PROJECT 4

ZERO ENERGY HOUSE
PROJECT DOCUMENTATION

AARHUS UNIVERSITY

DUE DATE: 22-12-2017

GROUP 2

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0.1 Distribution of tasks

Task	Made of
Software, Implementation and Design	BN and RM
Hardware, Implementation and Design	CJ and HTA
Analysis	
PhotoVoltaic	CJ
Battery	HTA
Charge Controller	BN
Current Transformer	CJ
Trip Relay Circuit	CJ
Hall Sensor	CJ
Zero Cross Detection	CJ
DC Current Shunt Transmitter	HTA
DC Voltage Sense Transmitter	HTA
Safe Communication	BN
Combined Heat And Power	BN
PLC	BN And RM
Inverter	RM

Table 0.1. Task list

0.2 Keywords

In this sections a overview of the abbreviations used throughout this document will be listed and described.

Abbreviation	Full name	Abbreviation	Full name
SOC	State of Charge	PV	PhotoVoltaics
CHP	Combined Heat and Power	NACK	Not Acknowledged
HMI	Human Machine Interface	OC	Open Circuit
PLC	Programmable Logic Controller	SC	Short Circuit
GUI	Graphical User Interface	MPP	Maximum Power Point
DOD	Depth Of Discharge	MPPT	Maximum Power Point Tracking
STC	Standard Test Conditions	NOCT	Nominal Operation Cell Temperature
SLA	Sealed Lead Acid	AGM	Absorbed Glass Mat
VRLA	Valve Regulated Lead Acid	PWM	Pulse Width Modulation
TCP	Transmission Control Protocol	UDP	User Datagram Protocol
ACK	Acknowledged	RES	Renewable Energy Sources

Table 0.2. Keywords

Project Description | 1

1.1 | Background

Denmark is among the leading countries when it concerns renewable energy [1]. The danish government has a goal, which is to be independent of fossil fuels in 2050 [2]. This goal will be achieved through implementation of wind turbines, solar systems, biomass and geothermal energy.

Denmark has over the last decades made a huge increase in renewable energy [3]. The biggest increase has been in wind turbines but also solar system is increasing slowly. In 2015 42,1% of the total electricity consumption came from wind turbines [4]. Some of the reasons for the increase in renewable energy is the increment in wind farms and solar farms combined with higher efficiency of both kind.

1.2 | Purpose

To help the process of turning Denmark green, a complete system will be designed as a 100% self-sufficient system. To make this possible both solar panels and wind turbines will be a part of the system to enable energy production in all kind of weather. The storage of energy in a power-wall(Battery) will increase the efficiency of the house and help in times of low production from the sustainable sources.

1.3 | Idea

The vision of this product is to have a system which automatically measures and controls the energy produced and stored in the house. This energy will be harvested from sun and wind. Because the energy production and load various over time, it's essential that the system controls the energy flow. Beside the ability to do this automatically, the user should be able to manually control the system, and choose when to sell excessive energy or to store it. To backup this system an alternative source should be able to supply the house with energy in times of limited sun and wind. This source should also provide the house with heat to achieve the goal of self-sufficiency.

To enable the user to access the system remotely, a server will be made which contains the data measured in the system. This way the user can track the energy status in times away from home.

1.4 Target Group

The system will apply to costumers who want to take a social responsibility and want to focus more on the green conversion, to ensure that their consumption of electricity is solely derived from sustainable sources. Furthermore the system applies to costumers who doesn't want to be dependent of the power grid, but wants to be 100 % self-sufficient. It applies to costumers who have at least 45 m^2 of roof turning south and a consumption of energy of up to 5340 kWh per yeah. This equals the average consumption + 20% of a family with two children [5].

1.5 Functions

To give an overview of what is wanted from the product, the principles of MoSCoW is used to prioritize the functions of the system.

Must have:

- Solar panel to collect energy.
- PLC Controller.
- Voltage and current sensors.
- Battery to store energy.
- CHP.
- GUI/HMI for user.
- Actuator system to control the energy.

Should have:

- Measurement from all sources to optimize the distribution of energy.
- Wind Turbine to collect energy.
- Command to force charging the battery.
- Command to force sale of electric energy.

Could have:

- Web server to store data.
- Directional controller for solar panel.

Won't have:

- Geothermal heat.
- Optimizing of load used in the house.

Figure 1.1. MoSCoW

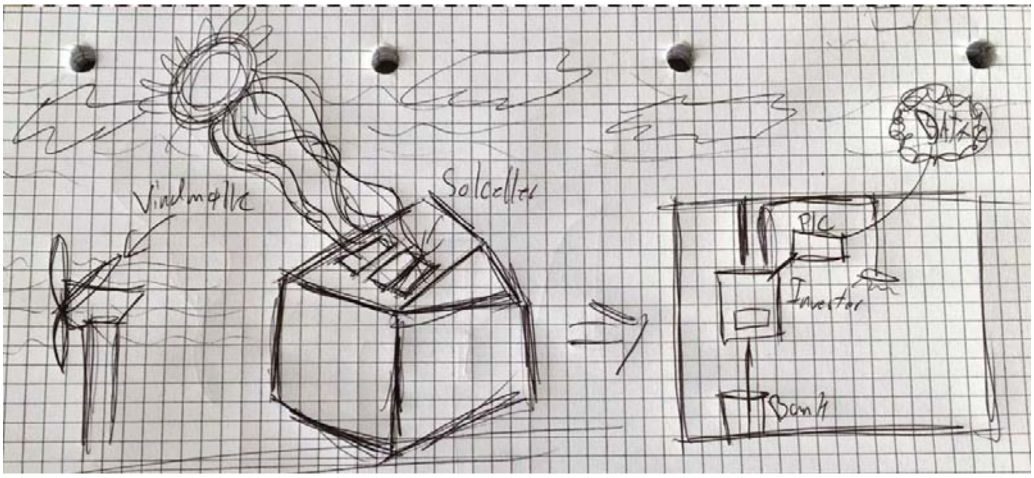

Figure 1.2. sketch of the system

Requirement specifications | 2

This section is about the requirements of the system and are established upon the project description. These requirements are then divided in functional and non functional requirements. The functional requirements are defining how the system is working externally. The non functional requirements are defining how the system is working internally, and are more technically based compared to the functional requirements. *The Functional requirements can be seen 1.1*

2.1 | System Specifications

The system is thought as 100 percent self-sufficient, where the main energy sources are solar panels and a wind turbine. The system should however, have the possibility to withdraw the energy from the CHP, if the situation occurs where the two sources and battery won't be able to supply the loads with enough energy.

There will be a power-wall(battery) in the house to where the energy from the sources will be connected, and through this charge the battery so this energy can be stored and saved for a later purpose. This is done in case the solar panels and wind turbine can't supply enough energy to the load. This will make it possible to first withdraw the energy from the battery and then, if it gets emptied, withdraw the energy from the CHP. The system will also have another function, if there is surplus of energy from the solar panel and wind turbine, if the battery is full then this surplus energy will be send out on the grid and from here on be sold.

These states which the system can be in, will be controlled by a PLC. The PLC will be connected to a HMI to enable the user to interact with the system. The system operates under two categories, these are Manual and Auto. Under these categories different modes will be available to either the user or the system. The user will not be able to choose "Force Sell, or "Force Charge" if the system are not yet in the Manual category. This PLC controller will be able to switch between different modes. **The system includes these modes:**

- Auto Mode
- Force Sell
- Force Charge

Auto mode: Operates as the systems normal function and will be declared as default mode in this project. This is also the mode that is being initialized when the system starts up, for the first time.

Under this function the PLC will control the inverter, to make sure that the house's loads have enough energy, and if there is any surplus energy it will be charged into the Power-Bank, or sold on the grid.

Force Sell mode: In this mode, the user choose to sell the surplus energy instead of charging it into the power-wall(battery). The PLC will still make sure to direct enough energy into the house's load.

Force Charge mode: In this mode, the PLC will direct all power from the inverter to the Power-wall(battery), and then the PLC will direct the CHP's power into the house instead of the inverter.

The PLC controller will make decisions on what mode it will be put in. This decision will be based upon a surveillance of the battery capacity, the energy produced by the main sources, and the demand of energy from the loads at the current time. Charging up the battery will have a higher priority than selling the excessive energy.

The heat in the house will be provided from a microCHP(Combined Heat and Power). The CHP will use bio gas to contribute to sustainable sources. The CHP will be connected to the Inverter in the house, so the electricity can be distributed either to the house, the grid or to charge the battery. The CHP will run at all time to constantly keep up the heat and the stability of the loads. The additional surplus energy will be sold to the grid.

2.2 | Actor diagram

The system contains three use cases, which consists of three actors. The primary actor is the user of the system, the secondary actors are the following two; Renewable energy and the household load's. These two secondary actors and the primary actor, are the only variables in this system.

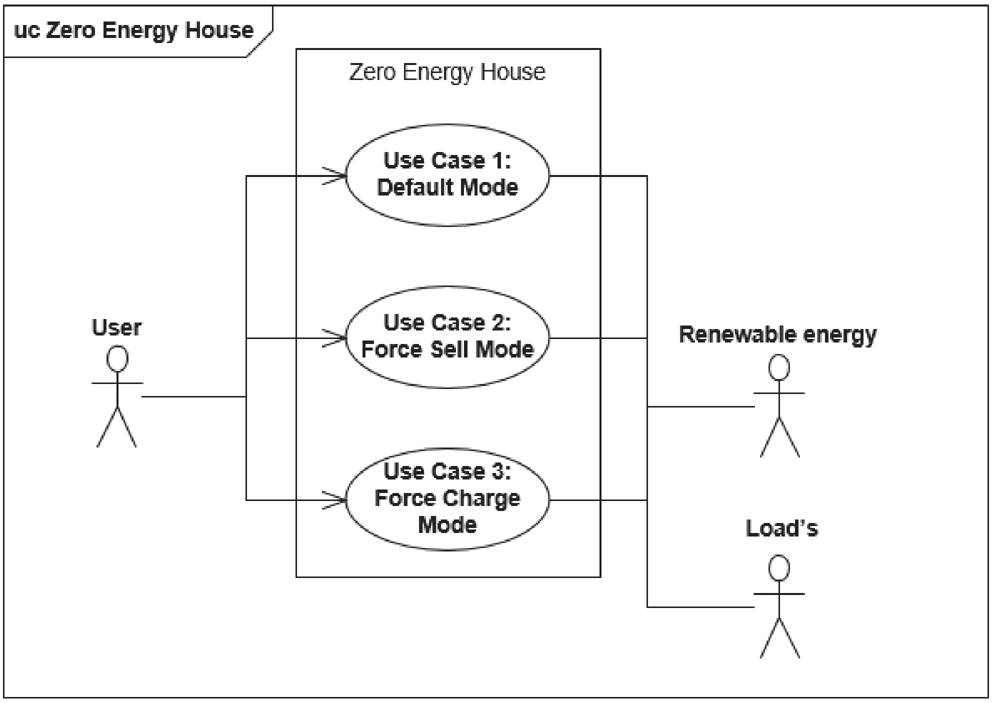

Figure 2.1. Actor diagram of the system

2.3 USE CASES

This section describes how the system interact with the different actors of the system. And how the system behaves, compared to what the actors does when they interact.

Use Case 1

Name	Use case 1: Default mode
Goal	Auto Distribution
Initiating	User press Auto Mode
All occurrences	1
Precondition	The system is on
Post condition	The system distributes the energy after demand
Main scenario	1. **User** Chooses auto 2. **PLC** change to default mode 3. **Inverter** provides energy to the loads • **Extension 1** *The excessive energy charges the battery* • **Extension 2** *The excessive energy, the battery can't use, is sold*
Extensions	**Extension 1:** *The excessive energy charges the battery* 1. Battery is charged through the main sources. 2. Battery is charged sufficiently. **Extension 2:** *The excessive energy that the battery can't use, is sold* 1. The excessive energy that the battery charger can't use, is sent out on the grid

Table 2.1. Use case 1

Use case 1 describes how the default mode operates, to provide the system the necessary energy.

Use Case 2

Name	Use case 2: Force Sell mode
Goal	Energy sold on grid
Initiating	User press Sell
All occurrences	1
Precondition	There is a production of energy, and there is a significant high capacity on the battery
Post condition	Energy have been sold on grid
Main scenario	1. **User** presses Sell 2. **PLC** change to Sell mode • **Extension 1** *Battery SOC to low* 3. **Battery** discharges 4. **Battery** have reached it's minimum SOC 5. **PLC** changes to Default mode
Extensions	**Extension 1:** *Battery SOC to low* 1. **PLC** change to Default mode.

Table 2.2. Use case 2

Use Case 2 describes the procedure of how the user can force the system into sell mode

Use Case 3

Name	Use case 3: Force charge
Goal	Charge the battery
Initiating	User press charge
All occurrences	1
Precondition	The system is on
Post condition	The battery is fully charged
Main scenario	1. **User** press charge 2. **PLC** change to charge mode • **Extension 1** *Battery is fully charged* 3. **Battery is charging** 4. **Battery is fully charged** 5. **PLC switches to default mode**
Extensions	**Extension 1:** *Battery is fully charged* 1. **PLC** changes to default mode

Table 2.3. Use case 3

Use Case 3 describes the procedure of how the user can force the system into Charging mode

2.4 Non functional requirements

The non functional requirements are used as a limit to how the system should behave externally.

- To start the system it is required that the battery is charged to 100% percent
- The inverter should have a capacity on minimum 8 **kW**
- PLC controller should change mode within 1 seconds
- The system should operate under 2 categories: Manual and Auto
- The level of the battery must stay between 50% and 100% to prolong the lifetime of the battery.
- The system should always have enough current to start up the CHP.

LIMITATIONS | 3

At this point a complete system has been described, however due to the lack of time because of the fact that the project runs along 25 ECTS-points of courses, some limitations have been made. The prototype of the product will work as a proof-of-concept, where some factors will be ignored to make a simplification of the system.

There is a natural limitation concerning the PLC and the Inverter. At best the PLC would have inputs enough to deal with all the sensors. In this project there is a limitation with the PLC to an input limit of two. Therefore it will not be possible to collect all the data required to make a full system. The other limitation is regarding the Inverter. It would be, again at best, if the Inverter of the system are capable of making a two way transfer of power, this is however not possible with the Inverter that is available to this system. A two way Inverter can be used for the CHP to make sure, that the battery at all time is charged with maximum SOC. This could be done by transferring the surplus energy the CHP makes for the loads, towards the battery to ensure the maximum SOC.

Furthermore the calculations for SOC is simplified. As far as the calculation goes, the efficiency will be ignored and will therefore not be a part of the calculation for SOC. The efficiency is still taken into account and explained, but will not be a part of the implementation.

The wind turbine will also be neglected, due to the lack of time. The main power source will then be limited to solar panels.

There won't be implemented a server to enable the user to access the data provided from the system remotely.

As mentioned earlier a complete system will not be implemented, instead the project will consist of two parts. The first part will be a scaled down version of the real system, which will work as a proof-of-concept product. The second part will be for the final product where the parts of the system have been scaled up to correspond to the idea of the project.

The first part as mentioned will be the proof-of-concept where the product will be sized and implemented as a downsized version of the theoretical part. This part will be implemented completely including hardware and software. The system will include the following items.

- PLC
- PV cells
- Charge controller
- Battery
- Variable load, which will be simulating the household variable loading through out a day.

The second part as mentioned, will be sized after the household which will be described through the requirement specifications down below. It will only be handled is fictional.

- The system should be able to supply a household consisting of four people
- The system should be able to measure SOC, production and how many kWh that have been sold.
- The systems CHP should be able to supply the household with heat and work as a generator when needed.
- The PV System should deliver enough energy to supply the Target Group mentioned i 1.4 .
- The PV should be placed after the best conditions for most radiation, and should be optimized for danish weather condition.
- The systems PLC should be able to operate under normal household conditions, which will be within the range of 15-30 degrees.
- The CHP should be able to deliver at least 12000 kWh of Heat and 2000 kWh Electricity.

Hardware architecture | 4

In this chapter the Hardware architecture will be described. The architecture will be described through BDD and IBD, which will be supplemented by signal- and block descriptions.

4.1 | Hardware BDD

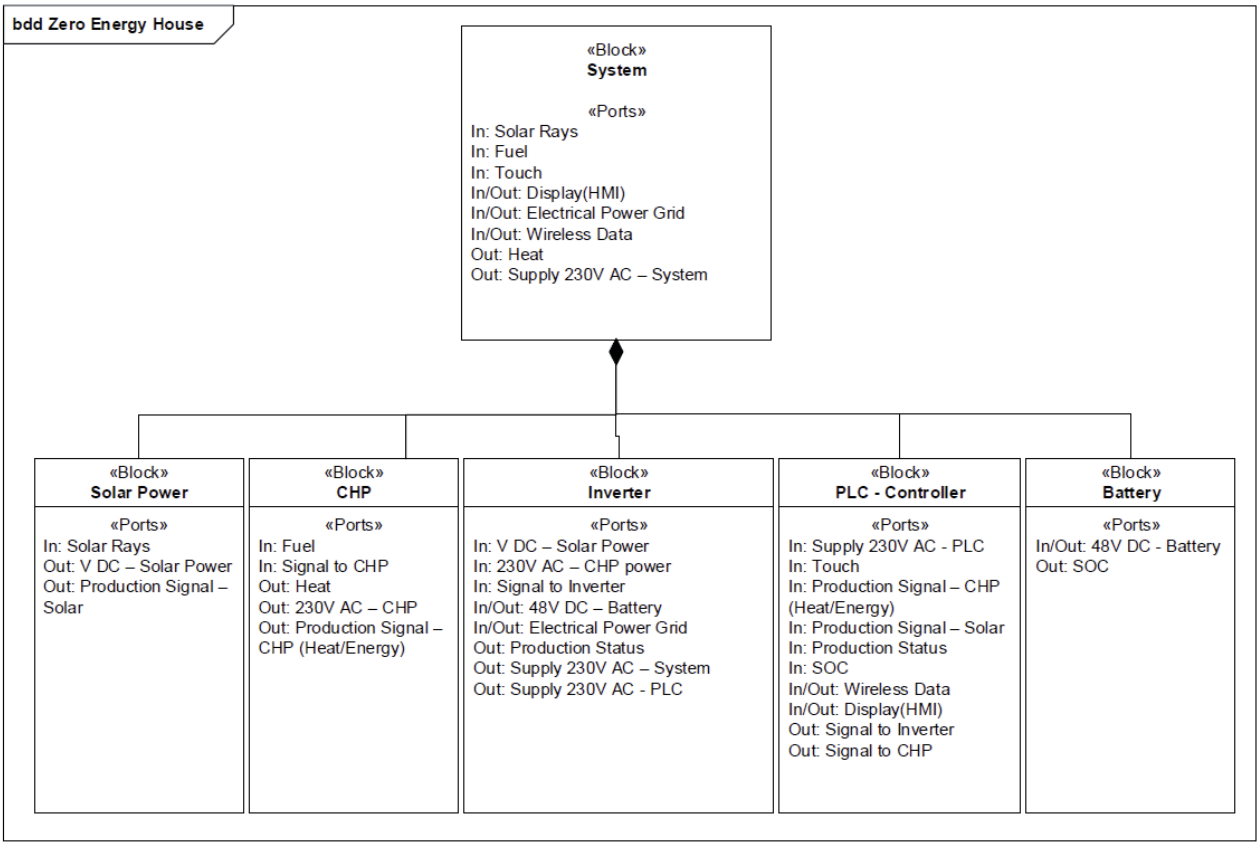

Figure 4.1. BDD diagram of the system

Figure 4.1 shows the BDD for the entire system. The BDD shows what blocks the system contains and how they connect. The blocks also contains input/output signals.

4.1.1 Block description

Block name	Description
System	Includes all elements of the project.
PhotoVoltiac array	Produces electrical power by collecting energy from the sunlight.
CHP	Produces heat and electrical power from sustainable combustible fuels.
Inverter	The inverter is the center element that channels electrical energy back and forth between the system elements and the load.
PLC	The PLC is collecting signals from all sensors, controlling all actuators, and brings information for the user.
Battery	Storage of electrical energy.

Table 4.1. Main block description

4.2 | HARDWARE IBD

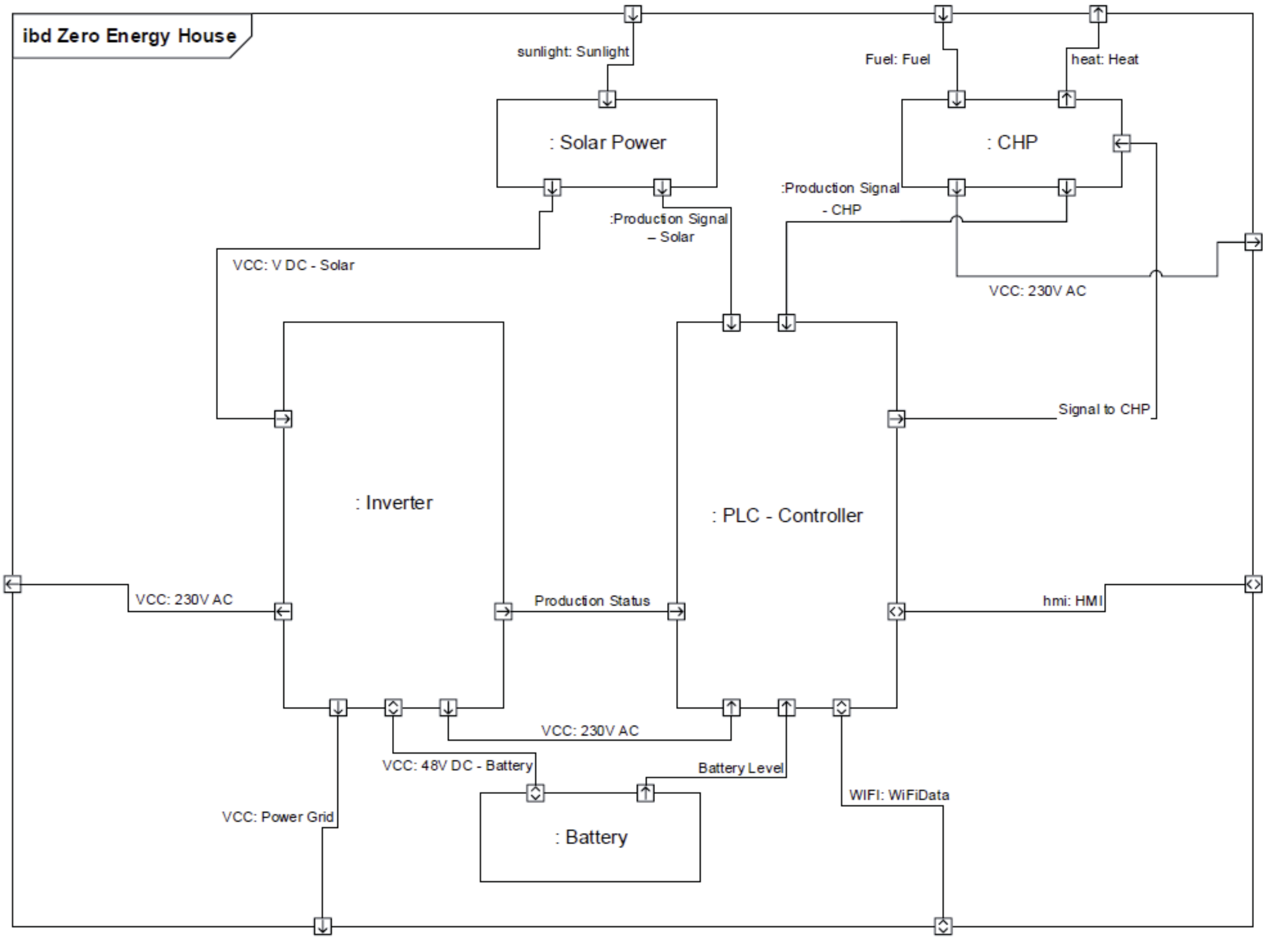

Figure 4.2. IBD diagram of the system

Figure 4.2 shows the overall IBD for the system. It shows the internal connections between the blocks in the system.

4.2.1 Overall signal description

Signal name	Description	Signal	From port	To port	Comments
sunlight	Sunlight which makes the electrons in the solar panel move	Sunlight	Sunlight	Solar Power	
fuel	sustainable Fuel which is being used to make electricity and heat through the CHP	Fuel	Sustainable sources	CHP	
HMI	The Interface that allows the user to interact with the system	HMI/PLC controller	HMI	HMI/PLC controller	InOut Port
Power Grid	Used to send out excessive power not used in the house	230V AC	Inverter	Power Grid	
WiFiData	Sends out the data, so the user can check up on the system from another place	WiFi	PLC Controller/WiFi-Data	PLC Controller/WiFi-Data	
Heat	Heat to keep the temperature up in the house and to provide hot water	heat	CHP	Heat	
Production signal	Sends a signal from each of the energy sources to the PLC controller to show production from the given sources	Voltage	Wind Power/Solar Power/CHP	PLC controller	

Table 4.2. Signal description table1

Battery level	Measured signal from the battery, that is being send to the PLC	Voltage	Sensor	PLC Controller	
24V DC - Battery	A two way charge and discharge from the battery to the Inverter	Voltage	Battery/Inverter	Battery/Inverter	InOut Port
Production status	Sends a signal to the PLC on how much energy there is currently being produced	Voltage	Inverter	PLC Controller	
230V AC	Sends 230V AC out on the Grid	Voltage	CHP/Inverter	Grid	
48V DC - Solar	Sends a DC signal	Voltage	Solar Power	Inverter	
Signal to CHP	Sends a signal for the CHP to turn on	Voltage	PLC Controller	CHP	

Table 4.3. Signal description table2

Software Architecture | 5

Through this chapter the software architecture will be described. To describe this, sequence- and state machine diagrams will be used, as well as a domain model and a draft of the HMI.

5.1 | Domain Model

The Domain Model is a visual presentation of the system. It shows the associations and multiplicity of the individual components in the system. The Domain Model gives a quick overview of the system, and how they interact. This is a foundation method to begin understanding the software of the system.

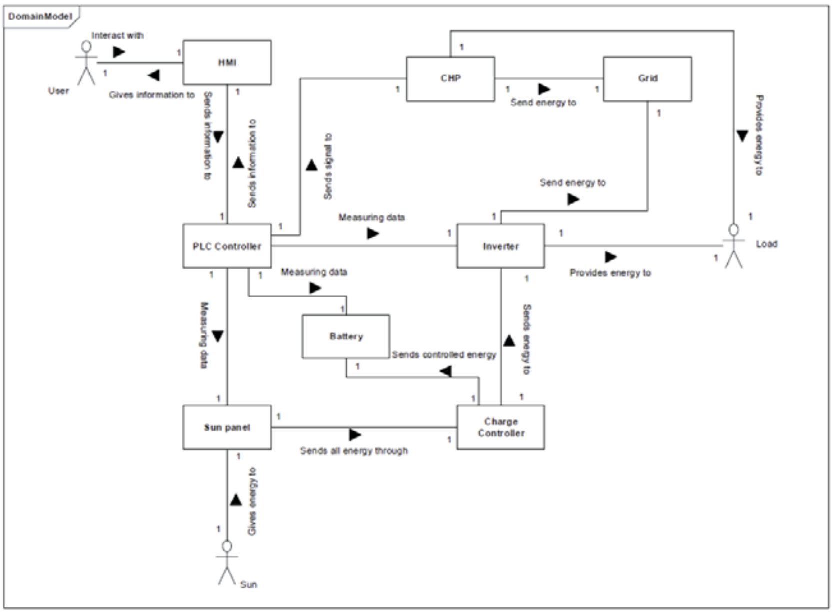

Figure 5.1. Domain Model

5.2 | Sequence diagrams

A Sequence diagram have been made for each use case to describe the internal communication of the system.

