Smart Energy Management For Household Prosumer

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Master's Thesis

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Abstract:

Solar energy is the most abundant energy available on Earth. While the photovoltaic system's output electricity energy is only accessible during day time, it is challenging to maximize the self-consumption of the system and minimize the electricity bill for the homeowner at the same time. This can be done by dividing the operation of the battery into day time part and night time part and treat them differently by two mixed-integer linear programming solvers from Matlab. The results indicate the high efficiency of the system. Simulink diagrams of the system have been mentioned.

Contents

Preface

This document describes the report of the project group "PED-4-1046". It has been developed from the 1st of February to the 29th of May of 2020, at Aalborg University, Institute of Energy Technology. The principles and methods used are based on Problem Based Learning (PBL). This thesis discusses the smart energy management system for household prosumer. The literature references appear as numbers in square brackets, with the number referring to the equivalent document which can be found in the bibliography. If the reference is in a figure caption, it means that it refers to the picture source. Figures and listings are denoted with the chapter and the figure number.

Aalborg University, May 29, 2020

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Nomenclature

Special Symbols and Denotations

Symbol	Description	Unit
P_{CH}	Charging Power	[W]
P_{DCH}	Discharging Power	[W]
P_{IN}	Requested Power	[W]
ϵ_{RT}	Round-trip efficiency	
E_{thr}	Total energy Throughput	[Wh]
E_{lost}	Total energy Lost	[Wh]
E_b	Surplus energy	[Wh]
E_{PV}	Generated Solar Energy	[Wh]
E_L	Consumed energy from the load	[Wh]
E_b	Surplus Energy	[Wh]
$P_{discharge-max}$	Maximum discharging power	[W]
$E_{bat-max}$	The maximum energy that the battery isable to store	[Wh]
E_e	effective solar irradiance	[W/m^2]
T_c	solar cell temperature	[$^{\circ}K$]
T_{ref}	Temperature at Standard Test Condition	[$^{\circ}C$]
$I_{mp,panel}$	Current at maximum power point of a PV panel	[A]
$I_{mp,panel,ref}$	$I_{mp,panel}$ in reference condition	[A]
α_{mp}	Normalized temperature coefficient for I_{mp} to effective irradiance	[]
β_{mp}	temperature coefficient for module V_{mp}	[V/$^{\circ}K$]
θ_Z	Solar zenith angle	[$^{\circ}$]
θ_A	Solar azimuth angle	[$^{\circ}$]
φ	Latitude of the site	
λ	longitude of the site	

Abbreviations

Abbreviation	Meaning
SOC	State of Charge
PV	Photovoltaic
PV+ES	Hybrid photovoltaic - energy storage
EMS	Energy Storage System
GHI	Global horizontal irradiance
DNI	Direct normal irradiance
DHI	diffuse horizontal irradiance

Chapter 1

Introduction

Nowadays, renewable energy has been becoming an optimal choice to replace fossil fuel in electricity production [1]. This trend is due to the fact that renewable energy has been considered as the key factor to fight with climate change [2], which is the most pervasive and threatening crisis of our time [3]. In 2018, the power capacity generated by renewable energy in developing countries surpassed the electricity production of fossil sources, accounted for 201 GW, just over half of the total power-generating capacity to their grids [4]. It is assured that renewable energy production would make up to two-thirds of energy consumption and 86% of power generation over the world by 2050 [5].

It can not be denied that solar energy is the most abundant energy source available on the Earth, but it has not been leveraged in the past due to the low efficiency and high cost of the solar photovoltaic (PV) system at that time. Thanks to the advanced technology in recent years, the solar PV modules cost has been cut off by 99% over the last four decades [6]. While homeowners usually receive quotes of $19-21\%$ PV panel efficiency, manufacturers can create PV panel with 30% of efficiency [7]. Those are the main reasons behind the surge in solar electricity production in recent years, and it is predicted to be the second-largest power generation source, just behind wind power by 2050 [8].

Figure 1.1 gives information about the solar PV capacity of the world from 2008 to 2018 in five countries and the rest of the world. It is noticeable that the country with the most significant solar PV capacity was Germany from 2008 to 2014, and since 2015, the place has been taken by China. There was a leap in total solar PV capacity of the world, with 505 Gigawatts (GW) in 2018, 33 times higher than that in 2008. The figure of the world was 593.9GW in 2019 and estimated to increase impressively 1,582.9GW in 2030 with especially additions in capacity by China, India, Germany, the US, and Japan [9]. Regarding to Denmark, the installed solar

PV capacity was also significantly rose in recent years, from 11 Megawatts (MW) to 900 MW in 2017 and expected to 4,900MW in 2030 [10].

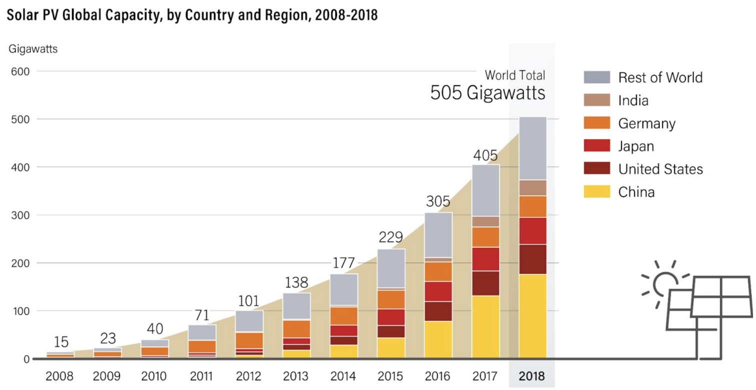

Figure 1.1: Solar PV Global Capacity, by Country and Region, 2008-2018 [11]

1.1 Background

The usage of renewable energy worldwide in 2017 is shown in figure 1.2 with 41.7% of renewable consumption energy was used by residential, commercial, and public services. With increasing climate change awareness of modern people and the decreasing solar panel price, solar technologies have gained the interest of homeowners who are eager to reduce their carbon footprint, improving the environment and cutting their electrical bill. According to the International Energy Agency, Residential solar PV capacity over the world was 58 GW in 2018, and it will jump to 143 GW in 2024 [12].

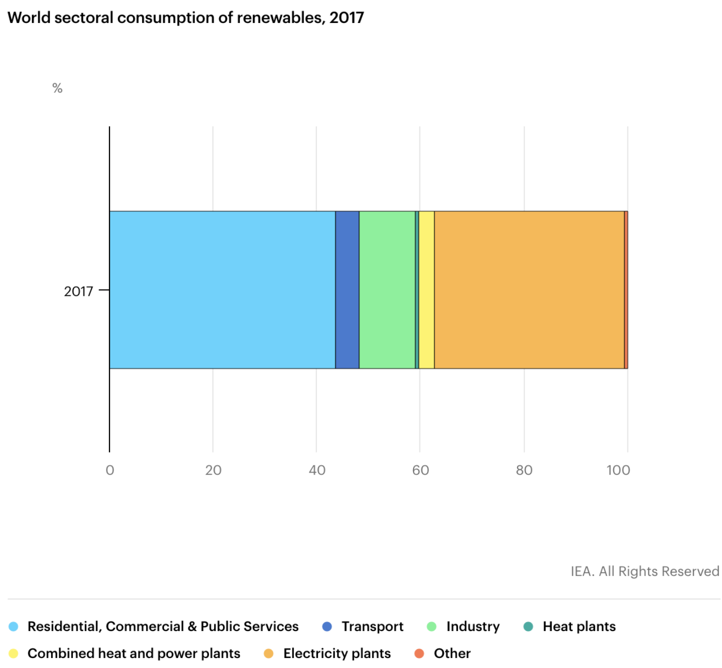

Figure 1.2: World sectoral consumption of renewables, 2017 [13]

In Denmark, regions and municipalities play a vital role in the installation of PV systems over the country. Dansk Solcelle Forening, a Danish PV association, composed a net-metering scheme with the aim to increase the electricity from the residential PV system to 5% of the total electricity of the country by 2020. During 2018, 2.8% of nation power consumption has come from solar PV electricity, increased 1% in comparison with that of 2015 [14].

There are three types of residential household PV systems, namely off-grid solar system, grid-tied solar system, and hybrid photovoltaic - energy storage (PV+ES) system. All of those three systems have their own advantages and disadvantages. When customers choose off-grid solar system, it means that all the energy for their house is supplied by the solar system. However, the initial cost for this type of system is higher than that of the other two systems [15]. As for grid-tied and PV+ES system, consumers are able to not only use the generated electricity for their house but also export it to the grid and become prosumers. It has been proven that the storage systems is a key solution for private household PV system in optimized self-consumption, reduce peak demand, and power smoothing [16]. So, the PV+ES system is the combination of off-grid and grid-tied solar system, and it is the best system among the three ones. In this project, only the PV+ES system is going to discuss.

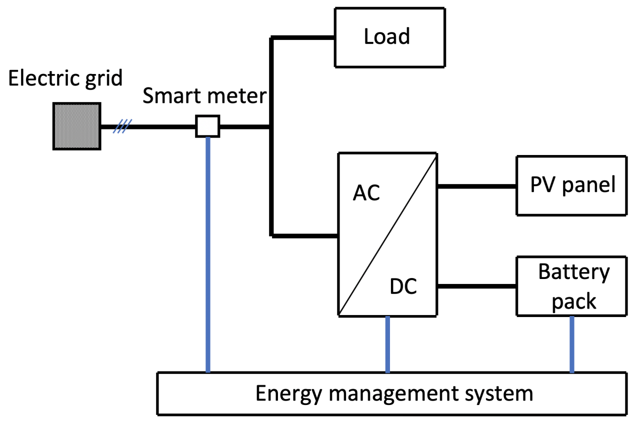

Figure 1.3: Hybrid Solar PV System

Basically, a hybrid solar system includes:

- Several PV panels are added up together to have the desired output power. A PV panel contains PV cells that are able to absorb solar energy and generate direct current (DC) electricity.
- A battery energy storage system (BESS).
- An inverter that is able to realize the interface of the grid, AC loads and the battery.
- A smart meter measures the voltage, current and power at the point of common coupling (PCC)

It is worth mentioning that an energy management system (EMS) is the heart of the system. Based on the information that the tool received from the inverter, it can control the power flow of the system, whether it stores the surplus energy on the battery pack or sell it to the grid. A recent trend of the EMS is to optimize self-consumption of the PV system [17]. As an illustration, it has been proven that with the existence of a home energy management system (HEMS), the electricity cost and the peak demand could be reduced by 20% and 50% respectively [18]. The HEMS market is very wide and has been significantly grown in recent years due to the interest of customers in automatic home devices, residential renewable energy, electric vehicles [19].

1.2 Scope of the project

1.2.1 Problem statement

As a prosumers, homeowners is able to sell generated electricity from their PV system to the grid; in other words, they can become seller and buyer at the same time. However, the prices for buying electricity is usually higher several times than selling electricity prices. This is due to buyers has to pay transportation fee, taxes, and other fees, while those fees are not available for sellers. As a result, the generated solar electricity is mainly used for maximize self-consumption of the PV system.

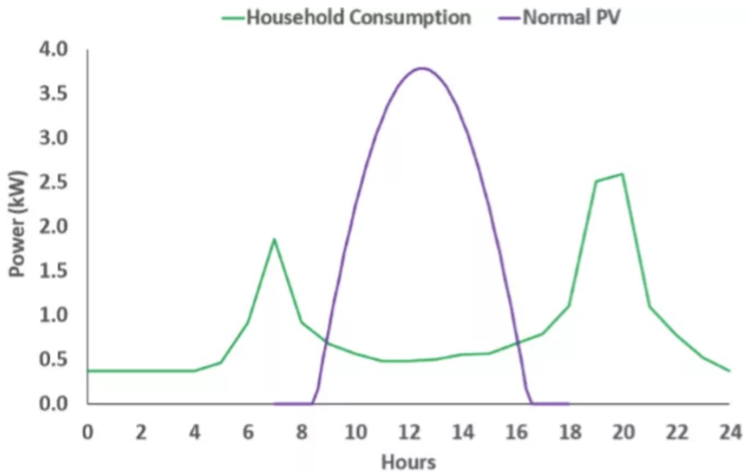

Figure 1.4: Household consumption and Normal PV [20]

Figure 1.4 indicates a normal PV energy output (purple curve) versus normal household consumption (green curve) [20]. It can be seen that the PV system only generates electricity during the day when the energy from the sun is accessible, while electricity is mainly used in the early morning and the nighttime. It means that the surplus energy (E_b) between generated energy (E_{PV}) and consumed energy (E_L) in the day time is required to be stored and be used afterward in order to flatten the purple curve and match it as much as possible with the green curve.

