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The Suitable Combination of Power Management Method and Electricity Tariff for Prosumers

TU Delft

The Suitable Combination of Power Management Method and Electricity Tariff for Prosumers

by

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Abstract

THE growing attention on renewable energy has already brought a rapid evolution in this field. As one of the most abundant energy on this planet, the solar energy starts to play an important role in the energy market. Various policies have already been proposed to encourage the renewable energy development. With the PV panels involved in the system, consumers can sell the extra energy from the PV panels' generation back to the grid, which makes them become prosumers. However, the PV panels generation cannot perfectly match the load peak, therefore, different power management methods are proposed to better schedule the power flow inside the grid-connected PV system. On the other hand, different tariff structures could also lead to the different energy bill. The prosumers also want to better allocate their load profiles to better suit for the tariff policies. Therefore, to find a suitable combination of power management method and electricity tariff are interested by prosumers.

This thesis aims at finding a suitable combination of power management method and electricity tariff for the prosumers based on the final energy bill. Four different power management methods are proposed to schedule the power flow inside the grid-connected PV system. The power flow data are simulated together with different tariff structures to calculate the final energy bill. A new method to generate the real-time electricity buy-in price is introduced, and four new feed-in tariff structures are designed with different compensation policies. Together with the power flow scheduled by power management methods, the final energy bill is calculated.

It is concluded that at least one of newly designed tariff structures can give a better or almost the same performance when compared with the existed tariff structures, and based on the final energy bill, a suitable combination of power management method and electricity tariff for prosumers can be found for the target countries/region.

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Abbreviations

List of Acronyms

PMM	Power Management Method
FIT	Feed-in Tariff
ToU	Time-of-Use
PV	Photovaltic
SOC	State of Charge
SOH	State of Health
DOD	Depth of Discharge
STC	Standard Test Condition
AOI	Angle of Incidence
RE	Renewable Energy
DNI	Direct Normal Irradiance
MPP	Maximum Power Point
DC	Direct Current
AC	Alternating Current
DSO	Distribution System Operator
KNMI	Koninklijk Nederlands Meteorological Institute
PAR	Peak-to-Average Ratio
RES	Renewable Energy Sources
DG	Distribute Generation
RPS	Renewable Portfolio Standards
NREL	National Renewable Energy Laboratory
NOAA	National Oceanic and Atmospheric Administration
MPPT	Maximum Power Point Tracking

1

INTRODUCTION

1.1. INTRODUCTION

To face the fact that climate change and the gradual depletion of fossil energy has already become one of the most challenging problems in the 21st century, scientists urgently want to find a solution to help stop the negative influence on the environment and solve the energy cries issues [1]. As the most promising choice, the renewable energy could be an attractive alternative choice and help ease the global warming and energy cries [2]. The abundant potential renewable energy source such as solar energy, wind energy, hydropower, geothermal energy, and biomass can provide enduring sustainable energy services [2, 3]. Compared with the traditional fossil fuel, the renewable energy can provide clean consumption and no air pollution [2, 4, 5]. By providing a more reliable, sustainable, and affordable energy, the local living standard could be improved and the sustainable development pattern could be implemented [2]. Governments around the world include the renewable energy in their long-term blueprint and have already set targets aiming to improve the percentage of renewable energy in the overall energy consumption [4, 6–10].

The PV panels can produce energy when there is solar irradiation and the stronger the solar irradiation is, the higher the output energy is. As one of the most abundant energy on this planet [11], the solar energy starts to play an important role in the energy market. Under such circumstance, various incentive policies are proposed to encourage the development of renewable energy. Despite the attractive policies, a decrease in the overall solar energy cost is also observed. Because of the decrease of both module and non-module costs, the installed prices for residential PV system has declined a lot in the past decades and will keep going down in the future [12, 13]. Since the hardware costs of PV manufacturing continue to decrease, the PV module price will maintain the downward trend in the near future. In Germany, the installation costs for small size PV panels system has reduced by two thirds since 2006 [14]. With the price of module costs decrease more quickly as the PV industry witnessed, the scientists and manufacturers are also focusing on reducing non-module costs [12]. Such as the American government also set targets to further lower the costs to make sure the PV panels become more competitive in the energy market [15]. Meanwhile, the total capacity of PV around the world are experiencing a blooming increasing in recent years [16].

Despite so many advantages the solar energy reveals, one fact that should be taken seriously is that the PV functioning period may not match the high load demand period. One possible solution is to transfer the extra PV generation from low demand period to high demand period, and in order to do so, the battery storage unit could be involved into the system to store the extra energy during the daytime and discharge later to support the load peak.

With the PV panels connected to the grid and battery used as the storage unit, different power management methods (PMM) are proposed to improve the overall efficiency and the degree of autarky. Meanwhile, different pricing mechanisms are introduced to encourage consumers better allocate their load profile, different feed-in tariffs (FIT) are proposed by governments to provide consumers incentives to involve renewable energy sources into their consumption system, under such circumstance, a suitable electricity tariff structure that includes both the buy-in tariff structure and FIT tariff structure that could pave the way for a more sustainable national energy mixes is urgently required.

This brings the intense interest to the author and hence aiming to find a suitable combination of power management method and electricity tariff for the prosumer.

1.2. LITERATURE REVIEW

THE energy control inside the system is the key to achieve an optimal system control, a suitable energy schedule mechanism can help balance the production and the consumption inside the system, in such a way, the energy can be better allocated to bring considerable benefits [17].

Different power management methods are proposed to manage the power flow inside the PV-connected system. Various methods are used to achieve the optimal power flow control. A simple power management method is described in [18], where both the PV panels and wind turbines are considered as potential energy sources for the system. The fuel cell works as the storage unit, by transferring the extra electric energy into chemical energy, the extra energy from renewable energy sources could be stored in the fuel cell; when there is an energy shortage, the fuel cell could transfer the chemical energy back into electric energy to support the energy gap. [1] describes the battery schedule methods together with PV panels' production to realize peak-shaving. The extra energy from PV generation could be charged into the battery, the PV panels can use to support the load when the demand is low, and later when the peak comes, the PV panels and the battery can work together to supply the peak load. [19] focus on the energy management for PV based multi-source system and try to optimize the system operation mode. The mix integer linear programming algorithm is used to schedule the energy allocation inside the system to achieve optimal operation for both the supply side and the demand side. Other related studies included [20], which use dynamic programming to perform the optimal power flow management for peak-shaving to minimize the overall energy bill. [21] proposes different power management strategies due to different operating conditions of the system.

In the thesis, four different power management methods are proposed, each of them has their own characteristics and schedule pattern. PMM1 is time-independent and the power flow is always the same around the year. PMM2 and PMM3 are time-dependent and introduced two periods named the battery forced charging period and the battery forced discharging period, respectively. The battery cannot be charged with the energy from PV panel during the peak-hour, it can also be discharged to sell energy back to the grid at the end of peak-hour if there is still some energy left in the battery. PMM4 take the advantage of peak-shaving and the battery is only used to shave the energy peak. These PMMs are programmed and simulated later to provide different energy flow pattern for the target countries/region.

The electricity retail prices from energy producers always fluctuate due to the fact that the demand changes from time to time. However, the consumers are charged with a relatively smooth tariff [22]. Some popular tariff models like fixed pricing mechanism, Time-of-Use pricing mechanism, real-time pricing mechanism, and day-ahead pricing mechanism are used worldwide. The first is the time-independent mechanism while the rest three are time-dependent mechanism [23]. The fixed tariff provides a fixed electricity buy-in price inside the contract period no matter when the energy is purchased or how much energy is purchased. While the time-dependent tariffs provide consumers different electricity buy-in price according to the different time period that the energy is consumed. This could encourage consumers to shift load and avoid the high demand when the electricity retail prices are high [24]. Another advantage of time-dependent pricing mechanism is that they could provide consumers economic incentives and therefore impel them to minimize the peak-to-average ratio (PAR) [25].

Real-time pricing is a promising pricing mechanism since the energy price could fluctuate based on the real-time demands. However, the load performance can change randomly. Despite the random activities, the consumers could also change their load capacity and react to the previous retail prices, which means the load profile for the upcoming period is difficult to forecast. Therefore, an accurate, reliable, and effective load forecasting has become one of the most popular topics. The prices should be reasonable enough to reflect the real-time total load capacity inside the grid to become more reasonable, a potential higher load capacity should lead to a higher retail price and vice versa.

There are different methods to generate the real-time price. [26] proposed a new real-time pricing algorithm and consider the real-time price depends on the total load demand. A model based on utility functions is proposed to maximize the total capacity of all subscribers and minimize the total energy cost at the same time. In order to find the suitable consumption level for each subscriber, a distributed algorithm is chosen to solve this optimization problem. The individual load consumption pattern has to be modeled and later used to find the optimal solution for the system. [27] focus on electric vehicle charging base on the real-time pricing model, first simulate the demand response with different retail prices is first simulated and later the electric vehicle charging performance is modelled with CRF model, with online convex programming, the CRF parameters can be tracked and real-time pricing model can be settled. [25] proposed a new real-time pricing model by minimizing the peak-to-average ratio with two different algorithms. The dynamic programming is chosen to simulate the consumers' reaction to fluctuating retail prices. [28] uses the Composite Demand Function to simulation the consumers' random load profiles according to different retail price structure. A comprehensive demand response model is then used to simulate the demand response to achieve an expected beneficial goal. With this model, energy providers could forecast the reaction of consumers and with the Q-learning method, the behavior of consumers could be recorded and later, with this optimization method, the day-ahead hourly real-time price from the energy providers' side could be proposed. Despite different algorithms used to generate the real-time price, the load response is always the important variable that needs to be simulated. In order to predict a reasonable load reaction on different price structures, the demand side management and demand response are two critical parts that could influence the feasibility of the final real-time price. In [29], the real-time price is decided with the model that could find a curve fit for typical data under the existed balancing mechanism.

These real-time generating models are complex and usually relates to the load forecasting. Multiple optimization equals are needed in order to generate a reasonable price. In the time, one formula is proposed and used to generate the real-time price based on the real-time energy bought from the grid, aiming at providing an almost the same energy buying bill as the existed retail tariff structure does.

Government and energy companies provide different policies to encourage the renewable energy and compensate the part of the energy that sold back to the grid generated by renewable energy. Among them, feed-in tariff (FIT), renewable portfolio standard (RPS), capital subsidies and net-metering are top popular mechanisms that are commonly used [6, 30]. Those mechanisms can also be used to support the other renewable energy sources (RES) [31]. However, although capital subsidies is a simple strategy, instead of depending on the energy amount, this financing policy depends on the PV power mounted on the roof. Net metering is still popular in some countries/regions, like California, Alaska [32], with this mechanism, the energy sold back to grid can be compensated with the same retail price when prosumers buy energy, and prosumers only need to pay for the part of energy that exceeds the total energy sold back to the grid [30]. The feed-in tariff (FIT) is an energy supply policy which can guarantee renewable energy generation projects a period of purchase agreements for the electricity they produce, sometimes the renewable energy environmental attributes from renewable energy generators are also included [33–35]. And usually, the agreement period can last 15-20 years to reward the electricity produced by RE generators for each kilowatt-hour [6, 33–35]. The RPS policy means the certified energy suppliers should provide part of the electricity generated by renewable energy to support the load and this part of renewable energy should always meet the legislated minimum level [36].

Until 2014, feed-in tariff policies have already been introduced and proposed in 108 countries/regions, while 99 countries/regions accept the RPS policies, making these two policies the most popular policies for renewable energy [37, 38].

Residents need incentives to invest in the renewable energy, therefore, different renewable energy policies are proposed to encourage consumers to involve renewable energy sources. For the residential use, the most common renewable energy sources that could be mounted near neighborhood is PV panels. People can have PV panels on roofs or walls to generate renewable electricity. Further policies also allow consumers to inject the abundant PV generated electricity into the grid, in this way, the consumers become prosumers. [17] gives the accurate definition of 'prosumer', it states when consumers install the DGs at their properties, the electricity generated from the DGs can partly or wholly cover their energy demands, in this case, the consumers can both consumer energy and produce energy are treated as prosumers.

In order to see the influence of power management methods and electricity tariff structures on the final energy bill, the countries/regions that have different longitude and latitude and different climate are chosen to do the simulation, that is when the Netherlands, Costa Rica and California arousing interest and becoming ideal target countries/region for the simulation. The Netherlands has a maritime climate with warm summers and cool winters, the summer months have more sunshine hours than the winter months, and the length of days can change from almost 17 hours during the summer time to only 8 hours during the winter time [39]. Costa Rica is located near the Equator, despite many microclimates due to the abundant landforms, the country has a tropical climate all around the year [40]. For the offshore city in California, the climate is Mediterranean climate. The city like Los Angeles has abundant sunshine all through the year, compared with Costa Rica, the latitude is higher [41, 42]. These three countries/region are simulated with different combination of power management methods and tariff structures, and the suitable combination for each country/region are suggested based on the final energy bill.

1.3. Research Goal

The goal of this research is to find the suitable combination of power management method and electricity tariffs for the prosumers based on the final energy bill.

1.4. Research Objectives

The research is started by determining the system size base on AC coupled topology, and then design different power management methods to optimize power flow, based on that, the electricity tariffs are tested together with the newly designed tariffs. The final goal is to find out the suitable combination of power management method and electricity tariff for the target countries/regions based on the final energy bill. In order to achieve these goals, both the comprehensive design and simulation are needed. The research will include the following objectives:

1. Simulate four different power management methods;
2. Analyze the power/energy flow in the system;
3. Analyze the impact of PV panels and battery storage on the system;
4. Simulate the existing tariff structures for target countries/regions;
5. Propose the newly designed tariff structures for target countries/regions;
6. Simulate and verify the newly designed tariff structures according to the tariff prices and final energy bill;

7. Compare and analyze the simulation results and determine the suitable combination of power management method and electricity tariff for target countries/regions from the prosumer side.

1.5. RESEARCH QUESTIONS

THE following research questions are proposed:

1. What are the characteristics and advantages of each power management methods' power flow?

2. What impact does the battery or the PV panels have on the grid-connected system's power flow and energy exchange?

3. How to design a reasonable real-time pricing mechanism to provide suitable and accurate tariffs for prosumers without load forecasting?

4. From the prosumer side, based on the final energy bill, what is the best combination of power management method and electricity tariff structure for the Netherlands, Costa Rica and California, USA, respectively?

1.6. RESEARCH METHODOLOGY

IN order to accomplish the research, several steps needed to be followed in the thesis to achieve the research goal. These steps are designed and presented in the following paragraphs.

The thesis starts with the background introduction and literature review in Chapter 1, which gives basic information about the current state of the energy market and how far the research is going. The necessary information is gathered and present in Section 1.1 and Section 1.2.

In Chapter 2, the grid architecture is chosen and the system is sized for each country/region. Four important units in the grid-connected system need to be sized are: the load, the PV panels, the battery, and the inverters help connect the PV panels and the battery to the AC bus.

Four different power management methods are introduced in Chapter 3. These power management methods are realized with programs and simulated with Matlab. With the fixed load data and PV panels' production data, the battery size is changed at least 3 times with each power management method to simulate different power flow patterns. The power flow inside the system is then analyzed and shown with conclusions. The impact of the PV panels and the battery on the system's power flow is also demonstrated by simulating three different scenarios in Section 3.4. In the first scenario, neither the PV panels nor the battery is in the system; in the second scenario, PV panels are added to the system; in the third scenario, the PV panels are removed and only battery storage is added to the system. With a fix system size, the impact of PV panels and battery on the system can be determined by analyzing the power flow data in the system.

Chapter 4 focuses on the tariff structures. The existing tariff structures from each country/region are introduced first, followed by the newly designed tariff structures.

One important basic formula is proposed to calculate the real-time price. The equation's parameters are first determined, then this basic formula is further expanded to adapt to different power management methods according to their own characteristics. Three different real-time generating price structures are proposed, and for each power management method, the basic principle of the real-time price generating structure is fixed. However, due to the different charging mode for each country/region, the detail form could be different to better suit for their own characteristics. Later, four feed-in tariff structures are proposed, together with the real-time price generating structures, different tariff structures are generated. Based on the power flow data get from Chapter 3, these newly designed tariff structures are simulated together with the existing tariff structures to see which one could give the best power flow and the lowest energy bill.

The contribution of this thesis are listed in Chapter 5, Section 5.1. Important conclusions are summarized in Section 5.2 and future work is suggested in 5.3.

2

SYSTEM SIZE

This chapter focuses on system sizing. A suitable system size is critical, from energy aspect, a suitable system size can make sure the energy in the system is better used and not wasted; from the economic point, a suitable system size can avoid unnecessary investment at the beginning when prosumers build the system.

The system architecture is first decided in Section 2.1, AC coupled topology is chosen as the grid-connected PV system architecture. The PV panels and the battery are connected to the AC bus through two different inverters, AC load is directly connected to the AC bus, so does the grid. Several meters are used to record the power flow data in the system. The load is first introduced in Section 2.2, followed by PV panels sizing in Section 2.3. Battery sizing is introduced in Section 2.4. Section 2.5 is focus on inverter sizing and two different inverters are chosen for PV panels connection and battery connection, respectively.

2.1. SYSTEM ARCHITECTURE

FOUR different grid-connected PV system architectures are considered as the potential topologies first, namely, in-line topology, DC coupled topology, AC coupled topology and DC/AC coupled topology. Each of these four PV- battery architectures has its own advantages and disadvantages due to the different connection. A good system architecture is very important since it has a huge influence on the system's overall performance.

For in-line topology, the PV panels and battery are directly connected to the DC bus, while the AC load and grid are directly connected to the AC bus. There is a DC/AC inverter which interconnects the DC bus and AC bus together. The in-line topology is shown in Figure 2.1.

DC coupled topology looks very similar to in-line topology, which is depicted in Figure 2.2. The PV panels and battery are connected to DC bus, and the AC load and grid are connected to AC bus. A DC/AC inverter is used to change DC power into AC power. The difference is that a bi-directional DC/DC converter is needed to connect the battery to DC bus.

For the AC coupled topology, the PV panels, battery storage, load, and grid are all connected to the AC bus. Since the PV panels can directly produce DC current, and current that charged into the battery or discharged from the battery are both in DC form, so that two inverters are needed to help the PV panels and battery connect to the AC bus. The difference is that the inverter used for PV panels' connection is unidirectional, it transfers the DC current into AC current that suits for the grid transfer; this inverter also helps smooth the unstable current generated by PV panels and make it easier to flow in the grid; for battery, a bi-directional inverter is needed in order to charge or discharge battery. The AC coupled topology is shown in Figure 2.3.

The DC/AC coupled topology is very similar to DC coupled topology, which can be seen in Figure 2.4. The only difference is that in this topology, the load has already been distinguished with DC part and AC part. The DC load is directly connected to DC bus; the AC load is directly connected to AC bus. In this architecture, if the energy from grid side wants to support the DC load, the energy has to go through an inverter first.

AC coupled topology is chosen as the architecture to test the power management methods. Article [43] suggests this structure has the best performance among the four topologies under the consideration of autarky, savings, and system loss.

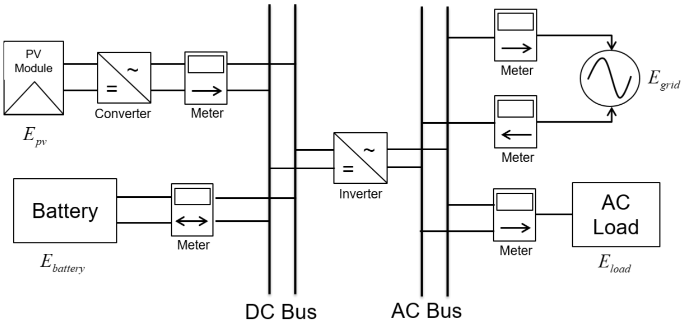


Figure 2.1: Inline Topology

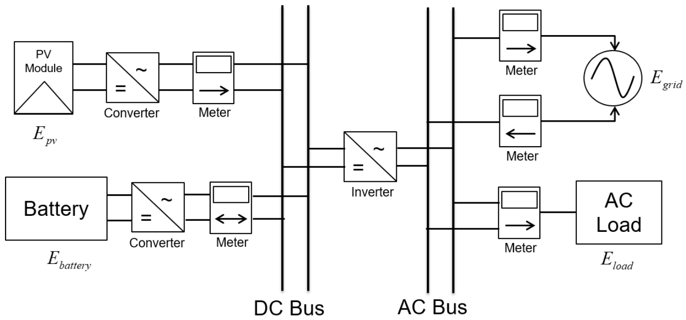


Figure 2.2: DC Coupled Topology

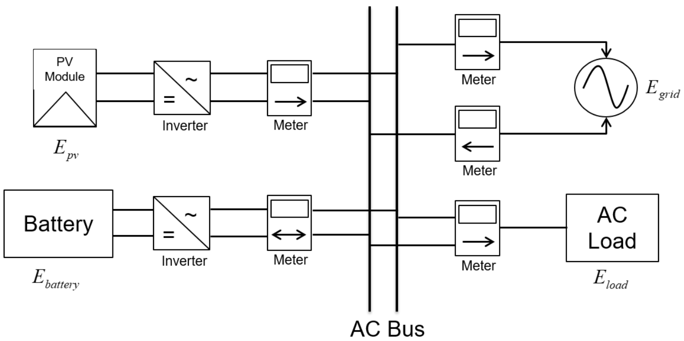


Figure 2.3: AC Coupled Topology

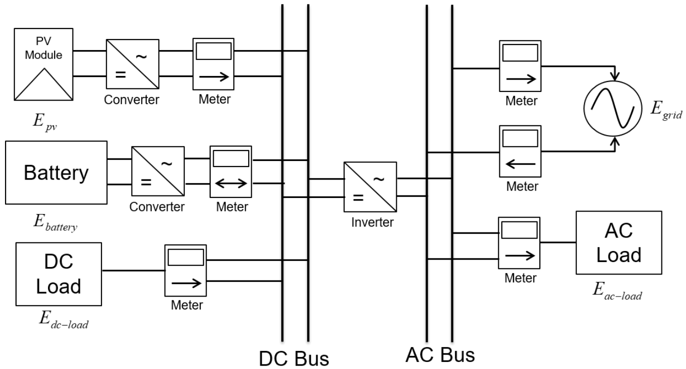


Figure 2.4: DCAC Coupled Topology

2

2

2.2. LOAD DIMENSIONING

THE load data are acquired from different sources. The original load data have different time interval, for the Netherlands case, the step of load data is every 10 minutes; but for Costa Rica and California cases, the original load data is hourly data. In order to be unified and accurate, for Costa Rica and California cases, all the load data are transferred into every-10-minute data with Matlab. In this way, for each country/region, the yearly load data are all with the same 10 minutes data, and these three sets of load data are used for the simulation in this thesis for the three corresponding countries/region.

For the Netherlands and Costa Rica cases, the load data are directly got from [44]. The selected data for households do not include heavy loads, like heat pumps and electric vehicles. For the Netherlands case, the original yearly is collected every 10 minutes; but for Costa Rica case, the original yearly load data is collected every hour. In order to be unified and accurate, the original load data for Costa Rica transferred into every-10-minute-data with the help of Matlab. The Matlab value-insert function is "interp1", with this function, four different value-insert methods are provided, according to the different value-insert principle, they are called "linear", "nearest", "spline" and "pchip", respectively. These four methods all have their own characteristics and can give different value-insert results, in order to decide which one is the best method, the original hourly load data for a random day (January 1st) is used as an example here to find the best choice. Figure 2.5, Figure 2.6, Figure 2.7, and Figure 2.8 show the value-insert results with method "linear", "nearest", "spline", and "pchip", respectively. Figure 2.9 shows the original hourly load data for January 1st. Among the four figures, "pchip" can give the best performance since it provides the smoothest curve and is similar to the original hourly data curve.

To finish the data insertion, the 8761st data must be forecasted, which is the first data for the new year. This is because the "interp1" function can only insert a value between too existed data. In order to finish value-insert for the last hour on December 31st (data for 23:10, 23:20, 23:30, 23:40 and 23:50 on December 31st), since the original load data is only for one year, the first value of load consumption for the new year must be provided. This data is the very data for 00:00 on January 1st for the new year, which becomes the 8761st for the load profile to finish forecasting. Decade polynomial is used to forecast this datum because it could give the best r-square value and adjusted r-square value. With decade polynomial, the forecasting load data is 336.4537424W, which is in the line with the load trend.

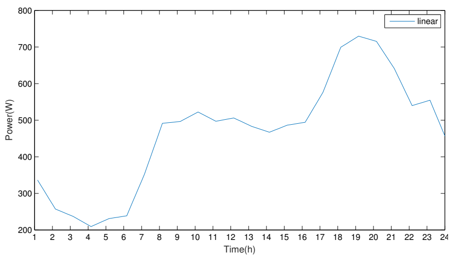


Figure 2.5: Value Insert with Linear

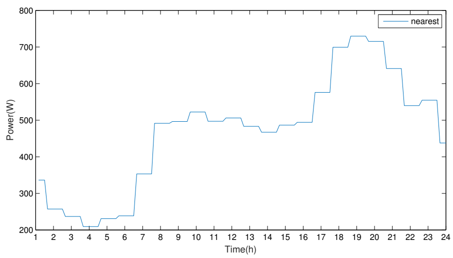


Figure 2.6: Value Insert with Nearest

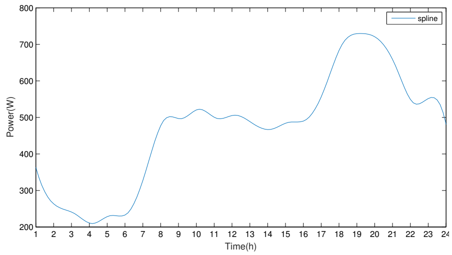


Figure 2.7: Value Insert with Spline

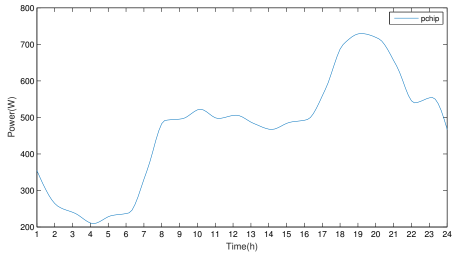


Figure 2.8: Value Insert with Pchip

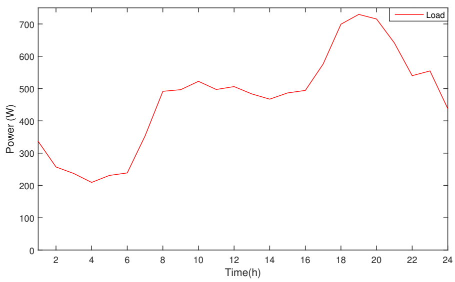


Figure 2.9: Costa Rica Original Load for January 1st

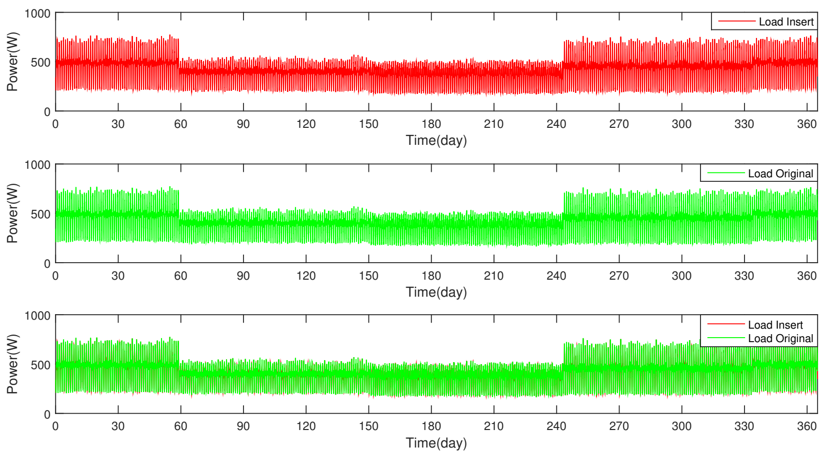


Figure 2.10: Load Comparison

Figure 2.10 compares the original hourly load data and the every-10-minute-data for Costa Rica case. The red line from the upper subgraph is the load profile for the entire year after the value insertion. The middle subgraph with green line is the original hourly load profile for the entire year. In the lower subgraph, the original hourly load data and the new every-10-minute data are combined together. It is easy to find out that the every-10-minute data reasonably match the original hourly load data.

For California case, the load data is from [45], it is based on the low load model characteristics from Los Angeles, the selected building for data gathering is from the urban area and each apartment contains two bedrooms and one full bathroom [46]. The original data is hourly data, and it is transferred to every-10-minute data with the same method mentioned before when insert values for Costa Rica case. The Matlab value-insert function is "interp1" with method "pchip", again the first load data for the new year is forecasted with decade polynomial function. The first value for the new year is 1056.31Wh, which is also in line with the load trend.

2.3. PV PANELS SIZING

PV panels are the renewable energy source in the system. They can provide energy during sunny days. PV panels play an important role in the whole system since a suitable numbers of PV panels can not only improve the autarky of the entire system, but also can bring profits to consumers through selling energy back to the grid and directly satisfying the load.

Like the load, the PV panels' generation data are got from different sources. For the Netherlands and Costa Rica case, [44] has already provided the PV production data. It already considers the efficiency, the irradiation, the tilt angle and the effective area, which means the PV production data can be directly used and considered as the real production from PV panels. Again, the data resolution is different. For the Netherlands case, the original data are every-10-minute data, while for Costa Rica case, the original data are hourly data. In order to be unifying for the three selected countries/region, for Costa Rica case, values are inserted with the help of Matlab to transfer hourly data into every-10-minute data. The Matlab interpolation function is still "interp1" with the method "pchip", which is the same used for the load value insertion. Since the original data is only for one year, the first PV production data should be forecasted. The 'decade' polynomial statement is used and based on the data for this year, the forecasted 8761st PV production data as the first data for the next year is 0, which is reasonable and acceptable because during the night the PV panels may not produce any energy, which conforms to the natural law. For California case, the PV generation data are not ready-made and has to be calculated based on the normal irradiation data, the tilt angle, the sun location and PV panels' datasheet.

Article [44] chooses JKM265P PV panels from Jinko Solar Company for both the Netherlands data and Costa Rica data, it is a kind of poly-crystalline silicon module. The important parameters of this type of PV panels have already listed in Table 2.1 and Appendix D Section D.1. For simplify reason, this type of PV panels is also used for California case.

For California case, the PV panels' generation data can be calculated with Equation 2.1.

$$P_{PV} = A \times \eta \times G \tag{2.1}$$

where:
P_{PV} is the total energy output of one PV panel with the unit kW;
A is the total effective area of one PV panel with the unit m^2;
η is the module efficiency of PV panels;
G is the solar irradiation data of the very location with the unit kW/m^2.

G is the irradiation normal to PV panels, which is different from the irradiation normal to the ground because usually there is a tilt angle when PV panels are mounted on the ground or roof. From [47], only the irradiation data normal to the ground is available, that means this data should be transferred to get the normal irradiation data on PV panels.

From [48], the direct irradiance on the module can be calculated with Equation 2.2,

$$G_M^{dir} = I_M^{dir} \times \cos\gamma \tag{2.2}$$

where:
G_M^{dir} is the direct irradiance on the module;
I_M^{dir} is the direct normal irradiance (DNI) on the surface;
γ is the angle between the surface normal and the incident direction of the sunlight, which is also known as the angle of incidence (AOI).

Since the sun location is always changing during the year, it depends on the time and location on the earth. In order to get the irradiance on the modules, the sun position should also be considered. Together with the module position, sun location and tilt angle of solar module, $\cos\gamma$ is given by Equation 2.3,

$$\cos\gamma = \cos a_M \times \cos a_S \times \cos(A_M - A_S) + \sin a_M \times \sin a_S \tag{2.3}$$

With $a_M = 90^{\diamond} - \theta_M$, Equation 2.3 becomes,

$$\cos\gamma = \sin\theta_M \times \cos a_S \times \cos(A_M - A_S) + \sin a_M \times \sin a_S \tag{2.4}$$

In this way, the direct irradiance on the module G_M^{dir} can be calculated with Equation 2.5,

$$G_M^{dir} = I_M^{dir} \times \cos\gamma = I_M^{dir} \times [\sin\theta_M \times \cos a_S \times \cos(A_M - A_S) + \sin a_M \times \sin a_S] \tag{2.5}$$

where:
θ_M is the PV panels' tilt angle if the PV panels are mounted on a horizontal plane;
A_M is the module azimuth, where A=0° corresponds to due North;
a_M is the module altitude;
A_S is the solar azimuth;
a_S is the solar altitude.

For Los Angeles, The optimal angle is 31°, which can be seen from Figure 2.11 [49].
The solar position is from with a time step of every 10 minutes. However, the data does not cover the whole day span, the data break when the sun has dropped more than 12 degrees below the horizon, the data start again when the next indicated time comes when the sun is near the horizon again [50]. In such case, during the rest day when [50] does not indicate the exactly sun position, both the altitude and azimuth of sun location are manually set to 0 in order to get a 24-hour sun location table with a time step of every 10 minutes. This does not influence the final results because Equation 2.5 only holds when the Sun is above the horizon ($a_S > 0$) and the azimuth of the Sun is within ±90° of A_M, which means $A_S \in [A_M - 90°, A_M + 90°]$. Otherwise, the direct irradiance on the module considered to be zero, which is $G_M^{dir} = 0$ [48].
In this case, the direct irradiance on the module is calculated with Equation 2.5 and the PV production for California for the entire year with a time step of every 10 minutes is obtained.
PV panels performance can be influenced by temperature and can only work within the operating temperature range provided by the manufacturer. With different operating temperature, the PV panels' overall performance can be different. For JKM265P, the

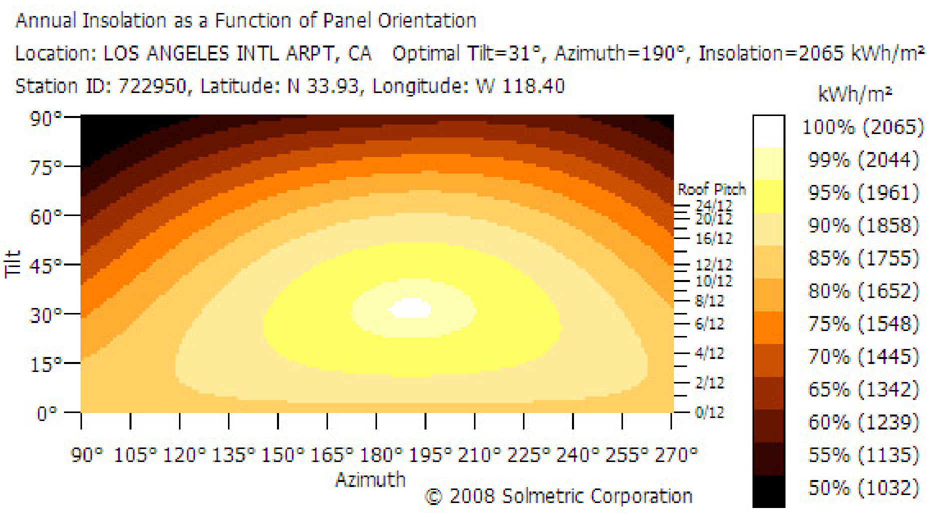


Figure 2.11: Los Angeles Annual Insolation as a Function of Panel Orientation [49]

operating temperature range is −40°C ∼ +85°C ; the temperature coefficients of P_{max} is −0.41%/°C , which means if the temperature goes up 1°C above +25°C , the value of P_{max} will decrease 0.41%, which equals to 1.0865W; the temperature coefficient of V_{oc} is −0.31%/°C , equals to −0.11966V/°C ; the temperature coefficients of I_{sc} is 0.06%/°C , equals to 0.005388A/°C ;these value are gathered under standard test condition (STC). STC means the irradiance is 1000W/m^2 , with the cell temperature equals to 25°C, and AM=1.5.

In order to get the number of PV panels, an important assumption has been made. It is assumed that all the energy consumed by the load can be directly supported with PV panels' production. So that the following Equation 2.6 can be established:

$$\sum_{n=1}^{52560} P_L(n) = \sum_{n=1}^{52560} P_{PV}(n) \times \eta_{DC} \times \eta_{iv} \times \eta_{AC} \times \eta_{AC} \times N_{PV} \tag{2.6}$$

where:

$P_L(n)$ is the power consumed by Load in period n;

$P_{PV}(n)$ is the power produced by one PV panel in period n;

η_{DC} is the DC cable efficiency, which is assumed to be 97% [51];

η_{iv} is the efficiency of inverter that connected with PV panels, which is assumed to be 95%;

η_{AC} is the AC cable efficiency, which is assumed to be 99% [51].

N_{PV} is the number of PV panels needed.

For the Netherlands case, the load consumption for the entire year is 3557.44kWh, one PV panel production for the whole year is 216.95kWh, with Equation 2.6, 18.16 PV panels are needed for the Netherlands case in theory.

Since the number of PV panels should be an integer, 19 should be used for the Netherlands case, which leads to a total 4122.02kWh PV production for the whole year. However, this number will be changed to 18 due to a reasonable system connection. Details are discussed in Section 2.5. 18 PV panels are used for all the later simulation for the Netherlands case.

While for Costa Rica case, the load consumption for the entire year is 3552.56kWh, one PV panel production for the whole year is 510.66kWh, with Equation 2.6, 7.70 PV panels are needed for Costa Rica case in theory.

So that the number of PV panels for Costa Rica case is 8, which leads to a total 4085.26kWh productions for the whole year.

For California case, the load consumption for the entire year is 8120.12kWh, one PV panel production for the whole year is 893.67kWh, with Equation 2.6, 10.06 PV panels are needed for California case in theory.

Again, based on the integer principle, for California case, in theory, 11 PV panels are needed, which leads to a total 9830.39kWh production for the whole year. However, the irradiance in California is strong and the PV generation from one PV panel is high, one PV panel's yearly energy production from California is more than 3 times higher than the Netherlands case. If 11 PV panels are used, then the system will be oversized by 9.34%. Therefore, the number of PV panels is downsized to 10 and 10 PV panels are used for later simulation for California case.

Table 2.1: PV Modules-Key Parameters

Parameters	Value
Maximum Power (P_{max})	265W_p
Maximum Power Voltage (V_{mp})	31.4 V
Maximum Power Current (I_{mp})	8.44 A
Open-Circuit Voltage (V_{oc})	38.6 V
Short-circuit Current (I_{sc})	9.03 A
Module Efficiency STC	16.19 %
Operating Temperature	-40°C ~+85°C
Temperature Coefficient of P_{max}	-0.41 %/°C
Temperature Coefficient of V_{oc}	-0.31 %/°C
Temperature Coefficient of I_{sc}	0.06 %/°C

Figure 2.12, Figure 2.13, and Figure 2.14 show the PV production profile together with load consumption profile for the Netherlands case, Costa Rica case, and California case for the entire simulation year, respectively. The red lines represent the load profile and the green lines represent the PV generation profile. For the Netherlands case, the PV production is high and concentrated during the summer period, a lot of high peaks appear during that time period; however, for the winter period, the PV production is low and cannot meet the load requirement. The load profile for winter time is higher compared with the summer time, and load data is relatively stable in the entire year. While for Costa Rica case, the PV production does not change too much as the Netherlands case does, the seasonal factor seems does not influence the PV panels' production too much. The

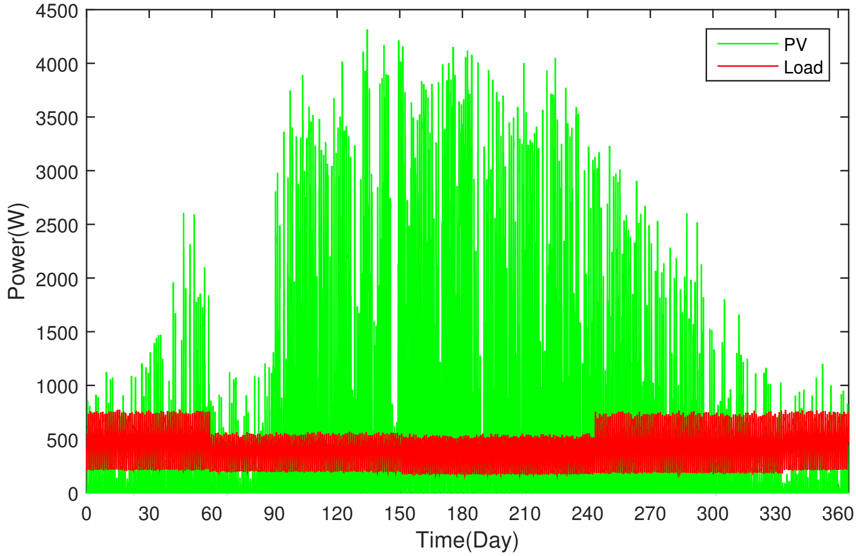


Figure 2.12: PV Generation Profile and Load Profile for the Netherlands

load profile is also distinguished between the winter time and summer time. The load is relatively stable and no sudden peaks appear. For California case, the PV production data does not vary too much in the entire year, the irradiation is abundant during the entire year and can provide smooth PV generation profile. The load profile is not stable during the year and sudden peaks appear, especially during the summer time. Compared with the Netherlands case and Costa Rica case, both the PV production and load consumption are higher during the entire year for California case.

2

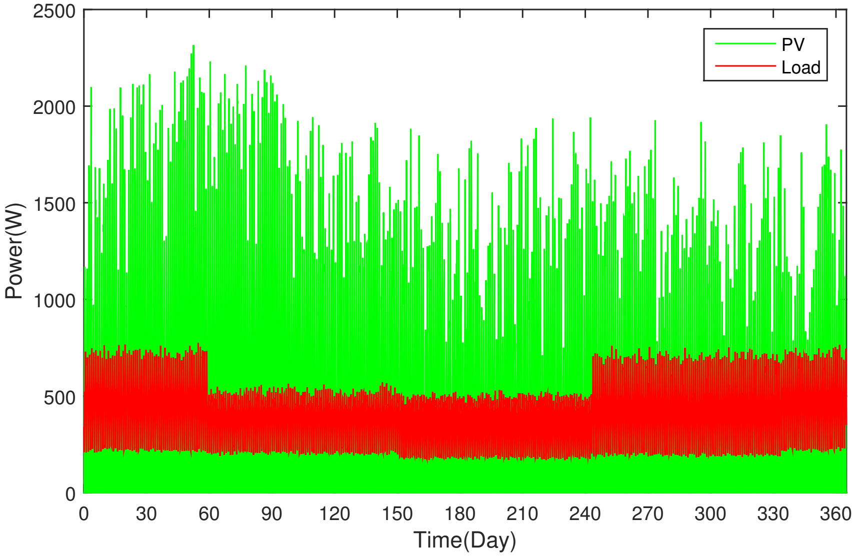


Figure 2.13: PV Generation Profile and Load Profile for Costa Rica

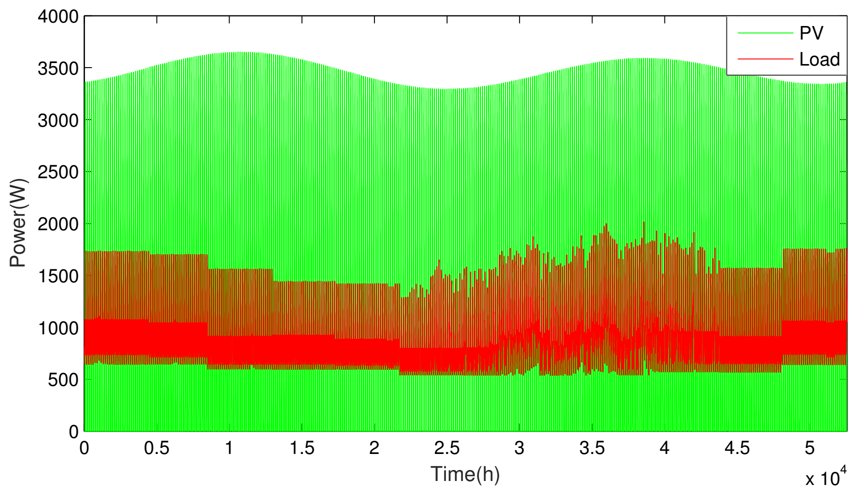


Figure 2.14: PV Generation Profile and Load Profile for California

2.4. BATTERY SIZING

THE battery is responsible for energy consumption when the PV production is not enough to satisfy the load or the energy price is high. The battery can also store the extra energy from PV panels' production or the energy bought from the grid for later use. For different power management methods, the main function of the battery can be different. The detail information about battery schedule is introduced in Chapter 3, Section 3.2.

Battery size is critical to the system because if the battery size is too large, if the only source to charge the battery is PV panels, the battery cannot always be fully charged; while if the battery can also be charged with energy from grid, then too much energy may be needed to fully charge the battery; plus, the battery is expensive and a large battery size can remarkably increase the system building cost. However, if the battery size is too small, only a small amount of energy is stored in battery and battery cannot support the load for enough time, in this case, the battery cannot fulfill its obligations to the system. It should be clear that due to the different functions of battery in each PMM, the battery sizes could be different for each PMM.

There are various types of batteries available on the market, such as Lithium-Ion battery (Li-ion), Lead Acid battery, Nickel Cadmium battery (NiCd), Nickel-Metal Hydride battery (NiMH), etc. Each of them has their own advantages and limitations. As the fastest developing battery, Lithium-ion battery draws a lot of attention recent years. It is stands out due to the following reasons. The abundant storage of Li on earth makes it possible for long time use gives the basis advantage [52]; plus Li is one of the lightest elements on earth, with one of the smallest ionic radii of the single charged ion and the highest possible cell potential, it is possible to make Li-based batteries to have higher energy density, which means this kind of battery can store more energy with smaller volume and less weight [53, 54]; due to heat development, only small amount of energy is lost during charging and discharging period, which provides higher efficiency with good cycle life [54, 55]; although the lithium-ion battery is expensive nowadays, it can provide longer battery life span with more cycles, from an economic standpoint, it can reduce the investment from long term perspective .

The voltage of the stand-alone power system is another critical parameter that needed to be chosen carefully. Usually, the standard DC voltage for residence-used could be 12V, 24V and 48V. This voltage can influence the system's current, and a large current may cause a lot of problems. For example, the larger the current is, the more energy dissipated with the form of heat in the energy exchange process, which means the lower the system efficiency will be; besides, the bigger system components are needed because high currents require larger diameter of cables and fuses, which is not only more expensive, but also more dangerous could be potentially induced. Another reason is that nowadays a lot of systems are 24V or 48V together with a 230V AV inverter, so that a 48V the wiring of the house does not have to be different from any other grid-connected household and thus the cabling cost can be reduced remarkably, also it will be much easier to buy the relevant components which are much cheaper on the market.

Due to these reasons, it is suggested a 48V lithium-ion battery should be used for the AC coupled topology. The battery involved in the system comes from LG Chem Company, they provide RESU series especially for 48V models.

Until now, a lithium-ion battery with 48V connection has already been decided. The next step is to choose the energy capacity of the battery. At first, it is assumed that all the energy consumed by the load can be supported only by the battery through the whole year. The load consumption for the whole year is 3557.436kWh, which equals to 9.7464kWh per day if one year is considered to have 365 days. From the data provided by [39], the daytime for the Netherlands can vary between 07 hours 40 minutes and 16 hours 48 minutes during the whole year, from [56], the average daylight hours and minutes is 12 hours for the whole year, which means if the battery is used to satisfy the rest 12 hours, the battery size should be larger than 4.8732kWh. So that RESU10 is chosen to do the simulation at first, which has the energy capacity equals to 9.8 kWh. But the simulation results show that this battery size is too large because the SOC of the battery packs for the whole year does not change too much when the battery size change from 1 (1 RESU10, 9.8kWh), to 2 (2 RESU10, 19.6kWh) and later to 3 (3 RESU10, 29.4kWh).

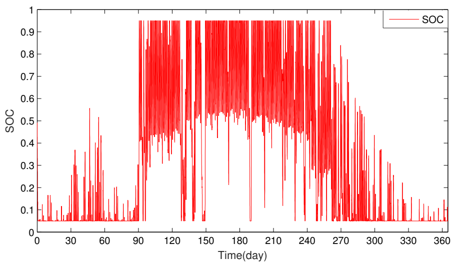


Figure 2.15: SOC for 1 Battery

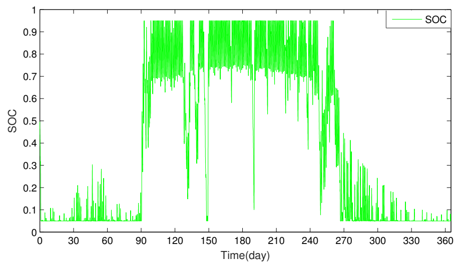


Figure 2.16: SOC for 2 Battery

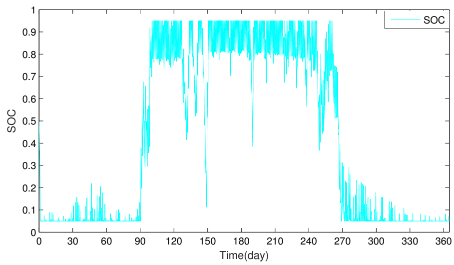


Figure 2.17: SOC for 3 Battery

From Figure 2.15, Figure 2.16 and Figure 2.17, the SOC fluctuation mode does not change too much, the battery cannot be fully charged at the beginning and at the end of the year, and in the middle of the year, the battery cannot be totally discharged. This means the battery is almost empty during winter seasons and almost full during summer seasons, a large part of the battery is not used during the year, the change of battery size only has a small influence on system's power flow. This is because the sunlight hours change a lot during the whole year, and usually during the summer, the irradiation is much stronger and the PV production is much higher than it is in winter. In winter periods, the PV production is not enough and a lot of energy is still needed to be bought from grid; while in summer periods, PV panels' production can already support a large part of load, a lot of energy is stored in battery and cannot be sold back to grid to gain profit. In other words, the battery cannot be fully used during both the summer time and winter time, the function of battery in the whole system has been restricted. The battery is a costly unit in the system and it is not economical to invest a large capital into the system only paid back with limited function. Due to these reasons, it is better to downscale the battery size and RESU3.3 from the same company is chosen to run the simulation. 1 unit means 1 RESU3.3, which has the total energy equals to $3.3kWh$, the important parameters are listed in Table 2.2 and the battery datasheet can be found in Appendix D, Section D.2.

In order to find out the suitable battery size for the first PMM, simulations are run with different battery sizes for each country/region. For the Netherlands case, the battery size changes from 0.25 unit to 3 units with a step of 0.25 unit. The simulation results are shown in Appendix B, Section B.1.1. It is easy to find out that it is better to keep the battery size smaller than 1.5 units since for larger battery units, the battery can not always be fully discharged during summer time and during winter time, the battery cannot always be fully charged. In order to have the battery frequently used and play an important role in the system. 0.5 battery unit (0.5 RESU3.3, 1.65kWh), 1 battery unit (1 RESU3.3, 3.3 kWh) and 1.5 battery units (1.5 RESU3.3, 4.95kWh) are chosen for the Netherlands case. The same method is used to decide the suitable battery size for PMM4, where the battery function is kind of limited because the battery is only used to supply the part that exceeds the pre-determined reference value, the simulation results are shown in Appendix B, Section B.1.2. The simulation is run with $P_{ref} = 500W$ with battery size changes from 0.125 unit to 2 units with a step of 0.125 unit, based on the SOC for the entire year, 0.25 battery unit (0.25 RESU3.3, 0.825 kWh), 0.5 battery unit (0.5 RESU3.3, 1.65 kWh) and 1 battery unit (1 RESU3.3, 3.3 kWh) is chosen for the Netherlands case. Of course, with lower reference values, a larger battery size is needed to store more energy and shave more peaks during the year.

For Costa Rica, the same method is used to decide the battery size for PMM1. The battery size is also changed from 0.25 battery unit to 3 battery units with a step of 0.25 unit. The battery sizes chosen do the simulation are 0.5 battery unit, 1 battery unit and 1.5 battery units. Section B.2.1 shows the SOC variations inside the battery. For PMM4, the battery SOC with different battery size is shown in Section B.2.2. 0.125 battery unit, 0.25 battery unit and 0.375 battery unit are chosen for the simulation with $P_{ref} = 500W$.

For California case, for PMM1, the battery size changes from 0.25 battery unit to 6 battery units with a step of 0.25, the SOC variations are shown in Section B.3.1. 1 battery unit, 2 battery units and 3 battery units are chosen to do the simulation. For PMM4, $P_{ref} = 1400W$ and 0.25 battery unit, 0.5 battery unit, and 0.75 battery units are chosen for the simulation. For PMM4, the SOC variations are shown in Section B.3.2

For all three countries/regions, PMM2 and PMM3 should have the same battery size as PMM1 has, this is because the battery is always forced to be charged with energy from the grid before the peak-hour begins and always forced to be discharged at the end of peak-hour, no matter what battery size is used for these two PMMs, the energy exchange with the grid is always more frequently. Thus, the battery size cannot be decided with battery SOC. To make this easier, the same battery size is used as the PMM1 does.

About the battery, there are several important assumptions about battery performance, from the battery datasheet, the new RESU series can achieve a 95% DC round-trip efficiency with continuous power. It is assumed that the charge efficiency equals to discharge efficiency and both equal to 97%. Also, during the entire simulation year, the battery state-of-health (SOH) is always remaining the same and equals to 1.

In the system, the charging process and discharge process cannot happen at the same time slot, that means if the battery is charging at this moment, then no energy will be discharged from the battery; if the battery is discharging at this moment, then no energy will be charged into battery. This unidirectional working mode is also suited for other units in the system. For example, at the interface of gird, if some energy is sold back to the grid, then no energy will be bought from the grid at this moment; if the prosumers buy energy from the grid, then no energy will be sold back to the grid. This makes sure that at any moment, for battery, the energy flow is always one same direction, which is easy to schedule and manage.

Table 2.2: Battery-Key Parameters

Parameters	Value
Total Energy	3.3 kWh
Usable Energy	2.9 kWh
Capacity	63 Ah
Nominal Voltage	51.8 V
Max Power	3.0 kW
DC Round-Trip Efficiency	95%

2.5. INVERTER SIZING

THE inverter plays an important role in the whole system since it converts direct current to alternating current at a given voltage and frequency, or vice versa. In the AC coupled topology, one unidirectional inverter is needed to connect PV panels to the AC bus. This inverter converts the DC current generated directly by PV modules into AC current, which can be used by local consumption units or fed into the electricity grid. The solar inverter can also track the maximum power point and proceed anti-islanding protection [57, 58]. Another bi-directional inverter is needed to connect battery storage to the AC bus. This bi-directional inverter converts the DC current into AC current when the battery is discharged to support the load or sell energy back to the grid and converts the AC current into DC current when the battery is charged with the energy from PV panels or the grid, making it possible to have energy exchange between the battery and other units in the system. Usually, the selection of the inverter for installation depends on the input voltage and the input current of the inverter, the operating range of the inverter and the output power of the inverter. Due to the difference function of the inverters used for PV panels' and battery's connection, two different inverters are chosen for PV panels' connection and battery connection.