5.2.1 Default Mode

The Default mode is also the initialization mode. This mode consist of a huge loop which constantly measures the values of production and compares this to the loads. It also keeps an eye on the battery to make sure the SOC is at a certain interval. Besides this it connect the different parts of the system to maintain an effectively flow of energy.

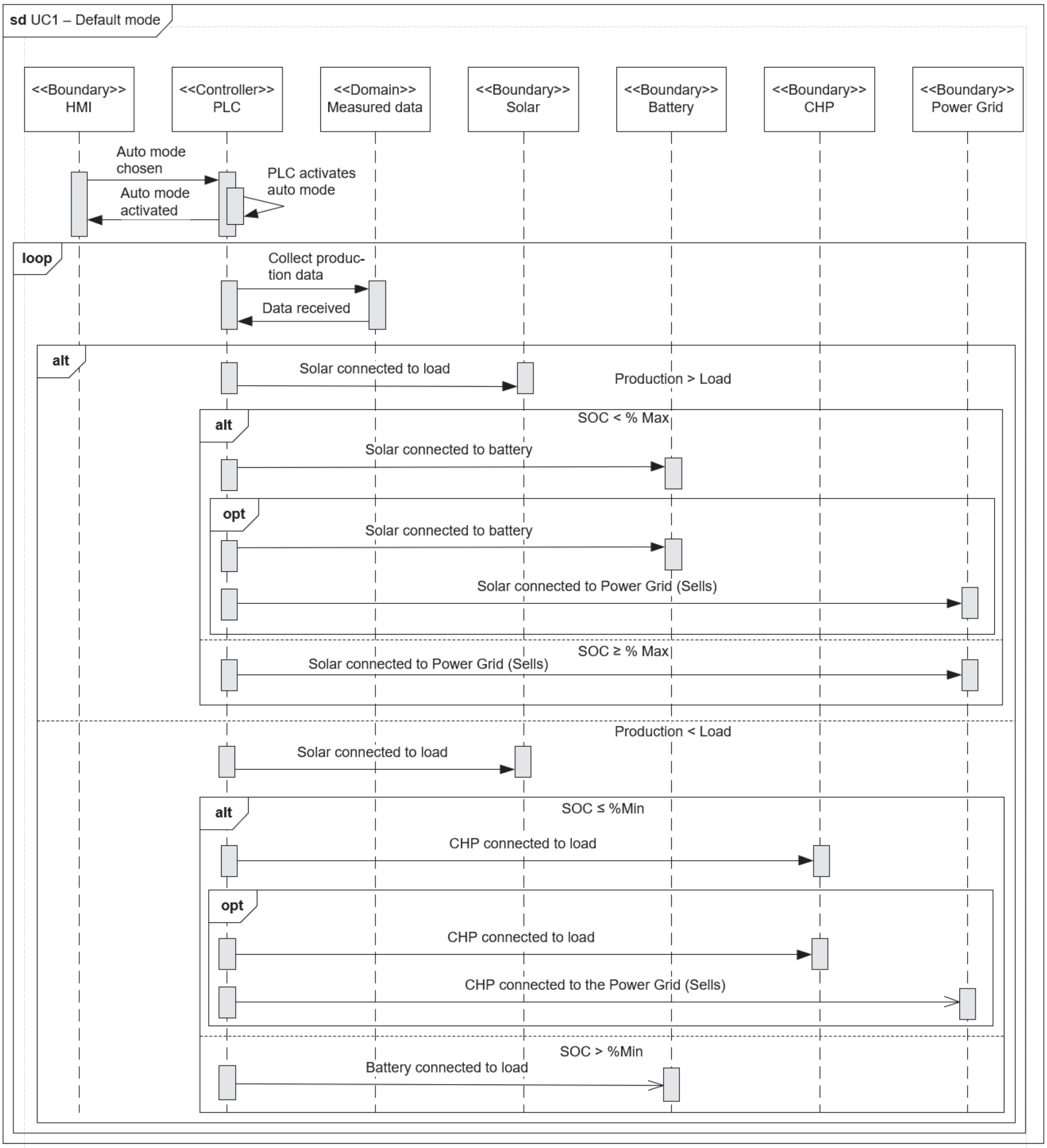

Figure 5.2. Sequence diagram of UC1 - Default Mode

5.2.2 FORCE SELL MODE

The Force Sell Mode is an opportunity to enable the user to sell the energy produced, as long as the SOC is beyond its lower limit. When the SOC reaches its lower limit the system will return to Default Mode.

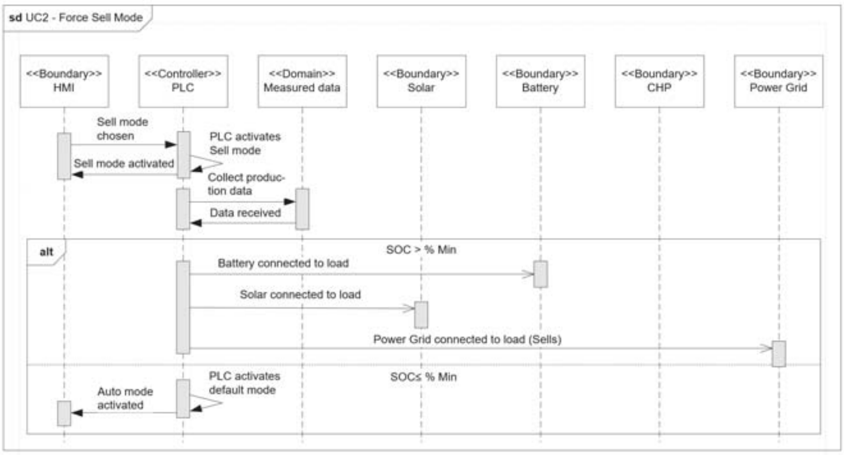

Figure 5.3. Sequence diagram of UC2 - Force Sell Mode

5.2.3 FORCE CHARGE MODE

The Force Charge Mode is an opportunity to enable the user to charge up the battery, independent of the production. Force Charge Mode will use the CHP for the loads, while all energy from Solar will be used to charge up the battery. When the SOC reaches its higher limit the system will return to Default Mode

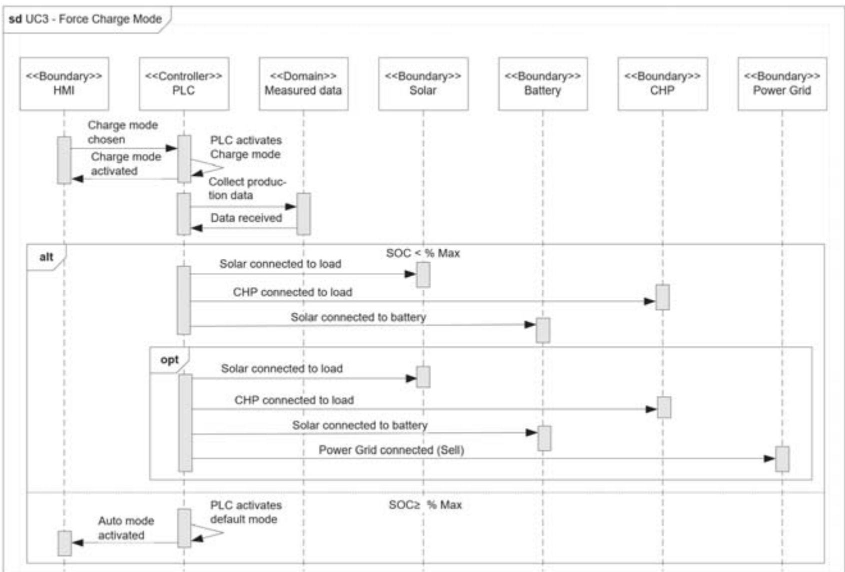

Figure 5.4. Sequence diagram of UC3 - Force Charge Mode

5.3 | State Machine Diagram

A state machine diagram gives an overview over which state the system operates in and which factors that causes the state to change to a different state.

As shown in figure 5.5 the different states in the system is controlled of SOC, production and the amount of energy used to charge up the the battery. The state CF and BF is though not showed in this diagram, connected to all states to enable the user to force the state the system is operating in, if the criteria is met.

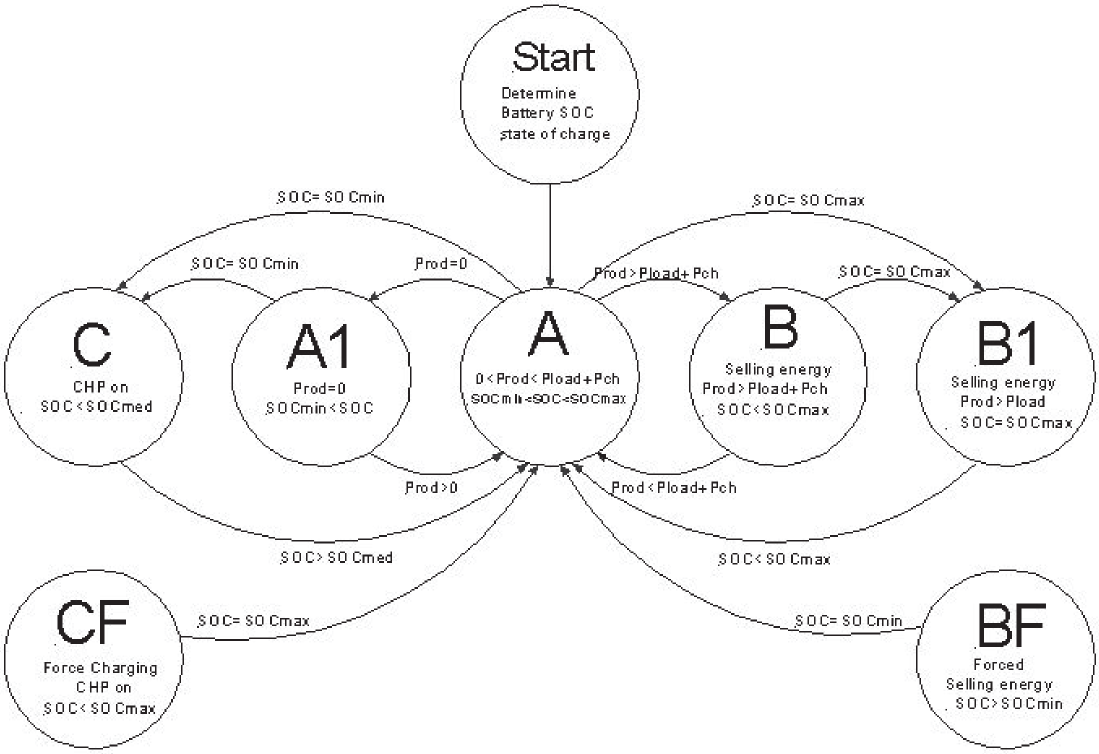

Figure 5.5. State Machine Diagram

Analysis | 6

Through out this chapter, there will be explained the analysis done throughout this project. How PV works, battery, the communication and how the CHP works.

6.1 | Photovoltaics

6.1.1 How solar cells work

To understand how solar cells work, it is needed to dig in and understand the layers of a solar cell. A solar cell consist of semiconductors which are laid on each other. There is a P/N typed semiconductor, the semiconductors will become electrically conductive when the solar rays hits the panel or they are exposed to heat.

There are many types of semiconductors which can be used as a PV-cell. But the most commonly used is the silicon. Silicon is commonly found in quartz sand(SiO2), where it have to go through a process to be separated into silicon it self. The end product of these processes are high purity silicon rods, which are used in **Mono/Polycrystalline solar cells**. When the silicon crystal receive external energy in the form of solar rays or heat, the energy is absorbed into the electrons. When the electrons have absorbed enough energy they move around inside the crystal. This movement makes the silicon crystal conductive, this process is know as the *Intrinsic conductivity* of a semiconductor.

This means that the number of excited electrons and holes are equal N = P. When the energy is interrupted, the electron will release its energy and return to a free electron hole. To use the energy that is released, it needs one of the sides to be a (N-typed) which means it have an extra atom with five electrons instead of four. The other side should be a (P-typed) which have an atom with three electrons. The P-typed side then have one free electron-hole from the silicon.

When a layer of the semiconductor is a P type and the other layer is an N-type, the electrons can drift between the layers. When the charges separates from each layer, they crate an electric field across the junction.

When the PV-cell is combined, and the light hits the PV-cell, the atoms inside the P-N junction are excited to form electron-hole pairs. Electron-hole pairs inside the P-N junction will then be separated by the local electric field. The result of the separation and drift of the electrons will cause the PV-cells voltage to rise. A current will then flow, if it's connected to a load.

Figure 6.1 show what happens when the PV-cell is affected by the photo effect.

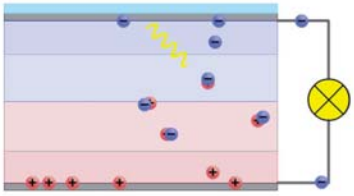

Figure 6.1. Picture of photo effect connected to load. [6]

6.1.2 Different types of PV-cells

There are a few different types of PV panels, this section will give a short presentation about the two most common types of PV's which is the: Mono- & Polycrystalline cell.

Monocrystalline solar cells

Monocrystalline is the most efficient photovoltaic technology at the moment. The efficiency of the cells are typically around 15-18 % (but can by higher) at the highest. The silicon is formed into bars and then cut into wafers to form the panel. This type of cell requires more time and energy to manufacture compared to the other types. This is why this is the most expensive cell.

Figure 6.2. Picture of a monocrystalline panel [7]

Polycrystalline solar cells

Polycrystalline solar cells are not as efficient as Monocystalline, but they are a lot cheaper to produce. This is due to the manufacturing process. The cells are made out of silicon that is going through a controlled cooling process and then sawed into thin wafers. The efficiency of these cells are around typically around 13% to 16% (but can be higher).

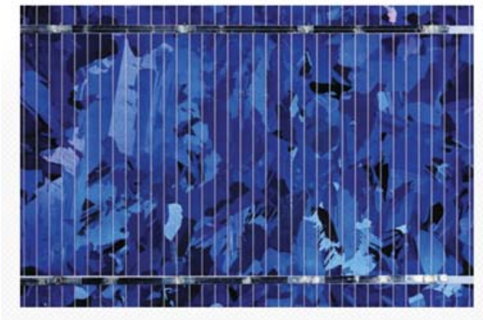

Figure 6.3. Picture of a Polycrystalline panel [8]

6.1.3 EQUIVALENT CIRCUIT DIAGRAM OF A PV CELL

A photovoltaic cell consists as written in 6.1.1 of N- and P-type semiconductors. This means that when the solar cell's are not irradiated, it behaves almost as an diode. This can be said because when there isn't running any current in a diode, it is not able to glow. The same thing can be said about the solar panels, when they aren't receiving any irradiated they won't produce any current and thereby won't be able to run.

Therefore an equivalent circuit for the solar cells can be made with a diode.

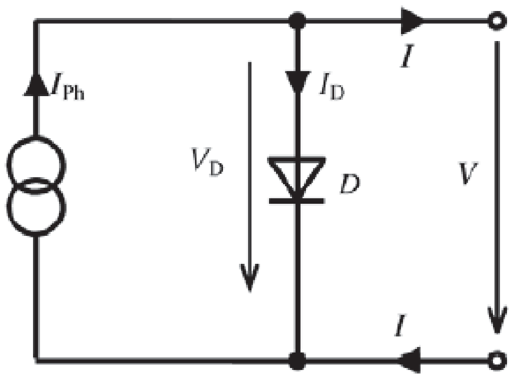

Figure 6.4. Equivalent circuit for solar cell. [9]

It is here important to find the current *I* of the solar cell's, because it is this current that should supply the loads. This current *I* is depended on the Voltage of the solar cell V and V_D, with the saturation current I_S and a diode factor m.

$$I = -I_D = -I_S * (exp(\frac{V_D}{m * V_T}) - 1) \tag{6.1}$$

The diode factor of an ideal diode is equal one, but for an solar cell it can be allowed between 1-5 for a better simulation. The thermal voltage V_T is at 25 mV at 25 degrees Celsius, and the saturation current

I_S is at the range of 10^{-10} to 10^{-5} Amps.

A current source generates the I_{ph} which is the current generated when the solar cell's are being irradiated. I_{ph} is dependent of the irradiation *E* and the coefficient c_0.

$$I_p h = E * c_0 \tag{6.2}$$

This simple equivalent circuit of the solar cell's only has a deviation on a few percent, but if there should be made an exactly equivalent circuit and calculation of the solar cell's, the *One diode model* can be made. On this model there is further resistance for the voltage drop in the junction with the N and P, R_S *The name R_S because is is in series* and a resistor that describes leakage in the edges of the solar cell R_P *The name R_P because it is in parallel.*

This model however, will not be analyzed. It can be seen on the figure 6.5

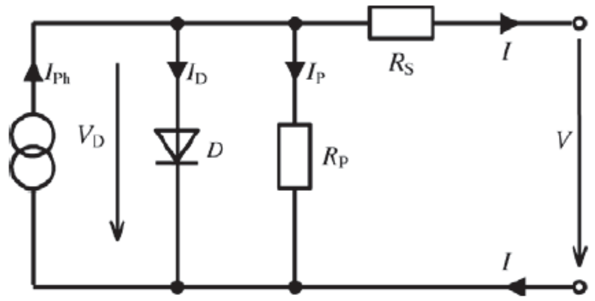

Figure 6.5. Extended equivalent circuit for solar cell. [10]

6.1.4 Characteristic & Efficiency of a PV-cell

Characteristic

To see how the irradiance effects the power output of the panel, a test between the two operating points have to be made, the two points are the open circuit(OC) and the short-circuit(SC).

The Short-circuit current is only slighter above the rated current for the panel. The Open-circuit voltage is the highest output that the PV-cell can produce. The output is not linear with the irradiance.

A typical diagram of a PV-cell is shown in figure 6.6. You can see how the irradiance effects the PV-cell a lot, the more sun the higher the output.

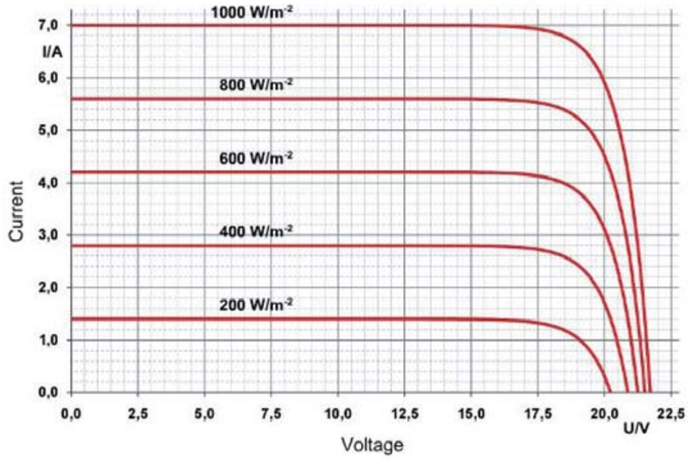

Figure 6.6. Picture of a typcal PV charateristic.[11]

EFFICIENCY OF A PV-CELL

To get the best efficiency of the PV-cell it is necessary to use the MPP of the cell, which is described in the section about the charge controller 6.2.1.

Another factor to be taken into account, is the *Fill Factor*. The fill factor is the quality of the PV-cell, where it states the MPP. The fill factor can be found with this equation: [11] The units of P, U and I is respectively in Watts, Voltage and Amps.

$$FF = \frac{P_{MPP}}{U_{OC} * I_{SC}} = \frac{U_{MPP} * I_{MPP}}{U_{OC} * I_{SC}} \tag{6.3}$$

The parameters found in equation 6.4 is from the PV-cell it self, which is stated in the data-sheets of the cells.

To determine the efficiency PV-cell, it is necessary to know the MPP, the irradiance(E) and the surface area(A) of the module. The equation is as follows: [11]

$$\eta = \frac{P_{MPP}}{E * A} = \frac{FF * U_{OC} * I_{SC}}{E * A} \tag{6.4}$$

The temperature can affect the efficiency of the panel. All modules are tested under STC and NOCT (More info about that under section 7.2. When the temperature rises, the efficiency of the cell drops and so does the MPP. The hotter the panel is, the poorer the performance and vise versa. It is therefore important, under strong irradiation and heat, to the have the panels properly cooled.

The figure 6.7 shows a typical characteristic under different temperature. As shown the hotter panel has a lower MPP and a poorer performance.

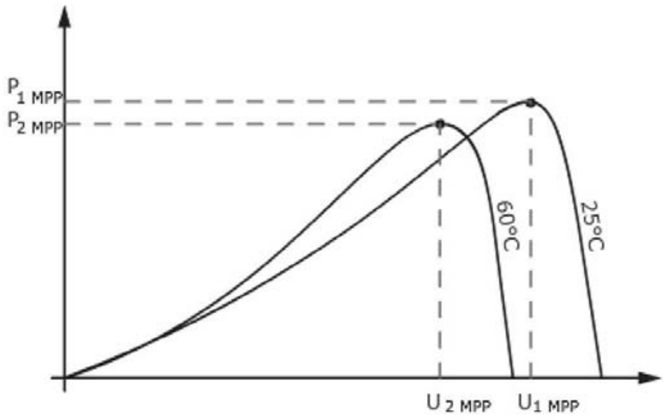

Figure 6.7. Picture of a typical PV characteristic under different temperature. [11]

6.2 Charge Controller

A Charge Controller is a regulator for insuring that the battery won't overcharge. The Charge Controller regulates the voltage and current coming from the solar panels and going towards the battery. The Charge Controller have to change the voltage and current for charging, to prevent the battery of taking damage. The battery is allowed to have a normal voltage for charging at 14.4V 6.3.3.

Figure 6.8. BlueSolar Charge Controller. [12]

On figure 6.8 an example of a Charge Controller is shown. It can here be seen that it is a MPPT which is described in section 6.2.1 and it have a maximum input from the solar panels on 75V and 15A. It have a Battery input/output on 12/24V and 15A, and a fuse on 20A for protection.

It can be seen that it have a yellow LED to indicate which charging mode it is in. *See more of these modes in 6.3.3*

6.2.1 Charge Controller Types

The Charge Controller often comes in three types, they will here be gone through:

Simple 1 or 2 stage controllers

A simple 1 or 2 stage controller is made of relays and shunt transistors. This type of controller is simply just disconnecting the solar panels so it can't charge anymore. This is therefore also the most reliable and cheapest kind because it doesn't have a lot of components. It is though only used in old systems because it can't do anything else than connecting or disconnecting at a certain value.

PWM

A PWM type controller stands for Pulse Width Modulation. Instead of sending out a steady voltage signal to the battery, it modulates these signals into pulses. By doing this it can be regulated with the duty-cycle of how much voltage there is being transferred to the battery. The PWM type also measures the battery at all time, so it can calculate what the duty-cycle value should be.

Maximum Power Point Tracking (MPPT)

A MPPT controller is a controller which are controlling the voltage and current from the solar panels, and making this voltage and current at the most efficient value. This value is calculated from information of the battery on how much the battery is charged or discharged, and how much the solar panels are generating.

A MPPT controller receives the DC power from the solar panels and converts this into AC. The AC signal goes through a transformer and transforming this AC signal value into the calculated value. The AC signal is after this rectified into a DC signal again, and transferred into the battery now with the new and improved signal value. The value of the battery can vary if it is in Bulk, Absorption or Float mode. *These can be seen on figure 6.10*

The MPPT controller will constantly calculate the new voltage and current for achieving the most efficient values for charging the battery. This means that the MPP will change all the time into a new value.

On the figure 6.9 it can be seen that the MPP always is lower than the P_{MPP}. The MPP is the value delivered to the load, or in this case the battery. The P_{MPP} is the value that the solar cell can produce at maximum production.

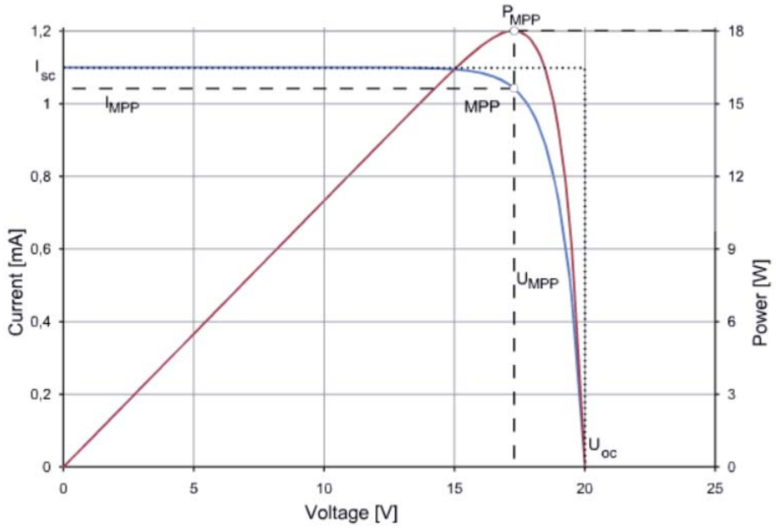

Figure 6.9. Maximum Power Point Tracking. [11]

The I_{sc} is the short circuit current, this is calculated when the voltage is at 0. *I (at V=0)*=I_{sc}[13].

The U_{oc} is the voltage at the open circuit, this is when there is no current running through the solar panels. *V (at I=0)*=V_{oc}

From this current and voltage curve and from the P_{MPP} the MPP can be seen from these.

6.3 | Battery Management

6.3.1 Lead acid battery

Batteries are used for storage of electrical energy. The most common type is the lead-acid battery that has been used in the car industry as energy storage for many years. The battery consist of 6 cells at 2 Volts nominal coupled in series to obtain the normal voltage of 12 Volt. Each cell has two plates (electrodes) of different materials submerged in a diluted acid solution. The positive electrode is made of lead dioxide and the negative electrode is made of pure lead and both is submerged in diluted sulphuric acid. This arrangement makes it possible to store electrical energy on chemical form and later on draw out electrical energy again.

6.3.2 Variations of lead acid batteries

Lead acid batteries comes in different variations that is optimized for different uses.

The starting battery version has been used in cars for many years and is the normal flooded type that can be topped with water. This type is mainly designed for large starting currents for the combustion motor where it is mostly charged directly after starting the motor and after that helps to maintain a stable dc voltage in the car. Starting batteries comes in a variation that is called maintenance free.

This version requires no water refilling in the lifetime of the battery. Starting batteries are not ideal for use in systems where the battery is deeply discharged more than 30-50 % because the lifetime of the battery is then shortened.

When it comes to lead acid batteries for deep cycle use there are two variations that both comes under the SLA, Sealed Lead Acid, category. The two variations is called AGM and gel batteries. The AGM battery, Absorbed Glass Mat, is equipped with glass felt mat in between the plates to hold the fluid electrolyte in place. In the gel battery the electrolyte is absorbed in a silica gel that gelifies it and holds it in place. Both variations is optimized for deep cycle use and has a much longer lifetime when used in deep cycle applications. The important differences between the AGM and gel battery is that the AGM battery is slightly cheaper and can be charged with a higher currents. Furthermore the AGM can put out a higher discharge current. A disadvantage of the gel battery is that it can be destroyed easily with high currents. Both variations has low self-discharge. Another advantage of the gel and AGM batteries is that they are VRLA type batteries, Valve Regulated Lead Acid, that has the ability of recombining the gases, hydrogen and oxygen, formed at the plates late in the charge-cycle, back into water instead of ventilating them out of the battery.

6.3.3 Charge voltages and currents AGM

CURRENT: To ensure long battery life when charging a battery it is advisable to limit the charge current below a certain level relative to the capacity of the battery. Normally the charge current should be kept below 25 % and not exceed 35 % of its Ah capacity. (Capacity 100Ah -> 25-35A max charge current). Other recommendations has mentioned that a chargers charge capability should be at 10 to 20 % of the battery Ah capacity.