1.2.2 Objectives

Based on the challenges that have been stated before, the first objective of this thesis is to develop an EMS for the residential PV+ES system in order to maximize the self-consumption, and minimize the electricity bill of the system.

The second objective is to build a simulation model for the system in order to verify the proposed EMS. In this model, sub-models for PV panels, an inverter, and a battery will be closely discussed in the next chapter.

Last but not least, validating the EMS by using a laboratory setup will be implemented as the final objective. The setup is built by using commercial products that can be implemented in the real-life system, proving that the EMS is suitable for commercial service.

1.2.3 Limitations

- As the inverter in the PV+ES system is a commercial inverter from Fronius company, the equivalent circuit and the control topology of the inverter is not shareable due to business secrets. Thus, the controlling topology of the inverter is not going to be discussed.
- The EMS is built based on the forecast solar data and the simulation is required the real solar data corresponding with the forecast solar data. Besides, only the real solar data with very low accuracy (1 hour sampling time) is available.

Assumption

- Power factor of the inverter = 1
- Roundtrip efficiency of the battery = 95.3%. Self-discharge of the battery is neglected.
- The sunrise time is 6 a.m.

1.2.4 Content of report

In this section, a list of chapters and its summary is presented. Each bullet point represents a chapter.

- **Chapter 1** gives an overview of renewable energy, especially solar PV energy. Moreover, the background of the solar PV system, EMS is handed out. In addition, this chapter contains the problem statement, objectives, limitations, assumptions, and content of the report.
- **Chapter 2** presents the characteristic of the battery, the PV array and the inverter. The simulation modelling for each individual component is also going to be discussed.
- **Chapter 3** discusses the objective function and the algorithm of the EMS.

- **Chapter 4** is the simulation of the PV+ES system with the solar data of Alborg on May 1st, two 24-hour load profiles.
- **Chapter 5** introduces a system controller, which is able to control the battery based on the EMS.
- **Chapter 6** manifests the conclusion of the current work and recommendations for future work.

Chapter 2

System description

There are four main components of a hybrid PV+ES system for household customers, which are a solar energy source (PV array), a BESS, an inverter, and an EMS. In this chapter, the literature review and simulation report of the first three components are going to be presented. Besides, the EMS will be discussed in the next chapter.

2.1 Energy Storage System

A battery is a device that can store the surplus energy from the PV array for later use. There are several types of battery that can be used for energy storage systems, i.e. lithium-ion battery (Li-ion), nickel-cadmium battery (NiCd), nickel-metal hydride battery (NiMH), lead-acid battery (Pb-acid) and so on [21]. Among those types, the Li-ion battery is the most favored battery due to the advantages it offers, which are lighter, smaller, and more potent than other types of batter with high power density, high efficiency, and low self-discharge rate [22].

While there are different types of models for battery available, which are general model, performance model, and lifetime model [23], it is vital to determine which model is suitable for the thesis. The performance model can estimate the voltage and current of the battery under different operating conditions, and the lifetime model can predict the degradation and the duration of the battery to verify whether the battery is matched with the requirements of a particular application. In addition, the general model is a simple storage system model that works only as an energy buffer and is able to take into account round-trip efficiency, maximum energy storage, the limit of the battery's state of charge (SOC). Based on the goal of the thesis, the general model is chosen.

2.1.1 Important Parameters of The Battery

Before going into further details about the battery model, some important parameters are going to be explained below:

- **Maximum Discharging Power ($P_{discharge-max}$ [W])** : The maximum continuous discharge power of the battery
- **Maximum Energy ($E_{bat-max}$ [Wh])**: The maximum energy that the battery is able to store.
- **State of Charge**
  The SOC of the battery at any time is defined as following [21]:

  SOC = (Ah capacity remaning in the battery)/(Rated Ah capacity)

  or it can be calculated as:

$$SOC = SOC_{init} \pm \frac{1}{C_{max}} \int_t^0 Idt \tag{2.1}$$

  The equation above can be express as below:

$$SOC = SOC_{init} \pm \frac{1}{E_{max}} \int_t^0 Pdt \tag{2.2}$$

  where SOC_{init} is the initial value of SOC

  Usually, the maximum and minimum value of SOC (SOC_{max} and SOC_{min}) are 100% and 0% respectively, but they can be changed depending on the EMS to minimize the battery degradation. According to [24], the cycling lifetime of the battery is proportional to the level of SOC_{min}, and the value of SOC_{min} has chosen to be 40%. Besides, in order to maintain a fast charging rate for the battery, the SOC_{max} has chosen to be 80% [25].
- **Round-trip Energy Efficiency** ϵ_{RT}
  The ratio of energy put into energy retrieved from storage. Based on the ϵ_{RT}, the charging and discharging efficiency are taken into account. The charging power (P_{CH}) and discharging power (P_{DCH}) can be calculated as follow:

$$P_{CH} = P_{IN} * \sqrt{\epsilon_{RT}} \tag{2.3}$$

$$P_{DCH} = \frac{P_{IN}}{\sqrt{\epsilon_{RT}}} \tag{2.4}$$

  where P_{IN} is the requested power.

- **Total energy throughput (E_{thr} [Wh])**
  Total energy going in and going out of the battery.

$$E_{thr} = \int_t^0 |P_{IN}| dt \tag{2.5}$$

- **Total energy lost in storage system (E_{lost} [Wh])**

$$E_{lost} = \int_t^0 |P_{IN}| dt * (1 - \sqrt{\epsilon_{RT}}) \tag{2.6}$$

2.1.2 Battery Modeling

The model of the battery should has:

- An input P_{IN}, the amount of power that is requested to be charged or discharged to/from the battery.
- Four outputs: the power that the battery can charge or discharge, SOC, E_{lost} and E_{thr}.

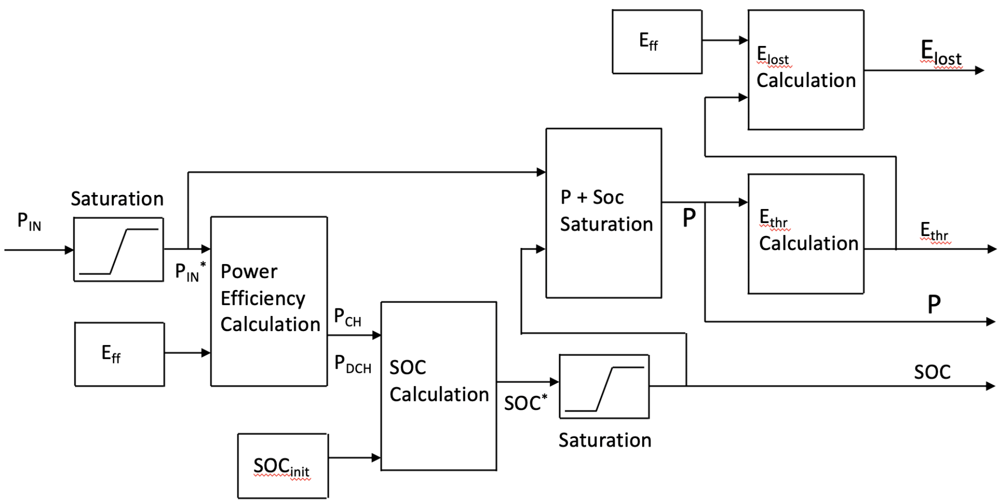

Figure 2.1: Battery Model

Figure 2.1 indicates how the battery model works. When P_{IN} is requested to be charged or discharged to/from the battery, it goes through a saturation block to make sure its value satisfies a constrain -$P_{IN} \leq P_{discharge-max}$. The value of P_{IN} shows the required state of the battery. When $P_{IN} < 0$, the battery is at charging condition and when P_{IN} is positive, the battery is discharging.

The Power Efficiency Calculation block is based on equation 2.3 and 2.4 with two input value is the value of P_{IN}^{*} and ϵ_{ff} (or E_{ff} in the figure 2.1). The output of this block is P_{CH}/P_{DCH}.

The following block is SOC calculation. With two inputs P_{CH}/P_{DCH} and SOC_{init}, the value of SOC^{*} can be calculated based on equation 2.2. Note that this value is the value of SOC before checking saturation ($SOC_{min} \leq SOC \leq SOC_{max}$). If $SOC^{*} > SOC_{max}$, the output value of SOC is SOC_{max} and the output value P of "P+SOC Saturation" block is 0. Similarly, $SOC^{*} < SOC_{min}$, the output value of SOC is SOC_{min} and the output value P of "P+SOC Saturation" block is 0. Otherwise, SOC = SOC^{*} and P = P_{IN}^{*}.

From two equations 2.5 and 2.6, two last outputs E_{lost} and E_{thr} can be calculated and be used in future work.

2.2 PV Array

PV array is the generating power source of the PV system, and it is made of silicon, the second most abundant element on the Earth. The PV array is built from several PV panels that are connected in series and parallel. In the meantime, a PV panel is created by numerous PV cells. By absorbing the solar energy, a few square inches in size of a PV cell generates typically is about 1 W power and a PV panel has the rated power ranging from 250W to 400W [26].

2.2.1 I-V and P-V curve

The most two essential parameters to describe the electrical performance of a PV cell are the open-circuit voltage V_{oc} and the short-circuit current I_{sc}. The I_{sc} is measured by shorting the output terminals and measuring the terminal current, and the open-circuit voltage V_{oc} is obtained under no-load condition.

Figure 2.2(a) indicates the electrical characteristic of a PV cell by current vs. voltage (I-V) curve in sunlight. In the left-shaded region, the cell is operating as a constant current source and a generating voltage to match with the load resistance. Similarly, in the right-shaded region, due to the rapid drop in the current and small increase in the voltage, the cell can be considered as working as a constant voltage source. In the middle region, there is a knee point of the curve. [21].

Figure 2.2(b) shows the power-voltage (P-V) curve characteristic of a PV cell with the maximum power point is matched with the knee point of the I-V curve. In addition, the PV power circuit is always designed to operate close to the maximum power point with a slight slant on the left-hand side. This is the reason why the PV circuit is modeled approximately as a constant current source [21].

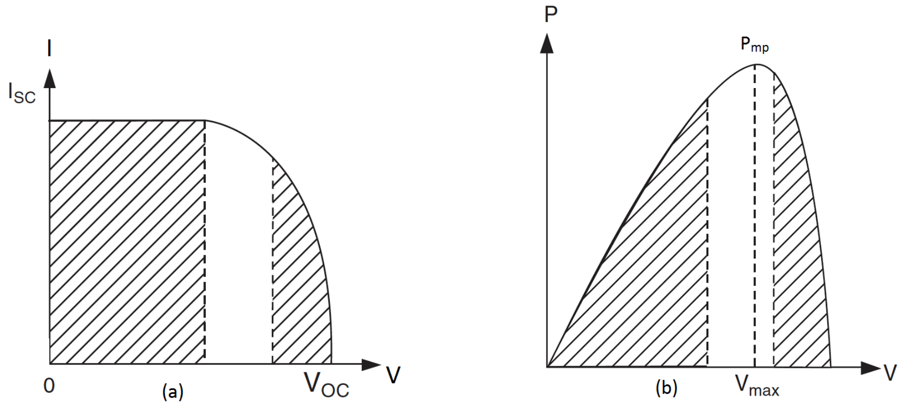

Figure 2.2: (a) I-V characteristic and (b) P-V characteristic of the PV cell in sunlight [21]

2.2.2 Modelling PV Array

There are four PV array models available, which are:

- Simple PV panel efficiency model.
- Power temperature coefficient model.
- PV Watts model.
- Sandia PV array performance model (SAPM).