2.5.1. INVERTER FOR PV PANELS

IN general, when deciding the inverter size for PV panels' connection, the maximum DC input power, the maximum DC input current and the maximum specified output power should be carefully considered.

From Table 2.1, the maximum DC input power of 19 PV panels equals to:

$$P_{max-DC-input} = 265W_p \times 19 = 5035W_p$$

the maximum DC input current is $8.44A$; Article [51] suggests that the inverter nominal AC output power should not be less than 75% of the array peak power, which is $265W_p \times 19 \times 75\% = 3776.25W_p$. Based on this, Sunny Boy 4.0 is chosen as the inverter connected with PV panels for the Netherlands case. The datasheet for Sunny Boy 4.0 can be found in Table 2.3 and Appendix D, Section D.3.1.

Inverters can only work inside the voltage operating window that provided by the manufacturer, it requires the solar array voltage cannot be either too large or too small, because if the voltage is outside the operating window, the solar array will either not work or work with low efficiency. Therefore, it is critical to decide both the minimum input voltage and the maximum input voltage. A suitable inverter means the solar array voltage is matched to the inverter's voltage operating window. Article [51] provides detail procedures to calculate the minimum input voltage and maximum input voltage, it also introduces the ways to calculate the number of modules of each string with the help of minimum input voltage and maximum input voltage.

To maximize the PV panels' performance, the minimum array voltage should never fall below the minimum input voltage of the inverter. Since the temperature could influence the PV panels' performance, and usually, the higher the temperature is, the lower the voltage will be, even with the highest acceptable temperature, the array voltage should still above the minimum operating voltage window of the inverter.

The minimum maximum power point (MPP) could be calculated by Equation 2.7:

$$V_{mpp-cell} = V_{mp-STC} + \left[V_{oc} \times \left(T_{max-cell-eff} - T_{STC}\right)\right] \tag{2.7}$$

Where:

$V_{min-mpp}$ is the maximum power point voltage at maximum cell temperature, the unit is V;

V_{mp-STC} is the maximum power point voltage at STC, the unit is V;

V_{oc} is the PV panel's voltage-temperature coefficient, the unit is $\%/^{\circ}C$ or $V/^{\circ}C$;

$T_{max-cell-eff}$ is the maximum cell temperature the PV panels can be expected, the unit is $^{\circ}C$;

T_{STC} is the cell temperature at STC, the unit is $^{\circ}C$.

For JKM 265M, the temperature coefficients of V_{oc} is: $V_{oc} = -0.31\%/°\text{C}{=}-0.11966V/°\text{C}$;

According to Royal Netherlands Meteorological Institute (KNMI) [59], the highest temperature of Amsterdam Schiphol International Airport in 2000 was $22.5313^{\circ}C$, which happened on August 6th. So that the maximum effective cell temperature is assumed to be $70^{\circ}C$. Thus, with Equation 2.7, $V_{min-vpp} = 26.02V$

Usually, some voltage is dropped in the cables and if this value is assumed to be 3%, then the voltage at the inverter for each module would be: $V_{min-mpp-inv} = 26.02V \times 97\% = 25.23V$;

$V_{min-mpp-inv} = 25.23V$ is the effective minimum MPP voltage input at the inverter for each module in the array.

With this number, the minimum number of modules in each string can be calculated with the following Equation 2.8:

$$N_{min-per-string} = \frac{1.1 \times V_{inv-min}}{V_{min-mpp-inv}} \tag{2.8}$$

where:

$N_{min-per-string}$ is the minimum number of modules in a string;

$V_{inv-min}$ is the minimum inverter input voltage.

The exact variation is dependent on the quality of the solar cell so a safety margin of 10% is used.

Based on the inverter datasheet of Sunny Boy 4.0, the minimum input voltage is $100V$, which leads to $N_{min-per-string} \approx 4.36$.

For the coldest daytime temperature, the open circuit voltage of the array must exceed the maximum allowed input voltage for the inverter [51]. The open circuit voltage is used because this is larger than the MPP voltage and it is the applied voltage when the system is first connected (prior to the inverter starting to operate and connecting to the grid);

In the early morning, at first light, the cell temperature will be very close to the ambient temperature because the sun has no time to heat up the module. Therefore, the lowest daytime temperature in the area where the system is installed is the lowest working temperature for PV panels and should be used to determine the maximum V_{oc};

The maximum allowed input voltage could be calculated by Equation 2.9:

$$V_{max-oc} = V_{oc-STC} + \left[V_{oc} \times \left(T_{min-cell-eff} - T_{STC}\right)\right] \tag{2.9}$$

Where:
V_{max-oc} is the open circuit voltage at minimum cell temperature, the unit is V;
V_{oc-STC} is the open circuit voltage at STC, the unit is V;
V_{oc} is the PV panel's voltage-temperature coefficient, the unit is $\%/^{\circ}C$ or $V/^{\circ}C$;
$T_{min-cell-eff}$ is the minimum daily temperature the PV panels can be expected, the unit is $^{\circ}C$;
T_{STC} is the cell temperature at STC, the unit is $^{\circ}C$.

According to the data provided by KNMI [59], the lowest temperature in 2000 of Amsterdam Schiphol International Airport was $-0.795588^{\circ}C$, which happened on February 16th. Thus $-10^{\circ}C$ is used to determine the maximum open circuit voltage; $V_{max-oc} = 42.79V$

Then the maximum number of modules in a string can be calculated with Equation 2.5.1:

$$N_{max-per-string} = \frac{V_{inv-max}}{V_{oc-max}} \tag{2.10}$$

where:
$N_{max-per-string}$ is the maximum number of modules in a string;
V_{oc-max} is the maximum voltage allowed by the inverter.

Based on the inverter datasheet of Sunny Boy 4.0, the maximum voltage allowed by the inverter is $600V$, which means the $N_{max-per-string} \approx 14.02$.

So that the number of modules per string should be $4.36 \leq N \leq 14.02$. In this way, for the Netherlands case, if the PV panels' number is 19, it could have 2, 3 or 4 parallel strings, but no matter how many parallel strings are there, there is no way to uniformly allocate the PV panels to each string. Therefore, it is suggested to use 18 or 20 PV panels here. Based on the assumption that the PV panels' production during the entire year should equal to all the load consumption for the whole year, the number should be 18.16, if 20 PV panels are used, the system would be oversized by 9.22%, therefore, 18 PV panels are used for the Netherlands case, and those 18 PV panels could either connected with 2 parallel strings with 9 PV panels on each string or connected with 3 parallel strings with 6 PV panels on each string.

With 18 PV panels, the maximum DC input power equals to:

$$P_{max-DC-input} = 265W_p \times 18 = 4770W_p$$

the 75% of the array peak power equals to: $265W_p \times 18 \times 75\% = 3577.5W_p$. The Sunny Boy 4.0 is still suitable for the Netherlands case. However, Sunny Boy 4.0 only has two inputs, so that 3 parallel strings with 6 PV panels on each string is not feasible. In conclusion, Sunny Boy 4.0 is chosen as the inverter connected with PV panels for the Netherlands case with two parallel strings and 9 PV panels on each string.

For Costa Rica case, 8 PV panels are used. The maximum DC input power equals to:

$$P_{max-DC-input} = 265W_p \times 8 = 2120W_p$$

75% of the array peak power equals $265W_p \times 8 \times 75\% = 1590W_p$. According to Instituto Meteorologico Nacional de Costa Rica (IMN) [60], the highest temperature for San Jose, Costa Rica is $26.3°C$ and usually happens in September, so that the maximum effective cell temperature is still assumed to be $70°C$. With Equation 2.7, $V_{min-vpp} = 26.02V$.

Again, it is assumed that 3% voltage is dropped in the cables, then the voltage at the inverter for each module would be: $V_{min-mpp-inv} = 26.02V \times 97\% = 25.23V$;

$V_{min-mpp-inv} = 25.23V$ is the effective minimum MPP voltage input at the inverter for each module in the array.

With Equation 2.5.1, the minimum number of modules in each string approximately equals to 4.36 if a safety margin of 10% is used.

According to the data provided by IMN [60], the lowest temperature for San Jose, Costa Rica is about $16.4°C$, and usually happens in January, thus $0°C$ is used to determine the maximum open circuit voltage; with Equation 2.9, $V_{max-oc} = 41.59V$

With Equation 2.5.1, the maximum number of modules in a string equals to:

$$N_{max-per-string} = \frac{V_{inv-max}}{V_{oc-max}} = \frac{600V}{41.59V} \approx 14.43$$

So that the number of modules per string should be $4.36 \leq N \leq 14.43$. In this way, for Costa Rica case, only 1 string is needed with 8 PV panels in it.

For California case, 10 PV panels are used, making the maximum DC input power equals to:

$$P_{max-DC-input} = 265W_p \times 11 = 2915W_p$$

and 75% of the array peak power yields $265W_p \times 11 \times 75\% = 2186.25W_p$. From National Oceanic and Atmospheric Administration (NOAA) [61], the highest temperature for Los Angeles Downtown in 2010 was around $84.8°F$, which was approximately $29.3°C$ and happened on August 25th, 26th, 27th, 28th, 29th, and 30th. So that the maximum effective cell temperature is still assumed to be $70°C$. Thus with Equation 2.7: $V_{min-vpp} = 26.02V$

If assume that 3% of voltage is dropped in the cables, then the voltage at the inverter for each module would be: $V_{min-mpp-inv} = 26.02V \times 97\% = 25.23V$;

$V_{min-mpp-inv} = 25.23V$ is the effective minimum MPP voltage input at the inverter for each module in the array.

With Equation 2.5.1, the minimum number of modules in each string approximately equals to 4.36 if a safety margin of 10% is used.

According to the data provided by NOAA [61], the lowest temperature in 2010 at Los Angeles Downtown happened on December 21st, 22nd, and 23rd. The temperature was $47.1°F$, which was approximately $8.4°C$, thus $0°C$ is used to determine the maximum open circuit voltage. With Equation 2.9, $V_{max-oc} = 41.59V$

With Equation 2.5.1, the maximum number of modules in a string equals to:

$$N_{max-per-string} = \frac{V_{inv-max}}{V_{oc-max}} = \frac{600V}{41.5915V} \approx 14.43$$

So that the number of modules per string should be $4.36 \leq N \leq 14.43$. In this way, for the California case, if 10 PV panels' are mounted, they can connected all together in series within 1 string or connected with 2 parallel strings with 5 PV panels on each string.

Table 2.3: Inverter Sunny Boy 4.0 —— Key Parameters

Parameters	Value
Maximum Generator Power	$7500 W_p$
Maximum Input Voltage	600 V
Minimum Input Voltage	100 V
Maximum Input Current Input A/Input B	15 A/15 A
Rated Power (at 230 V,50 Hz)	4000 W
Maximum Efficiency	97.0 %

2.5.2. INVERTER FOR BATTERY

FOR the battery, a bidirectional DC/AC inverter is needed. The standard DC voltage for the system is $48V$. The largest C-rate of battery is assumed to be 0.5, which means for RESU3.3, the largest charging current and discharging current are both $31.5A$; that means the input power should not excess $1512W$. Based on these requirements, the 48/3000/35 inverter from Victron Energy Company is chosen and used in the later simulation. The datasheet of this inverter can be found in Table 2.4 and Appendix D, Section D.3.2.

Table 2.4: Inverter Victron Energy 48/3000/35 —— Key Parameters

Parameters	Value
Input Voltage Range	38——66 V
Cont. Output Power at 25 °C	3000 VA
Charge Current	35 V
Maximum Efficiency	95.0 %

3

POWER MANAGEMENT METHOD

In this chapter, four different power management methods used to better dispatch the power flow in the system are introduced. An optimal power flow can help prosumers reduce their electricity bill and gain some profit. Some popular concepts like load shifting and load shedding are not considered as long-term strategies because these methods all need consumers to make some sacrifice and cannot always use all the electrical products as they want, thus, these ideas cannot solve the issue fundamentally. Within this vision, neither load shifting nor load shedding was considered when the PMMs were designed. An optimal power flow can be achieved with suitable power management, and thanks to the PV panels and battery storage units in the system, more options can be proposed and selected according to different load profile and consumption patterns. Based on the different electricity tariffs for different time periods or different consumption levels, four different power management methods are designed and will be introduced one by one in this chapter.

Four different power management methods are introduced with detail power flow in this chapter. As one of the basic backups, these power management methods are used to schedule the power flows and simulated for later use. The most important assumptions used during the simulations are first listed in Section 3.1. Section 3.2 focuses on the four PMMs, detail power flow and power dispatch methods are discussed. The simulation results of each PMM for different countries/regions are presented in Section 3.3, in the sequence of the Netherlands results, Costa Rica results and California results. In Section 3.4, the impact of PV panels and battery storage unit on the system's power flow are discussed. The important conclusions from this chapter are summarized in Section 3.5.

3

3.1. ASSUMPTIONS

BELOW some important assumptions that are commonly used in the simulation are listed. These assumptions are applicative to all three countries/regions.

1. The AC cables loss is 1% [51];
2. The DC cables loss is 3% [51];
3. The battery charging efficiency equals battery discharging efficiency and both are assumed to be 97%;
4. The largest C-rate of battery charging and discharging are 0.5;

   For the battery size larger than 1 RESU3.3, consider the battery is made up of several RESU3.3 and they are connected in parallel. For example, if the battery size is 2, then in the system, 2 RESU3.3 are connected in parallel. In this way, on each string, there is a battery inverter that helps connect the battery to the AC bus. The largest battery charging and discharging C-rate is still 0.5, and on each string, the current can never exceed the inverter's maximum input current.
5. The battery lower SOC limit is 5%, the upper SOC limit is 95%; the battery functional SOC range is between 5% and 95%, which means the maximum depth of discharge (DOD) is 90%;
6. The battery charging and discharging voltage always keep the same during the whole charging and discharging process; the voltages for charging and discharging process are assumed to be stable;
7. During the simulation year, the battery's state-of-health (SOH) will not change and always assume to be 1;
8. The efficiencies for both the unidirectional inverter connected with PV panels and the bi-directional inverter connected with battery are assumed to be 95%;
9. 1 Battery unit means 1 RESU3.3.

3.2. DETAIL POWER FLOW OF EACH POWER MANAGEMENT METHOD

3.2.1. POWER MANAGEMENT METHOD ONE

THIS power management method is called "All" since the power flow pattern for the whole year is always the same. From the PV panels' side, the PV production is always used to support the load first, if the load can be totally satisfied, then the rest energy from PV panels' production will be used to charge the battery with an acceptable current. And if the battery is fully charged, the rest energy will be directly sold back to the grid to gain some profit. The acceptable current means the C-rate equals to 0.5, 0.5 is used as the largest C-rate to protect the battery from suddenly overlarge current to better use the battery and avoid any damage to the battery. Several cases could happen during this battery charging process because neither the C-rate nor the battery's SOC can exceed the pre-determined limits.

1. If the prosumer want to charge all the excess energy into battery, the battery charging current I_c will be larger than the largest acceptable current I_{max}; then the consumers can only use the largest acceptable current I_{max} to charge the battery in the following 10 minutes; in this case, there will be some energy left after charging the battery, and this amount of energy will be sold back to the grid;
   (a) If the prosumer charge the battery with current I_{max} for 10 minutes, the battery SOC will surpass the upper SOC limit, which is unacceptable; in this case, the real battery charging current I_{rc} is smaller than I_{max} because the charging process is considered to be stable during the whole charging period; more energy is left than expecting after charging the battery, and this amount of energy will be sold back to the grid; the battery is fully charged at the end of this period;
   (b) If the prosumer charge the battery with current I_{max} for 10 minutes, the battery SOC is still lower than the upper SOC limit; in this case, the real battery charging current I_{rc} is equal to I_{max}, the rest amount of energy is sold back to the grid; the battery is not fully charged at the end of this period.
2. If the prosumer want to charge all the excess energy into the battery, the battery charging current I_c is smaller than the largest acceptable current I_{max}; then the prosumer can use current I_c to charge the battery in the following 10 minutes; in this case, all the excess energy could be charged into battery in theory;
   (a) If the prosumer charge the battery with current I_c for 10 minutes, the battery SOC will surpass the upper SOC limit, which is unacceptable; in this case, the real battery charging current I_{rc} is smaller than I_c, and there will be some energy left to be sold back to grid; the battery is fully charged at the end of this period;
   (b) If the prosumer charge the battery with current I_c for 10 minutes, the battery SOC is still lower than the upper SOC limit; in this case, the real battery charging current I_{rc} is equal to I_c, all the excess energy is charged into the battery and the prosumer do not sell any energy back to grid; the battery is not fully charged at the end of this period.

While from the load side, the energy requirement is always satisfied with PV panels' generation first, if there is some PV production. However, what always happens is that the PV production is not enough or what is worse, there is no PV production, then if there is some energy stored in the battery, the battery will try its best to satisfy the load to minimize the amount of energy bought from the grid. Therefore, the battery is considered as the second choice for the loads. The last choice is to buy energy directly from the grid to support the loads.

Battery discharging process is constrained with two conditions, one is that the discharging current cannot exceed the largest acceptable current, the other is that it should always make sure the battery SOC does not go lower than the lowest acceptable SOC limit. Again, several cases could happen regarding the battery discharging process.

1. If the energy stored in the battery is higher than the energy required by the load, then, in theory, the battery can fully satisfy the load and the prosumer do not need to purchase any energy from the grid to support the load;

   (a) If all the rest load requirement is satisfied by battery discharging, then the discharging current I_d will exceed the largest acceptable current I_{max}; in this case, the battery can only be discharged with the largest acceptable current I_{max}, leading to only part of load requirement can be supported by the battery, the rest will be satisfied with the energy bought directly from the grid; there is still some energy stored in the battery at the end of this period;

   (b) If all the rest load requirement is satisfied by battery discharging, a discharging current I_d that does not exceed the largest acceptable current I_{max} is needed; in this case, the battery will be discharged with this current I_d and the battery can fully satisfy all the rest of load requirement, the prosumer do not need to buy any energy from grid; there is still some energy stored in the battery at the end of this period.

2. If the energy stored in the battery is already less than the energy required by the load, then the battery cannot fully satisfy the load and the prosumer definitely need to purchase some extra energy from the grid to support the rest of load; the amount of energy bought from grid depends on the discharging current and battery SOC state;

   (a) If the battery is totally discharged, the discharging current I_d will exceed the largest acceptable current I_{max}; in this case, the battery can only be discharged with the largest acceptable current I_{max}; under such circumstance, the battery can only support part of load requirement and more energy needed to be bought directly from grid than theory to satisfy the rest of energy gap; the battery is not fully discharged at the end of this period;

   (b) If the battery is totally discharged, the discharging current I_d does not exceed the largest acceptable current I_{max}, then the battery can be discharged with this current I_d; in this case, the battery can only support part of load requirement, the rest of energy gap must be supported with the energy directly bought from the grid; the battery is totally discharged at the end of this period.

3. It could also happen that no energy is stored in battery, which is the worst case; in this case, battery cannot help to reduce the amount of energy bought from grid; all the rest needs from loads can only be bought directly from grid; the battery can be considered empty at the end of this period;

From the battery side, for PMM1, the energy used to charge the battery can only come from PV panels' production, no energy is bought from the grid to charge the battery. While for battery discharging process, the energy can only be used to support the load and must not be sold back to the grid to gain profit. So that from the grid side, the grid can only sell energy to load when there is energy gap, the grid can never sell energy to charge the battery. The only energy source that sells energy to the grid is PV panels, no energy from battery discharging can be sold back to the grid. In short, in this power management method, the only way to gain profit for prosumers is to sell energy back to the grid from PV panels' production.

There is no need to discuss how much amount of energy is bought from the grid to charge the battery or sold back to the grid from the battery discharging process for PMM1 because of the following two reasons:

1. Since the electricity price is fixed all the time, there is no need to buy energy from the grid and stored in the battery in advance, in other words, there is no price difference, buying electricity from the grid and then charged into the battery and later discharged to support the load, has the same energy price as directly buy energy from the grid later whenever is needed;

2. As long as the energy users buy more energy from the grid than the amount of energy they sell back to gird, the feed-in tariff is always the same with the buy-in tariff; when the energy users inject more energy to the grid than they buy, the feed-in tariff will always be much lower than the buy-in tariff. Which means there is no need to sell energy back to the grid when the electricity buy-in price is fixed.

However, nowadays, some experts have already suggested that if the battery storages are owned and maintained by DSOs, then charging the battery from grid should be tax-free. This is because tax should be paid only when the electricity is used for consumption, and if the battery storage is located just in the middle of the grid, this grid-connected storage unit should not be considered as consumption from consumers side. In this case, the tax-free model can be considered to avoid charging tax for multiple time [62]. In this way, it will be necessary to discuss how much amount of energy is bought from the grid to charge the battery or sold back to the grid from the battery discharging process since there is price difference. Some governments have already approved to build the pilot run project to test this policy, as the Finland government did in 2017 introduced in the article [62]. However, since this policy is not considered in this thesis, and the detail energy exchange between battery and grid is not discussed in the PMM1.

Figure 3.1 shows the power flow inside the system on January 1st under the power schedule of PMM1. The red line is the energy consumption from the load side, the green line represents the PV generation. The cyan line stands for the energy charged into the battery, the pink line shows the energy discharged from the battery. The blue line shows the energy directly bought from the grid.

The detail power flow information can be found from Table 3.1 and Flow Chart 3.2;

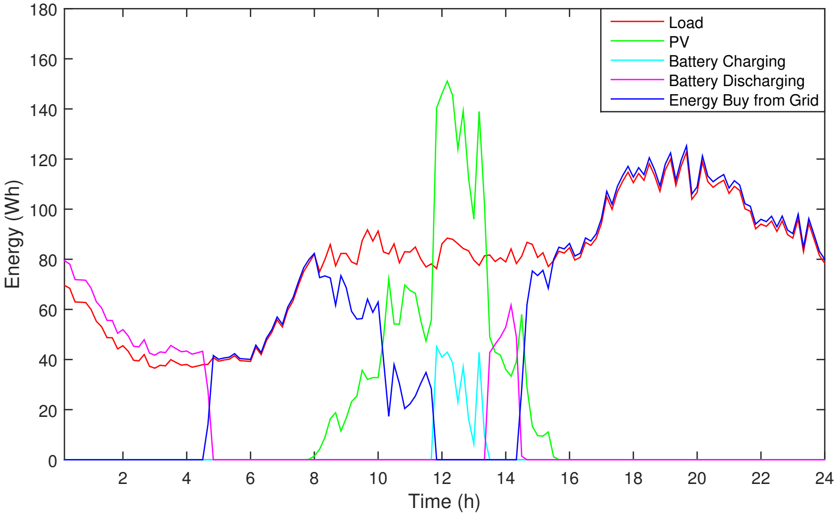


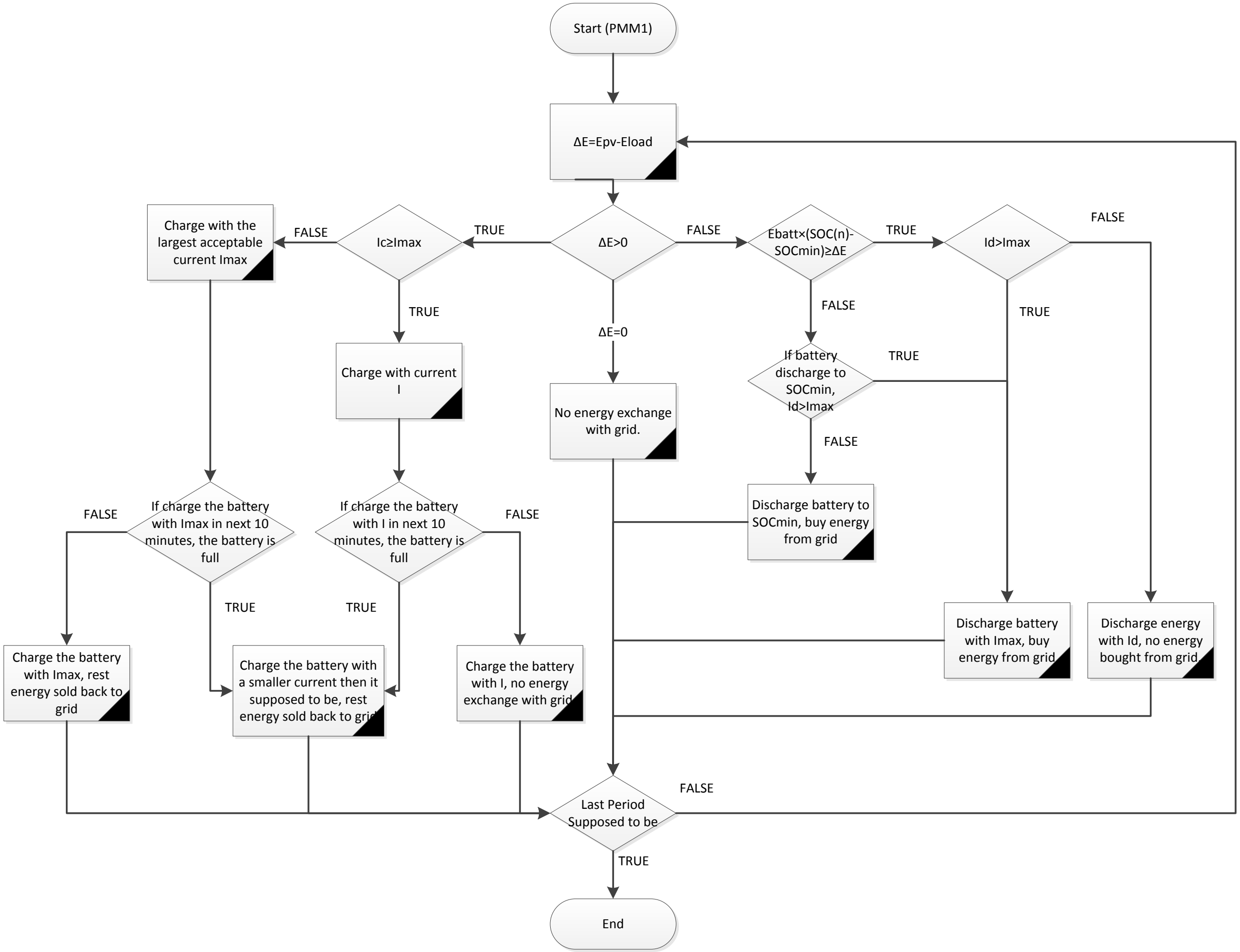
Figure 3.1: Power Management Method One

Table 3.1: Power Management Method One——Power Flow

Time	PV Power Flow	Load Power Flow	Battery Power Flow	Grid Power Flow
00:00-24:00	(1) Satisfy the Load; (2) Charge the Battery; (3) Sold to Grid;	(1)Consuming PV generation; (2)Discharge the Battery; (3) Buy from Grid;	Battery Charging: PV; Battery Discharging: Load	Power Accepted by Grid: PV; Power Sold by Grid: Load;

Table 3.2: The Largest Acceptable Current for Different Battery Size

Battery Size [1]	Battery Lowest Energy	Battery Highest Energy	Battery Usable Energy	The Largest Acceptable Current
0.125 Battery	20.39625 Wh	387.52875 Wh	367.1325 Wh	3.9375 A
0.25 Battery	40.7925 Wh	775.0575 Wh	734.265 Wh	7.875 A
0.375 Battery	61.18875 Wh	1162.58625 Wh	1101.3975 Wh	11.8125 A
0.5 Battery	81.585 Wh	1550.115 Wh	1485.53 Wh	15.75 A
0.75 Battery	122.3775 Wh	2325.1725 Wh	2202.795 Wh	23.625 A
1 Battery	163.17 Wh	3100.23 Wh	2937.06 Wh	31.5 A
1.5 Battery	244.755 Wh	4650.345 Wh	4405.59 Wh	47.25 A
2 Battery	326.34 Wh	6200.46 Wh	5874.12 Wh	63 A
2.5 Battery	407.925 Wh	7750.575 Wh	7342.64 Wh	78.75 A
3 Battery	489.51 Wh	9300.69 Wh	8811.18 Wh	94.5 A
[1] 1 battery size means 1 RESU3.3, the total energy inside the battery is 3.3 kWh.				


Start (PMM1)
ΔE=Epv-Eload
ΔE>0
TRUE
FALSE
ΔE=0
Ic≥Imax
Charge with the largest acceptable current Imax
Charge with current I
No energy exchange with grid.
Ebatt×(SOC(n)-SOCmin)≥ΔE
Id>Imax
If battery discharge to SOCmin, Id>Imax
Discharge battery to SOCmin, buy energy from grid
Discharge battery with Imax, buy energy from grid
Discharge energy with Id, no energy bought from grid
If charge the battery with Imax in next 10 minutes, the battery is full
If charge the battery with I in next 10 minutes, the battery is full
Charge the battery with Imax, rest energy sold back to grid
Charge the battery with a smaller current then it supposed to be, rest energy sold back to grid
Charge the battery with I, no energy exchange with grid
Last Period Supposed to be
End

3.2.2. POWER MANAGEMENT METHOD TWO

THE second power management method is called “Daytime” and referred to as PMM2. In this power management method, there are two different electricity price periods, which are referred to as off-peak period and peak period, respectively. The electricity buy-in price for peak-hour is higher than the price for off-peak-hour.

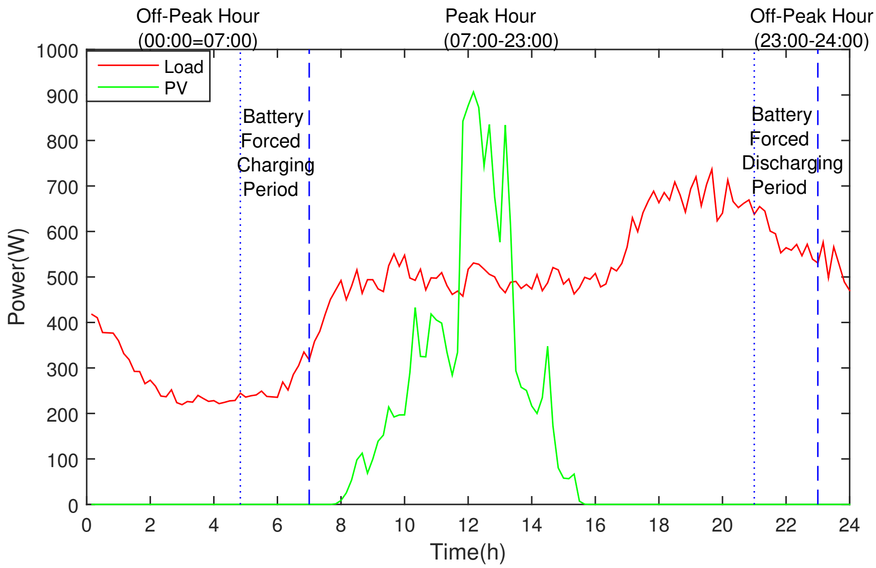


Figure 3.3: Power Management Method Two

Due to the different electricity buy-in price in different periods, the idea of this power management method is to try to consume less energy from the grid during peak-hour to lower the money spending on buying energy with the high price and sell as much energy as possible back to the grid during peak-hour to gain the maximum profit. In order to achieve this, the battery is always forced to fully charged before the peak-hour starts and forced to totally discharged at the end of peak-hour. In Figure 3.3, there is a time span called the battery forced charging period right before the peak-hour begins, and there is a time span called the battery forced discharging period right before the peak-hour ends.

In [63], due to the electrochemistry reaction, the battery SOC is estimated by taking the heating effect into consideration. The way [63] uses to handle the losses can also be used to handle the battery charging loss or battery discharging loss during the battery forced charging period and the battery forced discharging period. In this way, the time spans of battery forced charging period and battery forced discharging period can be calculated with different battery sizes by the following equation:

$$N_C = \frac{E_B \times (SOC_u - SOC_l)}{V_B \times I_{max} \times \eta_{BC}} \tag{3.1}$$

$$N_D = \frac{E_B \times (SOC_u - SOC_l)}{V_B \times I_{max} \div \eta_{BD}} \tag{3.2}$$

where:
N_C is the forced charging time span length;
N_D is the forced discharging time span length;
E_B is the usable energy stored in battery when the battery is full;
SOC_u is the upper SOC limit, which is 95%;
SOC_l is the lower SOC limit, which is 5%;
V_B is the battery voltage;
I_{max} is the largest acceptable current; the largest acceptable current means the C-rate is 0.5; it is also assumed that for a fixed battery size, during charging and discharging process, the largest acceptable current are equal to each other;
η_{BC} is the battery charging efficiency, which equals to 97%;
η_{BD} is the battery discharging efficiency, which equals to 97%.

The relationship of battery C-rate and battery current can be calculated with Equation .

$$C - rate = \frac{I}{C_{battery}} \tag{3.3}$$

Where:
I is the battery current, which could be the charging current or the discharging current, the unit is A;
$C_{battery}$ is the capacity of battery, with the unit Ah.

For different battery sizes, the largest acceptable current for battery charging and discharging process is different. Along with the usabel energy in the battery, the largest acceptable current with different battery sizes is shown in Table 3.2.

With different battery sizes and different SOC limits, different amount of energy is charged into the battery before peak-hour starts and discharged from the battery at the end of peak-hour. Three important assumptions about battery charging and discharging are made:

1. Always assume the maximum acceptable C-rate during charging and discharging process is always 0.5 for the entire simulation period, which equals to 31.5A for RESU3.3;
2. The upper SOC limit of the battery is 95%, while the lower limit of the battery is 5%;
3. The battery charging efficiency is equal to battery discharging efficiency, both are equal to 97%.

During off-peak period, the PV production is always used to satisfy the load consumption first, and then if there is some excess energy, the battery will be charged with the excess energy; then the surplus energy will be sold back to the grid. It should be careful that if there is excess energy after supplying the load, and if the prosumer want to charge the battery, the following cases could happen:

1. If the prosumer want to charge all the excess energy into battery, the battery charging current I_c will be larger than the largest acceptable current I_{max}; then the consumers can only use the largest acceptable current I_{max} to charge the battery in the following 10 minutes; in this case, there will be some energy left after charging battery, and this amount of energy will be sold back to grid;
   (a) If the prosumer charge the battery with current I_{max} for 10 minutes, the battery SOC will surpass the upper SOC limit, which is unacceptable; in this case, the real battery charging current I_{rc} is smaller than I_{max}, more energy is left than expecting after charging battery, and this amount of energy will be sold back to grid; the battery is fully charged at the end of this period;
   (b) If the prosumer charge the battery with current I_{max} for 10 minutes, the battery SOC is still lower than the upper SOC limit; in this case, the real battery charging current I_{rc} is equal to I_{max}, the rest amount of energy is sold back to grid; the battery is not fully charged at the end of this period;
2. If the prosumer want to charge all the excess energy into the battery, the battery charging current I_c is smaller than the largest acceptable current I_{max}; then the consumers can use current I_c to charge the battery in the following 10 minutes; in this case, all the excess energy could be charged into battery in theory;
   (a) If the prosumer charge the battery with current I_c for 10 minutes, the battery SOC will surpass the upper SOC limit, which is unacceptable; in this case, the real battery charging current I_{rc} is smaller than I_c, there will be some energy left to be sold back to grid; the battery is fully charged at the end of this period;
   (b) If the prosumer charge the battery with current I_c for 10 minutes, the battery SOC is still lower than the upper SOC limit; in this case, the real battery charging current I_{rc} is equal to I_c, all the excess energy is charged into battery and the prosumer do not sell any energy back to grid; the battery is not fully charged at the end of this period;

From load side, loads always consume the energy directly from PV panels' production first, if it's not enough, then the battery will be discharged and providing energy to loads; if the battery is not enough to satisfy the loads, the rest part of the energy will be bought directly from the grid. It should be careful that if there is not enough energy from PV panels' production, and if the prosumer want to discharge the battery, the following cases could happen:

1. If the prosumer want to discharge the battery to satisfy the load and the energy stored in the battery is more than the energy required by the load, then, in theory, the battery can fully satisfy the load requirement and the prosumer do not need to purchase energy from the grid to support the load;

(a) If all the rest load requirement is satisfied by battery discharging, then the discharging current I_d will exceed the largest acceptable current I_{max}; in this case, the battery can only be discharged with the largest acceptable current I_{max}, leading to only part of load requirement can be supported by battery, the rest will be satisfied with the energy bought directly from grid; there is still some energy stored in the battery at the end of this period;

(b) If all the rest load requirement is satisfied by battery discharging, a discharging current I_d that does not exceed the largest acceptable current I_{max} is needed; in this case, the battery will be discharged with this current I_d and the battery can fully satisfy all the rest of load requirement, prosumer do not need to buy any energy from grid; there is still some energy stored in the battery at the end of this period;

2. If the consumers want to discharge the battery to satisfy the load, however, the energy stored in the battery is already less than the energy required by the load, then the battery cannot fully satisfy the load and the consumers need to purchase some extra energy from the grid to support the rest of load;

   (a) If the battery is totally discharged, the discharging current I_d will exceed the largest acceptable current I_{max}; in this case, the battery can only be discharged with the largest acceptable current I_{max}; under such circumstance, the battery can only support part of load requirement and more energy needed to be bought directly from grid to satisfy the rest of energy gap; the battery is not fully discharged at the end of this period;

   (b) If the battery is totally discharged, the discharging current I_d does not exceed the largest acceptable current I_{max}, then the battery can be discharged with this current I_d; in this case, the battery can only support part of load requirement, the rest of energy gap has to be supported with the energy directly bought from grid; the battery is totally discharged at the end of this period;

From battery side, outside the battery forced charging time span, the battery is charged whenever there is excess energy from PV panels' production; since the prosumer do not know what the PV panels' production and the load consumption are in the coming periods, the idea is always assume the best cases will happen, which means the prosumer can not only fully satisfied themselves with their own PV panels' production, but also will have some excess energy left to be sold back to grid to gain some profit. So that as long as the forced charging period does not come, the battery will not be charged with energy bought from the grid. The same happens for battery discharging process, outside the forced discharging time span, the only unit that uses the battery energy is loads. The battery will not be discharged to sell energy back to the grid because of the unknown future, and the best way is to keep as much energy as possible in the battery for future use. So that the grid only sells energy to load and the only energy source for grid energy acceptance is PV panels during this off-peak period.

However, in order to lower the energy bill and gain more profits for consumers, people would like to buy more energy with lower electricity price, buy less energy with higher electricity price, while at the same time, sell more energy back to grid during the high electricity price period to get more compensation from energy companies. The idea is that to make sure the battery is always fully charged ($SOC = 95\%$) before the peak period comes, and the battery is always totally discharged ($SOC = 5\%$) at the end of the peak period. Thus, here comes the forced charging period and forced discharging period. The lengths of these two time periods are calculated with Equation 3.1 and Equation 3.2. The definition of the length of forced charging period is that if the battery is empty at the beginning, then with the largest acceptable current I_{max}, the battery needs a certain time span to charge the battery to full, this very time span during charging process is called the forced charging period. In other words, if the battery starts from the lowest acceptable SOC state $SOC_{min}(n)$ at the beginning, then the battery can definitely be fully charged within this forced charging period, even though no energy will be charged into the battery from PV panels' production. The idea is during this compulsory charging period, there is a minimum SOC lower limit every 10 minutes, which is called the lowest acceptable SOC limits for the very period, for different period, this lowest acceptable SOC limits varied; these values are pre-calculated values related to battery size and increase as time closer to the beginning of peak-hour; the important assumption used to determine these values is that if the battery reach the lowest acceptable SOC value for the very period, than the battery can be charged to full during the rest forced charging periods if the charging rate is always the maximum C-rate and the battery won't be discharged during the rest periods; so that if the battery cannot reach this lowest acceptable SOC limits with PV panels as the only source, then the battery should buy some energy from grid to reach this SOC limits value; the battery forced charging time is approximately 111 minutes and 18 seconds. In a similar way, if the battery is fully charged at the beginning, then with the largest acceptable current I_{max}, the battery needs a certain time span to be totally discharged, this very time span during the discharging process is called the forced discharging period. That means even if the battery has the highest acceptable SOC state $SOC_{max}(n)$ at the beginning, the battery can definitely be totally discharged within this forced discharging period, even if during the whole forced discharging period, no energy is discharged from the battery to support the load. The idea is during this compulsory discharging period, there is a maximum SOC lower limit every 10 minutes, which is called the highest acceptable SOC limits for the very period, like the lowest acceptable SOC limits for charging period, for different period, this highest acceptable SOC limits varied; the closer the time to the end of base-peak-hour, the smaller the values be; these values are pre-calculated values related to battery size and decrease as time closer to the end of peak-hour; the important assumption used to determine these values is that if the battery reach the highest acceptable SOC value for the very period, than the battery can be totally discharged during the rest forced discharging periods if the discharging rate is always the maximum C-rate and the battery won't be charged during the rest periods; so that if the battery cannot reach this highest acceptable SOC limits with loads as the only consumption unit, then the battery should sell some energy back to grid to reach this SOC limits value; the battery discharge time is approximately 104 minutes and 45.6 seconds. The SOC state must be checked every 10 minutes to see whether the real-time battery SOC state has reached the acceptable value or not. Based on this real-time SOC value, the system will automatically decide what amount of energy needed to be charged into the battery or discharged from the battery in the next period.

During the forced charging period, because of the concept that the consumers always want to buy less energy from the grid and be more self-sufficient during the entire year, it could happen that the battery can still be discharged to provide some energy to loads. Whether to discharge the battery or not is decided with the real-time SOC state together with the following methods:

1. If the real-time SOC state $SOC_r(n)$ at this period is already higher than the lowest acceptable SOC limit $SOC_{min}(n)$ for this moment, than the battery will not need to be charged for this moment; plus, if the PV panels' production is not enough to support all the load requirement, the battery can even discharge some energy and try it best to narrow the energy gap; what amount of energy could be discharged depends on whether the discharge current is acceptable or not; again, it could have the following cases:

    (a) If the battery discharged to the lowest acceptable SOC limit for this moment, the energy released from battery could satisfy the rest of load requirement in theory; then, in theory, the consumers do not need to buy any energy from grid to support the load and the battery would be enough for the rest of load consumption;

        i. If the discharging current I_d exceeds the largest acceptable current I_{max}, then the battery can only be discharged with the largest acceptable current I_{max}; in this case, the consumers need some extra energy from grid to satisfy the rest of load requirements; after discharging process, the battery SOC will still be higher than the lowest acceptable SOC limit for this moment;

        ii. If the discharging current I_d does not exceed the largest acceptable current I_{max}, then the battery will discharge with this current I_d; in this case, the energy from battery discharging can already fill all the energy gap from load side, the consumers do not need to buy any energy from grid; after discharging process, the energy SOC will not fall below the lowest acceptable SOC limit for this moment

    (b) If the battery discharged to the lowest acceptable SOC limit for this moment, the energy released from battery still cannot satisfy the rest of load requirement; then the prosumer definitely need to buy some energy from the grid to support the rest of load consumption;

        i. If the battery discharged to the lowest acceptable SOC limit of this moment, the discharging current I_d will exceed the largest acceptable current I_{max}, then the battery can only discharge with the largest acceptable current I_{max}; in this case, the prosumer need to buy more energy from grid than expected to satisfy the rest of load requirements; after discharging process, the energy SOC will still be higher than the lowest acceptable SOC limit for this moment;

        ii. If the discharging current I_d does not exceed the largest acceptable current I_{max}, then the battery will discharge with this current I_d; in this case, the battery will be discharged to the lowest acceptable SOC limit for this moment and the prosumer still need to buy some extra energy from grid; after battery discharging, the battery SOC will reach the lowest acceptable SOC limit for this moment;

2. If the real-time SOC state $SOC_r(n)$ is still below the lowest acceptable SOC limit $SOC_{min}(n)$ for this moment, then the battery will need to be forced to charge to the lowest acceptable SOC limit $SOC_{min}(n)$ for this moment; the charging current will never exceed the largest acceptable current I_{max}; the exactly charging current depends on the battery SOC state at the end of last time period; if at the end of last period, the battery SOC state $SOC_r(n-1)$ equals to the lowest acceptable SOC limit $SOC_{min}(n-1)$ for last period, and during this period, no energy is charged into battery from PV panels' production, then during this charging period, the forced charging current I_c equals to the largest acceptable current I_{max}; however, if during this period, after battery charging with energy from PV panels' production, the battery SOC state $SOC_r^{'}(n)$ is higher than the lowest acceptable SOC limit $SOC_{min}(n-1)$ for last period, then at this moment, the forced charging current I_c will be smaller than the largest acceptable current I_{max}. Another limit of battery charging process is that if the battery needs to be forced to charge, then after charging, the real-time battery SOC state will be the lowest acceptable SOC limit $SOC_{min}(n)$ for this moment, which means even if the charging current is acceptable, it is not suggested to charge the battery to reach a higher SOC state that exceeds the lowest acceptable SOC state $SOC_{min}(n)$ for that moment; the reason is simple, it is because no one knows what will happen in the next moment, there is always a chance that during next period, the PV panels can provide some extra energy to charge the battery, in the spirit of saving money and building a more self-sufficient system, the consumers do not need to take the chance to buy more energy in this period; of course what could also happen is that the battery SOC state $SOC_r(n)$ is already higher than the lowest acceptable SOC limit $SOC_{min}(n)$ of this moment, then just leave the battery at the state as it is and nothing needs to be done.

From Table 3.2, it can be found that for 1 battery size (1 RESU3.3), the battery forced charging period consists of 12 time slots, which means for the Netherlands case, the forced discharging period is 120 minutes. It should be clear that the calculation result shows that the accurate charging time is 111 minutes 18 seconds, but since everything is measured every 10 minutes, the forced charging period should include 12 time slots. Usually, during battery forced charging period, the charging currents during each time slot are not always the same, it depends on the difference between battery SOC state from last period and the lowest acceptable SOC state of this period. Based on the this difference, the system can automatically decide the charging current during the very period. If at the beginning of the battery forced charging period, the battery SOC state is the lowest SOC state, which can be considered the battery is empty and cannot provide any energy. Then in theory, if during the rest period of the battery forced charging period, the battery is charged with the largest C-rate, then during the first period of the battery forced charging period, the C-rate does not need to be the largest C-rate, actually, according to the calculation results, during the first period, the C-rate is 0.065, in this way, it could make sure the energy bought from the grid to charge the battery is the lowest, while the system can achieve higher autarky degree.

From grid side, during the off-peak period, the grid can only sell energy to support the loads, no any will be used to charge the battery. However, when the forced charging period comes, the grid can sell energy to charge the battery if the PV panels' production is not enough. The only energy source that could sell energy back to the grid during off-peak period is PV panels, the battery will never be discharged to sell energy back to the grid during this period.

During the peak period, in order to gain maximum profit based on the high tariff, the idea is to minimize the amount of energy buying from the grid and maximize the energy sold to the grid, in this way, there are some differences of power flow patterns between peak-hour with off-peak-hour.

The PV panel's production is always used to satisfy the load consumption first, and then if there is some extra energy, it will be sold back to grid directly, which means during the peak-hour the battery will not be charged with energy from PV panels' production.

While from the load side, the loads will be firstly supported by PV panels' production and then by battery discharging; if it is still not enough for loads, then the prosumer have to buy energy from the grid to compensate the energy gap. Whether the battery is enough for load or not is decided by several factors, based on different conditions, the following cases could happen, and this is very similar to the cases during the off-peak-hour:

1. If the energy stored in the battery is more than the energy required by the load, then, in theory, the battery can fully satisfy the load and the consumers do not need to purchase energy from the grid to support the load;
   (a) If the battery discharging current I_d surpasses the largest acceptable current I_{max}, the battery can be discharged only with the largest acceptable current I_{max}; in this case, the battery can only support part of load requirement, the rest will be satisfied with the energy bought directly from the grid;
   (b) If the battery discharging current I_d does not exceed the largest acceptable current I_{max}, then the battery will discharge with this current I_d; in this case, the battery can fully satisfy all the rest of load requirement, consumers do not need to buy any energy from the grid;
2. If the energy stored in battery is not enough to satisfy all the load demand, then the battery cannot fully satisfy the load and the consumers need to purchase extra energy from grid to support the rest of load; how much energy needs to be bought from grid depends on whether the discharging current is acceptable or not;
   (a) If the battery is totally discharged, the discharging current I_d will exceed the largest acceptable current I_{max}, then the battery can be discharged only with the largest acceptable current I_{max}; in this case, the battery can only support part of load requirement and more energy than expected needed to be bought directly from grid to satisfy the rest of energy gap; the battery is not fully discharged at the end of this period;

(b) If the battery is totally discharged, the discharging current I_d does not exceed the largest acceptable current I_{max}, then the battery can be discharged with this current I_d; in this case, the battery can only support part of load requirement, the rest of energy gap has to be supported with the energy directly bought from grid; the battery is fully discharged at the end this period;

From battery side, the battery will not be charged by either the PV panels or grid during the whole peak period. This is because the total electricity demanded during peak-hour is higher, which leads to a higher retail electricity price. Some energy companies say that if consumers sell energy back to the grid during this period, they could enjoy a higher feed-in tariff. So that if the consumers buy less energy during peak-hour, and at the same time, sell more energy back to the grid during peak-hour, they can have a lower energy bill. That is the reason why the excess energy is sold back to the grid instead of charging the battery. However, not all the energy companies design the feed-in tariff as described above, they choose to compare the total energy bought from grid and sold back to grid for the entire year, if consumers buy more energy than they sell, then they will enjoy a high feed-in tariff for all the energy they sell back to grid; but if they sell more energy back to the grid than they buy, then the excess part will only be compensated with a low feed-in tariff. If the feed-in tariff is designed in this way, of course there is no reason to try to sell more energy back to the grid during the peak-time, but in accordance with the principle of simplifying and unifying, it is still assumed that the consumers should try to sell more energy back to the grid during peak-hour. For the battery discharging process, the energy from battery discharging can be used to support the load if the PV production is not enough. For the most time of peak-hour, the battery only provides energy to grid and not sells energy back to the grid, and this is because of the idea to always save more energy in battery for later use during base-peak-hour, However, before the ends of peak-hour, there is a time span called the battery forced discharging period. During this battery forced discharging period, there is a chance the battery may sell some energy back to the grid to gain some profit. The exact amount of energy that been sold back to grid depends on two factors, namely, the highest acceptable SOC state $SOC_{max}(n)$ for that moment and the largest acceptable discharging current I_{max}. Based on these two factors, the following cases could happen:

1. If after discharging to support the load, the battery SOC state $SOC_r(n)$ is still higher than the highest acceptable SOC limit $SOC_{max}(n)$ for this moment, the battery needs to be forced to discharge to the highest acceptable SOC limit $SOC_{max}(n)$ for this moment; this part of energy will be sold back to grid to gain some profit; there is no need to worry about whether the total discharging current (the current to load side + the current to grid side) is acceptable or not, this is because if the battery discharges from the previous highest acceptable SOC limit $SOC_{max}(n-1)$ to the present highest acceptable SOC limit $SOC_{max}(n)$, the current will be the largest acceptable discharging current I_{max}; in other words, as long as the battery SOC state does not fall below the highest acceptable SOC limit $SOC_{max}(n)$ for this moment, the discharging current will not exceed the largest acceptable discharging current I_{max};

2. If after discharging to support the load, the battery SOC state $SOC_r(n)$ is already

lower than the highest acceptable SOC limit $SOC_{max}(n)$ for this moment, than the battery will not need to be forced to discharge during this very time slot;

From Table 3.2, it can be found that for 1 battery size (1 RESU3.3), the battery forced discharging period consists of 12 time slots, to be exactly, it is 104 minutes and 45.6 seconds. Which means if the battery is full at the beginning of the battery forced discharging period and during the whole battery forced discharging period, no energy is required by load, the ideal case is that for the first 10 minutes of the battery forced discharging period, the discharging current is the smallest current during the whole forced discharging process, which is smaller than I_{max}; then the battery will be discharged with the largest C-rate during the rest time slots.

For the grid side, the energy accepted by grid can come from PV panels' production, and may also come from the battery during the compulsory discharging period; while the energy sold by grid are always used to support the load during the whole peak period. No energy is bought from the grid to charge the battery during peak-hour.

The detail power flow information can also be found from Table 3.3. Flow Chart 3.5 shows the power flow during off-peak hour before the battery forced charging period starts. Flow chart 3.6 shows the power flow during the battery forced charging period. Flow chart 3.7 shows the power flow during the peak-hour before the battery forced discharging period starts. Flow chart 3.8 shows the power flow during the battery forced discharging period.

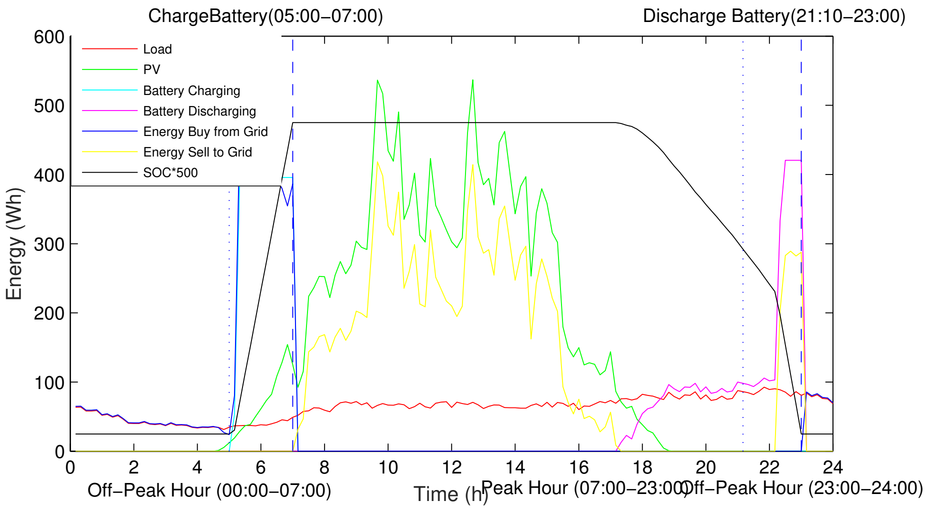


Figure 3.4: Power Flow of Power Management Two (April 28th)

Figure 3.4 shows the power flow for PMM2 on a random day (April 28th). The cyan lines shows how the battery is charged during the battery forced charged period, while the pink line shows how the battery is discharged during the battery forced discharging period.