VOLTAGE: In the same manner, during charging of the battery, the voltage shall be kept below a certain value to minimize the formation of gases at the electrodes. These gases is formed during electrolysis when water is split into its components, oxygen and hydrogen. The gases is in combination very explosive and another effect is that the amount of water reduces when the gases are not recombined and brought back into use. The lack of water will cause the battery to fail. The recommended voltage not to exceed for longer periods is 13.8V for a normal 12V AGM battery. During charging it is normal to allow the voltage to be as high as 14.4V until the battery is fully charged.

SUMMING UP: The limitations in current and voltages during charging results in the following battery charge curves.

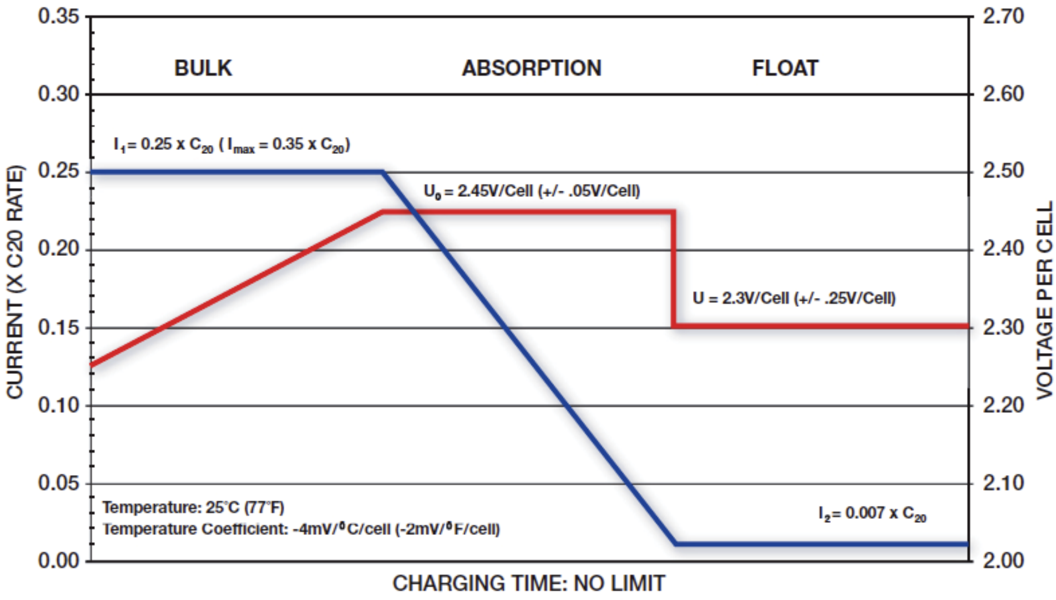

Figure 6.10. Battery charge curves. [14]

BULK: In this part of the charging process the current is limited by the charger and it can be observed that the current is constant until the voltage reaches the maximum charge voltage at 14.4V. The bulk period represents the majority of the charging process, that is up to 80 to 90 % of the capacity. After that the process enters a new state called the absorption.

ABSORPTION: In this part of the charging process where the battery is nearly fully charged, the voltage is limited to 14.4V and the current begins to decrease as the battery reaches full charge. When the current falls below a certain value (0.007*Ah Capacity) the battery is fully charged and the charger enters an new mode called float-mode.

FLOAT: In this mode the voltage is held at 13.8V by the charger. At this voltage the battery will maintain its fully charged condition without being overcharged. In some chargers this mode is called supply-mode and the charger will supply the load and maintain the battery at the same time.

6.3.4 Capacity and discharge current

The capacity of the battery is not a constant value but varies with the discharge current. The rated capacity of a lead-acid AGM battery is usually the C20 capacity. This notation indicates that it is the capacity when it is discharged during 20 hours from 100 % full to completely empty. If you have a 100Ah C20 battery it can put out 5 A for 20 hours before it is empty. The capacity changes when the discharge current changes.

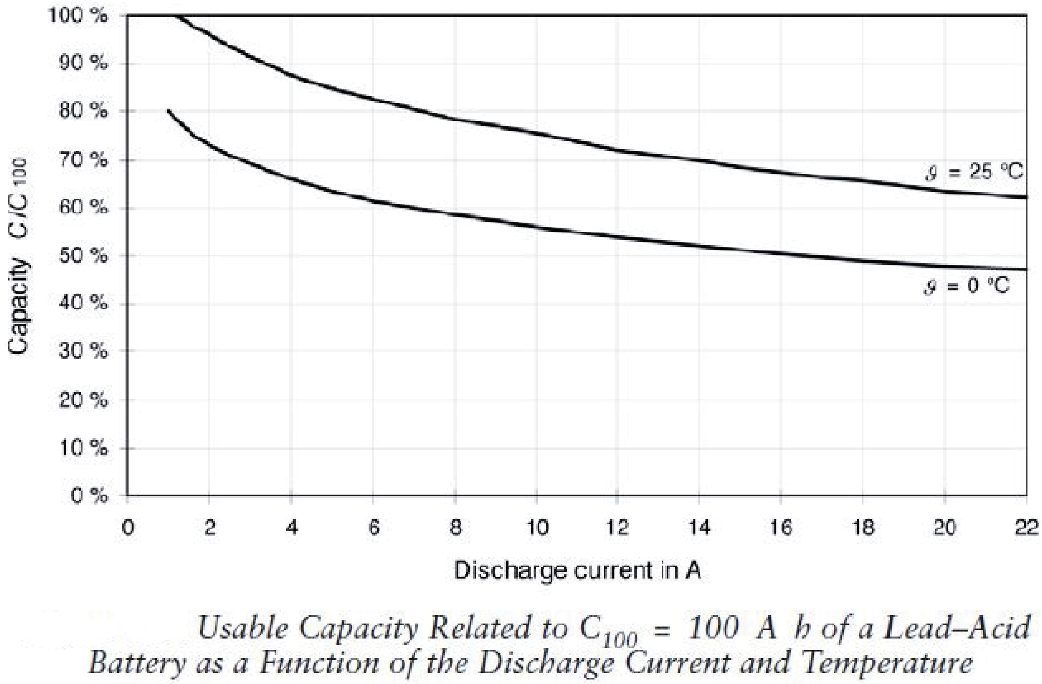

Figure 6.11. Battery discharge curves. [15]

This leads us to conclude that the discharge efficiency varies with the rate of discharge. Another disadvantage is that the lifetime of the battery can also be shortened with high rates of discharge.

6.3.5 Battery Lifetime and DOD - Depth Of Discharge

The lifetime of a battery is more or less directly connected to the number of ampere hours stored and used. This means that the deeper the battery is discharged the less cycles it has before it is worn out. The total numbers of Ah in a lifetime is not completely constant but also depends on the Depth Of Discharge. That is: Many deep cycles of cause uses many lifetime Ah but also reduces the total number of lifetime Ah. As mentioned before the rate of discharge (high discharge currents) also affects the lifetime.

The following figure shows the link between lifetime and DOD for an AGM battery from the manufacturer FullRiver.

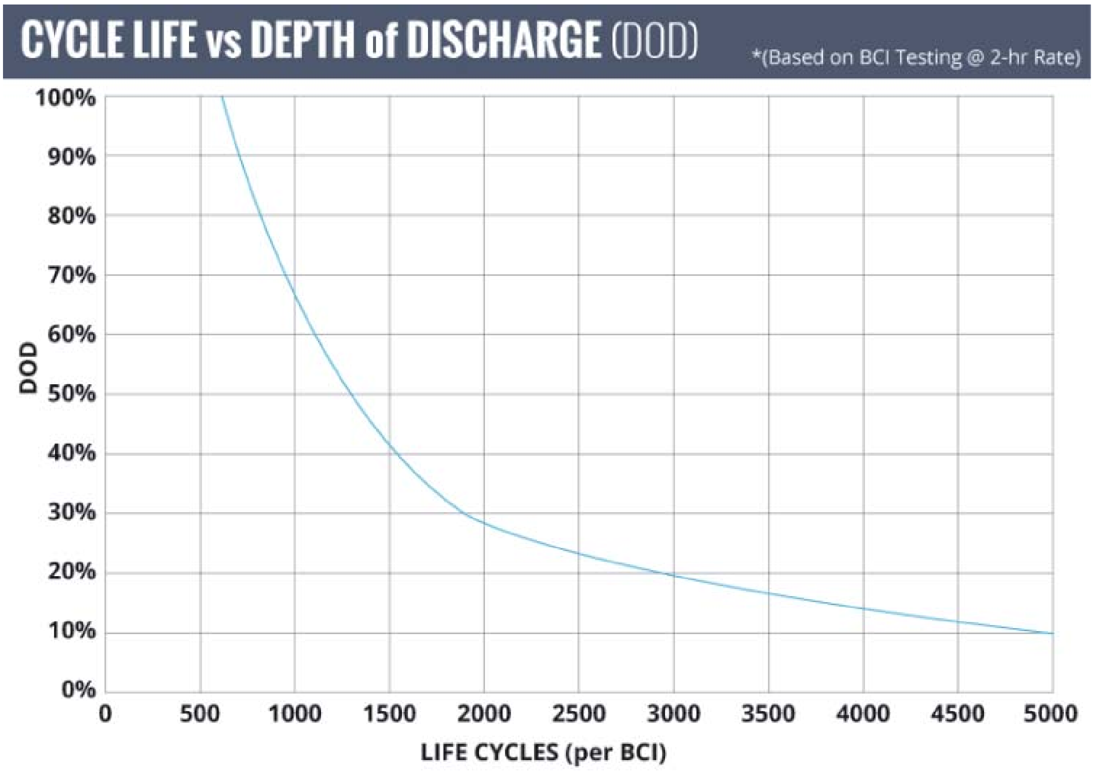

Figure 6.12. lifetime vs. DOD. [16]

From the figure there have been read the numbers and calculated a new graph that shows at which DOD the battery should be cycled to be most economic.

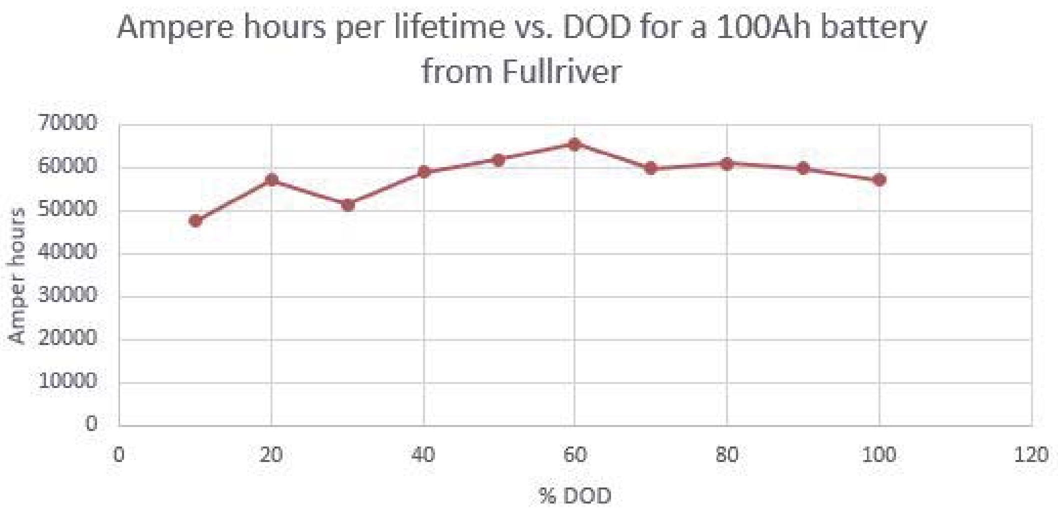

Figure 6.13. Total Ah in a lifetime vs. DOD

It seems that if the DOD is kept between 40 and 80 % it will give the most economic result. There can be read the total usable Ah for a 100Ah battery used in 100 to 60 % cycles to be 65000 Ah and if assumed that the cost of the 100Ah battery at 12 V is 1500Kr, the price of the battery per stored kWh can be calculated.

$$price = \frac{1500kr * 1000}{12V * 65000Ah} = 1.92kr/kWh \tag{6.5}$$

With the knowledge in mind that at higher DOD, the voltage will be lower and result in a bit lower Wh efficiency it probably would be wise to chose the working DOD for an AGM battery to be in the lower region of the 40-80 % interval.

6.3.6 Battery SOC - State Of Charge

The battery has a defined capacity measured in Ah.

The voltage observed at a battery at rest (open circuit voltage, no currents in or out) is dependent on the state of charge. 12,72V fully charged, 12.06V at 50 % empty, and 10.5V totally empty. Unfortunately this can only be observed when the battery is at rest and have been for a while (hours). When discharging the battery the voltages will be lower and when charging the battery voltages will be higher.

A different approach must be used to better achieve the SOC at all times. A better way is to sum up the energy Wh (Wh=3600Ws=3600Joule) or energy divided by the battery-voltage Ah (Wh/Ubat=Ah) put into or taken out of the battery. The average current through the battery is measured continuously for every constant time period and summed up to achieve the SOC, which is measured in Ampere Hours Ah. Unfortunately there are losses involved when charging and discharging the battery that causes the efficiency to be lower than 100 %. When charging and discharging the efficiency varies depending on the type of battery, amount of charge-current, temperature and age of the battery.

An equation for the SOC, State Of Charge in Ah with efficiency for charging n_{ch} and for discharging n_{dc} can be written as:

$$SOC_{now} = SOC_{start} + \frac{1}{T}\sum_{start}^{now} I_{bat} * (B * n_{ch} + \frac{1-B}{n_{dc}}) \tag{6.6}$$

T is the constant time interval measured in hours between measurements, and B is a logical 0 or 1 that depends on the polarity of the battery current I_{bat}.

In a sampled system the equations performed once per sample period, after the logical B is determined, can be written as:

$$SOC_{now} = SOC_{before} + \frac{I_{bat}}{T} * (B * n_{ch} + \frac{1-B}{n_{dc}}) \tag{6.7}$$

$$SOC_{before} = SOC_{now} \tag{6.8}$$

In the experimental system 100 % is used for both n_{ch} and n_{dc} due to lack of time.

HOW TO GET THE EFFICIENCY VALUES: When the battery is fully charged (the charging voltage has been applied for a period and the charge current falls below a certain limit for a period of time) the SOC can be set to full (100 %, or equal to battery capacity in Ah). When the battery is fully charged after a full cycle of discharge and charge it is possible to calculate the total efficiency of discharging and charging by comparing the sum of discharged Ah and sum of charged Ah. If the efficiency is repeatedly calculated and stored it can be used to predict/determine the SOC at all times. Furthermore the calculated efficiency can be used to determine when the batteries are worn out and should be replaced.

6.4 INVERTER

Most of the system is based upon DC supply except the CHP. This however can't be used with the loads operated in the house. All household electronic runs on AC power and because of this it's necessary to convert the energy produced in the system.

In this project a GP-12-300 have been used which is illustrated on figure 6.14. This inverter was chosen because one of the group members had one. This is only a one-way inverter which means that it will only convert the energy from DC to AC. This choice have been made because the CHP only will supply the loads and then sell the excessive energy produced. If the CHP should have been used to charge the battery as well a two-way inverter could be used to change the energy the other way around, from AC to DC.

Figure 6.14. GP-12-300 Inverter

An inverter uses PWM to generate a sinus wave. At a low amplitude at the sinus wave, it will use pulses of smaller width. As the signal rises so does the widths on the pulses. When these pulses have been generated, it takes the mean value of the pulses in small intervals, which will result in a sinus wave, which is illustrated in figure 6.15.

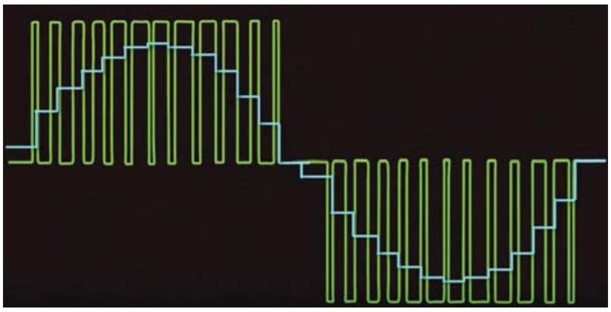

Figure 6.15. Converting DC to AC

6.5 | Combined Heat and Power

A Combined heat and power (also known as a CHP) is a power plant that makes both electricity and heat. It is working by adding fuel of any kind, this could be natural gas, oil, biomass or even garbage to be burnt. This fuel will be burnt as regular combustion engine. This engine is connected to a electrical generator by the shaft of the engine. Hereby the CHP will make electrical power.

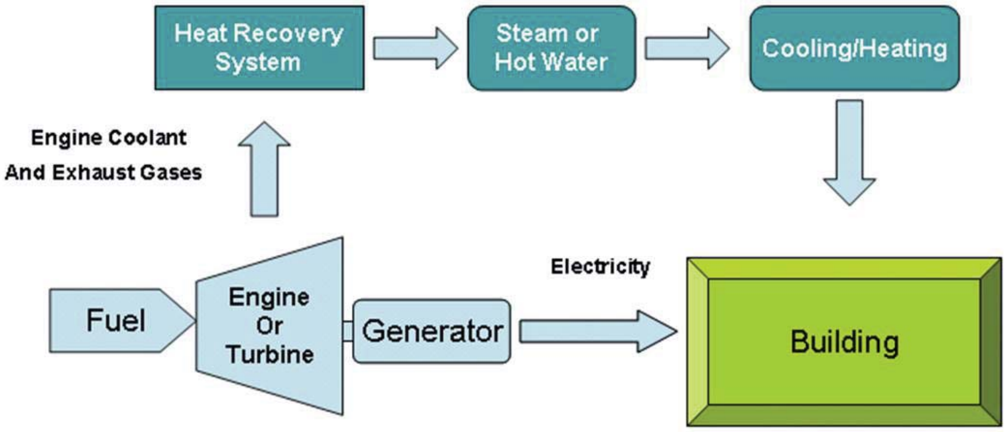

Figure 6.16. CHP System

The exhaust gases from the engine are directed from the engine and through several heat exchangers. Here the exhaust gas will heat up the water and thereby remove some of the heat into the water. This heat would have been waste if there wasn't a CHP system, but instead a regular power plant. This water that is getting heated up will be directed to the house and out to the houses radiators.

The rest of the exhaust gases that won't be obtained from the water, will be directed through a catalytic converter to remove some of the pollution of the gases.

By using this heat that would be wasted, the efficiency can by raised to about 80%. While normal power plants using gas or coal are down to approximately 38% efficiency.

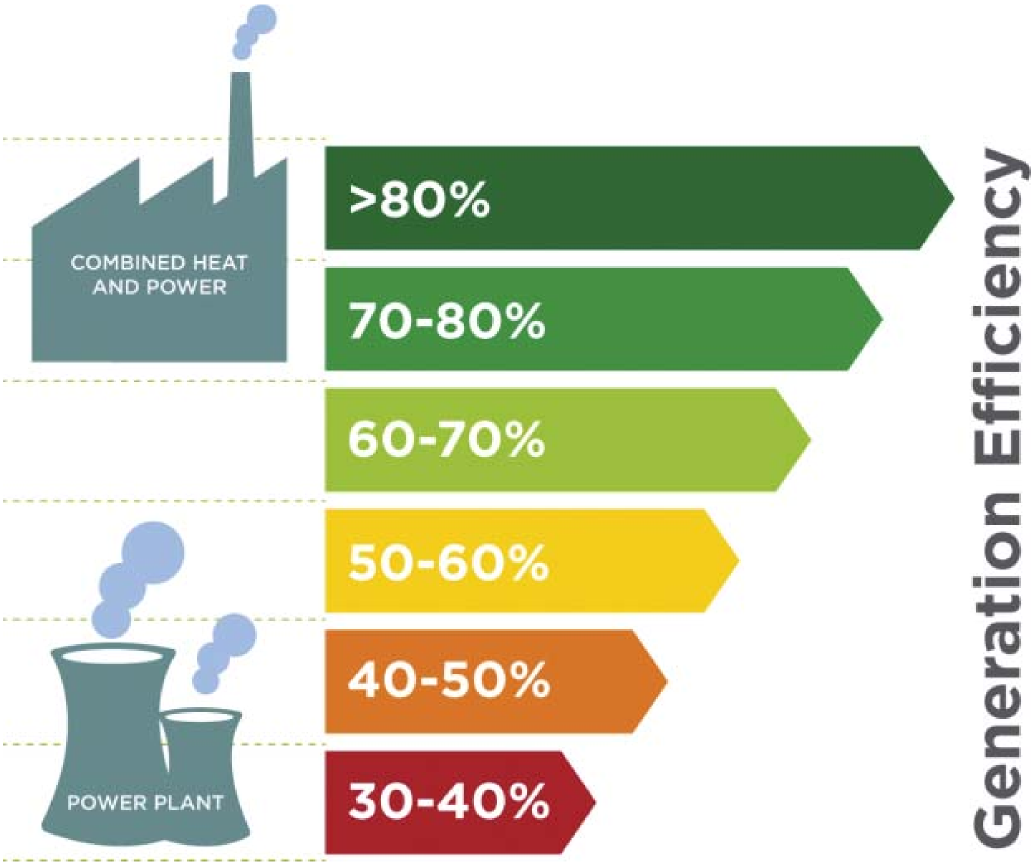

Figure 6.17. CHP Efficiency [17]

For calculating efficiency this formula can be used:

$$Efficiency = (OutputInPower / InputInPower) * 100 \tag{6.9}$$

The 100 in the end of this equation, is for making the result in percent.

For a load on the size of the house in this project, there will be needed a Micro-CHP. This is because a CHP power plants generates to much energy and heat, for just a normal house hold.

A Micro-CHP would be a good idea to use in this kind of project, because it will be possible to make the house more self-sufficient, by using the CHP to generate heat for the house. The electricity that is made in the CHP while making the heat, can either be used for the house loads, or sent out on the grid and sold.

6.6 | Current Transformers

To measure the current coming into the inverter there will be used a CT. A CT scales a higher current down to a more measurable value for measuring equipment. In our case the PLC. Since current measurements is done by being connected into series with the network, the primary winding's must be able to withstand the short-circuit currents coming from there.

6.6.1 CT TYPES

The book used in ESPR [18] states that there are generally two types of current transformers. One of them is the **Wound Primary Type** which is shown on figure 6.18. The wound type have winding's on both primary and secondary side of the magnetic core. This type is commonly used at lower levels of current.

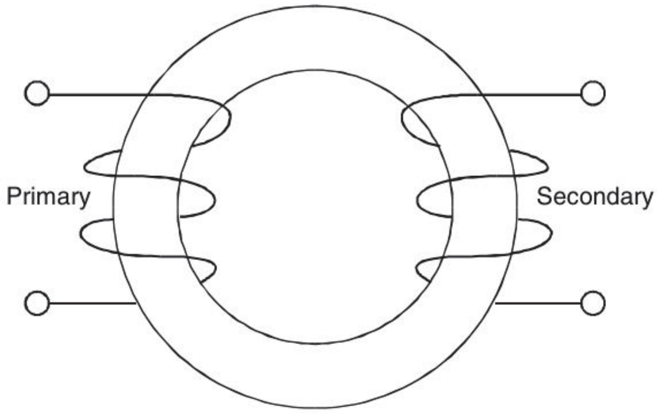

Figure 6.18. CT Wound primary type. [18]

The other type of CT is know as the **Bar Primary Type** which is shown on figure 6.19, where the cable is in the middle of the magnetic core instead of connecting a primary winding to the network. The cable is then used as the primary winding and on the secondary site, winding's are still used.

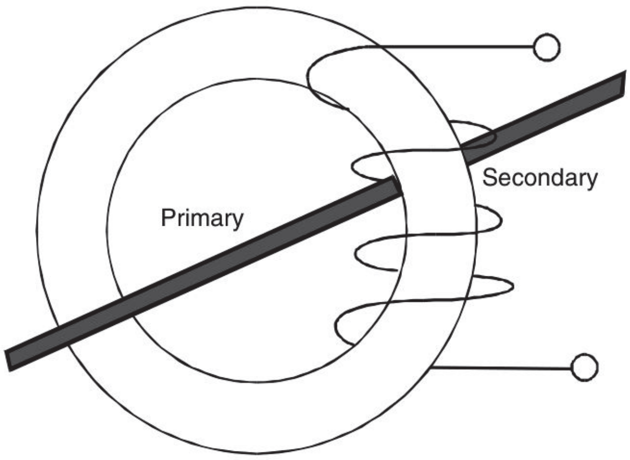

Figure 6.19. CT Bar primary type. [18]

The CT's measure the current passing through the primary winding's. The CT is able to do this measurement because of the current from the primary winding creating an electromagnetic field (B-field) in the magnetic core which will induce voltage into the secondary winding. The turn-to-turn ratio between primary and secondary side will determine the ratio between input at output. Because the CT's work by an exciting current passing through the winding, which is magnetizing the ferromagnetic material (the core), there will be introduced core losses, hysteresis, etc. Because of this a CT isn't ideal, no transformer is.

6.6.2 KNEE POINT AND MAGNETIZING CURVE

The best way to determine the CT's performance, is to look at it's magnetizing curve, since the core is non-linearly it follows the B-H characteristics. The magnetizing curve 6.20 focuses on three zones of the curve, the initial(when the core is starting to get magnetized), the unsaturated region (this region is approximately linear) and the saturated region (When the magnetic core is getting saturated and out of linearity) . The transition from the unsaturated to the saturated region introduces the **Knee Point**

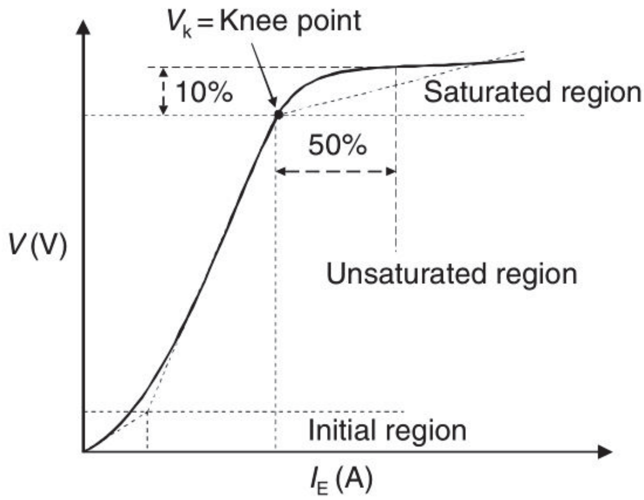

Figure 6.20. Typical CT magnetizing curve with Knee Point. [18]

The knee point is defined as the point where a further increase at 10% Volt on the secondary side, requires more than 50% increase in excitation current on the primary side. This means that the CT is close to linear in the unsaturated region.

Figure 6.20 is only showing the knee point curve for a protection CT. It's the same for a metering CT as used in this project. Metering CT's have to go into saturation earlier than the Protection CT. This is because it have to protect the measuring equipment on the secondary side of the CT. The measuring equipment used in cases where a metering CT is applied, is often more sensitive than a protection CT. Figure 6.21 shows the difference of the knee-point curves for metering and protection CT's. As the figure shows, it goes into saturation at a lower level than the protection CT.

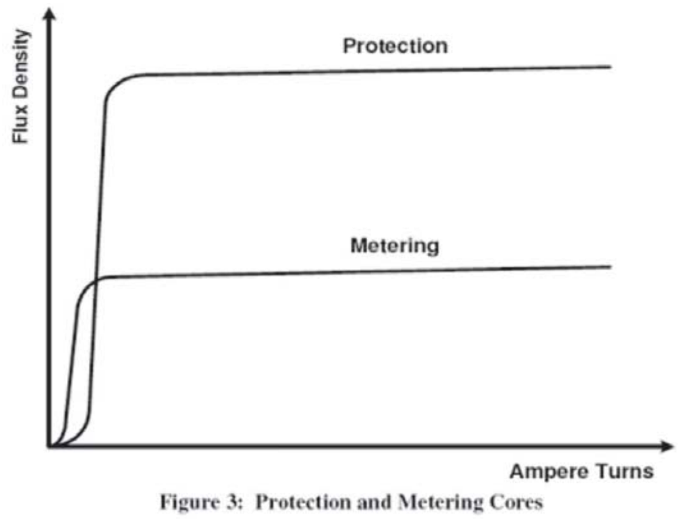

Figure 6.21. Magnetizing curve for metering vs protection ct. [19]

6.6.3 CT SPECIFICATION

There are many types of CT classes with different measuring areas and accuracy. They are specified after these terms.

