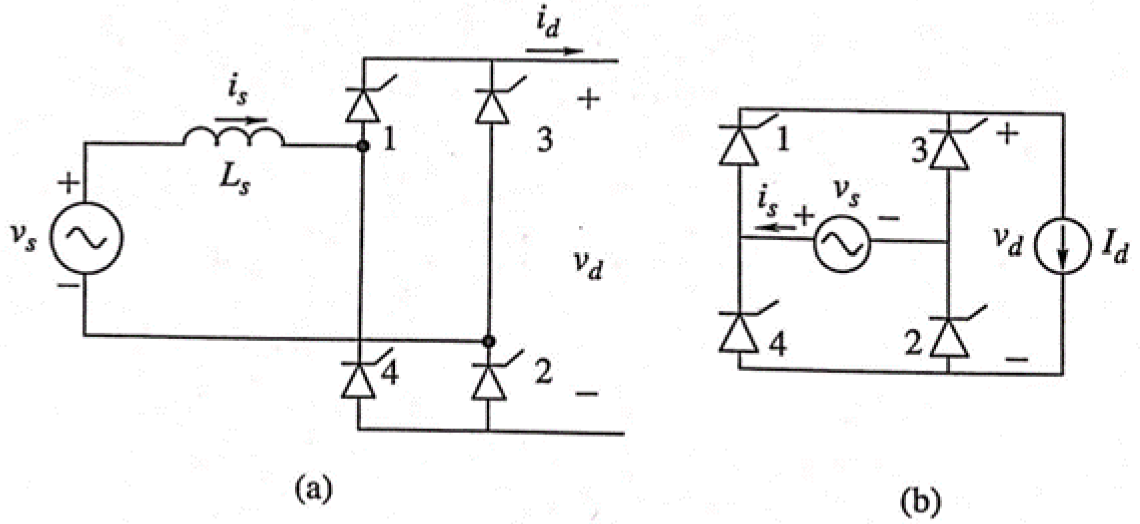


Figure 14 Full bridge single phase thyristor converter with redrawing for easier understanding [25].

The thyristors 1-2 and 3-4 are working as two pairs. α is the delay angle for the gate pulse supplied for the thyristors. For thyristors 1 and 2 is the natural conduction wt=0 applied and for thyristors 3 and 4 wt=180. In figure 15, the waveforms of V_d and I_d is shown.

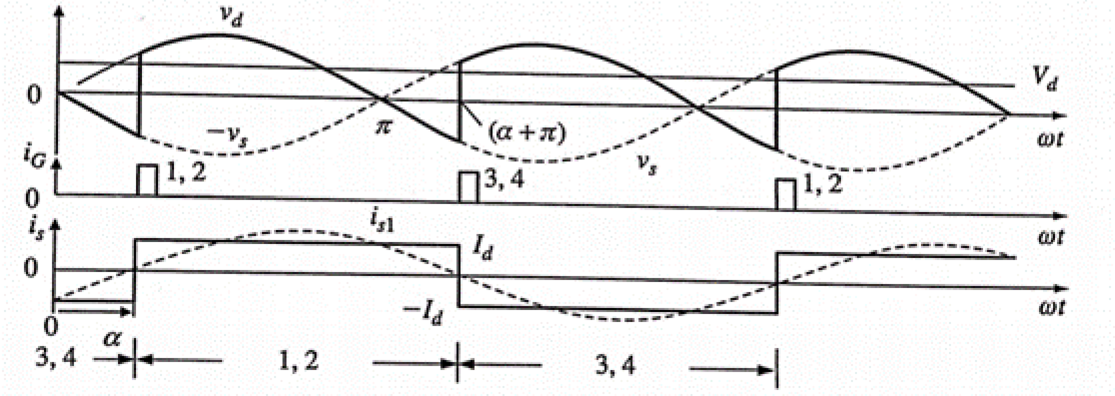


Figure 15 Waveform of Vd and Id [25].

For the input voltage positive half cycle, thyristor 1 and 2 are forward blocking until wt= α where they are gated when they immediately begin to conduct i_d because L_s is set to zero. In this state thyristor 3 and 4 becomes reverse blocking. For α < wt < α + π,

$$V_d(t) = V_s(t) \tag{13}$$

and

$$i_s(t) = I_d \tag{14}$$

Equation (13) and (14) are valid for the positive half cycle until it reaches $\alpha + \pi$ and negative half cycles. When it reaches the negative half cycles thyristor 3 and 4 is gated and I_d is being conducted. For $\alpha + \pi < wt < \alpha + 2\pi$,

$$V_d(t) = -V_s(t) \tag{15}$$

And,

$$i_s(t) = -I_d \tag{16}$$

Equation (15) and (16) are valid for the negative half cycle until it reaches $\alpha + 2\pi$ and the positive halve cycle again and it restarts with equation (13) and (14). It is possible to calculate the average voltage V_d across the dc load of the converter. It is done by averaging the $V_d(t)$ from figure 15, in the interval $\alpha < wt < \alpha + \pi$,

$$Vd = \frac{1}{\pi}\int_{\alpha}^{\alpha+\pi} Vs \sin\omega t * d(\omega t) = \frac{2}{\pi} Vs\cos(\alpha) \tag{17}$$

The input current on the ac side i_s is shifted by the angle α which is shown in figure 15. The $i_{s1}(t)$ fundamental frequency component has a peak value of,

$$Is1 = \frac{4}{\pi}\, Id \tag{18}$$

Now as V_s and I_{s1} is known, the power P from the AC side can be calculated with,

$$P = \frac{1}{2}\, Vs\ *\ Is1\cos(\alpha) \tag{19}$$

Assuming no power loss in the thyristor, the formula can be rewritten as,

$$P = \frac{1}{2}\, Vs\ *\ Is1\cos(\alpha) = Vd * Id \tag{20}$$

From the waveform in figure 15, the dotted waveform is the fundamental frequency amplitude I_{s1} and the current is rectangular. The harmonics h of i_s can be expressed with Fourier analysis as,

$$Ish = \frac{Is1}{h} \tag{21}$$

Where h is the odd values 3, 5 ,7 etc.

From the same graph, in figure 15, by the delay angle α, i_{s1} is displaced with respect to v_s and the reactive power is,

$$Q = \frac{1}{2} Vs * Is1 * \sin(\alpha) \tag{22}$$

So far, the inductance L_s is set to zero. Now it is assumed it is not zero, and the current on the ac side takes finite time to reverse its direction through the inductance. The dc side will still be the same. Now when the thyristors 1 and 2 is gated they will begin to conduct. The current is not jumping instantaneously from $-I_d$ to $+I_d$, but it changes smoothly through L_s. Instead of calculating the volt-seconds, volt-radian is calculated for $L_s>0$. Volt-radian can be calculated from $v_L= (L_s\, di_s/dt)$ in the interval $\alpha+u$,

$$\int_{\alpha}^{\alpha+u} Vl\, d(\omega t) = Ls \int_{\alpha}^{\alpha+u} \frac{dis}{dt}(\omega t) = \omega Ls \int_{-Id}^{Id} \frac{dis}{dt} dt = \omega Ls \int_{-Id}^{Id} dis = 2\omega Ls Id \tag{23}$$

Equation (23) shows the voltage lost to circumstances and for each half cycle or for each π, equation (24) can be used,

$$\Delta Vd = \frac{2}{\pi}\,\omega Ls Id \tag{24}$$

From the equation (17), Vd = 2/π V_s cos(α) it not calculated with the inductance. Now as the loss from inductance is known, the formula can be rewritten as

$$Vd = \frac{2}{\pi} Vs\cos(\alpha) - \frac{2}{\pi}\omega Ls Id \tag{25}$$

2.2.4 AC voltage controller

Ac voltage controllers are converters which controls the voltage, current and power delivered from and ac supply to and ac load. Switches are connected to the source for controlling voltage intervals. The switches are controlling the phase of during every cycle from the source. Some of the waveforms are removed before it reaches the load. There is also possible to connect and disconnect several cycles with integral cycle control. This controls have a fast response time and can change from each cycle. This technology is very common and used in everyday applications such as light dimmer circuits and speed control of motors. Both input and output voltage are ac [28].

2.2.5 Single phase ac voltage controller

In figure 16, a single-phase voltage controller is shown. There are 2 electronic switches, one in each direction. Because of these switches in parallel it is possible to have the current in both directions in the load. This SCR connection is called invers parallel or antiparallel and is equivalent to a triac. It is the same principle as in chapter 2.2.2 of SCR thyristors [29].

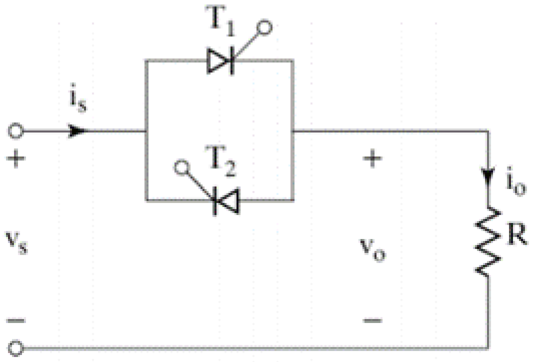


Figure 16 Single phase ac voltage controller [30].

In this case the current contains both negative and positive half cycles. For the circuit in the figure 16, switch T_1 conducts when it is gated in the positive half cycle and conduct until the current reaches zero. Here is the different from chapter 2.2.2, when the half cycle is negative. Switch T_2 is gated in the negative half cycle providing a negative load current. If the gate signal for T_2 is half period after T_1, the negative half cycle analysis is identical to the positive half cycle except of the algebraic sign for the current and voltage. The waveform is shown in figure 17 [16].

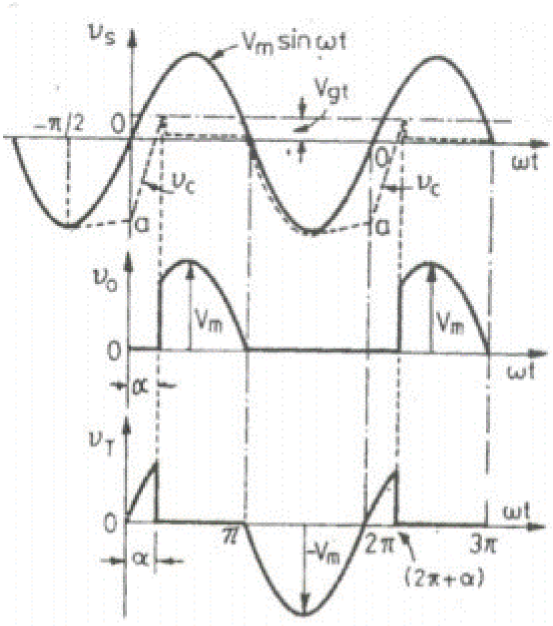


Figure 17 Waveforms for single phase ac voltage controller [31].

2.2.6 Single phase voltage controller with resistive load

The waveforms from figure 17 shows a single-phase controlled voltage controller with a resistive load like a common light dimmer circuit. The voltage v_s(wt) is,

$$Vs(\omega t) = Vm \sin(\omega t) \tag{26}$$

And the output voltage is,

$$v0(\omega t) = \begin{cases} Vm \sin(\omega t), & \alpha < \omega t < \pi, \alpha + \pi < \omega t < 2\pi \\ o, & else \end{cases} \tag{27}$$

To determine the rms load voltage, advantage of positive and negative symmetry of the voltage waveform is taken and necessitation evaluation of one-half period of the waveform,

$$V0, rms = \sqrt{\frac{1}{\pi} \int_{\alpha}^{\pi} ([Vm \sin(\omega t)])^2 \, d(\omega t)} = \frac{Vm}{\sqrt{2}} \sqrt{1 - \frac{\alpha}{\pi} + \frac{\sin(2\alpha)}{2\pi}} \tag{28}$$

When α is zero the load voltage is a sinus curve with the same rms value as the source. From this formula the rms current through the load can be calculated from,

$$I0, rms = \frac{V0, rms}{R} \tag{29}$$

The power factor (pf) can be calculated from,

$$pf = \frac{P}{S} = \frac{P}{Vs,rms\ Is,rms} = \frac{\frac{(V^2 0,rms)}{R}}{Vs,rms\ \frac{V0,rms}{R}} = \frac{V0,rms}{Vs,rms} = \frac{\frac{Vm}{2}\sqrt{1-\frac{\alpha}{\pi}+\frac{\sin(2\alpha)}{2\pi}}}{\frac{Vm}{\sqrt{2}}} = \sqrt{1-\frac{\alpha}{\pi}+\frac{\sin(2\alpha)}{2\pi}} \tag{30}$$

When α is 0 the pf is 1 which is the same for an uncontrolled load without any controller. When α > 0 the pf is between 0 and 1.

Because of the half wave symmetry, the average current in the source is zero. The average current in the SCR is,

$$Iscr,avg = \frac{1}{2\pi}\int_{\alpha}^{\pi}\frac{Vm}{R}\sin(\omega t)\,d(wt) = \frac{Vm}{2\pi R}\,(1+\cos(\alpha)) \tag{31}$$

And since each of the SCR carries half of the line current, the rms current through each SCR can be calculated from the equation (32) [29],

$$Iscr,rms = \frac{I0,rms}{\sqrt{2}} \tag{32}$$

2.2.7 Static VAR control

For power factor improvements a capacitor is placed in parallel with inductive load. For a load with a constant reactive volt ampere requirement (VAR) a fixed capacitor can be used to correct the power factor unity. A load with varying VAR requirement, changing power factor is arranged by the fixed capacitor. A circuit is shown in figure 18 where an ac voltage controller is used for maintaining unity power factor for varying load VAR requirements. A fixed amount of reactive power is supplied from the power factor correction capacitance and it is more than required from the load. Depending on the angle of the two SCRs, the parallel inductance absorbs a variable amount of reactive power. The reactive power absorbed by the load is controlled to match the reactive power supplied by the inductor capacitor. The delay angle is adjusted to maintain unity power factor after the VAR requirements of the load changes. This type of correction of the power factor is known as static VAR control. Static VAR control can change the load requirement quickly. Instead of having discrete levels like capacitor banks, which are switched in and out with circuit breakers, reactive power is continuously adjustable with the static VAR control [29].

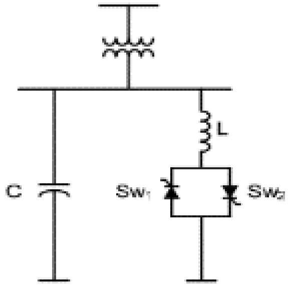


Figure 18 Static VAR control [32].

2.3 Energy storage

Thermal energy storage is storing heat which can be use later under varying conditions such as temperature or power. The main use of thermal energy storage is to overcome the mismatch between generation and use of energy. Energy is stored in a system where it is used at a later time. There are several benefits with storing thermal energy such as achieving more efficient use of energy, better system performance and reducing capital and operation costs because of high power peaks. There are three main types of thermal storage, sensible heat storage, latent heat storage and thermochemical storage [33].

Sensible heat storage is when temperature is increasing or decreasing temperature of a storage material. The material can occur in different shapes as water, air, oil and so. There are advantages and disadvantages for each material, but normally the material is chosen based on the heat capacity.

Latent heat storage is using the phase transition of a material usually by solid-liquid phase is changed. Upon melting, heat is transferred to the material which is storing the heat at constant temperature. An example for this is water used as ice for cold storage.

When a chemical reaction with high energy involved is used to store energy, it is called thermochemical energy storage. The heat and the product should be able to store separately. High temperature is used in the reactions, normally above 400 °C. Normally a heat exchanger is used to transfer the heat to desired shape [33].

2.3.1 Thermal boiler

In figure 19 it is shown a domestic hot water heater. DHWH are a thermal storage which stores energy as hot water. The cold water enters the tank in the bottom where the heating element is placed. As the water is lighter when it is hot, it rises to the top of the tank. In the top the outlet of the water is placed to utilize that the water is hottest in this area. The heating element is placed in bottom together with the valve for cold water, and at the top of the tank, the outlet of water is placed due to inertia in water temperature [34].

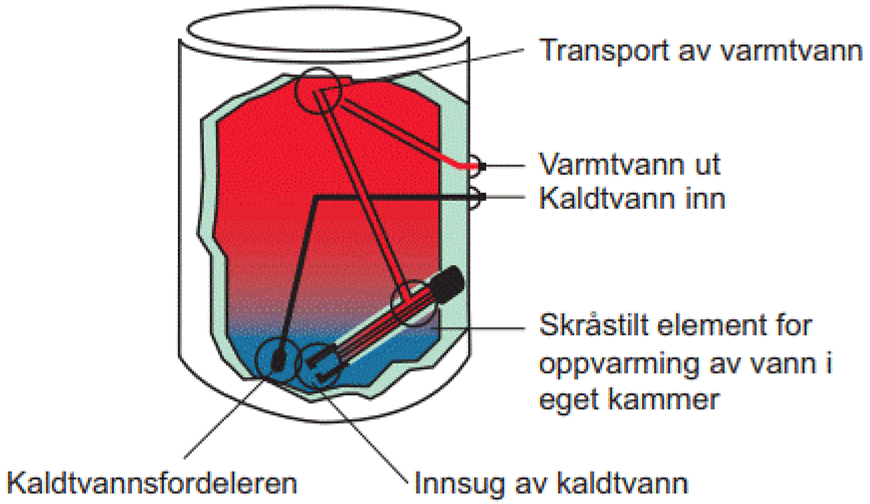


Figure 19 CTC hot water tank [34].

2.4 Energy consumption profile

In figure 20 an energy consumption profile of a typical house for two days is shown. This profile is based on the spot price in Kristiansand in January given by Nordpool and assume the grid load follows the spot price changed from hour to hour [35]. This graph shows that the power peak is in the morning between 06:00-10:00 and 18:00-22:00. The lowest grid load is during night-time at 3:00. For an average household the energy consumption is 25000 kWh yearly. This is 68.5 kWh each day and 2.85 kWh each hour. The graph below is adjusted so the average consumption is 2.85kW each hour.

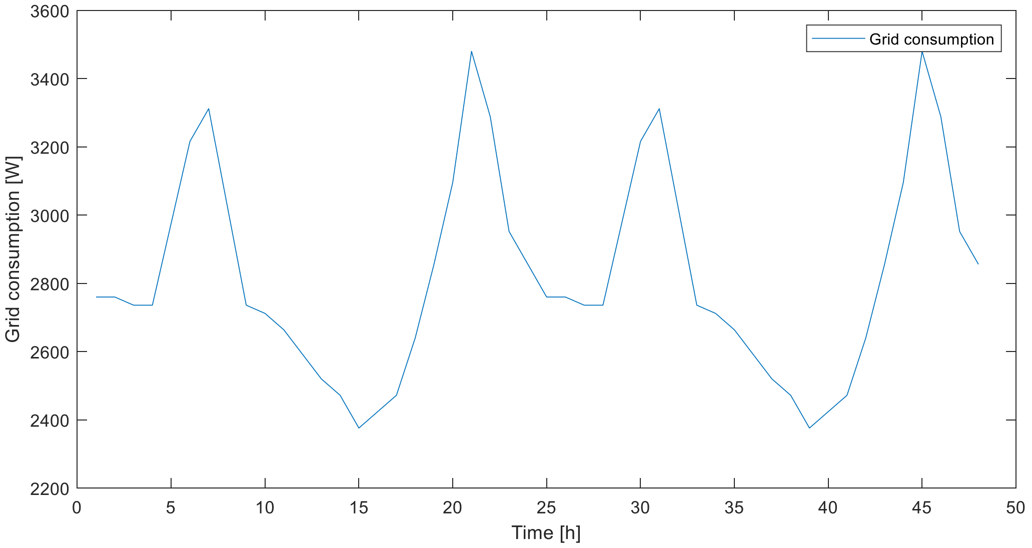


Figure 20 Power peaks for a household through 2 days.

