AC and DC Residential System Comparison with Penetration of PV and Battery Storage

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AC and DC Residential System Comparison with Penetration of PV and Battery Storage

by

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in partial fulfillment of the requirements for the degree of

Master of Science
in Electrical Engineering

at the Delft University of Technology,
to be defended publicly on Tuesday August 14th, 2018 at 09:00 AM.

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Abstract

The battle between the alternating current(AC) and direct current(DC) can be traced back to the late 19th century. Apparently, it ended up with the victory of AC. However, the growing use of the renewable energy sources that mostly are DC supplier, and the advancement of power electronics lead to the reconsideration of using DC power by public in these decades. In the residential sector, which is a highly energy consuming sector, an increasing number of home appliances operate with DC internally. By installing DC residential system, it not only removes the AC/DC conversion stage by the load side, but also offers the potential to use DC directly from the locally installed renewable energy sources without the requirement of the inverter stage. Therefore, the potential benefits from altering traditional AC residential system to DC version and the impact of the sizing of the renewable energy sources on the performance of the residential systems are of interest.

The main objective of this study is comparing the AC and DC residential system with the varying levels of the penetration of the PV and battery storage. Starting from the overview of the original AC and adopted DC residential system with the presence of the PV and battery storage, the main difference between AC and DC system architecture is investigated. Then, the various components such as converters, cables, PV and battery storage system in the residential system are modeled. Based on the modelling, a power management strategy is propsed. By using the load profile and local solar irradiance as the input, the energetic evaluation of both the AC and DC residential system regarding the system losses and energy saving is analyzed with the varying PV and battery storage size. Furthermore, an economic analysis is carried out by considering the electricity tariff, feed-in tariff and investment costs of PV and battery storage system.

Table of Contents

List of Figures

List of Tables

Acknowledgements

During the period of my master program, I received a lot of help and encourage from professors, my parents and friends. I would like to express my deepest gratitude to them.

I would like to start by expressing my gratitude to my supervisor, Prof.dr.ir.Pavol Bauer, Dr.ir.Zian Qin, and Ir.Soumya Bandyopadhyay. I appreciate all your guidance and invaluable suggestions, which helped to make this journey brighter. Especially thank you to my daily supervisors, Dr.ir. Zian Qin, and Ir. Soumya Bandyopadhyay. They always available and kindly to help me with my confusion on the thesis project, and they have spent a lot of time in helping me during the project and thesis writing.

To my parents. I would like to appreciate you all for your support, patience and encourage over years.

To my friends in the Netherlands. I would like to thank you all for your encourage and help on both study and daily life during these years.

Last but not least, to all the people I met during these years. Thank you all for your impact on my life. It was an incredible experience and I am grateful for that.

Delft, University of Technology   Wenjie Hu
August 7, 2018

Glossary

AC   Alternative Current

DC Direct Current

PV Photovoltaic

SoC State of Charge

DoD Depth of Discharge

EoL End of Life

Chapter 1

Introduction and background

This chapter aims to start with making a brief introduction regarding the background of AC and DC system, and discuss the motivation with potential advantages of converting traditional AC residential system to the proposed DC residential system. The main objective of this study will be illustrated. In order to achieve the main objective, several research questions will be considered and waiting to be resolved.

1-1 Background of AC and DC

The debate between the advocacy of AC and DC can be traced back to the late 19th century, which was known as the "War of Currents"[16]. In this fierce battle, Thomas Edison was on the side of supporting DC, while Nicola Tesla and George Westinghouse held favour of AC on the opposite side. Apparently, the battle ended up with the victory of AC with the invention of transformers from the Westinghouse team who provided the method to up and down the voltage. While DC could only be operated in a much lower and constant voltage level[17]. Furthermore, AC could be transmitted over a long distance, which also became an advantage at that time.

As a turning, the development of DC power has been shifted with the power electronics revolution[18]. Today, power electronic converters act as the DC transformers that can step-up and step-down a DC voltage. DC began to rise continuously attributes to the development of power electronics.

In the field of power transmission, DC transmission has already been a widespread technology in the world[19]. A number of high voltage DC transmission system over long distance have been widely installed, which performs more excellent than AC regarding the economy and environment.