1. A rated burden at rated current
2. An accuracy class
3. An accuracy limit factor

To show how an example could be for a CT, there will be used one from the book in ESPR [18].

There is a CT with the specification of: **15VA 0.5 Class 1,0**. It can now be determined what the burden, accuracy class and limit factor is.

1. The rated burden is specified to be 15VA. This is for the entire secondary site, not only CT but also cables and instruments after.
2. 0.5 Class 1,0 shows us that the CT have an accuracy of 0.5% up to 1 times the normal rated current.

6.7 | PLC

To control the modes of the system, there will be used a **PLC**. A PLC is a Programmable Logic Controller. As the name implies, it is a device that uses logic in form of Boolean expressions which can be programmed so it behaves as the programmer intends it to. There are different kinds of brands in the PLC world, the one being used here is a Siemens S7-1214C DC/DC/DC. This is one of the more basic PLC's. In this PLC there is a WinCC language for HMI (Human Machine Interface). The HMI is the interface of which the User will be able to interact with the PLC and thereby interact with the system.

Figure 6.22. PLC S7-1214C

The PLC is often used for industrial purposes because of several reasons, these reasons are also taking into account in this project.

One of the reasons is because of the high reliability. The PLC S7-1200 that are used here, are made to last approximately 24 years and some even up to 79 years. Therefore it is a cheap device because it shouldn't be changed to a new one before most of the code already is outdated or some of the other physical devices are outdated. Second reason is because it can easily take the analog inputs and convert them into data, the programmer of the PLC can work with. The PLC can take an input of **0-5V, 0-10V, -10-+10V, 0-20mA or 4-20mA**. In this project there will be used an input range of 0-10V because the range of the wire won't be large enough to make an impact on the signal strength. It could have been chosen to be a current signal and in some cases this would be better. This is because that if the voltage signal is being transmitted through a longer wire would cause a loss due to the resistance of the wire. If this voltage is converted into a current instead, then there won't be any loss on the signal because of Kirchoff's current law.

6.8 | Safe Communication

Safe communication are important when there are being data transmitted from one device to another. In every communication there needs to be a Server and a Client.

In this project there have been considered several transmitting protocols.

One sort is TCP (Transmission Control Protocol). TCP uses a server (This is the device who are sending the data). And a Client (This device retrieves the data). The server is sending the information through several layers before it is getting transmitted over the internet and have been received by the Client. The client also needs to process this data through the same kinds of layers, but backwards.

The server needs to send the data first through the Application layer. This layer is the only layer where the User are able to see and interact. The next layer is the Transport layer, this layer is responsible for handling the communications between the devices. The next layer is the Network layer, this layer will connect the devices and make sure that the data will be divided into packages, which the Client are able to read. The last layer is the Physical layer, this layer are connecting the device to the internet, this is only a link that will be established between the required devices. [20]

The Client receives this data through the Physical layer, up to the Network layer, up to the Transport layer and finally to the Application layer, where the user here are able to read the data or information which the Server has send.

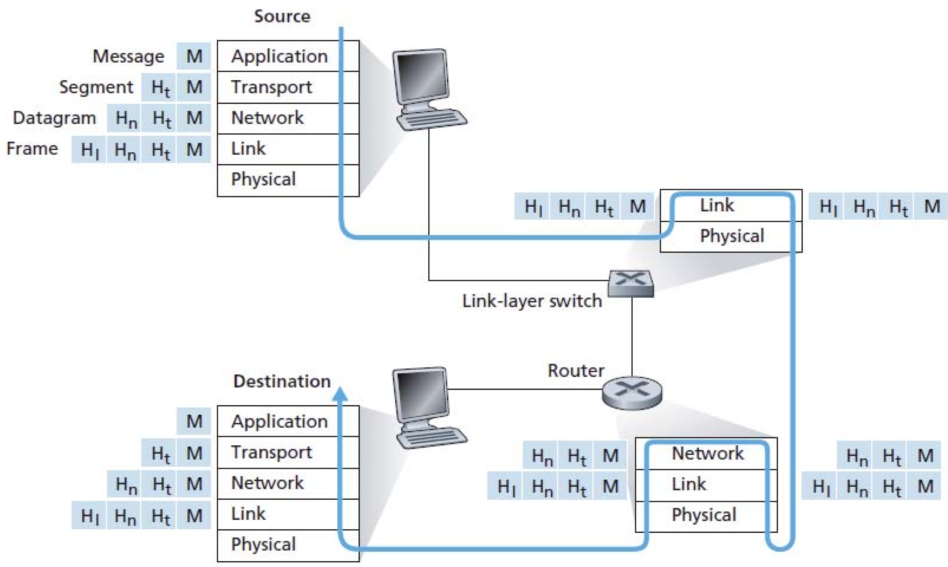

Figure 6.23. Route [21]

On this picture 6.23 the route of the signal can be seen. Here the Source is the Server and the Destination is the Client. There is also a Link-layer switch and a Router, these two devices are devices which can help making a way through the internet. These two devices won't need any transport layer or application layer, because the user won't have any impact on this stage.

Out from each layer (Except the physical layer), there is a writing with some blue text. This blue text is headers from code in the specific layer. In this way the different layers know when they should react.

The other sort of transmitting protocol considered are UDP (User Datagram Protocol). A UDP have the same layers as the TCP has. The difference between these two layers are that the TCP, makes sure that all the send data from the Server side will be received on the Client side.

This is able by using the terms of ACK (Acknowledged) and NACK (Not Acknowledged). If the Client received the data package, then there will be send a ACK to the Server to let the Server know, that it got the message and it should not be transmitted again. If the Client send a NACK instead, the Server knows that the Client haven't received the data, or it was damaged when it got the the Client, then the Server will send this data package again until the Server receives a ACK from the Client.

This ACK and NACK technique is not used by the UDP. Therefore the Client and thereby the User will not be sure to get all of the data or information from the Server.

The UDP on the other side are much faster than the TCP, because it won't have to check all of the data being transmitted if it is broken or not received. UDP is a good protocol to pick if the User are getting a lot of data and the information not will be ruined, if there is some data left behind.

This is therefore the protocol that would have been chosen to this project. There will be a lot of data transmitted and it won't be necessary to have all the information, to make the required decisions.

Sizing | 7

In this chapter there will be made a sizing of the individual products, to be able to be integrated in a average house consisting of a family of four. The house is based upon the average consumption which is about 150 m^2. It's assumed that the type of roof is pitched with a slope of 30 degrees.

To calculate the available area of roof, geometry has been used.

$$AreaOfRoof = \frac{\frac{WidthOfHouse}{2}}{cos(SlopeOfRoof)} * LengthOfHouse \tag{7.1}$$

$$AreaOfRoof = \frac{\frac{10m}{2}}{cos(30)} * 15m = 86.603m^2 \tag{7.2}$$

The proportion between width and length of house is indifferent as long as the multiplication of these to equals the area of the house wanted, which in this case was 150m^2

7.1 | Energy demand

As an example a group member has recorded the energy used in the house for the last 8.5 years. From that it can be seen that the daily consumption is 15kWh when the energy for heating is ignored. This average of daily consumption is almost equal to the energy used in a average house consisting of four. Therefore this recorded values will be used for further sizing.

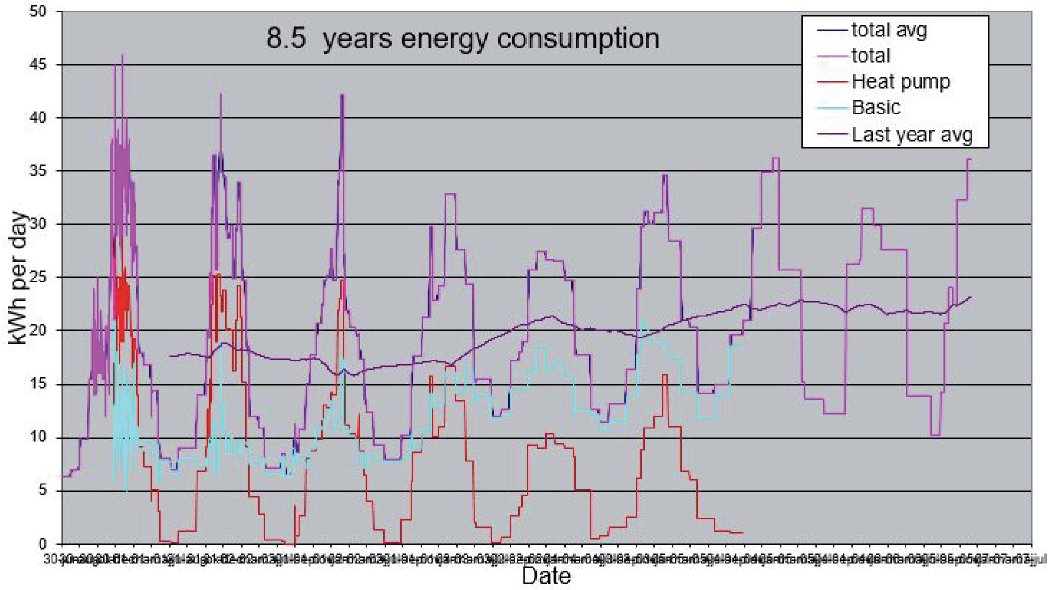

Figure 7.1. Energy consumption

7.2 | Calculations of PV-system

In this project, the intent was to find a PV-system that would be able to cover most of the electrical use for the house. As stated the house roof would be a size of 86.603m^2 from equation 7.2. To calculate the size of the system this equation is used:
The equation and information about these are found at [22]

$$P_{PV} = Y_{PV-STC} * F_{PV} * \frac{G_T}{G_{T-STC}} * (1 + \alpha_{Panel} * (T_C - T_{STC}) \quad (7.3)$$

The following parameters in the equation is explained below.

- $Y_{P_{PV}}$= Is the output of the PV-cell at any moment in Watts.
- Y_{PV-STC} = Is the rated power-output under STC test in Watts.
- F_{PV} = Is the PV derating factor from the panel, a standard setting is chosen at 75%
- G_T = Is the radiation on the panel at any moment. The factor chosen for this will be the annual radiation pr m^2 in Denmark. [23]
- G_{T-STC} = Is the radiation on the PV-panel during STC test
- α_{Panel} = Is the Temperature coefficient of P_{MPP} of the panel.
- T_{STC} = Is the PV-cells temperature during the STC test in °C.
- T_C = Is the temperature inside the cell in°C, the temperature is dependent on the ambient temperature of its surroundings and the radiations. T_C is givin by this equation $T_C = T_a + G_t * (\frac{NOCT_{temperature} - STC_{temperature}}{NOCT_{radiance}})$ [24].
- T_a Is the ambient temperature. The chosen factor is the average temperature in Denmark, which is 8.4°C.[25]

The choice for taking the annual irradiance production pr m^2 and the average temperature in Denmark, is to get an estimate of the annual production from one pane. When that information is acquired it can

then be multiplied to the desired amount of panels to suffice the consumption of the load.
The information there is needed to gather from the data sheet are Y_{PV-STC},G_{T-STC} and T_{STC}. These can be found in the data sheet under STC Test data. There are two types of test data in the data sheet. Two tests are done to determine the data of the PV. The first test is STC(Standard Test Conditions test are made under perfect laboratory conditions, irriadiance at 1000 W/m2 and a cell temperature at 25 degrees Celsius)
These conditions are far from real conditions. Instead there is made a test called NOCT (Nominal Operation Cell Temperature, where it aims to simulate reality, the irradiance is 800 W/m2 and a cell temperature is at 45 +- 3 degrees Celsius(This is because the panels heats up under use) and the ambient temperature outside of the panel is 20 degrees.).

The panels that are being used in this project is the following panel ***REC TWINPEAK 2 BLK2 Series - Best performance module. Which are the Polycrysttalin modules***. The sun panels effect is rated at 285W. This is the rated watts at STC.

The desired information to fill the equation have been gathered from the data sheet. The calculations are shown in figure 7.2

ELECTRICAL DATA @ STC	Product Code*: RECxxxTP2 BLK2		
Nominal Power - P_{MPP} (Wp)	275	280	285
Watt Class Sorting - (W)	0/+5	0/+5	0/+5
Nominal Power Voltage - V_{MPP} (V)	31.6	31.8	32.0
Nominal Power Current - I_{MPP} (A)	8.71	8.82	8.92
Open Circuit Voltage - V_{OC} (V)	38.2	38.4	38.6
Short Circuit Current - I_{SC} (A)	9.28	9.39	9.40
Panel Efficiency (%)	16.5	16.8	17.1

Values at standard test conditions STC (airmass AM 1.5, irradiance 1000 W/m², cell temperature 25°C).
At low irradiance of 200 W/m² (AM 1.5 and cell temperature 25°C) at least 95% of the STC module efficiency will be achieved.
*Where xxx indicates the nominal power class (P_{MPP}) at STC indicated above.

TEMPERATURE RATINGS	
Nominal operating cell temperature (NOCT)	44.6°C (±2°C)
Temperature coefficient of P_{MPP}	-0.36 %/°C
Temperature coefficient of V_{OC}	-0.30 %/°C
Temperature coefficient of I_{SC}	0.066 %/°C

REC TWINPEAK 2 BLK2 Seriues - Best performance module.

$$Y_{PV\_STC} := 285 \quad F_{PV} := 0.75 \quad G_t := 1040 \quad G_{T\_STC} := 1000 \quad T_{NOCT} := 44.6 \quad T_{gennemsnit} := 8.4$$

$$T_{STC} := 25 \quad T_C := T_{gennemsnit} + 1040 \cdot \left(\frac{T_{NOCT} - 20}{800}\right) \quad \alpha_p := -0.36\% \quad A_{panel} := 1.67$$

$$P_{req} := 15 \cdot 365 = 5.475 \cdot 10^3 \quad P_{req\_plus20percent} := P_{req} \cdot 1.20 = 6.57 \cdot 10^3 \quad P_{daily} := \frac{P_{req\_plus20percent}}{365} = 18$$

$$P_{PV\_panel} := Y_{PV\_STC} \cdot F_{PV} \cdot \left(\frac{G_t}{G_{T\_STC}}\right) \cdot \left(1 + \alpha_p \cdot \left(T_C - T_{STC}\right)\right) = 209.992 \quad \text{kWh/year}$$

$$PV_{panels} := P_{PV\_panel} \cdot x = P_{req\_plus20percent} \xrightarrow{solve, x, float, 3} 31.3$$

$$PV_{Panels} := 31$$

$$Roof_{Area} := PV_{Panels} \cdot A_{panel} = 51.77$$

$$PV_{Production\_yearly} := P_{PV\_panel} \cdot PV_{Panels} = 6.51 \cdot 10^3$$

$$P_{total\_of\_system\_PEAK} := Y_{PV\_STC} \cdot PV_{Panels} = 8.835 \cdot 10^3$$

$$P_{Daily\_kWh} := \frac{PV_{Production\_yearly}}{365} = 17.835$$

Figure 7.2. Calculations of PV under annual danish radiation and average temperature

As seen in the calculations at figure 7.2, there would need a total amount of 31 panels to fulfill the desired power consumption of the household. When a 20% factor is taken into account of the daily use, it ends up with a daily use of **18 kWh**. The production estimate of the system would be **17.385 kWh** This can of course deviate because of different weather conditions. These calculation should give a fair estimate that should be efficient enough to supply the household. It is important when choosing the *Inverter* that it can handle the $P_{total-of-system-peak}$ *on 8835 kW.*

In the summer it would produce more than the estimate due to more radiation. In the winter where the radiation is lower due to the earths orbit around the sun, the production will be lower. This is where the CHP will step in and help supplying the electricity for the household.

When using this many PV-panels, the setup of the strings have to be taken into account, because of the voltage that the inverter can tolerate has a limit.

7.3 | Choice of inverter

When choosing the inverter for the house, several demands have to be taken into account:

- 3 fased hybrid inverter with the ability to go on grid.
- Can handle a lead-acid battery bank at 48V, and capacity of 525Ah.
- Must be able to handle at least 9kW from the solarpanels.
- 1 or 2 strings for the solarpanels depending on the the max input voltage.

As an example of an inverter that can meet these demands is the MPI 10K hybrid inverter.

Figure 7.3. Inverter MPI-10K hybrid. [26]

DC spændingsområde	350 – 900V (Voc)
DC MPP område	400 – 800V
MPP tracker	2 stk.
Max. paneleffekt	2 x 7500W2x 10.000Wp2x 12.000Wp (mindre tab)
Batteri ladning max.	200A (48V)
AC spændingsområde	184 – 264V per fase / 400V 3-faser
Max. udgangseffekt	10000W / 3 x 14,5A
EU virkningsgrad	96% / 95%

Figure 7.4. Data MPI-10K hybrid. [26]

7.4 | Battery

The required solar power produced is mainly dependent on the power required for the loads and loss in the system. The sizing of the battery is dependent on the amount and timing of produced energy and used energy. This leads to the use of Matlab to simulate the SOC to determine the battery size.

To simulate it is necessary to have a profile for used energy and produced energy.

In the project a system is sized to a load of 15kWh per day, which is equal to the consumed electrical energy in the house of one of the group members. This consumption is considered sufficient to cover the consumption mentioned in section 1.4. These value is almost identical and because of this the sizing will be done from the data measured by the group member. Same group member has obtained an offer from a provider of hybrid solar panel systems. In the offer is included the estimated power profile normalized for one day.

Figure 7.5. Estimated day load profile. Picture is from appendix 1A

In Matlab there have been established an array that represents the load profile, and another array that represents a simplified profile of produced power from the solar panels. Both arrays has 1440 points per day. Each point represents 1 minute.

Figure 7.6. Power profiles. Matlab simulation

The next figure displays a cumulative summation of the load energy and a cumulative summation of the produced energy.

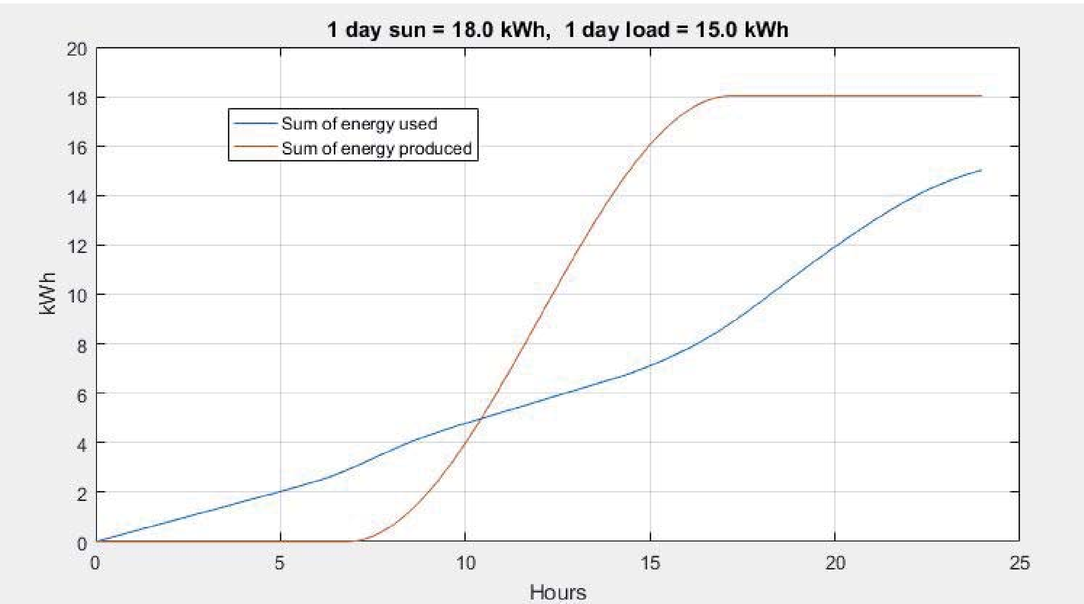

Figure 7.7. Sum of energy. Matlab simulation

With the use of the profiles of the load power and produced power is established a representation of the SOC for the battery which also includes the loss of energy at charging and discharging.

The equation for the SOC, State Of Charge in kWh with efficiency for charging n_{ch} and for discharging n_{dc} can be written as:

$$SOC_{now} = SOC_{start} + \frac{1}{T}\sum_{start}^{now} P_{bat} * (B * n_{ch} + \frac{1-B}{n_{dc}}) \tag{7.4}$$

T is the constant time interval measured in hours between measurements, P_{bat} is the battery power in kWh, and B is a logical 0 or 1 that depends on the direction of the battery power. (charging or discharging)

The PSOC in % can be calculated from the SOC in kWh and the batterycapacity Bat_{cap} in kWh:

$$PSOC = \frac{100 * SOC}{Bat_{cap}} \tag{7.5}$$

The equations 6.3 and 6.4 is calculated in the Matlab code part 3 in fig6.8

The span of the simulation has been expanded to a full week to get a better overview of the stabilization of the curve.

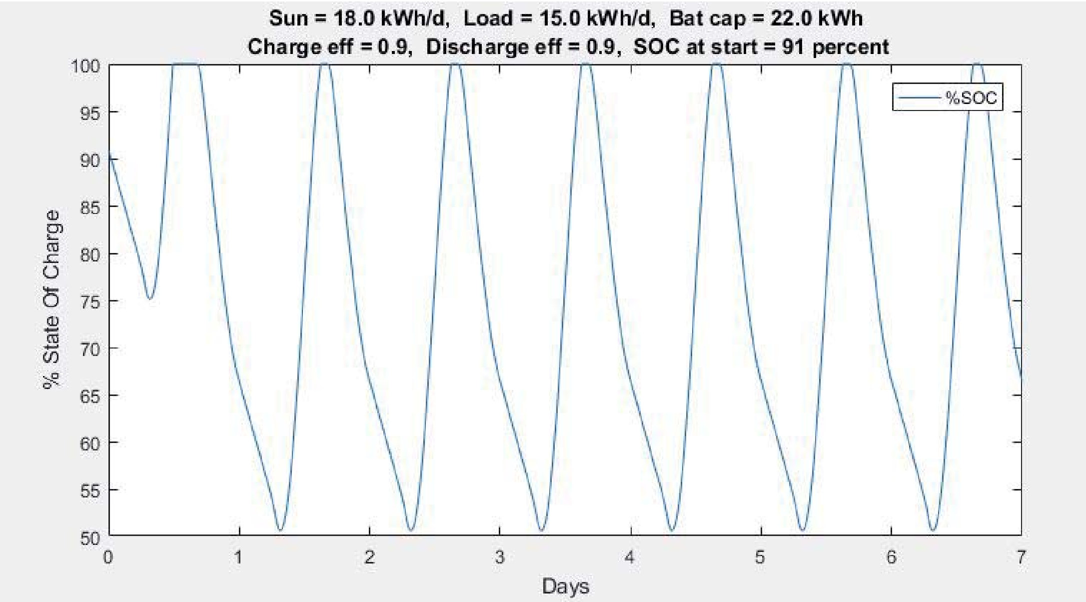

Figure 7.8. SOC for 1 week. Matlab simulation

After several iterations with different input values it seems that the battery size should be at least 22kWh, at 48V it is 22000/48 = 458Ah, to avoid that the State Of Charge goes below 50 percent. With the addition of charge and discharge efficiency at 0.9 the simulation shows that the daily produced energy should be more than 18 kWh.

In the following 3 figures is shown the essential Matlab code for calculating the SOC used for sizing the battery.

```matlab
%constants
min=1; hour=60*min; day=24*hour; week=7*day; year=52*week;
%input variables
daysun=18;%Energy produced i 1 day in kWh
avgload=15;% average load for 1 day in kWh
Batcap=22; %defines batterycapacity in kWh
socstart=20; %defines SOC at start in kWh
n_ch=0.9; n_dc=0.9;%defining the charge and discharge efficiency

%one day sunpower simulation.
t1=0:1/hour:(day-1)/hour;
peaksun=daysun/6.73;%empirial factor to get correct vaules
%simulated sunpower as cosinus func.
daysunpower=peaksun*(-0.25-(1+0.25)*cos(2*pi*t1*hour/day));
daysunpower(daysunpower<0)=0; %negative power rounds up to zero
daysumsunpower=cumsum(daysunpower/hour); %sum of produced energy
```

Figure 7.9. Matlab code part 1

```matlab
%one day load
dayloadprofile=[2.7,2.7,2.7,2.7,2.7,2.7,3,4.5,4.5,3.5,3,3,3,3,3,4,5,6.5,7.5,7.5,7,6.5,5.5,4,2.7];
dayload=t1;
for i=1:24
 for j=1:60
 dayload((i-1)*60+j)=(avgload/100)*(dayloadprofile(i)+(dayloadprofile(i+1)-dayloadprofile(i))*(j/60));
 end
end
daysumload=cumsum(dayload/hour);% Sum of load energy

%defining 1 week array length of simulation in minutes measured in hours
t=0:1/hour:(week-1)/hour;
% 1 week simulated sunpower as cosinus func.
sunpower=peaksun*(-0.25-(1+0.25)*cos(2*pi*t*hour/day));
sunpower(sunpower<0)=0; %negative power rounds up to zero
%produces 1 week array of load power.
Load=[dayload,dayload,dayload,dayload,dayload,dayload,dayload];
```

Figure 7.10. Matlab code part 2

```
soc=sunpower;%produces SOC array with same length as Sunpower
%summing up SOC minute by minute in a loop
M=length(t);%defining counter for loops
%First iteration uses start value of SOC (but not efficiency)
soc(1)=socstart+(sunpower(1)-Load(1))/hour;
for i=1:M-1 %summing up
    batpower=sunpower(i+1)-Load(i+1);
    if batpower>=0 %charging
        soc(i+1) = soc(i)+(batpower*n_ch)/hour;
    else            %discharging
        soc(i+1) = soc(i)+(batpower/n_dc)/hour;
    end
    soc(soc>Batcap)=Batcap;%limit when battery is full
    soc(soc<0)=0;%limit when battery is empty
end
psoc=100/Batcap*soc; %calculates SOC in percent
```

Figure 7.11. Matlab code part 3

7.4.1 Choice of battery

It seems that 20 pcs of the AGM battery "GNB Marathon M12V105FT" can be used to make a battery bank of 48V 525Ah which total capacity is 48*525=25.2kWh.

Figure 7.12. GNB Marathon M12V105FT. [27]

7.5 | CHP

With a house at the required kWh and heat that is in this project this CHP on figure 7.13, will make enough electricity and heat for the house. It has a electrical output on up to 6**kW** instantaneous. And a heat output on 12.2**kW** instantaneous. *(This is with a system that won't regulate power with a power controller)*.

This will mean that if the CHP runs with full load and thereby makes, 6**kW** instantaneous, there will be surplus of electricity and should therefore be sold onto the grid. In this way there will not be as much waste on electricity. It would of course not be economically good to use fuel on the CHP, just to sell the electricity on the grid, but only when there occurs surplus electricity by the CHP.

Figure 7.13. CHP System [28]

7.6 PLC

The PLC S7-1214 is sufficient in almost all ways for this project. The only lack it has is the needs for more analog inputs.

To enable more than the two analog inputs available in the PLC a module is required to extend this possibility. This module could for example be a **Siemens SM 1231 AI - 6ES7231-4HF32-0XB0** which will enable up to eight analog inputs. This is enough to enable all the measurements wanted for the finale product. These inputs would lead to a more accurate system because more factors could be a part of the calculations and control the modes operating. The module chosen is illustrated on figure 7.14.