2.5 Water consumption profile

In figure 21 a water consumption profile of a typical house for a day is shown. The graph shows its biggest consumption in the morning and in the evening. This graph shows the peak for a residential house, while for hospitals, commercial buildings, offices etc the consumption profile is different. For a European household the water consumption is distributed between shower, bath, sink and household applications like dishwasher, washing machine and cloth washes. It is showering which uses most of the hot water and an average shower uses around 14 litres per minute [36]. The temperature in a hot water tank must always be higher than 60 °C because of salmonella [37].

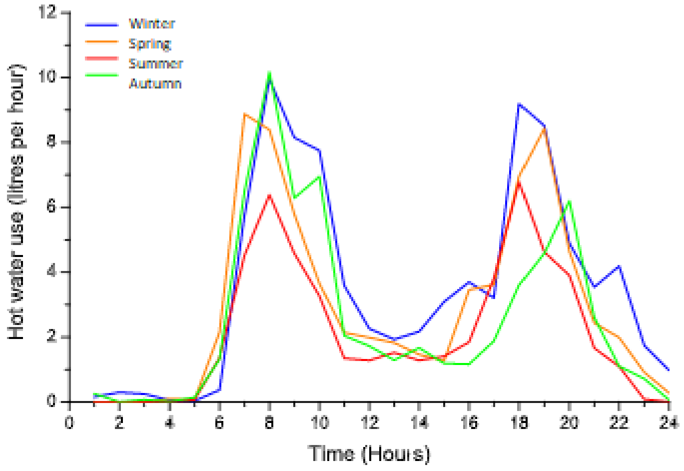


Figure 21 Hot water profile for residential houses in Europe [36].

In Norway a household have a yearly average water consumption for both cold and hot water of 137000 litres. Each day this is an average of $\frac{137000}{365} = 375\ l$ [38]. Around 190 l of this is hot water [36].

The specific heat capacity for water (Cv) is 4.186 J/g ϕ °C. Calculation for how much energy is needed for heating 1 litre water is shown in equation (36)

Density of water is shown equation (33)

$$\rho = 997\frac{\text{kg}}{\text{m}^3} \text{ where 1 m}^3 \text{ is 1000 l.} \qquad (33)$$

$$\rho = \frac{997\text{ kg}}{1000\ l} = 0.997\frac{kg}{l}.$$

And with density, the specific heat capacity (Cv) for water can be calculated in equation (34)

$$4.186\frac{J}{g}\ ^{\circ}\text{C} \ * 1000\frac{\text{g}}{\text{kg}} * 0.997\frac{kg}{l} = \ 4173\ \frac{J}{l}\ \phi^{\circ}\text{C} \qquad (34)$$

.

Calculations from J to W is shown in equation (35)

$$1\,J \ = \ 1\,Ws \qquad (35)$$

$$3600\,J \ = \ 3600\ Ws = 1\ W * 3600\ s * \frac{1h}{3600\ s} = 1Wh$$

And the calculation for how much energy is needed to heat up 1 l water 1 ˚C is shown in equation (36)

$$\frac{4173\frac{J}{kg}\phi^{\circ}\text{C}}{3600} \ = \ 1.15917\frac{Wh}{l}\ \phi^{\circ}\text{C} \qquad (36)$$

3. Research Questions

In this thesis, the energy produced by a PV system is being stored as hot water. A controller is made to control the water flow- and heating of water in a DHWH. The energy from the solar cells is heating the water, and the system is connected to the grid which prevents the water from getting cold in case of poor PV production. The water will be heated when the grid is outside the peak period, to reduce load on the grid. An AMS meter is connected to measure the use of energy. Production from solar cells will be picked up and registered on a computer to utilize the power produced. The controller is connected to a temperature sensor, valve control of water and the heating element to simulate relevant tests in a household. The system was tested during the energy research project and a program was made in labview. From the results and discussion, it was concluded that a thyristor had to be installed for more controls and further testing to reduce grid load in peak periods. From this research, the thesis title is,

“System design for a solar powered thermal storage - to obtain reduction of demand side power peaks”

The purpose of this work is to optimize heating of hot-water and to utilize PV-production with the grid and water consumption in consideration, without affecting the end-user. The PV produced energy is used to heat the water rather than deliver back on the grid. To avoid grid load peaks a thyristor is controlled, and the electrical heater is only supplied with the solar production as much as possible. From research the electricity and water consumption profile are high in the evening and in the morning. Since the PV production is highest in the middle of the day, this task will try to store this energy and use it in grid load peaks. Is it possible to avoid grid peak periods and heat up the water with solar power without affecting the end user?
Different tests which corresponds to a household are set up and simulated. The results show how the temperature in the tank is changing and how this affects the grid.

4. Methods

4.1 Physical model

In figure 22, an overview over the system is shown. The PV panels are connected to micro grid inverter. Two panels are connected in parallel to one micro grid inverter. These inverters are connected to wifi and are sending production information to a computer in the lab. It is also connected to grid and its own fuse. On the fuse, a smart meter is installed to measure the energy consumption. This fuse is installed for this system, and only the domestic hot water heater is connected. On the DHWH, it is installed a temperature sensor and a switch to open and close a valve for the water. The computer is receiving data from the temperature sensor and the labview model specifies when the valve should open and close. There is also a thyristor controller connected before the hot water tank to control the power delivered to the heating element. How much power delivered to the heating element in the hot water tank is specified by the computer and the labview model.

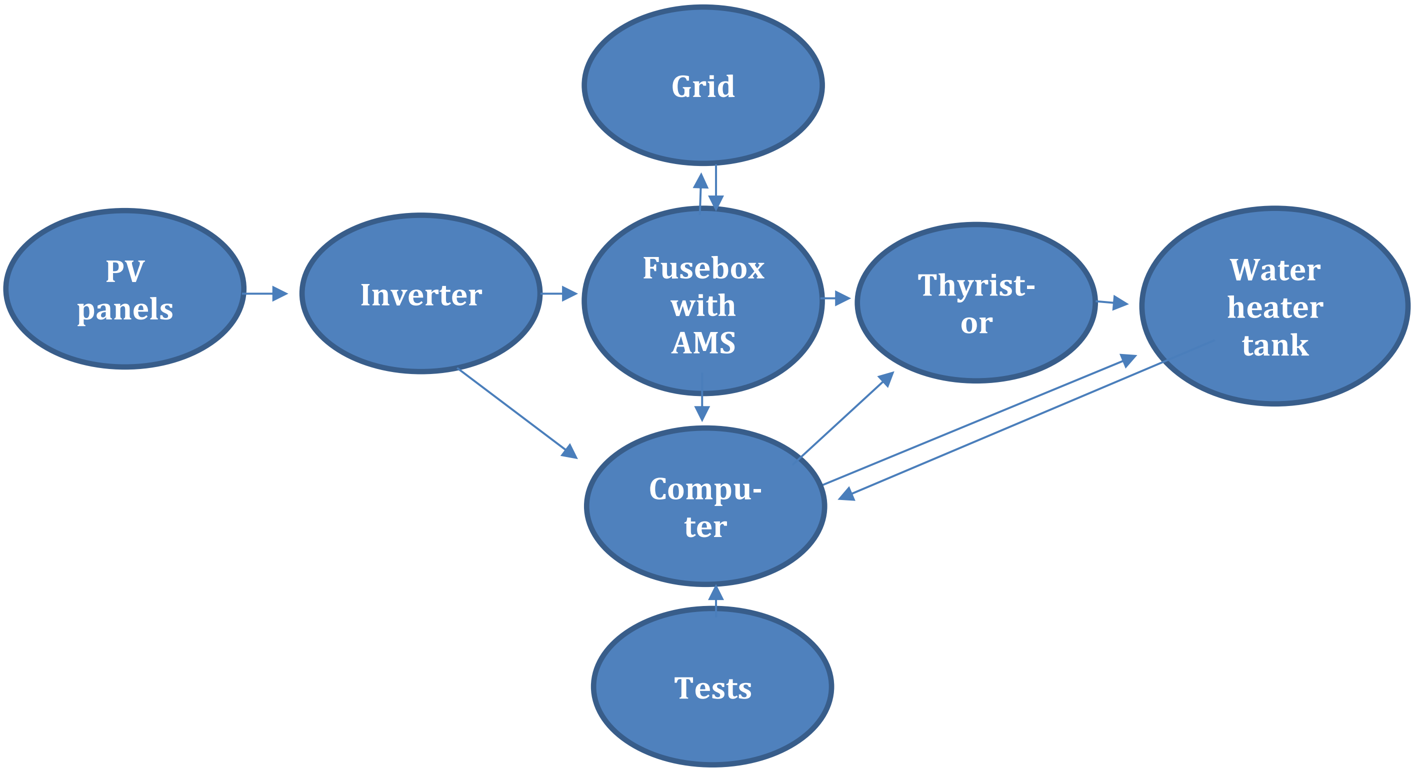


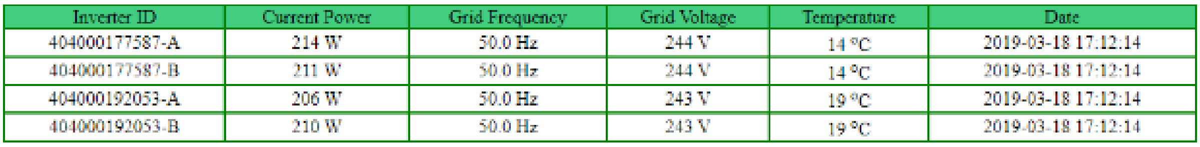
Figure 22 Flowchart of the system.

4.1.1 PV panels

Figure 23 shows 4 PV panels which is used in this report. Each PV panel has a peak power at 250 W and 2 panels are connected to 1 inverter in parallel. These PV panels uses polycrystalline technology which has lower efficiency, but also lower cost [39]. A picture of the panels is shown below. They are mounted on top of the roof at UiA. The micro grid inverters are mounted at the back of 2 panels.

Figure 23 Picture of the 4 PV panels used.

In figure 24, it shows how the values from the PV panels are shown in the computer in the lab. The power of each panel is measured, and they are added together for the total production.



Inverter ID	Current Power	Grid Frequency	Grid Voltage	Temperature	Date
404000177587-A	214 W	50.0 Hz	244 V	14 °C	2019-03-18 17:12:14
404000177587-B	211 W	50.0 Hz	244 V	14 °C	2019-03-18 17:12:14
404000192053-A	206 W	50.0 Hz	243 V	19 °C	2019-03-18 17:12:14
404000192053-B	210 W	50.0 Hz	243 V	19 °C	2019-03-18 17:12:14

Figure 24 Picture of the PV production.

Figure 25 shows the electricity demand for a household and the PV production over 2 days. The PV production are at highest at daytime when the electricity demand is quite low. Therefore, it is useful to store the energy and use it when the electricity demand is high. The water demand profile follows the grid profile. The DHWH will work as the energy storage in this thesis.

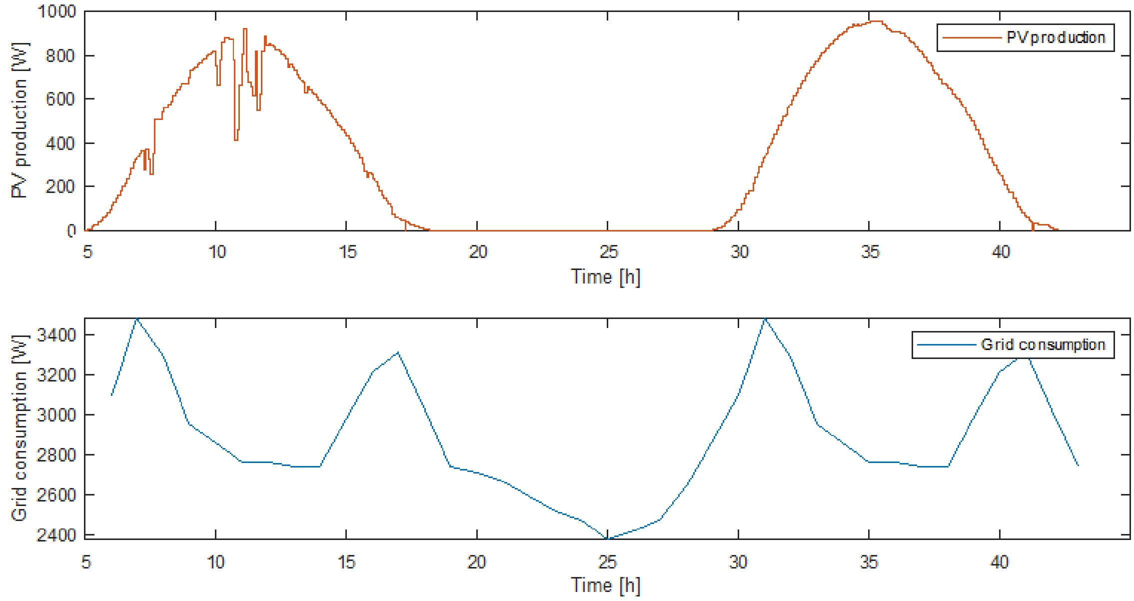


Figure 25 PV productions and electricity demand over 2 days.

4.1.2 Micro inverter

In figure 26, one of the two micro inverters mounted on the PV panel is shown. This micro inverter has maximum input 500W and has 2 inputs for PV panels. Two panels are connected to each inverter in parallel, and the inverter transmits the power from dc to ac with 95.5% efficiency. A cable is stretched from the roof and to the PV-lab. In the PV lab it is connected to its own fuse. From this fuse there is one socket for the water heat tank.

Figure 26 Micro grid inverter mounted at back on the PV panel.

To use the power from the PV panels to heat up the water, the production must be known. A wifi module is connected to the microinverters to show the production. This production is then possible to read on the computer in the PV-lab for further experiments. It also has a display where the production can be read without the computer in the PV lab.

In figure 27, the fuse box in the PV lab is shown. One fuse is connected to the micro grid inverter and one fuse has a socket for the DHWH. The third fuse is for another PV system which is disconnected and not used in this thesis. For measuring how much electricity is used from the fuse with the hot water tank, an AMS is installed. This is also connected to wifi and the values can be read on the computer in the lab.

Figure 27 Fuse box in the PV lab.

4.1.3 Control system

To be able to control the water heater tank, some measurements and controls are necessary. One sensor installed is for the temperature in the water. This is important for the control system, so the water temperature won't be too low or too high. There are two control signals for the tank, one is for the valve and one is for the heating element. The valve switch is used to discharge the hot water from the tank and fill it up with cold water, just like in households. The other control is the thyristor regulator to control how much power the heating element is allowed to use. This is used for the heating element to heat the water only with the self-produced PV energy. On sunny days where the solar panels can produce up to 1 kW, the heating element is only supplied with the self-produced PV power between 0-1000 W and no power from the grid is used. In figure 28, an overview of the national instrument (NI) modules are shown.

Figure 28 Overview of the NI modules connected to the hot water heater and labview.

In figure 29 it is shown the valve controller installed for the system. With this controller it is possible to open and close the valve with a water profile from labview.

Figure 29 In this picture the valve controller for the water tank is shown.

4.1.4 DAQ modules, NI 9474, NI 9216 and NI 6211

NI 9474 is a digital output module connected to labview. It is compatible with signals from 5 to 30V and works with logic levels and signals directly to a lot of switches, transducers and other devices. In this case it is used for the valve and can open/close the valve. This device is connected with the logic in LabVIEW to control the valve as desired. By discharging the tank with this valve control, a simulation for normal households can be done.

NI 9216 is a resistance temperature detector temperature input module. It receives digital signals and they can be read in LabVIEW. This module is connected to LabVIEW to measure the temperature in the water tank, so it won’t be too high or too low. This is used in the simulations to simulate normal households. The temperature sensor is installed in the bottom of the tank where the cold water is entering. This is done because the temperature can be different in different places in the tank. It is important that the water is minimum 60 °C because of salmonella.

NI 6211 is a multifunction module which is used to send analog output signal from labview to the thyristor. The thyristor can then be controlled to powering the heating element as wished. The signal used in this task is 0-10 V. In figure 30, all the NI modules used in this thesis is shown.

Figure 30 DAQ modules.

4.1.5 Thyro HRLP3

To utilize the power produced from the PV panels, a converter for control of the power delivered to the hot water tank was needed. After some research a Thyro HRLP3 was ordered so it could be installed in the system. The Thyro is a thyristor power controller with system bus interface, integrated semiconductor fuse, synchronization option and control of voltage. It is possible to program it and read data from a software adapted to this converter. The ac input voltage range for the converter is 172V to 440V. A 24V power supply ac or dc is installed to power the internal system in the thyristor. It is 1 phase and has 50 Hz operating frequency, so it fits to the grid in the lab. The operation mode can be TAKT, VAR or QTM. The setpoint input can be 0-20mA or 0-10V where the precision is better than 3% with U control and better than 1.5% with I control. The Thyro also has led lights for error message and for how much the output is. This is an indicator and is useful for monitoring the system and to troubleshoot if there is something wrong. A picture of the Thyro is shown in figure 31.

Figure 31 Picture of the Thyro after it is installed.

The software which came with the Thyro was limited, so the parameters was set manually. Table 1 shows the DIP switch for the Thyro. S1.1 and S1.2 are the operating mode. S1.1 is set to zero and S1.2 is set to one, then the operating mode is VAR. S1.3, S1.4 and S1.5 are all set to zero and this is the control mode which is set to U*U. Setpoint is given by S1.6, S1.7 and S1.8. They are all set to zero which is 0-10V setpoint. This signal is supplied to the Thyro from Labview. S.9 is set to 0 and S.10 is set to one. This is analog output which are set to 0-10V.

Table 1 Setpoint for the thyristor.

Switch	Value
S1	0
S2	1
S3	0
S4	0
S5	0
S6	0
S7	0
S8	0
S9	0
S10	1

The DIP switches are shown in figure 32.

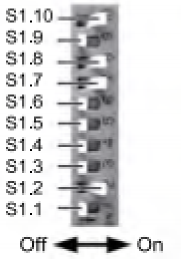


Figure 32 DIP switch for Thyro.

Figure 33 shows the electrical connectors for the Thyro. It is installed before the heating element for the hot water tank. L1 is entering at U1 and leaving at U2 where it continues to the heating element. After U2 there is a connection between N and X.1.1 with a 2 A fuse. This is done to synchronization of the ignition pulse. The ground is connected to GND. The setpoint 0-10 V is connected to X2.3 and X2.4. A pulse lock jumper is installed between X2.1 and X2.2. The power supply which is 24V dc is connected to X11.1 and X11.2.