Table 3.3: Power Management Method Two——Power Flow

Time		PV Power Flow	Load Power Flow	Battery Power Flow	Grid Power Flow
00:00 – 07:00 (Off-Peak-Hour)	00:00-05:00	(1) Satisfy the Load; (2) Charge the Battery; (3) Sold to Grid.	(1) Consuming PV generation; (2) Discharge the Battery; (3) Buy from Grid.	Battery Charging: PV; Battery Discharging: Load.	Power Accepted by Grid: PV; Power Sold by Grid: Load.
	05:00-07:00 (Battery Forced Charging Period)	(1) Satisfy the Load; (2) Charge the Battery; (3) Sold to Grid.	(1) Consuming PV generation; (2) Discharge the Battery; (3) Buy from Grid.	Battery Charging: (1)PV (2)Grid; Battery Discharging: Load.	Power Accepted by Grid: PV; Power Sold by Grid: Load + Battery.
07:00 – 23:00 (Peak-Hour)	07:00-21:10	(1) Satisfy the Load; (2) Sold to Grid.	(1) Consuming PV generation; (2) Discharge the Battery; (3) Buy from Grid.	Battery Charging: None; Battery Discharging: Load.	Power Accepted: PV; Power Sold: Load.
	21:10-23:00 (Battery Forced Discharging Period)	(1) Satisfy the Load; (2) Sold to Grid.	(1) Consuming PV generation; (2) Discharge the Battery; (3) Buy from Grid.	Battery Charging: None; Battery Discharging: (1)Load (2)Grid.	Power Accepted: PV + Battery; Power Sold: Load.
23:00 – 24:00 (Off-Peak-Hour)		(1) Satisfy the Load; (2) Charge the Battery; (3) Sold to Grid.	(1) Consuming PV generation; (2) Discharge the Battery; (3) Buy from Grid.	Battery Charging: (1)PV (2)Grid; Battery Discharging: Load.	Power Accepted: PV; Power Sold: Load + Battery.

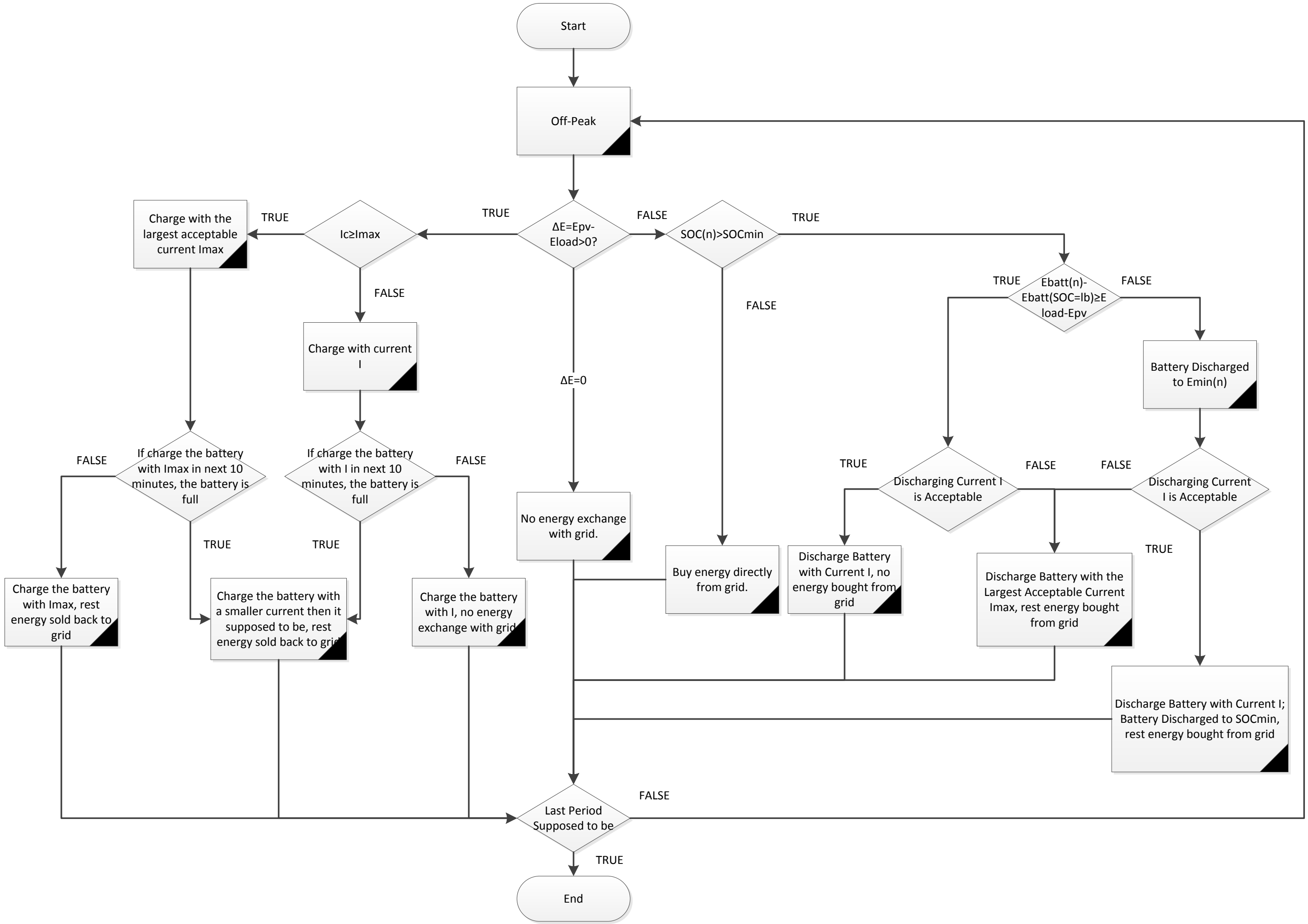


Figure 3.5: Power Flow for PMM2 and PMM3 During Off-Peak-Hour (Before the Battery Forced Charging Period Starts)

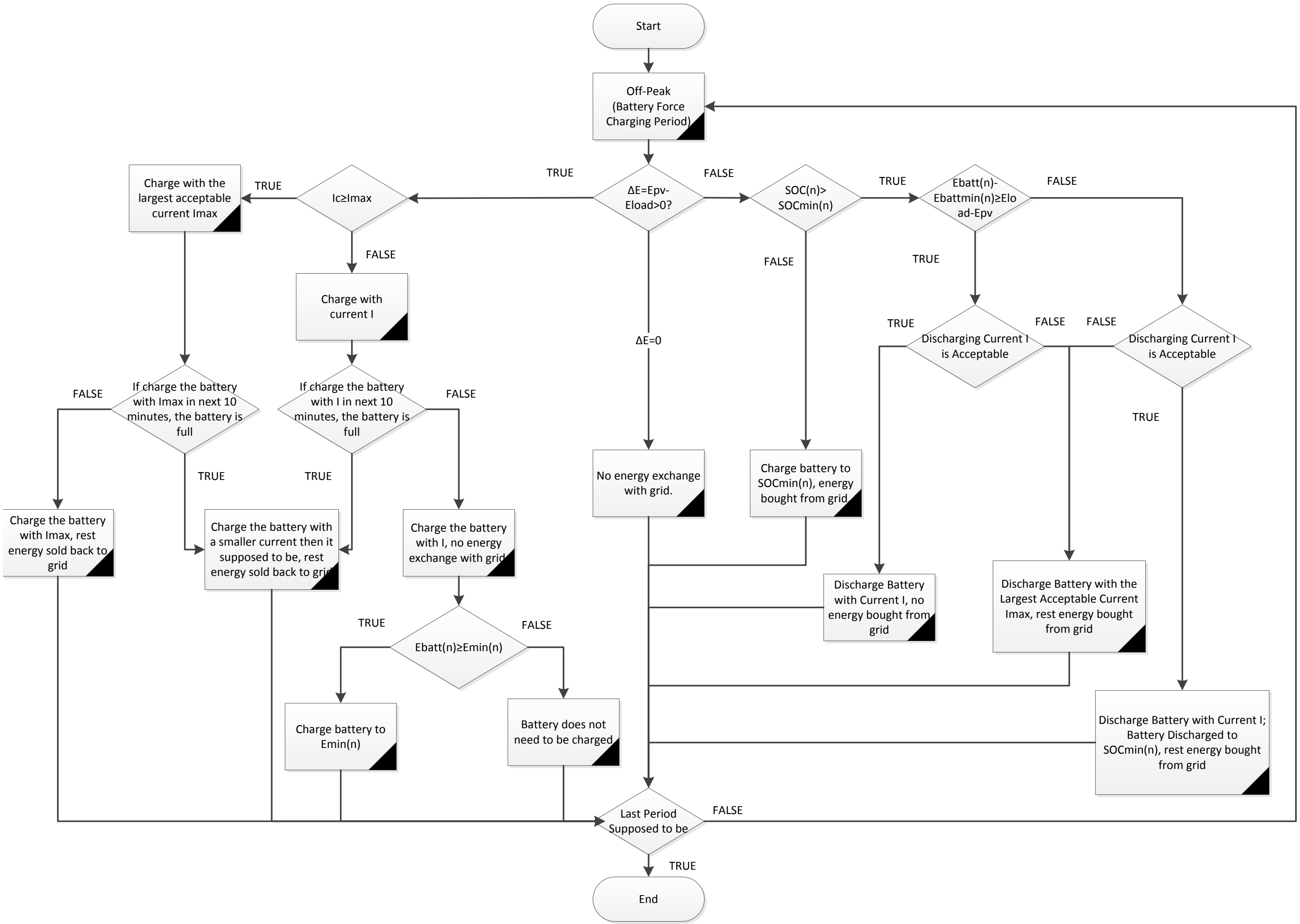


Figure 3.6: Power Flow for PMM2 and PMM3 During the Battery Forced Charging Period

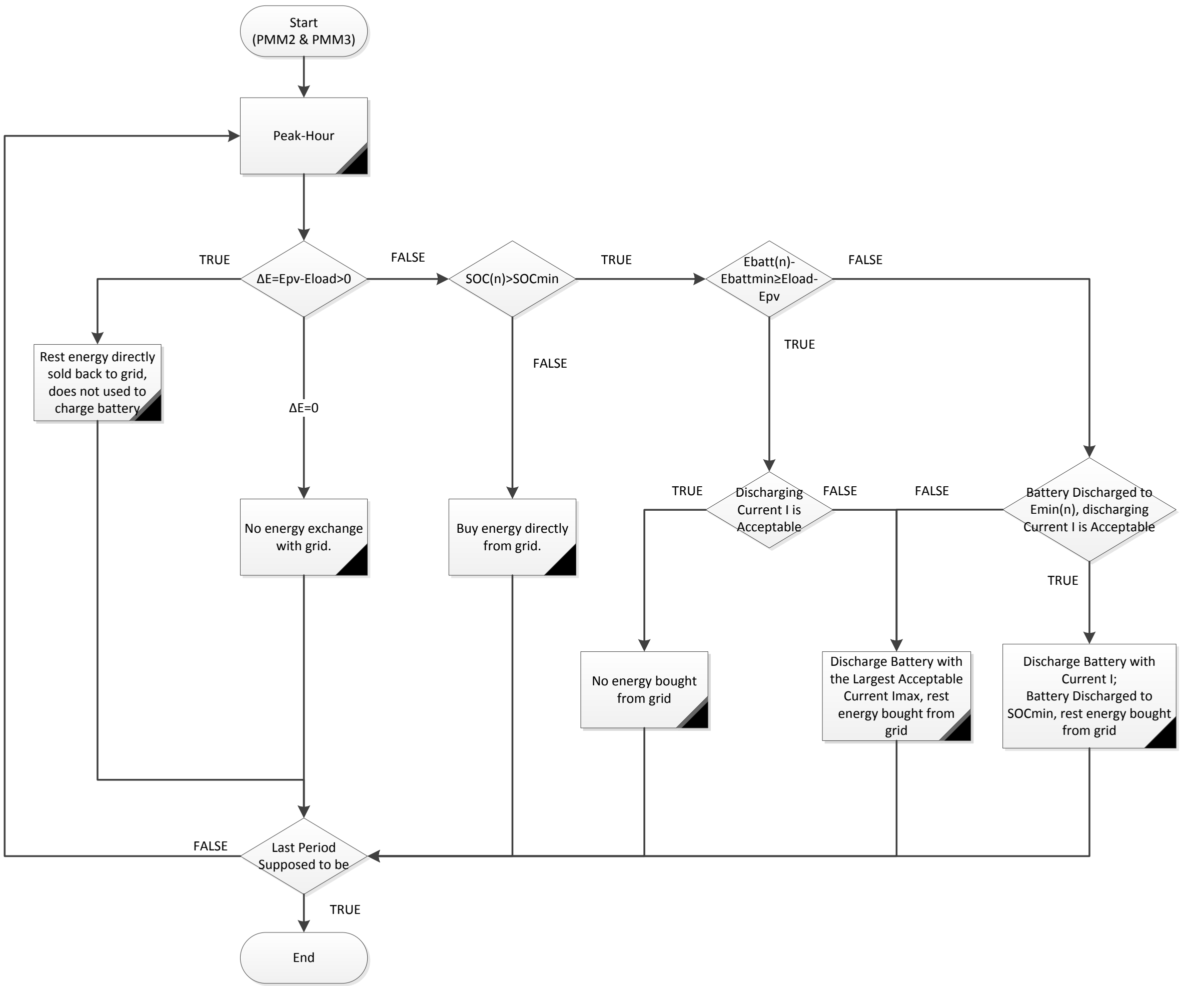


Figure 3.7: Power Flow for PMM2 and PMM3 During Peak-Hour (Before the Battery Forced Discharging Period Starts)

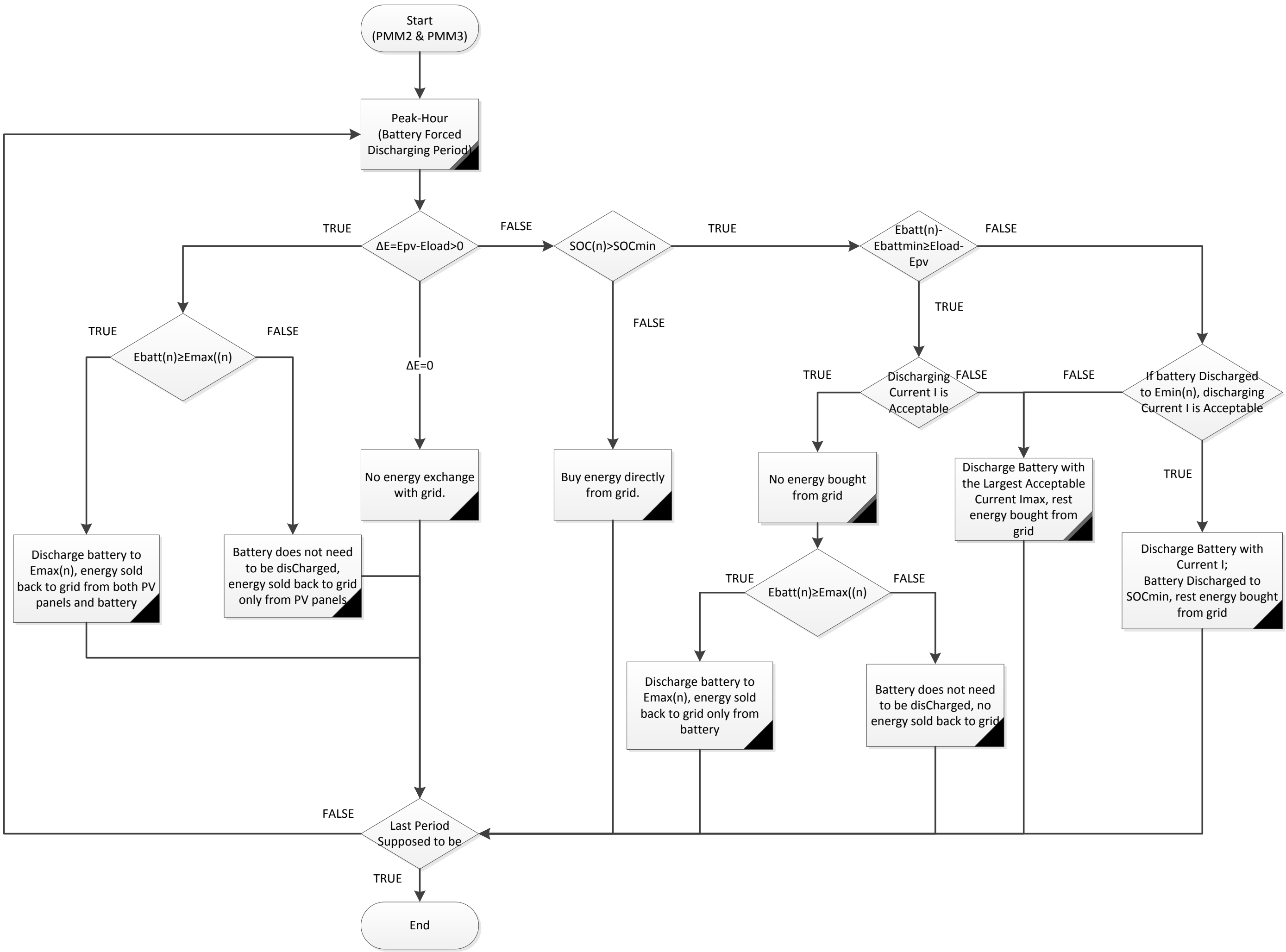


Figure 3.8: Power Flow for PMM2 and PMM3 During Battery Forced Discharging Period

3.2.3. POWER MANAGEMENT METHOD THREE

THIS power management method is called Time of Use (ToU) and referred as PMM3. ToU is a very popular PMM that used by a lot of energy providers. This PMM is very similar to PMM2, the only difference is the length of peak-hour. Compared with PMM2, the length of peak-hour is shorter for PMM3. This shorter peak-hour usually connects with a higher electricity buy-in price. For the Netherlands, the peak-hour definition is shown in Table 4.2. For Costa Rica, the peak-hour definition from CNFL with TOU-D-A type can be found in Table 4.8. For California, the peak-hour definition from South California EDISON is listed in Table 4.9.

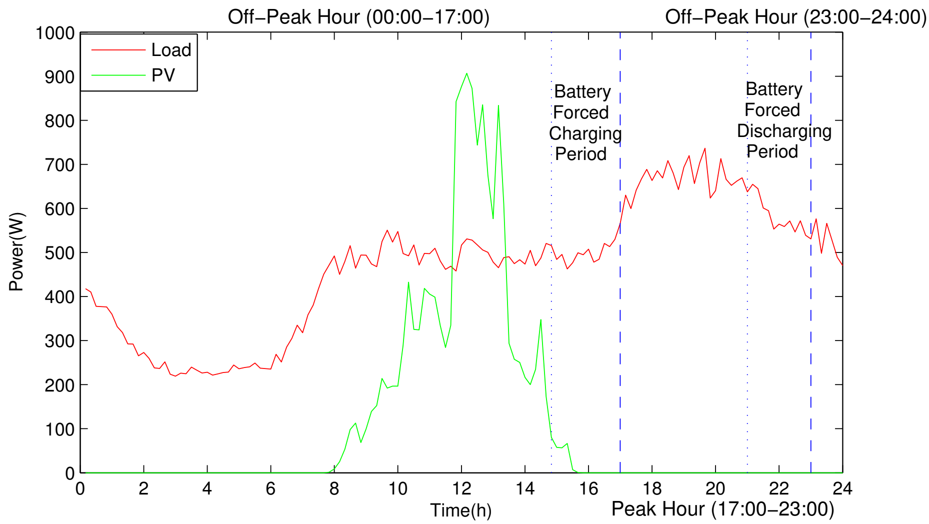


Figure 3.9: Power Management Method Three

Besides the definition of peak-hour, the basic idea to manage the power flow is the same with PMM2, so that instead of describing every detail of power flow, only some important power flow patterns are mentioned here, the rest of details can be found in the last subsection used to describe PMM2. The detail power flow of PMM3 can be found in Table 3.4. The power flow chart is the same as the PMM2 and the power flow during off-peak-hour before the battery forced charging period starts, during the battery forced charging period, during peak-hour before the battery forced discharged period, and during the battery forced discharging period can be found in Flow chart 3.5, 3.6, 3.7, and 3.8, respectively. Figure 3.9 shows the load profile and PV panels' production for a typical day to help better understand this power management method.

During the off-peak hour, PV panels' production is always used to support the load first, if there is any extra energy left after load consumption, the extra energy will be used to charge the battery; the battery should never be overcharged and the charging current should never exceed the largest acceptable current I_{max}. If there is still some energy left after battery charging, then this part of energy will be sold back to the grid to gain some profit. From load side, the load will always be supported by PV panels' production first, if PV panels' production is not enough, the battery will discharge and try to narrow the energy gap. If it is still not enough, then some energy needs to be bought from the grid to satisfy the rest of load. Before the peak-hour comes, there is also a time period called forced charging period. Inside this period, the battery SOC state is checked every 10 minutes and if the real-time battery SOC state $SOC_r(n)$ is lower than the minimum acceptable SOC value $SOC_{min}(n)$ for this moment, the battery needs to be forced to charge to this minimum acceptable SOC value $SOC_{min}(n)$. This is to make sure that at the beginning of peak-hour, the battery is fully charged. So that inside this forced charging period, there is a chance that the grid may not only sell energy to loads, but also sell energy to the battery. For the rest time that outside this forced charging period, the battery can only be charged with the energy from PV panels' production, so that from grid side, the grid can only sell energy to loads. While for battery discharging process, the battery can only be discharged to support the loads, which means no energy will be sold back to the grid through battery discharging. One thing should pay attention to is that even if during the forced charging period, the battery can still discharge to support the load, as long as the real-time battery SOC state $SOC_r(n)$ does not fall below the lowest acceptable SOC value $SOC_{min}(n)$ for that moment. It is very easy to understand that the only energy source that sells energy back to the grid during off-peak period is the PV panels.

During the peak-hour, PV panels' production is always used to support the load first, the rest will be sold directly to gird, instead of charging the battery first. From load side, the first choice is always to use the PV panels' production directly, if it is not enough, the battery will discharge as much as possible to satisfy the load, this means the battery SOC state should never fall below the lower SOC limit and the discharging current should never exceed the largest acceptable current I_{max}. If there is still some energy gap, it has to be covered with energy from the grid. At the end of peak-hour, there is a time period called forced discharging period. Inside this period, the battery SOC state is checked every 10 minutes and if the real-time battery SOC state $SOC_r(n)$ is higher than the maximum acceptable SOC value $SOC_{max}(n)$ for this moment, the battery needs to be forced to discharge to this maximum acceptable SOC value $SOC_{max}(n)$. This is to make sure that at the end of peak-hour, the battery is totally discharged. So that inside this forced discharging period, there is a chance that the battery may not only provide energy to loads, but also sell energy back to gird, making it possible for the grid to accept energy from both PV panels and battery. While if it is outside the forced discharging period, the battery can only be discharged to satisfy the load requirement; so that from grid side, the grid can only accept energy from PV panels. The battery must never be charged during the peak-hour, no matter is inside the forced discharging period or outside the forced discharging period, resulting in that during the entire peak-hour, the grid can only sell energy to support the load.

In this power management method, since the peak-hour does not overlap with all the daylight time, some energy from PV panels' production could be used to charge the battery. With a shorter and more precise period of peak-hour, the electricity tariff will be higher than the longtime off-peak-hour. Common sense is that the shorter the peak-hour lasts, the more expensive the electricity tariff will be during the peak-hour. This power management method is programmed to study what the influence will be if the peak period is shorter. It is also possible to see what the influence is if the battery has a narrower SOC range, for example, reducing from 5% – 95% to 20% – 80%.

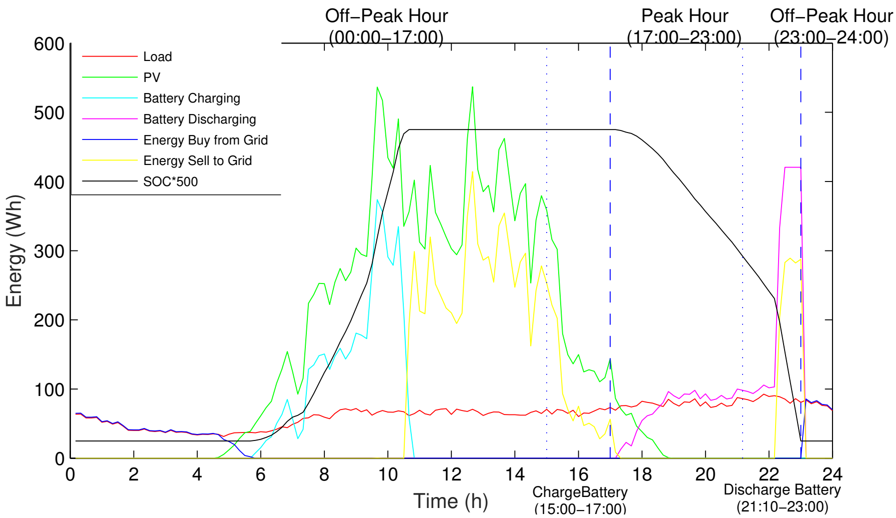


Figure 3.10: Power Flow of Power Management Three (April 28th)

Figure 3.10 shows the power flow for PMM3 on a random day (April 28th). The cyan lines shows how the battery is charged during the battery forced charged period, the battery may not be charged with the largest C-rate at the beginning of the battery forced charging period; while the pink line shows how the battery is discharged during the battery forced discharging period, the battery may not be discharged with the largest C-rate at the beginning of the battery forced discharging period, either.

Table 3.4: Power Management Method Three——Power Flow

Time		PV Power Flow	Load Power Flow	Battery Power Flow	Grid Power Flow
00:00 – 17:00 (Off-Peak-Hour)	00:00-14:50	(1) Satisfy the Load; (2) Charge the Battery; (3) Sold to Grid.	(1) Consuming PV generation; (2) Discharge the Battery; (3) Buy from Grid.	Battery Charging: PV; Battery Discharging: Load.	Power Accepted by Grid: PV; Power Sold by Grid: Load.
	14:50-17:00 (Battery Forced Charging Period)	(1) Satisfy the Load; (2) Charge the Battery; (3) Sold to Grid.	(1) Consuming PV generation; (2) Discharge the Battery; (3) Buy from Grid.	Battery Charging: (1)PV (2)Grid; Battery Discharging: Load.	Power Accepted by Grid: PV; Power Sold by Grid: Load + Battery.
17:00 – 23:00 (Peak-Hour)	17:00-21:00	(1) Satisfy the Load; (2) Sold to Grid.	(1) Consuming PV generation; (2) Discharge the Battery; (3) Buy from Grid.	Battery Charging: None; Battery Discharging: Load.	Power Accepted: PV + Battery; Power Sold: Load.
	21:00-23:00 (Battery Forced Discharging Period)	(1) Satisfy the Load; (2) Sold to Grid.	(1) Consuming PV generation; (2) Discharge the Battery; (3) Buy from Grid.	Battery Charging: None; Battery Discharging: (1)Load (2)Grid.	Power Accepted: PV + Battery; Power Sold: Load.
23:00 – 24:00 (Off-Peak-Hour)		(1) Satisfy the Load; (2) Charge the Battery; (3) Sold to Grid.	(1) Consuming PV generation; (2) Discharge the Battery; (3) Buy from Grid.	Battery Charging: (1)PV (2)Grid; Battery Discharging: Load.	Power Accepted: PV; Power Sold: Load + Battery.

3.2.4. POWER MANAGEMENT METHOD FOUR

PEAK shaving is another popular power management method in the market nowadays. The basic idea of this power management method is to use the battery to shave the load peak in order to avoid a large amount of energy imported from the grid in a short time, which could trigger a very high electricity buy-in tariff.

A predetermined reference value is settled and energy retailers try to encourage consumers to reallocate their power consumption pattern in order to avoid the peak energy requirement, which will be charged with a higher price than the normal price. Usually, a peak is considered formed when the energy requirement from grid exceeds the predetermined reference value. With the higher electricity price, energy retailers try to encourage the consumers to smooth the energy required from grid by taking some actions like using battery to supply the part of energy that surpass the predetermined reference value or remove the secondary load to low energy consumption period, which in return can reduce the total energy bill as well as smooth the load.

This power management method is also programmed and simulated with different combinations of reference values and battery sizes. Figure 3.11 shows the based idea of this power management method. The detail power flow can also be found in Table 3.5. Flow chart 3.12 shows the power flow when at AC bus side, PV panels production is higher or equal to the load consumption. Flow chart 3.13 shows the power flow when at AC bus side, PV panels production is lower than load consumption.

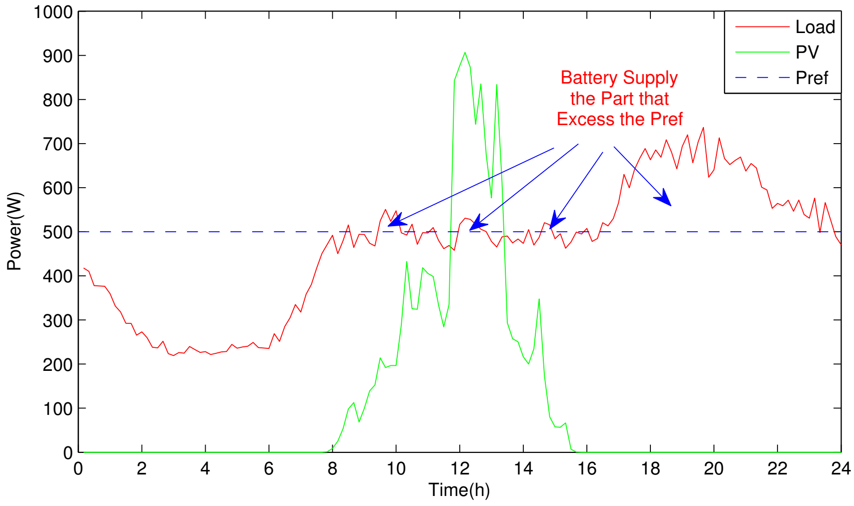


Figure 3.11: Power Management Method Four

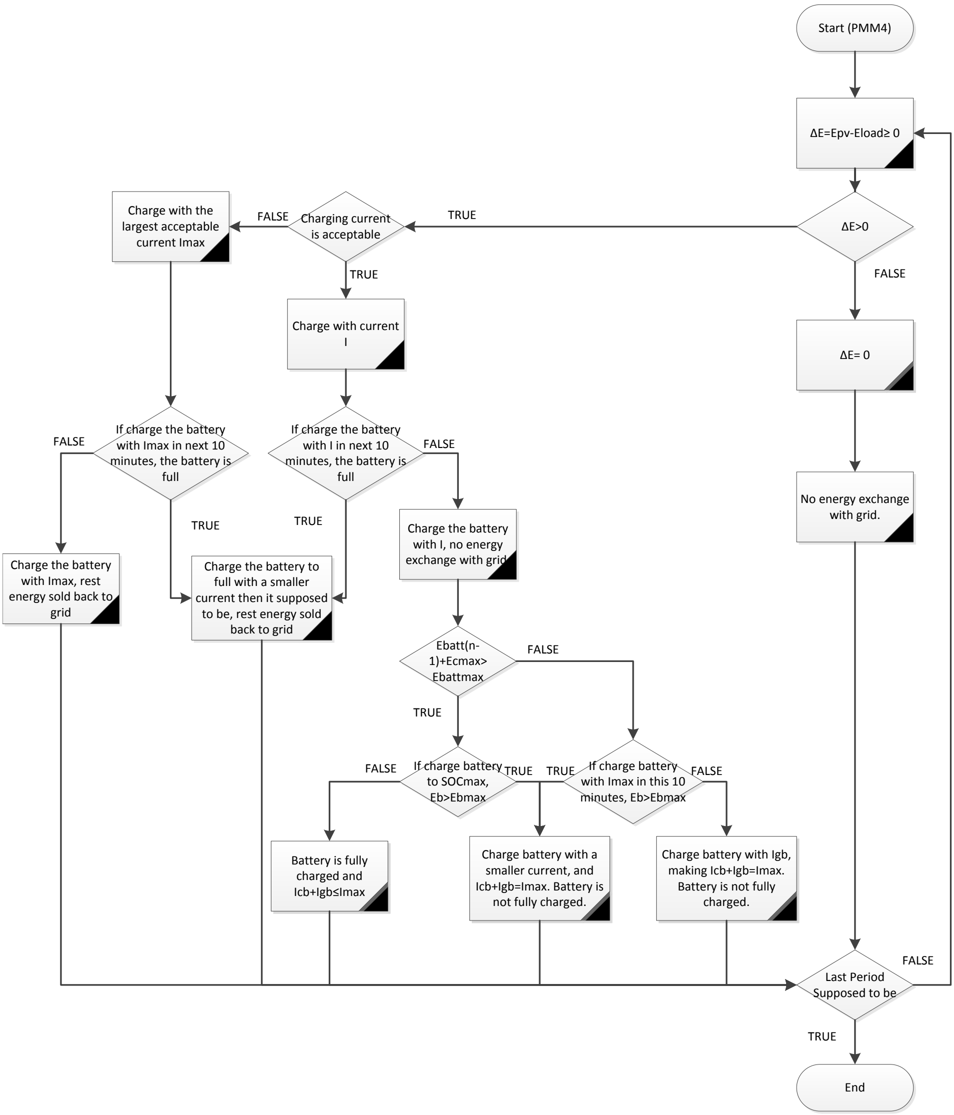


Figure 3.12: Power Flow for Power Management Method ($P_{PV} \geq P_{load}$)

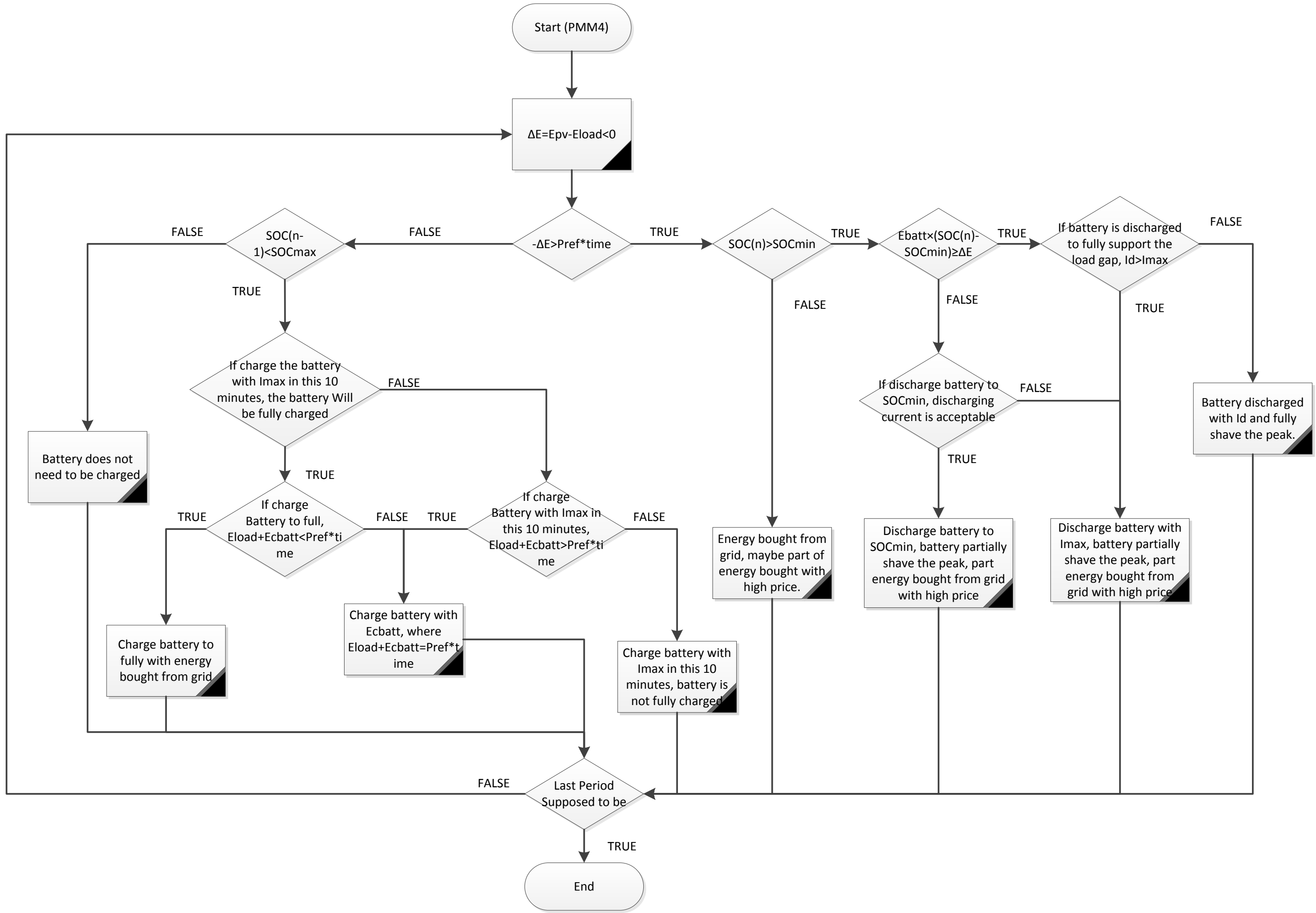


Figure 3.13: Power Flow for Power Management Method ($P_{PV} < P_{load}$)

If the PV panels' production is much enough to totally satisfy the load requirement, then the load can be fully supported and the rest energy will be used to charge the battery. After charging the battery, the rest of energy can be sold back to the grid. Again, there are several different cases as far as the battery SOC and the magnitude of the current is considered.

1. If the consumers want to charge all the excess energy into battery, the battery charging current I_c will be larger than the largest acceptable current I_{max}; then the consumers can only use the largest acceptable current I_{max} to charge the battery in the following 10 minutes; in this case, there will be some energy left after charging battery, and this amount of energy will be sold back to grid;
   (a) If the consumers charge the battery with current I_{max} for 10 minutes, the battery SOC will surpass the upper SOC limit, which is unacceptable; in this case, the real battery charging current I_{rc} is smaller than I_{max}, more energy is left than expecting after charging battery, and this amount of energy is sold back to grid; the battery is fully charged at the end of this period;
   (b) If the consumers charge the battery with current I_{max} for 10 minutes, the battery SOC is still lower than the upper SOC limit; in this case, I_{max} will be used to charge the battery in the following 10 minutes, the rest amount of energy is sold back to grid; the battery is not fully charged at the end of this period;
2. If the consumers want to charge all the energy into the battery, the battery charging current I_c will be smaller than the largest acceptable current I_{max}; then the consumers can use current I_c to charge the battery in the following 10 minutes; in this case, all the excess energy could be charged into battery in theory;
   (a) If the consumers charge the battery with current I_c for 10 minutes, the battery SOC will surpass the upper SOC limit, which is unacceptable; in this case, the real battery charging current I_{rc} is smaller than I_c, there will be some energy left to be sold back to grid; the battery is fully charged at the end of this period;
   (b) If the consumers charge the battery with current I_c for 10 minutes, the battery SOC is still lower than the upper SOC limit; in this case, the real battery charging current I_{rc} is equal to I_c, all the excess energy is charged into battery and no energy will be sold back to grid; the battery is not fully charged at the end of this period;

While from load side, the load will first be satisfied by PV panels' production, if it is not enough, then the second choice is the energy bought from the grid rather than the energy from battery discharging. The idea is that as long as the total amount of energy required from grid does not exceed the predetermined reference value, then the battery does not need to be discharged. In other words, the role of battery in this power management method is only to compensate the part of energy that exceeds the reference value. Compared with the other three power management methods, the function of the battery is limited in the fourth power management method. However, this could be considered as an advantage of peak shaving, since the smaller the battery size is, the lower the investment is at the beginning. The reference value is very important because it determines when the battery should start to work, it can indirectly decide the battery size and the high electricity price for the part that exceeds the reference value, and the usual case is that the higher the reference value is, the smaller the battery size and the higher the energy price for the part that exceeds the reference value will be. Since it is very hard the forecast the upcoming peaks, and the battery is used to compensate the unknown upcoming peaks, the battery should be better scheduled to save as much energy as possible for future use. The battery will be charged as soon as the entire energy requirement from the grid is lower than the reference value, in other words, the battery will be charged as much as possible during the off-peak intervals between two peak periods in order to better satisfy the next peak period. The energy exchange with battery is described below:

1. If the PV panels' production is not enough to fully support the load, prosumer will buy energy directly from grid side to satisfy the load. If the energy needed to be bought from the grid is larger than the reference value, then one energy peak is considered formed. The battery will be discharged to shave this peak.

    (a) If there is some energy stored in the battery and the battery SOC state is higher than the lower SOC limit, which means the battery can discharge;

    i. If the energy stored in the battery is enough to compensate the peak, then in theory, the battery can fully shave the peak. The real situation depends on whether the discharging current is acceptable or not.

    A. If the peak is totally shaved by battery, the discharging battery I_d is larger than the largest acceptable current I_{max}, then the battery can only be discharged with the largest acceptable current I_{max}; in this case, the battery cannot fully shave the peak, some energy has to be bought with high buy-in price;

    B. If the peak is totally shaved by battery, the battery discharging current I_d is small than the largest acceptable current I_{max}, then the battery can be discharged with this current I_d; in this case, the battery can fully shave the peak, no energy needed to be bought with high buy-in price;

    ii. If the energy stored in battery is not enough to compensate the peak, then the battery will try its best to shave the peak and some energy has to be bought from grid with high buy-in price; how much energy needed to be bought from grid depends on how much energy could be discharged from battery in this period.

    A. If the battery is totally discharged, the discharging battery I_d is larger than the largest acceptable current I_{max}, then the battery can only be discharged with the largest acceptable current I_{max}; in this case, the battery cannot fully shave the peak and more energy than expected is bought with high buy-in price; the battery is not fully discharged at the end of this period;

B. If the battery is totally discharged, the discharging current I_d is smaller than the largest acceptable current I_{max}, the battery can be discharged with this current I_d; in this case, some energy still needed to be bought with high buy-in price; the battery is fully discharged at the end of this period;

(b) However, it could also happen that the battery SOC has already reached the lower SOC boundary, which means in this period battery cannot shave the peak; than some energy has to be bought with high buy-in price; the battery is still at lower SOC limit at the end of this period;

2. If the PV panels' production is not enough to fully support the load, prosumer will buy energy directly from grid side to satisfy the load. If the energy needed to be bought from grid is smaller than the reference value, then no peak is considered formed and the battery does not need to discharge; on the contrary, the battery can be charged with energy from during this period; and this period is considered as one of the off-peak intervals between two peak periods;

(a) If the battery SOC state is lower than the upper SOC boundary, the battery will be charged with energy from the grid; how much energy is charged into depends on the magnitude of charging current and the initial battery state.

i. If in the next 10 minutes, the battery is charged with the largest acceptable current I_{max}, the final SOC state will exceed the upper SOC boundary, then the battery will be charged with a smaller current and in theory, the battery can be fully charged;

A. If the energy used to charge the battery plus the energy used to support the load exceeds the predetermined reference value, then the energy can be used to charge the battery is even lower, the real charging current is smaller than and the battery is not fully charged at the end of this period;

B. If the energy used to charge the battery plus the energy used to support the load does not exceed the predetermined reference value, then the real charging current is equal to and the battery is fully charged at the end of this period;

ii. If in the next 10 minutes, the battery is charged with the largest acceptable current I_{max}, the final SOC state will not exceed the upper SOC boundary, then the battery can be charged with the largest acceptable current I_{max} in theory, the battery is not fully charged at the end of this period;

A. If the energy used to charge the battery plus the energy used to support the load excesses the predetermined reference value, then the energy can be used to charge the battery is even lower, the real charging current is smaller than the largest acceptable current I_{max};

B. If the energy used to charge the battery plus the energy used to support the load does not exceed the predetermined reference value, then the real charging current is equal to the largest acceptable current I_{max};

(b) It could also happen that the battery is already fully charged at the beginning of this period, then no energy is needed to be bought from the grid to charge the battery; grid only needs to support the load;

3

So that in total, the battery can be charged with both PV panels and grid. But can only discharged to shave the peaks and does not sell energy back to the grid through discharging. From grid side, energy can only be injected into the grid from PV panels, while the grid can sell energy to both loads and battery. The detail power flow can also be found in Table 3.5. Figure 3.11 shows the load profile and PV panels' production for a typical day to help better understand this power management method.

As mentioned before, because the role of the battery is weakened, the battery size used for this power management method is usually smaller than the battery size used for the other three power management methods, which could also be verified by the simulation results. As a fact, for the Netherlands case, the battery size used for peak-shaving is 0.25 battery, 0.5 Battery, and 1 battery, with the reference value equals to $500/6kWh$, which approximately equals to $83kWh$ if the energy is calculated every 10 minutes. The standard battery size for the Netherlands case is 0.25 battery unit (0.25 RESU 3.3). It should be clear that this reference value is considered from bus side, instead of load side. This is because all the physical other quantities are transferred to bus side to simplify the calculation.

In order to choose the reference value, the load profile is reordered in descending order from the largest value to the smallest value for the whole year.

The most expensive part of the energy is usually close to the highest energy demand and contribute most to the final energy bill, even these energy peaks only exist during short time spans [64]. Articles [65, 66] also suggest that the research shows the most expensive energy draws from the grid is only the top 1% to 2%, and it is also this part of energy that could challenge the grid operation condition. So that if someone wants to reduce the energy bill, the best way is to reduce the magnitudes of these energy peaks. From Figure 3.14, it is obvious that for the Netherlands case, around Power=500W, the slope suddenly changes. Before 500W, the slope is relatively steep; after 500W, the slope is relatively smooth. Plus, with the x-axis as time and y-axis as power, which makes the area enclosed by load curve and two axes equals to energy. The area enclosed by load curve, the line Power=500W and the y-axis is small (Area 1 as indicated in Figure 3.14), but these part of energy is the costliest part of the energy bill. That is the reason why 500W is chosen as the reference value at the beginning. It is also interesting to see what will happen if this reference value is lower. Of course, with a lower reference value, a larger battery is required because more peaks are considered formed and more energy needed to be compensated by the battery. The following combinations are also simulated, $Power = 400W$ with 0.5 battery size, $Power = 350W$ with 1 battery size, $Power = 300W$ with 1 battery size.

Table 3.5: Power Management Four——Power Flow

Time Period		PV Power Flow	Load Consumption	Battery Power Flow	Grid Power Flow
00:00 - 24:00	$P_{pv} \geq P_{load}$	(1) Satisfy the Load; (2) Charge the Battery; (3) Sold to Grid.	(1) Consuming PV generation; (2) Buy from Grid.	Battery Charging: (1)PV (2)Grid; During the off-peak-intervals between two peak-periods, the battery can be charged as much energy as possible in order to better satisfy the next peak-period; Battery Discharging: None;	Power Accepted by Grid: PV. Power Sold by Grid: Battery.
	$P_{pv} < P_{load}$ & $P_{load} - P_{pv} \leq P_{ref}$	Satisfy the Load;	(1) Consuming PV generation; (2) Buy from Grid.	Battery Charging: Grid; During the off-peak-intervals between two peak-periods, the battery can be charged as much energy as possible in order to better satisfy the next peak-period. Battery Discharging: None;	Power Accepted by Grid: None. Power Sold by Grid: Load + Battery.
	$P_{pv} < P_{load}$ & $P_{load} - P_{pv} > P_{ref}$	Satisfy the Load;	For the part smaller than reference value: (1) Consuming PV generation; (2) Buy from Grid. For the part larger than reference value: (1) Consuming PV generation; (2) Discharge the Battery. (3) Buy from Grid.	Battery Charging: None. Battery Discharging: Load (Peak-Shaving).	Power Accepted by Grid: None. Power Sold by Grid: Load.

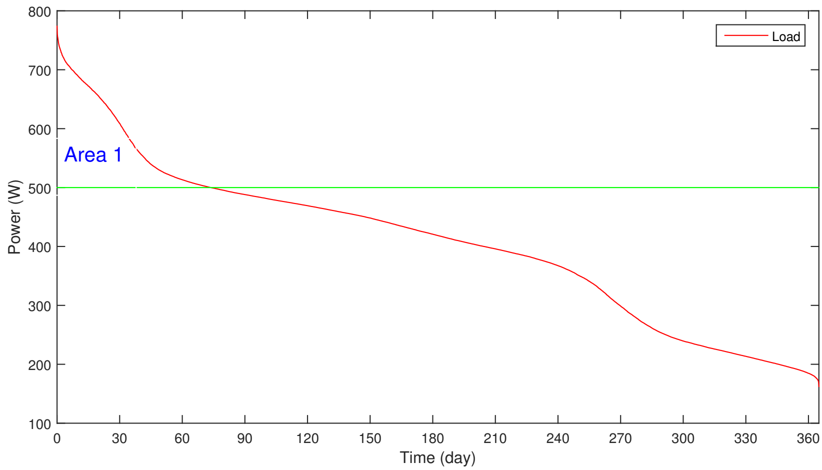


Figure 3.14: Load Profile in Descending Order (The Netherlands)

For Costa Rica case, the same way is used to decide this reference value. The load profile in descending order for Costa Rica case is shown in Figure 3.15. At about $P = 500W$, the slope of the curve suddenly changes and therefore, the reference value is also chosen to be $500W$, which equals to $83kWh$ with an every-10-minute step data. The following combinations are also simulated: $Power = 500W$ with 0.25 battery size, $Power = 500W$ with 0.375 battery size, $Power = 500W$ with 0.5 battery size. The standard battery size for Costa Rica with peak shaving is 0.25 battery unit (0.375 RESU 3.3). The influence on power flow pattern with different reference values is also studied, the combinations are also listed here: $Power = 400W$ with 0.5 battery unit, $Power = 350W$ with 0.75 battery unit, $Power = 300W$ with 1 battery unit.

For California case, the load profile in descending order is shown in Figure 3.16. Unlike the Netherlands and Costa Rica cases, the slope changes almost linear for California case. The reference value is chosen to be $P = 1400W$, which equals to $233.33kWh$ with an every-10-minute step data. The following combinations are also simulated: $Power = 1400W$ with 0.25 battery size, $Power = 1400W$ with 0.5 battery size, $Power = 1400W$ with 0.75 battery size. The standard battery size for California with peak shaving is 0.25 battery unit (0.25 RESU 3.3). The influence on power flow pattern with different reference values is also studied, the combinations are also listed here: $Power = 400W$ with 0.5 battery unit, $Power = 350W$ with 0.75 battery unit, $Power = 300W$ with 1 battery unit.

These four power management methods are programmed and simulated with different countries/regions. The simulation results are later combined with different electricity tariff structures to find out which is the suitable combinations for each country/region.

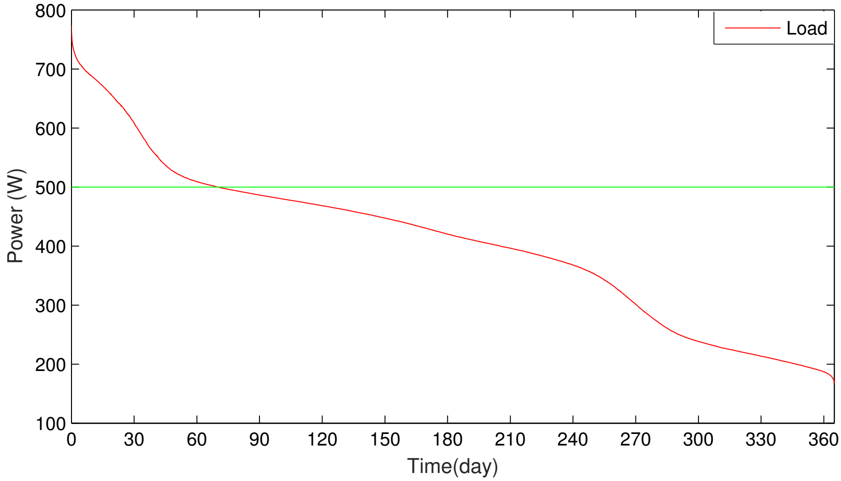


Figure 3.15: Load Profile in Descending Order (Costa Rica)

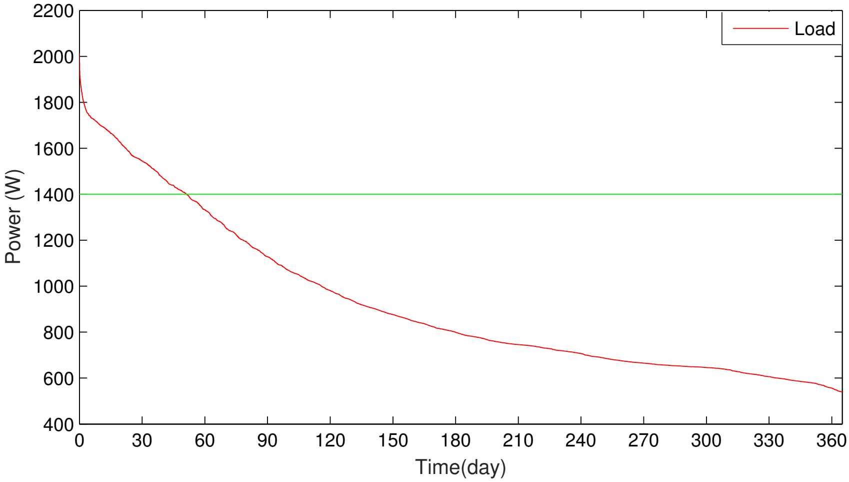


Figure 3.16: Load Profile in Descending Order (California)

3.3. POWER MANAGEMENT METHODS' SIMULATION RESULTS

IN this section, the simulation results for the Netherlands, Costa Rica, California are presented. For each country/region, the simulation results are based on the four PMMs that mentioned before. With the same assumptions mentioned in Section 3.1, the simulation results for the Netherlands, Costa Rica, and California are shown in order.

3.3.1. POWER MANAGEMENT METHODS' SIMULATION RESULTS FOR THE NETHERLANDS CASE

FOR the Netherlands case, for PMM1, PMM2, and PMM3, the battery size involved in the simulation is 0.5 battery unit (0.5 RESU3.3), 1 battery unit (1 RESU3.3) and 1.5 battery units (1.5 RESU3.3). For PMM4, 0.125 battery unit (0.125 RESU 3.3), 0.25 battery unit (0.25 RESU 3.3) and 0.375 battery unit (0.375 RESU 3.3) combined with $P = 500W$ are simulated; in order to see the influence reference value on the system power flow, the flowing combinations are also simulated: $P = 400W$ with 0.5 battery unit (0.5 RESU3.3), $P = 350W$ with 1 battery unit (1 RESU3.3), $P = 300W$ with 1 battery unit (1 RESU3.3).

With the assumptions mentioned in Section 3.1, four power management methods are simulated for the entire year with the data sampled every 10 minutes. The standard battery size of power management one, two and three are 1 RESU3.3, for the fourth power management method the standard battery size is 0.25 RESU3.3 with $P_{ref} = 500W$.

The important conclusions are listed here.