While the three first models can be deployed from the PV panel datasheet, the last model is based on a series of tests with very high accuracy. Thus, Sandia PV array performance model is chosen for the thesis, and two equations for calculating voltage (V_{mp}) and current (I_{mp}) at maximum power point can be found below [27].

$$I_{mp,panel} = I_{mp,panel,ref}(C_0 E_e + C_1 E_e^2)[1 + \alpha_{mp}(T_c - T_{ref})] \tag{2.7}$$

$$I_{mp} = I_{mp,array} = I_{mp,panel} n_{np} \tag{2.8}$$

$$V_{mp,panel} = V_{mp,panel,ref} + C_2 n_s \delta(T_c) ln(E_e) + C_3 n_s [\delta(T_c) ln(E_e)]^2 + \beta_{mp}(T_c - T_{ref}) \tag{2.9}$$

$$V_{mp} = V_{mp,array} = V_{mp,panel} n_{ns} \tag{2.10}$$

$$\delta(T_c) = A\frac{kT_c}{q} = AV_t \tag{2.11}$$

where

- E_e - effective solar irradiance (W/m^2)
- T_c - solar cell temperature (°K)
- T_{ref} - temperature at Standard Test Condition (STC) (25 °C)
- $I_{mp,panel,ref}$ - $I_{mp,panel}$ in reference condition (A)
- $V_{mp,panel,ref}$ - $V_{mp,panel}$ in reference condition (V)
- α_{mp} - normalized temperature coefficient for I_{mp} to effective irradiance
- β_{mp} - temperature coefficient for module V_{mp} (V/°K)
- C_0, C_1 - SAPM coefficients relating I_{mp} to effective irradiance
- C_2, C_3 - SAPM coefficients relating V_{mp} to effective irradiance
- n_s - number of series conencted cells in a module
- n_{ns} - number of series panels
- n_{np} - number of parallel panels
- A - diode ideality factor
- k - Boltzmann's constant (J/K)
- q - Elementary charge (C)

Effective irradiance is the actual part of the light that reaches to the PV cells. The effective irradiance depends on surface irradiance, the sun location, PV array orientation, outside temperature, and wind speed.

The Sun's Position

The sun's position represents by the solar zenith (θ_Z) angle and the azimuth angle (θ_A) (figure 2.3). The solar zenith is the angle between the sun and the vertical, and the azimuth angle is the compass direction from the sun.

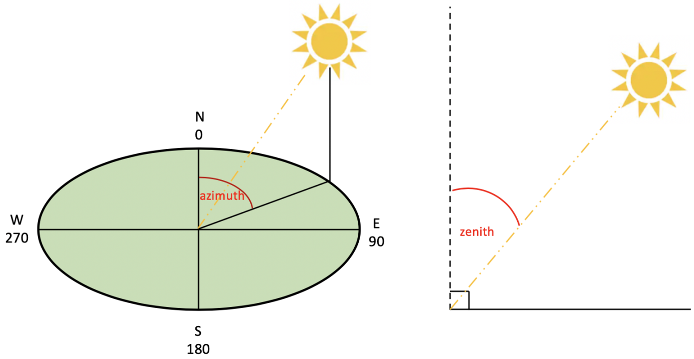

Figure 2.3: Azimuth and Zenith Angle

The sun's position can be calculated as follow ([28]):

$$LSTM = 15^\circ * \Delta T_{GMT} \tag{2.12}$$

$$B = \frac{360}{365}(j - 81) \tag{2.13}$$

$$EoT = 9.87sin(2B) - 7.53cos(B) - 1.5sin(B) \tag{2.14}$$

$$TC = 4(\lambda - LSTM) + EoT \tag{2.15}$$

$$LST = LT + \frac{TC}{60} \tag{2.16}$$

$$\omega = (LST - 12) * 15^\circ \tag{2.17}$$

$$\delta = 23.45 * sin(B) \tag{2.18}$$

$$cos(\theta_Z) = cos(\varphi) * cos(\delta) * cos(\omega) + sin(\varphi) * sin(\delta) \tag{2.19}$$

$$tan(\theta_A) = \frac{sin(\omega)}{sin(\varphi) * cos(\omega) - tan(\delta) * cos(\varphi)} \tag{2.20}$$

where:

- φ - latitude of the site
- λ - longitude of the site

- LT - local time
- ΔT_{GMT} - difference of the Local Time (LT) from GMT in hours
- j - Julian day number
- TC - time correct factor
- EoT - equation of time
- LSTM - local standard time meridian
- ω - hour angle
- δ - solar declination angle

Surface Irradiance

There is enormous energy coming out from the sun instantaneously. About 70% of solar energy reaches the Earth is absorbed by the atmosphere, and the rest is reflected back to space. At the Earth's surface, solar energy is represented by surface irradiance, which includes global horizontal irradiance (GHI), direct normal irradiance (DNI) and diffuse horizontal irradiance (DHI) (figure 2.4). As its name, DNI is the sunbeam that reaches the Earth's surface directly, and DHI is scattered light by molecules, clouds, and so on. Besides, GHI is total irradiance from the sun on the Earth's surface and can be calculated as:

$$GHI = DHI + DNI * cos(\theta_z) \tag{2.21}$$

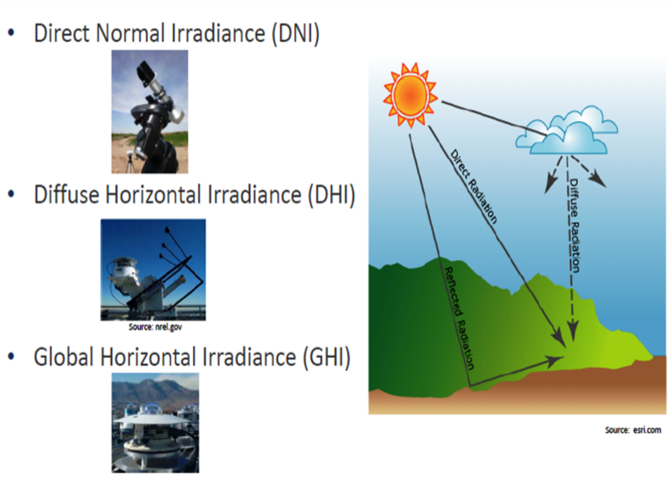

Figure 2.4: Solar Radiation [29]

Plane-of-Array Irradiance

Plane-of-array irradiance (E_{POA}) is the result of the surface solar irradiance incident on the PV panel surface (figure 2.5), which can be divided into three components: beam component (E_b), sky diffused component (E_d) and ground diffused component (E_g) (figure 2.6).

$$E_{POA} = E_d + E_b + E_g \tag{2.22}$$

The POA beam component can be calculated as follow:

$$cos(\theta_{AOI}) = cos(\theta_Z) * cos(\theta_T) + sin(\theta_Z) sin(\theta_T) cos(\theta_A - \theta_{A,array} \tag{2.23}$$

$$E_b = DNI cos(\theta_{AOI}) \tag{2.24}$$

where:

- θ_T - PV array tilt
- $\theta_{A,array}$ - PV array azimuth
- θ_{AOI} - angle of incidence

The POA Sandia sky diffused beam component can be calculated as follow [30]:

$$E_d = DHI \frac{1 + cos(\theta_T)}{2} + GHI \frac{(0.012\theta_Z - 0.04) - (1 - cos(\theta_T))}{2} \tag{2.25}$$

The equation of POA sky diffused component is:

$$E_g = GHI * albedo * \frac{1 - cos(\theta_T)}{2} \tag{2.26}$$

where albedo is ground albedo coefficient.

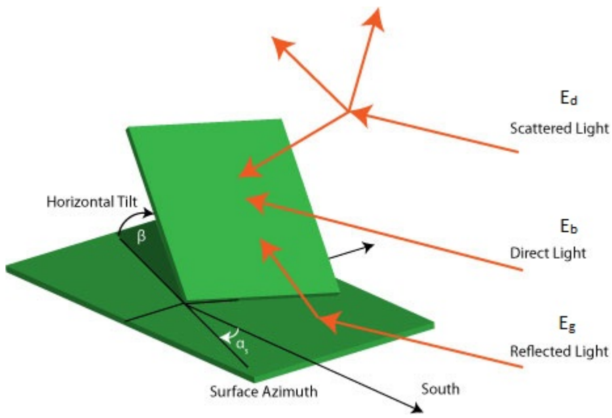

Figure 2.5: Plane-of-Array Irradiance [31]

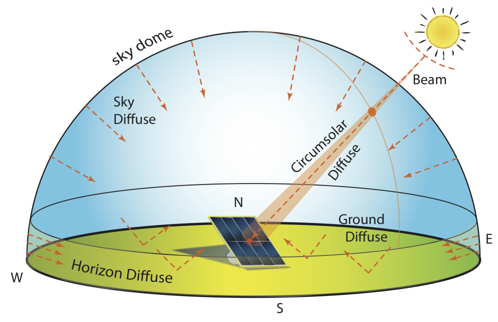

Figure 2.6: E_{POA} Components [32]

Finally, the formula of E_e can be established from E_{POA}, adjusted angle of incidence losses/reflection, soiling, and spectral mismatch [27].

$$E_e = M * (IAM * E_b + E_d) * SF \tag{2.27}$$

$$IAM = b_0 + b_1\theta_{AOI} + b_2\theta_{AOI}^2 + b_3\theta_{AOI}^3 + b_4\theta_{AOI}^4 + b_5\theta_{AOI}^5 \tag{2.28}$$

$$M = a_0 + a_1 AM + a_2 AM^2 + a_3 AM^3 + a_4 AM^4 \tag{2.29}$$

$$AM = 1/cos(\theta_Z) \tag{2.30}$$

where

- b_0-b_5 - Sandia IAM model parameters
- a_0-a_4 - Sandia spectral mismatch model parameters
- M - spectral mismatch modifier

Cell Temperature

According to [27], the cell temperature can be calculated as follow:

$$T_c = T_m + \frac{E_{POA}}{E_{STC}}\Delta_T \tag{2.31}$$

$$T_m = T_a + E_{POA} exp(a + bW_s) \tag{2.32}$$

where:

- T_a - outside temperature or ambient temperature
- T_m - module temperature

- E_{STC} - reference irradiance (1000 W/m2)
- Δ_T - module material and construction parameter - represents the difference between the module and cell temperature

Due to the goal of the thesis, only P_{mp} is going to be used, the other variables (V_{mp} and I_{mp}) can be considered as references for future work. The PV array model is expressed in figure 2.7. It has two inputs which are E_e and T_c and two outputs are V_{mp} and P_{mp} ($P_{mp} = V_{mp}I_{mp}$).

With a high accuracy solar data, a low pass filter (LPF) is required in order to smoothen the irradiance curve. The cut-off frequency ($f_{c,PV}$) is calculated below based on [33] with a = 0.26 and b = -0.499:

$$f_{c,PV} = aP^{b}_{PV,rated} \tag{2.33}$$

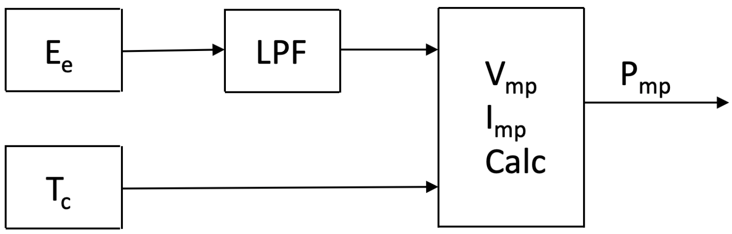

Figure 2.7: PV Array Model

2.3 Inverter

The inverter of PV+ES system has the main function to convert the DC power from the PV array and the battery to AC power, which is able to import to the grid. With the goal of the thesis is to study the power flow of the PV+ES system, a simple model of the inverter is introduced (figure 2.8) with one input is DC power (P_{DC}). The output AC power (P_{AC}) of the inverter can be calculated by an equation below:

$$P_{AC} = \eta * P_{DC} \tag{2.34}$$

where η is the efficiency which can be found in the datasheet of the inverter.

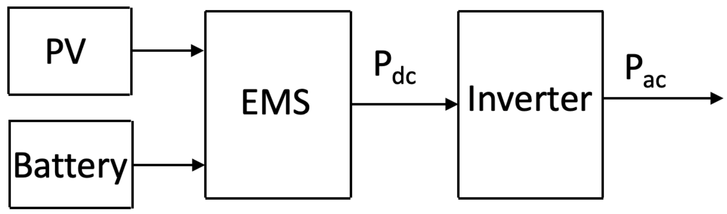

Figure 2.8: Simple diagram of the Inverter

In order to maximize the power out of the system, the power factor of the invert is set to be 1. In this case, all the required reactive power of the load will be supplied by the grid.