In the field of the distribution system, data center became a promising market for DC system due to its high requirement of DC[20]. Some of the pilot projects reported that distribution systems in the DC version are able to avoid conversion stage losses and result in more than

10% energy saving, even 20% reduction of the overall operating cost of data center can be achieved[20][21]. Therefore, DC distribution presents a more efficient way for data center. In addition, telecommunication systems are used to transfer large amount of data, where the 48V DC distribution system is used to provide high reliability[22].

The public concerns on the microgrid are increasingly growing these years since it is able to disconnect from the grid when there is a blackout and continue to supply a part of local loads. DC distribution is advantageous since microgrids are local electrical networks that consist of renewable energy sources and storage system, which are mostly inherently DC supplies. Several pilot projects of microgrid are developed around the world, and one of the most successful examples is the one in Sendai, Japan. It performed excellently during the severe earthquake in 2011[23].

1-2   Motivation

These decades have witnessed a rapid increase in electrical energy consumption in the residential sector as shown in figure 1-1[1]. The main energy sources in the world such as fossil and organic fuels are increasingly depleted. The large energy consumption not only leads to exhaust in fossil fuels but also causes serious environmental problems such as climate change and environmental pollution. In order to relieve the stress of energy crisis and environmental issues, in the past decade, people have paid more concerns on renewable energy sources which are more sustainable and environmental-friendly. The penetration of renewable energy sources such as photovoltaic, wind farm, hydropower and fuel cells can share the burden of growing energy consumption.
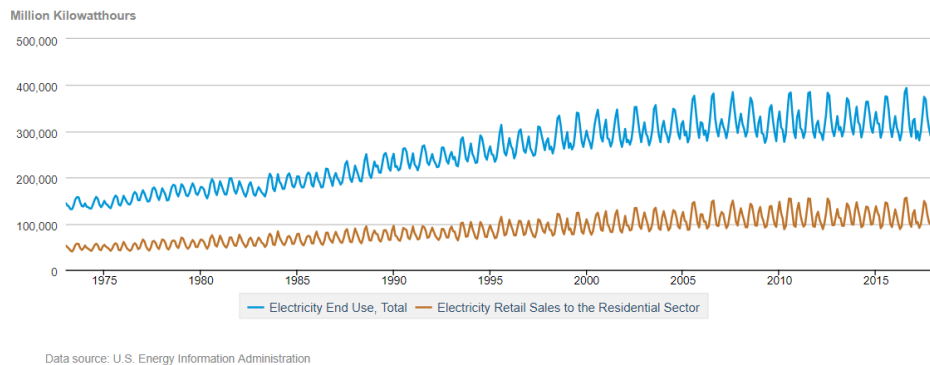
Figure 1-1: The total electricity energy for end use and for residential sector utility[1]

Although renewable energy sources share the burden of energy generation, to use energy efficiently is significant. Today, with the growing trend of using renewable energy sources, construction of the DC distribution system in residential homes can be benefited from the installation of small-scale renewable energy sources generation[12]. Firstly, most of the renewable energy sources such as PV generators and fuel cells are DC sources. In the traditional AC distribution system, a DC/AC inverter is needed to connect the renewable energy sources generation with the distribution system. However, by constructing DC distribution system, the inverter stage can be removed, which have the potential to improve the overall system efficiency.

At the same time, with the development of modern power electronics, an increasing number of appliances in the household such as mobile phones, laptop, and lightings use DC power supply. Currently, the electricity from the utility grid is AC power. Therefore, these appliances have to be converted the from AC to DC. However, by using DC power, the stage of AC/DC conversion could be avoided. Based on the considerations above, a DC residential system can be developed and compared with traditional AC system in terms of energetic and economic evaluations to discover the potential benefits of the DC residential system.

1-3   Research objective and research questions

The main research objective of this study is **to compare the AC and DC residential system with varying levels of penetration of PV and battery storage.** In order to achieve the main research objective, there are more specific sub-questions listed below:

1. What will be the major power losses in residential AC and DC system? And how to model them?

2. What factors should be considered when comparing the residential AC and DC system?

3. How to model the PV and battery storage system?

4. What kind of energy management strategy will be considered to control the energy allocation?

5. How does PV and battery sizing affect overall system consumption and costs?

6. What benefits regarding energetic and economic aspects can we get from DC residential system when compared to the AC system?

1-4   Outline of the thesis

Chapter 1: The background information, research motivation and goals were illustrated.