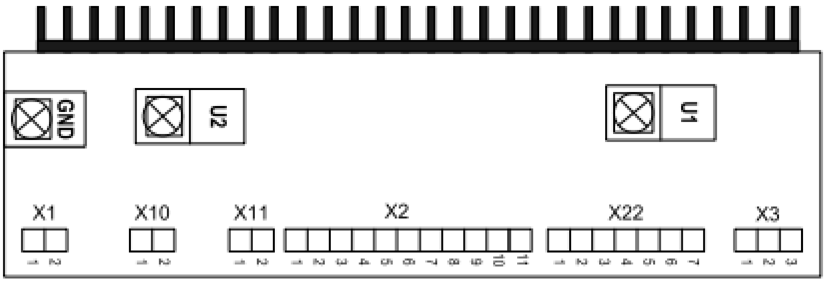


Figure 33 Electrical connection on the Thyro.

To test he thyristor in the program it was logged for 20 hours. At some intervals it should run for 1.95 kW and when the PV panels had production it should only deliver the same amount of power to the heating element as the PV production. The dc voltage delivered from the labview program was 0-10 V. This was a rainy day with lack of sun, but the graph below shows the input dc voltage and how the temperature raise with it. When the dc voltage is 10 V the temperature is growing fast, and when the dc voltage is around 1 V, there is some temperature raise. The temperature is falling when the dc voltage is below 0.25 V which is under 50 W delivered to the heating element.

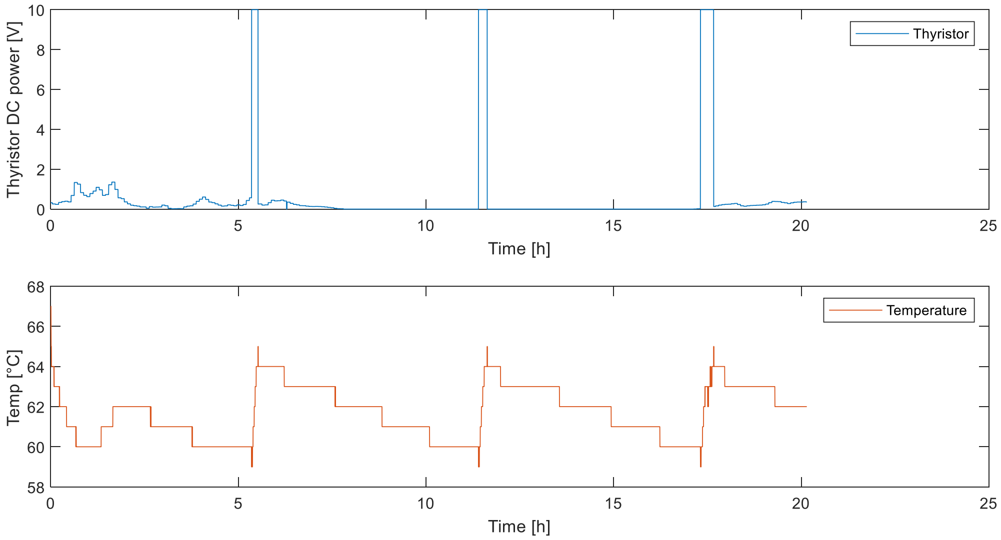


Figure 34 DC power delivered to the thyristor and temperature.

4.1.6 Water tank

Figure 35 shows the water tank with the junction box and the thyristor at top of it. There is also other sensors and controls installed to the tank which is not used in this task. There is also installed an on/off button for the valve and the heating element on top of this junction box. The water tank has 194 litres capacity. The heating element for this tank is 1.95 kW.

Figure 35 Hot water tank with junction box and thyristor at top of it.

The tank with 194 l water capacity is a normal hot water tank for households. It has a mechanical thermostat which can be turned from 65-80 °C. Water is entering the tank with around 7 °C. Calculation to heat up whole the tank from 7 °C to 65 °C is,

$$Cv = 1.15917\frac{Wh}{l}\ \phi°\mathrm{C} * 194\ l\ * (65-7)\ °\mathrm{C} = 13042\frac{\mathrm{Wh}}{1000\frac{\mathrm{Wh}}{\mathrm{kWh}}} = 13.04\ kWh \tag{37}$$

And the time needed to heat 194 liters to 65 °C is,

$$\frac{13.04\ kWh}{1.95\ kW} = 6.67\ h \tag{38}$$

6.67 hours is the time the electrical heater must be turned on to heat the water from 7 to 65 °C. This test is also done with the labview model and the water tank. The valve was opened for a long time and the water was stabilised at around 7 °C. After 23200 seconds or 6.72 hours, the temperature reached 65 °C. This is a bit more than the theoretical value, due to inaccuracies in the temperature and due to some heat loss. The graph of this test is shown in figure 36.

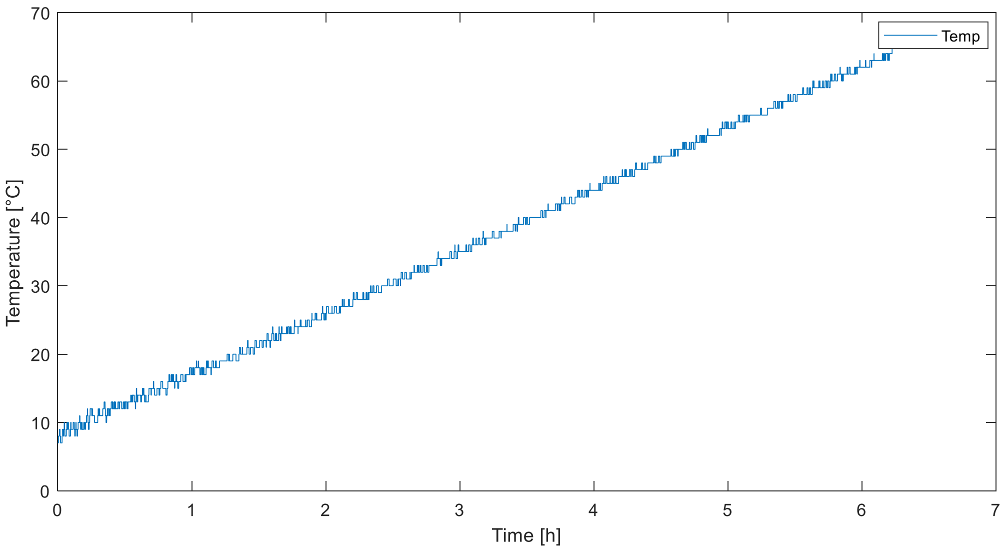


Figure 36 Water temperature in the tank.

375 l is total consumption of cold- and hot water. According to Hafslund, the water heater tank is on for 70 hours each week which is 7 hours each day [1]. The equation below shows how much energy is needed each day,

$$7\ h * 1.95\ kW = 13.65\ kWh \tag{39}$$

With 13.65 kWh, it can be calculated how much water is heated each day. The mechanical thermostat is set to 70 °C standard, and the calculation is shown in equation 40,

$$\frac{13650\ Wh}{1.15917\ \frac{Wh}{l\ \phi°\mathrm{C}} * (70-7)°\mathrm{C}} = 186.9\ \mathrm{l} \tag{40}$$

According to CTC, Ferro Term is their bestseller of all times. Therefore, the thesis is based on the fact that this hot water tank is average for households in Norway. When the valve is discharging the DHWH, 1 litre is discharged every 3 seconds [40].

Comparing the water profile from the theory and the fact that a house uses around 190 l hot water each day, different water profiles can be made. The main usage of water is in the morning and in the evening due to showering, and household appliance is running at these times. Figure 37 shows a typical valve profile for a household and similar profiles are used in tests. In the morning, the valve is open until 75 liters is emptied, and the same for the evening. In the middle of the day, the valve is opened for 2 small cycles and emptying the tank for 15 liters each time.

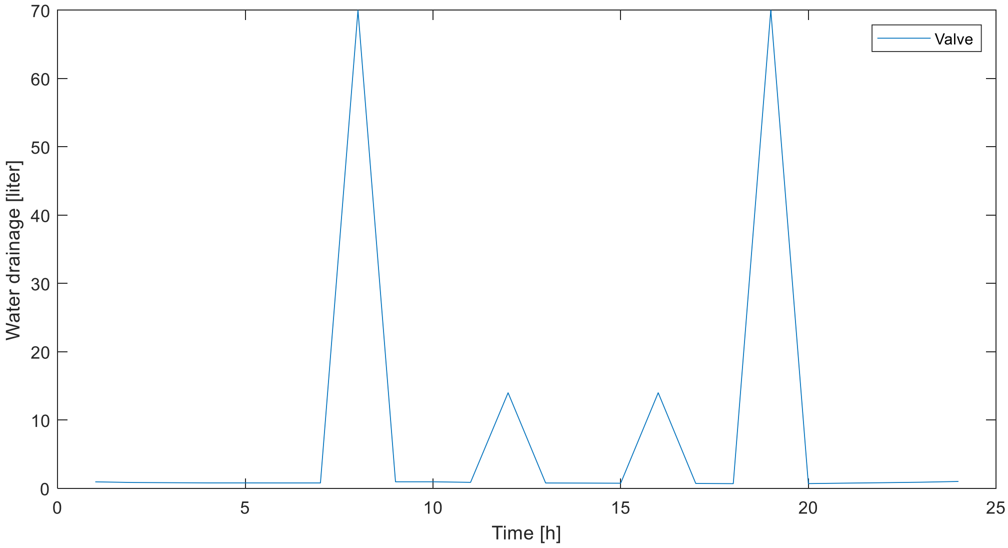


Figure 37 Water profile.

There is also some heat loss in the water to the surroundings. To measure this the tank was heated up and the temperature fall was logged over 5 hours. The temperature dropped from 63.9 °C to 60.3 °C. Calculation of the heat loss is shown in equation 41,

$$1.15917\frac{Wh}{l}\ \phi°\mathrm{C} * 194\ l\ * (63.9 - 60.3)\ °\mathrm{C} * \frac{1\mathrm{Wh}}{1000\frac{\mathrm{Wh}}{\mathrm{kWh}}} = 0.81\ kWh \tag{41}$$

0.81 kWh is the power lost over 5 hours which means 3.88 kWh is lost over 1 day. This is shown in figure 38.

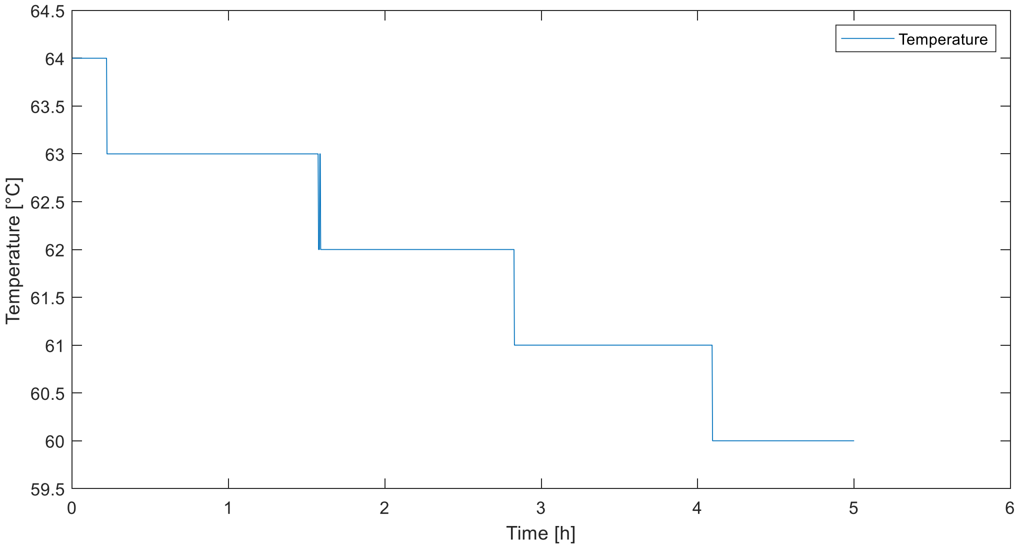


Figure 38 Temperature drop over 5 hours.

It is also interesting looking at the water demand profile and the electricity demand profile. Figure 39 shows the electricity profile and the water profile over 48 hours. It shows that the water is used when the electricity demand is high. The hot water tank normally uses around 15-20% of the total electricity demand in a household and that is why the electricity demand is high at the same time as the water consumption is high, which makes the grid load high in the same period.

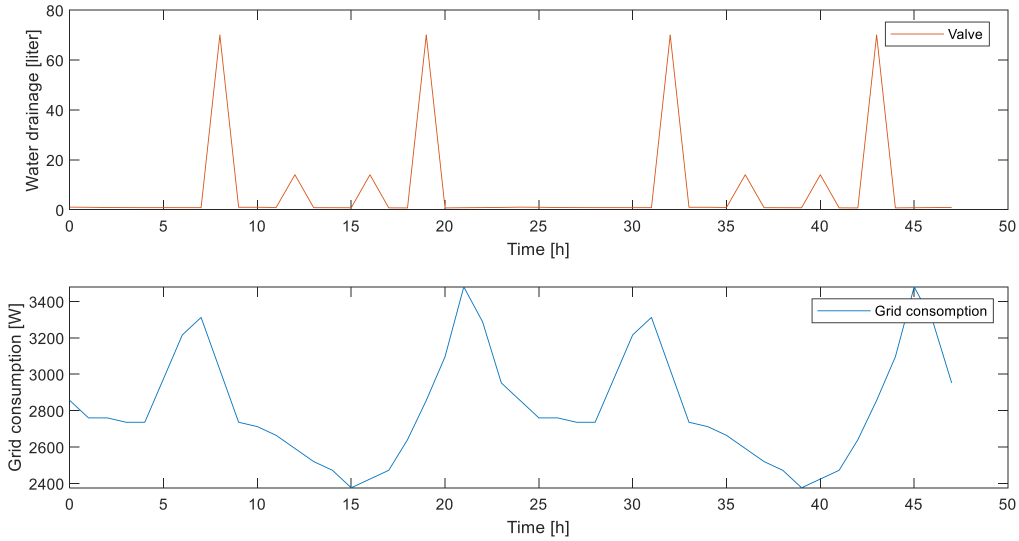


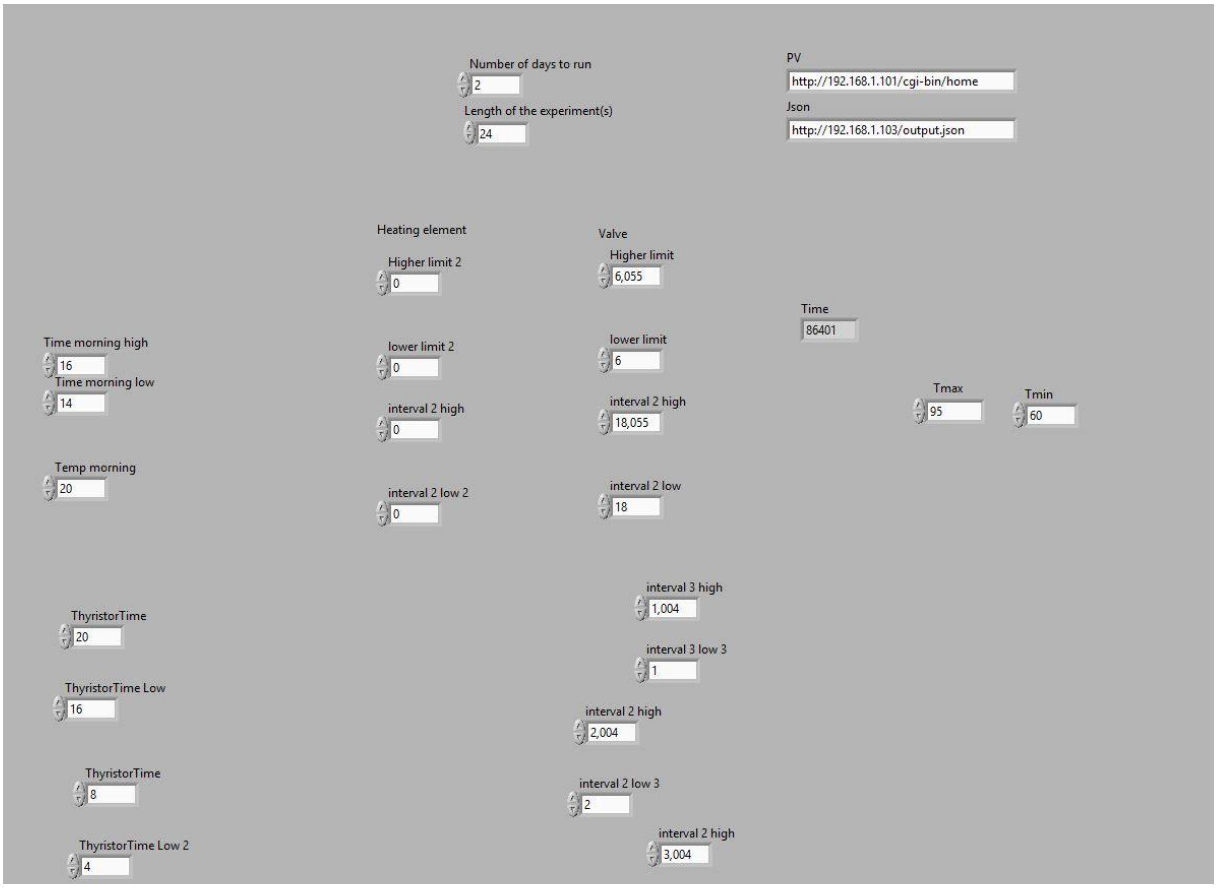
Figure 39 Electricity profile and water profile.

4.2 Labview

Labview is a graphical program which visualize every aspect of application including hardware configuration, controls and measurement data. With labview it is possible to read temperature, read PV production, turn on and off the valve, and with the thyristor, it can deliver power from 0-1950W to the heating element. Each part is inserted into a logical program so that every part depends on each other and communicates. The valve is open and closed based on a water consumption profile.

Labview is sending a digital output signal to the NI 9474 module which opens and close the valve. Temperature in the tank is measured and sent as a digital input signal to NI 9216 so it can be read in labview. To heat the water an analog output signal is sent through NI 6211 to the thyristor to control the heating element. Data from the PV system is also measured and used in labview to make constrains for the system. This data is coming from the micro grid inverter which send it by wifi.

Figure 40 shows where the parameters for the heating element and valve is set. Tmax and Tmin is also set here. The time in hours and days is set for how long the simulation will last. There are intervals where a lower limit and higher limit is set for heating element and valve. When the time is between these limits, it turns on. Else it is off. Tmax morning and Tmin morning is used to increase the temperature in the tank in an interval. This is useful to heat the water in the night when the load on the grid is low. Thyristor time is set to reduce the power in grid load peaks. PV and Json is the URL address to get the production from the PV panels and to measure the load on the fuse with the hot water tank from the AMS.