Chapter 3

Energy Management System

In the previous chapter, all the hardware of the PV+ES system have been closely discussed and the EMS, a controlling strategy, with a goal to maximize the self-consumption and the profit of the system will be presented in this chapter. The EMS is for 24-hour operation of the battery and it will be re-calculated before the following day comes.

The EMS is divided into two EMS: EMS1 and EMS2. While the EMS1 is a plan builder, the EMS2 is a controller of the system (figure 3.1). The details of EMS1 and EMS2 is going to be discussed below.

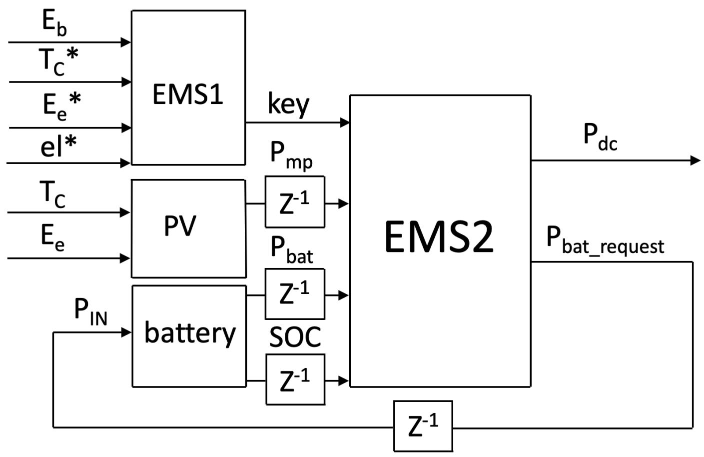

Figure 3.1: the EMS diagram

3.1 Objective Function of the EMS1

As mentioned before, the energy from the sun is accessible during the day, while the electricity is mainly used in the early morning and the night time. Therefore, in order to maximize the selft-consumption and maximize the profit (or minimize the electricity bill) of the system, the EMS1 can be separated into two parts:

- Part 1 - the EMS in the day time. The surplus energy is going to be stored in the battery as much as possible before the night time. If all surplus energy can not be stored in the battery, the excess energy will be sold to the grid with maximum profit.
- Part 2 - the EMS for the night time. The energy inside the battery is only used for self-consumption to minimize the money for buying electricity from the grid by discharging at the highest possible electricity prices.

3.1.1 The EMS1 - part 1

The idea to calculate the battery's operation during the day time is from day-ahead electricity prices, forecast solar data, and forecast residential electricity consumption. The forecast surplus energy (E_b) can be calculated and used as a constraint of the battery operation from the last two inputs. Let's dividing 24-hours into m minutes sampling-interval, and the whole operating condition of the battery in one sample will be the same. If $n = \frac{24*60}{m}$, x_i (i=1..n, unit kWh) is the energy coming to the battery in the ith sample (x_i>0, the battery is charging and vice versa), E_{PV-i} is total generated energy in the i-th sample from the PV array, and $elsell_i$ is selling electricity price in the i-th sample. Assuming total charged energy of the battery E_{charge} = $E_{discharge}$, the EMS1 - part 1 objective function now can be formed:

$$Minimize\ f_1 = \sum_{i=1}^{n} x_i * elsell_i \tag{3.1}$$

Note that from equation (3.1), only the day time operation of the battery is going to be used. The night time part will be replaced by the EMS1 - part 2. The constraints for equation (3.1) will be discussed in the next section.

It can not be denied that the home energy consumption is repeatable can be divided into two categories: week profile and weekend profile. As an example, during the week or the weekend, the 24-hour residential energy consumption can change but not much. Therefore, forecast energy consumption profiles for both categories can be built by storing the recent profile and update it day by day.

Thanks to the development of technology, the solar irradiance can be forecasted with the accuracy depending on a particular location. Not to mention, day-ahead electricity price is available at Nordpool [34] for both selling and buying electricity purposes. All of that valuable information could be used to calculate day-ahead operation for the battery in order to satisfy equation (3.1).

3.1.2 The EMS1 - part 2

Normally, the energy available in the battery (the battery can discharge to 40%) can not cover all the consumption of the home user during the whole day. Therefore, it is vital to have a discharging strategy in order to minimize the money for buying electricity from the grid. The objective function of the EMS1 - part 2 can be found in equation (3.1) and its constraints will be discussed in the next section.

$$Minimize\ f_2 = \sum_{i=1}^{n} x_i * elbuy_i \tag{3.2}$$

where $elbuy_i$ is the buying price for electricity at sample i-th.

3.2 EMS1 - Minizming f1

There is an option to solve (3.1) by mixed-integer linear programming (MILP) "intlinprog" which is provided by Matlab. The intlinprog function finds a minimum value for a function specific by:

$$Minimize\ f(x) = \begin{cases} x(intcon) \\ A * x \leq b \\ lb \leq x \leq ub \end{cases} \tag{3.3}$$

where

- f : a vector representing a function what need to be minimized
- x : a vector with all variables of f
- intcon : a vector defines all integer variables
- A : a coefficients matrix of inequality functions
- b : a solution vector of the inequality functions
- lb and ub : two vectors of lower and upper boundaries of variables x

The function in Matlab for calling this MILP solver is:

$$x = intlinprog(f, intcon, A, b) \tag{3.4}$$

Note that the vector f in equation (3.4) represents the electricity price vector (3.5). Usually, a new day starts at 0 a.m, and the output energy of the PV array is 0 for the first hour. For that reason, "intcon" is set to be 1 (x_1 = 0).

$$f = (el_1,\ el_2,\ \dots\ ,\ el_n) \tag{3.5}$$

3.2.1 Objective Function

The objective function is to maximize the electricity sale and can be found in equation 3.1.

3.2.2 Constraints

There are five constraints of the variable x which have been found.

Constraint 1

The first constraint is the upper limit of x_i and only apply for i with E_{b-i} > 0: $x_i \leq E_{b-i}$. This constraint indicates that if the forecast surplus energy at i-th sample is positive, the maximum energy that the battery can charge is E_{b-i}

- A_1 = eye(n)
- b_1 = P_b

If E_{b-i} < 0 => A_{1-i} = 0 and b_{1-i} = 0.

Constraint 2

The second constraint is apply for x_i when $E_{b-i} \leq 0$: $x_i \leq 0$. This constraint shows that when the forecast surplus energy at i-th sample is less or equal to 0, the battery will be discharged in order to achieve $E_{ac-i} = E_{L-i}$, where E_{ac-i} is the output AC energy of the inverter and E_{L-i} is the consumed energy of the load at i-th sample.

- A_2 = eye(n)
- b_2 = zeros(1,n)

If $E_{b-i} \geq 0$ => A_{3-i} = 0.

Constraint 3

It is true that the output energy is always smaller or equal to the input energy. As a result, total discharging energy and charging energy from first operation to i-th operation (i=1..n) is not bigger than 0.

$$
\begin{aligned}
& -x_1 \leq 0 \\
& -x_1 - x_2 \leq 0 \\
& ... \\
& -x_1 - ... - x_n \leq 0
\end{aligned}
$$

Or:

- $$A_3 = \begin{pmatrix} -1 & 0 & \cdots & 0 \\ -1 & -1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ -1 & -1 & \cdots & -1 \end{pmatrix}$$
- b_3 = zeros(1,n)

Constraint 4

The fourth constraint is the maximum energy that the battery is able to store. In chapter 2, it has been mentioned that the SOC_{max} and SOC_{min} are set to 80% and 40% respectively. As a result, total x from 1 to i (i=1..n) is smaller than 40% of E_{max} of the battery. This constraint is to verify that the battery can be charged up to 80%.

$$
\begin{aligned}
& x_1 \leq 0.4 * E_{max} \\
& x_1 + x_2 \leq 0.4 * E_{max} \\
& ... \\
& x_1 + ... + x_n \leq 0.4 * E_{max}
\end{aligned}
$$

- $$A_4 = \begin{pmatrix} 1 & 0 & \cdots & 0 \\ 1 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 1 & 1 & \cdots & 1 \end{pmatrix}$$
- b_4 = (0.4*E_{max})*ones(1,n)

Constraint 5

The fifth constraint is the maximum input energy of the inverter per m minutes (E_{dc-max}) based on a maximum input power (P_{dc-max}) of the inverter which can be found in its datasheet. The input energy of the inverter or the DC energy at i-th operation of the system (E_{dc-i}) can be considered :

$$E_{dc-i} = -x_i + E_{pv-i} \tag{3.6}$$

Note that the equation 3.6 is correct for discharging condition but the constraint can be used for both discharging and charging condition.
$-x_i$ + E_{PV-i} <= E_{dc-max}
Or:

- A_5 = -eye(n)
- b_5 = ($E_{dc-max} - E_{PV-1}$, $E_{dc-max} - E_{PV-2}$, ... , $E_{dc-max} - E_{PV-n}$)

Finally, the A and b vectors can be formed:

$$A = \begin{pmatrix} A_1 \\ A_2 \\ A_3 \\ A_4 \\ A_5 \end{pmatrix} \tag{3.7}$$

and b = (b_1, b_2, b_3, b_4, b_5)

3.3 EMS1 - Minimizing f2

The idea of the EMS1 - part 2 for minimizing f_2 is that after 4 p.m., the generated electricity from the PV array is going to used by the load directly and the shortage energy can be bought from the grid. However, the discharging operation of the battery will be calculated by the MILP solver in order to minimize the money from buying electricity from the grid.

Note that after 4 p.m. the generated electricity from the PV array is usually lower than the consumed electricity from the load. In addition, the electricity price waveform usually peaks in 7 - 8 p.m. As a result, after 4 p.m., the battery is not going to discharge in order to compensate with the shortage between generated electricity from the PV array and the consumed energy from the load.

Before going into details about four constraints of the equation (3.2), there are three vector that need to be created first: buying electricity prices (elbuy), load consumption (E_L) and E_{PV}. The length of those three vector is from $\frac{16*60}{m}$+1 to n, or equal to from 1 to h.

3.3.1 Objective Function

The objective function is to maximize the electricity sale and can be found in equation 3.2.

3.3.2 Constraints

Constraint 1

The first constraint is the maximum energy that the battery can discharge per one sample: $-x_i \leq E_{L-i}$.

- A_1 = -eye(h)
- b_1 = reshape(loaddis,[1,h])

Constraint 2

The second constraint indicates that the battery can only discharge: $x_i \leq 0$

- A_2 = eye(h)
- b_2 = zeros(1,h)

Constraint 3

The third constraint is the maximum energy that total the battery can discharge. Assuming the initial SOC of the battery is 80%

$$
\begin{aligned}
&-x_1 \leq 0.4 * E_{max} \\
&-(x_1 + x_2) \leq 0.4 * E_{max} \\
&... \\
&-(x_1 + ... + x_n) \leq 0.4 * E_{max}
\end{aligned}
$$

- $$A_3 = \begin{pmatrix} -1 & 0 & \cdots & 0 \\ -1 & -1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ -1 & -1 & \cdots & -1 \end{pmatrix}$$
- b_3 = (0.4*E_{max})*ones(1,n)

Constraint 4

The fourth constraint is the maximum input energy of the inverter per m minutes (E_{dc-max}) based on a maximum input power (P_{dc-max}) of the inverter which can be found in its datasheet. The input energy of the inverter or the DC energy at i-th operation of the system (E_{dc-i}) can be considered :

$$E_{dc-i} = -x_i + E_{pv-i} \tag{3.8}$$

Note that the equation 3.8 is correct for discharging condition but the constraint can be used for both discharging and charging condition.
$-x_i + E_{PV-i} <= E_{dc-max}$
Or:

- A_4= -eye(h)
- b_4 = ($E_{dc-max} - E_{PV-1}$, $E_{dc-max} - E_{PV-2}$, ... , $E_{dc-max} - E_{PV-h}$)

Finally, the A and b vectors can be formed:

$$A = \begin{pmatrix} A_1 \\ A_2 \\ A_3 \\ A_4 \end{pmatrix} \tag{3.9}$$

and b = (b_1,b_2,b_3,b_4)

3.4 EMS2

While the EMS1 is a plan builder, the EMS2 is a controller of the system and is working based on the forecast solar data. According to the input of key, the real output power of the PV array, and the boundary for the input power of the inverter, the value of two outputs P_{dc} and $P_{bat-request}$ is calculated. Due to P_{dc} is a combination of P_{mp} and P_{bat}, the value of $P_{bat-request}$ is calculated based on the available discharging $P_{discharge-avail}$ and available charging $P_{charge-avail}$ power of the battery. Afterward, the value of $P_{bat-request}$ is sending back to the battery and outputting SOC and P_{bat} for the next sample time.

$$P_{discharge-avail} = E_{bat-max} * 3600 * (SOC - 40)/100[W] \tag{3.10}$$

$$P_{charge-avail} = E_{bat-max} * 3600 * (80 - SOC)/100[W] \tag{3.11}$$

In the case of P_{bat}:

- $P_{bat} \geq 0$: $P_{dc} = P_{dc} + P_{bat}$
- $P_{bat} < 0$: $P_{dc} = P_{dc}$

Note that the value of P_{dc} will be set to 0 in the beginning of every sampling period.