Figure 7.14. Siemens SM 1231 AI - 6ES7231-4HF32-0XB0

HW Design and Implementation | 8

This chapter will be focused on the prototype ("Proof of concept") This chapter will include hardware design and implementation. There will be calculations, design, thoughts and a final result of the prototype components. Which includes Hardware sensors and transmitters.

8.1 | Over all circuit design

In this section there will be gone through the hardware components of the prototype. In the prototype there is wanted a simulation of a small house. The primarily hardware components consist of the following:

- **Charge Controller** which makes sure that the battery is charged with the best current and voltage. The charge controller which is used is the BlueSolar MPPT 75 / 15
- **Battery**, is a 6613 Brandford 12 volts 60aH battery. It is a car battery but will serve its purpose for the prototype.
- **Inverter** the inverter is GP-12-300, which is used to convert DC to AC for supplying the household loads and the grid. See analysis section 6.4 for further information
- **CHP**, which will be simulated by using the **Schneider LC1D09BD**, for further information look at the Analysis section 6.5 for further information.

The intent for the use of these relays (Schneider LC1D09BD) was to be used as simulation of the different 230 Volts loads in the house. But instead there is used a variable 230 Volt power load to simulate the different loads through out a day. The relays will be used as switches instead to turn on the Battery, activate the CHP to grid and when to sell the surplus energy from the PV. To see when the switches are active, a small LED has been placed over each relay, to indicate if it is active.
The relays are not connected to anything on the prototype.

The overall circuit design is shown in figure 8.1. There have been implemented a sensor circuit which consist of multiple components described in the sections about the different sensors. The sensor circuits are shown in figure 8.2

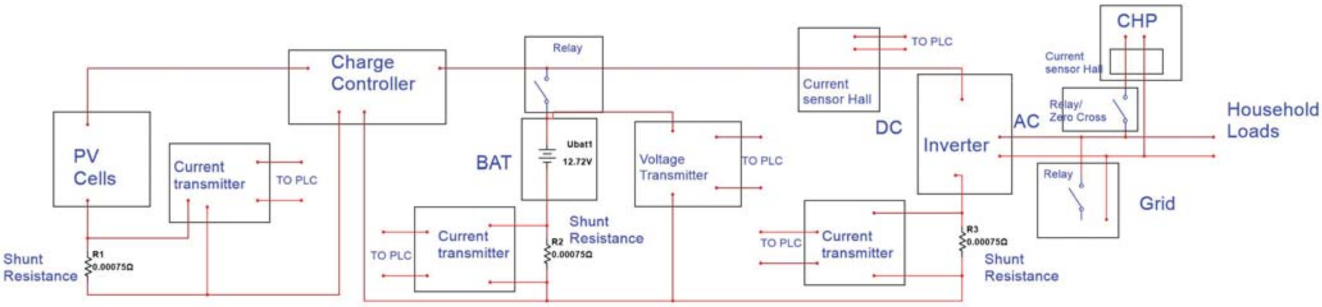

Figure 8.1. Over all circuit design

Explanation for the figure 8.1 is that there is DC on the left side of the inverter, the right side is converted to AC where the CHP will help to supply energy to the grid if the SOC and solar productions isn't high enough.

There should be a current transducer on the AC side to measure the consumption in the household and the production of the CHP. But due to the lack of inputs in the PLC it haven't been implemented. There could be used the same circuit with the Honeywell Transducer.

There is a PV (*see further in analysis section 6.1*) which goes into the Charge controller. The Charge controller supply's the battery, the build in MPPT will make sure that it is charged properly. The battery and PV cells will provide DC to the inverter. To measure how much the production there are on the PV's, a shunt resister and a current transmitter have been used to measure the voltage. there are used the same to determine how much power is being used in the house by having it on the battery.

The measurement for the PV's are not used in the prototype, they are implemented but due to the lack of inputs they aren't used. There isn't a PV connected to the system, but there is made a sun-profile to implement that function. For further information about the sun profile see section 9.2.5

For this measurement there is two different sensors, a IC design (Integrated Circuit) and a CT design (*Current Transformer, see section 6.6 for further information*) which in this case is a current transducer from Honeywell. Further information about the design, is explained further down in the section.

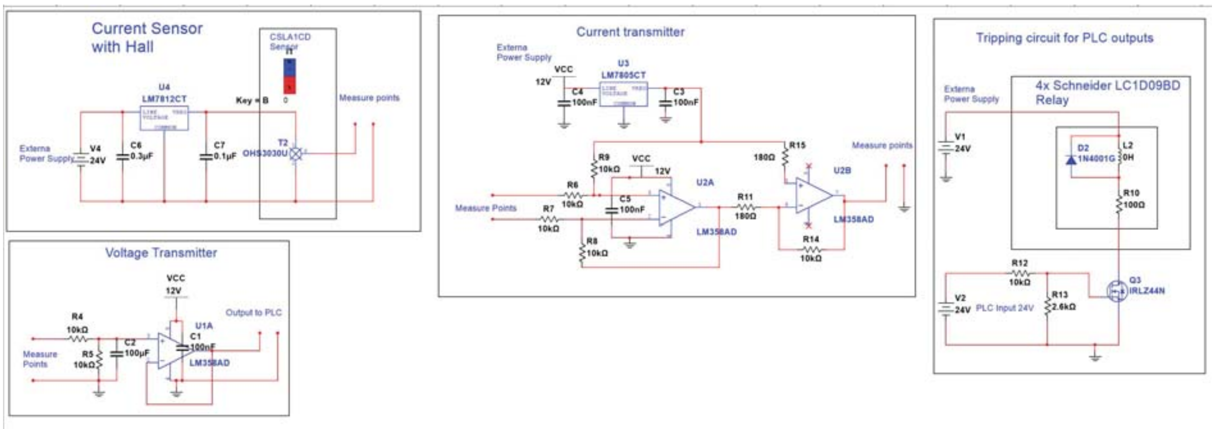

Figure 8.2. Sensor and transmitter design

The circuit was made in mind to have a simplified circuit, that could show the concepts of what the project could be developed into.

8.2 | Design and implementation

In this section, it is possible to find information about the hardware components design and realization. Which include different currents and voltage transmitters and sensors. These sensors and transmitters will be used to send information to the PLC. The PLC will handle this information (which will be in volts) and makes calculations to what the power consumption in the house is and the voltage on the DC side.

8.2.1 Circuit for the PLC to trip relay

Since it is a simulated system in this prototype, there is needed some relays to simulate when the PLC is activating the different parts in the system. It was possible to find some relays in school that could be used for the project.
The relays where a **Schneider LC1D09BD** which is a relay for industrial use. It can be used for Resistive Load(Heaters and such) or Motor control. If it was to be used for motor load it would need to be in series with some motor protection. It will be used to simulate the most realistic way possible.

Figure 8.3. Picture of the Schneider LC1D09BD. Picture is from [29]

There is made a test for the relay to see if the output current from the PLC were enough to activate the coil inside the relay. There is then found in the manual for the PLC-S7-1200 series, that the output voltages where 24V DC with up to 40mA of current. During the test, it was shown that the output from the PLC wasn't high enough to trigger the relay. Because of this an external power supply was needed to help trigger the LC1D09BD relay.

There is made a new test where it were found that the internal Resistance of the relay, was 100 Ohms. When tested on a power supply, it would trip at 14 Volts with a current of 140 mA. It were found that the current is linearly with the voltage on the coil. It is stated to trigger at 24Volt and a minimum of 17Volt. It were found that it could trigger as low as 14Volt. The Module test can be found at table 8.2

There are used an external Power supply which comes with the PLC. It was desired to trip the relay with the help of the PLC outputs. There needed a circuit which would help with that. For that there was needed an external PSU and something that could help to trigger the Relay. It was found that it would be able to use a MOSFET called **IRLZ44N** which is working best with 5 volts on the Gate. Since the PLC had an output on 24 volts. a voltage divider would be needed. which is derived out from the following equation.

U_{plc} is the output voltage from the PLC 24 Volts
R_1, R_2 is the resistors. We chose resistor R1 to be 10k
U_{req} is the required voltage of 5Volts

$$U_{PLC} = U_{req} * \frac{R_2}{R_1 + R_2} => 24V \quad = 5 * \frac{10K}{10K + R_2} solve, R_2 = R_2 = 2.6K \tag{8.1}$$

After the last resistor was found the voltage divider, a simulation was performed. Multisim was used as simulation tool. Since the correct relay isn't in the program, there is made a configuration in Multisim to simulate it. The relay consist of a *Built-in bidirectional peak limiting diode suppressor* to suppress the peak current. So the need for an external diode is removed. Since the measured internal resistance of the relay is 100 Ohm's, that is been used. Since the impedance isn't know of the inductor, it doesn't have a value in the simulation. The circuit is shown in figure 8.4.

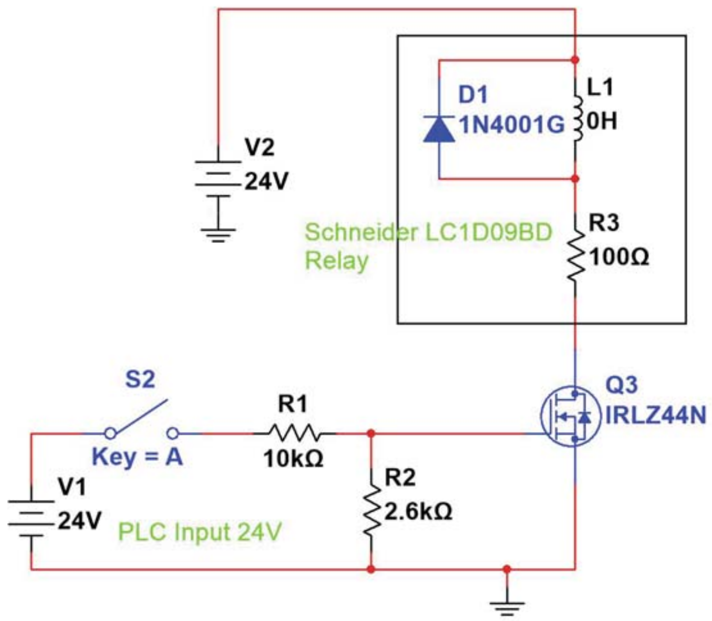

Figure 8.4. Circuit design for the PLC to trip the LC1D09BD relay

8.2.2 Implementation of the PLC trip relay circuit

For the implementation was made a board consisting of 4 of the circuit designs, since the relay is an external thing, it isn't on the print. The only thing on the print is the implementation of the voltage divider circuit and the MOSFET IRLZ44N. The implementation is shown in 8.5

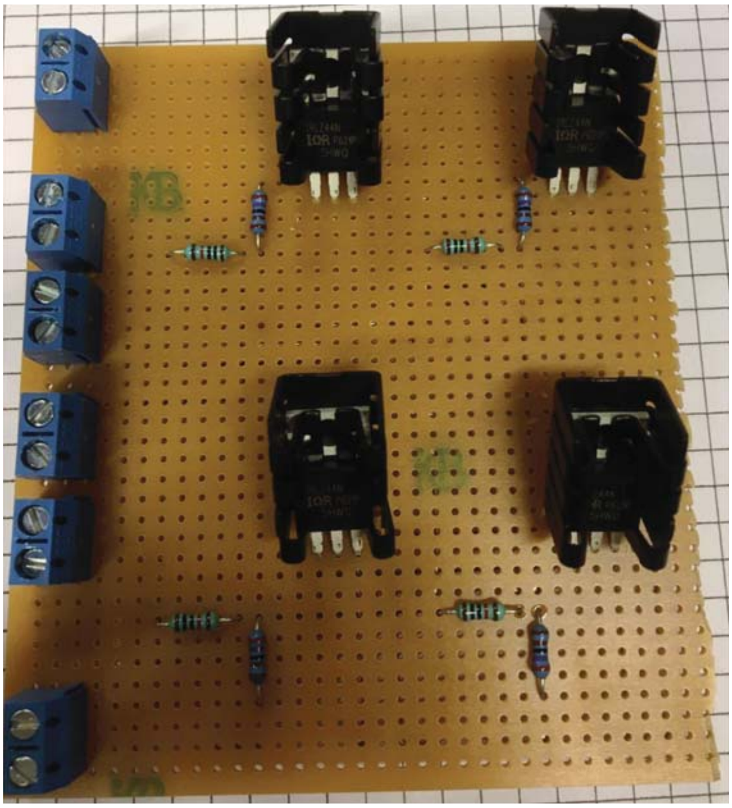

Figure 8.5. Implemented Circuit design for the PLC to trip the LC1D09BD relay

COMPONENT LIST

Component	Purpose	Further comment
R1: 10K ohms resistor	The purpose for the resistor is to lower the voltage from the PLC output	There is four of these since there is four of the circuits
R2: 2.6K ohms resistor	The purpose for the resistor is to lower the voltage from the PLC output	There is four of these since there is four of the circuits
IRLZ44N	The MOSFETs purpose is to to trigger when required by the PLC to enable ground connections to the LC1D09BD relay	There is four of these since there is four of the circuits
Schneider LC1D09BD Relay	The purpose of this component is show when the different components is activated from the PLC	There is four of these since there is four of the circuits

Table 8.1. Component list for the circuit design to trip the LC1D09BD relay

Module test

This module test is made to see what supply voltage and current there is needed to trip the Schneider LC1D09BD relay.

Supply voltage in V	Amps going through the relay in mA	Is it tripping
10	100	no
12	120	no
14	140	yes
16	160	yes
18	180	yes
20	200	yes
22	220	yes
24	240	yes

Table 8.2. Module test for the Schneider LC1D09BD relay

8.2.3 Current transducer with Hall-element

In this section there will be described one of the current sensors that have been used in this project. This current sensor is build upon the *Honeywell CSLA1CD seen in 8.6* which is a current transducer, that uses a ferromagnetic materiel and a Hall-sensor. This sensor can be used to measure current with a DC or AC circuit. When it's measuring current either as DC or AC, the output voltage will be DC if it's a DC supply it's measuring and AC if it's a AC supply. Honeywell states that it's linearly, we have made a module test for the circuit and the sensor to see if it was true. See the module test at table 8.4

The CSLA1CD transducer was the biggest in that series from Honeywell but it was the only one that the University had available. It has a max peak sensor current at 57Amps. At 12 volts it corresponds to more than 600W and the sensor is far better than needed in the prototype.

Figure 8.6. Honeywell CSLA1CD current transducer. Picture is taken from [30]

8.2.4 How the sensor works

Since the sensor is build up with a ferromagnetic material as a core, a hall-element to measure a DC or AC current flowing through a conductor, when the current passes through the conductor the electromagnetic field will be produced. Since the conductor is going through the middle of the ferromagnetic materiel, this materiel will induce an magnetic field. The magnetic field is on both sides of the element. The hall sensor is supplied with a voltage, in this case from a voltage regulator. The voltages charges will be disrupted due to **Lorentz force**. This is making the electrons going to one side of the hall sensor, and the protons to the other side. Then the hall-sensor is measuring on both sides and a voltage can be measured. This voltages will be used to calculate the current, the signal will go to the PLC and the PLC will scale and measure it.
For further information how CT's generally work, see 6.6

The sensor is made so the voltage that is measured is from this equation 8.2 which is provided by the manufacture. [31]

$$Offsetvolt = \frac{Vcc}{2} \tag{8.2}$$

The sensor Offset voltage is increased by 0.05$Volt$ for each Amp that are being measured. this information is given in the data sheet from the manufacture [31]

8.2.5 Design of circuit

The following design for the circuit is shown in figure 8.7, during the Integration test, it was found that there were a lot of noise, so a Low-Pas filter was applied on the output of the sensor.
The Cut-off frequency that was wanted should be around 1-2 Hz, to remove the high frequent noise. Further pictures of the signal before and after the Low-Pass filter is shown in figure 8.10 and in figure 8.11

- R: 10K Ohm
- C: 10uF

The equation for the cut-off frequency of the low-pass filter is:

$$F_{Cut-off} = \frac{1}{2 * pi * R * C} = \frac{1}{2 * pi * 10 * 10^3 * 10 * 10^{-6}} = 1.592 Hz \tag{8.3}$$

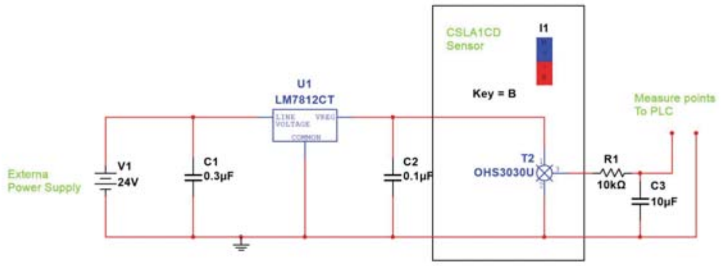

Figure 8.7. Circuit design for Honeywell CSLA1CD current transducer

The implementation of figure 8.7 is shown on figure 8.8

Figure 8.8. Implementation of 8.7

COMPONENT LIST

Component	Purpose	Further comment
LM7812 Voltage regulator	The purpose of the voltage regulator is to provide a stable voltage to the Honeywell CSLA1CD current transducer	One component is used.
C1: 0.3 uF Capacitor	The Capacitor is there to provide a stable input for the LM7812. This size is recommended by the manufacture	one component is used
C2: 0.1 uF Capacitor	The Capacitor is there to provide a stable output for the LM7812. This size is recommended by the manufacture	one component is used
C3: 10 uF capacitor	This capacitor is a part of the Low-Pass filter for the output	one component is used
R1: 10K ohm	This resistor is a part of the Low-Pass filter for the output	one component is used
Honeywell CSLA1CD	The Current transducer is there to measure the current which it will provide an output with an offset	one component is used

Table 8.3. Component list for the Honeywell CSLA1CD current transducer

MODULE TEST

1. **The first module test**, is to see if the current transducer is working as the manufacture says. The test is to see if the offset voltage will increase with 49.6 mV (+- 5.8 mV in tolerance) for each ampere that are increased.
   From the module test, it can be seen from the tendency line that it has an increase at 53,1 mV pr ampere, which is what the manufacture promised it would be within. The tendency line is showed at figure 8.9.
2. **The second module test,** is to see if there were any output noise from the sensor.

Current going through the conductor	Measured output Voltage
0	6,257
0,58	6,28
1,76	6,352
2,02	6,365
2,54	6,391
2,99	6,417
3,54	6,446
4,02	6,47
4,5	6,495
5,02	6,523
5,52	6,548
6,03	6,573

Table 8.4. Module test for the Honeywell CSLA1CD current transducer

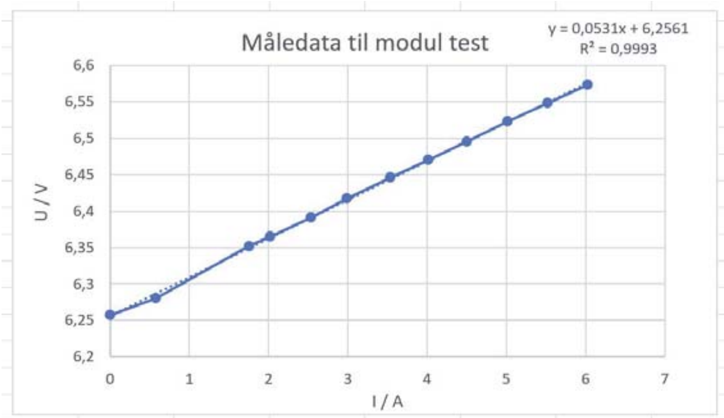

Figure 8.9. Tendency line and measurements from of table 8.4

During the module test, there were found that there were a lot of noise on the output. It was solved with a low-pass filter on the output of the sensor. The pictures here shows before and after the Low-pass filter was implemented.

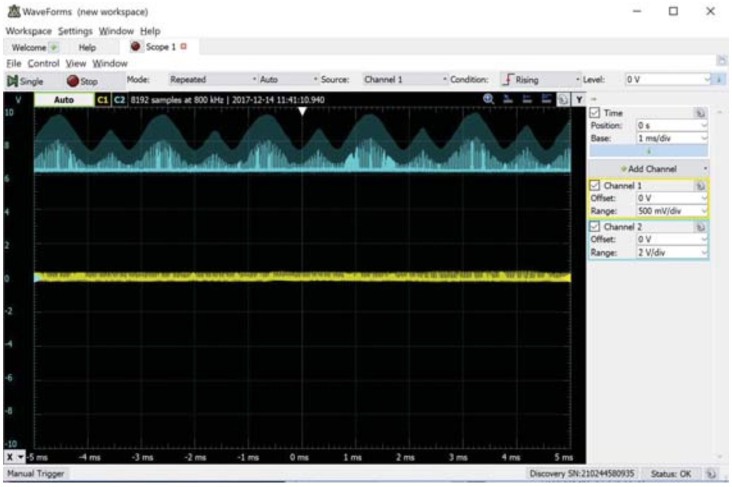

Figure 8.10. Honeywell sensor output before the LP was implemented

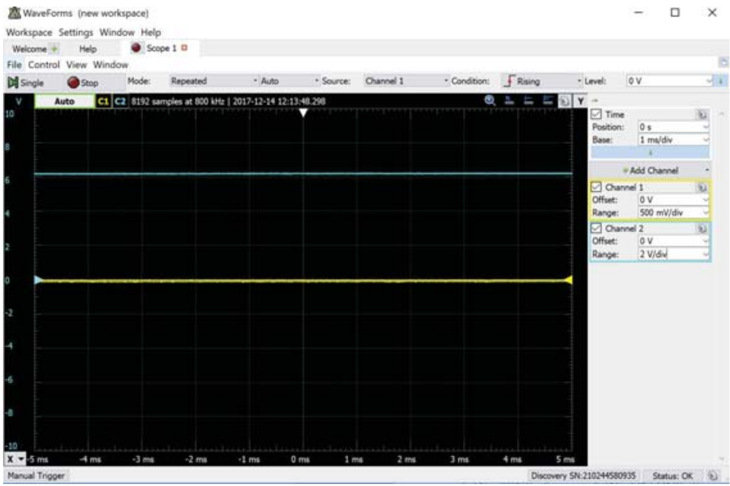

Figure 8.11. Honeywell sensor output after the LP was implemented

8.2.6 DC current shunt transmitter

Design

The circuit amplifies the weak voltage across the current shunt to a signal that can be connected to the 0-10V input on the PLC.

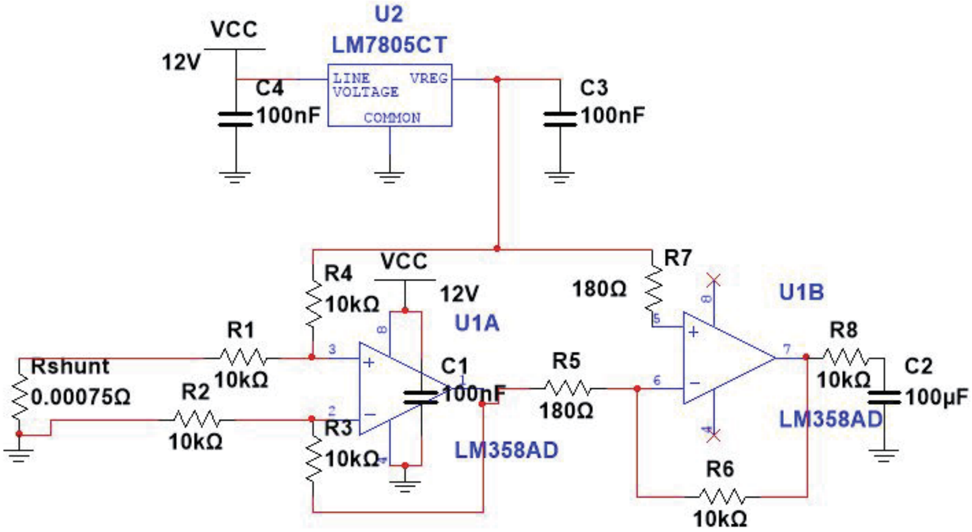

Figure 8.12. current shunt transmitter

The voltage regulator U2 makes a reference level of 5V. (virtual ground) The first op-amp U1A is a differential amplifier which output is equal to the voltage over the shunt elevated to the +5V level. When no current flows through the shunt the output of U1A will be 5 V, and when a current flows through the shunt the output of U1A will change from the 5V level with 0,75 mV per ampere shunt current. This tiny signal has to be amplified to a higher level that better uses the range of the PLC. Second op-amp U1B has a gain of 10000/180 = 55,5. This brings the signal up to around 42 mV per ampere varying from the 5V reference level. Our signal from 0-10V will then represent a current from -120 A to + 120 A.

An expression for the shunt voltage is:

$$V_{shunt} = I_{shunt} * R_{shunt} \tag{8.4}$$

When R2=R3 and R4=R1 we can write an expression for the first stage:

$$V_{U1A} = -V_{shunt} * \frac{R_2}{R_1} + V_{ref} \tag{8.5}$$

Second stage expression:

$$V_{out} = -(V_{U1A} - V_{ref}) * \frac{R_6}{R_5} + V_{ref} \tag{8.6}$$

from eq 8.4, 8.5 and 8.6:

$$V_{out} = I_{shunt} * R_{shunt} * \frac{R_2}{R_1} * \frac{R_6}{R_5} + V_{ref} \tag{8.7}$$

Rshunt=0,75mohm, R2=R1=R6=10kohm, R5=180ohm and Vref=5V we get:

$$V_{out} = (I_{shunt} * 0.0417 + 5)V \tag{8.8}$$

The first order low-pass filter R8/C2 has a crossover frequency of 0,159Hz and is added to reduce aliasing when there is sampled with 1Hz. The filtered output voltage will represent the averaged dc value, and there should be added a buffer to reduce the influence from the load (The PLC has a input impedance at 100 kohm).

IMPLEMENTATION

The 100A/75mV class 0.5 current shunt resistor is shown in 8.13

Figure 8.13. Current Shunt Resistor. [32]

The implementation of the three current shunt transmitters is shown in figure 8.14

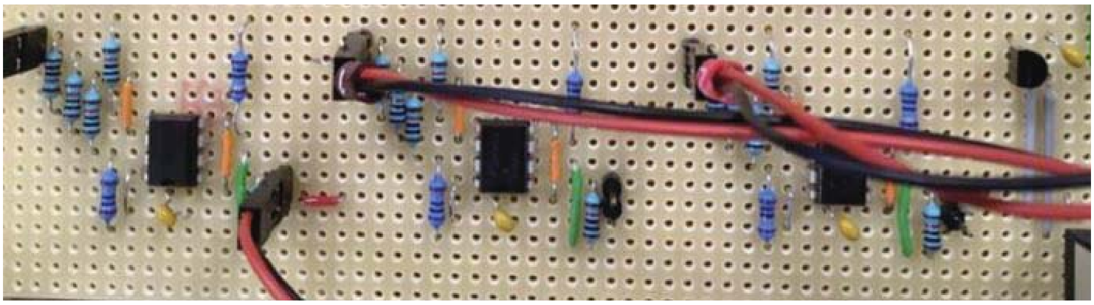

Figure 8.14. CST implementation

COMPONENT LIST

Component	Purpose	Further comment
Rshunt: 100A/75mV shunt resistor	This is the sensor element used for shunt type current sensing	One component is used for each shunt type current measuring point
U2:LM7805CT Voltage regulator	The purpose of the voltage regulator is to provide a stable voltage to the 5V reference level (virtual ground)	One component is used for three Current Shunt Transmitters.
U1:LM358AD dual op amp single supply	The op-amp that is the amplifying element in the circuits	One component is used for one current shunt transmitter
R1,R2,R3,R4,R6,R8 is 10 kohm resistors	The purpose is to get the right amplification of the circuit	six components is used for one current shunt transmitter
R5,R7 is 180 ohm resistors	The purpose is to get the right amplification	Two components is used for one current shunt transmitter
C1,C3,C4 is 100nF capacitors	The purpose is to stabilize the supply voltage	One component is used for each U1 and two for each U2
C2 is a 100uF capacitor	The purpose is to reduce the bandwidth	One component is used for each current shunt transmitter

Table 8.5. Component list Current Shunt transmitter

MODULE TEST

This test is to see if the module work as intended. As shown in equation 8.8 the voltage should increase about 41,7 mV pr amps. As the tendency line from module test shown in figure 8.15 it's all most correct, the increase is 40,4 mV. That is acceptable because none of the components used are ideal.