Chapter 2: The AC and DC system are overviewed. The necessary concept will be presented, including system architectures, voltage levels, converters and cables that will be used in both AC and DC system. The characteristics of PV generator and battery storage, as well as typical architectures of PV-battery storage system will be introduced.

Chapter 3: Systems will be modelled. The system modelling composed of the load classification, load converters and cables model, PV model and battery storage model. The system power management strategy will be developed as well. Based on the system models and system operation controlling, the system losses model will be obtained.

Chapter 4: Energetic evaluation of AC and DC residential system will be carried out. The analysis of PV-battery storage system generation will be presented. Battery degradation affected by varying PV and battery storage combination will be analyzed. Then, the energy savings from the utility grid by implementing PV-battery storage system and the overall

system losses of AC and DC residential system will be calculated and compared with varying size of PV and battery storage.

Chapter 5 Economic analysis will be presented. The electricity tariff, installation costs of PV and battery will be introduced. Then, the economic analysis model will be developed as net expenditure, which is composed of the investment costs of PV and battery storage system, the electricity bills and the feed-in benefits. Payback period of PV-battery storage system will be calculated as well.

Chapter 6 Conclusion will be drawn, and the challenges of future work will be proposed.

1-5   Contribution

In this study, with the construction and evaluation of the residential system, the main contribution that will be made in this study can be performed as follows.

- Comparison between residential load conversion losses and cable losses. The results showed that in both of AC and DC residential system, cable losses only have a tiny portion when compared to conversion losses.

- Battery storage degradation considered in system evaluation. By calculating one day accumulated capacity losses, the battery replacement times over simulation period can be obtained. It will be considered in the evaluation of the system, and it will have a dominant effect on economic analysis.

- Based on the model of system, system power management strategy is put forward, and overall system losses model is obtained based on the power management. The system losses are calculated with each operation modes.

Chapter 2

System overview

This chapter aims to introduce the basic concept of AC and DC residential system. It will be started with the system architectures of AC and DC residential system, and the voltage level of household DC system. The power electronic converters and cables that are used in the residential system will be analyzed. The architecture and the characteristics of PV and battery storage will be presented.

2-1 Layout of AC and DC residential system

2-1-1 System Architectures
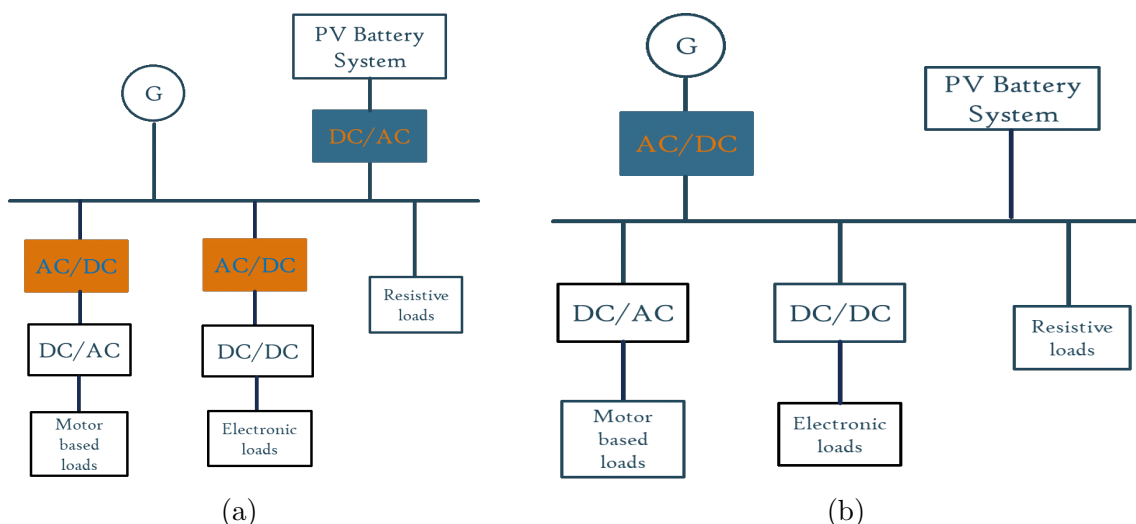
Figure 2-1: Block diagram of basic (a)AC and (b)DC residential system

The traditional AC residential system with PV-battery storage system and the proposed DC residential system with PV-battery storage system are shown in figure 2-1. It is easy to detect

from the figures that the most obvious differences between AC and DC residential system are the load side conversion stages and the supply side converters.