- key = 0: The state of the battery is on hold. $P_{bat_request}$ = 0 and P_{dc} = P_{dc} + P_{mp}
- key < 0 (key = -1): The state of the battery is charging. There is two cases available. If $P_{PV} \geq P_L$, all the required power from the load is supplied by the PV and the surplus power ($P_b \geq 0$) is charged by the battery. Else, if time < 4 p.m., the shortage power ($P_b \leq 0$) is supplied by the battery and otherwise, it is not.
- key > 0 (key = 1): The state of the battery is discharging. There is also two cases. If time < 4 p.m., the battery discharges with highest rate ($P_{PV} + P_{bat} =$ 4184 W). Else, $P_{bat} = P_L$

Chapter 4

Simulation Result

The one day simulation result of the system will be presented below with the forecast and real solar data of Aalborg in May 01, and two cases for load profile. Note that the real solar data is available with 1 hour sampling time, and the forecast solar data is available with 30-minutes sampling time.

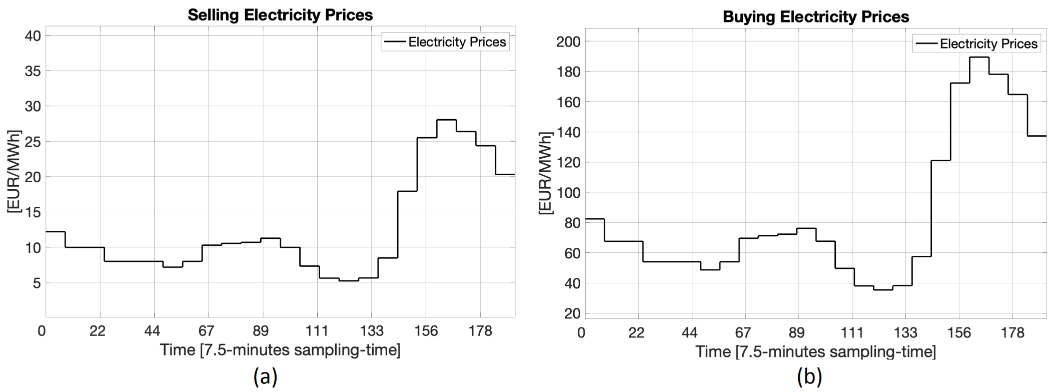

Figure 4.1: Selling Electricity Prices (a), Buying Electricity Prices (b)

Figure (4.1) indicates an electricity case which is going to be discussed. In Denmark, the buying electricity price is 105% higher than selling electricity price. However, while the buyer has to pay transportation fees, taxes, and other fees, those fees are not available for the seller. Therefore, the ratio between buying and selling electricity price surges to 675.6%.

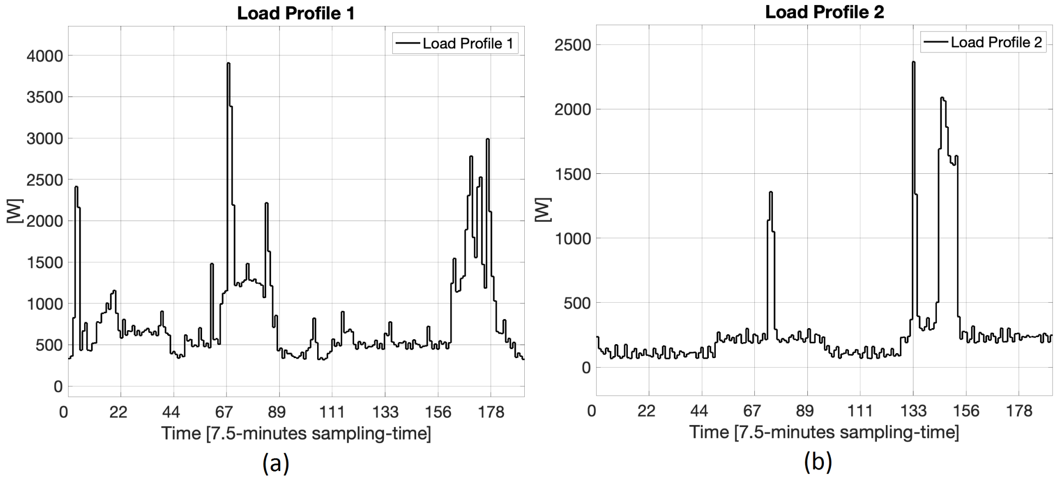

Figure 4.2: Load Profile 1 - (a), Load Profile 2 - (b)

Figure 4.2 shows the two load profiles that are going to be used for the simulation. The sampling-interval of the load profiles is 7.5 minutes; therefore, the value of m is chosen to be 7.5, and 24-hour profile is divided into 192 sampling-interval. It can be noticed that the peak of the load profile 1 is nearly 4000 W at sample 70th, while the peak of the load profile 2 is at sample 133rd. Besides, the average value of the load profile 1 is higher from two to three times than that of the load profile 2. With two different levels of load profile, the efficiency of the EMS can be assessed clearly.

Let's call a PV system without the EMS is case R. It means that in this case, the generated electricity is going to be sold directly to the grid. Ideal case is a PV+ES system with the EMS and the forecast solar data is identical with the real solar data. Optimized case is a PV+ES system with the EMS, including two inputs: real and forecast solar data.

4.1 System specification

A normal residential PV+ES system is chosen with a 3kWp PV array, a 6.4 kWh BYD HV box Li-ion battery storage and a 4 kW grid-connected solar inverter. The specifications of those three components will be discussed in this section.

Inverter

The inverter is 4 kW Fronius Symo Hybrid 4.0-3-S and its required specifications are listed in table 4.1 and 4.2 [35].

AC nominal output ($P_{ac,r}$) [W]	4000
Max. output power (P_{ac-max}) [VA]	4000
Power factor ($\cos\phi_{ac,r}$)	0,85 - 1

Table 4.1: Fronius Symo Hybrid 4.0-3-S detals

η at 5% ($P_{ac,r}$) [%]	80.1
η at 10% ($P_{ac,r}$) [%]	86.2
η at 20% ($P_{ac,r}$) [%]	91.6
η at 25% ($P_{ac,r}$) [%]	93.2
η at 30% ($P_{ac,r}$) [%]	93.9
η at 50% ($P_{ac,r}$) [%]	94.9
η at 75% ($P_{ac,r}$) [%]	95.4
η at 100% ($P_{ac,r}$) [%]	95.6

Table 4.2: The Inverter's Efficiency

Note that the power factor of the inverter is set to be 1. With P_{ac-max} = 4000 VA, and η = 95.6% when $P_{ac-max=P_{ac}}$, the maximum input power to the inverter P_{dc-max} = 4000*100/95.6 = 4184 W. E_{dc-max} for one sample is $\frac{4184*60*7.5}{1000*3600}$ = 0.523 kWh.

Battery

The battery's name is BYD B-Box H 6.4 high voltage battery storage 6.4 kWh [36] and its details can be found in table 4.3. Assuming ϵ_{RT} = 95.3%.

Usable Energy $E_{bat-max}$ [Wh]	6400
Max. output power $P_{discharge-max}$ [W]	6400
Round-Trip Efficiency [%]	$\leq$ 95.3%

Table 4.3: Battery's details

PV array

The chosen PV panel is Canadian Solar CS5P-220M with the specification is available at [37] (table 4.4). with 3 kWp PV array, n_{ns} and n_{np} are set to be 7 and 2 respectively.

Name [Wh]	Canadian Solar CS5P-220M
α_{mp}	1.8100e-04
β_{mp}	-0.2355
$I_{mp,panel,ref}$	4.5463
$V_{mp,panel,ref}$	48.3156
Ns	96
delT	3
n	1.4032
c	[1.0128 -0.0128 0.2793 -7.2446 0.9964 0.0036 1.1554 -0.1554]

Table 4.4: Battery's details

4.2 Simulation Result

The real and forecast effective solar irradiance of Aalborg on May 01 is shown in figure 4.3, and the forecast and real P_{mp} output of the PV array can be found in figure 4.4 with 7.5 minutes sampling-interval. In the real case, the waveform of E_e peaks from sample 81st to 88th with about 650 W/m2, while in the forecasting case, it reaches the maximum value of nearly 550 W/m2 from sample 120th to 124th. Note that in figure 4.3, the value of E_e is unchanged in one sampling-time period, while the value of P_{mp} in figure 4.4 is the total energy that the PV array could produce in one sampling period.