Current through the shunt	Measured transmitter output Voltage
0	5,041
0,37	5,057
1,75	5,113
2,04	5,124
2,48	5,124
3,03	5,165
3,49	5,183
4,03	5,205
4,48	5,223
4,98	5,243
5,52	5,265
6,00	5,284

Table 8.6. Module test for the Current Shunt Transmitter

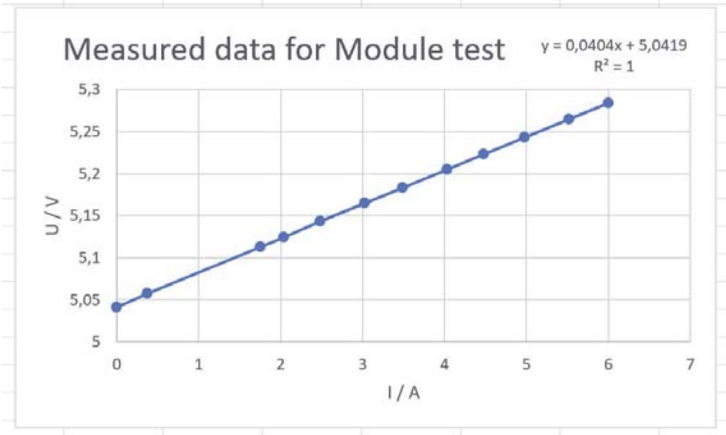

Figure 8.15. Tendency line and measurements from table 8.6

8.2.7 DC voltage sense transmitter

The circuit reduces the battery voltage to be measured to a level that the 0-10V input on the PLC can handle. When operating with a 12V system it only has to use a gain of 0.5 times. With that gain the 0-10V will represent sense voltages from 0 to 20V.

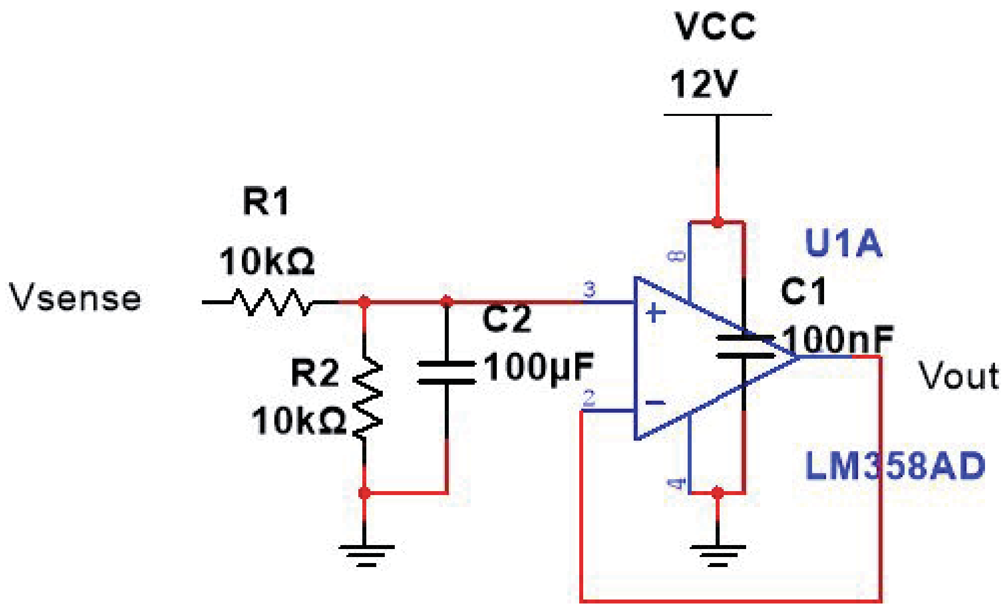

Figure 8.16. Voltage sense transmitter

An expression for the dc-gain is:

$$V_{out} = V_{sense} * \frac{R_2}{R_2 + R_1} \tag{8.9}$$

When R1=R2 it will be:

$$V_{out} = V_{sense} * \frac{1}{2} \tag{8.10}$$

The C2 capacitor reduces the upper frequency roll off to around:

$$f_{rolloff} = \frac{1}{2 * pi * (R_2||R_1) * C_2} = 0,32Hz \tag{8.11}$$

IMPLEMENTATION

The implementation of the voltage transmitter is shown in 8.17

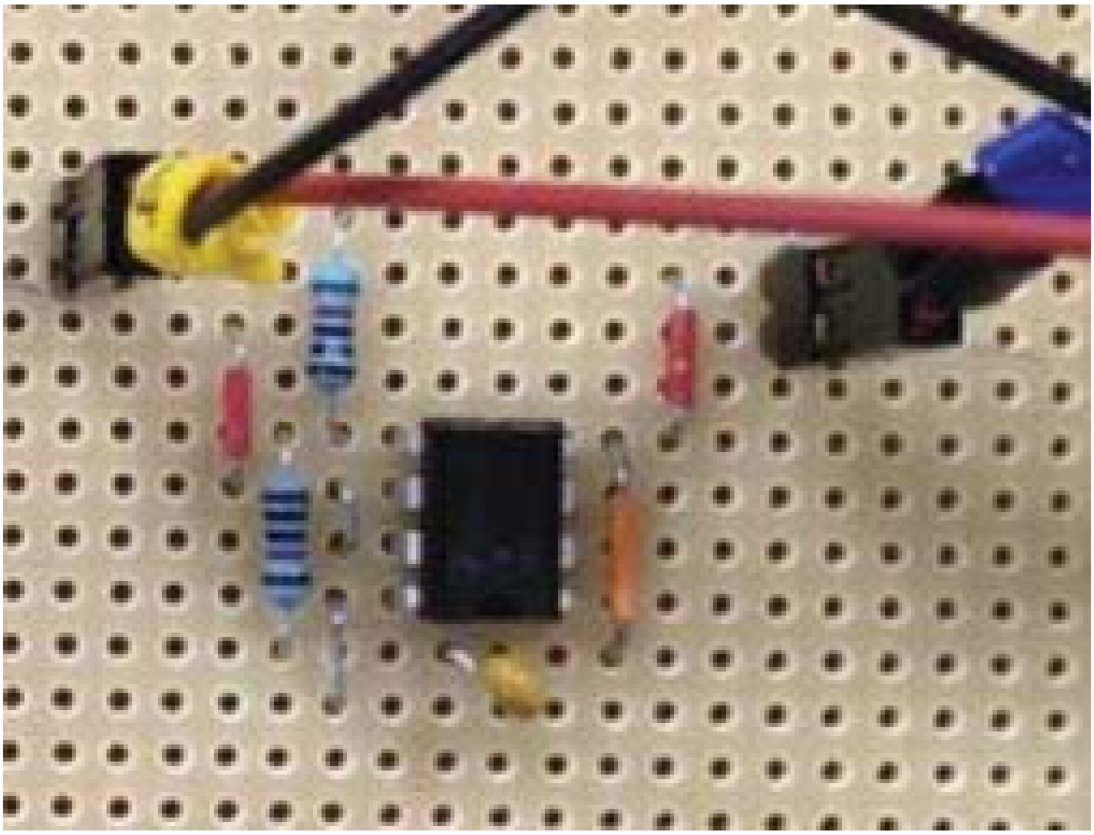

Figure 8.17. Voltage transmitter implementation

Component list

Component	Purpose	Further comment
U1A: LM358CT dual single supply operational amplifier	The purpose is to act as a buffer on the voltage divider	one half component is used in one voltage transmitter
R1,R2 is 10 kohm resistors	The purpose is to divide the measured voltage down to a value acceptable to the input on the PLC	two components is used in one transmitter
C1 is a 100 nF capacitor	The purpose is to stabilize the supply voltage	one component is used for one LM358CT
C2 is a 100 uF capacitor	The purpose is to limit the bandwidth to ensure that the signal represents an average of the dc value	one component is used for one voltage transmitter

Table 8.7. Component list Voltage transmitter

8.3 Zero Cross Detection

Because the system only is simulated with the CHP and Schneider LC1D09BD relay and there only is two analog inputs in the PLC the zero cross detection circuit isn't implemented

When the **CHP** needs to connect with the grid to sell excessive energy, it is needed to be taken into account when to connect the CHP to the grid, due to where on the sinus wave the connection is made. A device which can help us with that is a ***Zero Cross Detection device***. Zero cross detection is when a given sinusoidal signal crosses its zero point on the curve. The zero cross detector will create a square signal, it will be high on a *rising edge* and low on a *falling edge.* it then converts it to a square signal for other digital device to use. The square signal will be with the same time period and duty cycle as the sinusoidal.

It is needed to use the zero cross detection to make sure that when the CHP connect to the grid, there is the lowest chance to make an arc when it connects. This is for the protection of the CHP since it will course damage to the mechanical parts in the long run.

The circuit shown in figure 8.18 is build with an IC (MCP601-I/P) and a resistor to protect against in-rush currents.

The resistor is calculated out from the equation 8.12 from the data sheet [33] Since there is needed a VT to downscale the voltage on the grid, it would use a normal 230 to 12V transformer for the signal into the zero cross detector.

- R_2 to be calculated
- Voltage expected is 12 volts
- Vcc is expected to be 5 volts
- 2mA is given from the data sheet

$$R_2 = \frac{V_{expected} - V_{cc}}{2mA} = \frac{12V - 5V}{2mA} = 3500 Ohms \tag{8.12}$$

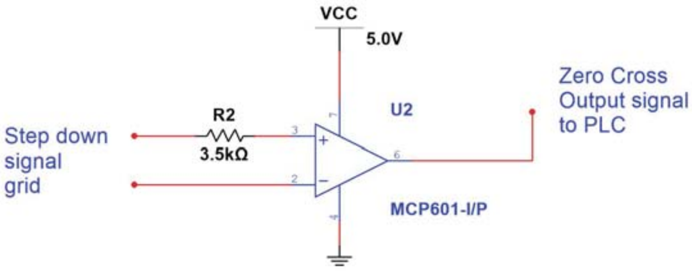

Figure 8.18. Zero cross prototype design

The figure 8.19 shows the simulation of how it works.

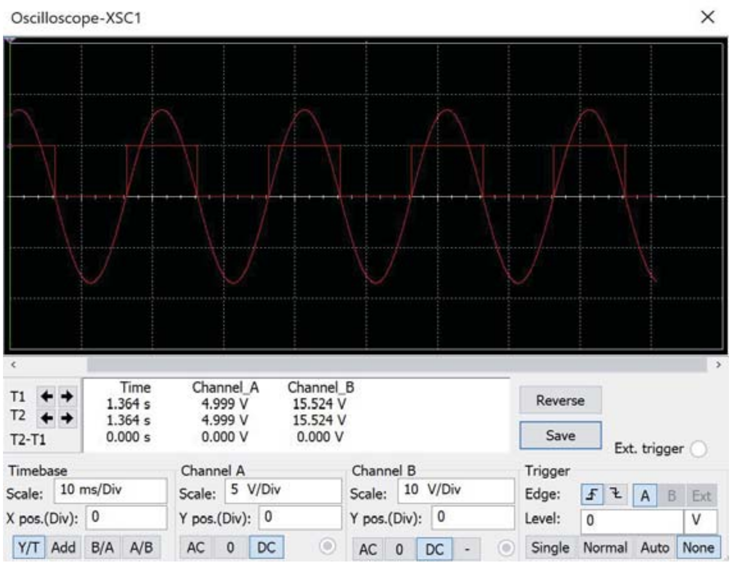

Figure 8.19. Zero cross simulation

COMPONENT LIST

Component	Purpose	Further comment
R2: 3.5K ohms Resistor	The purpose for this resistor is to protect the MCP601 against inrush currents.	one component is used.
MCP601-I/P	The comperator is the main component in the zero cross detection circuit	one component is used

Table 8.8. Component list for the zero cross detection circuit design

SW Design And Implementation | 9

9.1 | HMI Drafts

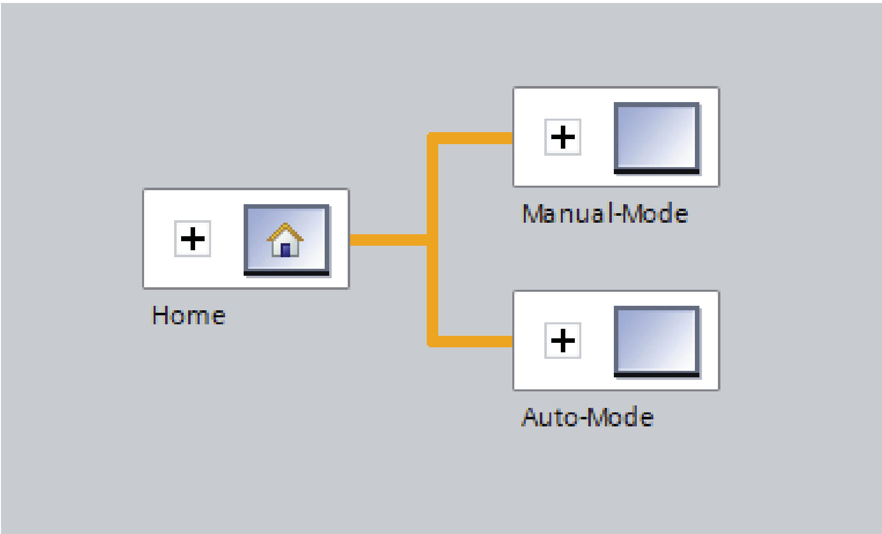

Figure 9.1. Screens of HMI

This picture 9.1 shows which screens there will be on the HMI and which screens the user will be able to choose. Manual Mode is the mode chosen to use the described functions: Force Sell and Force Charge. These are described in section 2.1 for further details.

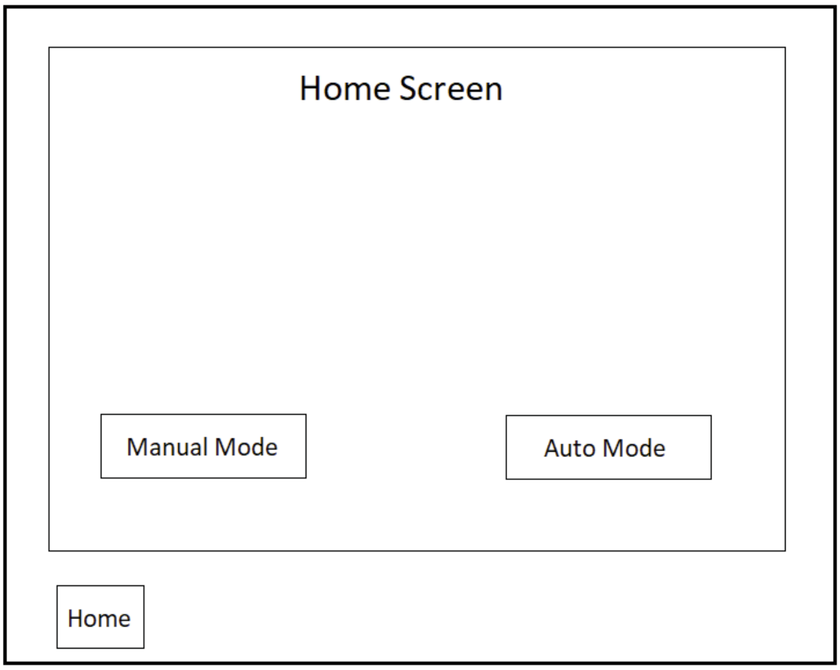

Figure 9.2. Home screen HMI

The Home screen is the main screen, where the user will be able to choose either the Manual Mode or the Auto Mode. On the bottom there is a button called "Home". This will be a global button. This means that the button will have the same functionality on every screen.

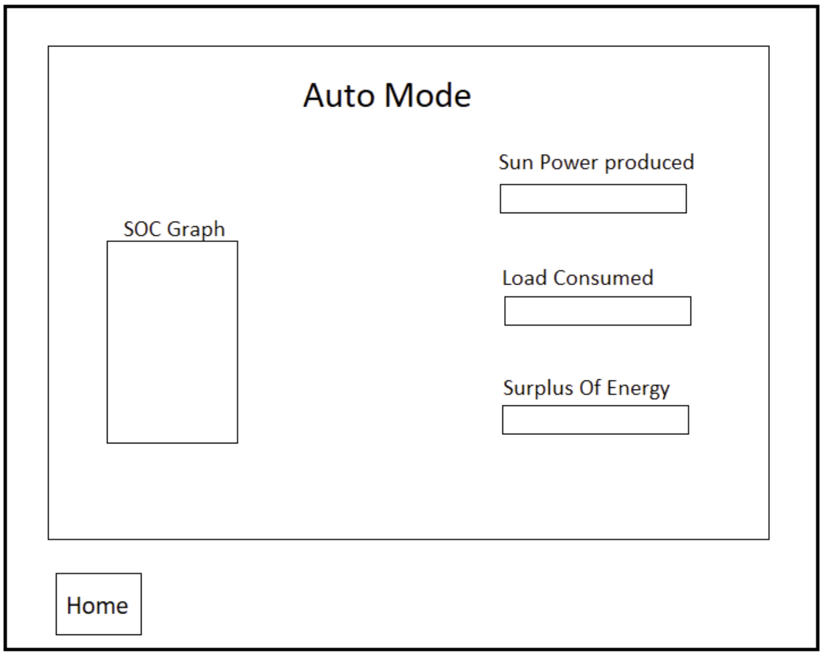

Figure 9.3. Auto-Mode screen HMI

When the user have chosen the Auto Mode the screen on figure 9.3 will appear. Here the user will be able to read the values of: Sun Power Produced, Load Consumed, Surplus Of Energy and how much energy there is on the battery, through the Battery level indicator.

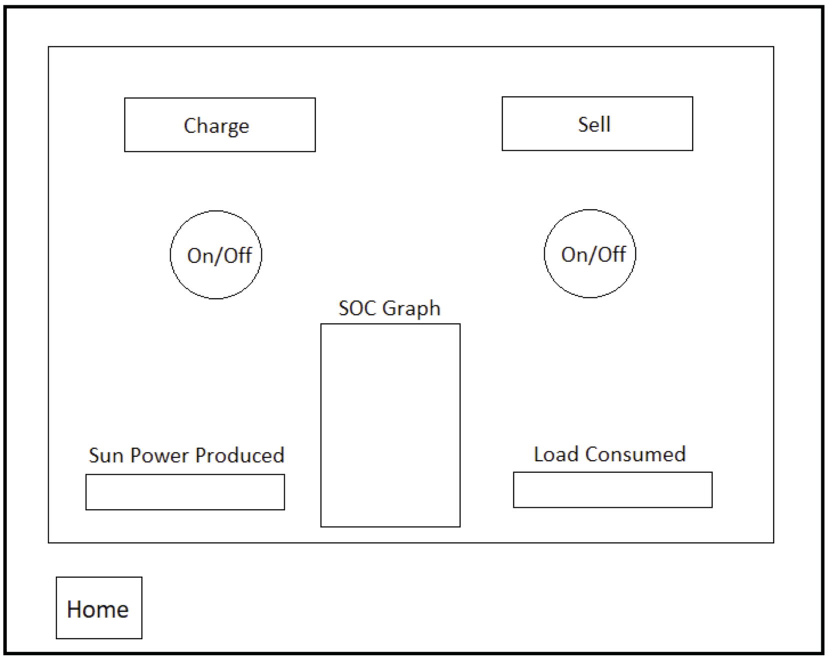

Figure 9.4. Manual-Mode screen HMI

When the user has chosen Manual Mode this screen 9.4 will appear. Here the user will be able to read the values of: Sun Power Produced, Load Consumed and how much energy there is on the battery. The user will also be able to see if the battery is charging or not, and if the system is selling energy or not. This is done by the two "On/Off" lamps made just beneath the two corresponding buttons.

9.2 PLC CODE

As mentioned in section 6.7, there will be used a PLC to control the modes of the system. SOC on the PLC will be made in the variable Ah *Amps/Hour*.

9.2.1 MAIN CYCLE

The main cycle is where the modes are being controlled. On the figure 9.5 there can be seen all the inputs and outputs. The input is either data coming from the physical world, Solar Panel and Load, or from the user's input. The user got the influence to change what mode it should be in. Though if the criteria are not fulfilled for the specific mode, the system will not change mode but instead stay in Auto Mode.

On most of the input and output pins, there are connected tags that all say *HMI.* This is because these tags are saved in a HMI Data Block, so the inputs and outputs can be read or written to on the HMI. This is done to make all communication between the PLC and HMI go through a Data Block.

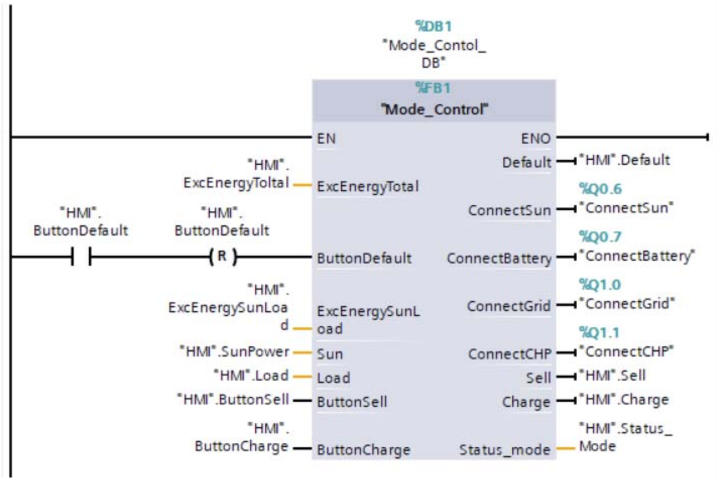

Figure 9.5. PLC Main

9.2.2 Modes

The modes of the system are Default/Auto-Mode, Sell Mode and Charge Mode. In this code it has been split even more up, so it can be controlled better. Sell and Charge Mode are two modes like it was before, but Default/Auto-Mode are split up into:

- If the produced Watt's from Solar-Panel is larger than the Load consumed
- If the Load consumed is larger that the produced Watt's from the Solar-Panel

It is this code that checks if the battery is above or below it's limits. If the amount of Watt's produced from the solar panels are above or below the Watt's consumed in the loads, or if the user selects Sell or Charge mode.

The last one is the HMI outputs, this network is made for the HMI, so it can be shown if the grid, sun, CHP or battery are on or off.

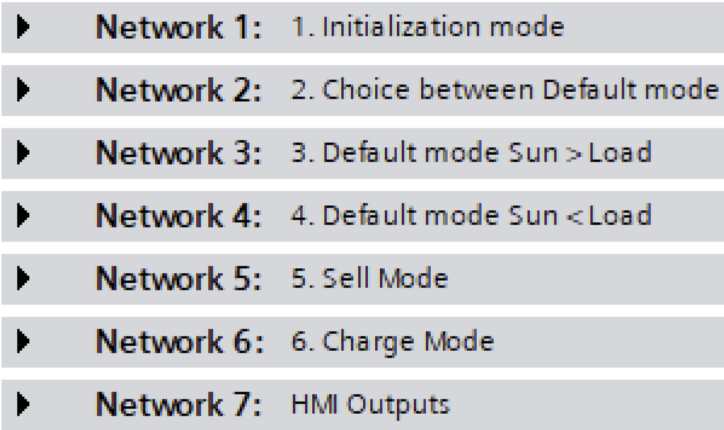

Figure 9.6. PLC Modes

9.2.3 Counter

In the PLC a counter has been made. This counter is made inside a interrupt, where it here are defined that it should interrupt once every second. This counter is then tracking time. The time is important because the first cycle of the program should run the SOC calculation with a specific default. *More of this can be read in subsection 9.2.4.*

There is another counter similar to the one just mentioned. The other counter has the task to count up for the index of the Sun profile or Load profile, because these two profiles have been made as an Array to contain the data.

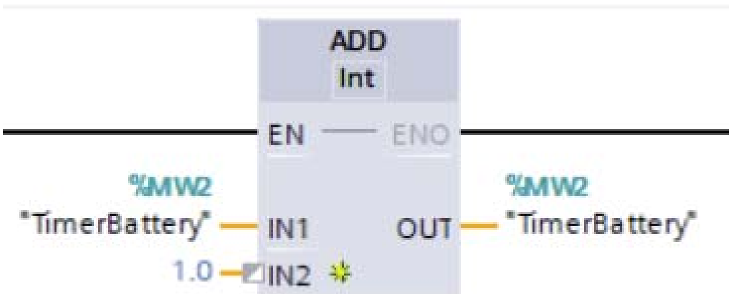

Figure 9.7. PLC Counter

The calculations will use the data measured or used in the Data Blocks for respectively Load and Sun Profile, these two combined with the timer mentioned in section 9.2.3 forms the inputs in the calculation. As shown in figure 9.8 an extra output besides SOC occur, this ExcEnergy output has been declared an output to enable the user to see the surplus/deficit of the energy from the loads and sun.

9.2.4 Calculation of SOC

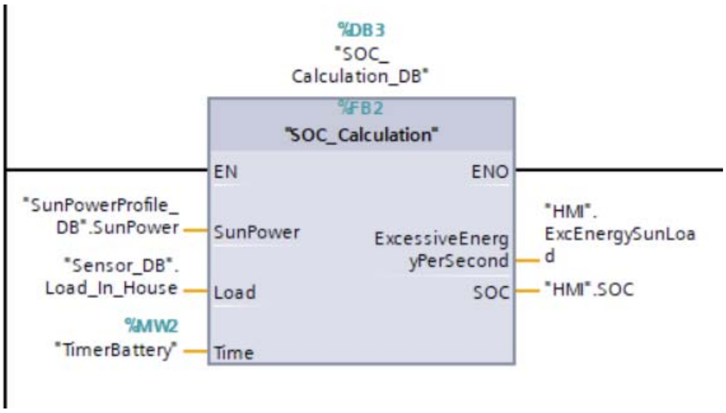

Figure 9.8. PLC Calculation Main

As mentioned in 9.2.3 the calculation of SOC depends of the time. At the beginning where time is equal or less than one, the calculation will use a default value of SOC to begin the calculation. This value is similar to the maximum capacity of the battery.

Due to the fact that the load and sun power values is measured in watts per second, the remaining energy from the subtraction will be changed to watts per hour instead. This step is being done, to make it easier to calculate the new SOC in Ah.

Before this change from watts per second to watts per hour is made, the calculation checks how much excessive energy the system produces. If the excessive energy exceeds the maximum charging capability which should be around the percentage mentioned in 6.3.3 (And have been set to 220.5W), the value of the excessive energy will be set with a constant equal to the maximum charging capability, to make sure the calculation match the MPPT.

It's important to notice that the SOC calculation is defined in Ah and not as a percentage. As well as the efficiency was neglected as described in section 3 an assumption has been made that the maximum charge on the battery is constant at any level of SOC.