Number of days to run
2

Length of the experiment(s)
24

PV
http://192.168.1.101/cgi-bin/home

Json
http://192.168.1.103/output.json

Heating element

Higher limit 2
0

lower limit 2
0

interval 2 high
0

interval 2 low 2
0

Valve

Higher limit
6,055

lower limit
6

interval 2 high
18,055

interval 2 low
18

interval 3 high
1,004

interval 3 low 3
1

interval 2 high
2,004

interval 2 low 3
2

interval 2 high
3,004

Time
86401

Tmax
95

Tmin
60

Time morning high
16

Time morning low
14

Temp morning
20

ThyristorTime
20

ThyristorTime Low
16

ThyristorTime
8

ThyristorTime Low 2
4

Figure 40 Screenshot of the controlpanel where the parameters are set.

Figure 41 shows the graphs in labview. This is helpful during the simulations to show the values and how each parameter is operating. The graphs from labview is not used in the report, but only an indicator during simulations. Instead the values are logged in another file so it can be handled with in matlab.

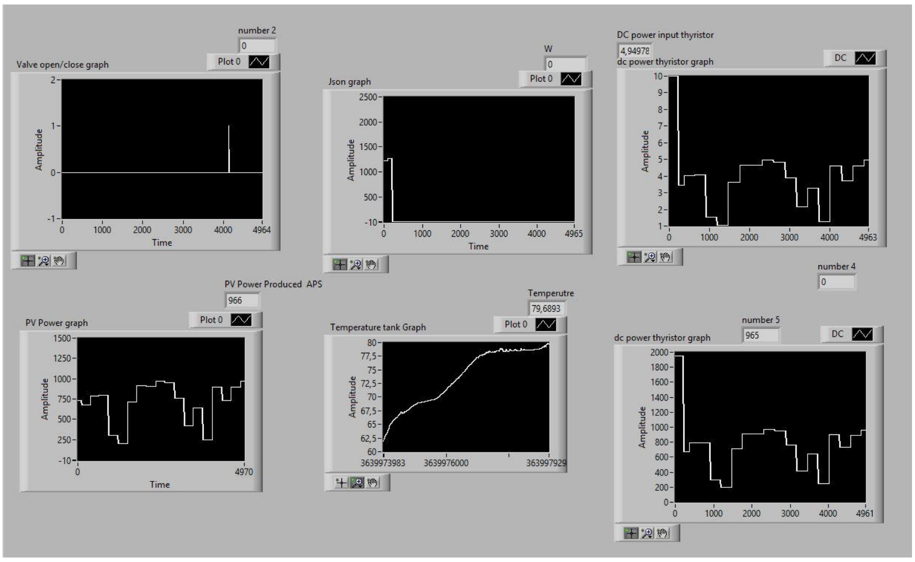
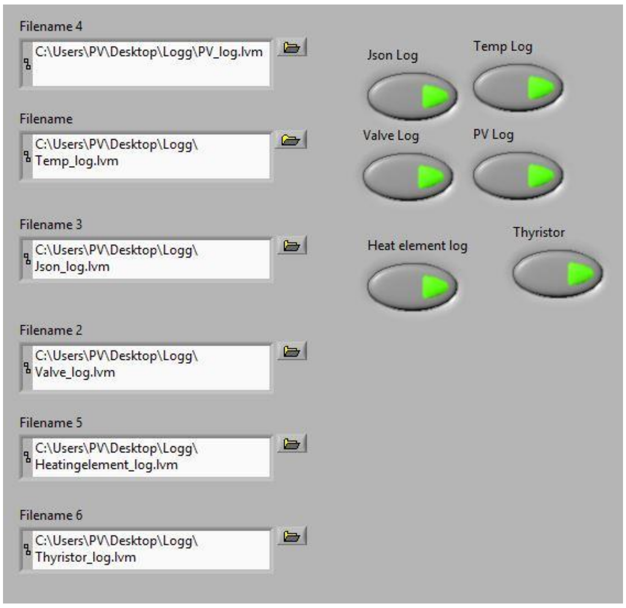


Figure 41 Screenshot of the graphs during a test.

In figure 42, the logging of the values is shown. Here it is possible to choose which values should be logged and which should not. When they are logged here, they can be handled in matlab for better display and more opportunities. Each parameter is logged as a .lvm file.



Filename 4
C:\Users\PV\Desktop\Logg\PV_log.lvm

Filename
C:\Users\PV\Desktop\Logg\Temp_log.lvm

Filename 3
C:\Users\PV\Desktop\Logg\Json_log.lvm

Filename 2
C:\Users\PV\Desktop\Logg\Valve_log.lvm

Filename 5
C:\Users\PV\Desktop\Logg\Heatingelement_log.lvm

Filename 6
C:\Users\PV\Desktop\Logg\Thyristor_log.lvm

Figure 42 Screenshot of the logging control.

4.3 Logic

In figure 43, a flow chart for the program is shown. When the time is on, the first thing that is checked is the temperature. If the temperature is below Tmin, heating element is always on, so the end user won’t be affected. Since the grid load is lowest in the night the Tmin is increased at this time. If the temperature is above Tmaks, the PV production is delivered to the grid due to high pressure in the tank. As an extra safety, the valve is opened if the temperature is above 100 °C. When there is PV production, all the power produced is delivered to the heating element to heat up the water and store the energy as hot water. Since the PV production is highest during daytime when the grid load is low, it is useful to store it and use it in the evening when the grid load is high.

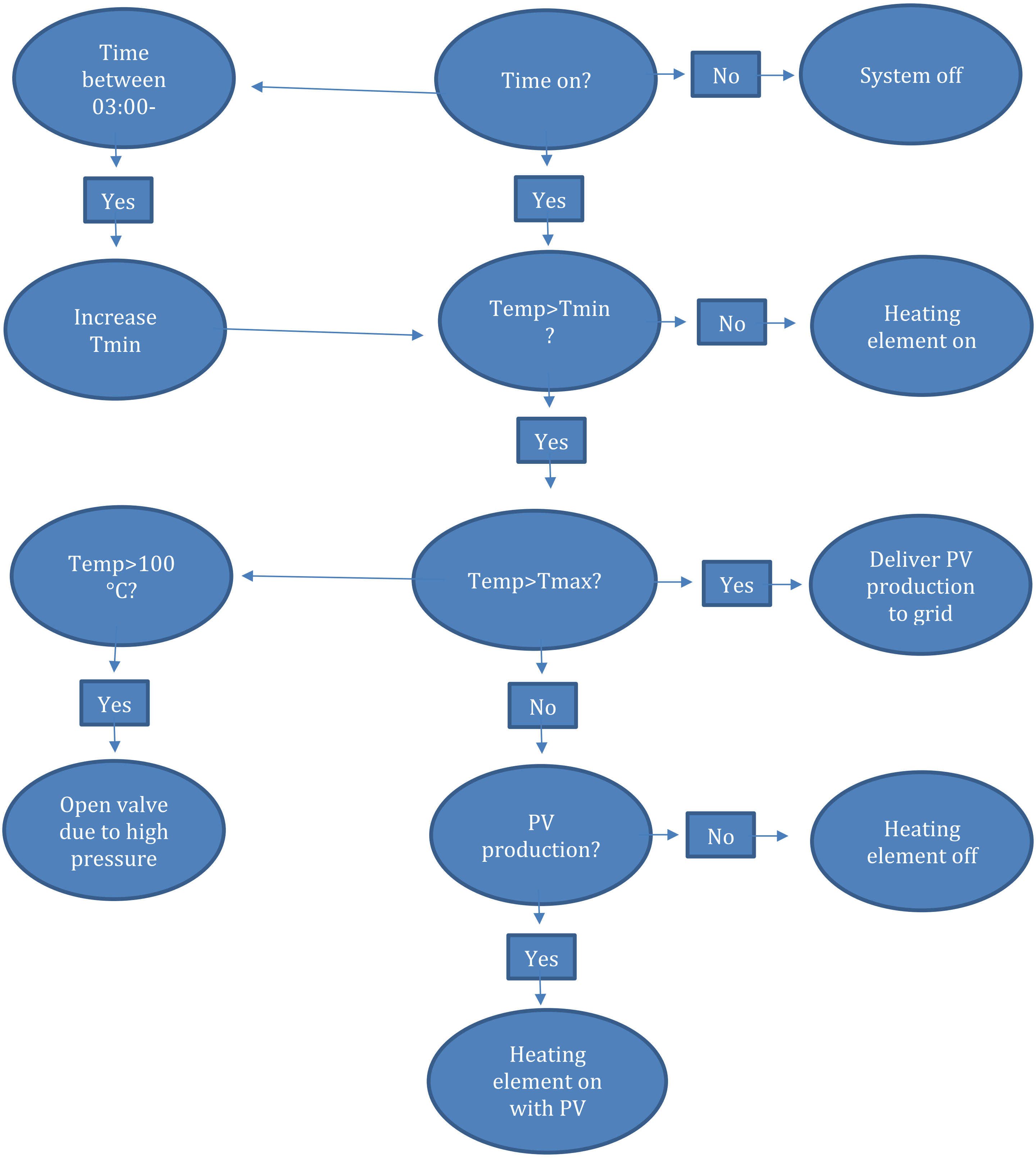


Figure 43 Flow chart of the labview logic.

5. Results

Several tests have been made to simulate different scenarios for a household. It is made a graph for the grid load, as it is quite similar each day. Because there are many houses connected and the average load on the grid is stable, the same grid load profile is used in every test. In the tests, the grid load peak has been avoided as good as possible. The most important is to not affect the end user, and make sure the hot water tank does not store bacteria. In the beginning, some tests were made before the thyristor were installed to compare the tests to each other. Since the average water consumption for a household is around 190 liters each day, each test empties the tank for this amount of water, but in different intervals. From research, the largest consumption is in the morning and in the evening, therefore the tank empties most water in these timeframes in every test. As the highest grid load is in the same interval, the heating element avoids these intervals as far as possible. The minimum temperature is also set for 60 °C and when the temperature is below, the program is set to turn on the heating element until the water is 5 °C above Tmin. Tmax is set to 95 °C due to high pressure if the water goes above this. When the temperature reaches Tmax, the PV produced power is delivered to the grid instead of to the heating element.

5.1 Test 1

This test was done before the thyristor was installed and the test was started in the morning at 10:00. At this point the labview program raised Tmin to 65 °C when there was PV production over 100 W. For PV production over 500 W, Tmin was raised to 70 °C.

As shown in figure 44 a, the temperature is stable at 60 °C until the valve is opened. In figure 44 b, the 3 valve openings in this test is shown, the first time it empties the tank for 20 litres, the second time 30 litres and the third time 80 litres. The parameters for test 1 are shown in table 2.
With this setup the heating element used a lot of power from the grid in the peak period. Figure 44 d shows the heating element power and figure 44 e shows a grid profile for an average household.

Table 2 Parameters for test 1.

Time	42 hours
Tmin	60
Tmax	95
Valve open during day	60 seconds
Valve open evening	240 seconds
Valve during day	90 seconds

During the night, it was still possible to increase Tmin to reduce the power needed in the morning when there is high water consumption. During the day when the PV panels produced power, it was not possible to heat the water without the grid. As shown in figure 44 c, the PV power varied from 0 to 700 W. With this production, it was needed 1250 to 1950 W from the grid. There were also some network problems with AMS and it was disconnected. It had to be reinstalled and were repaired for further tests.

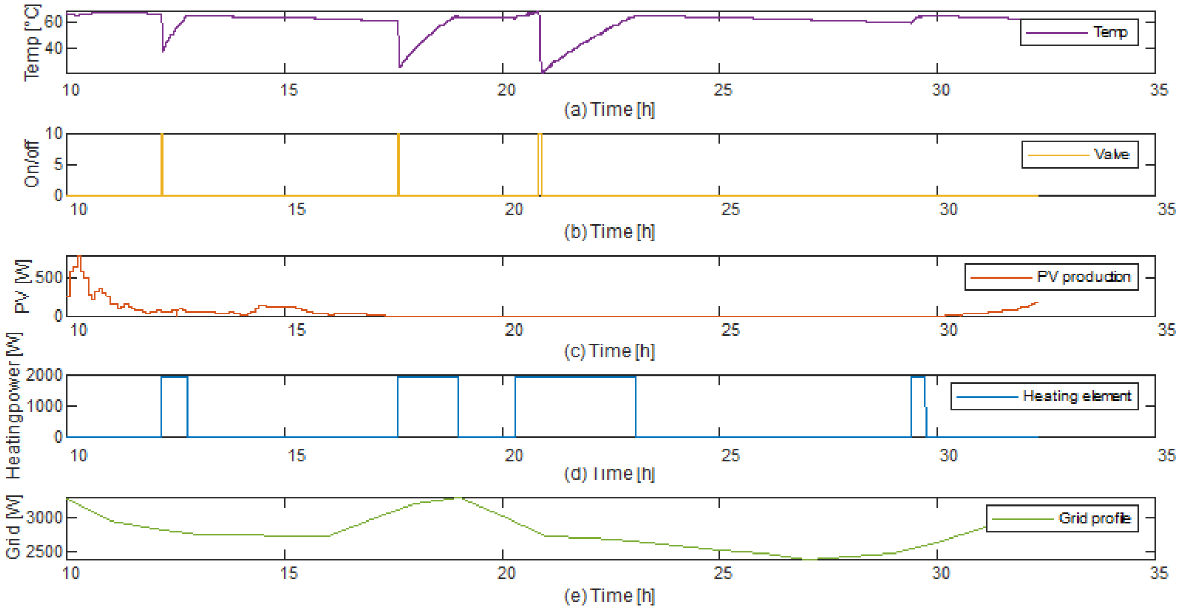


Figure 44 Results before the thyristor was installed, test 1.

5.2 Test 2

To look at the solar potential, the production was logged over 1 week. From PVGIS the average PV production in April is 4.7 kWh [13]. Figure 45 shows the production for the 4 PV panels which is installed for this system. The average production through this sunny week was 6.3 kWh each day. This is high, but it shows the potential for energy production and there is energy which could be stored. If this energy can be controlled and used when needed, the load on the grid can be reduced of the same amount of power. While the PV production was logged, the thyristor controller was installed for further tests.

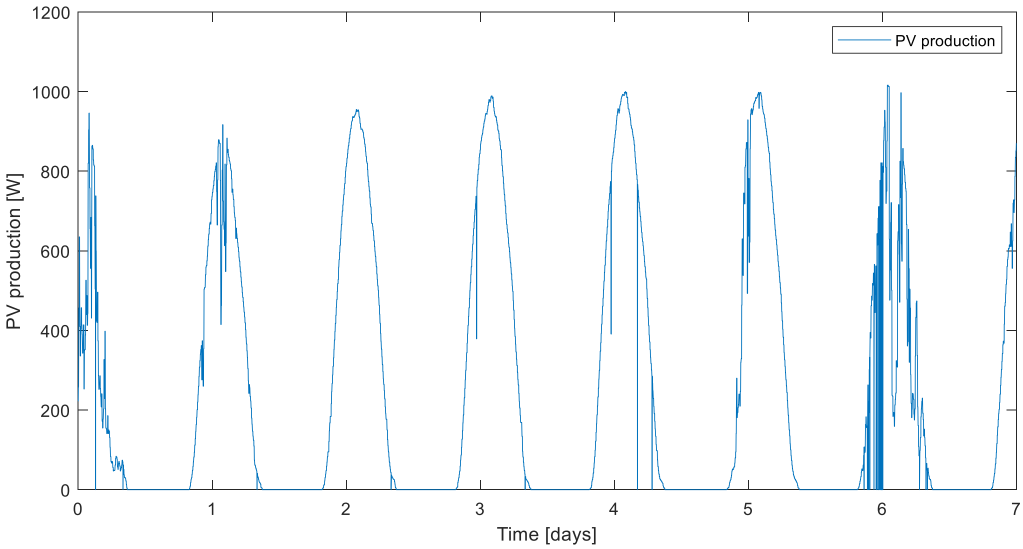


Figure 45 Results of self-produced PV power over a week, test 2.

5.3 Test 3

In this test the thyristor controller was installed. At a sunny day it was tested to heat the water only with the power from the PV panels and without affecting the grid. Over 10 hours, the temperature raised from 12 °C to 52 °C as shown in figure 46 a.

In figure 46 b the PV production is shown, and the highest temperature raise is in middle of the day when the production in the PV power is between 900 and 1000W. With the formula from equation 36, the total energy stored as water for this day is calculated to 8.9 kWh. This result shows the PV production can't heat all the water itself above Tmin, because the production is too low, and the grid is also needed to heat it up. The AMS meter shows no power taken or delivered to the grid in figure 46 c.

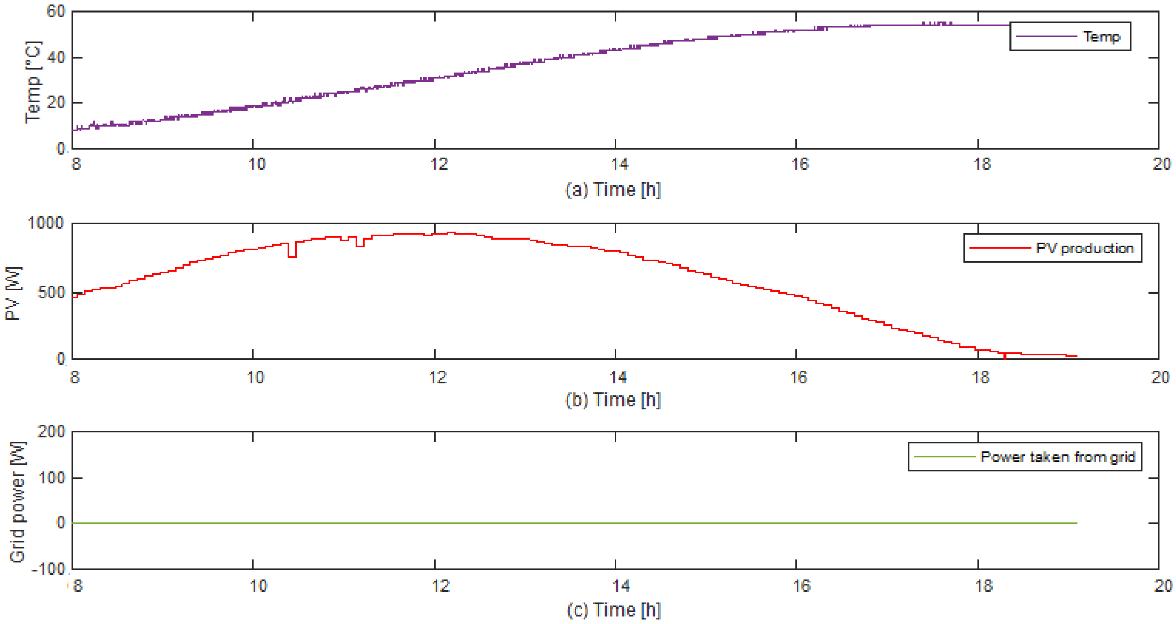


Figure 46 Temperature raise with self-produced PV-power, test 3.

5.4 Test 4

This test was going for 45 hours. The Tmin was set to 65 °C and Tmax to 95 °C. It started at 10:00 and there was just one small valve opening during the day, discharging the tank for 10 liters. The valve openings are shown in figure 47 b. In the evening there was a valve opening which discharged the tank for 80 litres. At this point the temperature decreased to 30 °C and the heating element was turned on to heat the water up to Tmin. Temperature during test 4 is shown in figure 47 a.