1. PMM2 and PMM3 can effectively reduce the amount of energy bought during peak-hour.

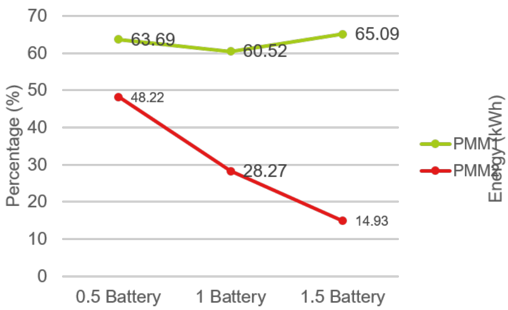


Figure 3.17: Peak-Hour Energy Consumption-Total Energy Consumption Ratio (PMM1 and PMM2)

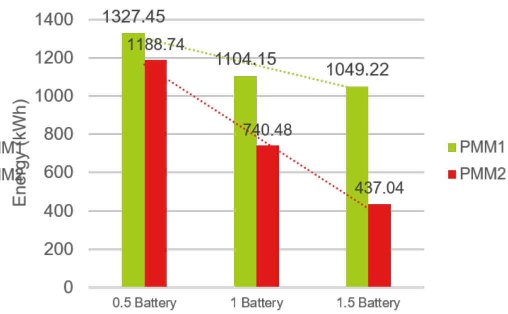


Figure 3.18: Peak-Hour Energy Consumption (PMM1 and PMM2)

From Figure 3.17 and Figure 3.18, it shows that if the peak-hour is between 07:00 and 23:00, then with PMM2 shown in Figure 3.3, the amount of energy bought from the grid can be remarkably reduced. With a larger battery size, like 1.5 battery unit, the amount of energy bought from the grid with high buy-in price can be even further reduced by more than two times from 48.22% to 14.93%. The result shows the larger battery size is, the less energy bought during the peak-hour. This

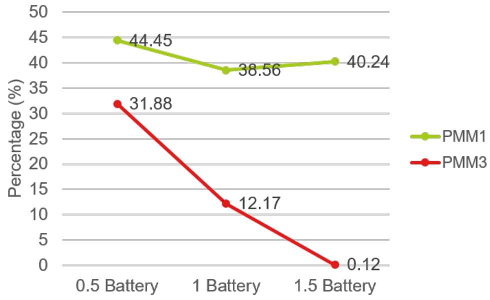


Figure 3.19: Peak-Hour Energy Consumption-Total Energy Consumption Ratio (PMM1 and PMM3)

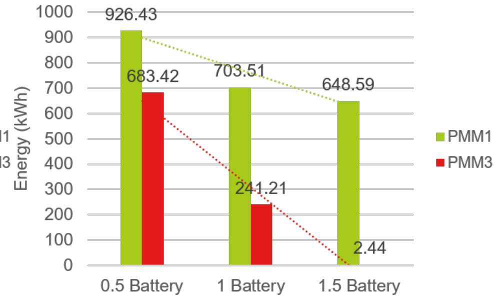


Figure 3.20: Peak-Hour Energy Consumption (PMM1 and PMM3)

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is because the larger battery size is, the more energy could be stored in the battery, and thus more energy could be used to satisfy the load during the peak-hour. However, for a long-period peak-hour, the amount of energy bought with the high price does not change too much with different battery sizes for PMM1. This is because the peak-hour is almost overlapped with all the daytime for the entire year. During this period, the contribution of PV panels to the system is almost the same despite different battery sizes, since the battery cannot be charged with the energy from the grid, the constitution of energy from load side does not vary too much, making the amount of energy bought from grid is almost same around 60% and does not depend on battery size.

Figure 3.19 and Figure 3.20 show that if the peak-hour is shorter from 17:00 to 23:00, with a larger battery size, the prosumers even do not need to buy energy from the grid with high electricity buy-in price. This is because the battery is always fully charged before the peak-hour begins, for a shorter peak-hour, a larger battery can almost satisfy all the load requirements, which effectively lower the amount of energy bought directly from the grid with the high retail price. With this shorter peak-hour, compared with the longer peak-hour case mentioned before, although the amount of energy bought during this peak period is also lower with PMM1, still, the grid is responsible for supporting 40% energy from the load side. Compared with Figure 3.18 and Figure 3.20, it could be found that the load consumption is twice during 17:00 and 23:00 than the consumption between 07:00 and 17:00.

What should be careful is that the battery cost is involved in the basic cost when building the system. Although a larger battery size can lower the amount of energy bought with the high retail price, it could also lead to a higher battery cost. This is the reason why a suitable battery size is very important for the system.

2. No matter which power management method is used, there is still about 40% to 60% of the energy from load side is supplied by the grid. The battery is better used with PMM2 and PMM3; while the battery contributes less in PMM4.

   As shown in Figure 3.21, for PMM1, PMM2, and PMM3, for the same battery size,

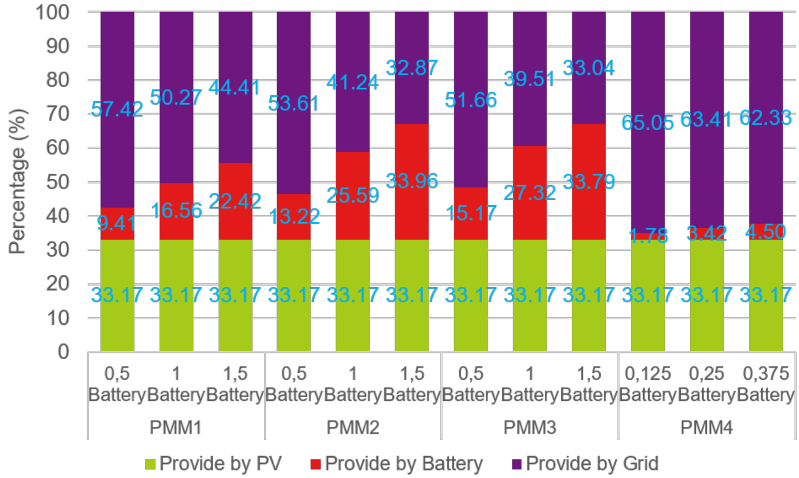

Figure 3.21: Load Side Energy Composition

if compared with PMM1, the battery with PMM2 and PMM3 can provide more energy for the load in a year, while for PMM4, the battery size does not influence the load side energy composition too much. For example, for PMM2 and PMM3 with 1 battery case, about 25% of energy requirement from load side can be satisfied by battery, while for PMM1, this value decreases to 16.56%. The main reason for this phenomenon is because the battery function is different for each power management method. For PMM2 and PMM3, the battery is always fully charged at the beginning of peak-hour and totally discharged at the end of peak-hour. This means more energy could be provided by the battery during peak-hour to avoid buying energy with the high retail price and some energy could even be sold back to the grid to gain some profit if, at the end of peak-hour, there is still some energy left inside the battery. Since the battery is always charged before the peak-hour and totally discharged at the end of peak-hour, more battery cycles could happen during the entire year than the other two power management methods, which leads to a more frequently battery participation during the whole year. However, it seems that the length of peak-hour does not have too much influence on the load side power flow, which could be found with the result of PMM2 and PMM3. This is because from the load side, the amount of energy needed to be bought after PV panels' support is fixed, which could change is the source of energy for the rest loads requirement. For a fixed battery size, a fixed amount of energy could be charged into the battery during the forced charging period, thus, the amount of energy could be discharged during the peak-hour to support the load is more or less the same, since from Figure 3.22, for a small battery size, almost no energy is sold back to the grid from battery discharging. Since the peak-hour for PMM3 is shorter and starts late in the afternoon, the battery could be charged with energy from PV panels production and discharged to support the load during morning and afternoon, therefore, for PMM3, with a fixed battery size, the battery could provide more energy for the load than PMM2. The difference mainly lies in the off-peak hour, outside the forced charging period, how much energy is exchanged between the battery and the loads. For PMM1, the cycles of battery only depend on the PV panels' generation pattern and load consumption pattern, since the battery may not always be fully charged at the beginning of peak-hour, it is reasonable that the battery contributes less in load consumption if PMM1 is involved.

The battery function is even more weakened with PMM4 because the battery is only used to shave the energy peak and supply the part of the consumption that exceeds the predetermined reference value. Although the battery can be charged with the energy from the grid between the two peak-intervals, the battery function is still limited to a great extent. Plus, the battery size used for PMM4 is smaller, leading to the least contribution in load side energy composition among the four power management methods. It can be inferred that with a lower predetermined reference value, the battery will participate more in the load side power flow. However, considering from a different aspect, the limit function of battery could be an advantage of PMM4, with a smaller battery size, the system cost can be remarkably decreased when the prosumers build the system.

3. No matter which power management method is used, the main source that brings profit to the prosumers is the amount of energy sold back to the grid from PV panels' generation.

   The results are shown in Figure 3.22 with different battery sizes and different PMMs.

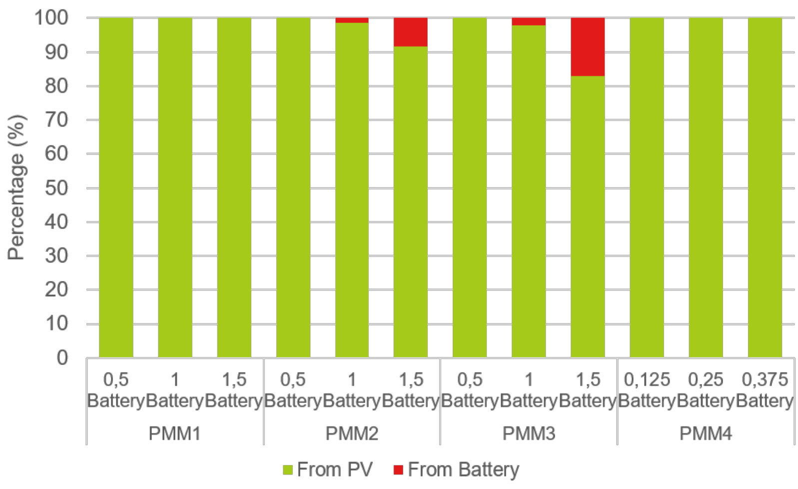

Figure 3.22: Gird Side Received Energy Composition

4. Peak shaving can effectively reduce the amount of energy bought with the high price, while at the same time, providing a smoother energy buying mode from the grid, almost no sudden energy peak exists anymore.

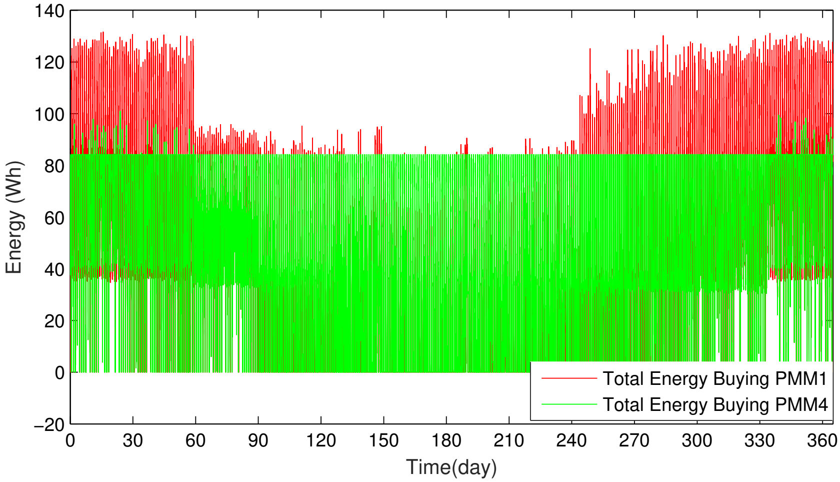

Figure 3.23: Real-Time Energy Buying Comparison (PMM1 and PMM4)

In Figure 3.23, the red line represents the energy bought from the grid for the entire year with PMM1; the green line is the energy bought from the grid for the entire year with PMM4. It is clear more energy needed to be bought from the grid during winter times than summer times for both power management methods. Also, the amount of energy bought from the grid can change a lot during different seasons. However, with "Peak Shaving", although during winter time, still more energy is needed than the summer time, the energy bought from the grid is much smoother from the picture of the whole year. And if the predetermined reference value and battery size are both chosen with suitable values, only a small part of energy or even no energy is bought with the high price. It should be clear that for peak shaving: only the part of energy exceeds the reference value will be charged with higher price, as long as the energy bought from grid is lower than this reference value, the electricity retail price is the low buy-in price; of course, the higher the reference value is, the more expensive the price will be for the high buy-in price. If after satisfying the load, there is still some energy gap before reach the reference value, the battery can be charged as much as possible within this gap, which makes it possible to buy some energy from the grid with low buy-in price to charge the battery for later use. Since each energy gap is better used, from the perspective of the whole year, it could help make the energy bought from grid be much smoother.

5. For peak-shaving, with a lower reference value, a larger battery size is need. However, the total amount of energy bought from the grid does not change too much.

   With a lower reference value, it means more frequently the peak could arrive, therefore, the battery should shave more peaks, and therefore a larger battery size is needed. Since the battery shaves more peak, the battery actually provide more energy to the load. However, since the energy from the grid are mainly used to

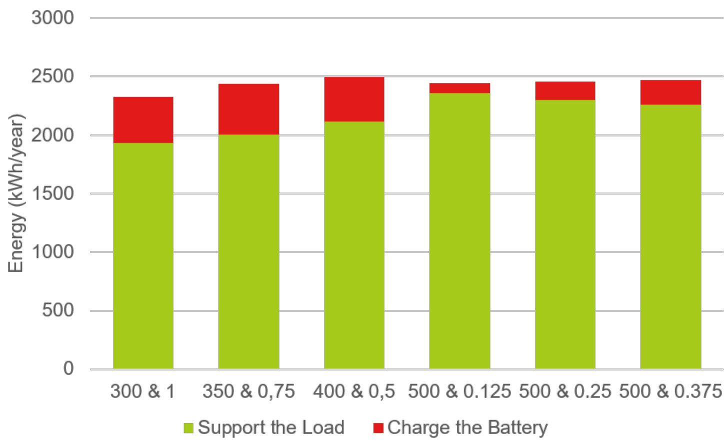

Figure 3.24: The Total Energy Bought from the Grid with Different Reference Value for Peak-Shaving

support the load and charge the battery between two peaks, and later, the energy stored in the battery are used to shave the peak. Since the battery does not neither need to be fully charged before the peak-hour comes, nor totally discharged at the end of peak-hour like PMM2 and PMM3 do, with the same PV production, the battery size does not influence the total amount of energy bought from the grid, as shown in Figure 3.24.

3.3.2. POWER MANAGEMENT METHODS' SIMULATION RESULTS FOR COSTA RICA CASE

FOR Costa Rica case, for PMM1, PMM2, and PMM3, the battery size involved in the simulation is 0.5 battery unit (0.5 RESU3.3), 1 battery unit (1 RESU3.3) and 1.5 battery unit (1.5 RESU3.3). The standard battery size for these three PMMs is 1 battery unit (1 RESU3.3). For PMM4, with the reference value equals 500 W, 0.125 battery unit (0.125 RESU3.3), 0.25 battery unit (0.25 RESU3.3), and 0.375 battery unit (0.375 RESU3.3) are simulated. Also, the following combinations are simulated with different reference values, namely: $P = 400W$ with 0.5 battery unit (0.5 RESU3.3), $P = 350$ W with 0.75 battery unit (0.75 RESU3.3), $P = 300$ W with 1 battery unit (1 RESU3.3).

With the assumptions mentioned in Section 3.1, four power management methods are simulated for the entire year with the data sampled every 10 minutes. The important conclusions for Costa Rica case are listed here.

1. PMM2 and PMM3 can effectively reduce the amount of energy bought during the peak-hour.

   From Figure 3.25 and Figure 3.26, it shows that if the peak-hour is from 07:00 to 23:00, then with PMM2 the amount of energy bought from the grid can be remarkably reduced. With a larger battery size, the amount of energy bought from the grid with high buy-in price can be even reduced by more than two times. The result shows the larger battery size is, the more obvious the effect is. The same result

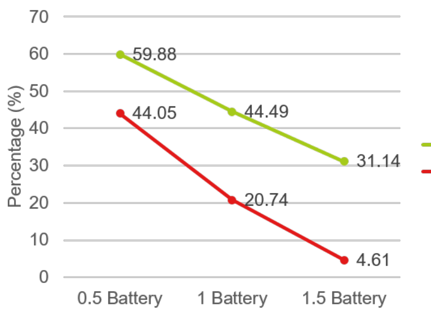

Figure 3.25: Peak-Hour Energy Consumption-Total Energy Consumption Ratio (PMM1 and PMM2)

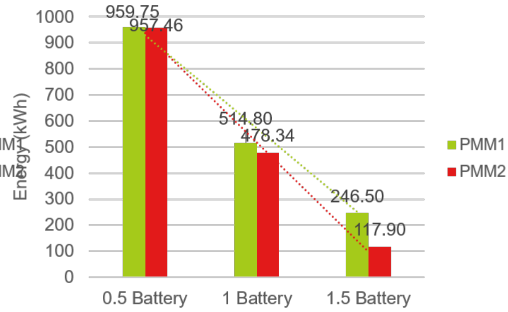

Figure 3.26: Peak-Hour Energy Consumption (PMM1 and PMM2)

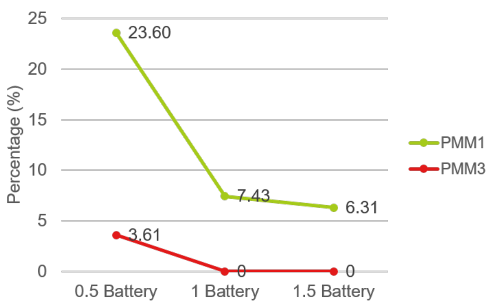

Figure 3.27: Peak-Hour Energy Consumption-Total Energy Consumption Ratio (PMM1 and PMM3)

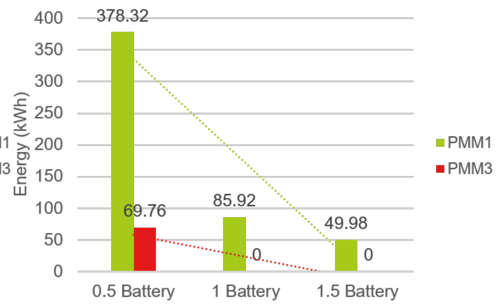

Figure 3.28: Peak-Hour Energy Consumption (PMM1 and PMM3)

can be gathered from Figure 3.27 and Figure 3.28. If the peak-hour is shorter from 17:00 to 23:00, with a larger battery size, the prosumers even do not need to buy any energy from the grid with high electricity buy-in price.

For PMM1, the amount of energy bought with the high price also decreases when battery size increases, meaning the battery does play an important role in Costa Rica case.

2. From the load side, for PMM3 and PMM4, battery size does not influence the energy composition too much; compared with the other three PMMs, the battery does not play a very important role in PMM4. For PMM3 and PMM4, the grid and PV panels are two main energy sources for the load; while for PMM1 and PMM2, with a larger battery size, the battery can contribute more to the load, which makes battery becomes more important in the system. The power flows of PMM1 and PMM2 are similar to each other.

   For PMM2, the peak-hour definition is overlapped with the most part of the daytime throughout the whole year. For the rest of the time outside the battery forced discharging period during the peak-hour, the power flow pattern is very similar to the power flow of PMM1, the difference is that with PMM1, the battery can be

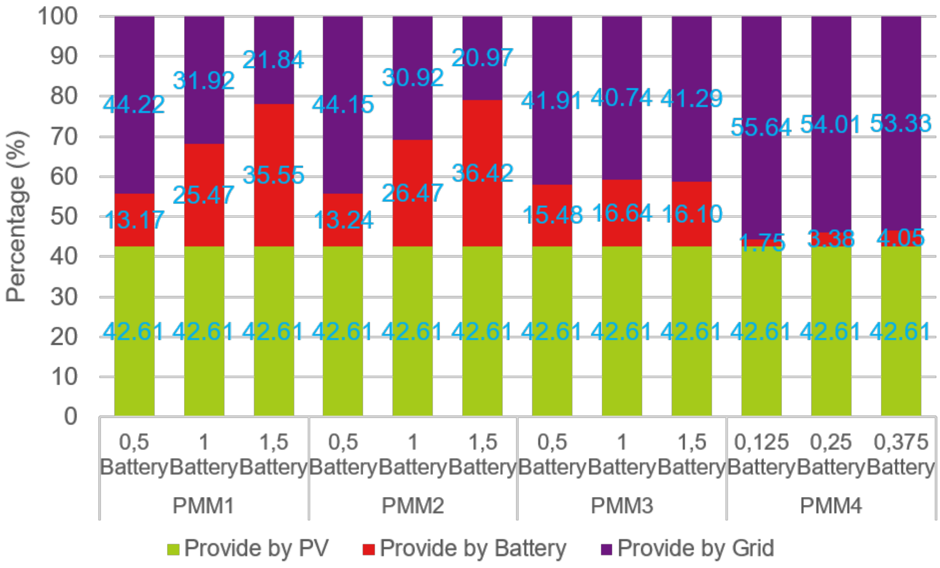

Figure 3.29: Load Side Energy Composition

charged with the energy from PV panels' production, while for PMM2, the battery can not be charged during the peak-hour. This is the reason why the power flow of PMM2 is similar to PMM1. While for PMM3 and PMM4, the most part of PV panels' production has been better utilized, the load does not need to require too much energy from the battery, and that is the reason why the battery size does not influence the system's performance too much as PMM1 and PMM2 do. The simulation results are shown in Figure 3.29.

3. For PMM3, the battery can have much more frequent energy exchange within the system compared with the other three PMMs; for the rest three PMMs, both the sources of battery charging and destinations of battery discharging can be considered unitary.

   In Figure 3.30, it shows that PMM3 has a more frequent energy exchange with other units than the other three PMMs. This is because for Costa Rica case, there are two peak-hour every day, one in the morning, the other one during the night. The battery always needs to be fully charged at the beginning of each peak period and totally discharged at the end of the peak period. This happens repeatedly twice times per day, which makes the energy exchange between the battery and the rest system much more frequently, thus the battery also plays a more important role in PMM3.

   Because of the different definition of battery function for each PMM, both the sources of battery charging and destinations of battery discharging can be considered to be unitary for the rest three PMMs except PMM3. For example, for

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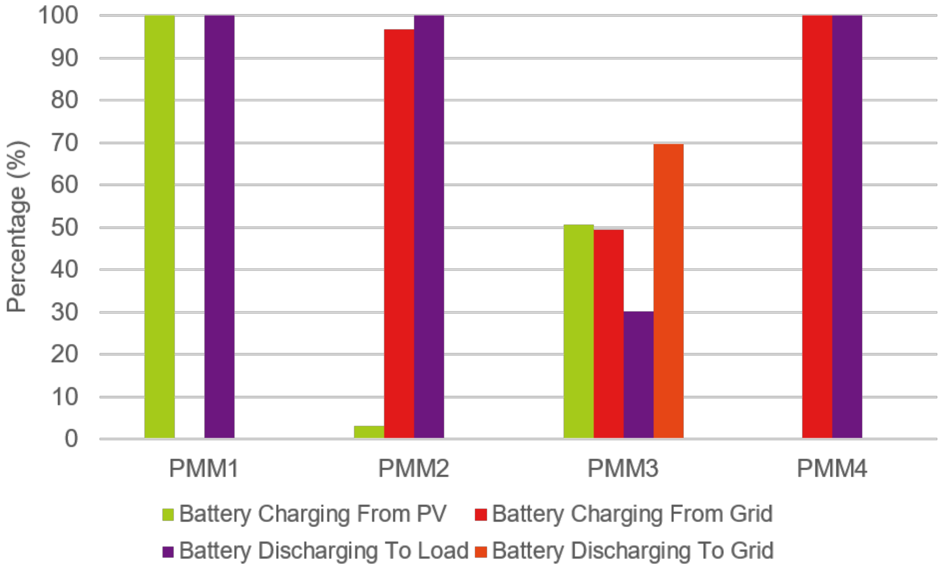


Figure 3.30: Battery Side Energy Exchange

PMM1, there is no energy exchange between battery and grid, battery can only be charged with the energy from PV panels' production, and when the battery is discharged, the energy can only be used to support the load; for PMM2, the main battery charging source is grid, while the main beneficiary for battery discharging is the load; and for PMM4, all the energy for battery charging is from the grid and all the energy discharged from the battery goes to load.

4. For PMM3, both the PV panels' production and battery discharging energy can bring considerable profit to prosumers even if the battery size is small, while for the rest three power management methods, the main source that could bring profit to prosumers is PV production, and this does not change when battery size changes.

   This is because with the ToU tariff structure defined by CNFL, there are two peak-hour periods in Costa Rica, and each period is only two and half hours. Due to the strong and smooth irradiation during the entire year, a lot of energy is still left in the battery before the forced discharging period begins. That is the reason why a lot of energy could be sold back to the grid through battery discharging. When increasing the battery size from 0.5 to 1, more energy could be stored in battery, thus more energy could be sold back to during forced discharging period; however, it the battery size keeps increasing to 1.5, the amount of energy that sold back to the grid through battery discharging does not change too much because the PV panels' production is limit, the amount of energy that charged into battery from PV panels' generation does not change too much, leading to only a small 5% increase in the amount of energy sold back to grid through battery discharging. For PMM1 and PMM4, the battery function is limited; for PMM2, due to a long

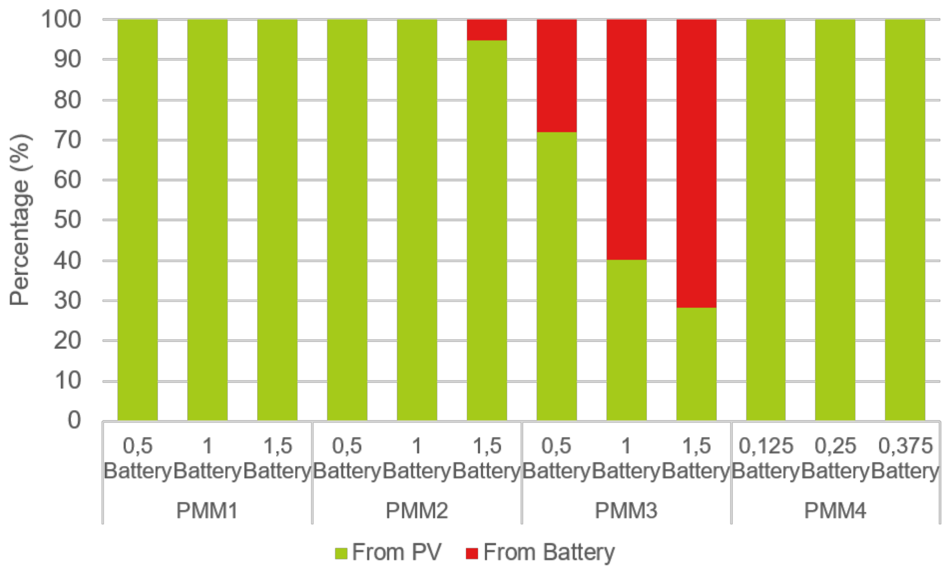


Figure 3.31: Grid Side Received Energy Composition

peak-hour period, the battery is almost empty when the forced discharging period comes, that is the reason why PV panels' production is the main source that brings profit to consumers.

3.3.3. Power Management Methods' Simulation Results for California Case

For California case, for PMM1, PMM2, and PMM3, the battery size involved in the simulation is 1 battery unit (1 RESU3.3), 2 battery unit (2 RESU3.3) and 3 battery units (3 RESU3.3). The standard battery size for these three PMMs is 3 battery unit (3 RESU3.3). For PMM4, with the reference value equals $1400W$, 0.25 battery unit (0.25 RESU3.3), 0.5 battery unit (0.5 RESU3.3), and 0.75 battery unit (0.75 RESU3.3) are simulated. Also, the following combinations are simulated with different reference values, namely: $P = 1200W$ with 1 battery unit (1 RESU3.3), $P = 1100W$ with 1 battery unit (1 RESU3.3), $P = 800W$ with 1.5 battery unit (1.5 RESU3.3).

With the assumptions mentioned in Section 3.1, four power management methods are simulated for the entire year. The important conclusions for California case are listed here.

1. From the load side, the energy flow of PMM1 is similar to PMM2, and with a larger battery size, more energy could be provided by the battery. However, for PMM3 and PMM4, the battery size has a minor influence on the system.

   For California case, the PV panels usually can provide enough energy for the load during the day, when the load consumption is relatively low; the load consump-

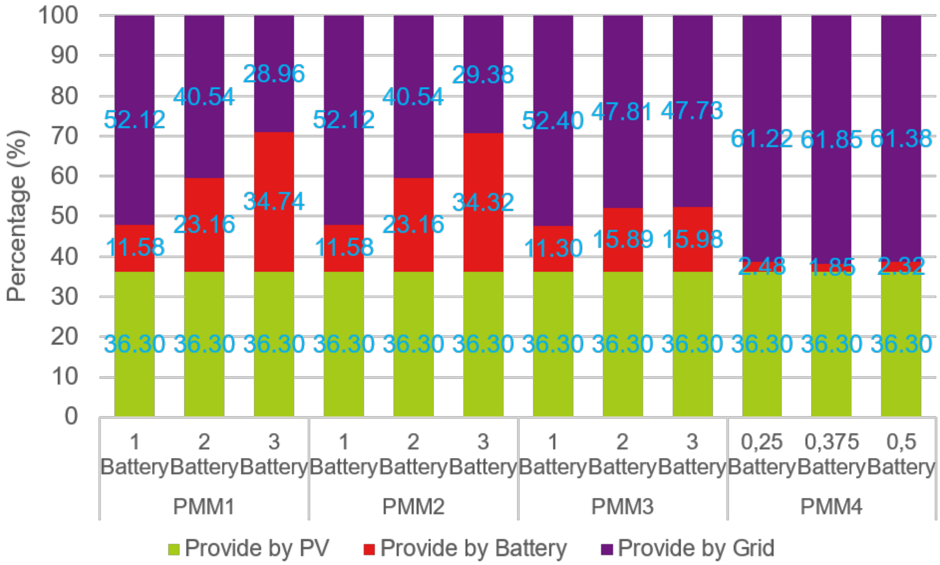


Figure 3.32: Load Side Energy Composition

tion increased since 18:00 when the PV panels' generation is already low. In this way, the PV panels' generation peak misses the load peak. With a relatively long peak-hour period, like PMM2, the peak-hour last until late in the night, giving the battery enough time to totally discharged to support the load, the energy stored in the battery is mainly used to support the load peak in the night, only a small amount of energy is sold back to the grid when the battery size is large enough. This is the reason why from the load side, the energy flow pattern of PMM1 is similar to PMM2. For PMM3, although the peak-hour also includes part of the night load peak, the battery enters the forced discharged period before the load reaching its peak consumption, making the amount of energy that could be used to support the load almost the same, that is why the energy flow pattern from the load side does not change too much when increasing the battery size.

2. For PMM1, PMM2, and PMM3, the only energy source that could bring profits to prosumers is the PV panels, even with a large battery size. For PMM3, if the battery size is large enough, even if the PV panels are the main energy source to sell energy back to the grid, the battery becomes an energy source that cannot be ignored.

   The peak-hour ends when the load consumption goes up, with a large battery size, for PMM3, there is still some energy left in the battery before the battery forced discharging period comes, therefore, instead of using the rest of energy stored in the battery to support the load, as PMM2 did, with PMM3, the energy stored in the battery are discharged and sold back to the grid to gain profits. Therefore, if PMM3 is involved, the battery becomes a significant energy source that sells energy back to the grid.

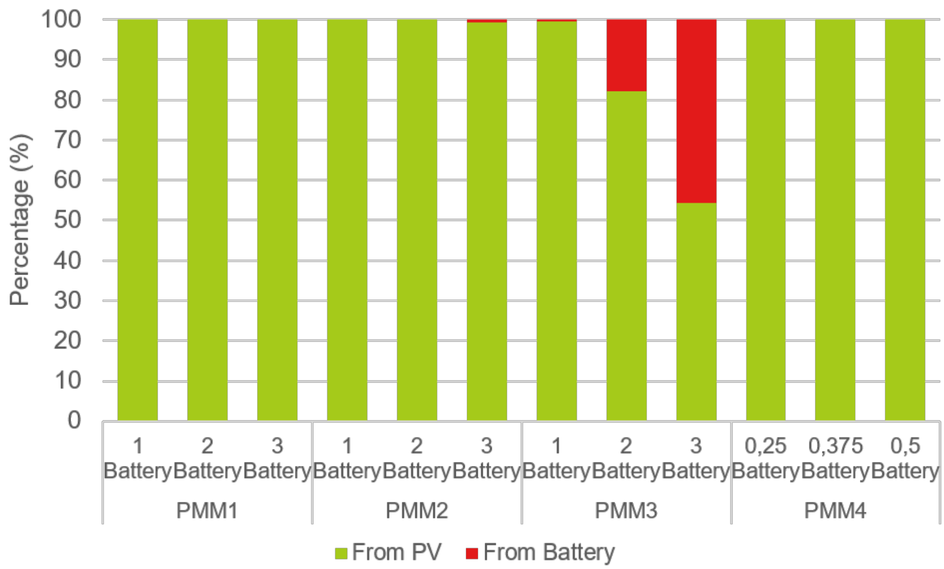


Figure 3.33: Grid Side Received Energy Composition

3. For California case, if 10 PV panels are used, the peak-hour starts from 14:00 and last until 20:00, and the battery sizes used for simulation are 1 battery unit (1 RESU3.3), 2 battery units (2 RESU3.3) and 3 battery units (3 RESU3.3), then from Table 3.6, it shows that with PMM3, the amount of energy bought during peak-hour is the same as PMM1.

Table 3.6: Peak-Hour Energy Consumption Comparison (California)

PMM		PMM1			PMM2		PMM3	
Time		07:00-23:00	14:00-20:00	00:00-24:00	07:00-23:00	00:00-24:00	14:00-20:00	00:00-24:00
1 Battery	Energy (kWh)	2218.14	384.88	4318.19	2218.14	5541.87	384.88	4341.63
	Percentage (%)	51.37	8.91	1	40.03	1	8.86	1
2 Battery	Energy (kWh)	1259.90	5.85	3358.64	1259.90	5806.01	5.85	3961.88
	Percentage (%)	37.51	0.17	1	21.70	1	0.14	1
3 Battery	Energy (kWh)	588.78	0.00	2399.55	336.75	6105.13	0.00	4252.60
	Percentage (%)	24.54	0	1	5.52	1	0	1

Two reasons can lead to this result, first, the number of PV panels; with a strong irradiation, the generation of PV panels is high; second, the definition of peak-hour does not perfectly match the real load peak.

Figure 3.34 shows part of energy flow data of a random day in a year (October 19th) for both PMM1 and PMM3. The results for PMM1 is shown with the upper figure in Figure 3.34 and the results for PMM3 is shown in the lower figure in Figure 3.34.

The red line represents the load data, the green line stands for PV generation data, the cyan line is the part of energy bought from the grid to support the load in every

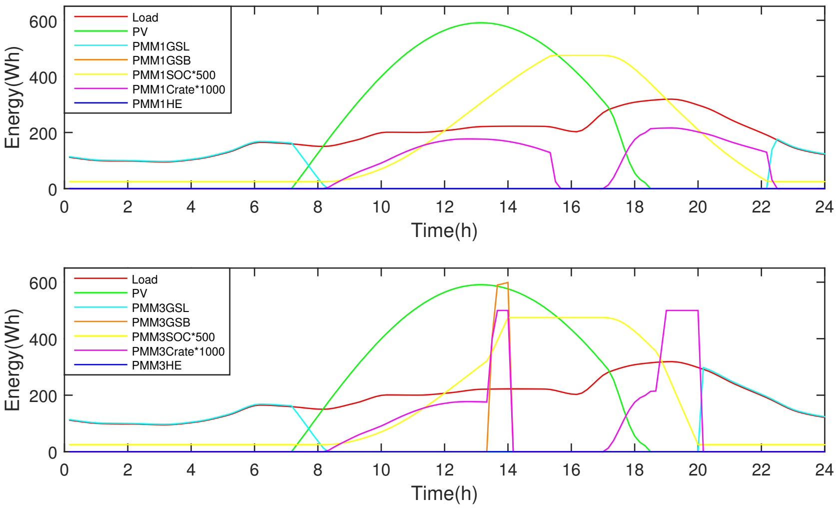


Figure 3.34: PMM1 and PMM3 Energy Flow Comparison (California-3 Battery)

10 minutes, the orange line is the part of energy bought from the grid to charge the battery, the yellow line is the battery SOC, which is amplified 500 times, the purple line is used to show the battery C-rate for charging and discharging process, which is amplified by 1000 times, the blue line shows the amount of energy bought from grid during peak-hour, which is between 14:00 and 20:00. The data is based on 3 battery case.

From Figure 3.34, at the beginning of the day, there is still some energy stored in the battery for PMM1, therefore, battery could be discharged to support the load until period 02:30-02:40, starts at the same period, some energy should be bought from the grid to support the load since the battery is fully discharged. However, at the beginning of the day, the battery is already empty for PMM3, thus, during the first few hours on that day, all the load requirements have to be supported by the energy bought from the grid.

The PV panels first start to produce energy during period 07:10-07:20, at this time, the PV panels generation is still not enough to support all the load requirements. The first time that PV panels' generation can fully satisfy the load starts during period 08:10-08:20 (although during period 08:00-08:10, the PV panel's production is already higher than the load consumption, the PV panels generation still cannot fully satisfy the load due to the system losses). After this period, the PV panels generation keeps increasing while the load consumption keeps decreasing, therefore, after supporting the load, the excess energy from PV panels generation could be used to charge the battery, from Figure 3.34, it could find the battery SOC goes up and the C-rate begins increasing.

The battery forced charging period starts at 12:00, 2 hours before the peak-hour starts. However, at first, the battery does not need to be forced charging with energy from grid since the battery is not empty and the excess energy from PV panels generation still keeps charging the battery. However, starts from period 13:20-13:30, the battery has to be forced charging with some extra energy bought from the grid to make sure that the battery can be fully charged before the peak-hour starts. With a large battery size, the largest acceptable current is relatively high, which means the energy charged into the battery during every 10 minutes is relatively high, that is the reason why in Figure 3.34, the slope of battery SOC state for PMM3 is steeper than PMM1 during 13:20-14:00. However, during this 40 minutes, the battery does not to be charged always with the largest acceptable current, the simulation data shows that if during the rest period of battery forced charging period, the battery is charged with the largest C-rate, which equals to 0.5, then during period 13:20-13:30, the battery can be charged with a smaller C-rate, which approximately equals to 0.40. This lower C-rate value can also be detected in the lower figure of Figure 3.34. Then during 13:30-14:00, the C-rate keeps equalling to 0.5. With the extra energy bought from the grid, for PMM3, the battery is fully charged at 14:00, right before the peak-hour starts. While for PMM1, the battery is only charged with the rest of PV panel's generation after fully support the load, that is the reason why the C-rate is below 0.5 and it takes a longer time to fully charged the battery.

For PMM3, the battery C-rate drops to 0 after the peak-hour starts. However, for PMM1, since the battery is still not fully charged, the battery can still be charged with the extra energy. The last battery charging period for PMM1 is between 15:20 and 15:30, the charging C-rate is approximate equals 0.023. For both PMM1 and PMM3, during that day, after the battery is fully charged, the PV panels' production is still enough to fully satisfy the load, and before 17:00, the power flow for PMM1 and PMM3 are the same and no energy exchange between the battery and other units in the system, the excess energy from PV panels' generation is sold back to the grid. Starts from period 17:00-17:10, the battery needed to be discharged to support the energy gap from the load side. With the load keeps increasing and the PV panels' production keeps decreasing, more energy needed to be discharged from the battery, leading to an increasing battery discharging C-rate.

The PV panels stop producing energy since 18:20, after that, the battery becomes the first choice for load consumption. For a large battery size, the battery can fully support the load for a long period during the load, even though the load consumption reaches its daily peak. Therefore, during night-load-peak, for both PMM1 and PMM3, no energy is needed from the grid.

The battery forced discharging period starts from 18:10. Since the battery already started discharging since period 17:00-17:10, the battery does not need to be forced discharged until period 18:40-18:50. Starts from 18:40, after satisfying the load, the battery sell the extra energy back to the grid. The simulation results show that during period 18:40-18:50, the C-rate approximately equals 0.35, while during the rest battery forced discharging time, the C-rate keeps at 0.5.

Therefore, starts from 20:00, for PMM3, the battery is empty, after that, all the energy requirements from the load side can be only supported by the energy bought from the grid, this is why the cyan line is suddenly increased right after 20:00 and always keeps the same slope as the red line does. However, for PMM1, at 20:00, the battery still has energy stored inside, the battery keeps discharging to support the load and no energy is needed to be bought from the grid. The battery is fully discharged after 22:20, and during the rest time of the day, the load is supported by the energy bought directly from the grid, just as PMM3 does, which can be also shown from Figure 3.34, the cyan line is overlapped with the red line.

Because of the strong irradiation and relatively large battery size, the PV panels' generation together with the energy discharged from the battery can fully support the load for a long time. Compared with PMM2, which has an early-start long peak-hour, PMM3 has a relatively short peak-hour which starts in the afternoon, making the energy bought during the peak-hour is limited. As explained before, the PMM1 and PMM3 may have identical power flow during the peak-hour. For larger battery size, it could make sure that no energy is bought during the peak-hour. For smaller battery size, PMM1 and PMM3 may buy the same amount of energy during the peak-hour. This could also be found with the simulation data listed in Table 3.6. Figure 3.35 shows the power flow of PMM1 and PMM3 with only 1 battery size on October 19th. With this smaller battery size, PMM3 performs identically to PMM1. This is because of the strong irradiation, even before the battery forced charging period comes, the battery can be fully charged only with the energy from PV panels production, therefore, the battery does not need any energy from the grid during the battery charging process. When the PV panels' production is not enough to support the load, the battery starts discharging to support the load. With an increasing load, the small battery size limits the energy that provides by the battery. As a fact, as shown in Figure 3.35, starts from 17:50, the battery has already begun to discharged with the largest acceptable current, leaving the same energy gap needs to be supported with the energy from the grid no matter PMM1 or PMM3 is used. This gives an identical performance for PMM1 and PMM3. Another important reason is that the peak-hour and the actual load does not match, making a lot of energy discharged from the battery is directly sold back to the grid during the first few hours of peak-hour, meaning only part of the energy stored in the battery is used to support the load. These three reasons together making the amount of energy bought from the grid during peak-hour is the same for PMM1 and PMM3.

However, for PMM2, since the peak-hour starts from 07:00 in the morning, the PV production cannot be well used. In fact, during the battery forced charging period, the grid is the main energy source for battery charging, making a large amount of energy being sold back during the day, also the amount of energy bought from the grid is higher due to the fact a lot of energy is required to charge the battery.

In order to make PMM2 or PMM3 better perform its own character and reduce the amount of energy bought during the peak-hour, there are several possible methods can be proposed for PMM3. First, to decrease the number of PV panels size. With a lower PV panels production, the battery can better reduce the amount of

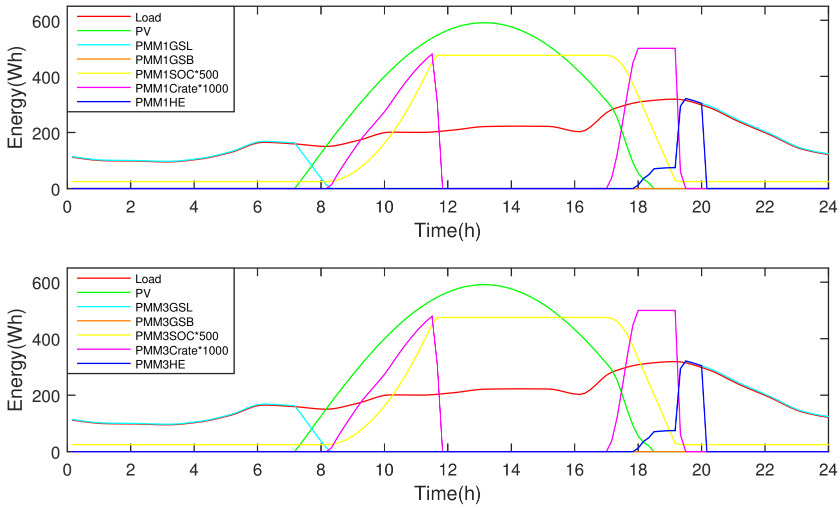


Figure 3.35: PMM1 and PMM3 Energy Flow Comparison (California-1 Battery)

energy bought from the grid during the peak-hour. Also, the peak-hour could be extended from 20:00 to 23:00, making the energy inside the battery to be better used by the load instead of selling back to the grid. The suitable combination of these methods could actually prove that both PMM2 and PMM3 can effectively decrease the amount of energy bought from grid side with the high retail price. Below, in Table 3.7, it shows when the PV panels size goes down to 8 with peak-hour existed between 14:00 and 23:00, with a large battery size, PMM2 and PMM3 can still reduce the energy bought during the peak-hour, however, the total energy bought from the grid during the whole may increase remarkable, making neither PMM2 nor PMM3 the best choice for prosumers.

Table 3.7: Peak-Hour Energy Consumption Comparison (California)

PMM		PMM1			PMM2		PMM3	
Time		07:00-23:00	14:00-23:00	00:00-24:00	07:00-23:00	00:00-24:00	14:00-23:00	00:00-24:00
1 Battery	Energy (kWh)	2296.52	1841.10	4397.28	2296.52	5620.96	1841.10	4397.28
	Percentage (%)	52.23	41.87	1	40.86	1	41.87	1
2 Battery	Energy (kWh)	1339.37	882.87	3438.82	1338.28	5885.09	882.87	3576.34
	Percentage (%)	38.95	25.71	1	22.74	1	24.69	1
3 Battery	Energy (kWh)	739.14	283.73	2651.54	400.36	6169.45	170.38	3790.54
	Percentage (%)	27.88	10.70	1	6.49	1	4.49	1
[1] The PV panels' number is downsized from 10 to 8, the peak hour is expanded from 20:00 to 23:00.								

3.4. The influence of PV panels and battery on the system

In order to study the influence of PV panels and battery on the system and power flow, it is essential to see what will happen if the PV panels or the battery is not included in the system. Together with PMM, the following 8 cases could happen:

Case 1: No PV panels, no battery storage, without PMM;
Case 2: With PV panels, no battery storage, without PMM;
Case 3: With battery storage, no PV panels, without PMM;
Case 4: With PV panels and battery storage, without PMM;
Case 5: No PV panels, no battery storage, with PMM;
Case 6: With PV panels, no battery storage, with PMM;
Case 7: With battery storage, no PV panels, with PMM;
Case 8: With PV panels and battery storage, with PMM.

For each PMM, no matter how the power flows or what time it is, PV panels' production is always used to support the load first, if there is some extra energy left, then based on different PMM, the extra energy will be used to charge the battery or directly sold back to the grid. From load side, no matter how the power flows or what time it is, the first energy source to support the load is always the PV panels' production, if the PV panel' production is not enough or there is no energy from PV panels, then based on different PMM, the system will decide whether to discharge the battery or directly buy the rest energy demand from grid. In other words, the PMMs control the energy exchange between battery storage and other units (PV panels, load, and grid). In this way, there is no need to discuss the PMM if there is no battery storage, therefore, case 5, and case 6 are not necessary to be discussed. Besides, if there is battery storage without PMM, the energy exchange between battery storage and other units will also be chaotic because there is no instruction to manage the energy exchange, in this way, case 3, and case 4 are also phased out. Case 8 is the normal case of this thesis and discussed in Chapter 3, Section 3.2, leaving case 1, case 2, and case 7 to be discussed in the section. Case 1 will be referred to as NPVNB in this section; Case 2 will be referred to as PVNB in this section; Case 7 will be referred to as NPVB in this section; Case 8 will be referred to as PVB in this section.

3.4.1. No PV panels, no battery storage, without PMM

If neither the PV panels nor the battery storage is in the system, the energy exchange could only happen between the load and the grid. In this case, the only energy source for the load is the grid, which means all the load requirement can only be supported with the energy from grid, prosumers directly buy energy from the grid to satisfy the load. From grid side, energy is only sold to the load and there is no energy injected into the grid. Table 3.8 shows the power flow for NPVNB case.

3.4.2. With PV panels, no battery storage, without PMM

The existence of PV panels provides another energy source for the load. Actually, in this case, PV panels' production is the first choice for load consumption, the rest energy gap will be satisfied by the energy bought from the grid. From PV panels side, the

Table 3.8: Power Flow for NPVNB case

Time	Load Power Flow	Grid Power Flow
00:00-24:00	Directly buy from grid.	Energy accepted by gird: None; Energy sold from grid: Load.

energy production can be used to support the load first, if there is some energy left, the excess energy will be sold back to grid directly. From grid side, the energy is only sold to support the load, while the PV panels are the only energy source that sold energy back to the grid. Table 3.9 shows the power flow for PVNB case.

Table 3.9: Power Flow for PVNB case

Time	PV Power Flow	Load Power Flow	Grid Power Flow
00:00-24:00	(1) Support the Load; (2) Sold back to grid.	(1) Consume PV generation; (2) Buy from grid.	Energy accepted by grid: PV. Energy sold by grid: Load.

3.4.3. WITH BATTERY STORAGE, NO PV PANELS, WITH PMM

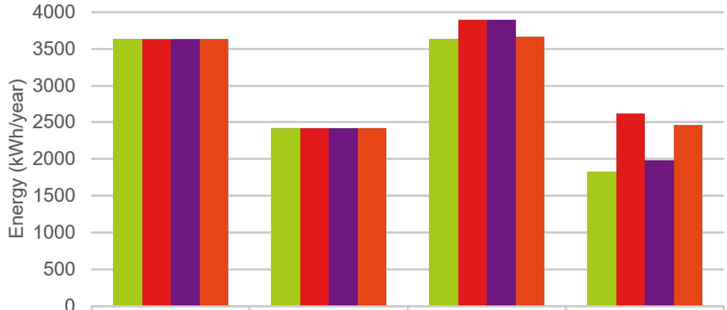
IN this case, both the battery and the grid can be the energy sources for load, the sequence order depends on which PMM is active. If it is possible to discharge the battery, the battery could be the first choice for the load, and the energy from grid can be used to satisfy the rest energy gap. However, if it is not possible to discharge the battery, then the grid is the only energy source for the load and all the energy from load side could be directly satisfied with the energy from grid. Because of the existence of the battery, the grid may sell some energy to charge the battery and support the load when the battery is not enough or not allowed to discharge. Based on different PMMs, the battery could sell some energy back to the grid by discharging. Table 3.10 shows the power flow for NPVB case.

Table 3.10: Power Flow for NPVB case

Time	Battery Power Flow	Load Power Flow	Grid Power Flow
00:00-24:00	(1) Support the Load; (2) Sold back to grid (PMM2 and PMM3).	(1) Discharge the battery; (2) Buy from grid.	Energy accepted by grid: battery (PMM2 and PMM3). Energy sold by grid: battery + load.

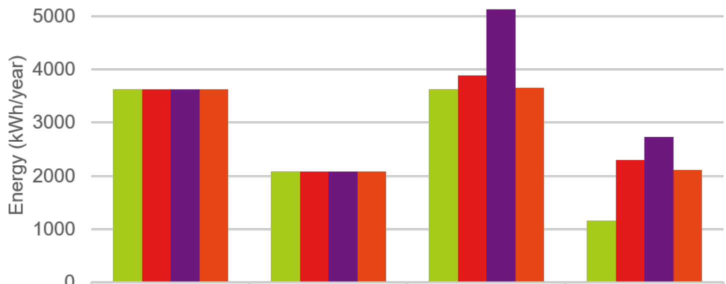
For all three countries/regions, compared with no PV panels and no battery case, adding both PV panels and battery into the system can effectively decrease the energy purchased directly from the grid, which can be seen from Figure 3.36, Figure 3.37, and Figure 3.38. However, for different PMMs, the existence of both PV panels and battery may not be the most economical choice for prosumers. Actually, only with PMM1, it is suggested to have both the PV panels and the battery together in the system for all three countries/regions. For the rest three PMMs, sometimes only PV panels are good enough for prosumers as far as only the energy bought from the grid is concerned. PV panels are very important to the system, for all three countries/regions, as long as the

PV panels are involved in the system, the energy directly purchased from the grid can be effectively lowered. It is also not suggested to only have battery storage in the system since the amount of energy supported by the grid cannot be lowered, and actually, the amount of energy purchased from grid can even be higher than no battery case, this is because charge battery needs extra energy and if there is only battery storage in the system, the only possible energy source is the grid, and due to the energy loss happens when charge the battery and discharge the battery, more energy is needed when use the battery energy to support the load.



	NPVNB	PVNB	NPVB	PVB
PMM1	3629.67	2425.69	3628.35	1824.46
PMM2	3629.67	2425.69	3893.80	2619.42
PMM3	3629.67	2425.69	3893.80	1981.60
PMM4	3629.67	2425.69	3665.10	2459.62

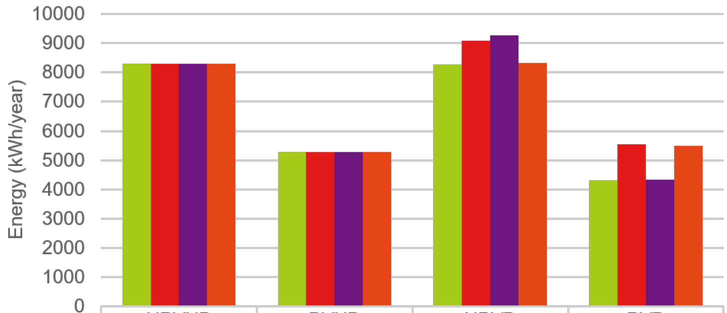
Figure 3.36: Comparison of Energy Bought from Grid Between NPVNB, PVNB, NPVB and PVB (the Netherlands)



	NPVNB	PVNB	NPVB	PVB
PMM1	3624.7	2080.18	3623.38	1157.09
PMM2	3624.7	2080.18	3888.82	2305.57
PMM3	3624.7	2080.18	5131.04	2734.16
PMM4	3624.7	2080.18	3659.19	2113.82

Figure 3.37: Comparison of Energy Bought from Grid Between NPVNB, PVNB, NPVB and PVB (Costa Rica)

However, the main function of the battery is to lower the amount of energy bought



	NPVNB	PVNB	NPVB	PVB
PMM1	8285.15	5277.74	8281.21	4318.19
PMM2	8285.15	5277.74	9077.46	5541.87
PMM3	8285.15	5277.74	9261.98	4341.63
PMM4	8285.15	5277.74	8329.23	5479.09

Figure 3.38: Comparison of Energy Bought from Grid Between NPVNB, PVNB, NPVB and PVB (California)

with a high retail price. This makes battery important in the system. Table3.11, Table 3.12, Table 3.13 show that although the amount of energy bought during other periods increases, the amount of energy bought during peak-hour can be remarkably lowered down for all three cases. This is the reason that battery is very important to the system structure.