In several studies and existing DC distribution systems, there are two types of connection, unipolar and bipolar system[24]. The unipolar system has one voltage level, as shown in figure2-2(a). The loads are connected between a voltage wire and a zero wire. It could benefit from the economic point of view.
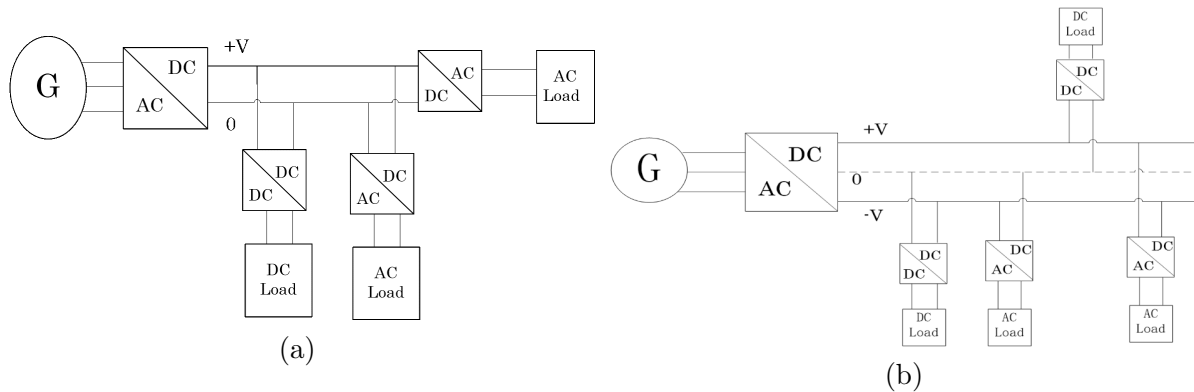
Figure 2-2: Block diagram of (a)unipolar and (b)bipolar connection

The bipolar connected has three lines, which are positive, negative and neutral, as shown in figure2-2(b). In this type of connection, loads can be connected in several ways between voltage levels[25]. The voltage level to the ground is reduced by using this type of connection, which helps to make the system safer. Power supply reliability is higher by using this type since the 3-wire structure provides a more flexible solution when faults occur. When there is a fault occurred on a line, then the power can be delivered by other two lines.

2-1-2 Voltage level of DC system

In DC system, unlike in AC system, the power electronic converters are used to perform as the transformer to step up and down the voltage. The EU low voltage directive provides the electrical equipment designed for use with an AC voltage rating between 50 and 1000V and the rating between 75 and 1500V for DC[26]. Furthermore, these voltage ratings do not refer to the voltages inside the equipment[27]. Today, the traditional ac power system has the voltage of 400Vline and 230Vphase. However, there is still not a standard voltage level for DC distribution network. Several possible voltage levels had been discussed in the literature of past studies[28][29][30], which are shown in table 2-1.

Table 2-1: Voltage level for DC system

Voltage level	Remarks
48V	Widely used for telecom Sutiable for small electronic appliances that are gererally fed with a small external DC.
120V	Defined as the upper boundary of extra lkow voltage. Using extra low voltage is one of the soulutions to protect system from eletrical shock.
230V	It equals tp the RMS vaulses of the exsiting AC system. It will have the same effect on resisitive loads with AC system.
380V	It has been the standard voltage elvel for DC based data center.

2-2   Power electronic converters in the system

Power electronic converters play a significant role in the development of DC system. There are three main converters in AC and DC residential system, which are AC/DC rectifier, DC/DC converter and DC/AC inverter. The type of converters and their applications in the residential system are listed in table2-2.

Table 2-2: Converters in residential system

Interface	Applications in household	Common topology
DC-DC converter	PV panels, Battery, and DC loads	Buck, boost, buck-boost, etc.
AC-DC rectifier	Power supply for DC loads in AC system, main rectifier in DC system and PFC	Single (three) phase controllable (uncontrollable) rectifier, etc.
DC-AC inverter	Motor drive, PV and battery interface with the AC bus	Half bridge, full bridge, etc.

It should be noted that in the DC residential system, the grid connected rectifier is needed. It is a bi-directional rectifier and plays a key role in grid supply and feed-in process. The power rating of this rectifier can be determined by the maximum power of household load consumption. Residential appliances are not used at the same time normally, sometimes the loads power even fall to the value that lower than 10% of power rating of the rectifier. In order to make it more efficient in supplying process as well as the electricity feed-in process, a modular rectifier can be used[31]. In this way, the rectifier efficiency will not be too low even loads are operating in a light load condition, which will reduce the power losses.