In the night, the Tmin was raised to 85 °C when the grid load was low. The valve then opened again in the morning discharging the tank for 80 litres. Due to low temperature, the heating element is turned on even if the grid load is high. The heating element power is shown in figure 47 d.

During the day when there is good PV production, the water is heated only with this self-produced energy. Figure 47 c shows the PV production and figure 47 a show the temperature raise to around 95 °C. At this point some energy is delivered to the grid due to avoid high pressure in the tank. There are also 2 small valves opening discharging the tank for 10 litres each time. The temperature is high here and no energy from the grid is needed. The parameters for test 4 are shown in table 3.

In the evening the valve is turned on, discharging the tank for 80 litres. The heating element is turned on until the water temperature reached Tmin.
The last time the heating element was turned on, this test was during the night to increase Tmin to the next morning.

The first 21 hours, the tank was emptied for 90 litres. The next 24 hours, the tank is emptying for 180 litres which a normal water consumption for a household. The heating element is only turned on for 1.39 hours the first day and 5.7 hours the other day. The heating element avoids the grid load peak in the evening, but in the morning the temperature gets too low due to long valve opening and need some power from the grid.

Table 3 Parameters for test 4

Time	45 hours
Tmin	65
Tmax	95
Tmin from 03:00-06:00	85
Valve open morning	240 seconds
Valve open evening	240 seconds
Valve during day	90 seconds

Figure 47 shows the temperature in the tank, the valve openings, the PV production, the heating element and how much power it is turned on with, and the average grid consumption.

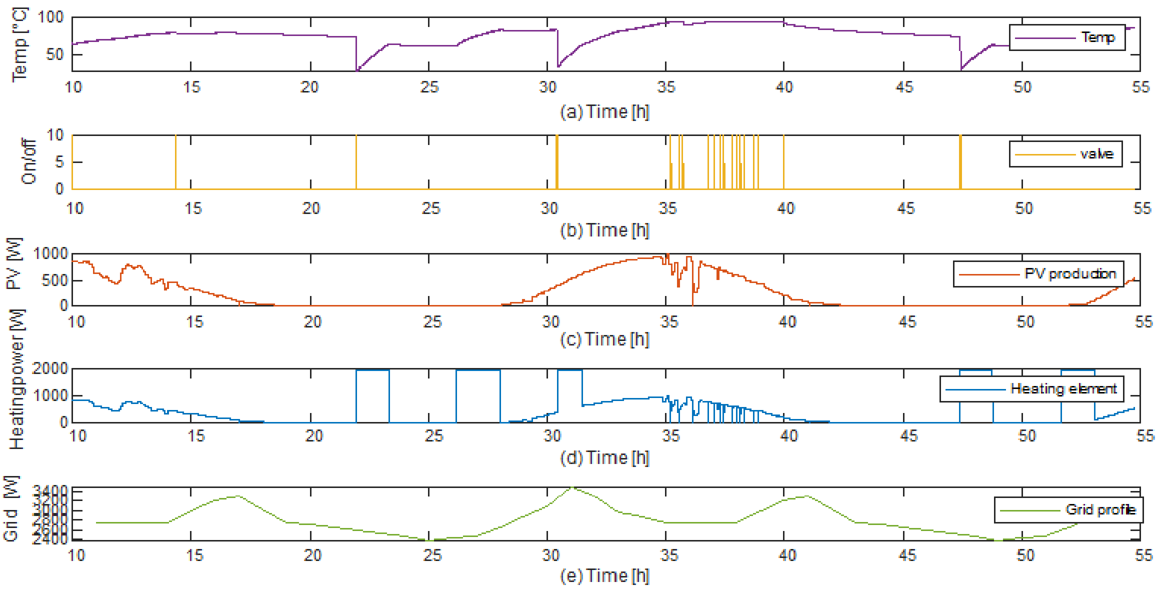


Figure 47 Results for test 4.

In table 4, it shows how much power is taken from the grid. The first interval, all the power is taken from the grid because of no PV production. The water is heated up during the day which reduce the power needed at this time to reach the Tmin.

The second interval is in the night to raise the Tmin and at this time the grid load is low.

The third interval is in the morning after a long valve opening. Here the temperature is high because of the Tmin raise in interval 2. Due to some PV production the grid is charged with 450 W less and the average power taken from the grid is 1500 W.

The fourth interval is similar to the first where there is a valve opening in the evening and the heating element is turned on to heat the water above Tmin.

The fifth interval is similar to the second one where Tmin is raised during the night to increase starting temperature for the morning.

Total water usage for this test was 270 litres and 12.4 kWh are taken from the grid to heat the water. From equation 36, to heat 270 litre of water, 18.1 kWh is needed which means 5.7 kWh have been produced with the PV system and stored. This is shown in the table below.

Table 4 Test results for test 4.

Interval	Time [hours]	Mean power taken from grid [W]	Total energy taken from grid [Wh]
1	1.39	1950	2710.5
2	1.89	1950	2685.5
3	1.06	1500	1590
4	1.35	1950	2710.5
5	1.41	1930	2721.3
	Total		**12417.8**

In figure 48, it is shown the heating element power (a) and a grid load profile for an average household (b). Figure 48 (a) is the actual power taken from grid to the heating element. Between hour 35 and 40 there is negative values because it delivers power to the grid. The second graph show the average energy consumption for a household.

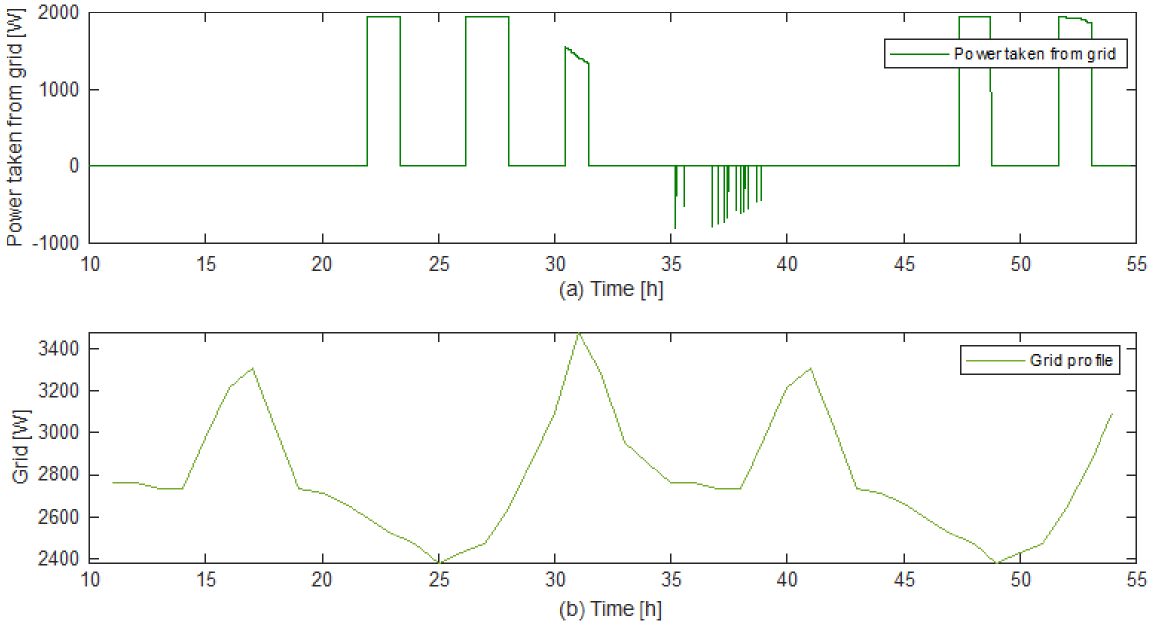


Figure 48 Energy taken from grid and grid profile from test 4.

Test 4 is the first one with the thyristor controller installed and where a water profile for a household is simulated. The parameters are set to simulate a household with an average water consumption. The results show 5.7 kWh is stored as hot water and the grid load is reduced with the same amount of energy. There is still energy taken from the gird in peak periods because of low temperature.

5.5 Test 5

This test was started at 10:00 and ended at 02:00. As the starting temperature was low, the heating element was turned on until the water reached 60 °C. Some of the power came from the PV panels and some from the grid. The temperature during the test is shown in figure 49 a.

After the temperature reached 60 °C, the power from the PV production continued to heat up the water to around 80 °C before the valve was opened and emptying the tank for 10 litres at 15:30. There is a drop in the temperature after the small valve opening to around 70 °C, but the PV is heating it up to around 80 °C again. There are three valve openings in test 5, and they are shown in figure 49 b.

Three hours later, at 18:30, the valve is opened for the second time and emptying the tank for 10 litres. Now the PV production is poor, and the temperature is not heated because there is high load on the grid in this period and the temperature is above Tmin. The PV production during the day is shown in figure 49 c and the power delivered to the heating element is shown in figure 49 d. Figure 49 e shows a gird profile for an average household.

In the evening the valve is opened for the last time and emptying the tank for around 80 litres. The temperature drops to around 30 °C and it is needed power from the grid to heat the water up again. This was a cloudy day with unstable PV production and still the temperature is raised to around 80 °C with 2 valve openings. The parameters for test 5 are shown in table 5.

Table 5 Parameters for test 5.

Time	16 hours
Tmin	60
Tmax	95
Valve open evening	240 seconds
Valve during day	30 seconds x2

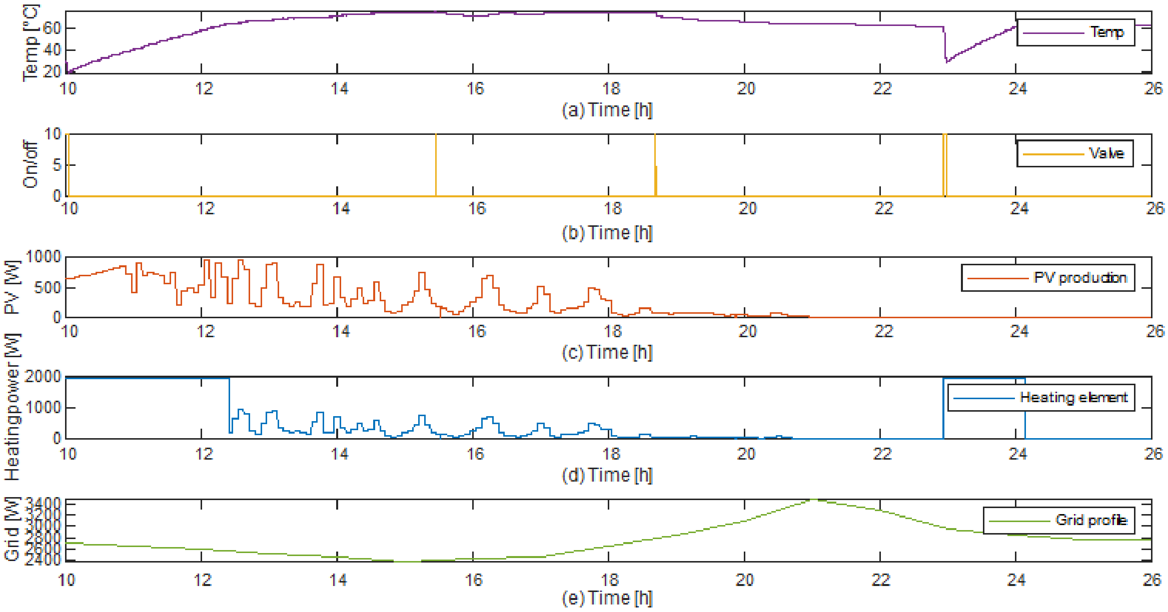


Figure 49 Results for test 5.

In table 6 it is shown how much power is taken from the grid. As the water started with low temperature the heating element was turned on for 2.41 hours with an average of 1250 W taken from the grid.

In the evening the heating element was turned on for 1.2 hours until the temperature reached Tmin.

Total water usage for this test was 90 litres and 5.3 kWh are taken from the grid to heat the water. As all the water also needed to be heated from 31 °C to 60 °C in the start. Total 90 litres are emptied, and 194 litres is heated from 31 to 60 °C. The energy needed for this is 11.6 kWh. This means the PV produced energy stored as hot water this day was 6.3 kWh. This is shown in table 6.

Table 6 Results for test 5.

Interval	Time [hours]	Mean power taken from grid [W]	Total energy taken from grid [Wh]
1	2.41	1250	3020
2	1.20	1950	2347.6

	Total	**5367.6**

Figure 50 shows the heating element power taken from grid (a) and a grid profile for an average household (b). Figure 50 a is the actual power taken from grid to the heating element. No power is delivered back to the grid in this test because the temperature in the tank never reached Tmax.

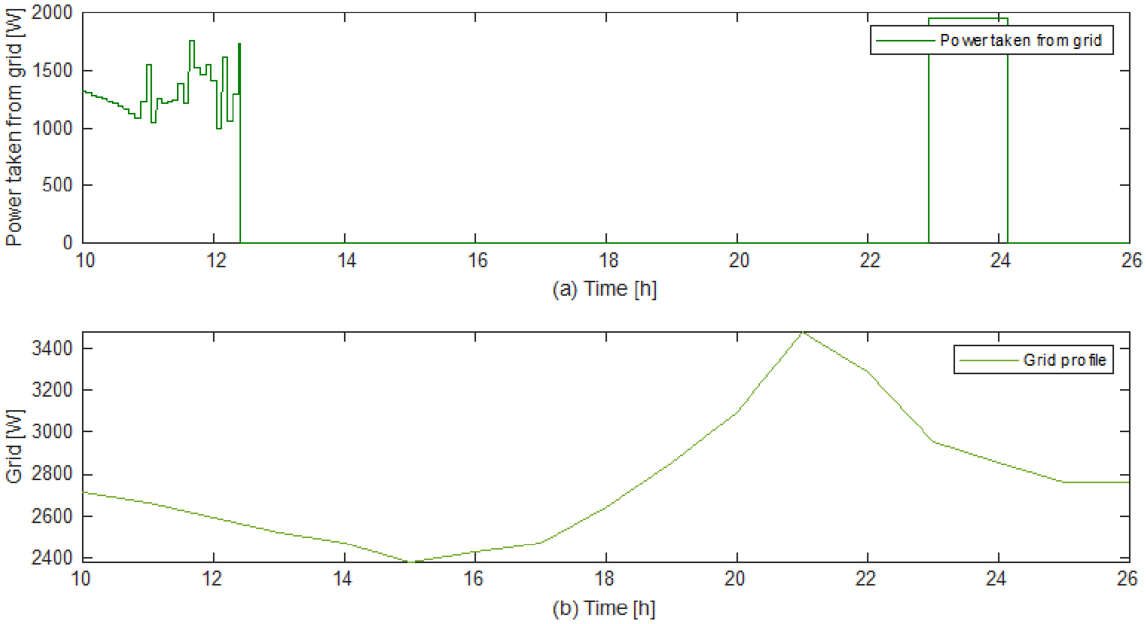


Figure 50 Energy taken from grid and grid profile from test 5.

This test was done to simulate a lower water consumption. From the graphs, it shows that energy still is needed in grid load peaks.

5.6 Test 6

Test 6 was started at 05:00 in the morning and lasted for 24 hours. The temperature started at 60 °C and the Tmin was raised to 85 °C due to low grid load. The tank used 111 min to heat the water up to 85 °C. There was also some PV production which increased the temperature to almost 90 °C. The temperature during the test is shown in figure 51 a.

After 6 hours when the clock was 11:00 the valve was turned on, discharging the tank for 70 litres. All the valve openings are shown in figure 51 b. The temperature dropped below Tmin to around 35 °C and was heated up as the heating element was turned on with full power until Tmin was reached. It used 53 minutes to reach Tmin and as shown in figure 51 c, the PV production was between 600 to 1000W, and the average power taken from grid was 1180 W.

In the middle of the day it was 10 small valves opening, emptying the tank for total 50 litres. There was enough PV production to heat the water without the grid at this point. In the evening there were two valve openings. The first one made the temperature drop to 55 °C and the heating element was turned on for 21 minutes to heat it up again. The average power taken from the grid was 1925 W.

The last valve opening this day, discharged the tank for 70 litres and dropped the temperature to 25 °C. At this time, there was no PV production and all the power were taken from the grid to heat the water up again. This time the heating element was turned on for 76 minutes and all the power was taken from the grid. The power delivered to the heating element is shown in figure 51 d. In figure 51 e a grid profile for an average household is shown to compare the power delivered to the heating element and the grid peak.

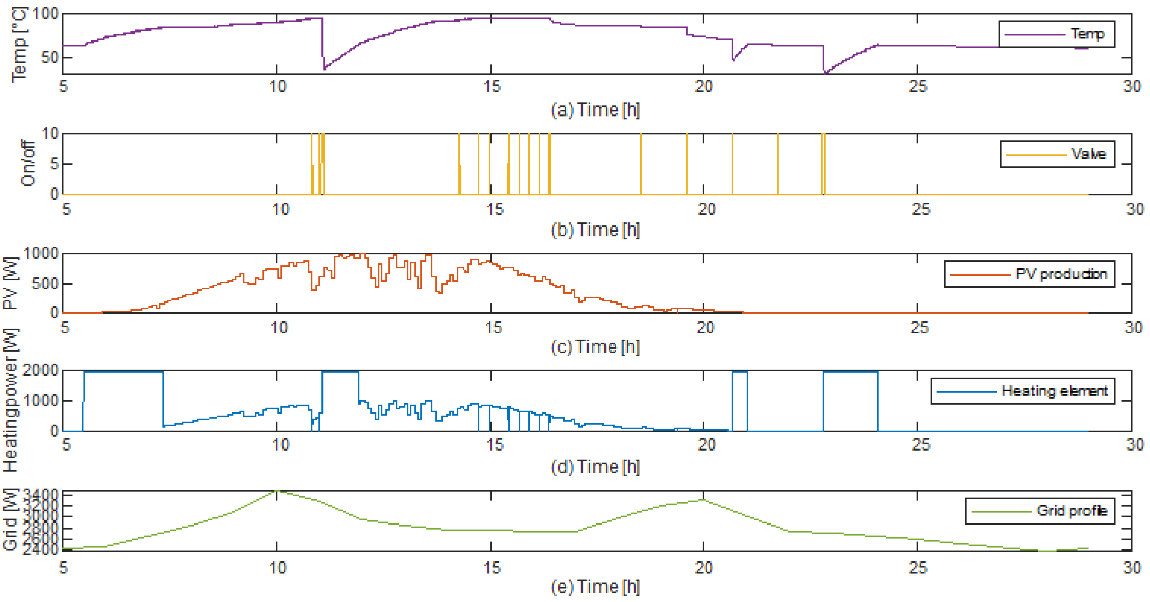


Figure 51 Results for test 6.

Table 7 shows the power taken from the grid. There were four intervals where the heating element was turned on with full power due to low temperature.

In the first interval the heating element was turned on for 1.85 hours, increasing Tmin before high water usage in the morning.

In the second interval, the heating element was turned on for 0.88 hours in the grid load peak period due to low temperature. The PV production was high, and the average power taken from grid was 1180W.

In the third interval the temperature was turned on for 0.35 hours due to low temperature. The water was quick heated to above Tmin.

The fourth interval is when there was a large valve opening and the temperature decreased to 25 °C. The heating element was turned on for 1.27 hours before the temperature reached Tmin.