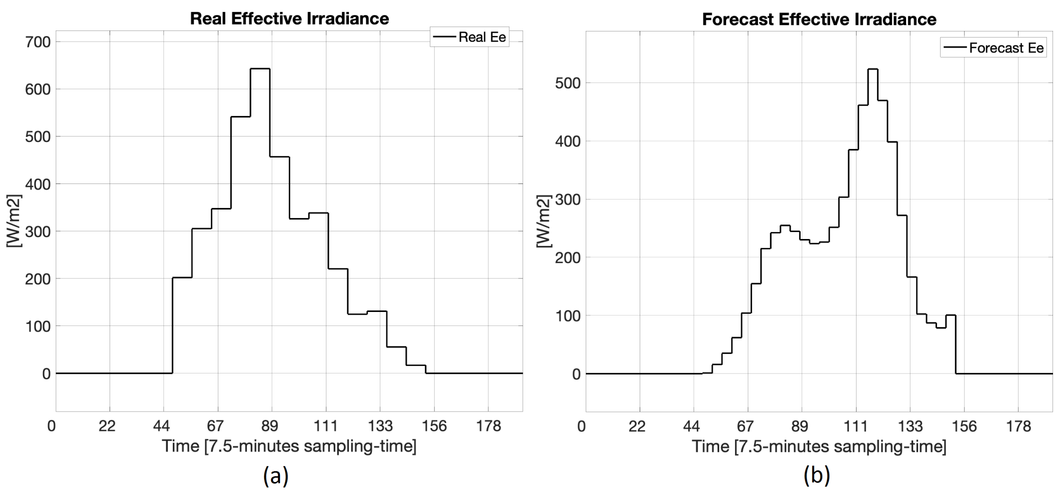

Figure 4.3: Aalborg real (a) and forecast (b) effective irradiance

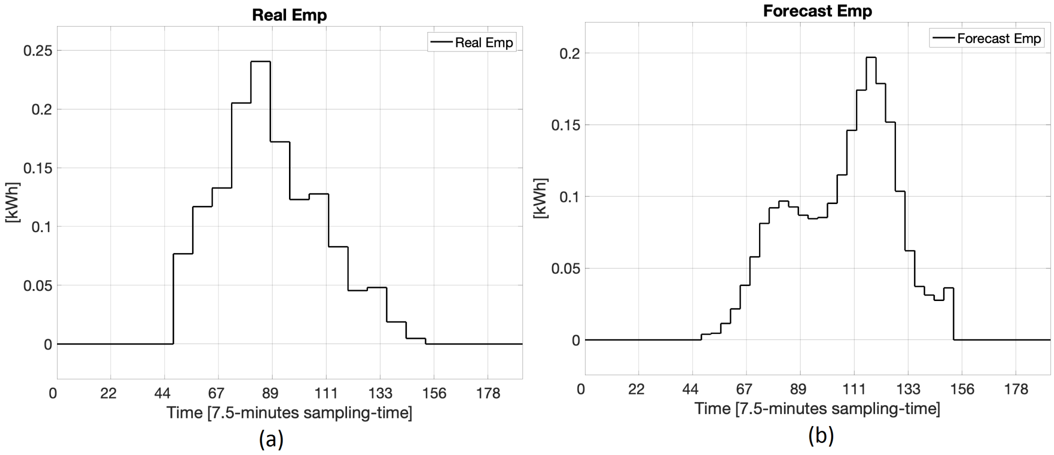

Figure 4.4: Aalborg real (a) and forecast (b) E_{mp}

4.2.1 Load Profile 1

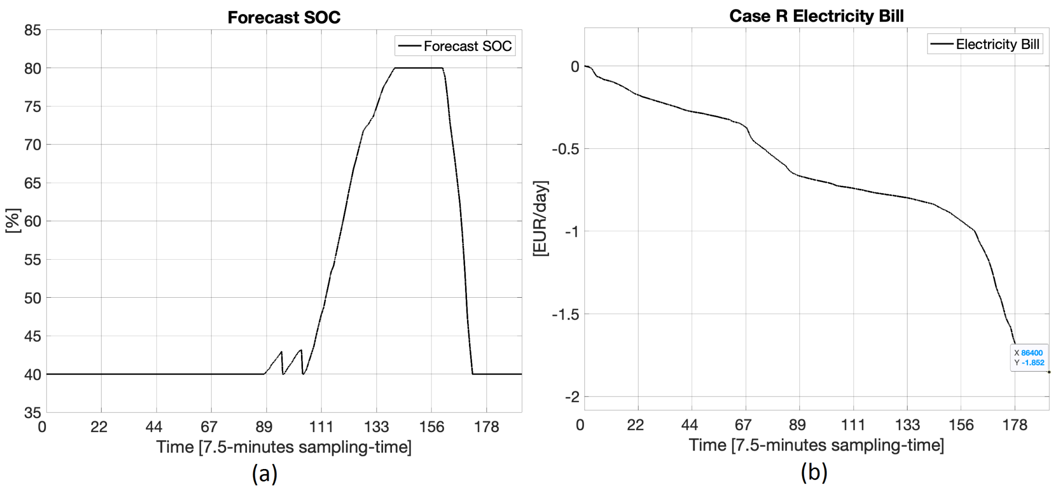

Figure 4.5: Forecast SOC - (a), Case R Electricity Bill - (b)

Figure 4.5.a shows the forecast operation the battery. It is noticeable that the battery is able to store energy when the electricity price is low, from sample 104th to sample 140th, with the average selling electricity price of 8 EUR/MWh and. The SOC of the battery reaches 80% of SOC at sample 141st and wait until sample 160th for discharging to maximize the self-consumption at the highest price. It means that with the EMS, the electricity bill can be minimized at the highest rate. Besides, figure 4.5.b indicates the electricity bill of the household in case R in one day, with -1.852 EUR (the homeowner has to pay 1.852 EUR).

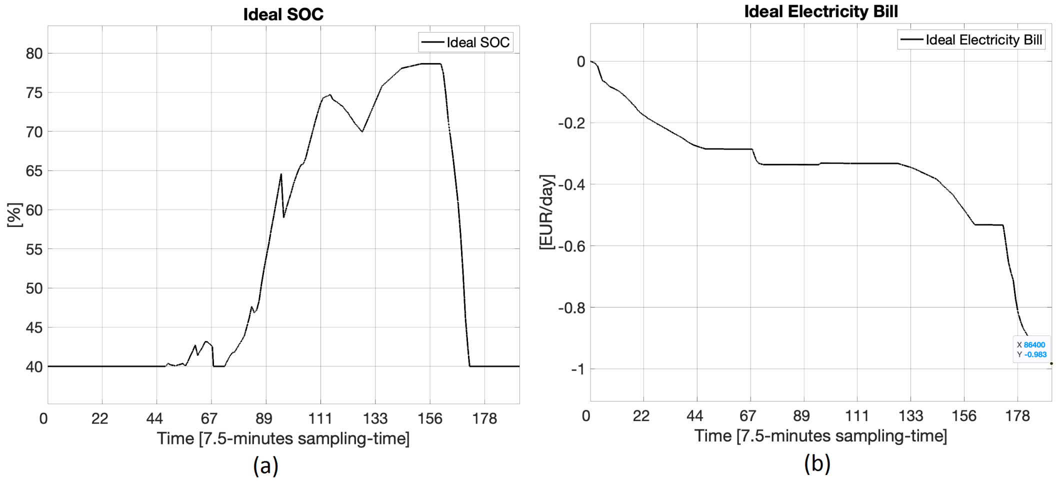

Figure 4.6: Ideal SOC - (a), Ideal Electricity Bill - (b)

Figure 4.6 manifests the ideal operation of the battery and the ideal electricity bill of the household. It is noted that there are eight discharging periods in the operation of the battery. The discharging period from 1st to 5th and the 7th is to maintain the self-consumption of the system, when P_{PV} is smaller than P_L. The 6th discharging period is when the electricity is at one local peak. However, the electricity bill, in this case, is -0.983 EUR.

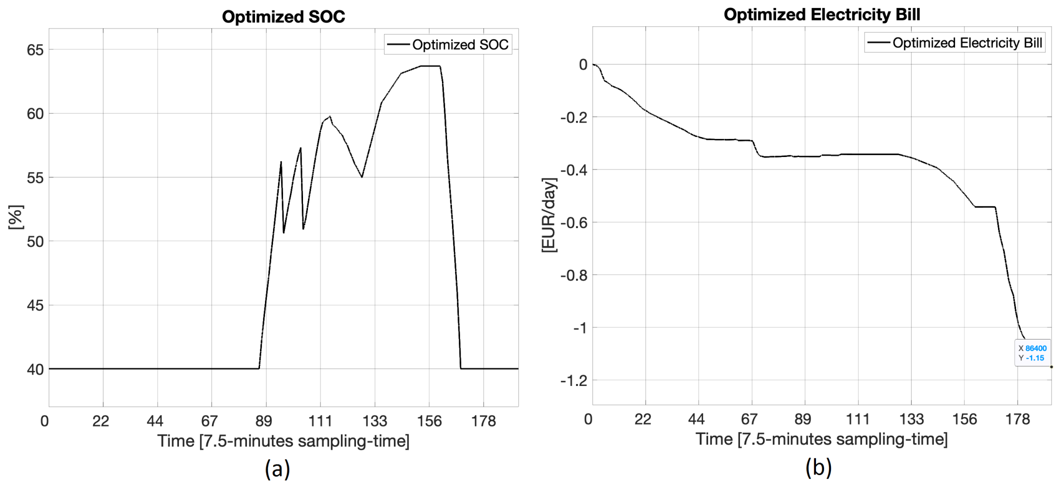

Figure 4.7: Optimized SOC - (a), Optimized Electricity Bill - (b)

Figure 4.7 displays the real operation of the battery and the real electricity bill. It is clear that the real SOC waveform is a combination of the forecast SOC and the ideal SOC. The money that the homeowner has to pay is 1.15 EUR.

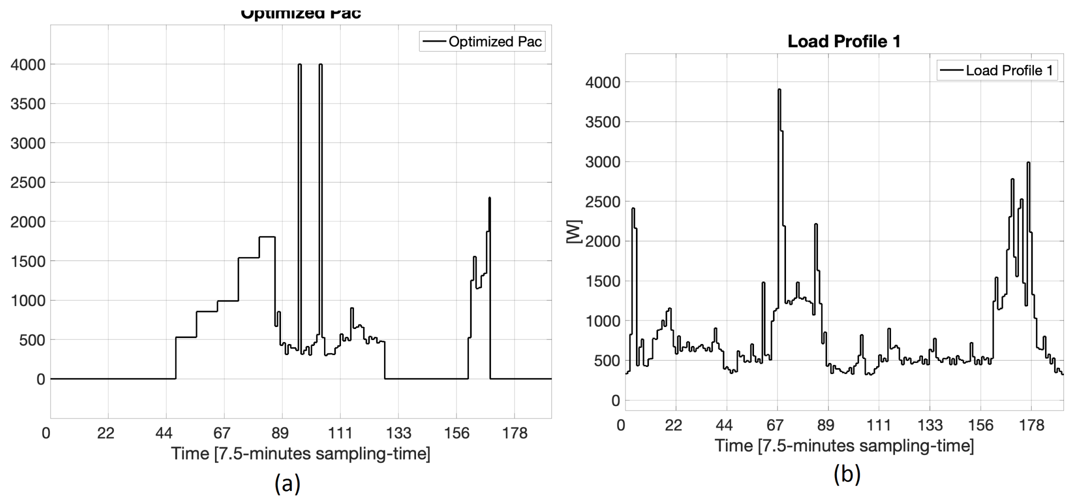

Figure 4.8: Optimized P_{ac} - (a), Load Profile 1 - (b)

Figure 4.8 compares the output P_{ac} of the inverter and the load profile 1. It can be seen that with the EMS, the PV system is not only to maximize the self-consumption of the system but also to minimize the money for the electricity bill.

It can not be denied that the case R contains the highest price and the ideal case is the lowest price for the electricity bill. Assuming the efficiency of case R and ideal case is 0% and 100% respectively, the efficiency of the optimized case can be as :

$$Eff - system = \frac{C - A}{B - A} * 100 \tag{4.1}$$

where A, B, C is the electricity bill of case R, ideal case and optimized case respectively.

x	Case R	Ideal Case	Optimization case 1
Total energy from PV [kWh]	11.16	11.16	11.16
Electricity Bill [EUR]	-1.852	-0.983	-1.15
Eff-system [%]	0	100	80.78

Table 4.5: Summary Aalborg - Load Profile 1

4.2.2 Load Profile 2

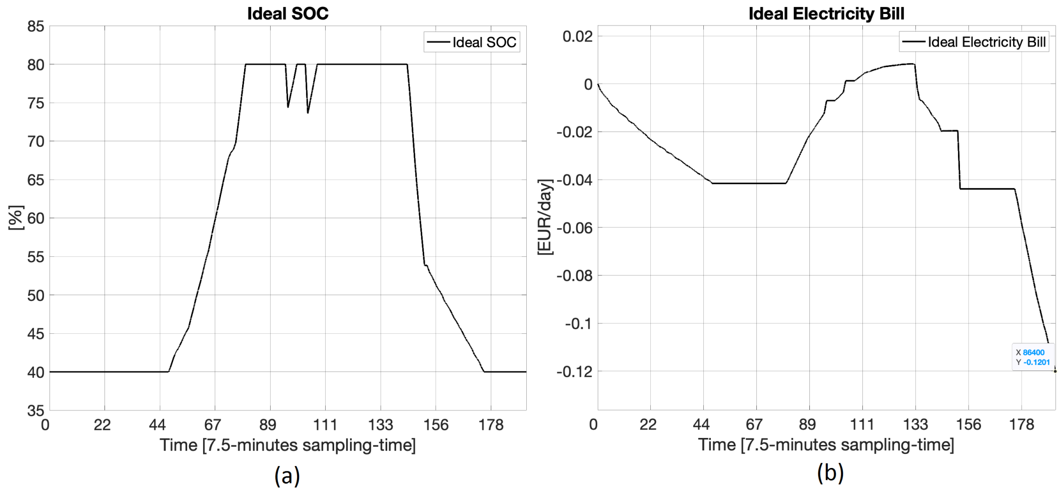

Figure 4.9: Ideal SOC - (a), Ideal Electricity Bill - (b)

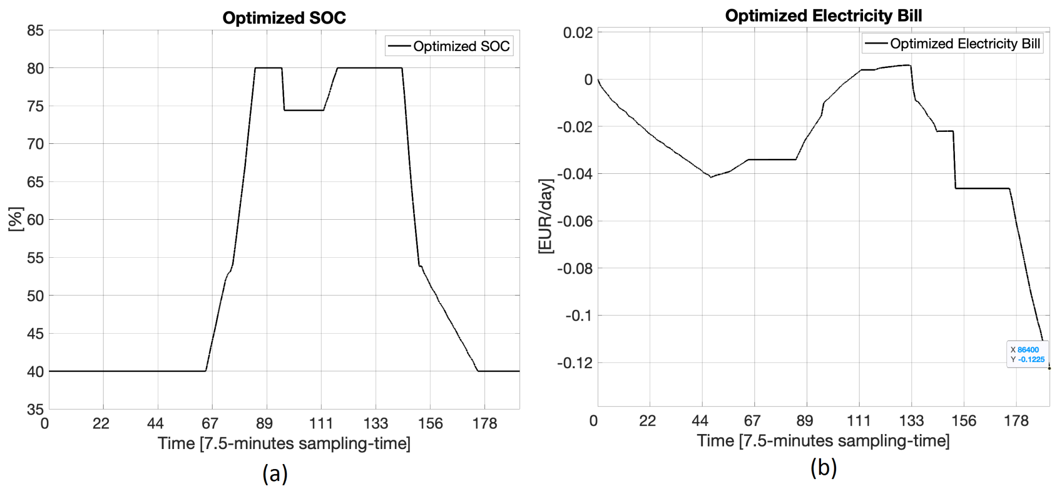

Figure 4.10: Optimized SOC - (a), Optimized Electricity Bill - (b)