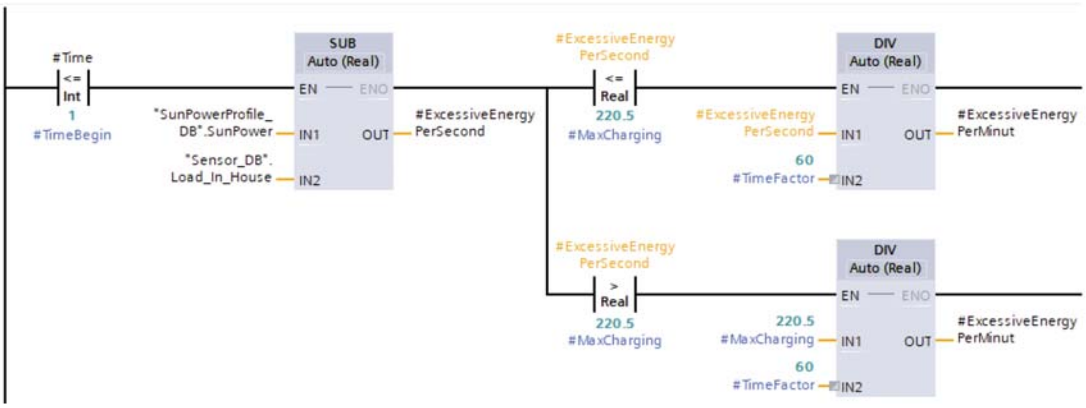

Figure 9.9. PLC SOC First Calculation Part 1

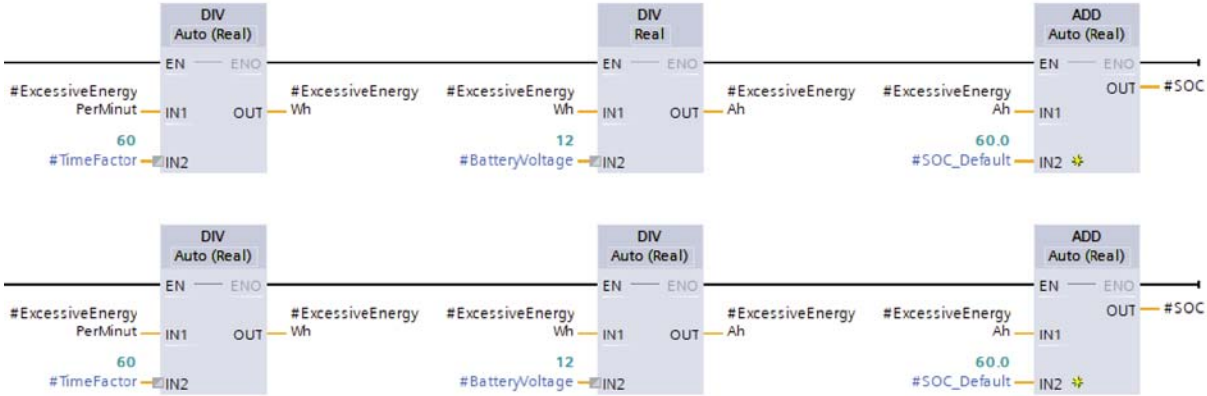

Figure 9.10. PLC SOC First Calculation Part 2

Below on figure 9.11 is the beginning of the calculation with a time above 1, this is only the first part of the calculation which replaces the figure 9.9 with figure 9.11. It's important to notice that if the CHP is turned on, the calculation will ignore the load, due to the fact that the CHP then will supply the loads. Beyond this, the rest of the calculation will operate as in the previous example with a time equal or lower than one.

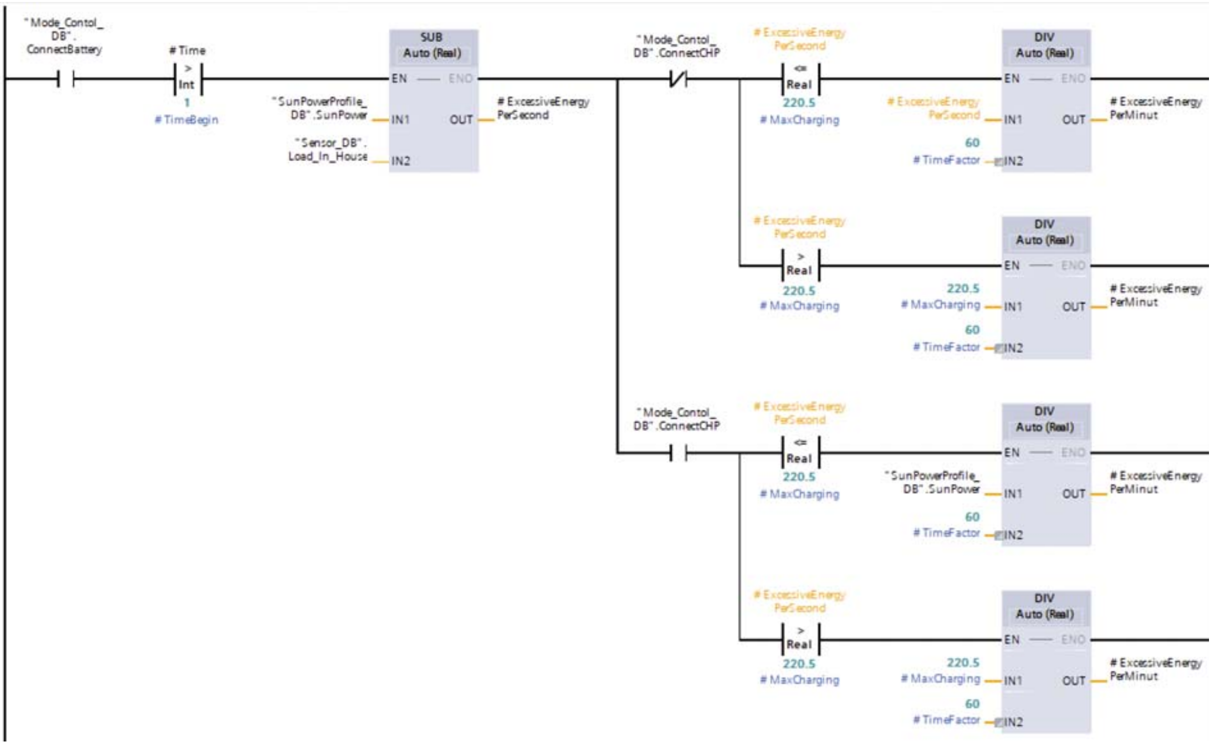

Figure 9.11. PLC Calculation with CHP and time above 1

9.2.5 Sun Profile

Instead of connecting a PV to the system a Sun profile has been made on the test bench. The purpose of this Sun Profile is to illustrate the energy produced during one day. The Sun Profiles data have been recorded through the SCADA viewer implemented in the Solar Panel simulator, and is later used in the PLC to simulate the PV. At section 9.2.5 further information about the implementation in the PLC is explained. The sun profile is made like this because it should be variable, to simulate all the conditions of the weather. This way it is possible to make a fast simulation on the PLC.

The sun profile used in this project is shown in figure 9.12

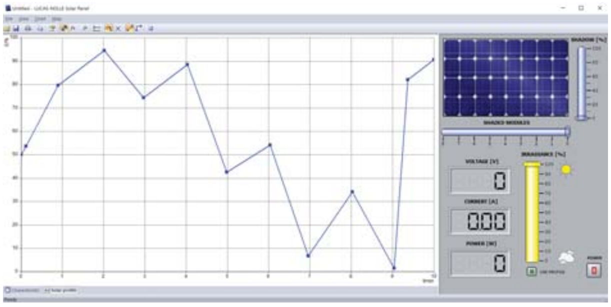

Figure 9.12. Sun profile used instead of PV

The Sun Profile gives out an output from close to zero to about 1300 watts. This have been scaled down with a factor of four times. This scaling has been implemented to ensure that the loads is able to exceed the energy simulated in the sun profile, to enable the test of all scenarios of the use cases.

The sun profile set is identical with the recorded data from the SCADA viewer. The only difference is that the SCADA viewer also shows the power produced in intervals of two minutes, this is illustrated in figure 9.13. The curve that is used is the green one seen on the figure, the other curve are being neglected. The neglected curve is the one with the two minutes interval.

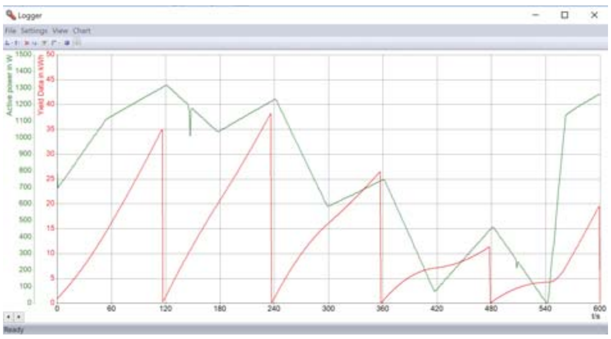

Figure 9.13. Recorded values from the sun profile

On figure 9.14 a data block containing the sun profile is shown. A data block is a block in the coding language LAD, that makes it possible to store data that can be used in other blocks. Here there is made an array of 600 slots. This is made from the data that have been drawn out of the sun profile in the simulation program Labsoft from figure 9.13. The 600 slots in the array simulates an entire day worth of sun.

This data is then worked through by a counter. This way every second the sun profile will have a new value. when the value is being updated, the SOC Calculation will calculate after this new value.

Every value in this array are in the parameter of Real. A Real can contain decimal numbers and are therefore important to this program, because the values may not change by much each time.

1	Static		
2	Static	Real	0.0
3	Data	Array[0..600] of Real	
4	Data[0]	Real	784.532
5	Data[1]	Real	695.871
6	Data[2]	Real	707.567
7	Data[3]	Real	715.306
8	Data[4]	Real	724.532
9	Data[5]	Real	733.016
10	Data[6]	Real	739.401
11	Data[7]	Real	744.537
12	Data[8]	Real	750.528
13	Data[9]	Real	760.847
14	Data[10]	Real	766.011

Figure 9.14. PLC Sun profile Data block

9.2.6 Selection Of Mode

This code section controls if the system shall go in Default, Sell or Charge mode. The first condition it has to get before it can make this choice is that step should be equal to 1. When the program starts up first time, the variable step will have a default value of 1, so this condition can be met. Beneath the condition step equals 1, there is a condition much alike, it's step equal 0. This is made because of the program had a bug that it would start up with a step value of 0, instead of 1.

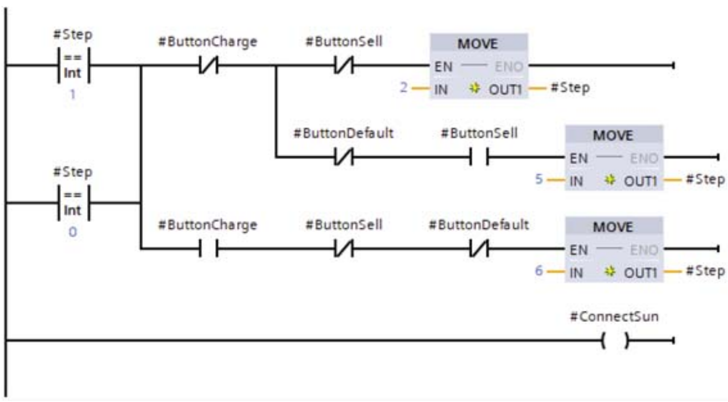

Figure 9.15. Initialization Mode

After this there are two more conditions if the system should reach choice between Default Mode.

These are that the button of Charge and Sell is not be pressed. If these two conditions are met, the system will go to step 2 and from there see if the load are bigger than the produced energy, or the produced energy are bigger that the loads. Step 2 is illustrated in figure 9.16

If the system shall reach Sell Mode the two first conditions have to be met, but after these there are made an branch down. From this branch two new conditions are made. The first condition is that the Default button shall not be pressed, meanwhile the Sell button should be pressed. If all of these conditions are made, the system will go into step 5 and thereby go into Sell Mode. *This mode can be seen in section 9.2.7.*

If the system instead shall reach the Charge Mode the first condition is still valid, but after this there is made a branch down. In this branch three conditions must be met. The first condition is that the button of charge shall be pressed. The second and third condition is that either the button for Default or for Sell shall be pressed. If these conditions are met, the system will go into step 6 and thereby go into Charge mode.

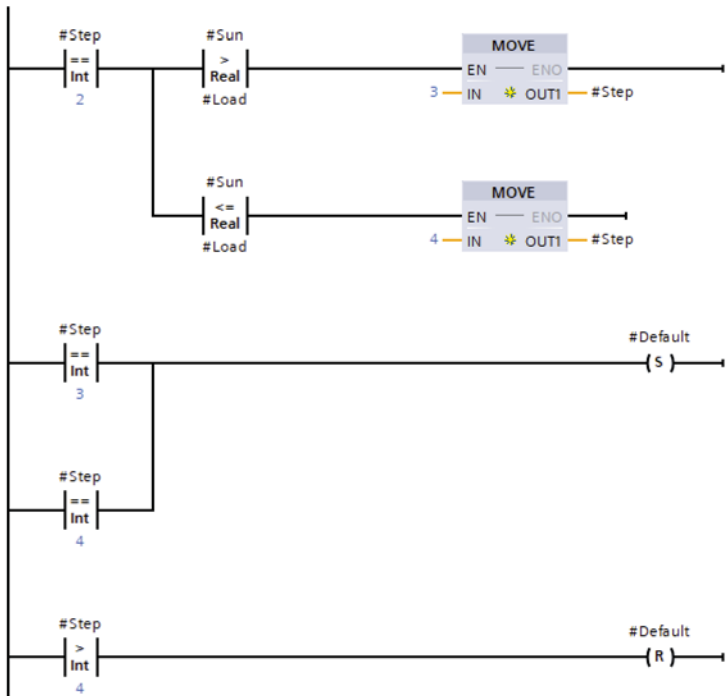

Figure 9.16. Choice of Default Mode

9.2.7 Selection Of State

In this section the code of Sell mode and default mode are shown and how the different states are being chosen. Sell and Default Mode with Sun Power bigger than Loads will be described with examples of code from the PLC. Charge Mode and Default Mode with sun power less than loads will only be described briefly and without code examples.

Default Mode - Sun > Load

When step reaches step 3 as described in section 9.2.6, the Mode will change to Default Mode. The Default Mode consists of two parts, one where the Sun exceeds the Load and vise versa. In this part of the Default mode, it's the connection to battery and grid which is controlled. The reason that the CHP isn't a part of this mode is because it's a requirement that the sun power exceeds the loads, and therefore the CHP isn't necessary in this Mode.

As illustrated on figure 9.17 the battery will only be connected if the SOC is below its upper limit on 60 Ah. If the SOC changes from being below this upper limit and reaches this point, the PLC will reset the relay and terminate the connection. Furthermore it can also be seen that the battery will be disconnected if the Mode is changed. This will be the case if the user pushes down the button of Change/Sell mode. The mode will not change if both buttons is pressed at the same time. The Last part shown on the figure is that the PLC will change Status Mode which is the mode shown in text on the HMI. This is illustrated on figure 9.24 where in the bottom of the screen is shown what mode it operates in.

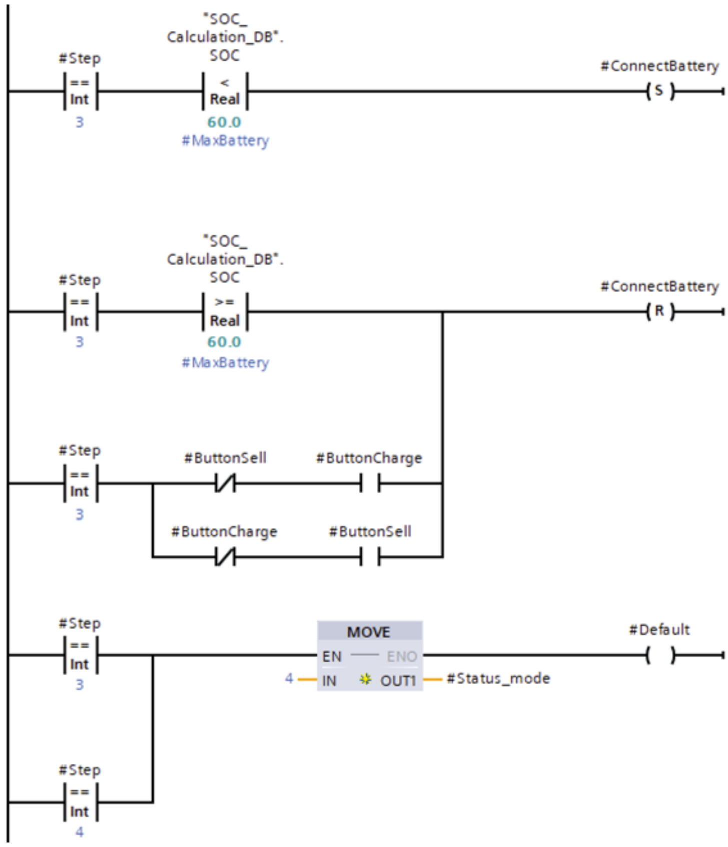

Figure 9.17. Default Mode 3 - Connection of Battery

On figure 9.18 the Grid should connect or disconnect according to the conditions. It can here be seen that if the Battery is connected or disconnected and, the excessive energy is larger than the allowed charging on the battery, the Grid will be connected. The Grid could also be connected if the SOC of the Battery is at it's maximum charge, and the excessive energy is larger than the allowed charging on the battery.

To reset the Grid again the following conditions should be fulfilled. If the excessive energy i equal or less than the allowed charging of the battery, and the SOC of the battery is equal or less, than the maximum charge on the battery. The grid could also be reset if the user chooses to change stage. Here either the button for Charge Mode should be pressed, while the button for Sell Mode not is pressed. Then the system will change stage into Charge Mode. Or if the button for Sell Mode is pressed, but the button for Charge Mode is not. Then the system will go into Sell Mode.

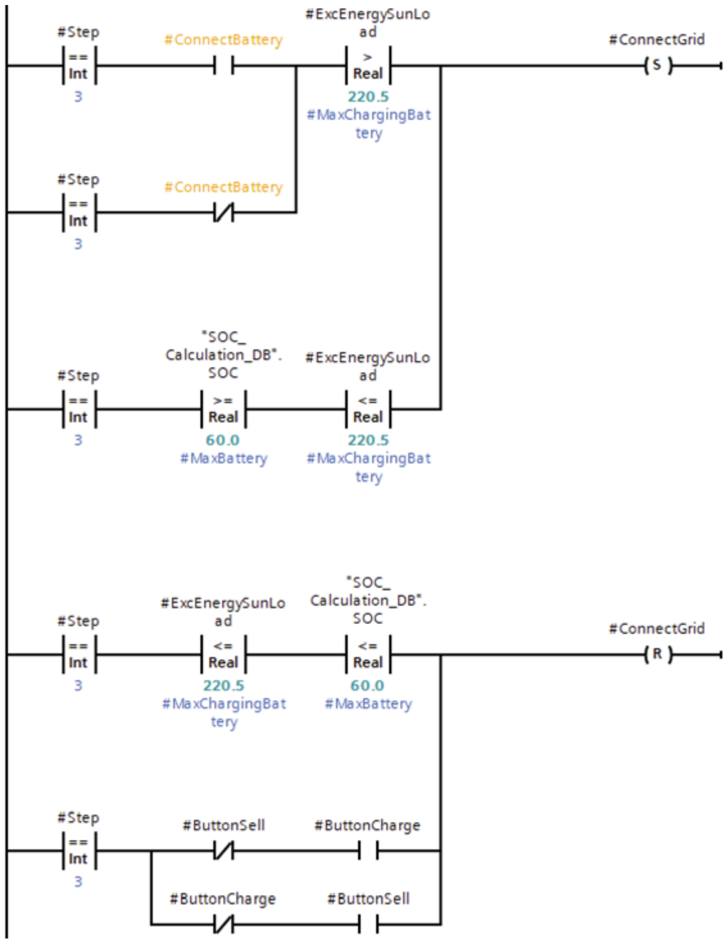

Figure 9.18. Default Mode 3 - Connection of Grid

If the system should change mode from Sun > Load into Sun < Load, then the value received from the sun profile should be less than the value received from the load sensors. If this happens it will change into step 4, and thereby into Default Mode - Sun < Load.

The system can also change it's stage into either Sell Mode or Charge Mode. This can be done if the button Sell not is pressed, and the button Charge is pressed, then the system will go into Charge Mode. If the Button Charge not is pressed, but the Button Sell is pressed, then the system will go into Sell Mode. This can be seen on figure 9.19.

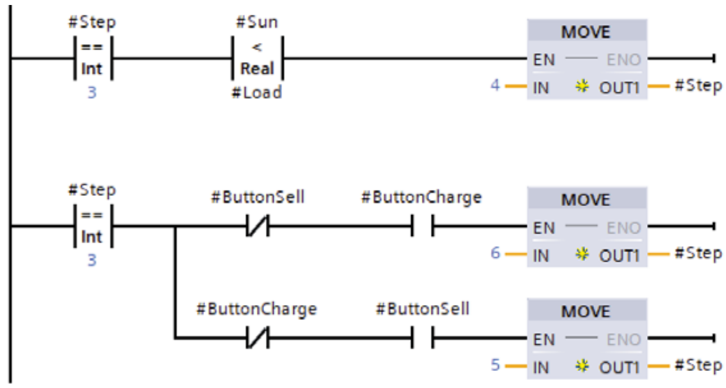

Figure 9.19. Default Mode 3 - Change of Mode

Default Mode - Sun < Load

As the previous mode just described the default mode consists of two parts, in this section the second part of the Default mode will be described.

If the Battery's SOC is above its lower limits, the battery will supply the loads. However if the SOC reaches its lower limit, the CHP will be connected and supply the loads, so the energy harvested from the Sun can be used to charge up the battery. The CHP will continue to be connected until it reach a predefined value of 45 Ah. This decision has been made to make sure the CHP connection doesn't constantly flip on and off at the SOC's lower limit.

Beyond this is keeps an eye one the surplus of energy, to make sure the energy provided to the battery doesn't exceed the allowed charging of the battery. If the surplus exceeds the allowed charging, the system will connect the grid to sell the excessive energy.

Sell Mode

The program will go into Sell Mode if step is equal 5. When this happen the "MOVE" block that can be seen in the code below, will send the number 5 into "Status_Mode". This status mode is used to change the text in the bottom of the HMI Home screen seen on figure 9.24, so this text can be changed to Sell Mode instead of the mode the text says it is in. After the "MOVE" block the Sell tag are set. This tag is set so the HMI and the output for the Relay knows when to switch on and off.

If this tag should be reset instead of being set, there are several conditions that could full filled that. One of these conditions that could make this change, is if the SOC is less than, or equal to the lowest charge level the battery should be in, then the Sell tag would be reset and go into Default Mode.

The other conditions for if the Sell tag should be reset is that if either the button for charge is not pressed and the button for default is pressed. Or if the button for default is not pressed but the button for charge is pressed.

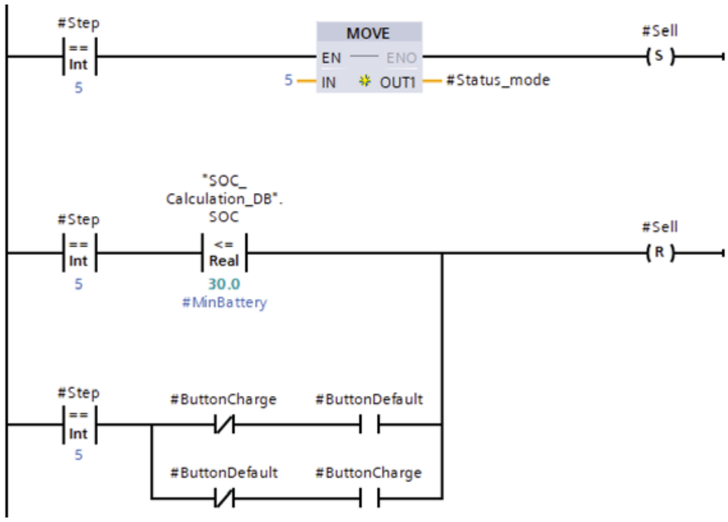

Figure 9.20. PLC Selection Of State Example1

The next figure 9.21 shows the code section where SOC of the battery is larger than the minimum charge on the battery. If this is true both the battery and the grid will connect. This is because in Sell Mode the battery should be used to supply the loads, while the excessive energy will be sold.

If both the battery and the grid should be reset in Sell Mode, the SOC should be less than, or equal to the minimum charge of the battery. Or the charge button should not be pressed while the default button should be pressed. The other condition is that if the default button is not pressed, while the charge button is pressed. In this way the system will change mode, and thereby reset the grid and battery.

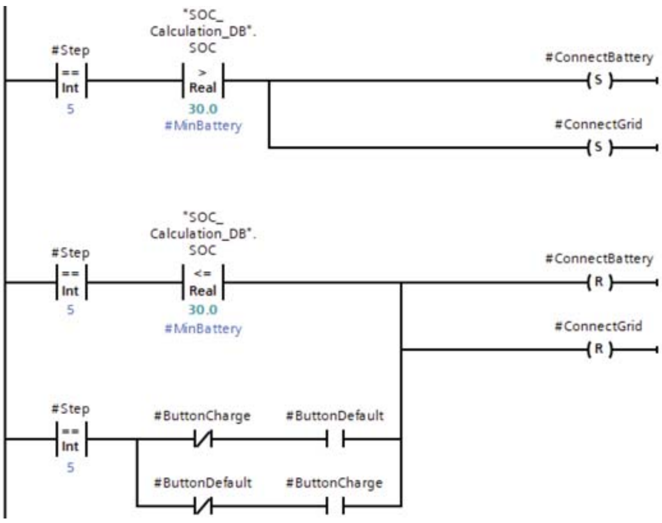

Figure 9.21. PLC Selection Of State Example2

On figure 9.22 it shows the code section for changing modes from Sell mode, to either Default Mode or Charge Mode.

The system will go in Default Mode of two reasons. The first reason is if the SOC is less than or equal to the battery's minimum charge, if this is so, the "MOVE" block will set the number 1 into step and thereby set it back to the initial Selection Of Mode 9.2.6.

The second reason is if the charge button is not pressed while the default button is pressed, thereby it will go into Default Mode. Or if the default buttons is not pressed while the charge button is pressed, thereby go into Charge Mode.

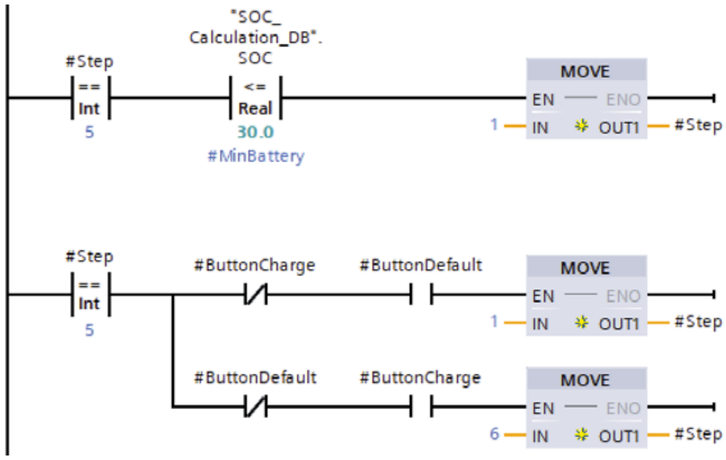

Figure 9.22. PLC Selection Of State Example3

Charge Mode

The Charge Mode can be chosen from the users input 9.19. In this mode all of the load are being neglected because the CHP is taking care of the loads. This way it can be made sure that the charging will be at the highest all times in use of the sun profile.

If the excessive energy is larger than the allowed charging for the battery, the grid will also be connected to Sell surplus energy.

The system will be in this mode until the battery is at its maximum SOC. Or until the user changes the stage manually.

9.2.8 Measurement and Scaling of Load

The two analog inputs on the PLC is used to measure data from the system to process these on the PLC. One of the inputs is used for measuring the load in the house, the other is used to measure the voltage. When multiplied, these measurements will represent the power used by the loads. This multiplication is seen in the bottom of figure 9.23.