Total water usage for this test was 190 litres and 7.8kWh is taken from the grid to heat the water. To heat 190 litres to 65 °C, 13.0 kWh is needed. In this test it means 5.2 kWh is produced and stored as hot water.

Table 7 Results for test 6.

Interval	Time [hours]	Mean power taken from grid [W]	Total energy taken from grid [Wh]
1	1.85	1950	3607.5
2	0.88	1180	1038.4
3	0.35	1925	673.7
4	1.27	1950	2476.5
	Total		**7796.1**

In figure 52, it is shown the heating element power (a) and a grid load profile for an average household (b). Figure 48 (a) is the actual power taken from grid to the heating element. At 11:00 and between hour 14:30 and 17:00, there is negative values because it delivers power to the grid. The second graph show the average energy consumption for a household.

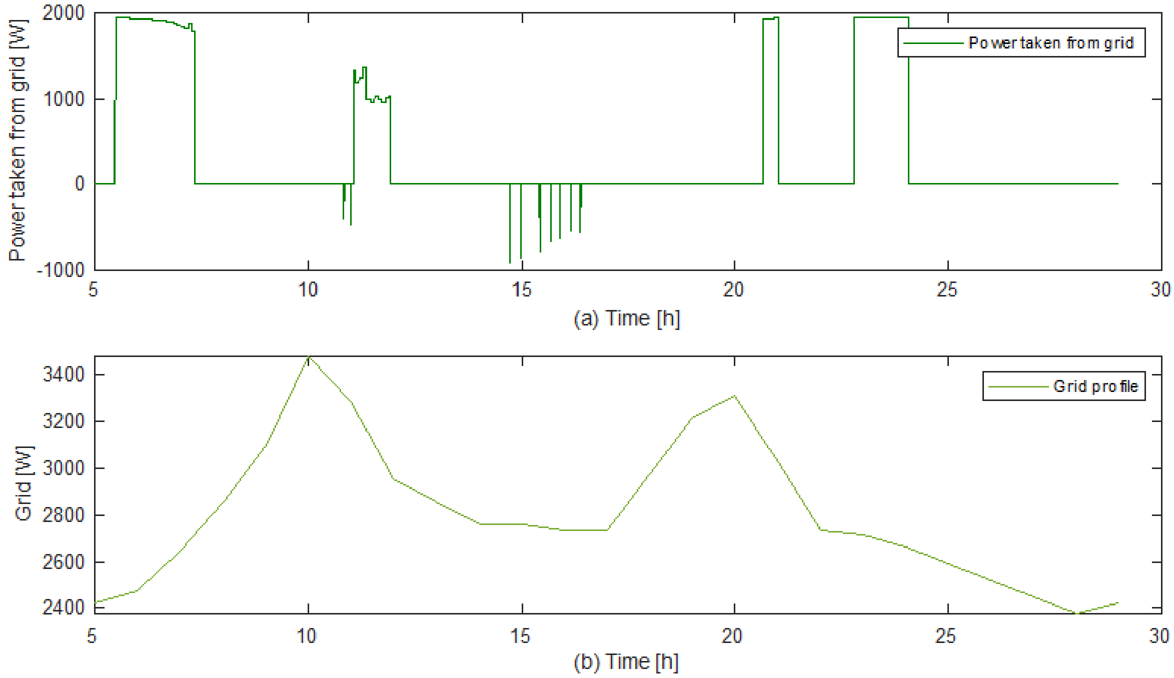


Figure 52 Energy taken from grid and grid profile for test 6.

In this test, there is needed a lot of energy in the grid load peak. There have been done 3 tests with different intervals and different water consumptions after the thyristor is installed. Even when the PV production is good, there is not possible to avoid grid load peaks. After these tests, the program is changed for test 7.

5.7 Test 7

Test 7 lasts for 45 hours, and before it was started, some changes were done in the labview program. From previous tests, it is known that the heating element is turn on for shorter intervals in the grid peak because the water is pre-heated during the night and during daytime with PV production. Now a new constrain is inserted, and the heating element will not use more than half the power in grid peak periods. This means in the morning between 06:00-10:00 and in the evening between 18:00-22:00, maximum power taken from the grid is $\frac{1950\,W}{2} = 975\,W$.

This test was stared 19:00 and the temperature started at 60 °C. To simulate a household the valve was first opened in the evening and emptying the tank for 80 litres. As this valve opening was in a grid load peak, the heating element was turned on with half power, even the temperature was low. The temperature in the DHWH during test 7 is shown in figure 53 a and the valve openings is shown in figure 53 b.

The heating element was on with half power until 22:00 when the grid load is lower and then it turned on with full power until the temperature reached 60 °C. Like the previous tests, it was turned on again during night to raise the starting temperature for the morning. The power delivered to the heating element is shown in figure 53 d.

In the morning the valve was opened and discharging the tank for 80 litres. As this is in a grid load peak, the heating element was turned on with half power. The PV production had also started for the day, and the power taken from grid is between 450 and 50 W. The valve openings during test 7 are shown in figure 53 b and the PV production is shown in figure 53 c.

During the day, the valve is opened 6 times discharging the tank for 9 litres each time. Because of high PV production, no load from the grid is needed.

In the evening 80 litres are discharged again, and the temperature decrease below Tmin. The heating element is turned on with half power again because it is in a grid load peak.

During the night Tmin is raised to 85 °C and the heating element is running for full power. The starting temperature for the last day is high, and the tank is discharged for 80 litres. As the PV production is poor, almost all the power delivered to the heating element is taken from the grid. The heating element is running for half power as it is grid load peak. The parameters used in test 7 is shown in table 8.

Table 8 Parameters for test 7.

Time	45 hours
Tmin	60
Tmax	95
Valve open morning/evening	240 seconds or 80 litres
Valve during day	27 seconds each time or 9 litres
Heating element power reduced to half	06:00 to 10:00 18:00 to 22:00

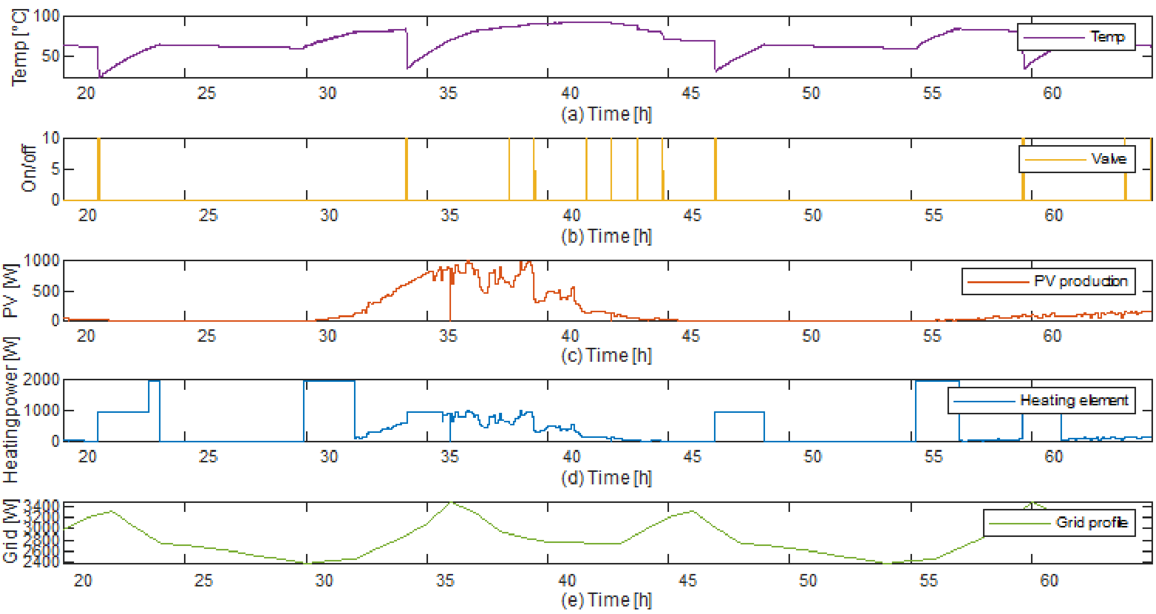


Figure 53 Results for test 7.

Figure 55 show the heating element power (a) and a grid profile for an average household. Figure 55 a is the actual power taken from grid to the heating element. As figure 55 a and b shows, the heating element is using max 975 W in grid load peaks to reduce the peak. In the first morning there is less than 450 W taken from grid due to good PV production. In the second morning the PV production is close to 0, and almost all the power is taken from the grid. In low grid load periods, the heating element is running with full power.

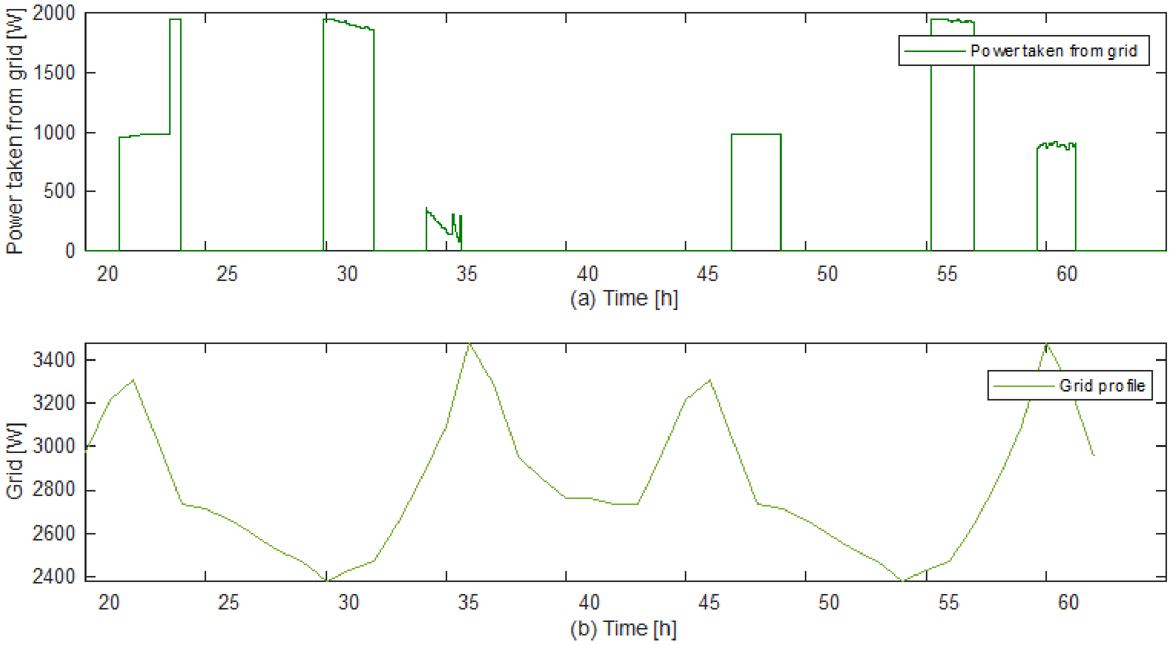


Figure 54 Energy taken from grid and grid profile for test 6.

The average and total power taken from the grid is shown in the table below. Total water usage for this test was 374 litres and 14.1 kWh are taken from the grid to heat the water. To heat 374 litres to 60 °C, 22.9 kWh is needed. In this test it means 8.8 kWh is produced and stored as hot water. The power taken from grid in peaks is never higher than 975 W. This is shown in table 9.

Table 9 Results for test 7..

Interval	Time [hours]	Mean power taken from grid [W]	Total energy taken from grid [Wh]
1	2.14	975	2085
2	0.42	1950	823
3	2.12	1890	4013
4	1.48	310	455
5	2.06	975	2013
6	1.76	1910	3353
7	1.56	910	1416
	Total		**14158**

In test 7 the total energy stored is comparable to test 4, 5 and 6. The main difference is that the power taken from grid in peaks are reduced to half. This makes the power taken from the grid more even through the day.

6. Results and Discussion

6.1 Discussion

Tests two show that there is big potential in the PV production. The water profile and grid profile show when the grid load is high. The PV production during a day is starting early in the morning and ending in the evening. The grid load peak is in the morning after the PV production has started, and in the evening before the PV production has ended. In the middle of the day when the PV production is at its highest, the grid load is low. Therefore, all the energy is stored and used in the peak period in the evening.

Because of high water consumption in the morning, Tmin is turned up during the night at low grid load period to decrease the power needed in the grid load peak. Figure 47, 49, 51 and 53 shows that increasing the temperature during the night, reduce the power needed in the morning, but not enough when much water is discharged from the DHWH. The heating element is turned on even in the grid load peak period to avoid temperature below Tmin in the first 6 tests. Since the PV production already has started, the heating element uses less than 1.95 kW depending on the sun conditions. From these test results and PV production graphs, it is known that in the peak period in the morning, the PV production is between 30-50% of max installed capacity in sunny days. For this system it means 300-500 W is coming from the PV production and the rest is coming from the grid. In the morning grid peak period, the power taken from the grid is reduced with 300 to 500 W in test 1-6.

From the first test, the labview program was tested and without the thyristor controller it is not possible to utilize all of the self-produced PV power. It was possible to choose intervals to turn on the heating element and avoid some of the grid load peaks. Tmin was increased when there was PV production to heat the water without taking all the power needed for the heating element from the grid. After this test the thyristor was installed and meanwhile the PV production was logged and showed in test 2.

For the third test the thyristor was installed. The first test after the thyristor was to heat the water only with the power from the PV system. It shows that the power from the PV system is not enough to heat the temperature to above Tmin during a day. All the power from the PV system is utilized with the thyristor controller and stored as hot water. From this test it is known the grid is needed and a logic between the PV production, grid load peaks and temperature are set up for further tests.

The fourth test lasted for 1.5 day. The first day it was used 90 litres of water and the second day it was used 180 litres of water. To heat 270 litres of water to 65 °C, which was Tmin in this test, it requires 18.2 kWh and in this test 12.4 kWh was taken from the grid. This means the PV system heated the water with total 5.8 kWh. The heating element was on in the grid load peak in the morning, but due to some PV production the power taken from grid was reduced from 1950 W to 1500 W. The water was also heated during the day from the produced PV power to reduce the amount of power needed in the evening. In the second day, the temperature was heated from 65 °C to 90 °C only with the PV production. To increase the water temperature with 25 °C, which the PV power did, 5.6 kWh is required. This means the grid load will be reduced with the same amount of power.

The fifth test lasted for 16 hours were the temperature started at 31 °C. In this test the heating element started on with an average power taken from the grid at 1250 W in the morning grid peak period. It was also turned on in the evening where all the power was taken from the grid. Total 5.3 kWh was taken from the grid. The tank was emptied for a total of 74 litres in this test which requires 4.5 kWh to heat up to 60 °C. Considering the water started at 31 °C, it also had to heat 194 litres to 60 °C which requires 4.5 kWh.

The sixth test lasted for 24 hours and total 7.8 kWh was taken from the grid. The tank was emptied for 190 litres, which require 11.6 kWh to heat from 7 to 60 °C. Here the grid peak in the morning was avoided as the starting temperature was high and due to PV production when the temperature was low, an average of 1180 W was taken from the grid. When there were 11 small valve openings in the day, the water was supplied only by produced PV power. In the evening the grid was needed due to low temperature and since there was no PV production all the power was taken from the grid.

The seventh test lasted for 45 hours, and before the test started some improvements were done in labview. Since the PV production varies from each day and even with good production much power is taken from grid, a constrain is made for the heating element. In grid load peaks, the heating element is only running for half power, regardless of the temperature. This reduce the power taken from grid to between 50-975 W depending on the self-produced PV power. During the test, 8.8 kWh is stored as hot water, and the power taken from grid is reduced to half in grid load peaks.
The average power used in a household is between 2400 and 3500 W. By reducing the power taken from grid to between 975 and 50 W in grid peaks, like in test 7, the average consumption will be reduced to between 1600 and 2525 W and the grid load will be more even. The grid load can be reduced with minimum (975/3500) W = 27.9% and maximum (1900/3500) W = 54.3% in grid peaks with this setup in labview.

6.2 Reflections

One way to avoid the grid load peaks, is to install more PV power. If the production is 500 W in grid load peak, like in some of the tests, it would need 4 times more installed PV power to avoid taking power from the grid. A system with 4 kW installed could possible deliver all the power needed for a hot water tank in the load grid period in the morning. Nevertheless, it will have high production in the middle of the day which will force this system to deliver power to the grid. For a normal house, this power will be used in other appliance, still, some of the power may be delivered back to the grid based on energy consumption in the household. Another way to increase the power produced in the morning and the evening, and have a smoother production, could be to turn the panels east-west instead of south.

The grid load profile for an average household varies from 2400 to 3500 W. From research, the DHWH uses 15-20% of the total energy, and the water consumption is high in grid peak periods. The DHWH is affecting the grid peaks and is one of the reasons the grid load is peaking in morning and evening. By reducing the heating element power in peaks and rather heat the water during night and with self-produced energy during the day, it would be a smoother consumption during a day.

The hot water tank is available in different sizes, 115 litres with 1.95 kW, 194 litres with 1.95 kW or 3 kW, and 285 litres with 3kW. The tank with 115 litres with 1.95 kW would heat the water up faster as the volume is lower, and the power could be reduced in grid peak periods for this water tank. With the tank which has 3 kW and 194 litres, the power could be reduced to 1.95 kW in grid peak periods as for the other model with 1.95 kW max. The model with 285 litres has a bigger volume and therefore needs more power to heat the water up with same amount of time.

There are many sensors and controllers installed in this system, which means there is many potential errors. The first one is the temperature sensor. The whole system is based on this value. Since the water has different temperature at different places inside the tank, the sensor is installed where the water is coldest. When the inlet water reaches the Tmin, the heating element is turned off. Still there is some increase in the temperature because the hot water will mix with the cold. The water is entering with around 7 °C and mixed with the water which can be up to 95 °C. At the same time, it is heated and then there will be some inaccuracies. Because the sensor is installed in the bottom of the tank, the water is heated up more than needed, but it is done to be sure there will be no bacteria and it will not affect the end user.

The thyristor installed are controlled from 0-10V. The margin is 3% which means it can deliver power up to 29.5 W more or less than it should. It also uses 2 W and together with the precision the heating element will be less efficient than without a thyristor controller.

In the tank there are installed temperature sensors and other sensors for previously tasks. This occurs to heat loss and is making the tank less efficient. The efficient was measured to be 4.32 kW which is high.

The valve openings are based on water profiles where mostly of the water are used in the morning and the evening which can be different for households. For more accurate profile this should be measured in some houses over longer time.

The grid load profile is taken from Norcool which controls the energy price and has statistics over energy consumption. This profile is accurate for average consumption but can be different for households. It is also based on consumption from hour to hour and for more detailed test it should change for each second. These values are taken from January in Agder. It will vary from month to month as most of the power goes to heating, the energy consumption is higher in the winter compared to the summer because of the outside temperature in the summer.

7. Conclusion

In this thesis, a domestic hot water heater was built with sensors and controls to simulate tests similar to a household. The main focus was to obtain reduction on demand side power peaks without affecting the end user. The domestic hot water heater should store as much of the produced energy as possible rather than deliver the energy back to the grid. The energy is stored as hot water. A domestic hot water is installed on almost every household and uses 15-20% of the total energy. By controlling when the heating element is turned on and heating the water during daytime with produced renewable energy, the demand side power peaks can be reduced.