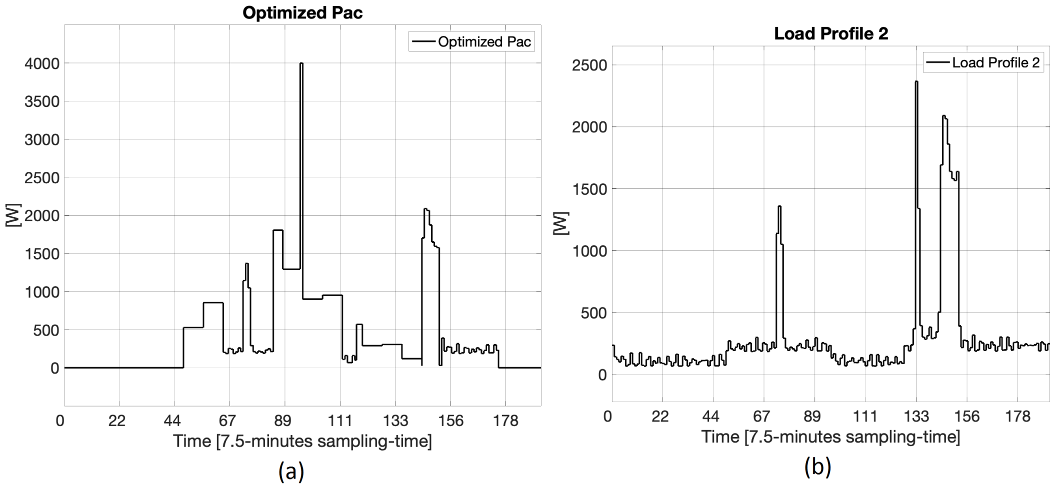

Figure 4.11: Optimized P_{ac} - (a), Load Profile 2 - (b)

From figure 4.10 and figure 4.9, it is noticed that there are two small difference between the operation of the battery during the day time in ideal case and optimized case. This is due to the surplus energy is mainly positive. However, the discharging operation during the night time of both cases are identical. Therefore, the efficiency of the system in the optimized case can achieve 99.168%.

x	Case R	Ideal Case	Optimization case 1
Total energy from PV [kWh]	11.16	11.16	11.16
Electricity Bill [EUR]	-0.4086	-0.1201	-0.1225
Eff-sys [%]	0	100	99.168

Table 4.6: Summary - Load Profile 2

Chapter 5

System Controller

As mentioned in Chapter 4, the PV+ES system contains a 3 kWp PV array, a 6.4 kWh BYD HV box Li-ion battery storage and a 4 kW grid-connect solar inverter from Fronius. While the job of the EMS is to build an day-ahead operation for the battery, there is needed an device that is able to control the battery based on the proposed plan. Fortunately, Fronius offers an opportunity to control the battery via Modbus TCP or Modbus RTU. The difference between Modbus TCP and Modbus RTU is that Modbus TCP is running based on Ethernet physical layer, while Modbus RTU runs on a serial level protocol [38]. In order to have a well-established, reliable, and fast connection, the Modbus TCP is chosen.

5.1 Modbus TCP

Modbus TCP is running on TCP/IP network via port 502. There are four types of message in Modbus TCP :

- Request: a request is sent from Modbus Client to Modbus server in order to initial a transaction
- Indication: the request has been received by Modbus server
- Response: the response has been sent by Modbus server
- Confirmation: the response has received by Mod client.

Figure 5.1: Modbus TCP 4 types of message

5.1.1 Modbus Application Protocol Header

The Modbus Application Protocol (MBAP) header is used for address and error check. Modbus request ADU includes [39]:

- Transaction Identifier contains two bytes and must be unique.
- Protocol Identifier is always 0
- The Lengths indicates the number of following bytes
- Unit Identifier is always 0xFF
- Function Code : 0x03 is read, 0x06 and 0x10 is read-write.
- Starting address is 0x0005, the read register is "6"
- Quantity of Register: the number of register is going to be read or read-write from the starting address.

	Description	Size (bytes)	Example
MBAP Header	Transaction Identifier Hi	1	0x11
	Transaction Identifier Lo	1	0x02
	Protocol Identifier	2	0x0000
	Length	2	0x0006
	Unit Identifier	1	0xFF
MODBUS request	Function Code	1	0x03
	Starting Address	2	0x0005
	Quantity of Registers	2	0x0003

Chapter 6

Conclusion and Future Work

As mentioned before, the buying electricity price is 6.756 times higher than the selling electricity price. In addition, the solar energy is only available in the day time, the global peak of electricity prices is usually in the night time, and the maximum stored energy of the battery is limited. Therefore, the key of minimizing the electricity bill is to maximize the self-consumption of the system, maximize the stored energy inside the battery before night time, and choose the right time for discharge in the night. Those conditions are offered by the thesis. However, In order to achieve the aforementioned goal, the battery operation is divided into two parts: day time operation and night time operation, which are treated separately by two different mixed-integer linear programming solvers. While the day time operation focuses on maximizing the self-consumption of the system, storing energy as much as the battery can and achieving highest selling price if possible, choosing the right time for discharge in the night time in order to reduce the electricity bill at the highest rate is the goal of the night time operation. Although there are always errors between the real and forecast solar data, the results indicate that the electricity bill of the optimized case is significantly lower than that of the case R, achieving near 100% of the ideal case in simulation with load profile 2.

In order to have a better assessment for the efficiency of the PV+ES system, a higher accuracy for real solar data is required. This is to have the output energy of the PV simulation is closed with the output energy of a real system.

It is vital for the EMS to work with a variety of residential PV+ES systems in commercial services. Although the EMS has implemented for a PV+ES system containing a 3kWp PV array, a 6.4 kWh BYD HV box Li-ion battery storage, and a 4 kW grid-connected solar inverter, it can easily apply for any residential PV+ES system by changing the constraints for the battery and the inverter.