Table 3.11: The Amount of Energy Bought with High Price (the Netherlands)

	NPVNB		NPVB		
Period (kWh)	Peak-Hour	Off-Peak-Hour	Peak-Hour	Off-Peak-Hour	Battery Size
PMM2	2802.41	827.26	1844.17	2049.63	1 Battery
PMM3	1232.14	2397.53	273.90	3619.90	1 Battery
PMM4	173.30	3456.36	43.91	3621.19	0.25 Battery

Table 3.12: The Amount of Energy Bought with High Price (Costa Rica)

	NPVNB			NPVB			
Period (kWh)	Peak-Hour	Valley-Hour	Night-Hour	Peak-Hour	Valley-Hour	Night-Hour	Battery Size
PMM2	2846.78	——	777.92	1888.54	——	2000.28	1 Battery
PMM3	939.71	1466.17	1218.82	0	3913.53	1217.51	1 Battery
PMM4	168.06	3456.64	——	42.47	3616.72	——	0.25 Battery

For the Netherlands case, the total amount of energy bought from the grid is the same for PMM2 and PMM3 if only the battery storage is involved in the system. This is because for the Netherlands case, the standard battery size is only 1 for PMM2 and PMM3, in this case, for the first day, during the first hours before dawn, the battery has already reached its lowest SOC, so that from the perspective of the entire year, the energy used to charge the battery during any day of the year is always the same for PMM2 and PMM3, leading to a same total amount of energy charged into the battery during the

Table 3.13: The Amount of Energy Bought with High Price (California)

	NPVNB			NPVB			
Period (kWh)	Peak-Hour	Valley-Hour	Night-Hour	Peak-Hour	Valley-Hour	Night-Hour	Battery Size
PMM2	6180.27	——	2104.88	3305.56	——	5771.90	3 Battery
PMM3	2807.16	2684.00	2793.99	116.88	6355.04	2790.05	3 Battery
PMM4	250.72	8034.43	——	92.14	8237.09	——	0.25 Battery

3

year. And actually, the amount of energy that used to charge the battery and support the load are both equal for PMM2 and PMM3, the simulation results the numbers are 1223.68kWh and 1670.12kWh, respectively.

For Costa Rica case, although the standard battery size for PMM2 and PMM3 are the same as the Netherlands case, the definitions of peak-hour are different. For Costa Rica, two peak-hour periods exist in the same day, making the battery being fully charged two times every day. This leads to a remarkably higher amount of energy bought from the grid if compared with PMM2. From Table 3.14, it can be found that PMM3 needs a little more than 2 times the energy for battery charging than PMM2, while the amount of energy to support the load is almost the same. The number is not exactly 2 is because on the first day when the battery starts being charged with PMM2 case, the battery is not fully discharged, to be exact, the charging process starts at 05 : 00 and 238.62 Wh is still left in the battery. While for PMM3, the battery is empty when battery forced charging period starts. The amount of energy bought from the grid to support the load is almost the same for PMM2 and PMM3.

Table 3.14: Comparison Between PMM2 and PMM3 for NPVB case (Costa Rica)

PMM	Battery Size	GSB (kWh)	GSL (kWh)	GS (kWh)
PMM2	1 Battery	1223.64	2665.18	3888.82
PMM3	1 Battery	2447.36	2683.68	5131.04

However, for California case, although the situation is very familiar with the Netherlands case, the larger battery size becomes a critical factor that directly decides the amount of energy charged into the battery during the entire year. With a standard battery size equals 3 for the PMM2 and PMM3 for California case, a relatively large battery size leads to a longer battery forced charging period, so does the battery forced discharging period. For PMM3, although the peak hour starts from 14 : 00 and ends at 20 : 00, the battery forced discharging period starts at 14 : 20, just 20 minutes after the peak hour starts. This results in more energy is sold back to the grid instead of supporting the load. In other words, although every day the same amount of energy could be charged into the battery for PMM2 and PMM3, the amount of energy could be used to support the load is different. For PMM2, due to a longer peak-hour, more energy from battery discharging could be used to support the load, in this way, from load side, less energy is needed and therefore less energy is bought directly from the grid, leading to the total amount of energy bought from the grid for the entire year is lower if compared with PMM2. However, since for both PMM2 and PMM3, every day the battery only be charged once from lowest SOC to highest SOC, the total amount of energy that used to charge the battery should be almost the same from the point of the whole year, just like the Netherlands case. Actually, unlike the Netherlands case, there is still some small differences. For PMM2 for California case, $3668.52kWh$ is used to charge the battery, while for PMM3 for California case, $3671.04kWh$ is used to charge the battery. The standard battery size is still the contributor to these differences. For PMM2, the peak-hour starts from $07:00$ in the morning, therefore, the battery forced charging period starts more than six hours before, to be exact, starts from $00:50$. Although for a relatively lower load demands during the night hours before dawn, the battery may not start being charged right after the battery forced charging period starts, some energy is still left in the battery when the battery starts being charged. Actually, the simulation results show that on the first day, the battery starts being charged at $03:40$, at that time, there is still about $2700.81Wh$ stored in the battery, which means the battery is not totally discharged on the first when the battery starts being forced charging. However, for PMM3, when the battery forced charging periods starts at $07:50$, the battery is already being totally discharged. It is these small differences that make the total amount of energy that used to charge the battery during the entire year looks different for PMM2 and PMM3. Actually, if the first day is not considered, for the rest 364 days in a year, the same amount of energy is used to charge the battery, and the amount equals $3660.99kWh$.

3.5. CONCLUSIONS

THIS chapter introduced four different power management methods and their power dispatch methods. Based on these four power management methods, the simulation results for the Netherlands, Costa Rica and California are explained in the third part of this chapter. The influence of battery storage and PV panels on the system are discussed in the last part of this chapter.

From the simulation results it can be found that with a suitable battery size, PMM2 and PMM3 can effectively reduce the amount of energy bought from the grid with high retail price. With a larger battery size, the energy bought with the high retail price could almost be reduced 0. to No matter which power management method is chosen, the grid is still one of the main energy source for the load, despite what the battery size is. Also, PV panels are the main energy source that sell energy back to the grid.

Peak-shaving can provide a smoother energy buying mode from the grid, the sudden energy peak can be effectively reduced. Plus, compared with other three power managemnent methods, the battery size is smaller if peak-shaving is chosen. The reference value could influence the load side energy composition. With the lower reference value, the larger the battery size is needed, however, the total amount of energy bought from the grid does not change too much.

If only consider the amount of energy bought from the grid, PMM1 is the best power management method.

Both the PV panels and battery storage unit play an important role in the system. PV panels can directly reduce the amount of energy purchased from the grid. Battery storage unit can lower the amount of energy bought with the high retail price. The existence of PV panels and the battery can effectively decrease the energy bought directly from the grid. However, the existence of both PV panels and the battery may not be the most economical choice for prosumers. Actually, for all three countries/regions, only with PMM1, it is suggested to have both PV panels and the battery together in the system, for the rest three PMMs, sometimes, only PV panels can be good enough for prosumers as far as only the energy buying process is concerned. However, no matter which case is considered, it is not recommended to only have battery storage unit in the system without PV panels.

4

ELECTRICITY TARIFFS

Electricity tariff is comprised of two parts, one is the buy-in tariff, which defines the electricity buy-in price; the other tariff defines the compensation price when prosumers sell energy back to grid; according to different working patterns, it could be called feed-in tariff, as for the Netherlands case and California case; or it could be called access tariff, as for Costa Rica case. In order to be consistent, the feed-in tariff is used hereafter for the Netherlands case and California case, while access tariff is used hereafter for Costa Rica case; the differences of these two tariffs will be described in Section 4.1. The electricity tariffs can decide the final energy bill, since different energy companies provide different tariff structures, customers can choose the tariff that best suits for their own energy consumption pattern. The energy bill is another way to reflect how the energy flows in the system, therefore, together with the suitable power management method, a suitable tariff can save more money and provide higher profit for prosumers. It is critical to study the detail of each electricity tariff structure, and then based on the profit the prosumers can finally get, a suitable combination of power management methods and electricity tariff can be found.

In this chapter, the popular electricity tariff structures for the Netherlands, Costa Rica and California are introduced in Section 4.1. The newly designed tariffs are introduced in Section 4.2, and later further expanded to suit for different countries/regions with different PMMs. The simulation results of newly designed tariff structures are shown in Section 4.3. Based on these simulation results, some important conclusions are explained and a suitable combination of power management method and electricity tariff will be suggested in the last part of this Chapter.

4.1. EXISTED TARIFF STRUCTURES

THE electricity tariff is made up with electricity buy-in tariff and feed-in tariff. The buy-in tariff explains the detail price information when prosumers buy energy from the grid, while the feed-in tariff indicates the price structures when consumers sell energy back to the grid. There are many different electricity tariff structures in the market, and each of them has their own advantages. It is important for a consumer to choose the suitable electricity tariff according to their own energy consumption pattern, since different electricity tariffs could lead to different energy bill; while on the other hand, it is also important for energy providers to design reasonable tariff that can not only match the market needs, but also make considerable profit at the same time. The electricity tariff is the link between prosumers and energy providers. A good tariff can bring considerable revenue for energy providers and lead to a reasonable cost for prosumers at the same time. For different countries/regions, different tariff structures are proposed by the government and the energy provides. The tariffs are designed to suit for their own characteristics, that is the reason why that sometimes even with the same tariff type, the details used to calculate the final energy bill are different. In this sector, the popular buy-in tariffs in the market and several common feed-in tariffs are introduced; the advantages and disadvantages of each tariff will also be mentioned right behind each tariff.

4.1.1. THE NETHERLANDS TARIFF STRUCTURES

FOR the Netherlands case, three different electricity buy-in tariff structures are gathered, they are the fixed tariff structure and time-of-use tariff from E.ON [67], and day-ahead tariff from ENTSO-E Company [68]. A different peak-hour definition of peak-hour is provided by [69], leading to a different time-of-use due to the different peak-hour. Those four electricity buy-in tariff structures are introduced in the following paragraphs.

The fixed tariff keeps the energy price fixed for a period of time, usually six months or one year, during this contract period, no matter what amount of energy is purchased by prosumers, and no matter when the energy is purchased, the energy price is always the same as the fixed value in the contract. Compared with the other two tariffs, this fixed price is usually between the peak-time-price and off-peak-price from the time-of-use tariff. This kind of tariff is more economic preferred if more energy is consumed during peak-hour and prosumers do not want to switch their loads to better suit for energy price.

The time-of-use (ToU) tariff is another popular buy-in tariff in the market, the most obvious characteristic of this tariff is the different electricity retail price for different time periods. The governments or energy providers will decide the time periods according to regular energy consumption patterns in the past and tie-in with off-peak hour, base-peak hour and peak hour. The electricity price for the off-peak period is the lowest and for peak hour is the highest, while for the base-peak hour, the price is a middle value between the off-peak-hour-price and peak-hour-price. The base-peak hour and peak hour may not exist at the same time, usually, energy companies choose one of these two to make the tariffs simpler, but there are some energy companies choose to have all of three periods together in one tariff structure. This leads to different buy-in price structures for the time-of-use tariff, the first is combined with off-peak-hour and base-peak-hour, the second is comprised by off-peak-hour and peak-hour, and the last structure is made up with all these three periods. It should be clear that during each period, the electricity price is fixed no matter how much energy is consumed. For structure one, the base-peak hour is usually a long period which starts in the morning and ends at night, the off-peak hour is usually during the night. But for structure two, the peak periods usually exist in the morning and night during the weekdays, the morning peak is because people get up to prepare for work and school during morning, the night peak is because people return home from work to enjoy the evening and all the other activities, like cooking and washing that happens before going to bed. The rest of time is defined as the off-peak hour, which includes the rest time of weekdays and the whole weekend. The consumers who are available during the off-peak-hour or willing to transfer more loads from peak-hour to off-peak-hour may choose this kind of tariff to use the advantage of low energy price during off-peak-hour. The third structure is mixed with off-peak-hour, base-peak-hour, and peak-hour, the definition of these periods during the week may be different according to different energy providers, but usually the peak-hour exists in the evening when people return home from work and school, while some energy companies consider the morning peak as part of peak-hour, others sort morning peak in the base-peak-hour; the base-peak-hour could last longer until the peak-hour begins in the evening; and the daytime of weekends are usually considered as part of base-peak-hour; the rest time is the off-peak-hour, which is mainly the night hours. This structure separated one day in different periods and is more accurate than the other two methods. Therefore, this structure can provide better load management choice than the first two time-of-use structures.

For the Netherlands, E.ON provides a clear definition of peak-hour and off-peak-hour along with the electricity buy-in prices for that two periods. The detail information is listed here in Table 4.1. The tax is included.

Table 4.1: Peak-Hour and Off-Peak-Hour Definition (E.ON)

Period	Time	Electricity Price (€/kWh)
Peak-Hour	07:00—23:00	0.2057000
Off-Peak-Hour	00:00—07:00 & 23:00—24:00	0.1871870

The time-of-use electricity buy-in tariff from E.ON Company is chosen as the standard tariff because it gives an explicit definition of the peak-hour period and the off-peak-hour period with definite buy-in prices for each period. In order to make different electricity buy-in tariffs comparable, the idea is to let different buy-in tariffs have the same average buy-in price, which is calculated based on the buy-in tariff from E.ON Company. E.ON considers the peak-hour is from 07:00 to 23:00 with the high buy-in price equals to 0.2057000 €/kWh, and the off-peak-hour is made up with two time slices, one is from 00:00 to 07:00, the other is from 23:00 to 24:00, the low buy-in tariff during these two time periods is 0.187187 €/kWh. So that the average buy-in price can be calculated with Equation 4.19,

$$P_{av-buy} = \frac{0.205700€/kWh \times 16 + 0.187187€/kWh \times 8}{24} = 0.199529€/kWh \tag{4.1}$$

which means the average buy-in price for the whole day is 0.199529 €/kWh. Thus, the fixed buy-in price is set to be 0.199529 €/kWh.

Another time-of-use structure is also introduced with a shorter peak-hour starts from 17:00 and last until 23:00, the rest time is considered as the off-peak hour, which is from 00:00 to 17:00 and from 23:00 to 24:00. The peak-hour is chosen in this form is because from [69], it gives an official definition of time-of-use structure for winter period for the Netherlands, it is said the peak-hour starts from 17:00 to 20:00 during the weekdays, while the rest of weekdays, as well as the whole weekends, are considered as off-peak-hour. The end of peak-hour is postponed from 20:00 to 23:00 because it can better match the real case of load pattern for the Netherlands. Figure 4.1 shows the load of six random days in the winter period (January 1st, February 1st, September 1st, October 1st, November 1st, December 1st,) and Figure 4.2 shows the load for six random days in the summer period (March 1st, April 1st, May 1st, June 1st, July 1st, August 1st). Both figures suggest that it will be more truthfulness if the peak-hour ends at 22:00 or 23:00, which also conforms to the normal pace of life. Another reason is that the article [69] only gives the time-of-use definition for winter weeks, but no information about summer weeks. Since E.ON precisely points out that the peak-hour ends at 23:00, in the second time-of-use structure, 23:00 is finally chosen instead of 22:00. The start time 17:00 matches the load profile and life rhythm and it is kept in the second time-of-use structure. It is assumed that for the second time-of-use buy-in tariff structure, the low buy-in price during the off-peak hour is still 0.1871870 €/kWh, based on the same average buy-in price principle, the high buy-in price during the peak-hour can be calculated with Equation 4.2, the entire definition of this time-of-use tariff structure is shown in Table 4.2.

$$P_{high-buy} = \frac{0.199529€/kWh \times 24 - 0.187187€/kWh \times 18}{6} = 0.236555€/kWh \tag{4.2}$$

Table 4.2: Second Time-of-use Tariff Structure (the Netherlands)

Period	Time	Electricity Price (€/kWh)
Peak Period	17:00 — 23:00	0.236555
Off-Peak Period	00:00 — 17:00 & 23:00 — 24:00	0.1871870

The fourth buy-in price structure is the day-ahead structure, the price is got from ENTSO-E Company [70]. These day-ahead prices are used to simulated the real-time prices case for the Netherlands case. The advantage of real-time tariff is obvious because the electricity buy-in price is changed every 30 minutes or hourly, and usually the price is higher when the energy requirement is higher, the price is lower when the energy requirement is lower. But it should be clear that although this tariff is called the real-time tariff, the price doesn't change according to the real-time requirement. The price is calculated based on the load forecasting and be announced several hours or even one day before, thus in return can help consumers better schedule their load consumption. In this way, a very good and accurate load and weather forecasting are required to provide a more reasonable buy-in price.

Due to the loss of part original data provided on ENTSO-E official website, some procedures has to be taken to fix up these problems, detail information is described in Ap-

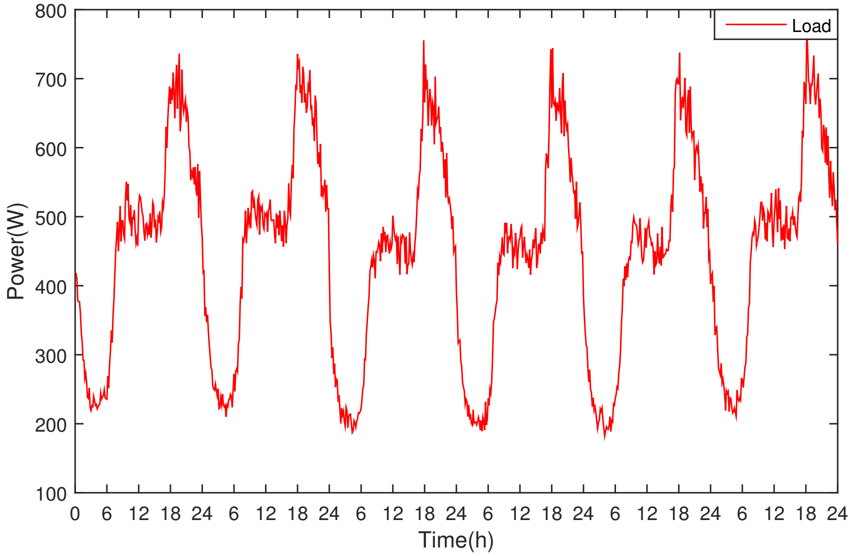


Figure 4.1: Load Profiles during Winter Months (The Netherlands)

pendix C.

Table 4.3: Electricity Buy-in Tariff Structures (the Netherlands)

Electricity Buy-in Tariff Structures		Price (cents/kWh)
Fixed	00:00—24:00	19.95
Time-of-Use Structure One (E.ON)	00:00—07:00 & 23:00—24:00	18.72
	07:00—23:00	20.57
Time-of-Use Structure Two	00:00—17:00 & 23:00—24:00	18.72
	17:00—23:00	23.36
Real-Time	00:00—24:00	[1]
[1] The day-ahead price is from Entso-e company, and enlarged by 6.18 times.		

All four tariff structure for the Netherlands is shown in Table 4.3 and Figure 4.3. In Figure 4.3, the red line represents the fixed price which equals to 0.199529 €/kWh; the green line stands for the first time-of-use buy-in structure defined by E.ON; the purple line is the second time-of-use buy-in structure with peak-hour between 17:00 and 23:00; the brown line shows the amplified day-ahead price from ENTSO-E Company. These four tariff structures all have the same average buy-in price, which equals to 0.199529 €/kWh.

The feed-in tariffs also vary between different energy companies. But they always related to the total amount of energy consumers buy from the grid and the total amount of energy consumers sell back to the grid in one year. For the Netherlands case, the most common structure is that when prosumers sell less energy back to the grid then

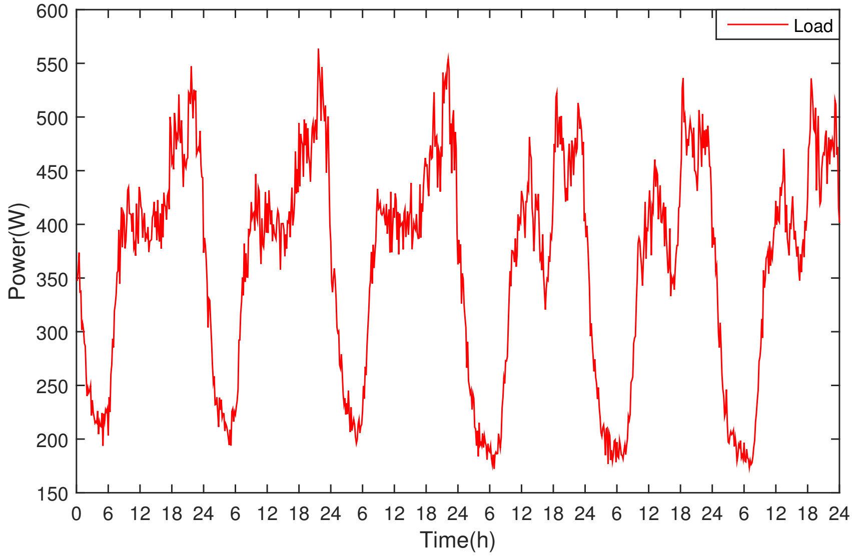


Figure 4.2: Load Profiles during Summer Months (The Netherlands)

they buy, then the energy sold back to the grid will be fully netted. When prosumers sell more energy back to the grid than they buy, then the excess amount of energy can only be compensated by a low feed-in tariff, and usually, this low tariff is much lower than the buy-in tariff. This value is different according to different energy companies, for example, E.ON will compensate consumers with 0.07 €/kWh, excluding the VAT [71]; while Nuon chooses to reimburse consumers for 0.07 €/kWh, including the VAT [71]; but the consumers with Eneco will receive a refund of 0.092 €/kWh, including the VAT [71]. However, there are other buy-in structures, even if they don't change too much, they are also listed here to better illustrate the buy-in tariff structure. Essent claims that from August 1st, 2014, when the grid receives less energy than the amount of energy it sells to consumer, the return energy will be fully netted; when the grid receives more energy than the amount of energy it sells to grid, the first 10000 kWh will be compensated with price 0.08 €/kWh, excluding the VAT, for the part larger than 10000 kWh, the purchase price is 0.04 €/kWh, excluding the VAT. Main Energy makes the buy-in tariff more detail in 2015 by saying that the consumption and return delivery energy are fully netted to a maximum amount of 50000 kWh. There are two different feed-in structures, neither of them including the VAT. The first structure is with peak-hour-price and off-peak-hour-price, which are 0.05 €/kWh and 0.03 €/kWh, respectively; the second structure is a single price structure with the single rate 0.045 €/kWh. However, it is not very clear what the price structure will be if consumers sell more than 50000 kWh electricity back to grid on the official website. The first feed-in structure is chosen to do the simulation together with the four different buy-in prices structures for the Netherlands in the thesis, and when consumers sell more energy back to the grid, the low compensation tariff is 0.092

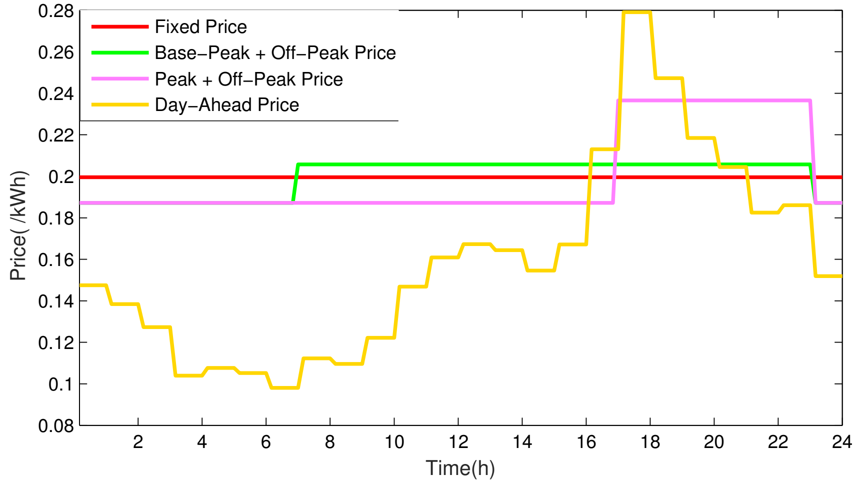


Figure 4.3: Price Structure (the Netherlands)

cents/kWh, VAT included.

4.1.2. COSTA RICA TARIFF STRUCTURE

FOR Costa Rica, ICE, CNFL, JASEC are several main energy providers. They all have their own electricity tariffs, which may differ from tariff structures and prices. The structures of Costa Rica electricity tariffs are more complex compared with the Netherlands case. In the following paragraphs, it will be explained in detail.

The electricity tariff is composed of buy-in tariff and access tariff. For residence use, there are two popular buy-in tariff structures, namely the fixed tariff and time-of-use tariff. No matter which tariff is used, the electricity buy-in price will change every month with different consumption levels. CNFL company defines both two structures, which are listed below in Table 4.6 and Table 4.8, respectively.

For the fixed tariff structure, the buy-in price changes every month; and for each month, there are four consumption levels. Level one can be considered as the basic level which has the energy range from 0 to 30 kWh. For the first 30 kWh, CNFL charges 1868.40 Colons together for January. That means, as long as the prosumers involve with this tariff structure, they will be changed 1868.49 Colons as the basic energy bill for January even if the prosumers do not buy any energy from the grid. However, start from the 31st kWh, the energy bought from the grid will be charged per kWh. The second level is from 31 kWh to 200 kWh, which has the price equals to 62.28 Colons/kWh for January. The third level is from 201 kWh to 300 kWh with the price equals to 95.58 Colons/kWh for January. And if the prosumers buy more than 300 kWh from the grid during that month, then they will be charged with a higher buy-in tariff, for example, the price will be 98.80 Colons/kWh for January. For each month, there are these four levels, the price for each level will change from month to month. The detail price structure can be found in Table 4.6. JASEC provides another different fixed tariff structure, the main difference is the definition of energy level. Instead of four different energy levels as CNFL does, JASEC only considers three different energy levels. The detail information is also listed here in Table 4.7.

For the time-of-use tariff, the price changes several times within a day and depends on the time that the energy is bought from the grid. CNFL gives a clear definition of these time periods. There are two peak-hour periods in a day, the first is in the morning, starting from 10:00 to 12:30, the other one is at night between 17:30 and 20:00. During the daytime there are also two valley periods, the first is in the morning, starting from 06:00 to 10:00; the other one is in the afternoon from 12:30 to 17:30. The night period is from 00:00 to 06:00 and 20:00 to 24:00. The detail definition can be found in Table 4.4. For each period, there are three different consumption levels, namely, from 0 to 300 kWh, from 300 kWh to 500 kWh and from 500 kWh or above. The electricity is charged per kWh with a fixed price for each level. During each month, during the same period, the more energy is bought from the grid, the higher the price is. The detail price structure can be found in Table 4.8.

Table 4.4: CNFL Time-of-Use Time Period Definition (Costa Rica)

Peak-Hour	10:00—12:30 & 17:30—20:00
Valley-Hour	06:00—10:00 & 12:30—17:30
Night-Hour	00:00—06:00 & 20:00—24:00

Table 4.5: Costa Rica Available Access Tariffs

Energy Provider	Access Tariff (Colon/kWh)
ICE	28.3
CNFL	18.0
JASEC	14.6
ESPH	11.6
COOPELESCA	29.4
COOPEGUANACASTE	21.3
COOPESANTOS	29.7
COOPEALFARO	28.6

Table 4.6: CNFL Fixed Tariff Definition

Level	January	February	March	April	May	June	July	August	September	October	November	December
First 30 kWh (Colons)	1868.40	1868.40	1868.40	1892.55	1892.10	1892.10	1883.10	1883.10	1883.10	2100.30	2100.03	2100.03
31 kWh – 200 kWh (Colons/kWh)	62.28	62.28	62.28	63.09	63.07	63.07	62.77	62.77	62.77	70.01	70.01	70.01
200 kWh – 300 kWh (Colons/kWh)	95.58	95.58	95.58	96.81	96.79	96.79	96.33	96.33	96.33	107.43	107.43	107.43
300 kWh and above	98.80	98.80	98.80	100.07	100.05	100.05	99.58	99.58	99.58	111.06	111.06	111.06

Table 4.7: JASEC Fixed Tariff Definition

Level	January	February	March	April	May	June	July	August	September	October	November	December
First 30 kWh (Colons)	2047.50	2047.50	2047.50	2070.20	2069.70	2069.70	2060.70	2060.70	2060.70	2060.40	2060.40	2060.40
31 kWh – 200 kWh (Colons/kWh)	68.25	68.25	68.25	69.01	68.99	68.99	68.69	68.69	68.69	68.68	68.68	68.68
200 kWh and above	83.55	83.55	83.55	84.47	84.45	84.45	84.08	84.08	84.08	84.06	84.06	84.06

Table 4.8: CNFL Time-of-Use Tariff Definition

Period	Level	January	February	March	April	May	June	July	August	September	October	November	December
Peak -Hour	0 - 300kWh*	132.09	132.09	132.09	133.80	133.77	133.77	133.13	133.13	133.13	148.48	148.48	148.48
	300 kWh –500 kWh*	150.35	150.35	150.09	152.30	152.26	152.26	151.54	151.54	151.54	169.00	169.00	169.00
	500 kWh and above*	178.27	178.27	178.27	180.57	180.53	180.53	179.68	179.68	179.68	200.39	200.39	200.39
Valley -Hour	0 - 300kWh*	54.76	54.76	54.76	55.47	55.46	55.46	55.20	55.20	55.20	61.57	61.57	61.57
	300 kWh –500 kWh*	61.21	61.21	61.21	62.00	61.99	61.99	61.69	61.69	61.69	68.79	68.79	68.79
	500 kWh and above*	71.95	71.95	71.95	72.88	72.86	72.86	72.52	72.52	72.52	80.89	80.89	80.89
Night -Hour	0 - 300kWh*	22.55	22.55	22.55	22.85	22.84	22.84	22.73	22.73	22.73	25.35	25.35	25.35
	300 kWh –500 kWh*	25.78	25.78	25.78	26.11	26.10	26.10	25.98	25.98	25.98	29.98	28.98	28.98
	500 kWh and above*	33.29	33.29	33.29	33.73	33.72	33.72	33.56	33.56	33.56	37.32	37.42	27.42
*Unit: Colons/kWh; the international exchange rate 1 dollar ≈ 567.81 colon.													

The access tariff is used to compensate prosumers when they sell energy back to the grid. It is different from feed-in tariff. For Costa Rica, different energy providers give different access tariffs and the price can vary a lot from one company to the other [72]. For example, the ICE access tariff is 28.30 Colons/kWh, CNFL is 18.00 Colons/kWh, JASEC is 14.60 Colons/kWh and for ESPH, the access tariff can even be as low as 11.60 Colons/kWh, the access tariff for main energy providers in Costa Rica can be found in Table 4.5. Costa Rica government establishes some rules about how this access tariff work. The energy compensated with access tariff cannot excess 49% of PV production. That means if the prosumers sell more than 49% of their PV panels' production back to the grid, the part of energy that excess 49% can be considered as being wasted. If the prosumers sell less than 49% of their PV panels' production, the final energy bill depends on what amount of energy is bought from the grid. If the prosumers buy more energy from the grid than the amount they sell back, then the energy sold back to the grid will be fully compensated with the fixed access tariff, and this amount of energy will be deducted from the total amount of energy bought from the grid. The rest of energy bought from the grid will be charged according to different levels. However, if the prosumers sell more energy back to the grid then they buy, then all the energy bought from the grid will be charged with the fixed access tariff, and the rest part will be accumulated to the next month. This process continues for the entire year. If at the last month of the year, the total amount of energy that could compensate with access tariff is higher than the buy-in energy, then all the buy-in energy can be charged with access tariff and the rest part of energy will be sold back to the grid with no money. An example in Appendix A, Section A.1 is given to better understand the working principle of Costa Rica electricity tariff.

4.1.3. CALIFORNIA TARIFF STRUCTURE

FOR California, time-of-use tariff structure is a widely used tariff structure. As one of the main energy providers in South California, Southern California Edison (SCE) provides an accurate tariff. The buy-in tariff is comprised of three time periods, the peak period starts from 14:00 and ends at 20:00 for weekdays, off-peak period is between 08:00 and 14:00 and 20:00 and 22:00 during weekdays, during weekends, off-peak hour is last all day long from 08:00 to 22:00; the rest is the super off-peak period, it includes 00:00 to 08:00 and 22:00 to 24:00 for the whole week. The electricity price is also different with summer rates and winter rates for each period, detail information can be found in Table 4.9. The feed-in tariff is a little bit similar to the Netherlands case but still have some differences. They use net energy metering (NEM) to compensate prosumers for the electricity they sell back to the grid over a 12-month period length, and this 12-month period is also referred to as the "Relevant Period" by SCE. During this relevant period, if prosumers consume more energy than the energy they sell back to grid, they are considered as "net consumer", the energy they generate should be fully netted; if prosumers export more energy than they import, they are considered as "net generator", the Net Surplus Compensation Rate (NSCR) is used to compensate prosumers with the part that exceeds their on-site consumption. The energy usage is tracked every month and may be settled monthly or annually depending on the rate schedule. For the "net generator", the NSCR depends on the when the relevant period ends because the price is different from one month to another, the NSCR for 2017 can be found in Table 4.10. This price is used to pay for the net surplus production over the entire relevant period. For example, if the relevant period ends in July of each year, then for the relevant period for 2017, $0.02565\$/kWh$ is used as the price to compensate prosumers for all the net surplus energy for this relevant period. For simulation, the average price for 2017 is used, which is $0.02595\$/kWh$.

Table 4.9: Peak and Off-Peak Time Periods Definition for California

<table>
<tr><th colspan="2" rowspan="2">Period</th><th rowspan="2">Time</th><th colspan="2">Electricity Price (dollar cents/kWh)</th></tr>
<tr><th>Summer Rates [1]</th><th>Winter Rates [1]</th></tr>
<tr><td rowspan="3">Weekdays</td><td>Peak Period</td><td>14:00 — 20:00</td><td>48.00</td><td>36.00</td></tr>
<tr><td>Off-peak Period</td><td>08:00 — 14:00 & 20:00 — 22:00</td><td>28.00</td><td>27.00</td></tr>
<tr><td>Super Off-peak Period</td><td>00:00 — 08:00 & 22:00 — 24:00</td><td>12.00</td><td>13.00</td></tr>
<tr><td rowspan="2">Weekends</td><td>Off-peak Period</td><td>08:00 — 22:00</td><td>28.00</td><td>27.00</td></tr>
<tr><td>Super Off-peak Period</td><td>00:00 — 08:00 & 22:00 — 24:00</td><td>12.00</td><td>13.00</td></tr>
<tr><td colspan="5">[1] Tax is included.</td></tr>
</table>

Table 4.10: NSCR Energy Prices

Relevant Period Ending Time	NSCR ($/kWh)
January 2017	0.02543
February 2017	0.02571
March 2017	0.02576
April 2017	0.02578
May 2017	0.02554
June 2017	0.02571
July 2017	0.02565
August 2017	0.02583
September 2017	0.02569
October 2017	0.02663
November 2017	0.02635
December 2017	0.02733
Average 2017	0.02595

SCE also provides a fixed tiered rate tariff structure, as listed in Table 4.11. The prices are different for each level and the amount of each tier depends on the baseline allocation. This baseline allocation depends on the location of the place and the number of days of the very month, which is calculated with Equation 4.3:

$$E_{b-m} = E_b \times N_m \tag{4.3}$$

Where:
E_b is the predetermined base allocation for each day for the very place;
N_m is the number of days of the very month;
E_{b-m} is the baseline allocation of the very month for the very place.

For Los Angeles, the base consumption is $10.4kWh$ for each day [73]. For each month, up until the baseline allocation, the electricity price is $17 cents/kWh$, if the consump-

Table 4.11: SCE Tiered Rate Tariff Structure

Tier	Level	Price
Tier One	Up to Baseline [1][2] Allocation	17 cents/kWh
Tier Two	101% — 400% Over Baseline Allocation	25 cents/kWh
Tier Three	More than 400% Over Baseline Allocation	35 cents/kWh
[1] For Los Angeles, the base consumption is 10.4 kWh for each day; [2] The energy bill is calculated every month, where the baseline for that month equals 10.4 kWh multiply the number of days of that month.		

tion reaches 101% to 400% of the baseline allocation, the second tier will be triggered and the electricity price will go up to $25 cents/kWh$; for the part more than 400% over the baseline allocation, the electricity price will be $35 cents/kWh$, which is the tier three and the highest electricity price.

Another time-of-use tariff structure is proposed for California case, which has a longer peak-hour starts from 07:00 in the morning and last until 23:00 at night. The definition of this ToU structure is similar to the Netherlands and Costa Rica cases, the prices only involve a high-price for peak-hour and a low-price for the rest of day. Based on the same average price policy, the average prices for both summer period and winter period should be the same as the average price get from ToU structure proposed by SCE. The high-price for summer period and winter period are calculated with Equation 4.4 and Equation 4.5, respectively:

$$\begin{aligned} 12 \times 10 + 28 \times 8 + 48 \times 6 &= 12 \times 8 + p_{high-summer} \times 16 \\ \Rightarrow p_{high-summer} &= 33.5 cents/kWh \end{aligned} \tag{4.4}$$

$$\begin{aligned} 13 \times 10 + 27 \times 8 + 36 \times 6 &= 13 \times 8 + p_{high-winter} \times 16 \\ \Rightarrow p_{high-winter} &= 28.625 cents/kWh \end{aligned} \tag{4.5}$$

The detail price information for the second time-of-use structure for California is also listed in Table 4.12:

Table 4.12: Second ToU Structure Price Information

Period	Time	Electricity Price (dollar cents/kWh)	
		Summer Rates [1]	Summer Rates [1]
Peak-Hour	07:00—23:00	12.00	13.00
Off-Peak-hour	00:00—07:00 & 23:00—24:00	33.50	28.625
[1] Tax is included.			

The average price of ToU structure is calculated with Equation 4.6:

$$\begin{aligned} P_{av-ca} &= \frac{12 \times 10 \times 243 + 28 \times 8 \times 243 + 48 \times 6 \times 243 + 13 \times 10 \times 122 + 27 \times 8 \times 122 + 36 \times 6 \times 122}{24 \times 365} \\ &= 25.36 cents/kWh \end{aligned} \tag{4.6}$$

4.2. NEWLY DESIGNED TARIFF STRUCTURES

IN this section, the newly designed tariff is introduced, it includes the electricity buy-in tariff and feed-in tariff. There are several different structures which are all expanded from the basic structure. The most important equation that used to generate the real-time price is introduced first, followed by several different electricity buy-in tariff structures, the last part is used to introduce three different feed-in tariff structures. The different combinations of these buy-in structures and feed-in structures is later selectively used by different countries/regions according to the existed tariff structures.

The real-time pricing structure is not used in the residential market nowadays. Usually, when people talk about the real-time price structure, it is more like to be electricity auction. In this way, the price of electricity is changed every 30 minutes or hourly, and this price usually will be informed to customers several hours before to let consumers manage their load profile, sometimes this price can even be published 48 hours before. How to generate the real-time tariff is a hot topic nowadays, scientists use different ways to generate real-time buy-in price. The methods they use are complex and sometimes is classified and not available to residents. Another hot topic today is the demand side management, people first forecast the load profile and weather condition, based on these forecasting data, a real-time price is published and prosumers are informed several hours before. After receiving the real-time price, prosumers will react and change their load data and this will be transferred back to energy providers. Based on the new load data, the final real-time price will be proposed and used in the coming period. despite the different principles to generate the real-time price, there is always a common characteristic that if the total amount of energy consumption is high, then the real-time buy-in price is high; if the total amount of energy consumption is low, then the real-time buy-in price is low; which means the price is always linking with the amount of energy prosumers buy from the grid.

The real-time price is attractive because the buy-in price is always changing, the price depends on how much is consumed instead of time. It will be better if each prosumer could have their own feed-in tariff, which means the buy-in price can be only decided by how much energy is bought from the grid at this time by themselves, and not be influenced by others' consumption. This is the original intention that motivates the author to design a new real-time tariff. The new real-time tariff should be easy and simple and can be used by each end consumer, it should not be influenced by other consumers' load data and can be only decided by the energy bought from the grid at this time by the very consumer. In article [74], Equation 4.7 is proposed to calculate the real-time charging rate of the vehicle based on the real-time marginal price of electricity.

$$\gamma_{RT} = r_{max} \times \left(1 - \frac{MP - MP_{min}}{MP_{max} - MP_{min}}\right) \tag{4.7}$$

where:
γ_{RT} is the real-time vehicle charging rate, the unit is kW;
r_{max} is the maximum physically allowable charge rate, the unit is kW;
MP is the real-time marginal price of electricity from the utility, the unit is \$/kWh;
MP_{min} is the daily minimum real-time marginal prices for the day, the unit is \$/kWh;
MP_{max} is the daily maximum real-time marginal prices for the day, the unit is \$/kWh.

In this equation, if the real-time price of electricity is equal to the minimum marginal price, then the charging rate is the largest; if the real-time electricity price is the maximum marginal price, then the charging rate is equal to 0. In this way, the charging rate is related to the real-time electricity price. The maximum real-time marginal price and the minimum real-time marginal price work as the boundary and can effectively decide the charging rate.

With some inspiration from Equation 4.7, some changes are made to it and make it into the form of Equation 4.8, which is the basic formula used to generate the real-time buy-in price.

$$p_{RT} = p_{ref} \times \left(1 + \frac{E - E_{ref}}{k}\right) \tag{4.8}$$

where:

p_{RT} is the real-time price, which is related to the real-time energy consumption;

k is a coefficient; the meaning of k is how much percentage the price will go up or go down if the consumption increases or decreases 1 kWh;

E_{ref} a reference value; the meaning of E_{ref} is if at this time, the energy consumption is E_{ref}, then the energy price will be reference price;

p_{ref} is the energy price when the consumption is E_{ref}; Consider it provided by energy companies;

E is the total amount of real-time buy-in energy consumers required.

From this equation, it is easy to find the relationship between the real-time consumption and the real-time buy-in price. The real-time buy-in price is decided by p_{ref}, E_{ref}, and k. With a fixed p_{ref}, E_{ref} and k, the more energy required by prosumers, the higher the real-time buy-in price will be, and vice versa, which conforms to the logic. Since these three physical quantities can influence the final real-time buy-in price, it is important to define the suitable value for these three quantities.

p_{ref} is like the baseline for the real-time price, it decides the real-time price will fluctuate around which value. To make things easier, p_{ref} is set equal to the average buy-in price, which is 0.199529 €/kWh. E_{ref} decides at this moment, how much energy can be purchased if the real-time buy-in price is the average buy-in price; k decides how much percentage the price will fluctuate up and down when increase or decrease 1 kWh. If E_{ref} or k is too large, the real-time price will be too cheap if the E_{ref} or k is too small, the real-time price will be too expensive, thus a suitable combination of E_{ref} and k is critical in the simulation. Due to different tariff structure in different countries/regions, the methods to decide p_{ref}, E_{ref}, and k is a little bit different. The details can be found later in subsection, subsection, and subsection.

The way used to find the best combination of E_{ref} and k is let k changes from 500 to 3000 with a step of 50, E_{ref} changes from 0 to 300 with a step of 10 (for example, first set $E_{ref} = 0$, and let k changes from 500 to 3000 with the step of 50, and then set $E_{ref} = 10$, let k changes from 500 to 3000 with the step of 50, and then set $E_{ref} = 20$, keeps doing this until E_{ref} reaches 300), for each buy-in structure, with the total amount of energy prosumer need to buy for the whole year, 1581 different combinations of E_{ref} and k can be calculated, and then the one that could give the closest average real-time buy-in price to the standard average buy-in price, which is 0.199529 €/kWh, will be used in the following simulation for that vary buy-in tariff structure. It should be clear that in this process, only one set of load data for the Netherlands case is available, which means this set of load data have to be used to first find out the best E_{ref} and k, then with this combination of E_{ref} and k, along with the same load data, to calculate the money prosumers get from selling energy back to grid. But for the energy providers, they have abundant load data from hundreds and thousands of different consumers, they can use the last year load data involved with the same power management methods to find out the best combination of E_{ref} and k for this very power management method, and then apply this combination to this year's data; which means the new customers whoever choose the same power management methods, will use this new combination of E_{ref} and k to get their real-time buy-in price for this year. This combination can be updated by energy providers every year, every season, every month or even every day and every hour, depends on which policy the energy providers choose to follow. It should also be clear that only the energy bought from the grid is used to help decide E_{ref} and k, how much energy is sold back to the grid is not influenced by E_{ref} and k. The power management method can influence the amount of energy bought from the grid and sold back to the grid, and they together can affect the final energy bill, but only the amount of energy bought from the grid can determine E_{ref} and k.

4

There are several advantages of this equation; first, the real-time price will not fluctuate too much during the whole year. Figure 4.4 shows the real-time buy-in price from website 2 and calculates with Equation 4.8; the red one is the amplified real-time price with the original data from Entso-e Company, the green one is the real-time price generated with Equation 4.8 based on the assumption that all the load requirement is supported directly from the grid. Compared with the green one, the red one fluctuate a lot and several really high peak prices are detected; but for the real-time price with formula 4.8, the whole price during the year is very smooth.

The second advantage is that this equation is easy to apply and it is possible for each end consumers to have their own real-time price, which means the electricity buy-in price for each end consumers at this moment can only be decided by the real-time energy bought from grid, and will not be influenced by the entire energy environment.

The third advantage is it does not need to forecast load data, which makes it simpler to apply; as long as the energy company fixes the p_{ref}, E_{ref}, and k for a specific power management method, the real-time price is only determined by real-time buy-in energy. Energy provider can adjust the value of 'p_{ref}', 'E_{ref}' and 'k' in a reasonable way to better adapt to the energy market, in this way, it is convenient for both energy providers and prosumers.

The resolution of real-time price can be very high, it can change even every second, so that the energy bill could be very accurate.

4.2.1. ELECTRICITY REAL-TIME BUY-IN TARIFF STRUCTURES

EQUATION 4.8 is used as the basic equation to be further expanded to derive several different real-time buy-in price structures. Three representative structures will be introduced here, and each of them has their own characteristics.

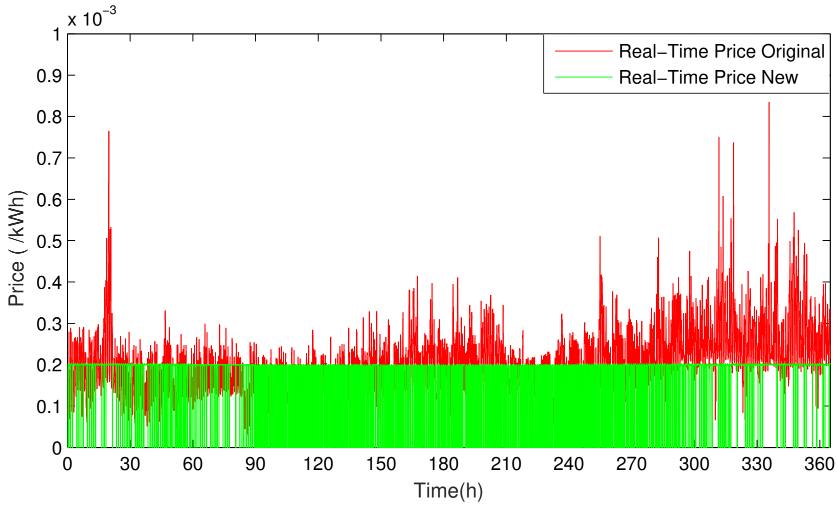


Figure 4.4: Real-Time Price Comparison

STRUCTURE ONE

$$p_{RT} = \begin{cases} p_{ref} \times \left(1 + \frac{E-E_{ref}}{k}\right), & E > 0 \\ 0, & E = 0 \end{cases} \tag{4.9}$$

In this structure, as long as consumers buy some energy from the grid, the real-time buy-in price will be decided by the basic formula; otherwise, the buy-in price equals to 0. It is clear the real-time buy-in price can be even lower than the p_{ref}; that means the fewer energy consumers buy from the grid, the lower the buy-in price will be, it is very reasonable and fair. The advantage of this structure is that the buy-in price is totally decided by what amount of energy is bought at that time and can even be lower than p_{ref}. However, the price cannot be unlimitedly low to tend to 0, and actually, the real-time buy-in can never be lower than $p_{ref} \times \left(\frac{k-E_{ref}}{k}\right)$, and the larger the difference between k and E_{ref}, the closer the lowest buy-in price to the 'p_{ref}' will be.

STRUCTURE TWO

Structure one can be further expanded and include the time-of-use characteristics. Compared with structure one, the advantage of structure two is that the basic price can be different during peak-hour and off-peak-hour. In this way, it can be further expanded if there are multiple time slots involved in a day, for example, base-peak-hour, night-hour, and super-off-hour are also included in a day, then for each period, they can have their own basic price for that very period.

For peak-hour

$$p_{RT} = \begin{cases} p_{refh} \times \left(1 + \frac{E-E_{ref}}{k}\right), & E > 0 \\ 0, & E = 0 \end{cases} \tag{4.10}$$

For off-peak-hour

$$p_{RT} = \begin{cases} p_{refl} \times \left(1 + \frac{E - E_{ref}}{k}\right), & E > 0 \\ 0, & E = 0 \end{cases} \tag{4.11}$$

STRUCTURE THREE

In this structure, the retail price for the part of energy that below E_{ref} may not depends on the total amount of energy bought from the grid, which means for this part of energy, the retail price maybe be fixed or a float value.

If during one period, the amount of energy bought from the grid is higher than E_{ref}, then the real-time price will only be used to calculate the price for the part that exceeds E_{ref}, for the rest part of the energy, it will be charged with a fixed price that equals p_{ref}. However, if the total amount of energy bought from the grid is lower than E_{ref}, then the retail price will be decided with the basic formula.

If $E \geq E_{ref}$

$$p_{RT} = \begin{cases} p_{ref} \times \left(1 + \frac{E - E_{ref}}{k}\right), & E > E_{ref} \\ p_{ref}, & E \leq E_{ref} \\ 0, & \text{E=0} \end{cases} \tag{4.12}$$

If $E < E_{ref}$

$$p_{RT} = \begin{cases} p_{ref} \times \left(1 + \frac{E - E_{ref}}{k}\right), & E < E_{ref} \\ 0, & E = 0 \end{cases} \tag{4.13}$$

4.2.2. FEED-IN TARIFF STRUCTURE

FOR the feed-in tariff, there are three different structures. The differences lie in how often it chooses to compare the data and what kind of data are compared. Three different feed-in tariff structures are explained in the following paragraphs.

STRUCTURE ONE

For feed-in tariff structure one, the money for every 10 minutes is compared. It means if it starts from the beginning of the year, until this moment, the total amount of money the prosumers spend on buying energy is more than the total amount of money consumers get from selling energy back to grid, the feed-in tariff will be the average buying price until this moment; if the total amount of money the consumers spend on buying energy is less than the total amount of money consumers get from selling energy back to grid, the feed-in tariff for the excess part equals to the low feed-in tariff, which is 0.092 €/kWh, VAT included. In order to better illustrate this feed-in tariff structure, an example is given in Appendix A, Section A.2 to better explain how the average buying price for this moment is calculated.

STRUCTURE TWO

The second structure of feed-in tariff compares the amount of energy for every 10 minutes. It means if it starts from the beginning of the year, until this moment, if the total amount of energy bought by prosumers is higher than the total amount of energy sold back to grid by prosumers, then the feed-in tariff will be the average buying price until this moment; if the total amount of energy bought by consumers is lower than the total amount of energy sold back to grid by consumers, then the feed-in tariff for the excess part will be the low feed-in tariff, which equals to 0.092 €/kWh, VAT included.

STRUCTURE THREE

The third structure is more like a traditional one. It compares the amount of energy for the whole year. It means the feed-in tariff depends on the consumption and generation of the whole year. If for the entire year, the total amount of energy bought by prosumers is higher than the total amount of energy sold back to grid, then the feed-in tariff will be the average buying price for the whole year; if the total amount of energy bought by consumers is lower than the total amount of energy sold back to grid, then the feed-in tariff for the excess part will be the low feed-in tariff, which is 0.092£/kWh, VAT included. The average buying price for the whole year can be calculated with Equation 4.14,

$$p_{avg} = \sum_{1}^{n} \frac{M_{buy}(n)}{E_{buy}(n)} = \frac{M_{buy}}{E_{buy}} \tag{4.14}$$

where:

p_{avg} is the average buying price for the whole year;
$M_{buy}(n)$ is the total money prosumers spend on buying energy during each period;
$E_{buy}(n)$ is the total amount of energy bought from grid during each period;

The idea is that to simulate to see for each country and region with the combination of different PMMs and tariff structures, which combination can bring more profit, or reduce the bill by the largest degree, in other words, the aim is to find out which PMM and tariff structure suit the country or region best. It should be clear that the tariff structures mean the combination of buy-in tariff and feed-in tariff, which could have several different combinations depending on what exactly the buy-in tariff and feed-in tariff are. I only simulated the first three buy-in structure together with the feed-in tariff.

STRUCTURE FOUR

The fourth feed-in tariff structure takes the time difference factor into consideration. Similar to the third structure, this structure compares the total energy bought from the grid during the whole year and the total energy sold back to the grid during the whole year. The difference is that this comparison is done with peak-hour and off-peak-hour. That means, during the whole year, the energy bought from the grid and the energy sold back to the grid are recorded based on different time period. In this feed-in tariff structure, the energy company always try to compensate the energy sold back to the grid from prosumers with the highest allowed price they could provide. Below, the abbreviations and the nomenclatures are used in this subsection are first listed here in Table 4.13.

Table 4.13: Abbreviations and Nomenclatures for FIT Structure 4

Abbreviations	Nomenclatures	Explanation
EB	E_b	Energy bought from the grid.
EBL	E_{bop}	Energy bought from the grid during off-peak-hour.
EBH	E_{bp}	Energy bought from the grid during peak-hour.
ES	E_s	Energy sold back to the grid.
ESL	E_{sop}	Energy sold back to the grid during off-peak-hour.
ESH	E_{sp}	Energy sold back to the grid during peak-hour.
AP	p_{avg}	The average energy buying price.
APL	p_{avgop}	The average energy buying price for off-peak-hour.
APH	p_{avgp}	The average energy buying price for peak-hour.
RPL	p_{rop}	The original electricity retail price for off-peak-hour.
RPH	p_{rp}	The original electricity retail price for peak-hour.
PF	p_{FIT}	The feed-in tariff price for the part (ES-EB), when ES>EB.
MS	R_s	The total money gets from selling energy back to the grid.
MSL	R_{sop}	The total money gets from selling energy back to the grid during off-peak-hour.
MSH	R_{sp}	The total money gets from selling energy back to the grid during peak-hour.
In this section, all the variables are based on the data for the whole year.		