From previous research thesis the domestic hot water heater is turned on and off based on grid power peaks. It was also turned on in periods when there was PV production, to reduce some of the demand side energy needed. By installing new controls, the labview system could be redesigned and utilize all the produced PV energy. During the daytime when the PV production is high and water consumption is low, all the energy is stored until the evening when the water consumption is higher. Since the water consumption also is high early in the morning when there are poor PV productions, the temperature in the tank is raised during the night when demand side power peaks are low.

In the first test, the system was running without the thyristor controller. Here it is shown how the heating element is turned on outside demand side power peaks and the temperature is raising. After this test the PV production was logged over a week while the thyristor controller was installed. The PV production was higher than expected and shows is a huge potential. With the thyristor controller installed, the water was heated over a day only with the produced energy. The water was heated to almost 60 °C which means it stored 8.9 kWh as hot water. The three following tests have different water profiles, PV production and duration time. It is discharging the tank for the same amount of water as an average household. The results in test 4,5 and 6 shows the demand side power peaks are reduced, but as there is only 1 kW installed PV power the demand side is still needed to heat up some of the water. As the temperature is raising during the night, the time interval for the heating element in the morning is shorter. There is also some PV production which reduce the demand side power needed. During the day the temperature is raising which makes the time interval for the heating element in the evening shorter.

With some improvements before test 7 was running, the power taken from grid in peaks was reduced to between 50-975 W depending on the PV production, which are less than half compared to test 1 before the thyristor was installed. When the PV production was at its highest, the grid load was reduced with 1900 W in peak period. The grid was reduced with 27.9 to 54.3 % power in gird peaks depending on the self-produced PV power and compared to the average grid power of 3500 W. Total 8.8 kWh was stored as hot water in this test.

As the prices will change with the demand side power in the future, this will benefit customers as much as grid operators. As there is still unknown how the prices will change, this thesis assumes they will follow the energy consumption profile. The controller is designed and can be implemented in a household for further tests and more accurate water- and energy consumption profile. With the labview, PV system and sensors/controls it is possible the reduce the demand side energy.

8. Further work

The physical model is built together with the labview model. Because of some parts needed to be ordered and installed in the system, and a new labview model needed to be designed, the testing started in April. Each test normally lasted for at least 1 day, and due to short time, there were only 7 tests done. Below there are some suggestion for improvement of the system.

- A sensor for valve opening and heating element could be installed in a household to compare the lab tests with a real water and electricity consumption.

- The whole system could be implemented in a household.

- Better water consumption profile and measuring for an actual house.

- The labview program could be changed to use real time and date for more accurate tests.

- There were some issues with the PV wifi connection, which turned the thyristor controller off. Wire connection instead of wifi would make it more accurate.

- The DAQ module connected to the thyristor could be changed and controlled with 4-20mA.

- Try the system with another domestic hot water heater as there are many different variants.

- In some tests the computer had problems logging all the values. The logging can be changed to log fewer values.

- Install more PV panels to increase production.

- The system can be tested over one year to look at the differences in the spring, summer, autumn and winter.

9. List of References

[1] Hafslund, “Hafslund.no,” 2019. [Online]. Available: https://www.hafslundstrom.no/strom/privat/stromforbruk/2025. [Accessed 10 03 2019].

[2] G. H. J. P. Peter Kepplinger, “Field testing of demand side management via autonomous optimal control of a domestic hot water heater,” illwerke vkw Professorship for Energy Efficiency, Vorarlberg University of Applied Science, Dornbirn, Austria, 2016.

[3] Statnett, “Statnett,” [Online]. Available: https://www.statnett.no/for-aktorer-i-kraftbransjen/tall-og-data-fra-kraftsystemet/. [Accessed 05 02 2019].

[4] LOS, “LOS,” [Online]. Available: https://www.los.no/kundeservice/strompris/historiske-strompriser/. [Accessed 05 03 2019].

[5] R. S. Y. N. Ebby Thomas, “Towards demand side management control using household specific Markovian models,” School of Information Technology and Electrical Engineerin, Queensland, Australia, 2018.

[6] H. LØVIK, “Prisen på solcellepanel har stupt - men nå blir det ikke stort billigere i Norge,” Solenergi, Oslo, 2018.

[7] Enova, “Enova.no,” [Online]. Available: https://www.enova.no/privat/alle-energitiltak/solenergi/el-produksjon-/. [Accessed 10 03 2019].

[8] norsk solenergiforening, “solenergi.no,” 07 03 2019. [Online]. Available: https://www.solenergi.no/nyhet/2019/3/7/nye-soltall-gir-grunn-til-smile. [Accessed 2019 03 2019].

[9] elbilforeningen, “ABC,” 14 01 2019. [Online]. Available: https://www.abcnyheter.no/motor/bil/2019/01/14/195491699/antallet-elbiler-i-norge-har-eksplodert. [Accessed 10 03 2019].

[10] NVE, “NVE.no,” 24 09 2016. [Online]. Available: https://www.nve.no/nytt-fra-nve/nyheter-energi/stromnettet-er-klar-for-elbilene/. [Accessed 19 03 2019].

[11] Statnett, “statnett.no,” 07 11 2017. [Online]. Available: https://www.statnett.no/om-statnett/nyheter-og-pressemeldinger/Nyhetsarkiv-2017/Statnett-25-ar-er-markedet-klart-for-nye-25-ar/. [Accessed 10 03 2019].

[12] G. H. M. P. J. P. Peter Kepplingera, “State estimation of resistive domestic hot water heaters in arbitrary operation modes for demand side management,” Illwerke VKW Professorship for Energy Efficiency, Dornbirn, Austria, 2018.

[13] PVGIS, [Online]. Available: http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php. [Accessed 01 02 2019].

[14] EnergiNorge, "EnergiNorge," [Online]. Available: https://www.energinorge.no/fagomrader/strommarked/sluttbruker/hvordan-forsta-stromregningen/. [Accessed 20 02 2019].

[15] A. L. Even Skaga, "Optimization of energy storage and utilization from solar cells and water," UiA, Grimstad, 2019.

[16] J. A. Mazer, SOLAR CELLS: An introduction to crystalline phovtovoltaic technology, Norwell, Massachusetts 02061: Kluwer Academic Publishers, 1997.

[17] H. Haberlin, Photovoltaics, System Design and Practice, Leichester: University of applied Sciences, 2012.

[18] R. Castro, "Data-driven PV modules modelling: Comparison between equivalent electric," Sustainable Energy Technologies and Assessments, Lisbon, 2018.

[19] W. G. L. S. M. L. Tao Ma, "An improved and comprehensive mathematical model for solar photovoltaic," Solar Energy, Shanghai, China, 2019.

[20] A. A. Roger Messenger, Photovoltaic System Engineering, Boca Raton: Taylor and Francis Group, 2007.

[21] Z. L. B. Z. W. A. H. Guidong Zhang, "Power electronics converters: Past, present and future," Faculty of Mathematics and Computer Science, Fernuniversität in Hagen, Germany, 2018.

[22] N. Mohan, Power Electronics, A First Course, Minneapolis, MN: John Wiley & Sons, Inv, 2012.

[23] P. P. V. U. A. K. M. E. I. Ç. Serkan Öztürka, "Operating principles and practical design aspects of all SiC DC/AC/DC," Artı Industrial Electronics Ltd, Ankara, Turkey, 2018.

[24] T. M. U. W. P. R. Ned Mohan, Power Electronics, Converters, applications and design, Minnesota: Department of Electrical Engineering, 2003.

[25] A. Ahmed, Power Electronics for Technology, Ohio: Purdue University-Calumet, 1999.

[26] D. W. Hart, Introduction to power electronics, Valparaiso, Indiana: Prentice-Hall, 1997.

[27] L. F. Cabeza, Advances in Thermal Energy Storage Systems, A volume in Woodhead Publishing Series in Energ, 2015.

[28] CTC, *CTC FerroTerm og CTC heat injection,* Årnes: CTC, 2018.

[29] Nordpool, "Nordpool.com," [Online]. Available: https://www.nordpoolgroup.com/Market-data1/Dayahead/Area-Prices/SYS1/Monthly/?view=table. [Accessed 31 01 2019].

[30] L. A. J. S. E. Fuentes, "A review of domestic hot water consumption profiles for application insystems and buildings energy performance analysis," Catalonia Institute for Energy Research, IREC, Barcelona, Spain, 2018.

[31] J. T. Y. J. J. S. R. Y. S. S. S. M.-J. Z. Jie Xua, “High temperature water activity as a key factor influencing survival of Salmonella Enteritidis PT30 in thermal processing,” Qingdao University, Qingdao, Shandong, China, 2019.

[32] M. B. W. H. T. a. T. K. R. Quentin Grafton, “Determinants of residential water consumption: Evidence and analysis from a 10-country household survey,” 2011.

[33] D. M. I. R. L. P. A. R. M. P. Tomislav Pavlovića, “Possibility of electricity generation using PV solar plants,” Renewable and Sustainable Energy Reviews, Serbia, 2013.

[34] CTC, “CTC,” 2017. [Online]. Available: http://www.ctc.no/product/ctc-ferroterm/. [Accessed 27 03 2019].

[35] Solcellespesialisten, “Solcellespesialisten.no,” [Online]. Available: https://solcellespesialisten.no/solcelleanlegg/solcellepanel-til-hus-med-solcellepanel-pa-taket/nokkelferdige-solcelleanlegg-med-montering/solcellepanel-til-hus-med-solcellepanel-pa-taket.html. [Accessed 03 04 2019].

[36] PV education, “PV education,” 2019. [Online]. Available: https://www.pveducation.org/pvcdrom/solar-cell-operation/solar-cell-structure. [Accessed 19 03 2019].

[37] Seaward, “http://www.seaward-groupusa.com/userfiles/curve-tracing.php,” 2019. [Online]. Available: http://www.seaward-groupusa.com/userfiles/curve-tracing.php. [Accessed 28 03 2019].

[38] studystuffz, “studystuffz,” 08 02 2014. [Online]. Available: http://studystuffz.blogspot.com/2014/02/power-electronics-introduction.html. [Accessed 29 03 2019].

[39] RMKCET, “RMKCET,” 2018. [Online]. Available: http://rmkcet.ac.in/eee/Notes/PowerElectronics/PowerElectronics.pdf. [Accessed 21 02 2019].

[40] M. M. M. S. Ms. G. Swapna, “POWER ELECTRONICS,” GokarajuRangaraju Institute of Engineering &, BACHUPALLY, MIYAPUR, HYDERABAD, 2018.

[41] International Journal of Scientific & Engineering Research, Volume 3, Issue 11, November-2012 1, 1 11 2012. [Online]. Available: https://www.ijser.org/paper/Design-of-Microcontroller-Based-Static-VAR-Compensator.html. [Accessed 15 02 2019].

10.Appendices

10.1 PV panels

Figure 55 shows the label of the PV panel. The panels are 250W, polycrystalline technology.

REC REC Peak Energy Series
REC250PE Q2
Serial Number: FCB-2004908405

Phone: +65 6495 9001
Fax: +65 6495 9050
http://www.recgroup.com

Peak Power (Pmpp)	250 W
Rated Voltage (Vmpp)	30.2 V
Rated Current (Impp)	8.30 A
Open Circuit Voltage (Voc)	37.4 V
Short Circuit Current (Isc)	8.86 A
Maximum System Voltage (UL 1703)	600 V
Maximum Series Fuse (DC) (UL 1703)	15 A
Fire Rating	Class C
Design Load (UL1703)	75.2 lbs/ft^2 [33.4 lbs/ft^2]*

At STC 1000 W/m^2 AM1.5, Cell Temp 25°C

For IEC:

Maximum System Voltage	1000 V
Maximum Series Fuse (DC)	25 A
Application Class	Class A
Maximum Load	5400 Pa [2400Pa]*

*) see installation manual

- IEC 61215
- IEC 61730
- Qualified, Heavy Accumulation (5400 Pa) Of snow and ice

Safety Class II Equipment

Manufactured: **16.02.2016**

Warning electrical hazard. This module produces electricity when exposed to light. Follow all applicable electricity safety precautions. Only qualified personnel should install or perform maintenance work on the module. Be aware of dangerous high DC voltage when connecting or disconnecting modules. Do not damage or scratch the rear surface of the module. Do not handle or install modules when they are wet. Refer to installation and operation manuals before installing, servicing or operating this unit.

Avertissement: Risque de choc électrique. Ce module solaire produit de l'électricité lorsqu'il est exposé à la lumière. Respecter toutes les précautions de sécurité applicables. L'installation, la mise en service, l'entretien et la réparation du module, doivent être réalisés que par du personnel qualifié. Attention aux éléments sous haute-tension CC pendant la connexion ou déconnexion des modules. Eviter d'endommager la surface arrière du module avec des objets pointus. Ne pas manipuler ni installer les modules s'ils sont humides. Référez vous au manuel d'installation avant l'installation, l'entretien ou l'opération de cet unité.

CAUTION: DO NOT DISCONNECT UNDER LOAD
ATTENTION: NE PAS DECONNECTER SOUS TENSION
Made in Singapore by REC SOLAR PTE. LTD.
20 TUAS SOUTH AVENUE 14, SINGAPORE 637312, SINGAPORE

Figure 55 PV panels lable.

10.2 Matlab script

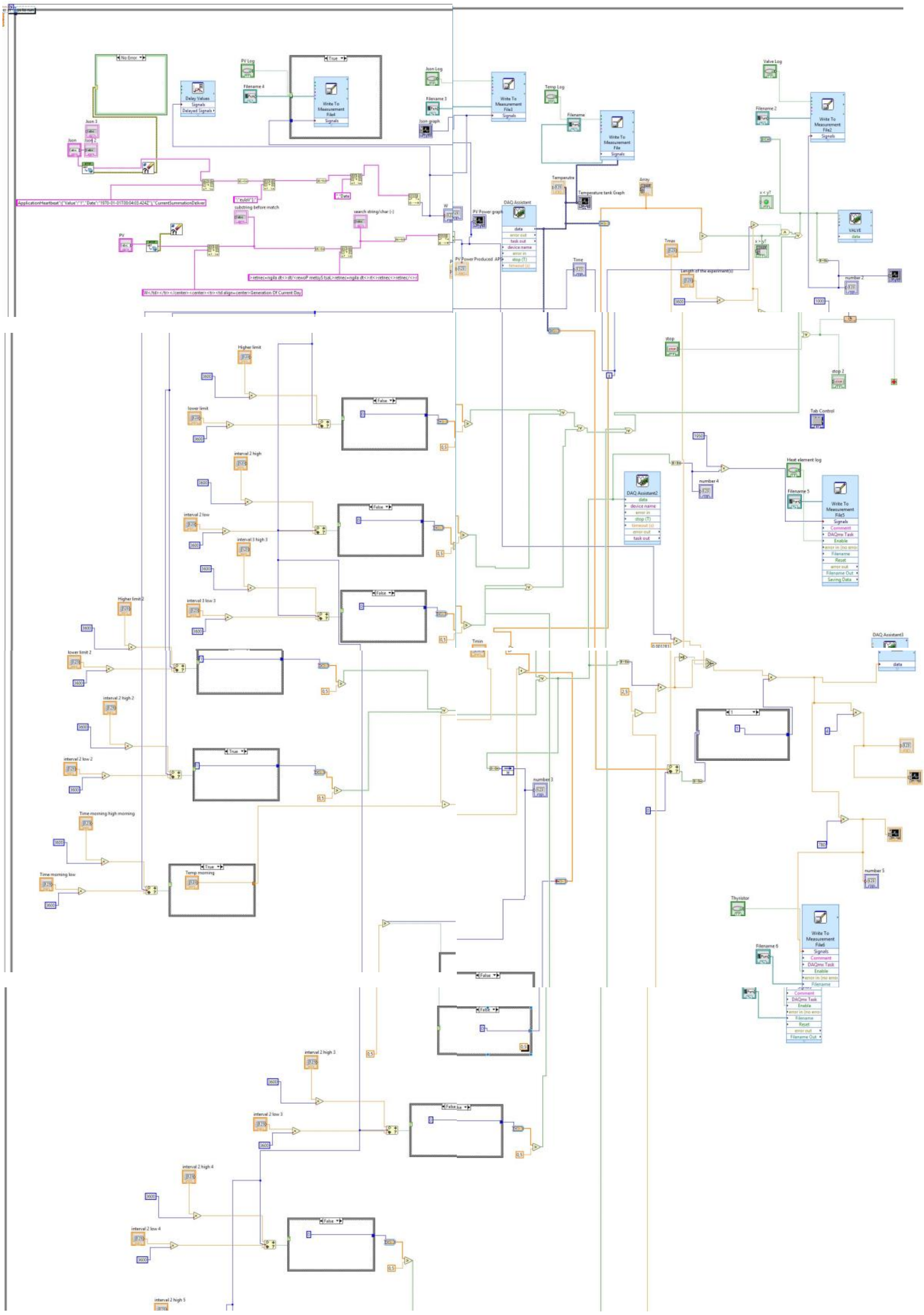
Below the matlab script is shown. There are some differences from the tests and for which results is being handled.

```
clear
close
clc

%load PV log
load PV_log.lvm
PV_time=(1/3600/24)*PV_log(:,1);
PV=PV_log(:,3);

%load Thyristor log
load Thyristor_log.lvm
Thyristor_time=(1/3600/24)*Thyristor_log(:,1);
Thryistor=Thyristor_log(:,3);

%load Heatingelement log
load Heatingelement_log.lvm
Heatingelement_time=(1/3600/24)*Heatingelement_log(:,1);
```

```
Heatingelement=Heatingelement_log(:,3);

%load Temperature log
load Temp_log.lvm
Temp_time=(1/3600/24)*Temp_log(:,1);
Temp = Temp_log(:,3);

%load Valve log
load Valve_log.lvm
Valve_time= (1/3600/24)*Valve_log(:,1);
Valve = 10*Valve_log(:,3);

%load json log
load json_log.lvm
Json_time= (1/3600/24)*json_log(:,1);
Json= json_log(:,3);

%load grid price
load price.lvm
price_time= price(:,1);
price= (2.4/10)*price(:,3);

%plotting
plot(Thyristor_time,Thryistor)
hold off
plot(Heatingelement_time,Heatingelement)
hold off
plot(PV_time,PV)
hold off
plot(Valve_time,Valve)
hold off
plot(Temp_time,Temp)
hold off
plot(Json_time,Json)
hold off
plot(price_time,price)
hold on
plot(water_time,water)
```

10.3 Labview setup

In figure 56, an overview of the labview program is shown. There is not possible to zoom in the program, so all pictures are grouped together. The main controls and sensors are temperature sensor, valve control, thyristor, AMS info and PV production info.