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Appendix A

EMS1 Code

```
%% load data
Albedo = 0.12;
Array.Tilt = 23; % Array tilt angle (deg)
Array.Azimuth = 180; %Array azimuth (180 deg indicates array faces South)
Array.Ms = 7; %Number of modules in series
NumSeriesPanels = 7;
Array.Mp = 2; %Number of paralell strings
NumParallelStrings = 2;
Array.a = -3.56;
Array.b = -0.075;
SiteLatitude = 35.040000000000000;
SiteLongitude = -1.066200000000000e+02;

alfa_imp = 1.8100e-04;
beta_vmp0 = -0.2355;
mbvmp = 0;
n = 1.4032;
Imp0 = 4.5463;
Vmp0 = 48.3156;
Ns = 96;
c0 = 1.0128;
c1 = -0.0128;
c2 = 0.2793;
c3 = -7.2446;

%% real - EMS2
%solarreal = xlsread('HCM_real.xlsx'); % 1 hour sample time
solarreal = xlsread('aalborgreal.xlsx'); % 1 hour sample time
% solarforecast = xlsread('aalborgforecast.xlsx'); % 30' sample time
Tambreal = solarreal(1:24,1); %load T ambient real
DHIreal = solarreal(1:24,2);
DNIreal = solarreal(1:24,3);
GHIreal = solarreal(1:24,4);
pressreal = solarreal(1:24,5); % load pressure
windreal = solarreal(1:24,6);
ModuleParameters = pvl_sapmmoduledb(123,'SandiaModuleDatabase_20120925.xlsx');

timetestfore = {}
```

```
timetestfore.UTCOffset = -7 * ones(24,1);
timetestfore.year = 2020 * ones(24,1);
timetestfore.month = 5 * ones(24,1);
timetestfore.day = ones(24,1);
for i = 1:1:24
timetestfore.hour(i,1) = i-1;
end
timetestfore.minute = zeros(24,1);
timetestfore.second = zeros(24,1);
Locationfore = pvl_makelocationstruct(SiteLatitude,SiteLongitude); %Altitude is optional
PresPafore = pressreal*100;
[SunAzfore, SunElfore, AppSunElfore, SolarTimefore] = pvl_ephemeris(timetestfore,Locationf
AMafore = pvl_absoluteairmass(pvl_relativeairmass(90-AppSunElfore),PresPafore);
AOIfore = pvl_getaoi(Array.Tilt, Array.Azimuth, 90-AppSunElfore, SunAzfore);
Ebfore = 0*AOIfore; %Initiallize variable
Ebfore(AOIfore<90) = DNIreal(AOIfore<90).*cosd(AOIfore(AOIfore<90)); %Only calculate when
EdiffSkyfore = pvl_isotropicsky(Array.Tilt,DHIreal);
Albedo = 0.2;
EdiffGroundfore = pvl_grounddiffuse(Array.Tilt,GHIreal, Albedo);
Efore = Ebfore + EdiffSkyfore + EdiffGroundfore; % Total incident irradiance (W/m^2) or E_
Edifffore = EdiffSkyfore + EdiffGroundfore; % Total diffuse incident irradiance (W/m^2)
SF=0.98;
E0 = 1000; %Reference irradiance (1000 W/m^2)
celltempreal = pvl_sapmcelltemp(Efore, E0, Array.a, Array.b, windreal, Tambreal, ModulePar
F1fore = max(0,polyval(ModuleParameters.a,AMafore)); %Spectral loss function
F2for = max(0,polyval(ModuleParameters.b,AOIfore)); % Angle of incidence loss function
Eereal = F1fore.*((Ebfore.*F2for+ModuleParameters.fd.*Edifffore)/E0)*SF; %Effective irradi
Eereal(isnan(Eereal))=0; % Set any NaNs to zero

t1sec_xs = zeros(86400,1);
Ee1sec = zeros(86400,1);
cell1sec = zeros(86400,1);
for i = 1:1:86400
    t1sec_xs(i) = i;
end

for i = 1:1:86400
    j = fix((i-1)/3600) +1;
    Ee1sec(i) = Eereal(j)*1000;
    cell1sec(i) = celltempreal(j);
end
Gtss = timeseries(double(Ee1sec), t1sec_xs);
Tcss = timeseries(double(cell1sec), t1sec_xs);

%% EMS1 forecast

%solarfore = xlsread('HCM_forecast.xlsx'); % 1 hour sample time
solarfore = xlsread('aalborgforecast.xlsx'); % 1 hour sample time
% solarforecast = xlsread('aalborgforecast.xlsx'); % 30' sample time
Tambfore = solarfore(1:48,1); %load T ambient real
DHIfore = solarfore(1:48,2);
DNIfore = solarfore(1:48,3);
GHIfore = solarfore(1:48,4);
pressfore = solarfore(1:48,5); % load pressure
windfore = solarfore(1:48,6);
ModuleParameters = pvl_sapmmoduledb(123,'SandiaModuleDatabase_20120925.xlsx');
```

```
timetestfore = {}
timetestfore.UTCOffset = -7 * ones(48,1);
timetestfore.year = 2020 * ones(48,1);
timetestfore.month = 5 * ones(48,1);
timetestfore.day = ones(48,1);
for i = 1:1:48
timetestfore.hour(i,1) = fix((i-1)/2);
    if rem(i,2) == 0
        timetestfore.minute(i) = 0;
    else
        timetestfore.minute(i) = 30;
    end
end

timetestfore.second = zeros(48,1);

Locationfore = pvl_makelocationstruct(SiteLatitude,SiteLongitude); %Altitude is optional
PresPafore = pressfore*100;
[SunAzfore, SunElfore, AppSunElfore, SolarTimefore] = pvl_ephemeris(timetestfore,Locationfore,Pre
AMafore = pvl_absoluteairmass(pvl_relativeairmass(90-AppSunElfore),PresPafore);
AOIfore = pvl_getaoi(Array.Tilt, Array.Azimuth, 90-AppSunElfore, SunAzfore);
Ebfore = 0*AOIfore; %Initiallize variable
Ebfore(AOIfore<90) = DNIfore(AOIfore<90).*cosd(AOIfore(AOIfore<90)); %Only calculate when sun is
EdiffSkyfore = pvl_isotropicsky(Array.Tilt,DHIfore);
Albedo = 0.2;
EdiffGroundfore = pvl_grounddiffuse(Array.Tilt,GHIfore, Albedo);
Efore = Ebfore + EdiffSkyfore + EdiffGroundfore; % Total incident irradiance (W/m^2) or E_POA
Edifffore = EdiffSkyfore + EdiffGroundfore; % Total diffuse incident irradiance (W/m^2)
SF=0.98;
E0 = 1000; %Reference irradiance (1000 W/m^2)
celltempfore = pvl_sapmcelltemp(Efore, E0, Array.a, Array.b, windfore, Tambfore, ModuleParameters
F1fore = max(0,polyval(ModuleParameters.a,AMafore)); %Spectral loss function
F2for = max(0,polyval(ModuleParameters.b,AOIfore)); % Angle of incidence loss function
Eefore = F1fore.*((Ebfore.*F2for+ModuleParameters.fd.*Edifffore)/E0)*SF; %Effective irradiance
Eefore(isnan(Eefore))=0; % Set any NaNs to zero

mSAPMResults = pvl_sapm(ModuleParameters, Eefore, celltempfore);
aSAPMResults.Vmp = Array.Ms  *mSAPMResults.Vmp;
aSAPMResults.Imp = Array.Mp  *mSAPMResults.Imp;
aSAPMResults.Pmp = aSAPMResults.Vmp .* aSAPMResults.Imp;
Ppv30aalforereal = zeros(48,1);
Ppv15aalforereal = zeros(96,1);
for i = 1:1:48
    Ppv30aalforereal(i) = mSAPMResults.Vmp(i)*mSAPMResults.Imp(i)*Array.Ms*Array.Mp; %P 1s to P 3
end
round(Ppv30aalforereal,2)

Ppvaalforereal_1sec = zeros(86400,1);
for i = 1:1:86400
    Ppvaalforereal_1sec(i) = Ppv30aalforereal(fix((i-1)/1800)+1);
end

for i = 1:1:96
    Ppv15aalforereal(i) = Ppv30aalforereal(fix((i-1)/2)+1);
```

```
end

Ppv15aalforereal = Ppv15aalforereal *900;  % total P - 15'

load('catalin-loads.mat')
%loadct = Loads_Power1; % load-1
loadct = Loads_Power2; % load-2
for i = 1:1:86400
    load1s(i) = loadct(fix((i-1)/450)+1);
end
loadct = loadct *450; % 1s to 450s

Pb = zeros(192,1);
Ppv75 = zeros(192,1);
for i = 1:1:192
    Ppv75(i) = Ppv30aalforereal(fix((i-1)/4)+1);
end



Ppv75 = Ppv75 * 450; % 7.5 mins sampling time
Pb = Ppv75 - loadct;



%% el
%urlwrite('http://thebetterhomes.store/boss/1dayel.xlsx','test.xlsx');
el_doc = xlsread('el_case1.xlsx');
 el_1hour = el_doc(1:24,2); %el_case1
%el_1hour = el_doc(2:25,2); % el_case2
%el_1hour = el_doc(1:24,2); % el_case4
% el_1hour;
 el1sec = ones(86400,1);
 el75 = ones(192,1);

 for i = 1:1:192
     j = fix((i-1)/8);
     el75(i,1) = el_1hour(j+1,1);
 end

 for i = 1:1:86400
     j = fix((i-1)/3600);
    el1sec(i,1) = el_1hour(j+1,1);
 end
 elbuy1sec = 6.756 * el1sec;


%% calculate battery operation plan
% find min f : x = intlinprog(f,intcon,A,b)
%vector Pmp : generated PV energy
%vector el : one day ahead electricity price
f = reshape(el75,[1,192]);
% f= el
intcon = 1; % x1 is integer
% create A matrix 72x24
A1 = eye(192); % Identity matrix A1
```

```
b1 = reshape(Pb,[1,192]); %Pb_i > 0, x_i <= Pb_i,
for i = 1:1:192
    if Pb(i) < 0
        A1(i,i) = 0;
        b1(i) = 0;
    end
end

A2 = eye(192); % Pb_i <0, x_i <= 0
b2 = zeros(1,192);
for i = 1:1:192
    if Pb(i) >= 0
        A2(i,i) = 0;
    end
end

A3 = zeros(192);
b3 = zeros(1,192);
for i = 1:1:192
    for j = 1:1:192
        if j<=i A3(i,j) = -1;
        end
    end
end

A4 = -A3;
b4 = 2560*3600*ones(1,192);

A5 = -eye(192);
b5 = 4184*60*7.5*ones(192,1) - Ppv75;
b5 = reshape(b4,[1,192]);

A = [A1;
    A2;
    A3;
    A4;
    A5];
b = [b1, b2, b3, b4, b5];

% result for charging/discharging plan
x = intlinprog(f, intcon, A, b); % EMS1-part1
x1 = x;
save('x1.mat','x1');
x1kwh = -x1;
xkwh = x1;
for i = 1:1:192 % remove very small x(i) ~ 5*10^-11
    if (x(i) > 0) && ( x(i) < 0.01 )
        x(i) = 0 ;
        x1(i) = 0 ;
    else if (x(i) < 0) && ( x(i) > -0.01 )
            x(i) = 0;
            x1(i) = 0;
        end
    end
end
save('x.mat','x');
```

```
lastdischarge = 0;
for i = 192:-1:1
    if x(i) < 0
        lastdischarge = i;
        break;
    end
end
save('lastdischarge.mat','lastdischarge');

j = 1;
for i = 1:1:192 % find the first Ppv15(i) # 0
    if Ppv75(i) <= 0
        j = j +1 ;
    else
        break;
    end
end

j = fix((j-1)/8); % 60/8=7.5

for i = j:1:23 % optimal battery step 1,
    tot = round((x(8*i+1) + x(8*i+2) + x(8*i+3) + x(8*i+4) + x(8*i+5) + x(8*i+6) + x(8*i+7
    if tot == 0
        x(8*i+1) = 0;
        x(8*i+2) = 0;
        x(8*i+3) = 0;
        x(8*i+4) = 0;
        x(8*i+5) = 0;
        x(8*i+6) = 0;
        x(8*i+7) = 0;
        x(8*i+8) = 0;
    end
end


eldis = zeros(64,1);
loaddis = zeros(64,1);
Ppvdis = zeros(64,1);
for i = 1:1:64
    eldis(i) = el75(i+128);
    loaddis(i) = loadct(i+128);
    Ppvdis(i) = Ppv75(i+128);
end
% loaddis = loaddis *450;
% Ppvdis = Ppvdis *450;

ff = reshape(eldis,[1,64]);
% f= el
intcon = 1; % x1 is integer
% create A matrix 72x24
AA1 = -eye(64); % Identity matrix A1
AA2 = eye(64); %A2
AA3 = zeros(64); %A3
for i = 1:1:64
    for j = 1:1:64
        if j<=i AA3(i,j) = -1;
```

```
        end
    end
end
AA4 = -eye(64);
AA = [AA1;
    AA2;
    AA3;
    AA4];

% create b matrix
bb1 = reshape(loaddis,[1,64]); % discharge power <= load
% b1 = k
bb2 = zeros(1,64); % x <= 0 discharge only
bb3  = 2560*3600*ones(1,64);
bb4 = zeros(1,64); % discharge power <= charge power

for i =1:1:64
    bb4(1,i) = 4184*60*7.5 - Ppvdis(i);
end
bb = [bb1, bb2, bb3, bb4];

% result for charging/discharging plan
y = intlinprog(ff, intcon, AA, bb); % EMS1-part2

for i = 1:1:64
    x(i+128) = y(i);
end



key = zeros(192,1);
key1 = zeros(192,1);

for i = 1:1:192
    if x(i) == 0
        key(i) =0;
    else if x(i) > 0
            key(i) = -1; % x(i) > 0 -> charging
        else key(i) = 1;% x(i) < 0 -> discharging
        end
    end
end


for i = 1:1:192
    if x1(i) == 0
        key1(i) =0;
    else if x1(i) > 0
            key1(i) = -1; % x(i) > 0 -> charging
        else key1(i) = 1;% x(i) < 0 -> discharging
        end
    end
end


key_1sec = zeros(86400,1);
```

```
key1_1sec = zeros(86400,1);


for i = 1:1:86400
    j = fix((i-1)/450) +1;
    key_1sec(i) = key(j);
    key1_1sec(i) = key1(j);
end



%% create time series fors x - 7.5' step
t_xs = ones(192,1);
t1sec_xs = zeros(86400,1);

for i =1:1:96
    t_xs(i) = 450*(i-1);
end

for i = 1:1:86400
    t1sec_xs(i) = i;
end

Lts = timeseries(double(load1s), t1sec_xs);

aalforerealopt1_ts = timeseries(double(key_1sec), t1sec_xs);
el1sec_ts = timeseries(double(el1sec), t1sec_xs);
el15_ts = timeseries(double(el75), t_xs);
elbuy1sec_ts = timeseries(double(elbuy1sec), t1sec_xs);
save('aalforerealopt1_ts.mat','aalforerealopt1_ts');
load('aalforerealopt1_ts.mat');
save('el15_ts.mat','el15_ts');
load('el15_ts.mat');
```

Appendix B

EMS2 Code

```
function [Pdc, Pbat_reg,keyy] = fcn(t,Lts,Ppv,Pbat,SOC,keys,key1)

Pb = Ppv - Lts;
Pcharge_avail = 6400*3600*(80-SOC)/100;
Pdis_avail = 6400*3600*(SOC-40)/100;
Pdc = 0;
PL = 0;
a = 100*Lts/4000;
if a < 8.01
    PL = 100 * Lts / 80.1;
    elseif a< 17.24
        PL = 100 * Lts / 86.2;
        elseif a < 22.9
            PL = 100 * Lts / 91.6;
            elseif a < 27.96
                PL = 100 * Lts / 93.2;
                elseif a <46.6
                    PL = 100 * Lts /93.2;
                    elseif a < 66.43
                        PL = 100 * Lts /94.9;
                        elseif a < 95.4
                            PL = 100 * Lts /95.4;
                            else
                                PL = 100 * Lts /95.6;
end


if key1 < 0 % previous state of bat = charge
    if keys == 0 % current state = idle
        if Ppv > 0
            if Pcharge_avail > 0 % SOC < 80
                keys = -1; % continue to charge
                keyy = keys; % save state of bat to the next step
            else
                keyy = keys;
            end
        else
            keyy = keys;
```

```
        end
     else
        keyy = keys;
    end
else
  keyy = keys;
end

if Pbat >= 0 % Pbat > 0, discharging
    Pdc = Pdc + Pbat;
else
    Pdc = Pdc;
end

if keys == 0
    Pbat_reg = 0;
    Pdc = Pdc + Ppv;

else if keys < 0 % = -1, battery charging, Pbat_reg = P_IN < 0
        if Ppv >= PL
            if Pcharge_avail > (Ppv - PL)
                Pbat_reg = -(Ppv - PL);
                Pdc = PL + Pdc;
            else
                Pbat_reg = - Pcharge_avail;
                Pdc = Pdc + Ppv + Pbat_reg;
            end
        else
            if t < 57600
                if Pdis_avail >= (PL - Ppv)
                    Pbat_reg = PL - Ppv;
                    Pdc = Pdc + Ppv;
                else
                    Pbat_reg = Pdis_avail;
                    Pdc = Pdc + Ppv;
                end
            else
                if Pcharge_avail > Ppv
                    Pbat_reg = -Ppv
                    Pdc = Pdc;
                else
                    Pbat_reg = - Pcharge_avail;
                    Pdc = Pdc + Ppv + Pbat_reg;
                end
            end
        end
    else % x_ts = 1 > 0, battery discharging, Pbat_reg = P_IN > 0

        if t < 57600
            if (Pdis_avail + Ppv) >= 4184
                Pbat_reg = 4184 - Ppv;
                Pdc = Pdc + Ppv;
            else
                Pbat_reg = Pdis_avail;
                Pdc = Pdc + Ppv;
            end
```

```
        else % t >= 57600, only discharge PL
            if (PL - Ppv) < Pdis_avail
                Pbat_reg = PL - Ppv;
                Pdc = Pdc + Ppv;
            else
                Pbat_reg = Pdis_avail;
                Pdc = Pdc + Ppv;
            end
        end
    end
end
```