Current Shunt Transmitter

The analog input range from 0-10V from where the PLC divides this up to 27648 steps[34]. Each of these steps will represent a voltage on 0.3617mV which is shown in the following equation.

$$scale = \frac{10V}{27648} = 0.3617mV \tag{9.1}$$

The reference level of the shunt sensor can then be multiplied on the scale factor to achieve what step represents this specific voltage. This voltage is calculated at equation 8.8 with a current of zero amps.

$$MinLimit = \frac{5.041V * 27648}{10V} = 13937.357 \tag{9.2}$$

The same way the limit with 100 amps can be calculated to get the value representing this voltage

$$MaxLimit = \frac{(5.041V + (0.0404V * 100)) * 27648}{10V} = 25107.149 \tag{9.3}$$

These two values calculated in equation 9.2 and 9.3 is then normalized inside the PLC and scaled to give an output from 0-100 amps.

Voltage Transmitter

The voltage from the battery is at a higher voltage than the input range on the PLC, because of this a circuit was made in section 8.2.7. Because of the gain on 0.5, the scale will go from 0-20V to take this gain into account.

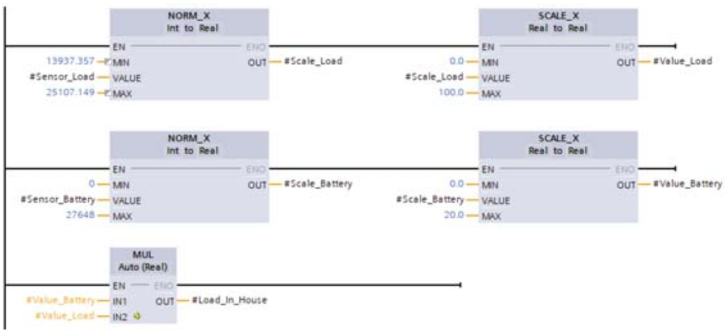

Figure 9.23. Measurement and scaling of Load

9.2.9 HMI

The HMI is the *Human Interface Machine*, this is the GUI *Graphical User Interface* where the user can see and interact with the system.

On figure 9.24 the Home screen can be seen. On this screen the currently sun power produced, load consumption and surplus of energy can be seen. The surplus of energy is calculated from the sun power produced and the load consumed.

$$CurrentlySurplusOfEnergy = CurrentlySunpowerProduced - CurrentlyLoadConsumed \tag{9.4}$$

Each of these values are shown in Watt.

On the left side of the Home screen a bar graph is shown. This bar graph is showing the SOC of the battery, to show the user at what value it is now. On this there are placed two arrows, these arrow's represents the maximum and minimum value of the SOC. If the SOC are equal or higher than the maximum value, the bar graph will change it's colour to green. If the value is equal or below the minimum value, the colour will turn red.

At the right of the screen two buttons can be seen. On the first button the user can choose the change the mode into Auto Mode, if this mode is chosen a new screen will appear this screen is shown on figure 9.25. Beneath this Auto Mode button is the Manual Mode button, if this one is chosen the screen from figure 9.26 will be shown instead.

Beneath the bottom of the button's there is a text that says *"The system is currently in Auto Mode"*, this text *"Auto Mode* will change if the mode changes, this means that it can change between *"Auto Mode, Sell Mode and Charge Mode"*. It is these modes because if the Manual Mode is chosen by the button, then the system requires the user to make another choice, Sell or Charge Mode, this can also be seen on this figure 9.26.

In the bottom of the screen there is six button's, only two of these buttons are being used, F1 and F6. F1is a global button that directs the user to the Home screen. A global button means that it is the same button on all of the screens, that is why the button got a colour of green in the corner.

The F6 button directs the user to a test screen, this test screen is only usable for testing the system, and are not directly a part of the system.

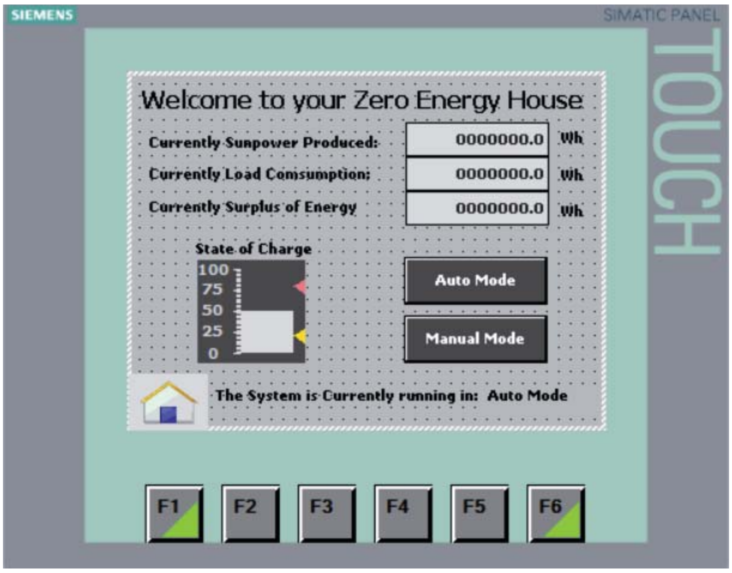

Figure 9.24. PLC Home Screen

The Auto Mode screen contains five lamps that each are connected to a tag in the program. In this way when the user have pressed the Auto Mode button on the Home screen, then til lamp (Circle) Beneath the text *Auto Mode* will lighten with a colour yellow, instead of the white colour.

From this screen the user can see if the Sun is connected, Battery is connected, Grid is connected or the CHP is connected to the system. If one or more of these are connected, it will lighten as the Auto Mode lamp.

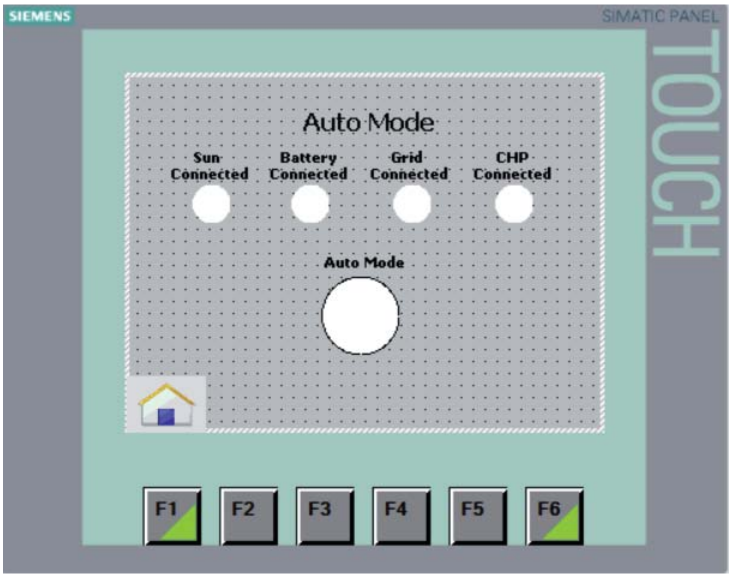

Figure 9.25. PLC Auto Mode

The Manual Mode screen contains six lamps to show status and two buttons. The top four lamps work identically as the four top lamps on the Auto Mode screen 9.25. The two lower lamps are only lightened if the user presses either the Force Charge or the Force Sell button. If the User presses one of these, the system will check if the criteria are fulfilled to be able to change mode. If it is not fulfilled, the mode will be in Auto.

One instance that it can't be fulfilled could be if the user are pressing Force Sell, but the SOC is already on it's minimum, thereby the battery can't provide the required power to the loads, and the energy from the Solar panels can't be used to a sale.

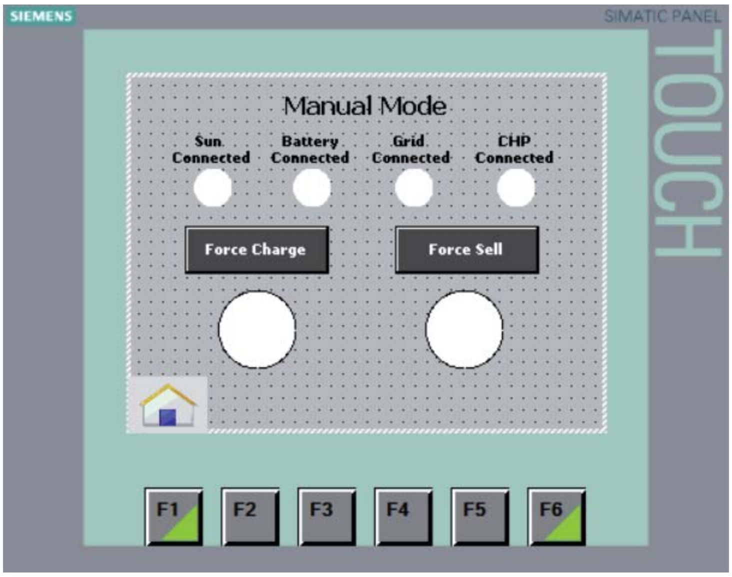

Figure 9.26. PLC Manual Mode

9.3 | Unit test

In this section there will be performed a Unit test of the PLC.

To make the unit test, an extra screen have been made with the essential parts for a test.

From the Home screen shown on figure 9.27, the three output fields (Currently Sunpower Produced, Currently Load Consumption and Currently Surplus of Energy) have been copied to the test screen together with the bar graph.

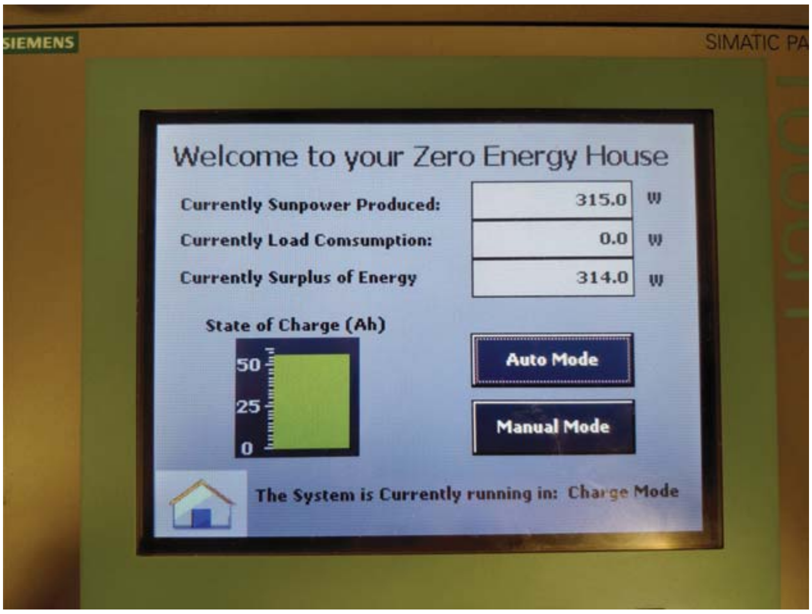

Figure 9.27. PLC Home screen

From the Manual Mode screen shown on figure 9.28 the six circles illustrating the modes and connections have been copied to the test screen.

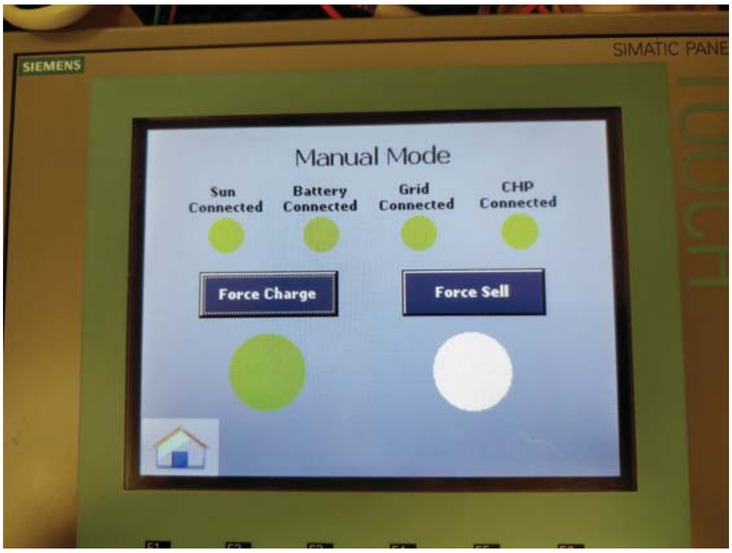

Figure 9.28. PLC Manual mode

From the Auto Mode screen shown on figure 9.29 the circle illustrating that the system is in auto mode has been copied to the test screen.

Figure 9.29. PLC Auto Mode

9.3.1 TEST OF AUTO MODE

When the system is in Auto Mode it will control which of the units that should be connected. On the first figure 9.30, the system can be seen with the minimum charge of the battery. Here it can be seen that the battery is connected, so it can be charged. The Grid is also connected because of the surplus energy, is larger than the maximum allowed to charge the battery, therefore the rest is being sold on the Grid.

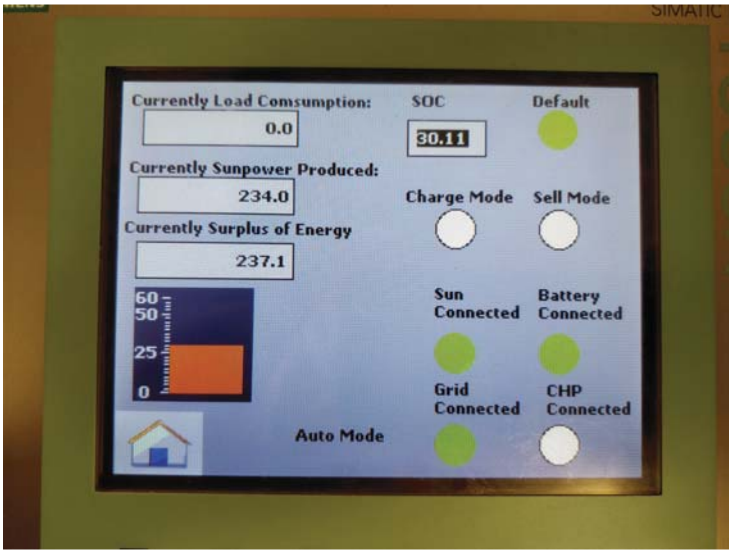

Figure 9.30. PLC Auto Mode Minimum SOC

On the second figure 9.31 the SOC is between the medium of the maximum and minimum of the SOC on the battery. It can be seen that the CHP is connected, this is because the sun panels couldn't supply enough power to the loads, therefore the CHP was connected and won't disconnect before it reaches a predefined value of 45 Ah. This is made so that the CHP won't connect and disconnect within a short amount of time.

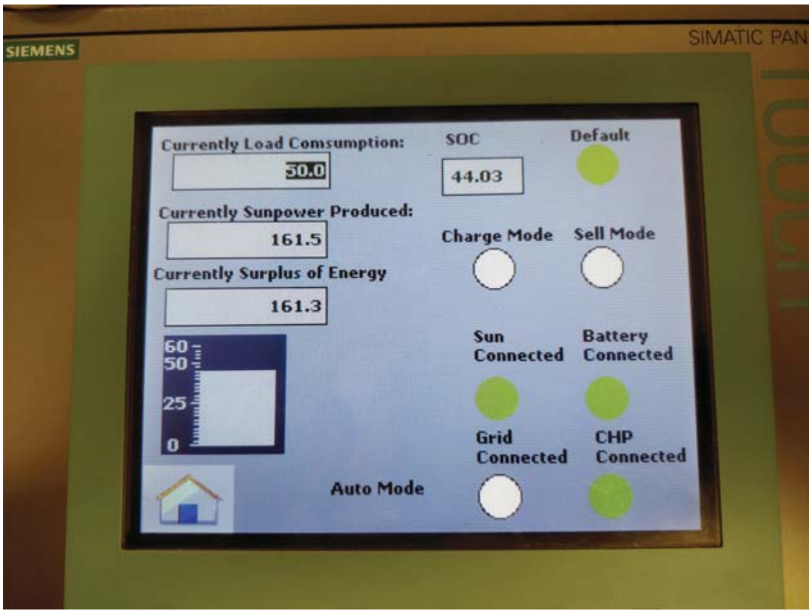

Figure 9.31. PLC Auto Mode Medium SOC

On the third figure of Auto Mode, shown on figure 9.32 the SOC has reached its upper limit on 60 Ah which results the system to disconnect the battery. Beside the disconnection of the battery, the system has connected the grid, to enable the sale of excessive energy.

Figure 9.32. PLC Auto Mode Max. SOC

9.3.2 Test of Sell Mode

When the system is in Sell Mode, the grid will automatically connect. This will only happen if the SOC is larger than the minimum allowed. On figure 9.33 it can be seen that the SOC is on 59.56 and therefore it can connect the grid.

Figure 9.33. PLC Sell Mode

9.3.3 Test of Charge Mode

When the system is in Charge Mode, the CHP will automatically turn on. This can also be seen on the figure 9.34. When the CHP is connected to the system, it will take full care of the loads so the battery can be charged with the sun power. The Grid is also connected because the surplus of energy, is larger than the maximum allowed for the battery.

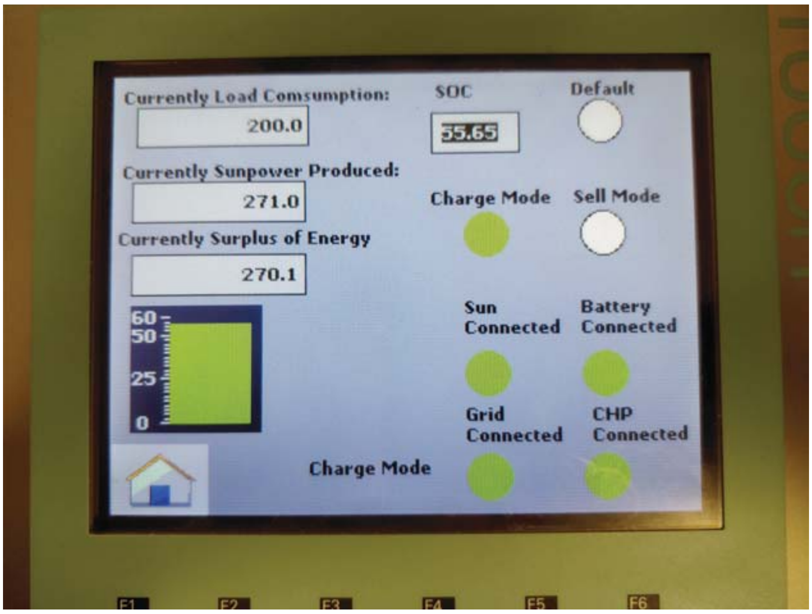

Figure 9.34. PLC Charge Mode

Acceptance & Integration test | 10

In this chapter the acceptance test specification will be described for the Zero Energy House. These test describes how the functional / non-functional demands will be tested, and what results that are expected to be seen. The test will also include every scenario from all the use cases, and describes how the use will interact with the system. The test will also describe what pre-condition that will have to be fulfilled and what observations and results that are expected to be seen from the tests. Furthermore the section includes the integration test of the HW and SW combined.

10.1 | Integration Tests

Throughout the integration tests, two parts of the system was connected and tested. If a error occurred during this test, the error was fixed until the test was completed successfully. After completion of a test, another part was implemented until the whole system composed. These tests is illustrated in table 10.1.

Action	**Expected Observation /result**	**Real Observation/result**	**Approval**
Test 1: The PLC sends a signal to the relays to turn on or off	The relays turn on or off according to the PLC signals	It could be observed that when the PLC send a signal to one of the relays, the corresponding relay switched on or off	Approved
Test 2: The Hall sensor sends a voltage signal to the PLC, this value is scaled for in the PLC to provide a valid value	The value on the PLC from the Hall sensor, is scaled and can be used further use in calculation of the SOC	It could be observed that the received signal from the Hall sensor is scaled and could be used for calculating the SOC. Though there is a offset from this sensor if it is use a amount of time. This offset disappears again after the system has been shut down for an amount of time. The offset it gives is approximately 0.5 Amps	Approved
Test 3: The current shunt transmitter sends a voltage signal to the PLC, this value is scaled for further use in calculation	The signal from the Hall sensor, is scaled and can be used further use in calculation of the SOC	It could be observed that the signal from the current shunt transmitter, are being scaled and can be used for calculation of the SOC	Approved
Test 4: The shunt sensor sends a voltage signal to the PLC, this value is scaled for further use in calculation	The value on the PLC from the Hall sensor, is scaled and can be used further use in calculation of the SOC	It could be observed that the signal from the shunt sensor, are being scaled and can be used in calculating the SOC	Approved
Test 5: Test for Noise on input to PLC from hardware circuits	When the hardware was assembled with the the software, the measurements were off. We found out that there were a lot of Noise on the signal, see figure 10.2.	This was fixed with an Low-Pass filer from the hardware output to the PLC input. See figure **??** for new signal.	Approved after the Filter was implemented.

Table 10.1. Integration's test

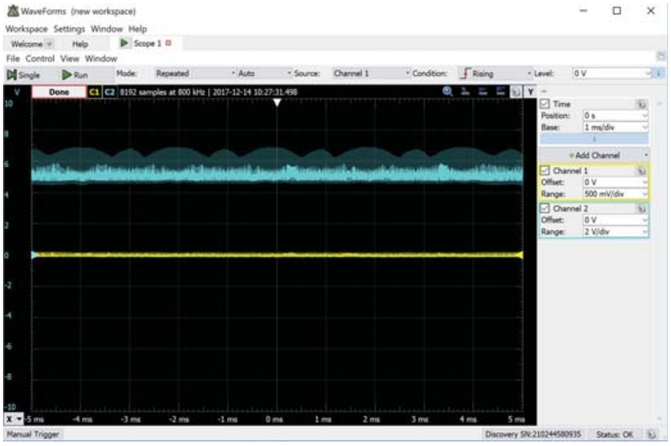

Figure 10.1. Noise from Hardware output to PLC input

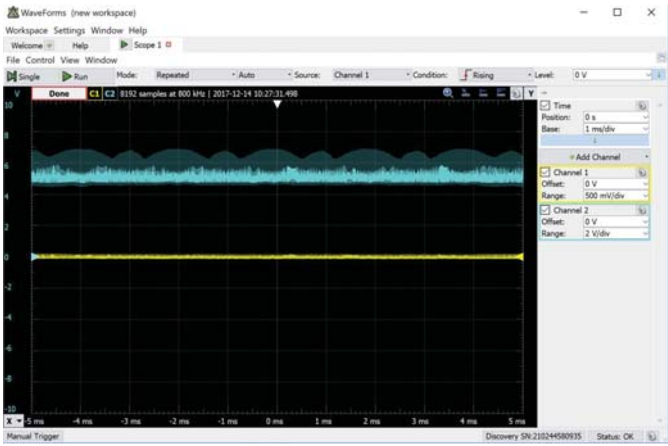

Figure 10.2. signal without noise from Hardware output to PLC input

10.2 Accept Tests

10.2.1 Test of Use Case 1

Test Use Case 1: Default mode - Main scenario				
Pre-condition The system is online and the connection to the HMI is established				
Step	**Action**	**Expected Observation /result**	**Real Observation/result**	**Approval**
1	User chooses Auto-Mode on the HMI	The display on the HMI will change stage to Auto Mode. The PLC will change into Auto Mode	The PLC and the HMI both changed stage into Auto Mode	Approved
2	User observes the HMI with the Auto Display on	The HMI has changed to Auto Display and shows which contact are on	The HMI changed screen to Auto Mode and showed which were connected with lamps	Approved
3	User Observes the Loads are provided with energy	The Inverter is supplying the households loads with energy	There are measured a power value over the loads	Approved

Table 10.2. Test of Use Case 1

Test of Use Case 1: Extension 1

Test Use Case 1: Default mode - Main scenario - [Extension 1: The excessive energy charges the battery				
Pre-condition Step 1 and 2 from table 10.2 is accomplished				
Step	**Action**	**Expected Observation /result**	**Real Observation/result**	**Approval**
1	User observes that the excessive energy will provide enough to charge the battery, along with supplying the loads.	The excessive energy from the production is charging the battery	It could be observed that the system is connecting the Grid	Approved
2	User observes that the battery is full charged	The PLC will send surplus energy to the grid, when the battery is fully charged	It could be observed that when the SOC was maximum, the PLC switched on the Grid	Approved

Table 10.3. Test of Use Case 1: Extension 1

TEST OF USE CASE 1: EXTENSION 2

Test Use Case 1: Default mode - Main scenario - [Extension 2: The excessive energy that the battery can't use, is sold				
Pre-condition Step 1 from table 10.2 is accomplished				
Step	**Action**	**Expected Observation /result**	**Real Observation/result**	**Approval**
1	Watch in Auto Mode, see if the PLC switches on grid	The PLC should show on the HMI, that now the grid is connected to the system and can therefore be sold	It could be observed that when the surplus energy rose higher than the maximum allowed charge for the battery, the PLC connected the Grid	Approved

Table 10.4. Test of Use Case 1: Extension 2

10.2.2 Test of Use Case 2

Test Use Case 2: Force Sell Mode - Main scenario				
Pre-condition The system is online and the connection to the HMI is established. The battery SOC is sufficient to supply the household loads.				
Step	**Action**	**Expected Observation /result**	**Real Observation/result**	**Approval**
1	User chooses Manual Mode on the HMI and chooses Sell	The display on the HMI will change to Manuel display setting. The PLC will change into Manual Mode and initiate the Sell procedure	It could be observed that the HMI and PLC both changed it's stage to Sell Mode	Approved
2	User observes the SOC of the battery and the energy production on the HMI	The HMI should show that the energy is drawn from the battery and produced energy is being sold	Both the SOC and the Energy production could be observed on the Home Screen	Approved
3	User observes the change to Default Mode on the HMI	After the battery have reached the minimum SOC. The PLC should switch back to Default Mode	It could be observed that when the SOC reached minimum value, the PLC switched back into Default Mode	Approved

Table 10.5. Test of Use Case 2

Test of Use Case 2: Extension 1

Test Use Case 2: Force Sell Mode - Main scenario - [Extension 1: Battery SOC to low				
Pre-condition The system is online and the connection to the HMI is established				
Step	**Action**	**Expected Observation /result**	**Real Observation/result**	**Approval**
1	User presses sell	The PLC will go into Sell mode	It could be observed that the PLC went to Sell Mode	Approved
2	PLC changes mode from sell to default.	The battery SOC is to low. The PLC will change the mode within the required time.	It could be observed that when the SOC reached it's minimum value, the PLC switched back into Default Mode	Approved

Table 10.6. Test of Use Case 2: Extension 1

10.2.3 Test of Use Case 3

Test Use Case 3: Force Charge - Main scenario				
Pre-condition The system is online and the connection to the HMI is established. The battery SOC isn't maxed charged				
Step	**Action**	**Expected Observation /result**	**Real Observation/result**	**Approval**
1	User chooses Manual Mode on the HMI and chooses charge	The display on the HMI will change to Manuel display setting. The PLC will change into Manual Mode and initiate the charge procedure	It could be observed that both the PLC and the HMI changed stage	Approved
2	User observes the battery SOC is changing on the HMI	The battery information on the HMI now shows the charge current and what the SOC is.	It could be observed that the SOC increased in Charge Mode	Approved
3	User observes that the battery is at full SOC on the HMI	When the battery is fully charged, the PLC switch's back to default mode	It could be observed that when the battery reached the maximum SOC, the PLC changed stage from Charge Mode to Default Mode	Approved

Table 10.7. Test of Use Case 3

Test of Use Case 3: Extension 1

Test Use Case 3: Force Charge Mode [Extension 1: Battery is fully charged				
Pre-condition The system is on and the user have pushed Force Charge				
Step	**Action**	**Expected Observation /result**	**Real Observation/result**	**Approval**
1	User press charge	The PLC will go into Charge mode	It could be observed that the PLC went into Charge Mode	Approved
2	PLC changes mode from charge to default.	The battery is fully charged. The PLC will change the mode within the required time.	It could be observed that when the battery reached maximum SOC, the PLC changed stage from Charge Mode to Default Mode	Approved

Table 10.8. Test of Use Case 1: Extension 3

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