The method to determine the final feed-in tariff price for each period is described below:

1. If during the whole year, EBH ≥ ESH, then all the ESH could all be compensated with the price APH.
   (a) At the same time, if during the same year, EBL≥ESL, then all the ESL could be compensated with the price APL.
   (b) At the same time, if during the same year, EBL<ESL, then only the part EBL out of ESL could be compensated with the price APL, the rest energy sold back to the grid during off-peak-hour (ESL-EBL) could only be compensated with the price PF.
2. If during the whole year, EBH<ESH, then only the part EBH out of ESH could be compensated with the price APH, the compensate price for rest part (ESH-EBH) depends on the relationship between EBL and ESL.
   (a) At the same time, if during the same year, EBL≥(ESH-EBH), then the rest energy that sold back to the grid during peak-hour (ESH-EBH) could all be compensated with the price APL.
      i. At the same time, if during the same year, after compensating all the energy sold back to the grid during off-peak-hour, still has [EBL-(ESH-EBH)]≥ESL, then all the ESL could be compensated with the price APL.
      ii. At the same time, if during the same year, after compensating all the energy sold back to the grid during off-peak-hour, [EBL-(ESH-EBH)]<ESL, then only the part [EBL-(ESH-EBH)] out of ESL could be compensated

with the price APL, the rest part {ESL-[EBL-(ESH-EBH)]} can only be compensated with the price PF.

(b) At the same time, if during the same year, EBL<(ESH-EBH), then only the part EBL out of (ESH-EBH) could be compensated with the price APL, the rest part [(ESH-EBH)-EBL] can only be compensated with the price $\frac{PF \times RPH}{RPL}$. In this case, all the ESL can only be compensated with the price PF.

This feed-in tariff structure could be expressed with the following equations:

If EBH ≥ ESH & EBL≥ESL:

$$\begin{cases} R_{sp} = E_{sp} \times p_{avgp} & (4.15a) \\ R_{sop} = E_{sop} \times p_{avgop} & (4.15b) \end{cases}$$

If EBH ≥ ESH & EBL<ESL:

$$\begin{cases} R_{sp} = E_{sp} \times p_{avgp} & (4.16a) \\ R_{sop} = E_{bop} \times p_{avgop} + (E_{sop} - E_{bop}) \times p_{FIT} & (4.16b) \end{cases}$$

If EBH<ESH & EBL≥(ESH-ESH) & [EBL-(ESH-ESH)] ≥ ESL:

$$\begin{cases} R_{sp} = E_{bp} \times p_{avgp} + (R_{sp} - R_{bp}) \times p_{avgop} & (4.17a) \\ R_{sop} = E_{sop} \times p_{avgop} & (4.17b) \end{cases}$$

If EBH<ESH & EBL≥(ESH-EBH) & [EBL-(ESH-EBH)]<ESL:

$$\begin{cases} R_{sp} = E_{bp} \times p_{avgp} + (R_{sp} - R_{bp}) \times p_{avgop} & (4.18a) \\ R_{sop} = [E_{bop} - (R_{sp} - R_{bp})] \times p_{avgop} + \{E_{sop} - [E_{bop} - (R_{sp} - R_{bp})]\} \times p_{FIT} & (4.18b) \end{cases}$$

If EBH<ESH & EBL<(ESH-EBH):

$$\begin{cases} R_{sp} = E_{bp} \times p_{avgp} + E_{bop} \times p_{avgop} + (R_{sp} - R_{bp} - E_{bop}) \times p_{avgop} \times \frac{p_{rp}}{p_{rop}} & (4.19a) \\ R_{sop} = E_{sop} \times p_{FIT} & (4.19b) \end{cases}$$

Since the energy compensation price depends on the time the energy are sold, this feed-in tariff structure could only be used for PMM2 and PMM3 and this is considered as a limitation for this feed-in tariff structure. For better understanding, an example is attached in Appendix A, Section A.3 to explain the method used to decide the feed-in tariff price for each period.

4.3. SIMULATION RESULTS OF NEWLY DESIGNED TARIFF STRUCTURES

THIS section shows the simulation of the electricity tariff designed by the author. Equation 4.8 can be further expanded to generate different electricity buy-in tariff structures. In this section, only the results for some specific types are shown. It should be clear that in Equation 4.8, three important coefficients are "p_{ref}", "E_{ref}" and "k". For different tariff structure, these three coefficients will have different values, and the way to decide these values will also be different.

In this section, for each power management method, only one buy-in tariff structure designed by myself is simulated. The buy-in tariff is chosen based on the characteristics of each power management method. Each buy-in tariff together with three different feed-in structures constitutes the electricity tariff for the very power management method. They are explained one by one in the following paragraphs.

It should be clear that for each PMM, the buy-in structure is fixed, however, the feed-in tariff structure can be changed and thus generate different combinations. In order to be consistent, for each PMM, the combination of buy-in tariff structure and feed-in tariff structure will be expressed by the acronym 'BF', where 'B' stands for the 'buy-in tariff structure' and 'F' stands for the 'feed-in tariff structure'. 'BF1', 'BF2', 'BF3', 'BF4' means for the very buy-in tariff structure, the feed-in tariff structures are the first, second, third, and fourth newly designed feed-in tariff structure, respectively.

4.3.1. THE NETHERLANDS

FOR the Netherlands case, four different buy-in structures are proposed based on each PMM's character. For each PMM, the very designed buy-in tariff together with the three feed-in tariffs mentions before are simulated to calculate the final energy bill, and then compared with the existed tariff structures to see which tariff structures have the best performance based on the final energy bill.

BUY-IN STRUCTURE FOR PMM1

For the first power management method, since the power flow is always the same for the entire year, the buy-in electricity price structure is the first buy-in structure described in the last section, which is also listed here again for a better explanation.

$$p_{RT} = \begin{cases} p_{ref} \times \left(1 + \frac{E - E_{ref}}{k}\right), & E > 0 \\ 0, & E = 0 \end{cases} \tag{4.20}$$

where p_{ref} is set to be the fixed tariff, which equals to 0.199529 €/kWh.

The method used to find the best combination of E_{ref} and k is to let k changes from 500 to 5500 with a step of 50, E_{ref} changes from 0 to 400 with a step of 10 (for example, first set $E_{ref} = 0$, and let k changes from 500 to 5500 with the step of 50, and then set $E_{ref} = 10$, let k changes from 500 to 5500 with the step of 50, and then set $E_{ref} = 0$, keeps doing this until E_{ref} reaches 400), with the real-time energy selling data from grid side under the first PPM as the input E, 45141 different combinations of E_{ref} and k can be calculated, and then the one that could give the closest average real-time buy-in price to the standard average buy-in price, which is 0.199529 €/kWh, will be used in the following simulation for this very buy-in tariff structure.

It should be clear that in this process, the input data E equals to the real-time energy selling data from grid side under the first PMM, this data is not the original load data for the Netherlands. In this way, $E_{ref} = 50$ with $k = 5500$.

Since only one set of load data is available for the Netherlands case, which means based on this set of load data, only one set of energy exchange data between the grid and other parts in the system is available, this set of energy exchange data has to be used firstly to find out the best E_{ref} and k, then with this combination of E_{ref} and k, along with the same load data, to calculate the money the prosumers get from selling energy back to grid. But for the energy providers, they have abundant energy exchange data from hundreds and thousands of different consumers, they can use the energy exchange data from last year who involved with the same PMM to find out the best combination of E_{ref} and k for this very PMM, and then apply this combination to this year's data; which means the new customers whoever choose the same PMM, will use this new combination of E_{ref} and k to get their real-time buy-in price for this year. This combination can be updated by energy providers every year, every season, every month or even every day and every hour, depends on which policy the energy providers choose to follow. It should also be clear that only the energy bought from the grid is used to help decide E_{ref} and k, how much energy is sold back to the grid is not influenced by E_{ref} and k. The PMM can influence the amount of energy bought from the grid and sold back to the grid, and they together can affect the final energy bill.

The simulation results are shown in Table 4.14 and Figure 4.5.

Table 4.14: Tariff Comparison with PMM1 (The Netherlands)

Price Structure	Money Buying (€)	Money Selling (€)	Energy Bill (€)
Fixed	364.03	318.46	45.57
ToU Structure 1	361.96	316.64	45.32
ToU Structure 2	381.23	333.50	47.73
Day-Ahead	376.25	329.14	47.11
BF1	365.67	242.43	123.25
BF2	365.67	242.34	123.34
BF3	365.67	319.89	45.78

Buy-in Structure for PMM2 and PMM3

For the second and third power management method, the time-of-use characteristic is also considered into the electricity buy-in structure. The buy-in tariff formula is shown below:

For peak-hour

$$p_{RT} = \begin{cases} p_{refh} \times \left(1 + \frac{E - E_{ref}}{k}\right), & E > 0 \\ 0, & E = 0 \end{cases} \tag{4.21}$$

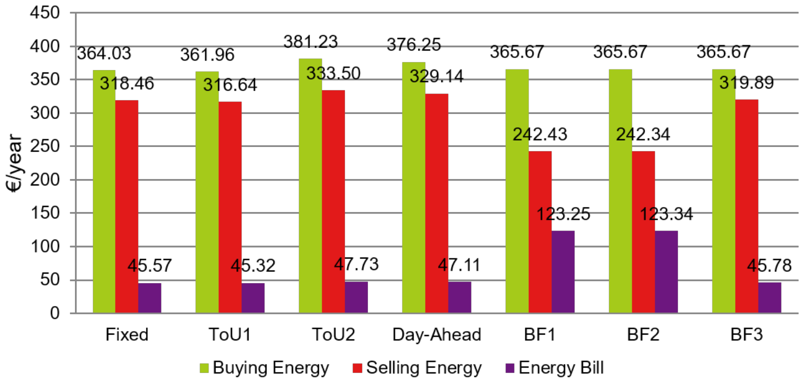


Figure 4.5: Tariff Comparison with PMM1 (the Netherlands)

For off-peak-hour

$$p_{RT} = \begin{cases} p_{refl} \times \left(1 + \frac{E - E_{ref}}{k}\right), & E > E_0 \\ 0, & E = 0 \end{cases} \tag{4.22}$$

The p_{ref} for the peak-hour and off-peak-hour are different, and the values are set to be equal to the retail price listed in Table. For the second power management method, p_{refh}=0.2057 €/kWh and p_{refl}=0.187187 €/kWh. This time k changes from 500 to 3000 with a step of 50, E_{ref} changes from 0 to 300 with a step of 10, with the real-time energy selling data from grid side under the second PPM as the input E, 1581 different combinations of E_{ref} and k can be calculated. The result shows when E_{ref} = 30 and k = 2400, the average real-time buy-in price is closest to the standard average buy-in price 0.199529 €/kWh. This combination is used for the second tariff structure for the Netherlands case. For the third power management method, p_{refh}=0.236555 €/kWh and p_{refl}=0.187187 €/kWh, with the same method describe ahead, the best combination for the third tariff structure is E_{ref} = 40 and k = 950. The simulation results are shown in Table 4.15 and Table 4.16, and Figure 4.6 and Figure 4.7 for the second tariff structure and the third tariff structure, respectively.

Table 4.15: Tariff Comparison with PMM2 (The Netherlands)

Price Structure	Money Buying (€)	Money Selling (€)	Money Paying (€)
Fixed	522.65	454.49	68.16
ToU Structure 1	504.03	438.30	65.73
ToU Structure 2	483.15	420.14	63.01
Day-Ahead	523.05	454.84	68.21
BF1	538.99	379.61	159.37
BF2	538.99	360.42	178.57
BF3	538.99	468.70	70.29
BF4	538.99	446.13	92.86

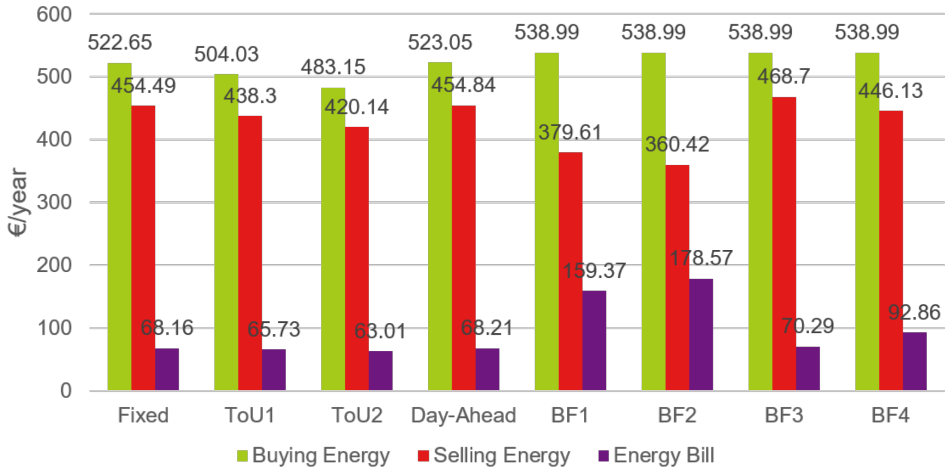


Figure 4.6: Tariff Comparison with PMM2 (the Netherlands)

Table 4.16: Tariff Comparison with PMM3 (The Netherlands)

Price Structure	Money Buying (€)	Money Selling (€)	Money Paying (€)
Fixed	395.39	326.04	69.35
ToU Structure 1	393.62	324.58	69.04
ToU Structure 2	403.08	332.38	70.70
Day-Ahead	382.84	315.69	67.15
BF1	418.27	268.31	149.96
BF2	418.27	268.30	149.96
BF3	418.27	344.90	73.36
BF4	418.27	339.23	79.04

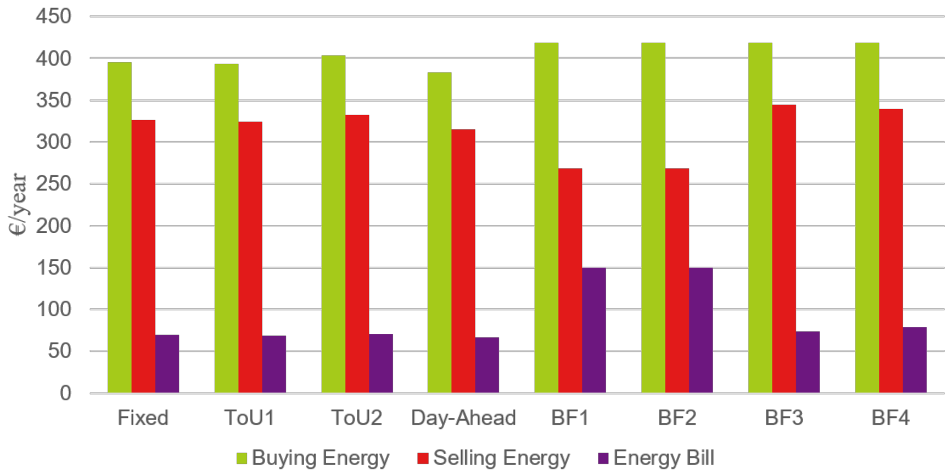


Figure 4.7: Tariff Comparison with PMM3 (the Netherlands)

BUY-IN STRUCTURE FOR PMM4

For the last power management method, if the amount of energy bought from grid is larger than E_{ref}, for the part that exceeds the E_{ref}, the real-time will be calculated with Equation 4.8, leading to a price that is higher than the reference price; the rest part will be charged with a fixed price equals to the reference price. If the amount of energy bought from the grid is lower than E_{ref}, then the real-time price will also only be calculated with Equation 4.8 and in this case, the real-time price is lower than the reference price. In this PMM, with different P_{ref}, the amount of energy bought from the grid is different, in other words, the amount of energy sold by the grid is linked with P_{ref}. With different P_{ref}, the reference price should be different. The way to decide the reference price for a particular P_{ref} is with the first PMM, if at this very period with time length equals to T, the amount of energy bought from grid is $P_{ref} \times T$, what the real-time buy-in price will be, and this real-time buy-in price will be used as the reference price for the fourth tariff structure. Equation is used to decide the reference price for this tariff structure.

4

$$p_{ref4} = p_{ref} \times \left(1 + \frac{\frac{P_{ref} \times T}{l_{lac}} - E_{ref1}}{k_1} \right) \tag{4.23}$$

where:

p_{ref} is the reference price for the first tariff structure, for the Netherlands case, p_{ref}=0.199529 €/kWh;

P_{ref} is the predetermined reference value for PMM4, for the Netherlands case, $P_{ref} = 500W$;

T is the time resolution, in this thesis, $T = 10min = \frac{1}{6}h$;

l_{lac} is the AC cable efficiency, in this thesis, $l_{lac} = 0.99$;

E_{ref1} is the energy reference value for the first tariff structure, for the Netherlands case, $E_{ref1} = 50kWh$;

k_1 is the constant for the first tariff structure, for the Netherlands case, $k_1 = 5500$.

In this way, if $P_{ref} = 500W$, the reference price for the fourth tariff structure equals to 0.20077 €/kWh. This time k changes from 500 to 5500 with a step of 50, E_{ref} changes from 0 to 400 with a step of 10, with the real-time energy selling data from grid side under the fourth PPM as the input E, 45141 different combinations of E_{ref} and k can be calculated. The result shows when $E_{ref} = 100$ and $k = 5300$, the average real-time buy-in price is closest to the standard average buy-in price 0.199529 €/kWh. This combination is used for the fourth tariff structure for the Netherlands case.

$$M_{RTB} = \begin{cases} p_{ref} \times \left(1 + \frac{E - E_{ref}}{k}\right) \times \left(E - E_{ref}\right) + p_{ref} \times E_{ref}, & E > E_{ref} \\ p_{ref} \times \left(1 + \frac{E - E_{ref}}{k}\right) \times E, & 0 < E \le E_{ref} \\ 0, & E = 0 \end{cases} \tag{4.24}$$

Where M_{RTB} is the money spend on buying energy from the grid during that very time period.

The simulation results for PMM4 can be found in in Table 4.17 and Figure 4.8.

Table 4.17: Tariff Comparison with PMM4 (The Netherlands)

Price Structure	Money Buying (€)	Money Selling (€)	Money Paying (€)
Fixed	490.76	468.27	22.49
ToU Structure 1	489.04	466.63	22.41
ToU Structure 2	503.33	480.26	23.07
Day-Ahead	512.00	488.54	23.46
BF1	491.75	353.59	138.15
BF2	491.75	342.17	149.57
BF3	491.75	469.21	22.54

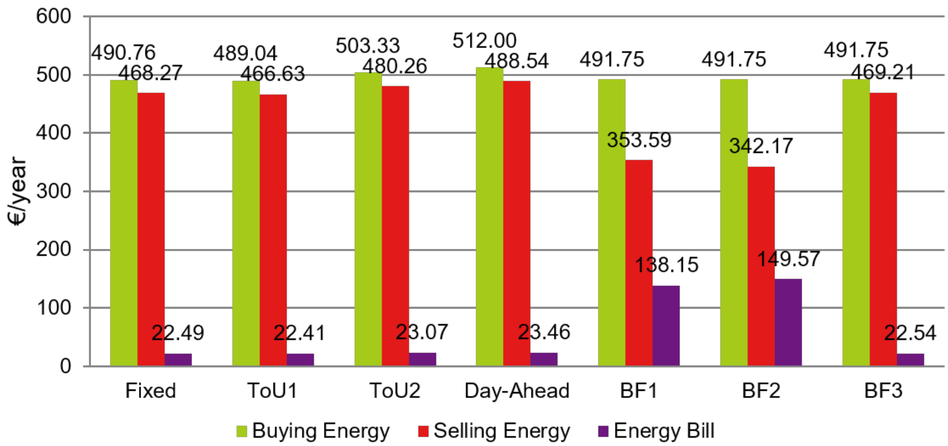


Figure 4.8: Tariff Comparison with PMM4 (the Netherlands)

For the Netherlands case, the third newly designed tariff structure can provide almost the same energy bill with the four existing tariff structures for all four PMMs. However, if the feed-in tariff is calculated every 10 minutes based on the accumulation of energy data, a lot of energy will be compensated with the lower feed-in tariff due to the fact that during summer, a lot of energy is sold back to grid, while during the winter period, a lot of energy is bought from grid. The every-10-minute policy makes the favourable balance disappear and can even become a disadvantage for the prosumers.

4.3.2. COSTA RICA

FOR Costa Rica case, four different tariff structures are designed according to its price mechanism.

Due to the existed tariff structures in Costa Rica, the buy-in price differ from month to month with different consumption levels. The way to decide reference price is a little bit different from the Netherlands case. The total load consumption for the entire year is 3552.56kWh, which equals to 296.05kWh per month if it is assumed to have the same number of days of each month, among this 296.05kWh, about 99.54kWh needed to be purchased during night-hour, another 119.75kWh is bought during valley-hour, the rest 76.75kWh will be purchased during peak-hour. Actually, for the whole year, during night-hour, the largest amount of energy to be bought is 111.59kWh and this happens in December; the lowest amount of energy to be bought is 90.88kWh and this happens in June. During valley-hour, the largest amount of energy to be bought is 144.40kWh, which happens in December; the lowest amount of energy to be bought is 93.86kWh and this happens in June. During peak-hour, the largest amount of energy to be bought is 91.65kWh and this happens in January; in June, only 65.31kWh needed to be bought, which is the lowest month during the year. Since from the tariff structure proposed by CNFL, no matter which month it is, the first level of peak-hour, valley-hour, and night-hour are all from 0 up to 300kWh, this means no matter which month is chosen, the energy consumption for that month will never exceed the first level of each period. In this way, the reference price is settled with the average value with the following method. Based on CNFL time-of-use tariff structure, the average electricity price for the first 300 kWh of each period is calculated first, as Figure shown, for peak-hour, the average price is 136.90$Colons/kWh$, for valley-hour, the average price is 56.76$Colons/kWh$, and for night-hour, the average price is 23.37$Colons/kWh$. In this case, the average price can be calculated in the following way:

$$\begin{aligned} p_{avg} &= p_{ref} \\ &= \frac{136.90Colons/kWh \times 5h + 56.76Colons/kWh \times 9h + 23.37Colons/kWh \times 10h}{24} \\ &= 59.55Colons/kWh \end{aligned} \tag{4.25}$$

59.55$Colons/kWh$ is used as the reference price for the first tariff structure in Costa Rica case.

The first tariff structure is the same with the Netherlands case, as long as consumers buy energy from the grid, the real-time buy-in price will be calculated with equation 4.8. The way to decide the real-time buy-in price is listed here again in equation.

$$p_{RT} = \begin{cases} p_{ref} \times \left(1 + \frac{E - E_{ref}}{k}\right), & E > 0 \\ 0, & E = 0 \end{cases} \tag{4.26}$$

with $p_{ref} = 59.55Colons/kWh$, k is set to change from 500 to 5500 with a step of 50, E_{ref} is set to change from 0 to 400 with a step of 10, with the real-time energy selling data from grid side under the first PPM from Costa Rica case as the input E, 45141 different combinations of E_{ref} and k can be calculated, again, the combination that could give the closest average real-time buy-in price to the standard average buy-in price, is used in the following simulation for this vary buy-in tariff structure. The simulation results suggest $E_{ref} = 40$ with $k = 5500$. The simulation results are shown in Table 4.18 and Figure 4.9.

The third newly designed tariff structure gives the lowest energy bill among all six tariff structures, followed by the first newly designed tariff structure. Although the ToU tariff structure cost the lowest amount of money from prosumers, the amount of energy

Table 4.18: Tariff Comparison with PMM1 (Costa Rica)

Price Structure	Money Buying ($)	Money Selling ($)	Money Paying ($)
Fixed	132.62	79.34	53.28
ToU Structure 1	67.87	19.44	48.43
ToU Structure 2	144.17	91.29	52.88
BF1	121.88	86.09	35.79
BF2	121.88	49.85	72.03
BF3	121.88	107.67	14.21

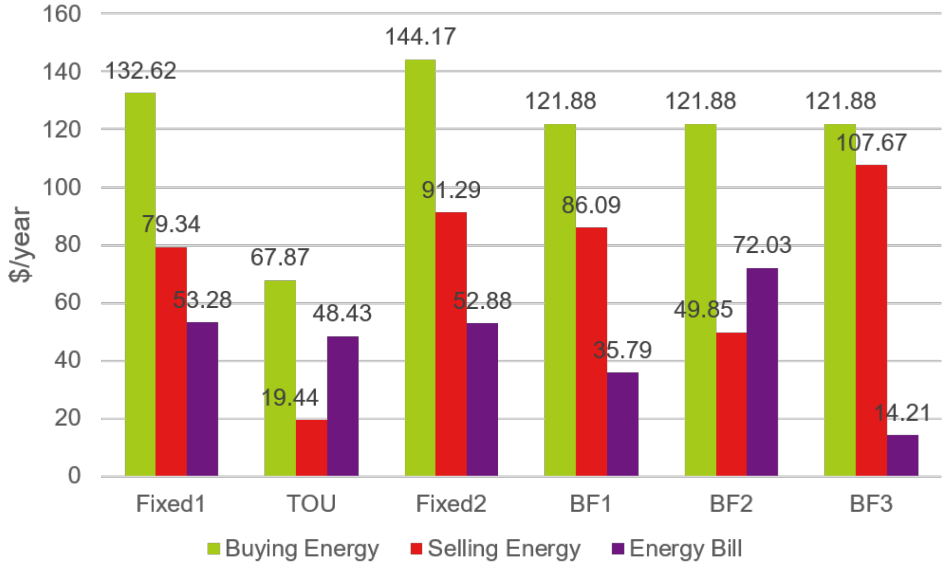


Figure 4.9: Tariff Comparison with PMM1 (Costa Rica)

that could be positively compensated with the access tariff is limited, leading to the ToU tariff structure become the third choice for prosumers involve with PMM1.

For the second and third power management method, the time-of-use characteristic is also considered into the electricity buy-in structure.

For the second power management method, the peak-hour definition is the same as the Netherlands case, peak-hour starts from 7:00 in the morning and last until 23:00 at night. The reference price for the peak-hour is calculated to ensure the same average price with the CNFL time-of-use tariff. Equation 4.27 is used to calculate the price for peak-hour of each month for the second tariff structure.

$$
\begin{aligned}
&p_{off2}(n) \times T_{off2}(n) + p_{peak2}(n) \times T_{peak2}(n) \\
= p_{off3}(n) \times T_{off3}(n) + p_{valley3}(n) \times T_{valley3}(n) + &p_{peak3}(n) \times T_{peak3}(n), \\
&n = 1,2,3,4,5,6,7,8,9,10,11,12 \text{ and } p_{off2}(n) = p_{off3}(n)
\end{aligned}
\tag{4.27}
$$

where:
n is an integer and represents each month; for example, $n = 1$ means January;
$p_{off2}(n)$ is the price for night-hour for second tariff structure for month n;
$T_{off2}(n)$ is the time length for night-hour for second tariff structure for month n;
$p_{peak2}(n)$ is the price for peak-hour for second tariff structure for month n;
$T_{peak2}(n)$ is the time length for peak-hour for second tariff structure for month n;
$p_{off3}(n)$ is the price for night-hour for third tariff structure for month n;
$T_{off3}(n)$ is the time length for night-hour for third tariff structure for month n;
$p_{valley3}(n)$ is the price for valley-hour for third tariff structure for month n;
$T_{valley3}(n)$ is the time length for valley-hour for third tariff structure for month n;
$p_{peak3}(n)$ is the price for peak-hour for third tariff structure for month n;
$T_{peak3}(n)$ is the time length for peak-hour for third tariff structure for month n;
With equation, the reference prices for the second tariff structure are listed in Table 4.19.

Table 4.19: Reference Prices for Each Period for PMM2 (Costa Rica)

	January	February	March	April	May	June
Peak-Hour ($Colons/kWh$)	74.90	74.90	74.90	75.87	75.85	75.85
Night-Hour ($Colons/kWh$)	22.55	22.55	22.55	22.85	22.84	22.84
	July	August	September	October	November	December
Peak-Hour ($Colons/kWh$)	75.49	75.49	75.49	84.20	84.20	84.20
Night-Hour ($Colons/kWh$)	22.73	22.73	22.73	25.35	25.35	25.35

The second buy-in tariff structure is shown in Equation 4.28 and Equation 4.29:
For peak-hour

$$
p_{RT} = \begin{cases} p_{refh} \times \left(1 + \frac{E - E_{ref}}{k}\right), & E > E_{ref} \\ 0, & E = 0 \end{cases} \tag{4.28}
$$

For night-hour

$$
p_{RT} = \begin{cases} p_{refl} \times \left(1 + \frac{E - E_{ref}}{k}\right), & E > E_{ref} \\ 0, & E = 0 \end{cases} \tag{4.29}
$$

This time k changes from 250 to 2750 with a step of 50, E_{ref} changes from -300 to 0 with a step of 10, with the real-time energy selling data from grid side under the second PPM as the input E, 1581 different combinations of E_{ref} and k can be calculated. The result shows when $E_{ref} = -60$ and $k = 250$, the average real-time buy-in price is closest to the standard average buy-in price $p_{ref} = 59.55 Colons/kWh$. This combination is used for the second tariff structure for Costa Rica.

For the third power management method, the buy-in tariff structure is shown below:

For peak-hour

$$p_{RT} = \begin{cases} p_{refh} \times \left(1 + \frac{E - E_{ref}}{k}\right), & E > E_{ref} \\ 0, & E = 0 \end{cases} \tag{4.30}$$

For valley-hour

$$p_{RT} = \begin{cases} p_{refm} \times \left(1 + \frac{E - E_{ref}}{k}\right), & E > E_{ref} \\ 0, & E = 0 \end{cases} \tag{4.31}$$

For night-hour

$$p_{RT} = \begin{cases} p_{refl} \times \left(1 + \frac{E - E_{ref}}{k}\right), & E > E_{ref} \\ 0, & E = 0 \end{cases} \tag{4.32}$$

The reference price for the peak-hour, valley-hour, and night-hour are different, each of them changes every month according to CNFL time-of-use tariff price. The values are set to be equal to the first level consumption price of that period. The detail prices are listed in Table. This time k changes from 250 to 2750 with a step of 50, E_{ref} changes from -300 to 0 with a step of 10, with the real-time energy selling data from grid side under the third PPM as the input E, 1581 different combinations of E_{ref} and k can be calculated. The result shows when $E_{ref} = -210$ and $k = 400$, the average real-time buy-in price is closest to the standard average buy-in price $p_{ref} = 59.55 Colons/kWh$. This combination is used for the third tariff structure for Costa Rica. The simulation results are shown in Table 4.20 and Table 4.21, and Figure 4.10 and Figure 4.11 for the second tariff structure and the third tariff structure, respectively.

Table 4.20: Tariff Comparison with PMM2 (Costa Rica)

Price Structure	Money Buying ($)	Money Selling ($)	Money Paying ($)
Fixed	268.83	163.76	105.07
ToU Structure 1	152.26	68.61	83.65
ToU Structure 2	294.76	190.50	104.26
BF1	246.19	182.47	63.72
BF2	246.19	109.22	136.97
BF3	246.19	213.75	32.44
BF4	246.19	223.10	23.09

The third newly designed tariff structure gives the lowest energy bill among all six tariff structures, followed by the first newly designed tariff structure. The two fixed tariff structures are not recommended here for PMM4 for Costa Rica case.

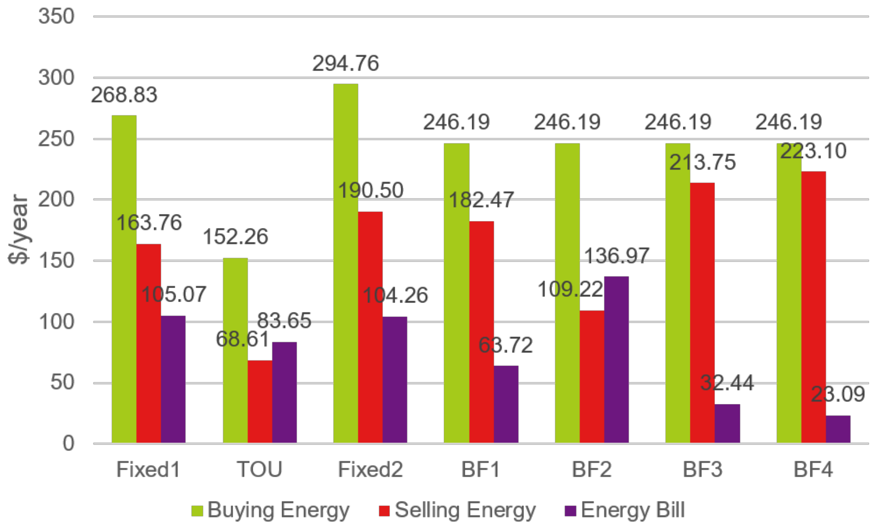


Figure 4.10: Tariff Comparison with PMM2 (Costa Rica)

Table 4.21: Tariff Comparison with PMM3 (Costa Rica)

Price Structure	Money Buying ($)	Money Selling ($)	Money Paying ($)
Fixed	338.59	184.02	154.57
ToU Structure 1	205.65	93.92	111.73
ToU Structure 2	358.99	206.15	152.84
BF1	462.15	302.92	159.23
BF2	462.15	229.48	232.67
BF3	462.15	338.36	123.79
BF4	462.15	407.56	54.59

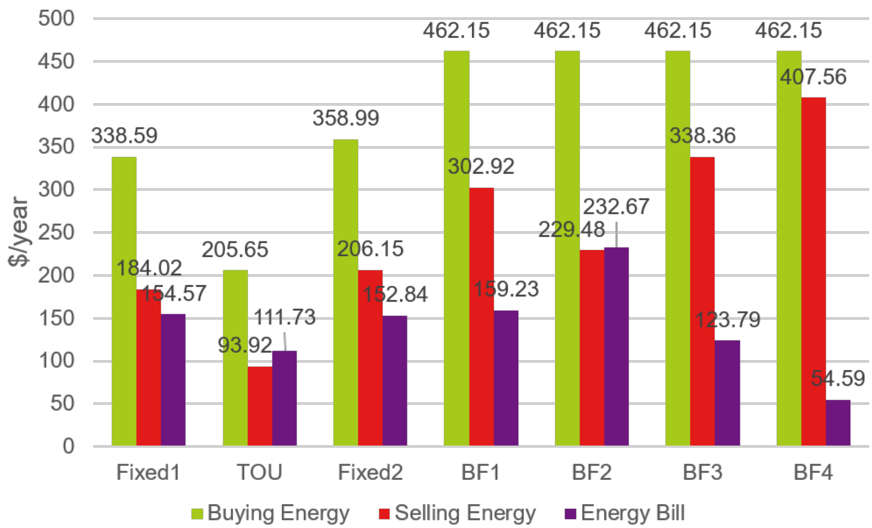


Figure 4.11: Tariff Comparison with PMM3 (Costa Rica)

This time ToU structure is the best choice for prosumers who involve with PMM3. However, the final energy bill from the third newly designed tariff structure is very close, making it a possible choice for prosumers.

For the last power management method, if the amount of energy bought from grid is larger than E_{ref}, for the part that exceeds the E_{ref}, the real-time will be calculated with Equation 4.8, leading to a price that is higher than the reference price; the rest part will be charged a fixed price equals to the reference price. If the amount of energy bought from the grid is lower than E_{ref}, then the real-time price will also only be calculated with Equation 4.8; and in this case, the real-time price is lower than the reference price. Equation is used to decide the reference price for this tariff structure. The predetermined reference value for Costa Rica Case is $P_{ref} = 500W$, $p_{ref1} = 59.55 Colons/kWh$, $E_{ref1} = 40$ and $k_1 = 5500$. The reference price for the fourth tariff structure equals to $p_{ref} = 60.00 Colons/kWh$.

Equation 4.33 shows the tariff structure of the fourth method.

$$M_{RTB} = \begin{cases} p_{ref} \times \left(1 + \frac{E - E_{ref}}{k}\right) \times \left(E - E_{ref}\right) + p_{ref} \times E_{ref}, & E > E_{ref} \\ p_{ref} \times \left(1 + \frac{E - E_{ref}}{k}\right) \times E, & 0 < E \leq E_{ref} \\ 0, & E = 0 \end{cases} \tag{4.33}$$

Where M_{RTB} is the money spend on buying energy from the grid during that very time period.

Table 4.22: Tariff Comparison with PMM4 (Costa Rica)

Price Structure	Money Buying ($)	Money Selling ($)	Money Paying ($)
Fixed	242.98	160.18	82.80
ToU Structure 1	197.63	130.62	67.01
ToU Structure 2	268.25	185.84	82.41
BF1	222.23	179.35	42.88
BF2	222.23	77.45	144.78
BF3	222.23	210.45	11.78

In this case k changes from 500 to 5500 with a step of 50, E_{ref} changes from 0 to 400 with a step of 10, with the real-time energy selling data from grid side under the second PPM as the input E, 45141 different combinations of E_{ref} and k can be calculated. The result shows when $E_{ref} = 110$ and $k = 5200$, the average real-time buy-in price is closest to the standard average buy-in price $p_{ref} = 59.55 Colons/kWh$. This combination is used for the fourth tariff structure for Costa Rica case.

The simulation results are shown in Table 4.22 and Figure 4.12.

The third newly designed tariff structure gives the lowest energy bill among all six tariff structures, followed by the first newly designed tariff structure. The two fixed tariff structures are not recommended here for PMM4 for Costa Rica case.

For Costa Rica case, the third newly designed tariff structure usually can give the lowest energy bill among all six tariff structures and is the best choice for prosumers

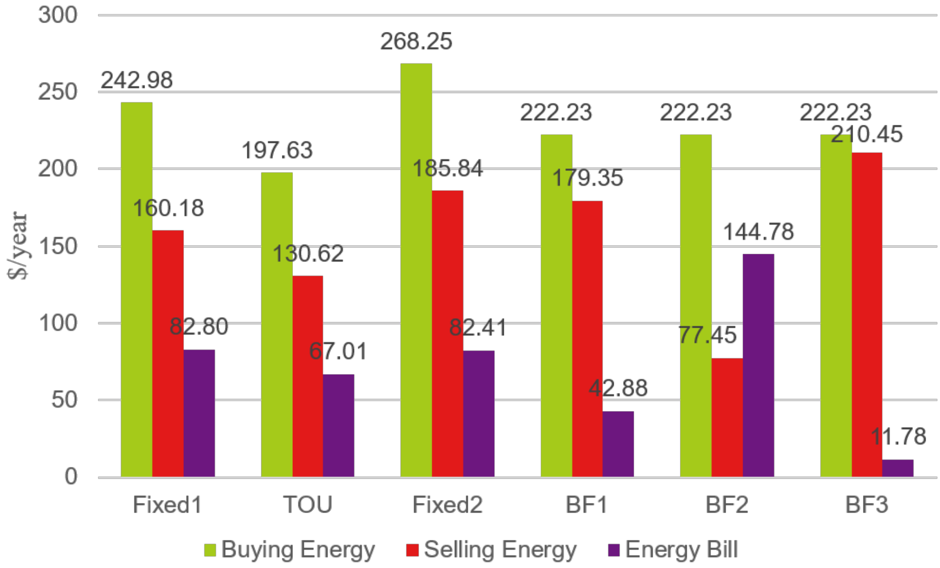


Figure 4.12: Tariff Comparison with PMM4 (Costa Rica)

involve with PMM1, PMM2, and PMM4. For PMM3, the existed ToU tariff is the best choice and the third newly designed tariff structure can provide a very close energy bill. Although the two fixed tariff structures have different energy charging levels, the final energy bill is almost the same. The second newly designed tariff structure always leads to the highest energy bill, which means a lot of energy is compensated with low price or just abandoned instead of compensated with the high price. The final energy bill with the first newly designed tariff structure differs a lot compared to the second newly designed tariff structure, meaning the access price and the real energy buy-in prices have a huge difference.

4.3.3. CALIFORNIA

FOR California case, four different tariff structures are designed according to its price mechanism.

SCE provides a precise definition of the time-of-use tariff, as shown in Table 4.23. The electricity buy-in price differs in the summer time and the winter time. As like for the Netherlands case, the weighted average price calculated by Equation 4.34 is used as the reference price for California.

Table 4.23: Peak and Off-Peak Time Periods Definition (California)

Period		Time	Electricity Price (dollar cents/kWh)	
			Summer Rates [1]	Winter Rates [1]
Weekdays	Peak Period	14:00 — 20:00	48.00	36.00
	Off-peak Period	08:00 — 14:00 & 20:00 — 22:00	28.00	27.00
	Super Off-peak Period	00:00 — 08:00 & 22:00 — 24:00	12.00	13.00
Weekends	Off-peak Period	08:00 — 22:00	28.00	27.00
	Super Off-peak Period	00:00 — 08:00 & 22:00 — 24:00	12.00	13.00
[1] Tax is included.				

$$P_{av-ca} = \frac{\sum_1^6 p(n) \times \sum_1^6 T(n) \times \sum_1^6 N(n)}{24 \times 365}$$
$$= \frac{12 \times 10 \times 243 + 28 \times 8 \times 243 + 48 \times 6 \times 243 + 13 \times 10 \times 122 + 27 \times 8 \times 122 + 36 \times 6 \times 122}{24 \times 365}$$
$$= 25.35844749 cents/kWh \tag{4.34}$$

where:
P_{av-ca} is the reference price for California case;
$p(n)$ is the electricity price for that period;
$T(n)$ is the time length for that period;
$N(n)$ is the number of days with the very electricity price;
$n = 1$ means the super off-peak period during the summer period; $n = 2$ represents the off-peak period during the summer period; $n = 3$ stands for the peak-period during the summer period; $n = 4$ means the super-off-period during the winter period; $n = 5$ represents the off-peak period during the winter period; $n = 6$ stands for the peak-period during the winter period.

From Equation 4.34, the reference value equals to $p_{ref} = p_{av-ca} = 25.36 cents/kWh$.

The first tariff structure is the same with the Netherlands and Costa Rica cases, as long as consumers buy energy from the grid, the real-time buy-in price will be calculated with Equation 4.8. The way to decide the real-time buy-in price is listed here again in equation.

$$p_{RT} = \begin{cases} p_{ref} \times \left(1 + \frac{E - E_{ref}}{k}\right), & E > 0 \\ 0, & E = 0 \end{cases} \tag{4.35}$$

with $p_{ref} = 25.36 cents/kWh$, k is set to change from 500 to 5500 with a step of 50, E_{ref} is set to change from 0 to 400 with a step of 10, with the real-time energy selling data from grid side under the first PPM from Costa Rica case as the input E, 45141 different combinations of E_{ref} and k can be calculated, again, the combination that could give the closest average real-time buy-in price to the standard average buy-in price, is used in the following simulation for this vary buy-in tariff structure. The simulation results suggest $E_{ref} = 90$ with $k = 5500$. The simulation results are shown in Table 4.24 and Figure 4.13.

Table 4.24: Tariff Comparison with PMM1 (California)

Price Structure	Money Buying ($)	Money Selling ($)	Money Paying ($)
Fixed	407.92	251.65	156.27
ToU Structure 1	329.60	38.54	291.06
ToU Structure 2	241.43	25.22	216.20
BF1	613.84	389.95	223.89
BF2	613.84	390.36	223.48
BF3	613.84	390.46	223.38

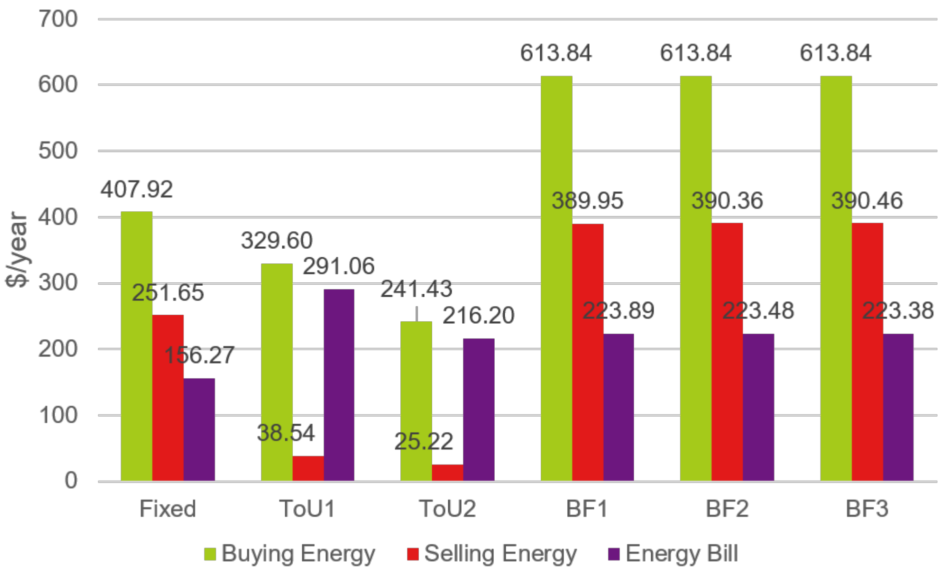


Figure 4.13: Tariff Comparison with PMM1 (California)

For the second and third power management method, the time-of-use characteristic is also considered into the electricity buy-in structure.

For the second power management method, the peak-hour definition is the same as the Netherlands case, peak-hour starts from 7:00 in the morning and last until 23:00 at night. The reference price for the peak-hour is calculated to ensure the same average price with the SCE time-of-use tariff. Equation 4.27 is used to calculate the price for peak-hour for both summer period and winter period for the second tariff structure. However, this time, n only equals 1 or 2, which represents the summer period and winter period, respectively. Equation 4.27 is listed here as Equation4.36.

$$\begin{aligned} p_{off2}(n) \times T_{off2}(n) + p_{peak2}(n) \times T_{peak2}(n) \\ = p_{off3}(n) \times T_{off3}(n) + p_{valley3}(n) \times T_{valley3}(n) + p_{peak3}(n) \times T_{peak3}(n), \\ n = 1,2 \text{ and } p_{off2}(n) = p_{off3}(n) \end{aligned} \tag{4.36}$$

With equation 4.36, the reference price for summer period equals to $p_{peak-summer} = 33.5cents/kWh$; the reference price for winter period equals to $p_{peak-winter} = 28.625cents/kWh$.

The second buy-in tariff structure is shown in equation:

For peak-hour

$$p_{RT} = \begin{cases} p_{refh} \times \left(1 + \frac{E-E_{ref}}{k}\right), & E > E_{ref} \\ 0, & E = 0 \end{cases} \tag{4.37}$$

For off-peak-hour

$$p_{RT} = \begin{cases} p_{refl} \times \left(1 + \frac{E-E_{ref}}{k}\right), & E > E_{ref} \\ 0, & E = 0 \end{cases} \tag{4.38}$$

This time k changes from 500 to 3000 with a step of 50, E_{ref} changes from -200 to 100 with a step of 10, with the real-time energy selling data from grid side under the second PPM as the input E, 1581 different combinations of E_{ref} and k can be calculated. The result shows when $E_{ref} = -150$ and $k = 900$, the average real-time buy-in price is closest to the standard average buy-in price $p_{ref} = 25.36cents/kWh$. This combination is used for the second tariff structure for California. The simulation results are shown in Table 4.25 and Figure 4.14.

Table 4.25: Tariff Comparison with PMM2 (California)

Price Structure	Money Buying ($)	Money Selling ($)	Money Paying ($)
Fixed	1222.60	1055.43	167.17
ToU Structure 1	755.28	130.15	625.13
ToU Structure 2	730.87	125.12	605.75
BF1	2071.03	1741.81	329.21
BF2	2071.03	1754.32	316.71
BF3	2071.03	1749.78	321.25
BF4	2071.03	1757.83	313.20

For the third power management method, the buy-in tariff structure is shown below:

For peak-hour

$$p_{RT} = \begin{cases} p_{refh} \times \left(1 + \frac{E-E_{ref}}{k}\right), & E > E_{ref} \\ 0, & E = 0 \end{cases} \tag{4.39}$$

For valley-hour

$$p_{RT} = \begin{cases} p_{refm} \times \left(1 + \frac{E-E_{ref}}{k}\right), & E > E_{ref} \\ 0, & E = 0 \end{cases} \tag{4.40}$$

For night-hour

$$p_{RT} = \begin{cases} p_{refl} \times \left(1 + \frac{E-E_{ref}}{k}\right), & E > E_{ref} \\ 0, & E = 0 \end{cases} \tag{4.41}$$

4

4

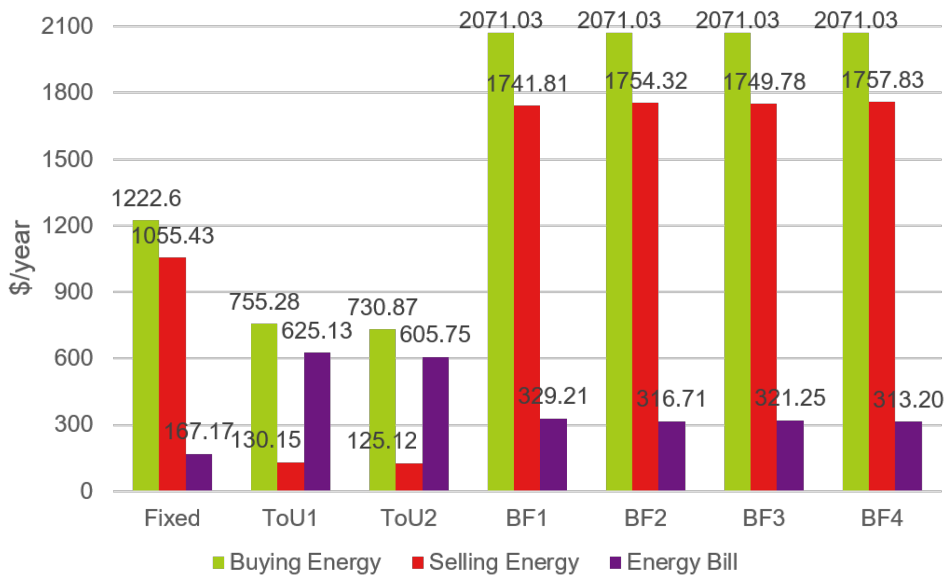


Figure 4.14: Tariff Comparison with PMM2 (California)

The reference price for the peak-hour, valley-hour, and night-hour are different, each of them is different for the summer period and the winter period according to SCE time-of-use tariff price. The detail prices are listed in Table. This time k changes from 300 to 3000 with a step of 50, E_{ref} changes from -200 to 100 with a step of 10, with the real-time energy selling data from grid side under the third PPM as the input E, 1581 different combinations of E_{ref} and k can be calculated. The result shows when $E_{ref} = -130$ and $k = 850$, the average real-time buy-in price is closest to the standard average buy-in price $p_{ref} = 25.36 cents/kWh$. This combination is used for the third tariff structure for California. The simulation results are shown in Table 4.26 and Figure 4.15.

Table 4.26: Tariff Comparison with PMM3 (California)

Price Structure	Money Buying ($)	Money Selling ($)	Money Paying ($)
Fixed	761.97	600.15	161.82
ToU Structure 1	703.52	80.51	623.01
ToU Structure 2	268.46	31.01	237.45
BF1	1254.48	994.94	259.55
BF2	1254.48	949.92	304.56
BF3	1254.48	985.98	268.51
BF4	1254.48	1080.31	174.17

For PMM1, PMM2, and PMM3, it is suggested to involve with the first ToU tariff structure for all three cases, which can provide the lowest energy bill among the six tariff structures. The three newly designed tariff structures can provide almost the same per-

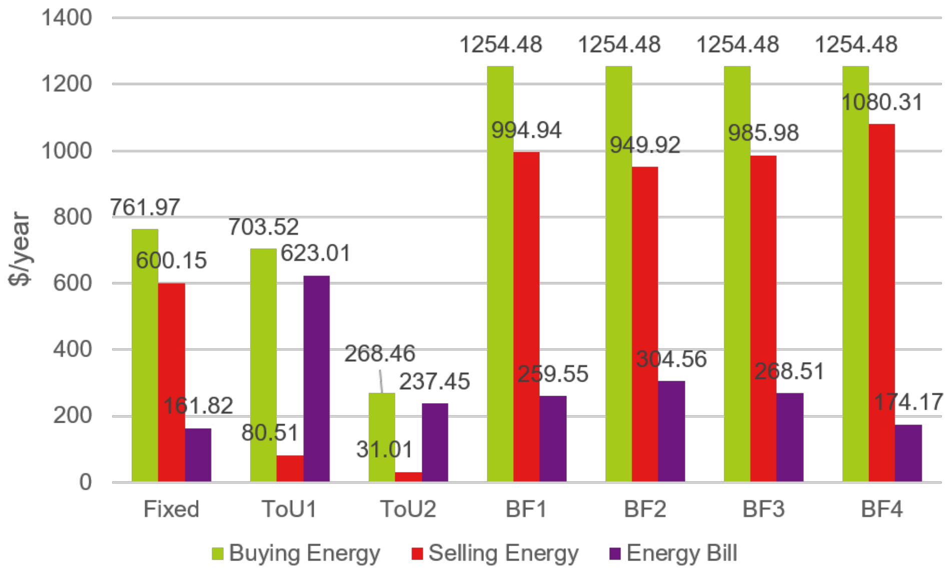


Figure 4.15: Tariff Comparison with PMM3 (California)

formances, this is because with a more stable PV production than the Netherlands and Costa Rica during the entire year, the energy exchange between the grid and system are almost the same no matter which tariff structures are used, the prosumers are compensated with almost the same amount of money, making the final energy bill almost the same.

For the last power management method, if the amount of energy bought from grid is larger than E_{ref}, for the part that exceeds the E_{ref}, the real-time will be calculated with Equation 4.8, leading to a price that is higher than the reference price; the rest part will be charged a fixed price equals to the reference price. If the amount of energy bought from the grid is lower than E_{ref}, then the real-time price will also only be calculated with Equation 4.8; and in this case, the real-time price is lower than the reference price. Equation is used to decide the reference price for this tariff structure. The predetermined reference value for California Case is $P_{ref} = 1400W$, $p_{ref1} = 25.36 cents/kWh$, $E_{ref1} = 90$ and $k_1 = 5500$. The reference price for the fourth tariff structure equals to $p_{ref} = 26.03 cents/kWh$.

$$M_{RTB} = \begin{cases} p_{ref} \times \left(1 + \frac{E - E_{ref}}{k}\right) \times (E - E_{ref}) + p_{ref} \times E_{ref}, & E > E_{ref} \\ p_{ref} \times \left(1 + \frac{E - E_{ref}}{k}\right) \times E, & 0 < E \leq E_{ref} \\ 0, & E = 0 \end{cases} \tag{4.42}$$

Where M_{RTB} is the money spend on buying energy from the grid during that very time period.

In this case k changes from 500 to 5500 with a step of 50, E_{ref} changes from 0 to 400 with a step of 10, with the real-time energy selling data from grid side under the second PPM as the input E, 45141 different combinations of E_{ref} and k can be calculated. The result shows when $E_{ref1} = 230$ and $k = 2700$, the average real-time buy-in price is closest to the standard average buy-in price $p_{ref} = 25.36 cents/kWh$. This combination is used for the fourth tariff structure for California case.