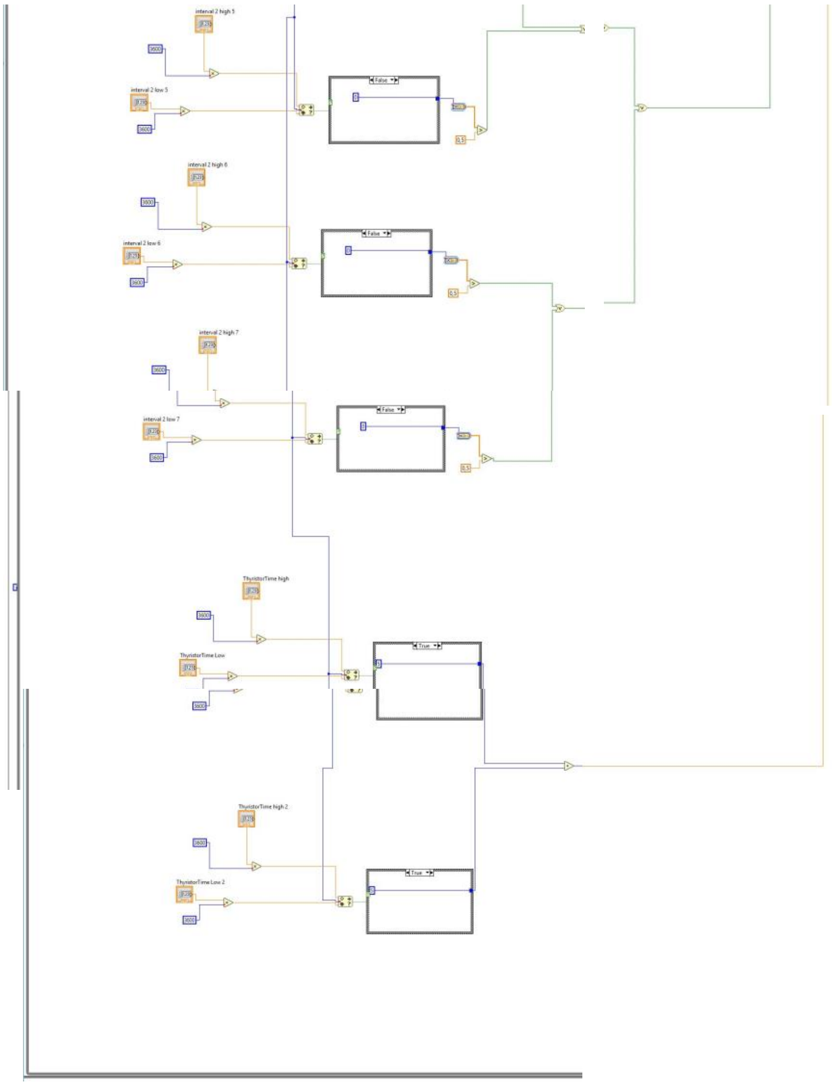


Figure 56 Overview of labview program.

In figure 57, it is shown how the PV information-, AMS information- and temperature information are sampled. The PV information is logged, and it is also connected to the thyristor for controls. A DAQ assistant is used to sample the temperature data and are also sending it to the thyristor for controls. The AMS is only for measuring load on the fuse and is not used in any logic.

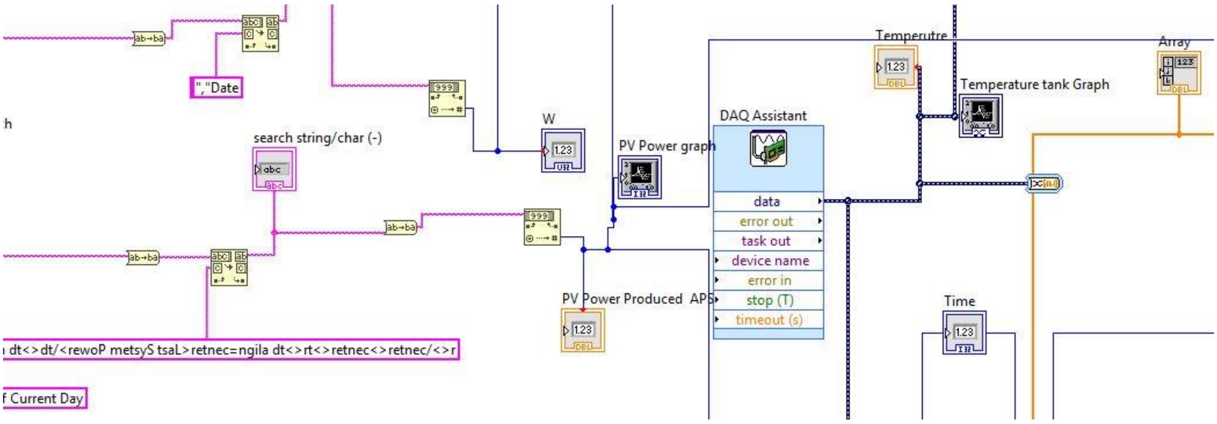


Figure 57 PV, AMS and temperature.

In figure 58, the valve control is shown. A DAQ assistant is used in labview and turned on/off to discharge the tank for water. The valve is opened based on a water profile, and normally around 190 litres are emptied each day.

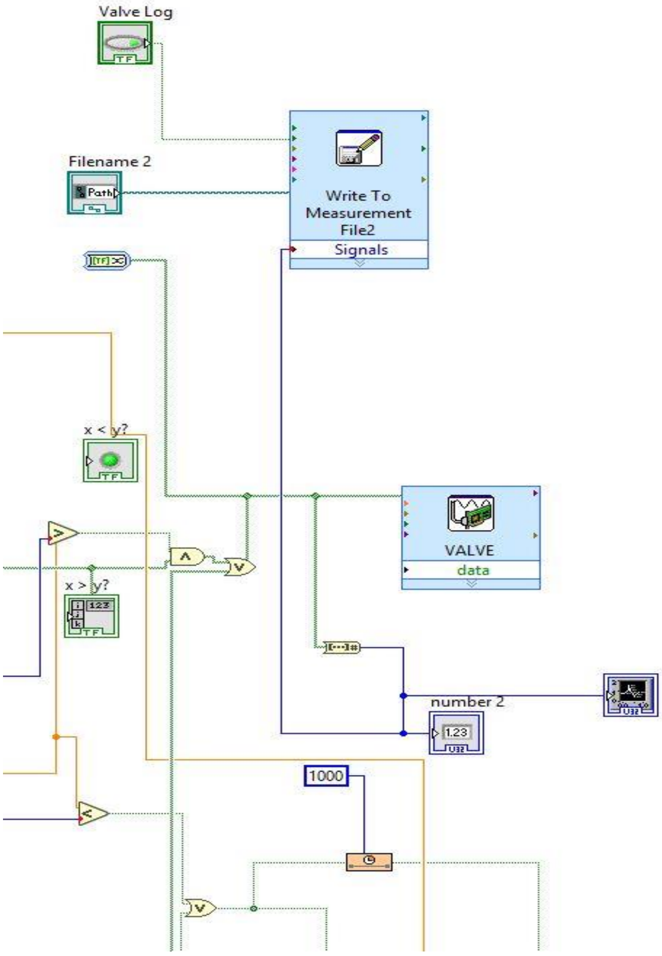


Figure 58 Valve in labview.

In figure 59 the thyrstor controller are shown. It is activated based on PV production, water temperature and a grid load profile. It is controlled between 0 to 1950 W and the input signals used is 0-10 V.

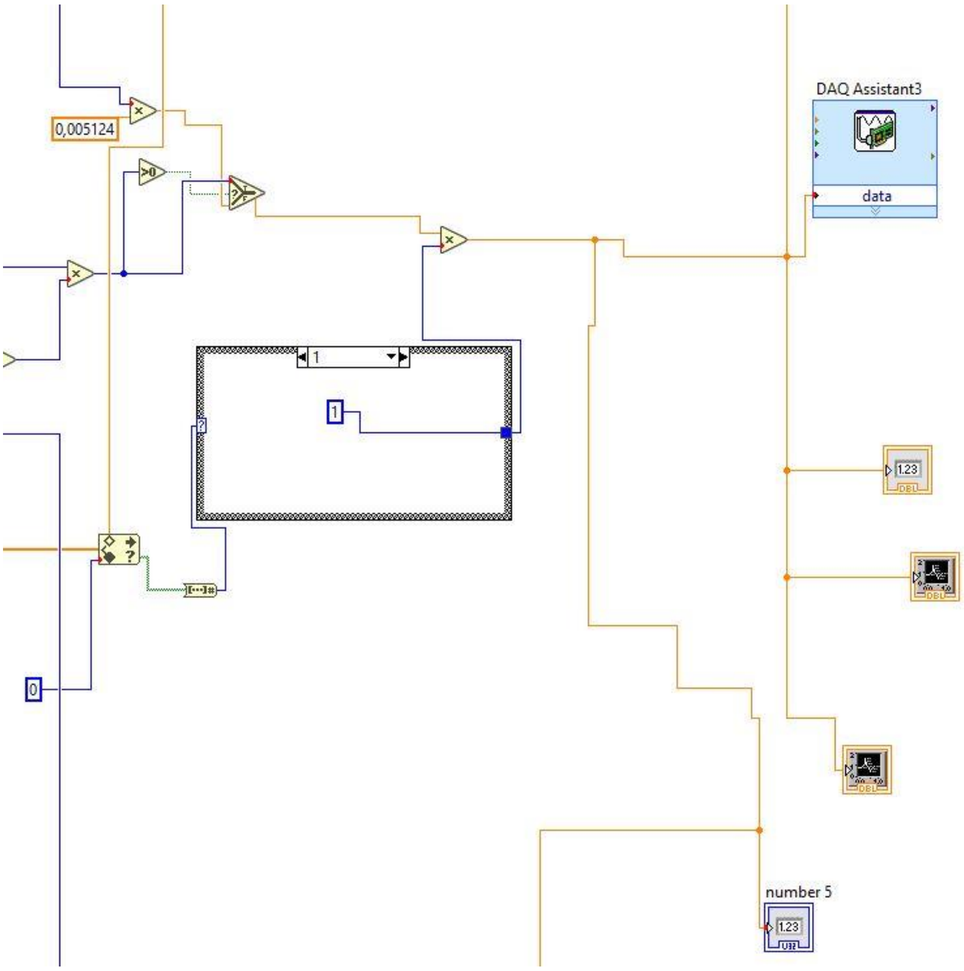


Figure 59 Thyristor in labview.

10.4 Installation of thyristor

Some pictures were taken during the installation of the thyristor controller and is shown in figure 60, 61 and 62. Figure 60 demonstrates the wires connected.

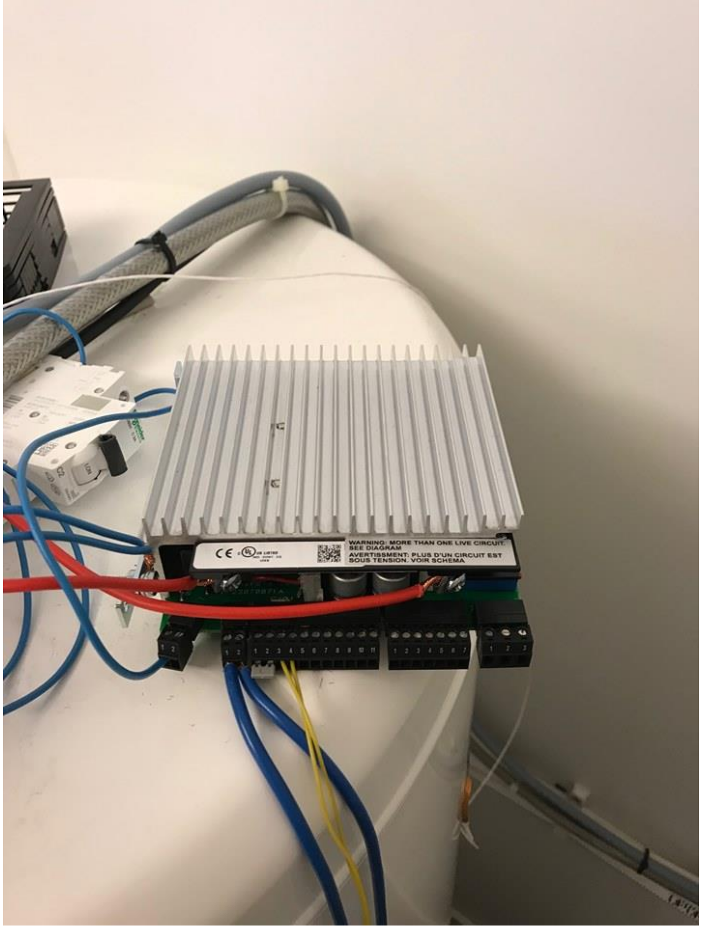


Figure 60 Thyristor during installation.

Figure 61 shows the indicators and where the connection for Thyrotool pro is placed.

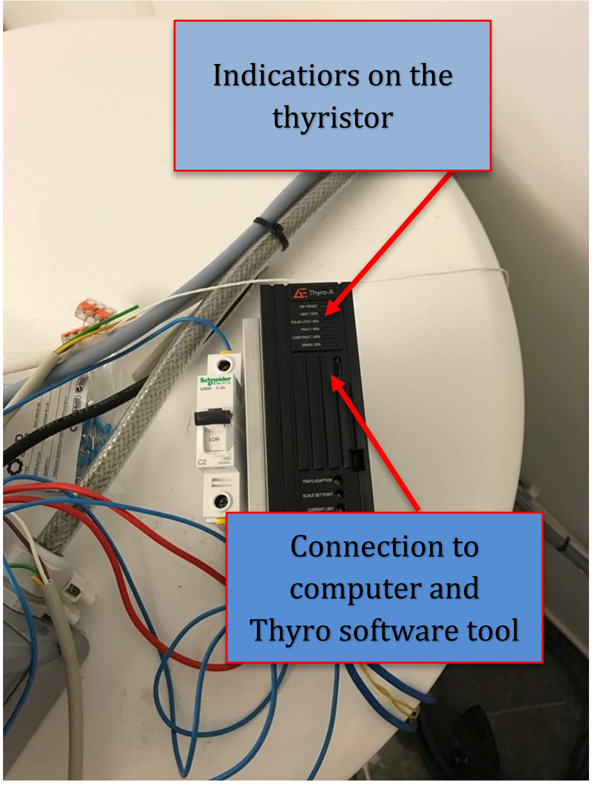


Figure 61 Thyristor with indicatiors.

Figure 61shows the DIP switches for the thyristor controller.

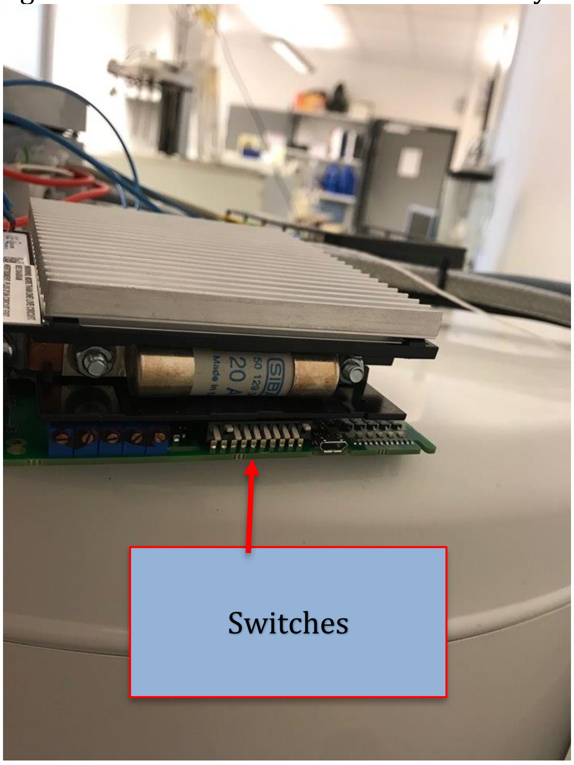
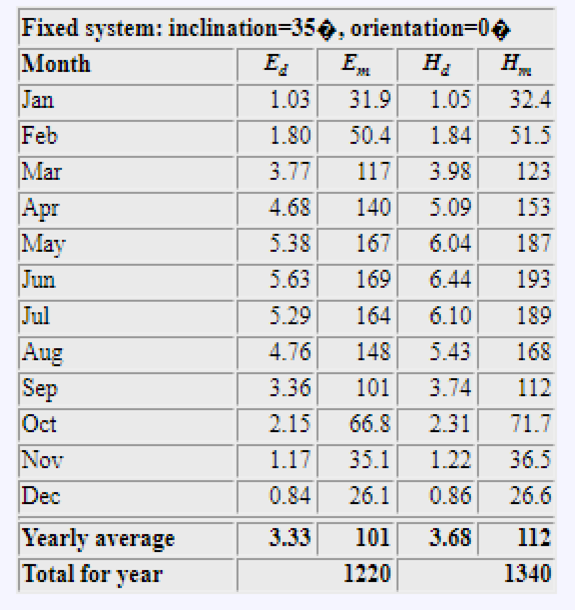


Figure 62 Thyrsitor switches.

10.5 PV potential

PV potential from PVGIS used to compare some of the PV production results in the thesis. This is for a system of 1kW turned against south, installed at UiA, Jon Lilletuns Vei 9, 4879 Grimstad. The total estimated energy production over a year is 1220 kWh. This is shown in figure 63.



Fixed system: inclination=35�, orientation=0�				
Month	E_d	E_m	H_d	H_m
Jan	1.03	31.9	1.05	32.4
Feb	1.80	50.4	1.84	51.5
Mar	3.77	117	3.98	123
Apr	4.68	140	5.09	153
May	5.38	167	6.04	187
Jun	5.63	169	6.44	193
Jul	5.29	164	6.10	189
Aug	4.76	148	5.43	168
Sep	3.36	101	3.74	112
Oct	2.15	66.8	2.31	71.7
Nov	1.17	35.1	1.22	36.5
Dec	0.84	26.1	0.86	26.6
Yearly average	**3.33**	**101**	**3.68**	**112**
Total for year		**1220**		**1340**

Figure 63 PV potential from PVGIS [13].

10.6 Valve measurements

To measure how much water is removed when the valve is opened, the time was taken while the valve was opened. At first the valve was closed when 5 litres where emptied of the tank, and after the test was done again, but for 10 litres. The results are shown in the table 10. The average discharge of water is 0.33 litres/second.

Table 10 Water discharge in the tank.

Valve opened until 5 liters are removed	
Test 1	15.19 s
Test 2	15.29 s
Test 3	14.99 s
Test 4	15.08 s
Test 5	15.18 s
Valve opened until 10 litres are removed	
Test 6	30,01 s
Test 7	30.40 s
Test 8	30,36 s
Test 9	30,42 s
Test 10	30,30 s

10.7 PV system installation

As PV systems are more common, the prices have also decreased a lot over the last few years. Solcellespesialisten are installing complete PV system for households on existing roofs. For a complete system which consists of 12 panels, inverter, mounting system and installation the total price is 56900,- NOK. The support from Enova is 14125,- NOK which makes the total price after Enova 42775,- NOK [41].

A PV system with 3.3 kW installed will produce 3696 kWh yearly according to PVGIS. With the electricity price of 1.19 NOK/kWh and 3696 kWh produced yearly, this will be a saving of 4398 NOK yearly. With the total price of the PV system, it will take 9.7 years before it is produced energy worth as much as the PV system. This is assumed all the energy is used in the house and not delivered back, and a constant price.