The simulation results are shown in Table 4.27 and Figure 4.16.

Table 4.27: Tariff Comparison with PMM4 (California)

Price Structure	Money Buying ($)	Money Selling ($)	Money Paying ($)
Fixed	1026.40	960.78	65.62
ToU Structure 1	406.95	72.45	334.50
ToU Structure 2	278.42	51.87	225.55
BF1	1359.39	1269.62	89.76
BF2	1359.39	887.27	472.11
BF34	1359.39	1309.16	50.23

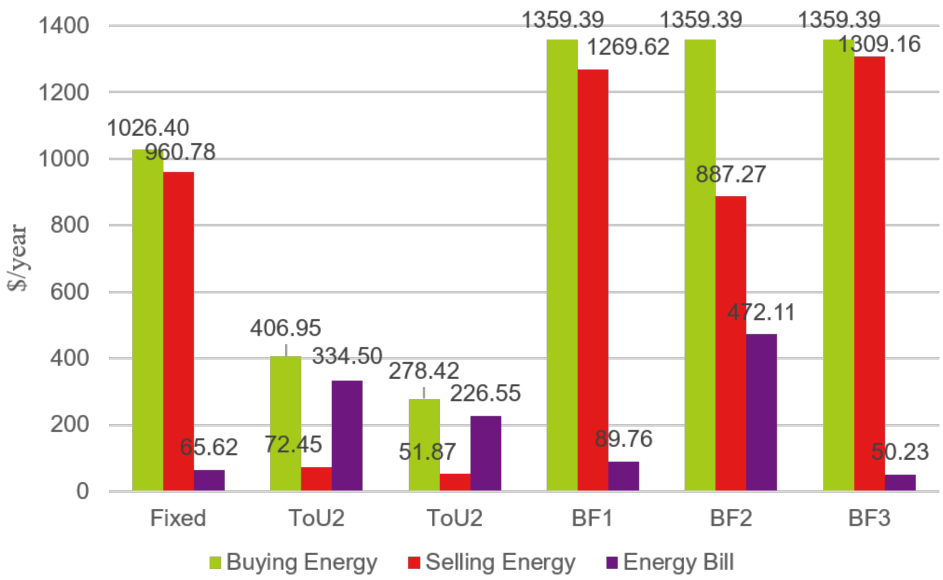


Figure 4.16: Tariff Comparison with PMM4 (California)

Although the three newly designed tariff structures cost prosumers more money to buy energy, the feed-in policies can effectively lower the final energy bill. Structure 3 leads to the lowest energy bill among the six tariff structures, followed by the first ToU structure, the fixed structure, and the second ToU structure. It could be seen that sometimes more money is spent on buying energy, however, more money is earned by selling energy back to the grid.

4.4. CONCLUSION

THE three newly designed tariff structures have different reactions to each country/region, this is mainly because of for different countries/regions, the load performance and the PV panels' production patterns are different, leading to different energy exchange patterns between units and the grid in the system. The newly designed tariff structures do have their own advantages, however, these structures are not always the best choices for all the prosumers.

The prototype of these newly designed tariff structures are first proposed based on the Netherlands case's characteristics and later further improved to fit the Costa Rica case and the California case. From the simulation results of the Netherlands case, it can be concluded that the newly designed tariff structures are reasonable to compete with the existing tariff structures. Since the average electricity buy-in prices for the newly designed tariffs are designed to be equal to the average electricity buy-in price of the existing tariffs, the money spends on buying energy should be more or less the same as those existing tariffs if the newly designed tariff structures are chosen. The feed-in tariff has some connection with the buy-in price, in other words, the feed-in tariff depends on the buy buy-in price. In this way, the money used to compensate the prosumers should be almost the same, leaving the final energy bill of newly designed tariff structures almost the same if compared with the existing tariff structures. In conclusion, the third newly designed feed-in tariff structures can be a promising choice for the prosumers in the Netherlands.

For the Costa Rica case and the California case, the existing tariffs structures sometimes are different with the Netherlands case and the same average policy may not be suitable and reasonable to apply to. This is because some tariffs are designed based on what amount of energy is consumed instead of the time. In this way, the average buy-in price depends on the different energy consumption patterns instead of different time periods, making the four newly designed tariff structures may not recommend as the best choice for the prosumers. But still, for the Costa Rica case, the third newly designed tariff structures still come as the best choice for the prosumers if they involve with either PMM1 or PMM4; for PMM2 and PMM3, the fourth newly designed tariff structures still come as the best choice for the prosumers. the newly designed tariff structures are one of the most competitive choices since it can give almost the same energy bill as the best choice. For California case, the third newly designed tariff structure together with PMM4 can gove the best performance for the prosumers, which can gives a much lower overall energy bill than the rest combinations. For the rest three PMMs, at least one of the newly designed tariff structures can provide the second best or the third best choice for the prosumers.

Based on these conclusions, it can be summarized that the newly designed tariff structures are feasible tariff structures, they are flexible and can be easily changed to adapt to new policies, it can be applied to the single individual or provided by the energy company as a unify tariff structures for prosumers, making each prosumer has their own tariff possible. The real-time prices generate by the newly designed buy-in tariff does not fluctuate too much during the whole year, the price can change every day, every hour, even every minute or every seconds, in this way, it is possible to provide accurate price for consumers. Since this real-time pricing mechanism does not need load forecasting, making it easy to applied to the real case.

5

CONCLUSIONS AND FUTURE WORK

In this thesis, four different power management methods are simulated based on the AC coupled topology. A new method to generate the real-time price is proposed. New electricity buy-in tariff structure and the feed-in tariff structures are designed for all three countries/region. Based on the simulation results get with different power management methods, the existing electricity tariff structures are simulated together with the newly designed tariff structures. The goal is to find out the suitable combination of power management method and electricity tariff for prosumers based on the final energy bill.

In this chapter, the main contributions of this thesis is listed in Section 5.1, follow by the important conclusions and future work in Section 5.2 and Section 5.3, respectively.

5.1. CONTRIBUTIONS

THE main contributions of this thesis are listed here:

1. Demonstrate four different power management methods and improving the detail power flow for power management methods two and three.
2. Demonstrate the influence of PV panels and battery storage unit on the system power flow.
3. Propose a new way to generate the real-time price without complex algorithm.
4. Design four different feed-in tariff structures and simulate them together with the newly design buy-in tariff structures to calculate the final energy bill.
5. Determine a suitable combination of power management method and electricity tariff for the Netherlands, Costa Rica, and California.

5.2. CONCLUSIONS

IN this section, the key finds that answer the research questions are mentioned here. The conclusions are categorized into two parts, namely, the power management method part and the electricity tariff part.

5.2.1. POWER MANAGEMENT METHOD

1. The PV panels can directly reduce the amount of energy bought directly from the grid.

   If only adds PV panels to the system, for all three countries/regions, the total amount of energy bought from the grid can be effectively lowered. PV panels work as another energy sources in the system and act as the first choice for the load.

2. The battery can reduce the amount of energy bought with high retail prices.

   If only adds the battery to the system, the amount of energy bought during peak-hour can be effectively lowered due to the battery discharging. The battery can be charged before the peak-hour comes, leading to the amount of energy bought outside the peak-hour is higher. Together, if compared with the no PV panels no battery case, the total amount of energy bought directly from the grid may be almost the same or even a little bit higher.

3. Among the four power management methods, peak-shaving can give the best performance.

   Peak-shaving can provide a smoother energy buying mode from the grid, the sudden peaks can be effectively shaved, therefore, peak-shaving also lower the amount of energy bought with the high retail price. Plus, the battery needed for peak-shaving is smaller than the rest three power management methods, which could save the capital cost when building the system. The battery is only used to support the part of loads that excess the reference value, and can be charged with the energy from the PV panels or the energy from the grid during two peak intervals, as long as the total energy bought from the grid does not excess the reference value, which brings a smoother energy buying mode and decreases the amount of energy bought with high retail price.

4. No matter which power management method is used, the grid still acts as one important energy sources for the load. For different power management method and battery size, the battery's impact on the system's energy flow varies a lot.

   Since the battery has different functions in different PMM, the battery impact on the system's power flow is different. For PMM4, the battery only used to support the energy peak that exceeds the reference value, making the role of function limited and contribute less to the system's power flow. For the rest three PMMs, with larger battery size, the battery can provide more energy for the load. Although the grid acts as the third choice for the load for the first three power management method and the second choice for PMM4, it still provides approximately 30% - 60% of the energy that consumed by the load.

5.2.2. ELECTRICITY TARIFF

1. At least one of newly designed tariff structures can give a better or almost the same performance when compared with the existed tariff structures in each country/region.

   Below, in Table 5.1, the final energy bill for the Netherlands, Costa Rica, California cases are shown. The tariff structure that can give the lowest energy bill for each power management method is shown in the fourth column. If the newly designed real-time pricing mechanism with one of the newly designed feed-in tariff structures can give the lowest energy bill, then in the last column, among all the tariff structures, the second best tariff structure is shown; however, if the lowest energy bill is provided by one of the existed tariff structures, then in the last column, among the newly designed tariff structures, the one could give the lowest energy bill is shown.

2. For the Netherlands case, the best combination of power management method and electricity tariff structure is peak-shaving together with the first time-of-use tariff structure. However, third newly designed tariff structure together with peak-shaving can provide the almost the same final energy bill.

3. For the Costa Rica case, the best combination of power management method and electricity tariff structure is peak-shaving together with the third newly designed tariff structure.

4. For the California case, the best combination of power management method and electricity tariffs structure is peak-shaving together with the third newly designed tariff structure.

5.3. FUTURE WORK

THE optimal system power flow schedule and the real-time tariff design is still a hot topic. As an extension of this thesis, there are several possible directions can be fur-

Table 5.1: The Best Tariff Structure Based on the Final Energy Bill

Country/Region	PMM	Structure/Value	The Best	[1]
The Netherlads	PMM1	Structure	TOU1	BF3
		Energy Bill (€/year)	45.32	45.78
	PMM2	Structure	TOU2	BF3
		Energy Bill (€/year)	63.01	70.29
	PMM3	Structure	Day-ahead	BF3
		Energy Bill (€/year)	67.15	73.36
	PMM4	Structure	TOU1	BF3
		Energy Bill (€/year)	22.41	22.54
Costa Rica	PMM1	Structure	BF3	BF1 (Second Best)
		Energy Bill ($/year)	14.21	35.79
	PMM2	Structure	BF4	BF3 (Second Best)
		Energy Bill ($/year)	23.09	32.44
	PMM3	Structure	BF4	TOU1
		Energy Bill ($/year)	54.59	111.73
	PMM4	Structure	BF3	BF1 (Second Best)
		Energy Bill ($/year)	11.78	42.88
California	PMM1	Structure	Fixed	BF3
		Energy Bill ($/year)	156.27	223.38
	PMM2	Structure	Fixed	BF4
		Energy Bill ($/year)	167.17	313.20
	PMM3	Structure	Fixed	BF4
		Energy Bill ($/year)	161.82	174.17
	PMM4	Structure	BF3	Fixed (Second Best)
		Energy Bill ($/year)	50.23	65.62

[1] If the lowest energy bill comes from one of newly designed tariff structures,then in this column, among all the tariff structures, the one leads to the second lowest energy bill is shown. If the lowest energy bill comes from one of the existed tariff structures, then in this column, among the newly designed tariff structures, the one could provide the lowest energy bill is shown is shown.

ther explored. The possible future works are listed below.

1. The accurate load forecasting.

   Due to the uncertainty and randomness of the load profile, an accurate load behavior forecasting is difficult to achieve. Consumers can react based on the energy retail price, which in return influence the energy retail price again, making the demand response and demand side management a hot topic. If a precise load forecast cannot be achieved, the power flow cannot be improved from basic. Plus, with a more precise load forecasting, the energy retail price could be more accurate and reasonable. With a better load forecasting, it is possible to lower the energy bill more intelligent, which may force an implementation of new power flow pattern like maybe the battery does not need to be fully charged at the beginning of peak-hour since the forecasting data predict that PV production and only half battery storage energy could be enough for the entire consumption during the peak-hour; another case could be the battery may not be discharged at the beginning of the peak-hour because later the retail price will be much higher due to the suddenly huge consumption.

2. The change of energy flow inside the system when multiple energy sources and multiple energy storage units are involved.

   The simulation results show that no matter which power management method is chosen, there is still about 30% 60% of energy from load consumption need to be bought directly from grid side. In this thesis, the only renewable energy source is PV panels; the only energy storage unit is the battery. However, the PV panels have their own limitations, the time factor and the location of PV panels can hugely influence the production. Multi energy sources could be an effective supplement to the system. Some other renewable energy sources like wind energy, tidal energy, hydropower, geothermal energy, and biomass could be the alternative energy sources in the system. Also, multiple energy storage units, like battery units together with the electrical vehicle, could be also be involved into the system to see how the power flow will change and what the degree of autarky will be.

3. Further explore the internal relationship among prosumers, energy providers and the electricity market.

   When both the relationships between the energy market and energy providers and energy providers and consumers are considered, the tariff structures could be better designed. The relationship between the energy market and energy providers could define the prices that could help energy providers gain profit, while the relationship between energy providers and consumers can help energy providers decide a reasonable retail price that could be accepted by consumers.

A

EXAMPLES

A.1. COSTA RICA ACCESS TARIFF MECHANISM

IN Costa Rica, the electricity tariff is made up of the buy-in tariff structure and the access tariff. Although the access tariff is also used to compensate prosumers who sell energy back to the grid, it works differently from the well-known feed-in tariff. This example is used to explain how the access tariff mechanism actually works. The data used in this example is randomly generated by the author only to make the example easy to understand.

CASE ONE

For January, PV generation is 100 kWh and 30 kWh is left after support the load energy bought from the grid is 50 kWh;

The 49% of PV generation is 49 kWh, so that it is possible to sell all 30 kWh back to the grid. After compensation, the first 30 kWh with access tariff, the rest 20 kWh bought from the grid will be charged with the standard buy-in tariff. The energy bill for January is:

$$M_{bill} = 30kWh \times 18colons/kWh + 1868.40colons = 2408.40colons \tag{A.1}$$

CASE TWO

For January, PV generation is 100 kWh and 30 kWh is left after support the load, energy bought from the grid is 200 kWh;

The 49% of PV generation is 49 kWh, so that it is possible to sell all 30 kWh back to the grid. After compensation, the first 30 kWh with access tariff, the rest 170 kWh bought from the grid will be charged with the standard buy-in tariff. The energy bill for January is:

$$\begin{aligned} M_{bill} &= 30kWh \times 18colons/kWh + 1868.40colons \\ &+140kWh \times 62.28colons/kWh = 11127.60colons \end{aligned} \tag{A.2}$$

A

CASE THREE

For January, PV generation is 100 kWh and 60 kWh is left after support the load; energy bought from the grid is 30 kWh;

The 49% of PV generation is 49kWh, so that only 49 kWh could be sold back to the grid. The rest 11 kWh can be considered as being abandoned. Since only 30 kWh is bought from the grid, so that there is 19 kWh left and accumulated to February. The energy bill for January is:

$$M_{bill} = 30kWh \times 18colons/kWh = 540colons \tag{A.3}$$

CASE FOUR

For December, PV generation is 100 kWh and 30 kWh is left after support the load; 30 kWh is accumulated to December from November, which could also be sold back to the grid to lower the energy bill; energy bought from the grid is 200 kWh;

The 49% of this month PV generation is 49 kWh, so that in theory all the 30 kWh sold back to the grid in December can be compensated with access tariff. Together with the 30 kWh left from November, the energy bill for December is:

$$\begin{aligned} M_{bill} = (30kWh + 30kWh) \times 18colons/kWh + 2100.03colons \\ +110kWh \times 70.01colons/kWh = 10881.13colons \end{aligned} \tag{A.4}$$

CASE FIVE

For December, PV generation is 100 kWh and 30 kWh is left after support the load; 30 kWh is accumulated to December from November, which could also be sold back to the grid to lower the energy bill; energy bought from the grid is 50 kWh;

The 49% of this month PV generation is 49 kWh, so that in theory all the 30 kWh sold back to the grid in December can be compensated with access tariff. However, together with the 30 kWh left from November, the amount of energy that prosumers intend to sell back to the grid is higher than the energy bought from the grid. In this case, all the energy bought from the grid can be charged with access tariff, while the rest of PV generation energy will be abandoned since the energy can only be accumulated for each twelve-month. The energy bill for December is:

$$M_{bill} = 50kWh \times 18colons/kWh = 900colons \tag{A.5}$$

A.2. THE AVERAGE BUY-IN PRICE

THIS example is used to calculate the average buy-in price. This average buy-in price is calculated every 10 minutes, and each time is updated to record the average buy-in price until this moment.

If $M_{net}(n) \geq 0$ && $M_{net}(n-1) \geq 0$, $P_{sell}(n) = P_{avg}(n-1)$, $P_{avg}(n) = P_{avg}(n-1)$.

If $M_{net}(n) < 0$ && $M_{net}(n-1) \geq 0$, $P_{sell}(n) = \begin{cases} P_{avg}(n-1), & \text{before compensation} \\ P_{low}, & \text{after compensation} \end{cases}$, $P_{avg}(n) = P_{low}$.
If $M_{net}(n) < 0$ && $M_{net}(n-1) < 0$, $P_{sell}(n) = P_{low}$, $P_{avg}(n) = P_{low}$.

Where:
$M_{net}(n) = \sum_1^n M_{buy}(n) - \sum_1^n M_{sell}(n)$ is the net money until this moment;
$P_{avg}(n)$ is the average energy price for moment n;
P_{low} is the energy selling price after total compensation, which equals to 7 cents/kWh here in the example.

PERIOD ONE

At period one, buy 10 kWh energy with price 20 cents/kWh;

$$P_{avg}(1) = 20cents/kWh$$

$$M_{buy}(1) = 10kWh \times 20cents/kWh = 200cents$$

$$M_{net}(1) = 200cents$$

PERIOD TWO

At period two, buy 5 kWh energy with price 14 cents/kWh;

$$P_{avg}(2) = \frac{10kWh \times 20cents/kWh + 5kWh \times 14cents/kWh}{10kWh + 5kWh} = \frac{200cents + 70cents}{15kWh} = 18cents/kWh$$

$$M_{buy}(2) = 5kWh \times 14cents/kWh = 70cents$$

$$M_{net}(2) = 200cents + 70cents = 270cents$$

PERIOD THREE

At period three, sell 5 kWh energy to grid;

$$P_{sell}(3) = P_{avg}(2) = 18cents/kWh$$

$$M_{sell}(3) = 5kWh \times 18cents/kWh = 90cents$$

$$M_{net}(3) = 270cents - 90cents = 180cents$$

$$P_{avg}(3) = P_{avg}(2) = 18cents/kWh$$

A

PERIOD FOUR
At period four, sell 20 kWh energy to grid;

$$P_{sell}(4) = \begin{cases} P_{avg}(3) = 18cents/kWh, & \text{before compensation, first 10 kWh} \\ P_{low} = 7cents/kWh, & \text{after compensation(rest 40 kWh)} \end{cases}$$

$$M_{sell}(4) = 10kWh \times 18cents/kWh + 10kWh \times 7cents/kWh = 180cents + 70cents = 250cents$$

$$M_{net}(4) = 180cents - 250cents = -70cents$$

$$P_{avg}(4) = P_{low} = 7cents/kWh$$

PERIOD FIVE
At period five, sell 10 kWh energy to grid;

$$M_{sell}(5) = P_{low} = 7cents/kWh$$

$$M_{sell}(5) = 10kWh \times 7cents/kWh = 70cents$$

$$M_{net}(5) = -70cents - 70cents = -140cents$$

$$P_{avg}(5) = P_{low} = 7cents/kWh$$

PERIOD SIX
At period six, buy 5 kWh energy from grid with price 14 cents/kWh;

$$M_{buy}(6) = 5kWh \times 14cents/kWh = 70cents$$

$$M_{net}(6) = -140cents + 70cents = 70cents$$

$$P_{avg}(6) = P_{low} = 7cents/kWh$$

PERIOD SEVEN
At period seven, buy 10 kWh energy from grid with price 20 cents/kWh;

$$M_{buy}(7) = 10kWh \times 20cents/kWh = 200cents$$

$$M_{net}(7) = -70cents + 200cents = 130cents$$

$$P_{avg}(7) = P_{low} = 20cents/kWh$$

A

A.3. DECIDE THE FIT PRICE FOR FIT STRUCTURE FOUR

FOR feed-in tariff structure four, the energy provides try to compensate the energy that sold back to the grid from prosumers with the 'highest allowed price'. This example explain the detail method to decide the final feed-in tariff price for each period. The abbreviations and the nomenclatures are used in this subsection are listed here again in Table A.1.

Table A.1: Abbreviations and Nomenclatures for FIT Structure 4

Abbreviations	Nomenclatures	Explanation
EB	E_b	Energy bought from the grid.
EBL	E_{bop}	Energy bought from the grid during off-peak-hour.
EBH	E_{bp}	Energy bought from the grid during peak-hour.
ES	E_s	Energy sold back to the grid.
ESL	E_{sop}	Energy sold back to the grid during off-peak-hour.
ESH	E_{sp}	Energy sold back to the grid during peak-hour.
AP	p_{avg}	The average energy buying price.
APL	p_{avgop}	The average energy buying price for off-peak-hour.
APH	p_{avgp}	The average energy buying price for peak-hour.
RPL	p_{rop}	The original electricity retail price for off-peak-hour.
RPH	p_{rp}	The original electricity retail price for peak-hour.
PF	p_{FIT}	The feed-in tariff price for the part (ES-EB), when ES>EB.
MS	R_s	The total money gets from selling energy back to the grid.
MSL	R_{sop}	The total money gets from selling energy back to the grid during off-peak-hour.
MSH	R_{sp}	The total money gets from selling energy back to the grid during peak-hour.
In this section, all the variables are based on the data for the whole year.		

It is assumed that the retail price for the energy bought from the grid during peak-hour (RPH) is $p_{rp} = 0.5$ €/kWh, the retail price for the energy bought from the grid during off-peak-hour (RPL) is $p_{rop} = 0.25$ €/kWh. When the amount of energy sold back to the grid is higher than the amount of energy bought from the grid, for the part of energy that excess the amount of energy bought from the grid, the feed-in tariff (PF) is $p_{FIT} = 0.1$ €/kWh. With the real-time price generated with Equation 4.8, the average energy buying price during peak-hour (APH) is $p_{avgp} = 0.6$ €/kWh, the average energy buying price during off-peak-hour (APL) is $p_{avgop} = 0.3$ €/kWh.

CASE ONE

EBH: $E_{bp} = 200$ kWh. ESH: $E_{sp} = 50$ kWh. EBL: $E_{bop} = 300$ kWh. ESL: $E_{sop} = 100$ kWh.

Since EBH>ESH, all the ESH can be compensated with APH.

$$R_{sp} = E_{sp} \times p_{avgp} = 50kWh \times 0.6€/kWh = 30€$$

Since EBL>ESL, all the ESL can be compensated with APL.

$$R_{sop} = E_{sop} \times p_{avgop} = 100kWh \times 0.3€/kWh = 30€$$

A

Therefore, in this case, the total money get from selling energy is:

$$R_s = R_{sp} + R_{sop} = 30€ + 30€ = 60€$$

CASE TWO

EBH: $E_{bp} = 200$ kWh. ESH: $E_{sp} = 50$ kWh. EBL: $E_{bop} = 200$ kWh. ESL: $E_{sop} = 300$ kWh.

Since EBH>ESH, all the ESH can be compensated with APH.

$$R_{sp} = E_{sp} \times p_{avgp} = 50kWh \times 0.6€/kWh = 30€$$

Since EBL<ESL, only EBL out of ESL can be compensated with APL, the rest part (ESL-EBL) is compensated with PF. In this case, for the energy sold back to the grid during off-peak hour, only 200 kWh out of 300 kWh is compensated with APL, the rest 100 kWh is compensated with PF.

$$R_{sop} = E_{bop} \times p_{avgop} + \left(E_{sop} - E_{bop}\right) \times p_{FIT}$$
$$= 200kWh \times 0.3€/kWh + (300kWh - 200kWh) \times 0.1€/kWh = 60€ + 10€ = 70€$$

Therefore, in this case, the total money get from selling energy is:

$$R_s = R_{sp} + R_{sop} = 30€ + 70€ = 100€$$

CASE THREE

EBH: $E_{bp} = 100$ kWh. ESH: $E_{sp} = 200$ kWh. EBL: $E_{bop} = 500$ kWh. ESL: $E_{sop} = 100$ kWh.

Since EBH<ESH and EBL>ESH-EBH, only EBH out of ESH can be compensated with APH, the rest part (ESH-EBH) can only be compensated with APL. In this case, for the energy sold back to the grid during peak-hour, only 100 kWh could be compensated with APH, the rest 100 kWh is compensated with APL.

$$R_{sp} = E_{bp} \times p_{avgp} + (E_{sp} - E_{bp}) \times p_{avgop}$$
$$= 100kWh \times 0.6€/kWh + (200kWh - 100kWh) \times 0.3€/kWh = 60€ + 30€ = 90€$$

Since EBL-(ESH-EBH)>ESL, all the ESL can be compensated with APL.

$$R_{sop} = E_{sop} \times p_{avgop} = 100kWh \times 0.3€/kWh = 30€$$

Therefore, in this case, the total money get from selling energy is:

$$R_s = R_{sp} + R_{sop} = 90€ + 30€ = 120€$$

CASE FOUR

EBH: $E_{bp} = 100$ kWh. ESH: $E_{sp} = 200$ kWh. EBL: $E_{bop} = 200$ kWh. ESL: $E_{sop} = 200$ kWh.

Since EBH<ESH and EBL>ESH-EBH, only EBH out of ESH can be compensated with APH, the rest part (ESH-EBH) can only be compensated with APL. In this case, for the energy sold back to the grid during peak-hour, only 100 kWh could be compensated with APH, the rest 100 kWh is compensated with APL.

$$R_{sp} = E_{bp} \times p_{avgp} + (E_{sp} - E_{bp}) \times p_{avgop}$$
$$= 100kWh \times 0.6€/kWh + (200kWh - 100kWh) \times 0.3€/kWh = 60€ + 30€ = 90€$$

Since after compensating some energy sold back to the grid during peak-hour with APL, EBL-(ESH-EBH)<ESL, only EBL-(ESH-EBH) out of ESL can be compensated with APL, the rest part [ESL-(EBL-(ESH-EBH))] is compensated with PF. In this case, after compensating 100 kWh from the energy sold back to the grid during peak-hour with APL, for the energy sold back to the grid during off-peak hour, only 100 kWh out of 200 kWh can be compensated with APL, the rest 100 kWh is compensated with PF.

$$R_{sop} = E_{bop} \times p_{avgop} + \left(E_{sop} - E_{bop}\right) \times p_{FIT}$$
$$= 100kWh \times 0.3€/kWh + (200kWh - 100kWh) \times 0.1€/kWh = 30€ + 10€ = 40€$$

Therefore, in this case, the total money get from selling energy is:

$$R_s = R_{sp} + R_{sop} = 90€ + 40€ = 130€$$

CASE FIVE

EBH: $E_{bp} = 100$ kWh. ESH: $E_{sp} = 300$ kWh. EBL: $E_{bop} = 150$ kWh. ESL: $E_{sop} = 100$ kWh.

Since EBH<ESH and EBL<ESH-EBH, only EBH out of ESH can be compensated with APH, and EBL out of ESH can only be compensated with APL, the rest (ESH-EBH-EBL) can only be compensated with $\frac{PF \times RPH}{RPL}$. In this case, for the energy sold back to the grid during peak-hour, only 100 kWh could be compensated with APH, another 150 kWh can be compensated with APL, the rest 50 kWh can only be compensated with $\frac{PF \times RPH}{RPL}$. At the same, all the ESL can only be compensated with PF.

$$R_{sp} = E_{bp} \times p_{avgp} + E_{bop} \times p_{avgop} + (E_{sp} - E_{bp} - E_{bop}) \times p_{FIT} \times \frac{p_{rp}}{p_{rop}}$$
$$= 100kWh \times 0.6€/kWh + 150kWh \times 0.3€/kWh + (300kWh - 100kWh - 150kWh) \times 0.1 \times \frac{0.5}{0.25}€/kWh$$
$$= 60€ + 45€ + 50kWh \times 0.2€/kWh = 115€$$

$$R_{sop} = E_{sop} \times p_{FIT} = 100kWh \times 0.1€/kWh = 10€$$

Therefore, in this case, the total money get from selling energy is:

$$R_s = R_{sp} + R_{sop} = 115€ + 10€ = 125€$$

RPH: $p_{rp} = 0.5$ €/kWh, RPL: $p_{rop} = 0.25$ €/kWh. PF: $p_{FIT} = 10$ cents/kWh. APH: $p_{avgp} = 0.6$ €/kWh, APL: $p_{avgop} = 0.3$ €/kWh.

B

SOC Change with Different Battery Sizes

B.1. Battery Size for the Netherlands

B.1.1. Power Management Method One

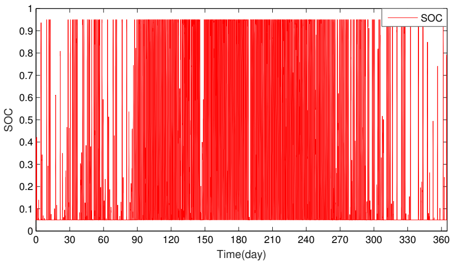


Figure B.1: PMM1 SOC with 0.25 Battery

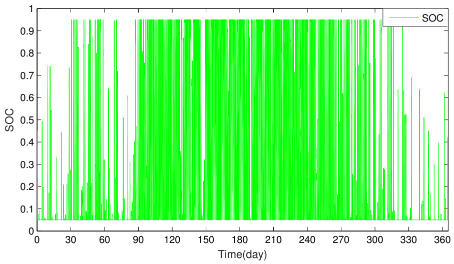


Figure B.2: PMM1 SOC with 0.50 Battery

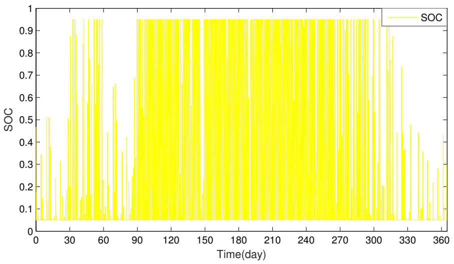


Figure B.3: PMM1 SOC with 0.75 Battery

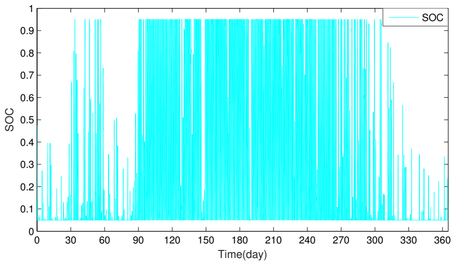


Figure B.4: PMM1 SOC with 1.00 Battery

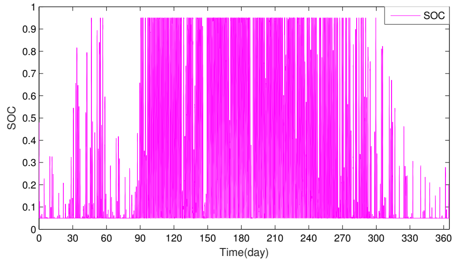


Figure B.5: PMM1 SOC with 1.25 Battery

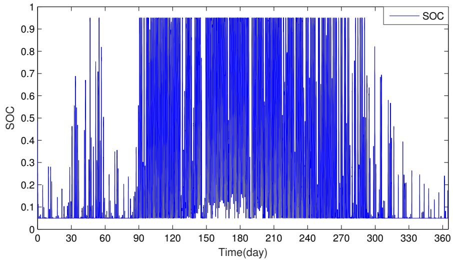


Figure B.6: PMM1 SOC with 1.50 Battery

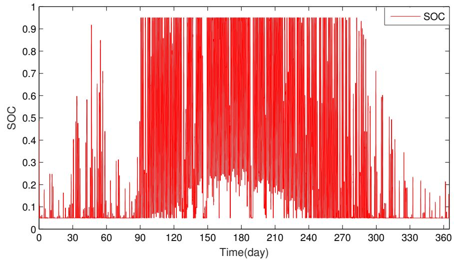


Figure B.7: PMM1 SOC with 1.75 Battery

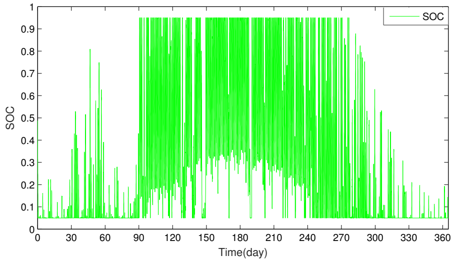


Figure B.8: PMM1 SOC with 2.00 Battery

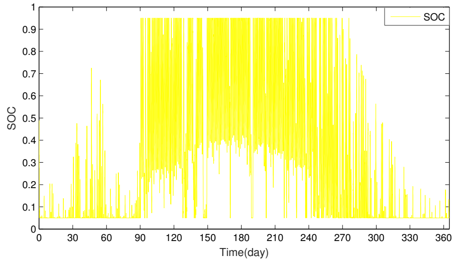


Figure B.9: PMM1 SOC with 2.25 Battery

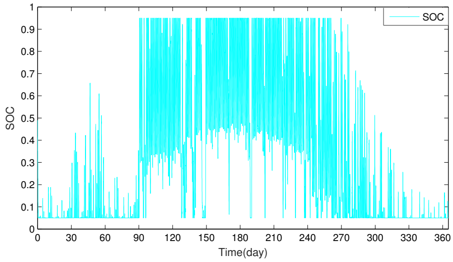


Figure B.10: PMM1 SOC with 2.50 Battery

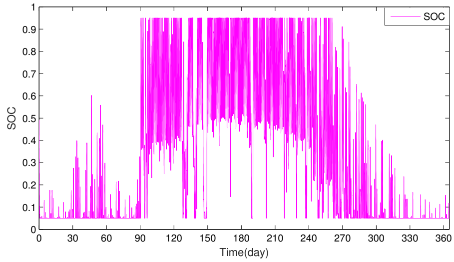


Figure B.11: PMM1 SOC with 2.75 Battery

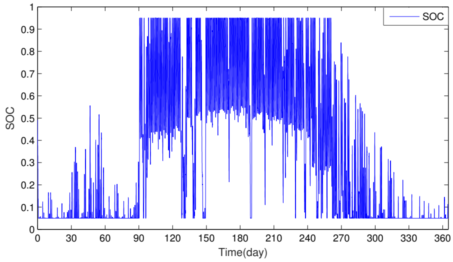


Figure B.12: PMM1 SOC with 3.00 Battery

B.1.2. POWER MANAGEMENT METHOD FOUR

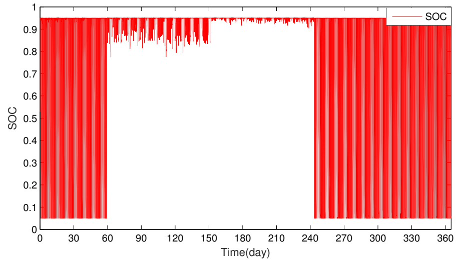


Figure B.13: PMM4 SOC with 0.125 Battery

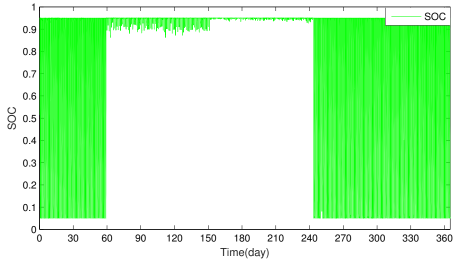


Figure B.14: PMM4 SOC with 0.250 Battery

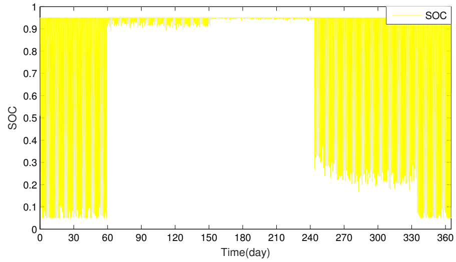


Figure B.15: PMM4 SOC with 0.375 Battery

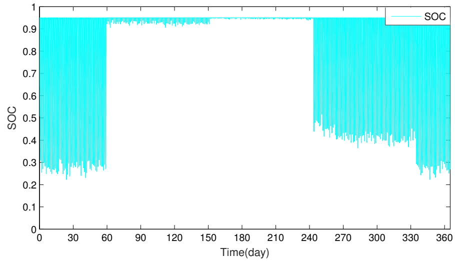


Figure B.16: PMM4 SOC with 0.500 Battery

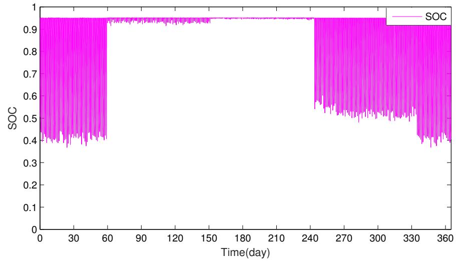


Figure B.17: PMM4 SOC with 0.625 Battery

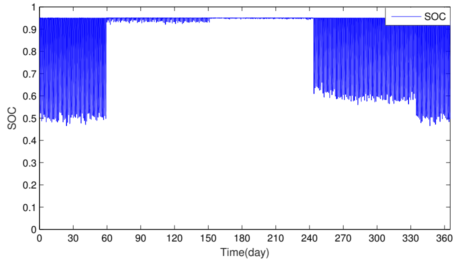


Figure B.18: PMM4 SOC with 0.750 Battery

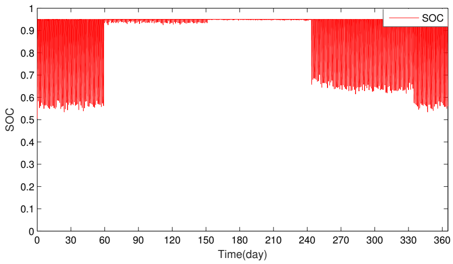


Figure B.19: PMM4 SOC with 0.875 Battery

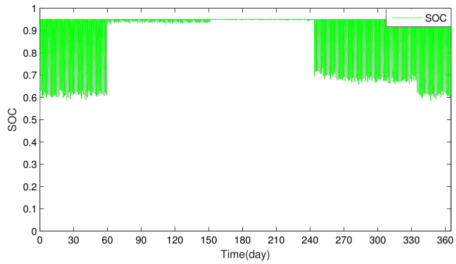


Figure B.20: PMM4 SOC with 1.000 Battery

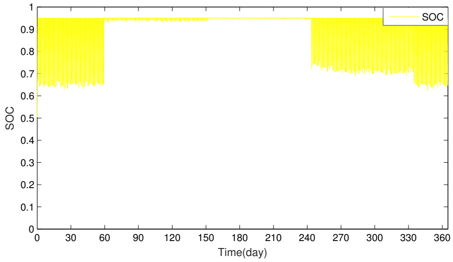


Figure B.21: PMM4 SOC with 1.125 Battery

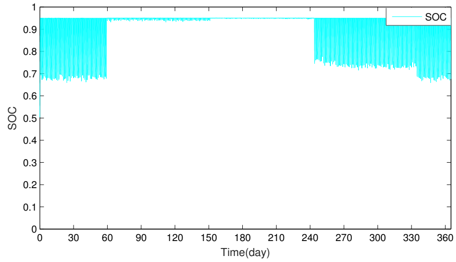


Figure B.22: PMM4 SOC with 1.250 Battery

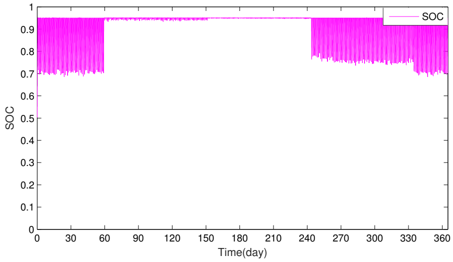


Figure B.23: PMM4 SOC with 1.375 Battery

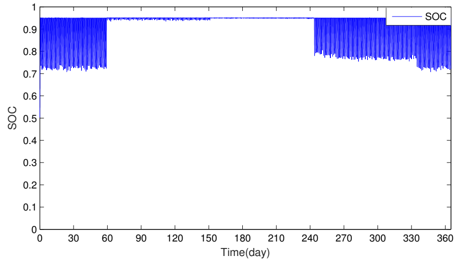


Figure B.24: PMM4 SOC with 1.500 Battery

B.2. BATTERY SIZE FOR COSTA RICA

B.2.1. POWER MANAGEMENT METHOD ONE

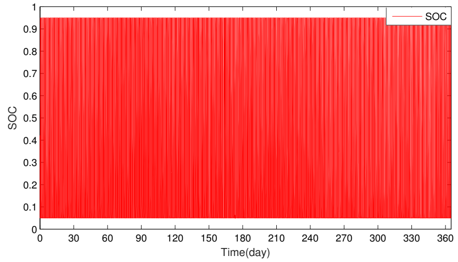


Figure B.25: PMM1 SOC with 0.25 Battery

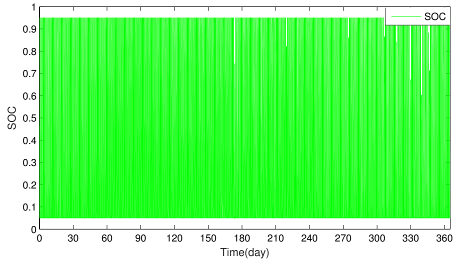


Figure B.26: PMM1 SOC with 0.50 Battery

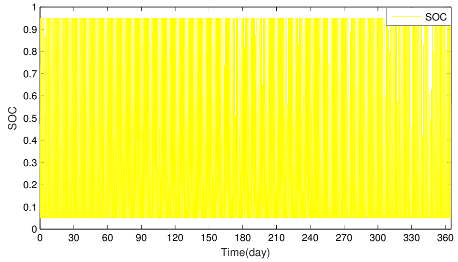


Figure B.27: PMM1 SOC with 0.75 Battery

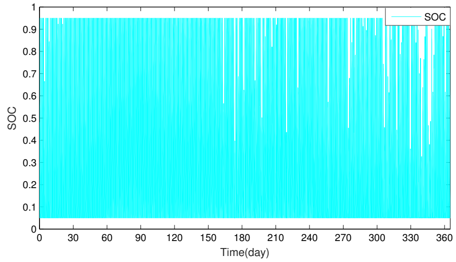


Figure B.28: PMM1 SOC with 1.00 Battery

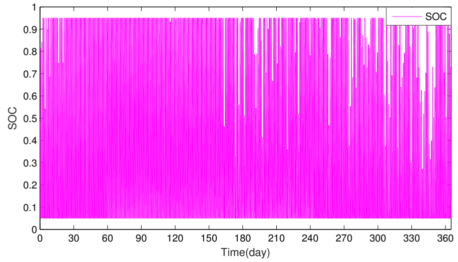


Figure B.29: PMM1 SOC with 1.25 Battery

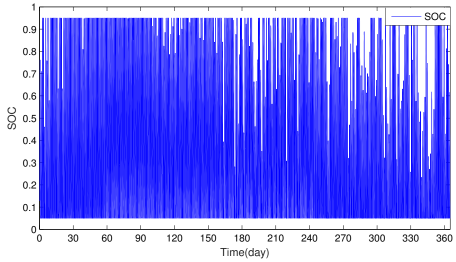


Figure B.30: PMM1 SOC with 1.50 Battery

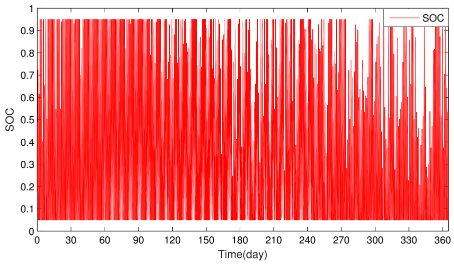


Figure B.31: PMM1 SOC with 1.75 Battery

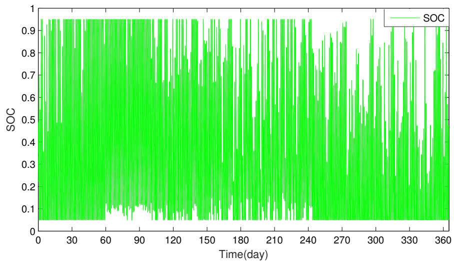


Figure B.32: PMM1 SOC with 2.00 Battery

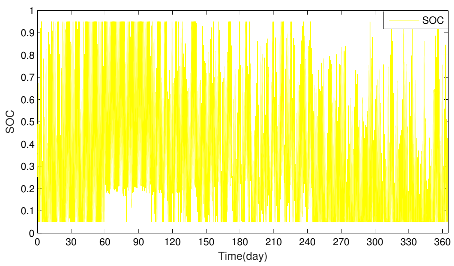


Figure B.33: PMM1 SOC with 2.25 Battery

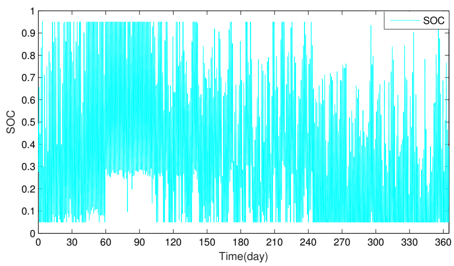


Figure B.34: PMM1 SOC with 2.50 Battery

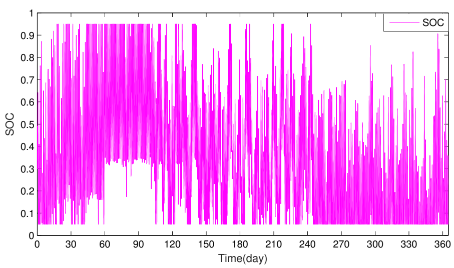


Figure B.35: PMM1 SOC with 2.75 Battery

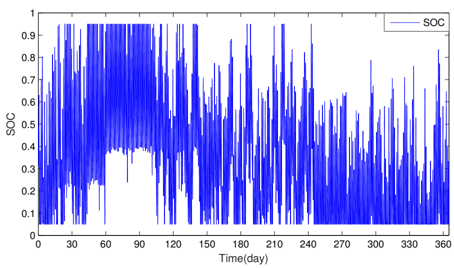


Figure B.36: PMM1 SOC with 3.00 Battery

B.2.2. POWER MANAGEMENT METHOD FOUR

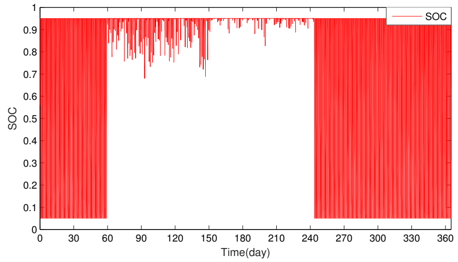


Figure B.37: PMM4 SOC with 0.125 Battery

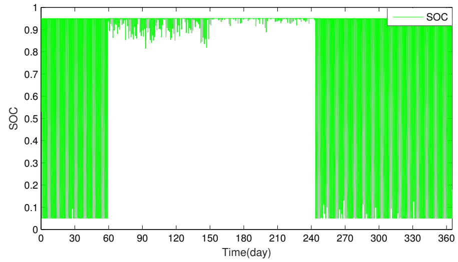


Figure B.38: PMM4 SOC with 0.250 Battery

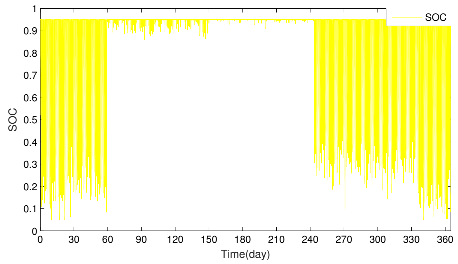


Figure B.39: PMM4 SOC with 0.375 Battery

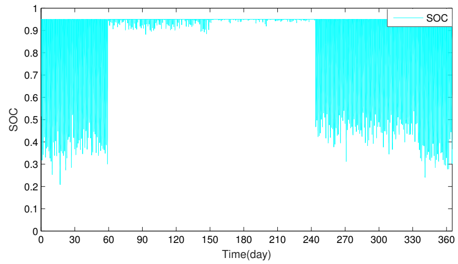


Figure B.40: PMM4 SOC with 0.500 Battery

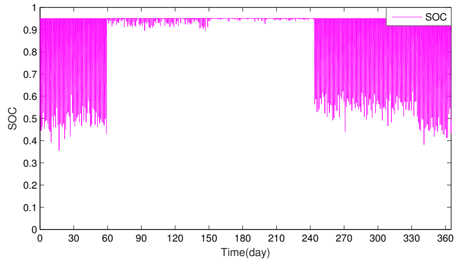


Figure B.41: PMM4 SOC with 0.625 Battery

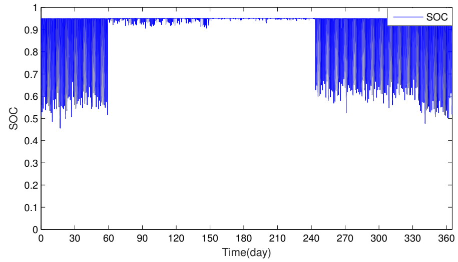


Figure B.42: PMM4 SOC with 0.750 Battery

B

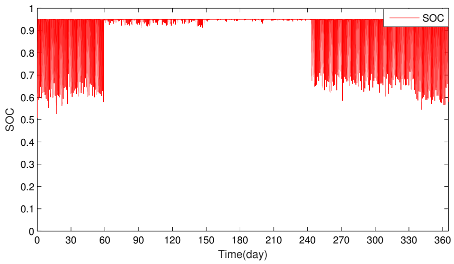


Figure B.43: PMM4 SOC with 0.875 Battery

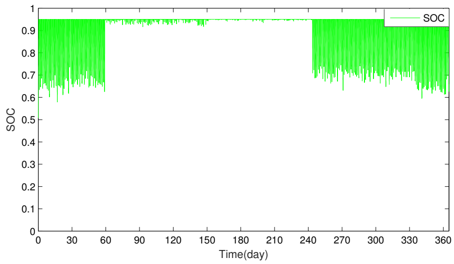


Figure B.44: PMM4 SOC with 1.000 Battery

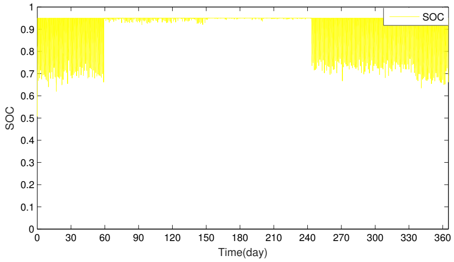


Figure B.45: PMM4 SOC with 1.125 Battery

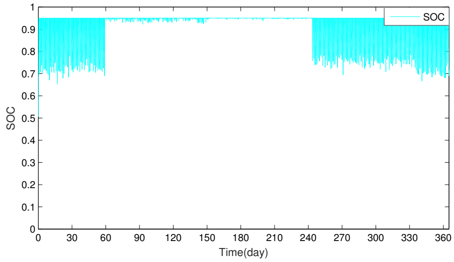


Figure B.46: PMM4 SOC with 1.250 Battery

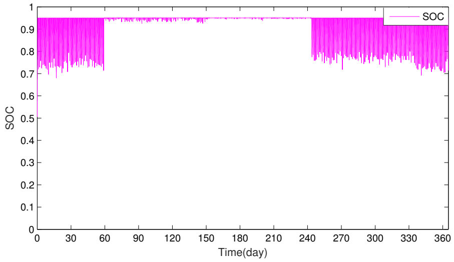


Figure B.47: PMM4 SOC with 1.375 Battery

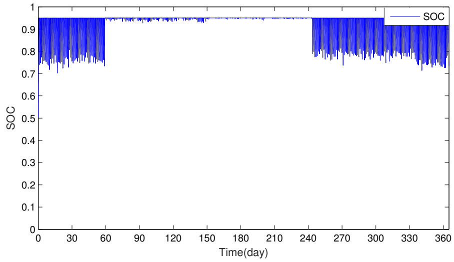


Figure B.48: PMM4 SOC with 1.500 Battery

B.3. BATTERY SIZE FOR CALIFORNIA

B.3.1. POWER MANAGEMENT METHOD ONE

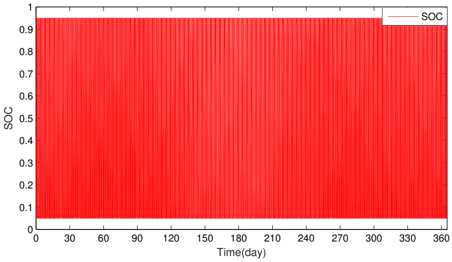


Figure B.49: PMM1 SOC with 0.25 Battery

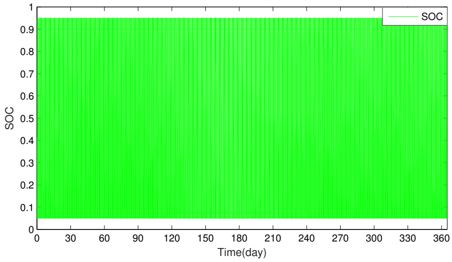


Figure B.50: PMM1 SOC with 0.50 Battery

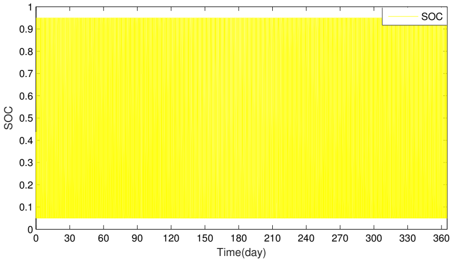


Figure B.51: PMM1 SOC with 0.75 Battery

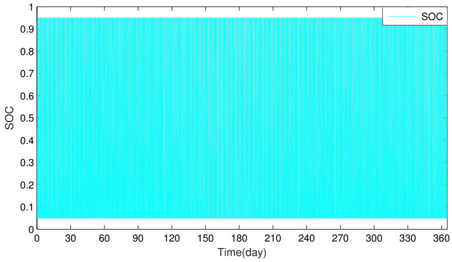


Figure B.52: PMM1 SOC with 1.00 Battery

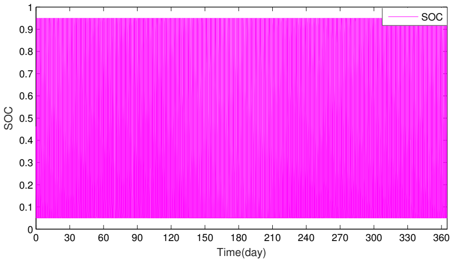


Figure B.53: PMM1 SOC with 1.25 Battery

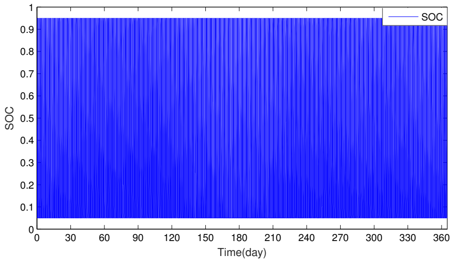


Figure B.54: PMM1 SOC with 1.50 Battery

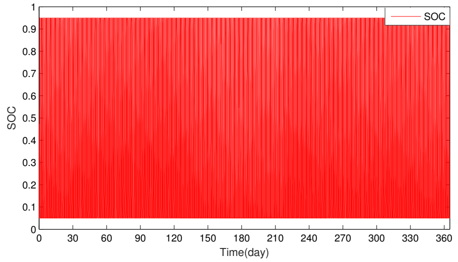


Figure B.55: PMM1 SOC with 1.75 Battery

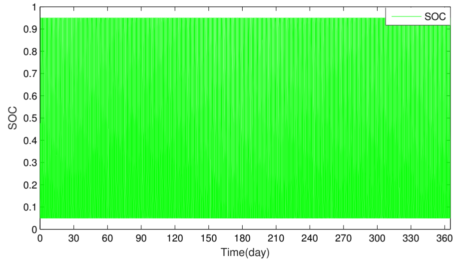


Figure B.56: PMM1 SOC with 2.00 Battery

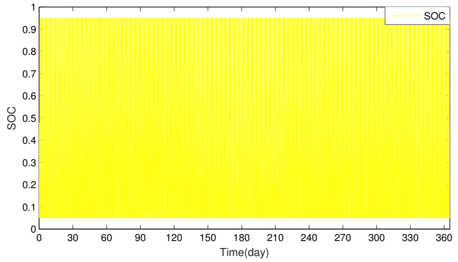


Figure B.57: PMM1 SOC with 2.25 Battery

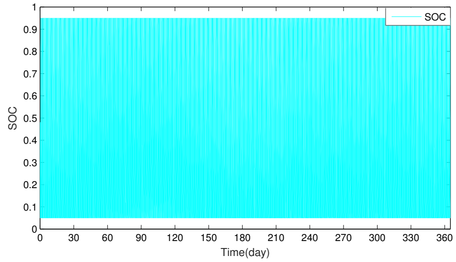


Figure B.58: PMM1 SOC with 2.50 Battery

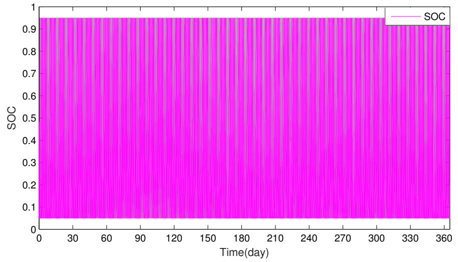


Figure B.59: PMM1 SOC with 2.75 Battery

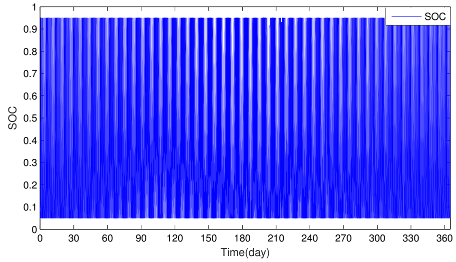


Figure B.60: PMM1 SOC with 3.00 Battery

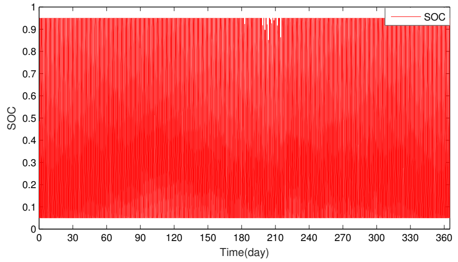


Figure B.61: PMM1 SOC with 3.25 Battery

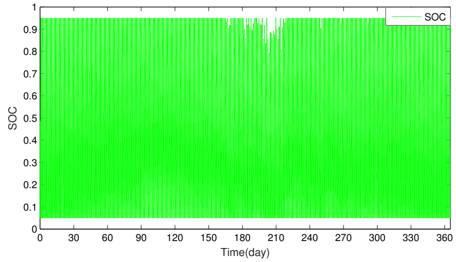


Figure B.62: PMM1 SOC with 3.50 Battery

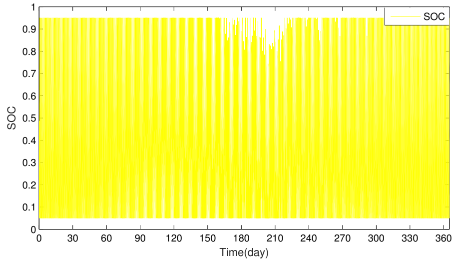


Figure B.63: PMM1 SOC with 3.75 Battery

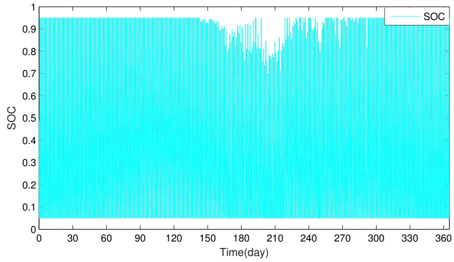


Figure B.64: PMM1 SOC with 4.00 Battery

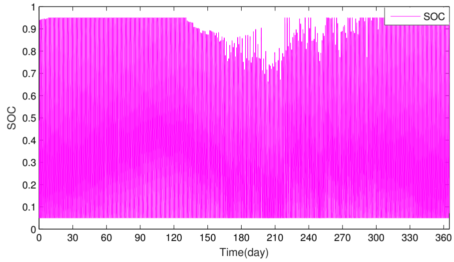


Figure B.65: PMM1 SOC with 4.25 Battery

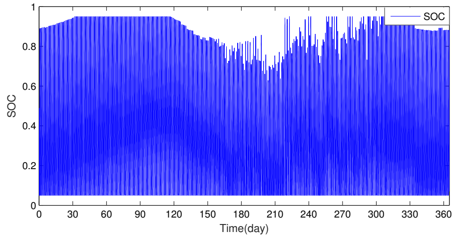


Figure B.66: PMM1 SOC with 4.50 Battery

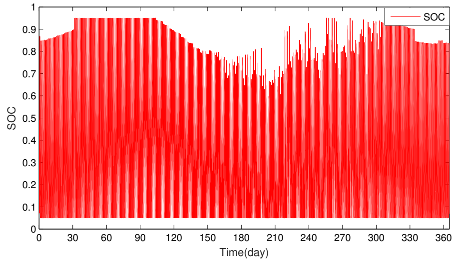


Figure B.67: PMM1 SOC with 4.75 Battery

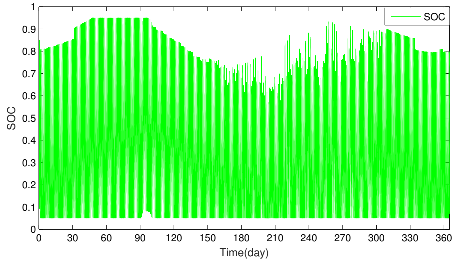


Figure B.68: PMM1 SOC with 5.00 Battery

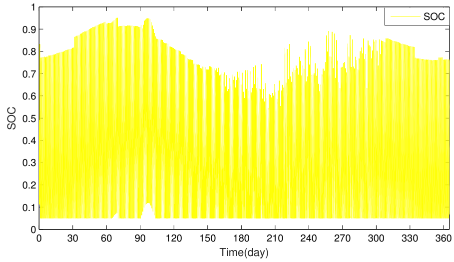


Figure B.69: PMM1 SOC with 5.25 Battery

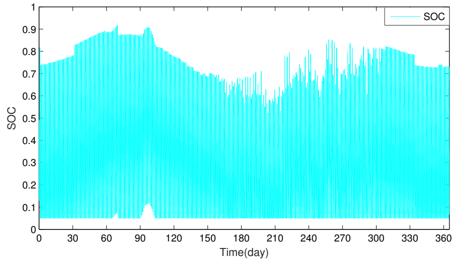


Figure B.70: PMM1 SOC with 5.50 Battery

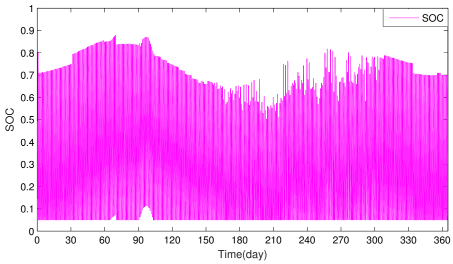


Figure B.71: PMM1 SOC with 5.75 Battery

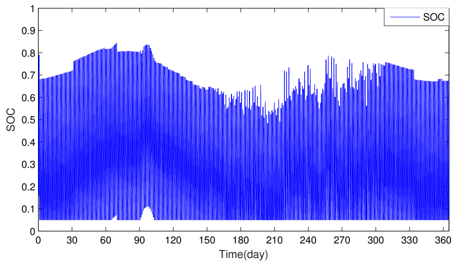


Figure B.72: PMM1 SOC with 6.00 Battery

B.3.2. Power Management Method Four

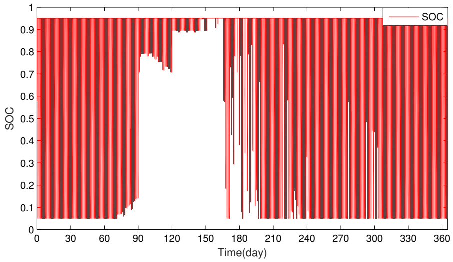


Figure B.73: PMM4 SOC with 0.125 Battery

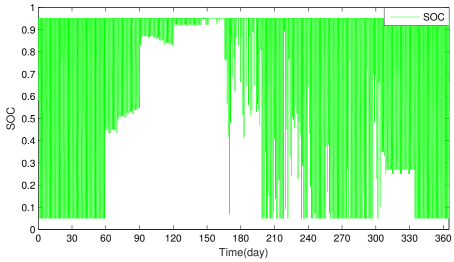


Figure B.74: PMM4 SOC with 0.250 Battery

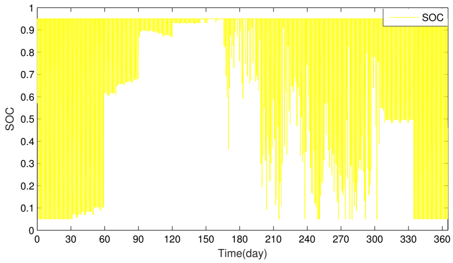


Figure B.75: PMM4 SOC with 0.375 Battery

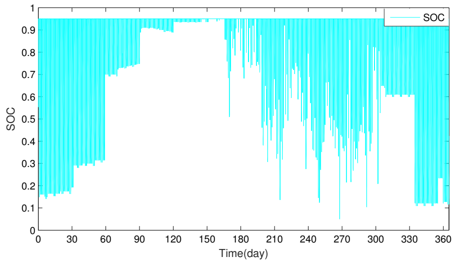


Figure B.76: PMM4 SOC with 0.500 Battery

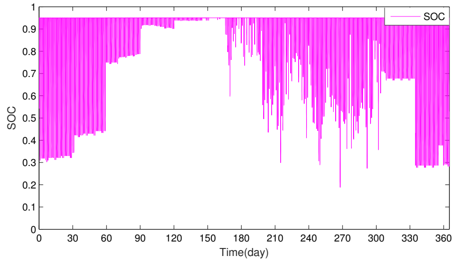


Figure B.77: PMM4 SOC with 0.625 Battery

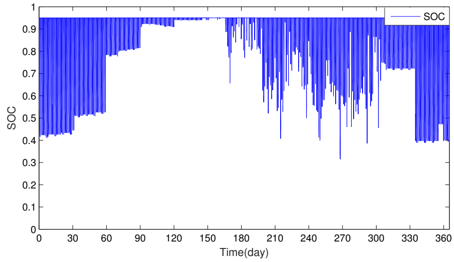


Figure B.78: PMM4 SOC with 0.750 Battery

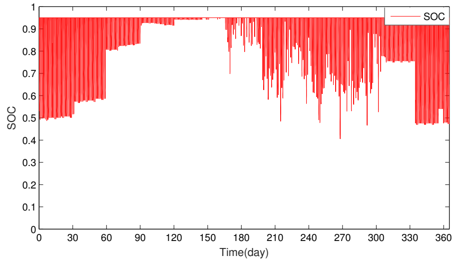


Figure B.79: PMM4 SOC with 0.875 Battery

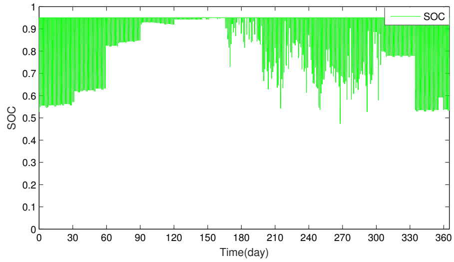


Figure B.80: PMM4 SOC with 1.000 Battery

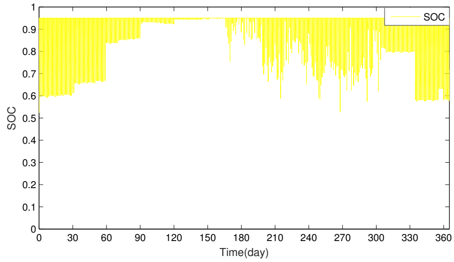


Figure B.81: PMM4 SOC with 1.125 Battery

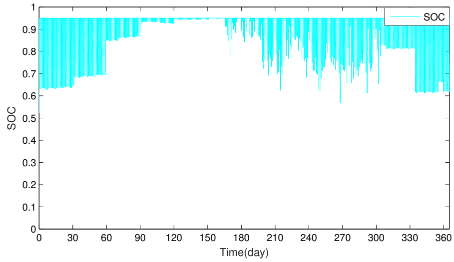


Figure B.82: PMM4 SOC with 1.250 Battery

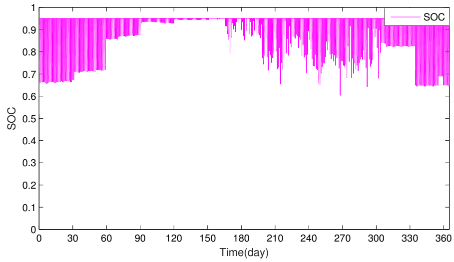


Figure B.83: PMM4 SOC with 1.375 Battery

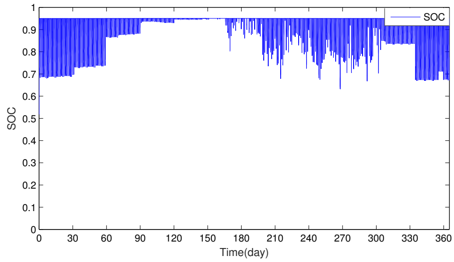


Figure B.84: PMM4 SOC with 1.500 Battery

C

Real-Time Price Improvement

1. This real-time price is not the final retail electricity buy-in price, it does not include the transmission and maintenance costs and the VAT and government tax; this original price is lower than the real buy-in price in market;

2. On January 24th, 2016, the real-time price for the whole day is missing; the average value of the same time slot from the previous day and the next day is used to generate the real-time price for any time slots on January 24th, 2016, the real-time price is equal to the average of the same time slot of January 23rd and January 25th, two digitals are kept after the decimal point, the detail price information can be found in Table C.1;

3. On March 27th, 2016, the real-time price for time slot 02:00 to 03:00 is missing, the average value of the previous slot (01:00 to 02:00) and the next slot (03:00 to 04:00) is used and inserted into this time slot; according to the website, the price for time slot 01:00 to 02:00 is 15.00 cents/kWh, the price for time slot 03:00 to 04:00 is 16.55 cents/kWh, thus the price for time slot 02:00 to 03:00 is (15.00+16.55)/2=15.775 cents/kWh, since the effective value is to keep 2 digitals after the decimal point for the whole year, the final value I chose for time slot 02:00 to 03:00 is 15.78 cents/kWh; the detail information can be found in Table C.2;

4. On September 7th, 2016, the real-time price for the whole day is missing; the same method is used to generate the real-time price as introduced above when decide the price for January 24th; for any time slot on September 7th, 2016, the real-time price is equal to the average value of the same time slot of September 8th and September 9th, two digitals is kept after the decimal point, the detail price information can be found in Table C.3;

5. On October 30th, 2016, the website gives two different real-time prices for time slot 02:00 to 03:00, they are 33.11 cents/kWh and 32.93 cents/kWh; the average value of these two prices is chosen as the new real-time price for this time slot, which is

(33.11 +32.93)/2=33.02 cents/kWh; so that the real-time buy-in price for time slot 02:00 to 03:00 is 33.02 cents/kWh;

6. On November 12th, 2016, the real-time price for the whole day is missing; the same method is used to generate the real-time price as introduced above when decide the price for January 24th, for any time slot on November 12th, 2016, the real-time price is equal to the average of the same time slot of November 11th and November 13th, two digitals are kept after the decimal point, the detail price information can be found in Table C.4;

C

7. After correcting and inserting necessary real-time price value, this real-time buy-in price for the whole year is ready for use; the average value is 0.0322768 €/kWh before amplifying, in order to have same average value, the whole real-time price data is amplified 6.18 times in order to achieve the same average value 0.199529 €/kWh, and these amplified data are used in the later simulation;

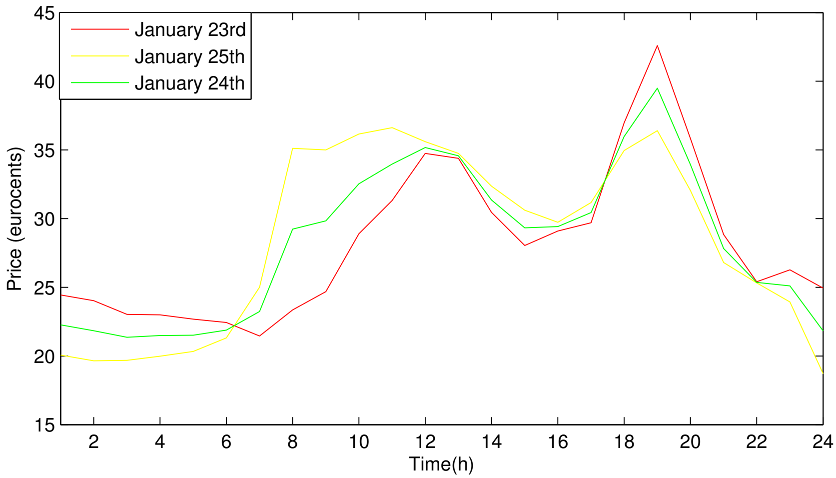


Figure C.1: The Real-time Price Information for January 24th

Table C.1: The Real-time Price Information for January 24th

Time Slot	00:00—01:00	01:00—02:00	02:00—03:00	03:00—04:00	04:00—05:00	05:00—06:00	06:00—07:00	07:00—08:00
January 23rd	24.44	24.02	23.03	22.99	22.68	22.44	21.46	23.35
January 25th	20.07	19.65	19.68	19.98	20.33	21.32	25.01	35.12
January 24th	22.26	21.84	21.36	21.49	21.51	21.88	23.24	29.24
Time Slot	08:00—09:00	09:00—10:00	10:00—11:00	11:00—12:00	12:00—13:00	13:00—14:00	14:00—15:00	15:00—16:00
January 23rd	24.68	28.90	31.32	34.75	34.39	30.45	28.04	29.10
January 25th	35.00	36.16	36.62	35.60	34.75	32.36	30.61	29.73
January 24th	29.84	32.53	33.97	35.18	34.57	31.36	29.33	29.42
Time Slot	16:00—17:00	17:00—18:00	18:00—19:00	19:00—20:00	20:00—21:00	21:00—22:00	22:00—23:00	23:00—24:00
January 23rd	29.70	36.97	42.60	35.83	28.84	25.40	26.27	24.94
January 25th	31.17	34.96	36.40	32.05	26.80	25.32	23.93	18.71
January 24th	30.44	35.97	39.50	33.94	27.82	25.36	25.10	21.83

Table C.2: The Real-time Price for Time Slot 02:00-03:00 on March 27th

01:00—02:00	03:00—04:00	02:00—03:00
15.00 cents/kWh	16.55 cents/kWh	15.78 cents/kWh

Table C.3: The Real-time Price Information for September 7th

Time Slot	00:00—01:00	01:00—02:00	02:00—03:00	03:00—04:00	04:00—05:00	05:00—06:00	06:00—07:00	07:00—08:00
January 23rd	22.88	23.44	24.84	23.59	23.75	26.25	34.37	42.97
January 25th	23.82	24.07	23.50	23.08	23.10	24.24	31.91	38.71
January 24th	23.35	23.76	24.17	23.34	23.43	25.25	33.14	40.84
Time Slot	08:00—09:00	09:00—10:00	10:00—11:00	11:00—12:00	12:00—13:00	13:00—14:00	14:00—15:00	15:00—16:00
January 23rd	44.63	43.08	37.44	36.02	28.48	27.98	29.69	31.32
January 25th	39.62	39.52	37.65	35.73	32.61	29.00	28.58	30.34
January 24th	42.13	41.30	37.55	35.88	30.55	28.49	29.14	30.83
Time Slot	16:00—17:00	17:00—18:00	18:00—19:00	19:00—20:00	20:00—21:00	21:00—22:00	22:00—23:00	23:00—24:00
January 23rd	43.95	38.90	42.01	45.16	43.92	39.72	28.77	26.70
January 25th	30.01	35.92	40.41	42.59	41.30	37.81	29.27	24.84
January 24th	36.98	37.41	41.21	43.88	42.61	38.77	29.02	25.77

Table C.4: The Real-time Price Information for November 12th

Time Slot	00:00—01:00	01:00—02:00	02:00—03:00	03:00—04:00	04:00—05:00	05:00—06:00	06:00—07:00	07:00—08:00
January 23rd	33.91	33.00	34.00	34.00	34.00	35.45	36.78	47.96
January 25th	36.59	36.33	34.45	36.33	36.39	36.44	36.77	35.00
January 24th	35.25	34.67	34.23	35.17	35.20	35.95	36.78	41.48
Time Slot	08:00—09:00	09:00—10:00	10:00—11:00	11:00—12:00	12:00—13:00	13:00—14:00	14:00—15:00	15:00—16:00
January 23rd	55.45	55.44	56.42	56.41	55.69	54.70	51.84	52.00
January 25th	40.24	42.39	37.05	37.57	40.00	37.65	37.98	39.76
January 24th	47.85	48.92	46.74	46.99	47.85	46.18	44.91	45.88
Time Slot	16:00—17:00	17:00—18:00	18:00—19:00	19:00—20:00	20:00—21:00	21:00—22:00	22:00—23:00	23:00—24:00
January 23rd	58.46	64.92	56.94	55.00	42.56	41.54	40.92	34.40
January 25th	44.74	69.37	70.01	50.00	54.00	39.32	37.44	37.54
January 24th	51.60	67.15	63.48	52.50	48.28	40.43	39.18	35.97

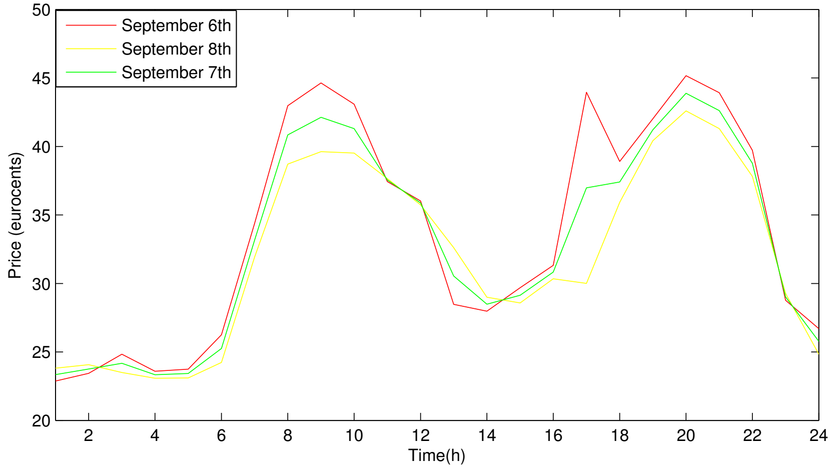


Figure C.2: The Real-time Price Information for September 7th

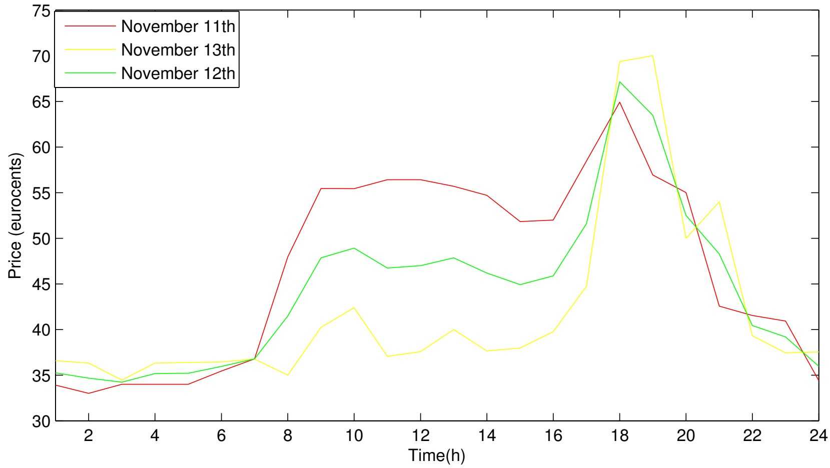


Figure C.3: The Real-time Price Information for November12

D

DATASHEET

D.1. PV PANELS DATASHEET

THE datasheet of the JKM265P PV panels from Jinko Solar is attached here.

www.jinkosolar.com

JinKO Solar
Building Your Trust in Solar

JKM265P-60
245-265 Watt
POLY CRYSTALLINE MODULE

Positive power tolerance of 0/+3%

ISO9001:2008、ISO14001:2004、OHSAS18001 certified factory.
IEC61215、IEC61730 certified products.

PV CYCLE

KEY FEATURES

High Efficiency:
High module conversion efficiency (up to 16.19%), through innovative manufacturing technology.

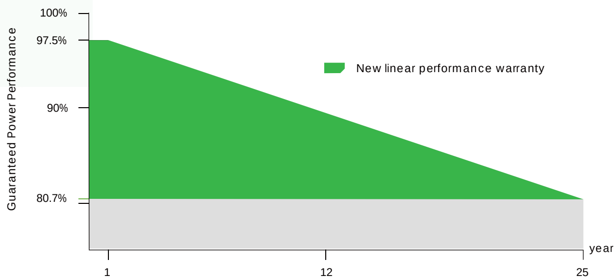
Low-light Performance:
Advanced glass and solar cell surface texturing allow for excellent performance in low-light environments.

Severe Weather Resilience:
Certified to withstand: wind load (2400 Pascal) and snow load (5400 Pascal).

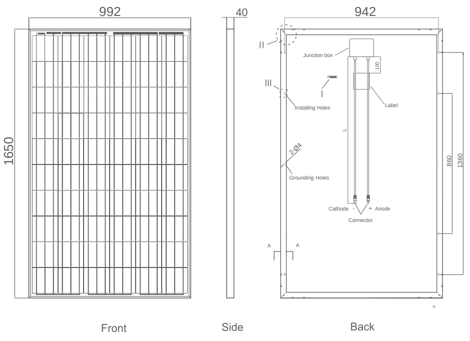
Durability against extreme environmental conditions:
High salt mist and ammonia resistance certified by TUV NORD.

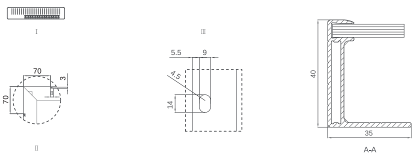
LINEAR PERFORMANCE WARRANTY

10 Year Product Warranty • 25 Year Linear Power Warranty



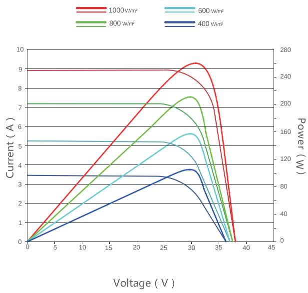
Engineering Drawings



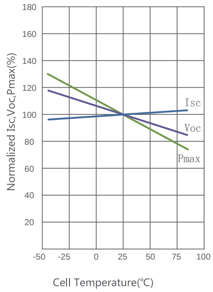


Electrical Performance & Temperature Dependence

Current-Voltage & Power-Voltage Curves (260W)



Temperature Dependence of Isc,Voc,Pmax



Packaging Configuration

(Two boxes=One pallet)

25pcs/ box, 50pcs/pallet, 700 pcs/40'HQ Container

Mechanical Characteristics

Cell Type	Poly-crystalline 156×156mm (6 inch)
No.of cells	60 (6×10)
Dimensions	1650×992×40mm (65.00×39.05×1.57 inch)
Weight	19.0 kg (41.9 lbs)
Front Glass	3.2mm, High Transmission, Low Iron, Tempered Glass
Frame	Anodized Aluminium Alloy
Junction Box	IP67 Rated
Output Cables	TÜV 1×4.0mm², Length:900mm

SPECIFICATIONS

Module Type	JKM245P		JKM250P		JKM255P		JKM260P		JKM265P	
	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT
Maximum Power (Pmax)	245Wp	181Wp	250Wp	184Wp	255Wp	189 Wp	260Wp	193Wp	265Wp	197Wp
Maximum Power Voltage (Vmp)	30.1V	27.8V	30.5V	28.0V	30.8V	28.5V	31.1V	28.7V	31.4V	29.0V
Maximum Power Current (Imp)	8.14A	6.50A	8.20A	6.56A	8.28A	6.63A	8.37A	6.71A	8.44A	6.78A
Open-circuit Voltage (Voc)	37.5V	34.8V	37.7V	34.9V	38.0V	35.2V	38.1V	35.2V	38.6V	35.3V
Short-circuit Current (Isc)	8.76A	7.16A	8.85A	7.21A	8.92A	7.26A	8.98A	7.31A	9.03A	7.36A
Module Efficiency STC (%)	14.97%		15.27%		15.58%		15.89%		16.19%	
Operating Temperature(℃)	-40℃~+85℃									
Maximum system voltage	1000VDC (IEC)									
Maximum series fuse rating	15A									
Power tolerance	0~+3%									
Temperature coefficients of Pmax	-0.41%/℃									
Temperature coefficients of Voc	-0.31%/℃									
Temperature coefficients of Isc	0.06%/℃									
Nominal operating cell temperature (NOCT)	45±2℃									

STC: Irradiance 1000W/m² Cell Temperature 25°C AM=1.5

NOCT: Irradiance 800W/m² Ambient Temperature 20°C AM=1.5 Wind Speed 1m/s

* Power measurement tolerance: ± 3%

D.2. BATTERY DATASHEET

THE datasheet of the RESU3.3 battery from LG Chem is attached here.

LG Chem

RESU

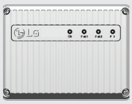
Change Your Energy, Charge Your Life

48V

Models		RESU3.3	RESU6.5	RESU10
Total Energy [kWh]		3.3	6.5	9.8
Usable Energy [kWh]		2.9	5.9	8.8
Capacity [Ah]		63	126	189
Nominal Voltage [V]		51.8	51.8	51.8
Voltage Range [V]		42.0~58.8	42.0~58.8	42.0~58.8
Max Power [kW]		3.0	4.2	5.0
Peak Power [kW] (for 3 sec.)		3.3	4.6	7.0
Dimension [W x H x D, mm]		452 x 401 x 120	452 x 654 x 120	452 x 483 x 227
Weight [kg]		31	52	75
Enclosure Protection Rating		IP55		
Communication		CAN 2.0 B		
Certificates	Cell	UL1642		
	Product	UL1973 / TUV (IEC 62619) / CE / FCC / RCM		

Compatible Inverter Brands : SMA, SolaX, Sungrow, Schneider, Ingeteam, GoodWe, Redback, Victron Energy (As of 3Q. 2016, More brands to be added)

RESU PLUS



RESU Plus is an expansion kit specially designed for 48V models of new RESU series.
With RESU Plus, all 48V models can be cross-connected with each other.

- Dimension: 385 x 240 x 65 (W x H x D, mm)
- Number of Expandable Battery Units: Up to 2EA
- IP55

400V

Models		RESU7H	RESU10H	
Total Energy [kWh]		7.0	9.8	
Usable Energy [kWh]		6.6	9.3	
Capacity [Ah]		63	63	
Voltage Range [V]		350~450	350~450	385~550
Max Power [kW]		3.5	5.0	
Peak Power [kW] (for 10 sec.)		5.0	7.0	
Dimension [W x H x D, mm]		744 x 692 x 206	744 x 907 x 206	
Weight [kg]		76	97	99.8
Enclosure Protection Rating		IP55		
Communication		RS485	RS485	CAN 2.0 B
Certificates	Cell	UL 1642		
	Product	TUV (IEC 62619) / CE / RCM	UL1973 / TUV (IEC 62619) / CE / FCC / RCM	

Compatible Inverter Brands : SMA(RESU10H) , SolarEdge(RESU7H,10H) (As of 3Q. 2016, More brands to be added)

D.3. INVERTER DATASHEET

D.3.1. PV PANELS' INVERTER DATASHEET

THE datasheet of the Sunny Boy 4.0 inverter from SMA is attached here.

D

SUNNY BOY 3.0 / 3.6 / 4.0 / 5.0
including SMA SMART CONNECTED

SMA Smart Connected

- Investment security included
- Automatic monitoring by SMA
- Proactive information and automatic service

Easy to Use

- Safe plug and play installation
- Commissioning via smartphone or tablet
- WLAN and intuitive webserver

Everything at a Glance

- Free online monitoring
- PV system data viewable via smartphone

Future-Proof

- SMA storage solutions, intelligent energy management and Smart-module technology can be added at any time
- Dynamic feed-in control

SUNNY BOY 3.0 / 3.6 / 4.0 / 5.0

More than just an inverter. Smaller, simpler and more convenient with SMA Smart Connected

The new Sunny Boy 3.0 – 5.0 succeeds the globally successful Sunny Boy 3000 – 5000TL. It is more than just a PV inverter: with the integrated SMA Smart Connected service, it offers all-round comfort for PV system operators and installers alike. The automatic inverter monitoring by SMA analyzes operation, reports irregularities and thus minimizes downtime.
The Sunny Boy is ideally suited to solar power generation in private homes. Thanks to its extremely light design and location of the external connections, the device can be quickly installed and easily commissioned thanks to the intuitive webserver.
Current communication standards mean that intelligent energy management solutions as well as SMA storage solutions can be flexibly added to the inverter at any time.

SMA SMART CONNECTED

The integrated service for ease and comfort

SMA Smart Connected* is the free monitoring of the inverter via the SMA Sunny Portal. If there is an inverter fault, SMA proactively informs the PV system operator and the installer. This saves valuable working time and costs.

With SMA Smart Connected, the installer benefits from rapid diagnoses by SMA. They can thus quickly rectify the fault and score points with the customer thanks to the attraction of additional services.

ACTIVATION OF SMA SMART CONNECTED

During registration of the system in the Sunny Portal, the installer activates SMA Smart Connected and benefits from the automatic inverter monitoring by SMA.

AUTOMATIC INVERTER MONITORING

SMA takes on the job of inverter monitoring with SMA Smart Connected. SMA automatically checks the individual inverters for anomalies around the clock during operation. Every customer thus benefits from SMA's long years of experience.

PROACTIVE COMMUNICATION IN THE EVENT OF FAULTS

After a fault has been diagnosed and analyzed, SMA informs the installer and end customer immediately by e-mail. Everyone is thus optimally prepared for the troubleshooting. This minimizes the downtime and saves time and money. The regular power reports also provide valuable information about the overall system.

REPLACEMENT SERVICE

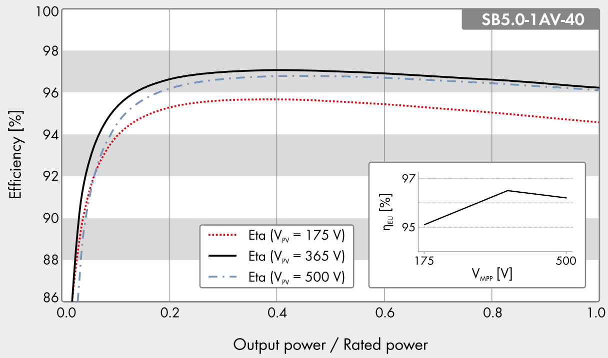
If a replacement device is necessary, SMA automatically supplies a new inverter within one to three days of the fault diagnosis. The installer can contact the PV system operator of their own accord and replace the inverter.

PERFORMANCE SERVICE

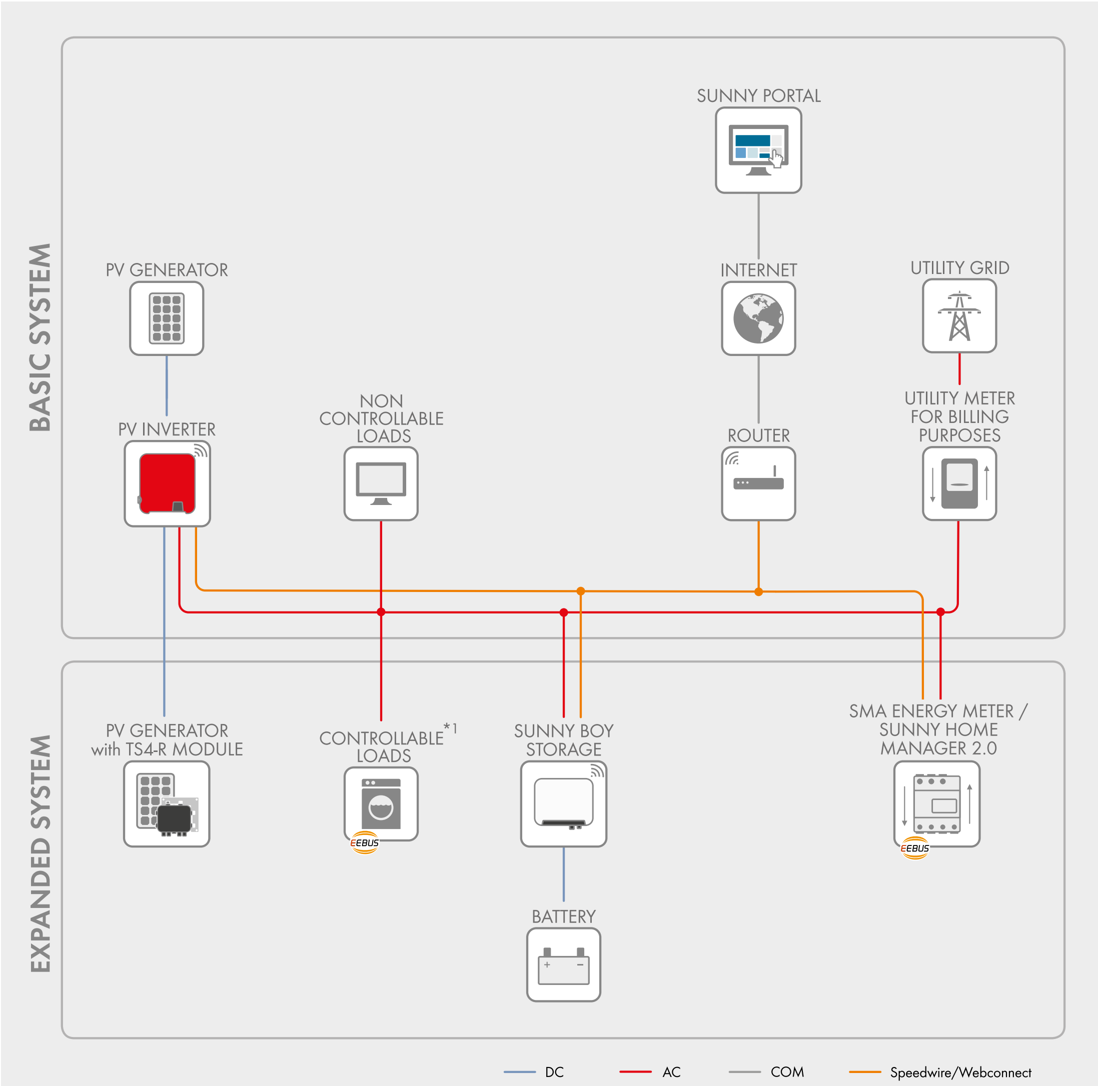
The PV system operator can claim compensation from SMA if the replacement inverter cannot be delivered within three days.

* Details: see document "Description of Services – SMA SMART CONNECTED"

Efficiency curve



Technical data	Sunny Boy 3.0	Sunny Boy 3.6	Sunny Boy 4.0	Sunny Boy 5.0
Input (DC)				
Max. generator power	5500 Wp	5500 Wp	7500 Wp	7500 Wp
Max. input voltage	600 V			
MPP voltage range	110 V to 500 V	130 V to 500 V	140 V to 500 V	175 V to 500 V
Rated input voltage	365 V			
Min. input voltage / initial input voltage	100 V / 125 V			
Max. input current input A / input B	15 A / 15 A			
Max. input current per string input A / input B	15 A / 15 A			
Number of independent MPP inputs / strings per MPP input	2 / A:2; B:2			
Output (AC)				
Rated power (at 230 V, 50 Hz)	3000 W	3680 W	4000 W	5000 W[1)]
Max. apparent power AC	3000 VA	3680 VA	4000 VA	5000 VA[2)]
Nominal AC voltage / range	220 V, 230 V, 240 V / 180 V to 280 V			
AC power frequency / range	50 Hz, 60 Hz / −5 Hz to +5 Hz			
Rated power frequency / rated grid voltage	50 Hz / 230 V			
Max. output current	16 A	16 A	22 A[2)]	22 A[2)]
Power factor at rated power	1			
Adjustable displacement power factor	0.8 overexcited to 0.8 underexcited			
Feed-in phases / connection phases	1 / 1			
Efficiency				
Max. efficiency / European Efficiency	97.0% / 96.4%	97.0% / 96.5%	97.0% / 96.5%	97.0% / 96.5%
Protective devices				
Input-side disconnection point	●			
Ground fault monitoring / grid monitoring	● / ●			
DC reverse polarity protection / AC short circuit current capability / galvanically isolated	● / ● / –			
All-pole-sensitive residual-current monitoring unit	●			
Protection class (as per IEC 62103) / overvoltage category (according to IEC 60664-1)	I / III			
General data				
Dimensions (W / H / D)	435 mm / 470 mm / 176 mm (17.1 inches / 18.5 inches / 6.9 inches)			
Weight	16 kg (35.3 lb)			
Operating temperature range	−25 °C to +60 °C (−13 °F to +140 °F)			
Noise emission, typical	25 dB(A)			
Self-consumption (at night)	1.0 W			
Topology	Transformerless			
Cooling method	Convection			
Degree of protection (as per IEC 60529)	IP65			
Climatic category (as per IEC 60721-3-4)	4K4H			
Max. permissible value for relative humidity (non-condensing)	100%			
Equipment				
DC connection / AC connection	SUNCLIX / AC connector			
Display via smartphone, tablet, laptop	●			
Interfaces: WLAN, Speedwire / Webconnect	● / ●			
Warranty: 5 / 10 / 15 years	● / ○ / ○			
Certificates and approvals (more available upon request)	AS 4777, C10/11, CE, CEI 0-21, EN 50438, G59/3, G83/2, DIN EN 62109 / IEC 62109, NEN-EN50438, RD1699, SI 4777, UTE C15-712, VDE-AR-N 4105, VDE0126-1-1, VFR 2014			
Certificates and approvals (planned)	IEC 61727, NRS 097-2-1			
Country availability of SMA Smart Connected	AU, AT, BE, CH, DE, ES, FR, IT, LU, NL, UK			
● Standard features ○ Optional features – Not available Data at nominal conditions Status: May 2017 1) 4600 W / 4600 VA according to VDE-AR-N 4105 2) AS 4777: 21.7 A				
Type designation	SB3.0-1AV-40	SB3.6-1AV-40	SB4.0-1AV-40	SB5.0-1AV-40



BASIC SYSTEM functions

- Easy commissioning via integrated WLAN and Speedwire interface
- Maximum transparency thanks to visualization in the Sunny Portal / Sunny Places
- Safe investment through SMA Smart Connected
- Modbus as interface for third-party providers

EXPANDED SYSTEM functions

- Basic system functions
- Reduction in purchased electricity and increase in self-consumption through use of stored solar energy
- Maximum energy use thanks to forecast-based charging
- Increased self-consumption thanks to intelligent load control
- Maximum system yield through Smart module technology

With SMA Energy Meter*2

- Maximum system usage through dynamic limiting of feed-in to the grid between 0% and 100%
- Visualization of energy consumption

*1) via SMA radio-controlled socket or standardized data communication
*2) from FW version 1.03.03

D.3.2. BATTERY INVERTER

THE datasheet of the 48/3000/35 inverter from Victron Energy is attached here.

MultiPlus Inverter/Charger

800 VA – 5 kVA   Lithium Ion battery compatible

www.victronenergy.com

MultiPlus
24/3000/70

MultiPlus Compact
12/2000/80

Two AC Outputs
The main output has no break functionality. The MultiPlus takes over the supply to the connected loads in the event of a grid failure or when shore/generator power is disconnected. This happens so fast (less than 20 milliseconds) that computers and other electronic equipment will continue to operate without disruption. The second output is live only when AC is available on the input of the MultiPlus. Loads that should not discharge the battery, like a water heater for example can be connected to this output (second output available on models rated at 3 kVA and more).

Virtually unlimited power thanks to parallel operation
Up to 6 Multis can operate in parallel to achieve higher power output. Six 24/5000/120 units, for example, will provide 25 kW / 30 kVA output power with 720 Amps charging capacity.

Three phase capability
In addition to parallel connection, three units of the same model can be configured for three phase output. But that's not all: up to 6 sets of three units can be parallel connected for a huge 75 kW / 90 kVA inverter and more than 2000 Amps charging capacity.

PowerControl - Dealing with limited generator, shore side or grid power
The MultiPlus is a very powerful battery charger. It will therefore draw a lot of current from the generator or shore side supply (nearly 10 A per 5 kVA Multi at 230 VAC). With the Multi Control Panel a maximum generator or shore current can be set. The MultiPlus will then take account of other AC loads and use whatever is extra for charging, thus preventing the generator or shore supply from being overloaded.

PowerAssist - Boosting the capacity of shore or generator power
This feature takes the principle of PowerControl to a further dimension. It allows the MultiPlus to supplement the capacity of the alternative source. Where peak power is so often required only for a limited period, the MultiPlus will make sure that insufficient shore or generator power is immediately compensated for by power from the battery. When the load reduces, the spare power is used to recharge the battery.

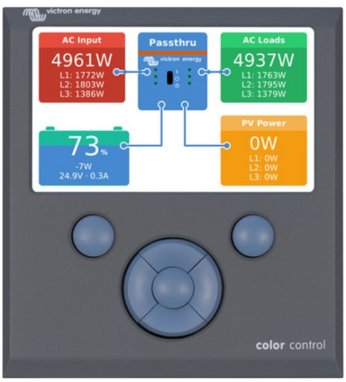
Solar energy: AC power available even during a grid failure
The MultiPlus can be used in off grid as well as grid connected PV and other alternative energy systems. Loss of mains detection software is available.

System configuring
- In case of a stand-alone application, if settings have to be changed, this can be done in a matter of minutes with a DIP switch setting procedure.
- Parallel and three phase applications can be configured with VE.Bus Quick Configure and VE.Bus System Configurator software.
- Off grid, grid interactive and self-consumption applications, involving grid-tie inverters and/or MPPT Solar Chargers can be configured with Assistants (dedicated software for specific applications).

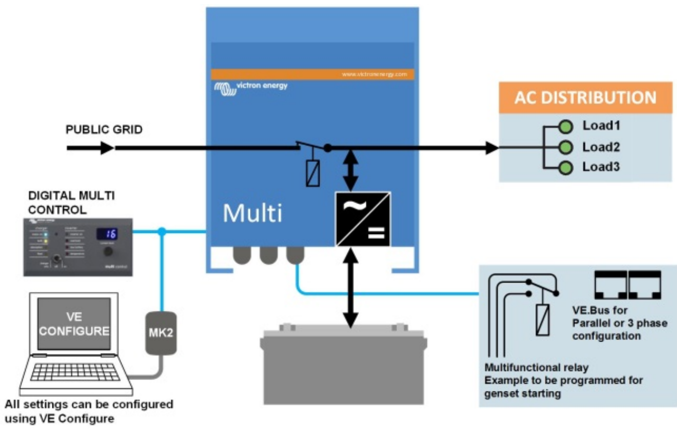
On-site Monitoring and control
Several options are available: Battery Monitor, Multi Control Panel, Ve.Net Blue Power Panel, Color Control Panel, smartphone or tablet (Bluetooth Smart), laptop or computer (USB or RS232).

Remote Monitoring and control
Victron Ethernet Remote, Venus GX and the Color Control Panel.
Data can be stored and displayed on our VRM (Victron Remote Management) website, free of charge.

Remote configuring
When connected to the Ethernet, systems with a Color Control panel can be accessed remotely and settings can be changed.



Color Control Panel, showing a PV application



MultiPlus 12 Volt / 24 Volt / 48 Volt	C 12/800/35 C 24/ 800/16	C 12/1200/50 C 24/1200/25	C 12/1600/70 C 24/1600/40	C 12/2000/80 C 24/2000/50	12/3000/120 24/3000/70 48/3000/35	24/5000/120 48/5000/70
PowerControl	Yes	Yes	Yes	Yes	Yes	Yes
PowerAssist	Yes	Yes	Yes	Yes	Yes	Yes
Transfer switch (A)	16	16	16	30	16 or 50	100
INVERTER						
Input voltage range (V DC)	9,5 – 17 V 19 – 33 V 38 – 66 V					
Output	Output voltage: 230 VAC ± 2% Frequency: 50 Hz ± 0,1% (1)					
Cont. output power at 25°C (VA) (3)	800	1200	1600	2000	3000	5000
Cont. output power at 25°C (W)	700	1000	1300	1600	2400	4000
Cont. output power at 40°C (W)	650	900	1200	1400	2200	3700
Cont. output power at 65°C (W)	400	600	800	1000	1700	3000
Peak power (W)	1600	2400	3000	4000	6000	10.000
Maximum efficiency (%)	92 / 94	93 / 94	93 / 94	93 / 94	93 / 94 / 95	94 / 95
Zero load power (W)	8 / 10	8 / 10	8 / 10	9 / 11	20 / 20 / 25	30 / 35
Zero load power in AES mode (W)	5 / 8	5 / 8	5 / 8	7 / 9	15 / 15 / 20	25 / 30
Zero load power in Search mode (W)	2 / 3	2 / 3	2 / 3	3 / 4	8 / 10 / 12	10 / 15
CHARGER						
AC Input	Input voltage range: 187-265 VAC Input frequency: 45 – 65 Hz Power factor: 1					
Charge voltage 'absorption' (V DC)	14,4 / 28,8 / 57,6					
Charge voltage 'float' (V DC)	13,8 / 27,6 / 55,2					
Storage mode (V DC)	13,2 / 26,4 / 52,8					
Charge current house battery (A) (4)	35 / 16	50 / 25	70 / 40	80 / 50	120 / 70 / 35	120 / 70
Charge current starter battery (A)	4 (12 V and 24 V models only)					
Battery temperature sensor	yes					
GENERAL						
Auxiliary output (5)	n. a.	n. a.	n. a.	n. a.	Yes (16A)	Yes (25A)
Programmable relay (6)	Yes					
Protection (2)	a - g					
VE.Bus communication port	For parallel and three phase operation, remote monitoring and system integration					
General purpose com. port	n. a.	n. a.	n. a.	n. a.	Yes	Yes
Remote on-off	Yes					
Common Characteristics	Operating temp. range: -40 to +65°C (fan assisted cooling) Humidity (non-condensing): max 95%					
ENCLOSURE						
Common Characteristics	Material & Colour: aluminium (blue RAL 5012) Protection category: IP 21					
Battery-connection	battery cables of 1.5 meter			M8 bolts	Four M8 bolts (2 plus and 2 minus connections)	
230 V AC-connection	G-ST18i connector			Spring-clamp	Screw terminals 13 mm² (6 AWG)	
Weight (kg)	10	10	10	12	18	30
Dimensions (hxwxd in mm)	375x214x110			520x255x125	362x258x218	444x328x240
STANDARDS						
Safety	EN-IEC 60335-1, EN-IEC 60335-2-29, IEC 62109-1					
Emission, Immunity	EN 55014-1, EN 55014-2, EN-IEC 61000-3-2, EN-IEC 61000-3-3, IEC 61000-6-1, IEC 61000-6-2, IEC 61000-6-3					
Road vehicles	12V and 24V models: ECE R10-4					
Anti-islanding	See our website					

1) Can be adjusted to 60 HZ; 120 V 60 Hz on request
2) Protection key:
  a) output short circuit
  b) overload
  c) battery voltage too high
  d) battery voltage too low
  e) temperature too high
  f) 230 VAC on inverter output
  g) input voltage ripple too high

3) Non-linear load, crest factor 3:1
4) At 25˚C ambient
5) Switches off when no external AC source available
6) Programmable relay that can a.o. be set for general alarm, DC under voltage or genset start/stop function
   AC rating: 230 V/4A
   DC rating: 4 A up to 35 VDC, 1 A up to 60 VDC

Digital Multi Control Panel

A convenient and low cost solution for remote monitoring, with a rotary knob to set PowerControl and PowerAssist levels.

Blue Power Panel

Connects to a Multi or Quattro and all VE.Net devices, in particular the VE.Net Battery Controller.
Graphic display of currents and voltages.

Computer controlled operation and monitoring

Several interfaces are available:

Color Control GX

Provides monitor and control. Locally, and also remotely on the [VRM Portal.]

MK3-USB VE.Bus to USB interface

Connects to a USB port [(see 'A guide to VEConfigure')]

VE.Bus to NMEA 2000 interface

Connects the device to a NMEA2000 marine electronics network.
See the [NMEA2000 & MFD integration guide]

BMV-700 Battery Monitor

The BMV-700 Battery Monitor features an advanced microprocessor control system combined with high resolution measuring systems for battery voltage and charge/discharge current. Besides this, the software includes complex calculation algorithms, like Peukert's formula, to exactly determine the state of charge of the battery. The BMV-700 selectively displays battery voltage, current, consumed Ah or time to go. The monitor also stores a host of data regarding performance and use of the battery.
Several models available (see battery monitor documentation).

Victron Energy B.V. | De Paal 35 | 1351 JG Almere | The Netherlands
General phone: +31 (0)36 535 97 00 | Fax: +31 (0)36 535 97 40
E-mail: sales@victronenergy.com | **www.victronenergy.com**

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