The power electronic devices in PV and battery storage system are composed of MPPT based unidirectional DC/DC converters for PV panels, bidirectional DC/DC converter for battery storage in both of AC and DC systems. An additional bidirectional PV inverter is needed

in AC system. The bidirectional DC/DC converter for battery storage is a key element, which is a buck converter in the process of charging, and a boost converter in the process of discharging.

2-3   Cables in residential house

The data of loads connected cable is described in table 2-3, with parameters of load power, cable length, cross section as well as the maximum current that provided by a project profile[14].

Table 2-3: Load and connected cable data for the system[14]

	Load type	Power (W)	Cable Length (m)	Cross Section (mm^2)	Maximum Current (A)
1	Fridge	120	10.2	2.5	10.837
2	Oven	3650	7.44	4	19.83
3	Hobs	3680	7.44	6	20.10
4	Dish washer	2400	11.24	2.5	13.04
5	Washing machine	2300	1.67	2.5	12.5
6	Dryer	1000	1.22	2.5	5.43
7	Lighting 1st floor	104	13.4	1.5	3
8	TV	21	8.8	2.5	6
9	Laptop	85	8.8	2.5	6

When comparing the traditional AC system with adopted DC residential system, it is necessary to know that if the same loads could be fed at the same distance when the system shifts from AC to DC. For the DC system in a household, the load that supplied by feeders can be shown in figure 2-3. We know that the resistivity of copper at temperature t is :

$$\rho_t = \rho_{20}(1 + \alpha(t - t_{20})) \tag{2-1}$$

where ρ_t is the resistivity at temperature t, ρ_{20} is the resistivity at 20 °C value is 0.0175,vα is the temperature coefficient at 20°C, α of copper is 0°C.

The cable resistance can be calculated as

$$R = \rho\frac{2l}{A} \tag{2-2}$$

When the cable carrying the maximum allowed current, the maximum power that the cable can be supplied is

$$P_{max} = V_{dc}I_{max} \tag{2-3}$$

When voltage drop is considered, the maximum current that the cable can carry is :

$$I_{\Delta max} = \frac{V_{drop}V_{dc}}{R} \tag{2-4}$$
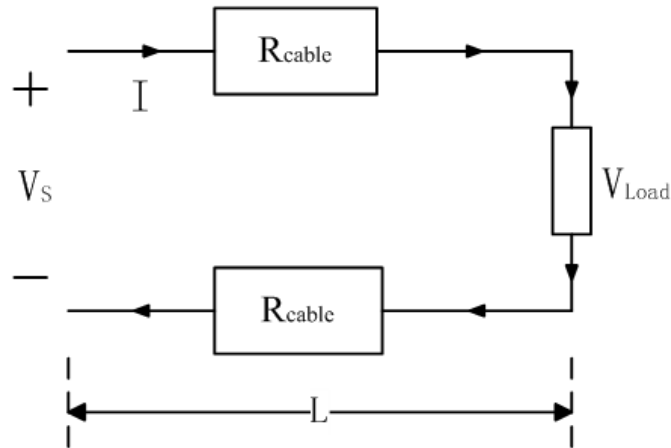
Figure 2-3: Load fed by feeder in dc system

When the voltage drop is considered not to exceed the limit 5%, the maximum power that can be supplied through the feeder is

$$P_{\Delta max} = \frac{V_{drop}SV_{dc}^2}{2\rho L} \qquad (2\text{-}5)$$

Figure 2-4 shows the cable length as a function of maximum power that different cables can transmit. Each of the curves consists of two parts: the first part is the constant part, this is the maximum power when the cable current equals to its maximum allowed current. When the cable length reaches a certain value, the maximum current that through the cable will be affected by the voltage drop limit, and then the maximum power can be determined.

Nearly all of the cables are sufficient to feed the connected loads with 350V voltage. As for 325V, the transferred the maximum power is slightly lower, and the most distance that can keep the maximum power is slightly shorter when compared with the same cable in 350V condition. However, when compared to the data in AC system, it can be seen that 325V is enough for the household appliances. When it comes to 230V, the transferred power is much lower than that of both 350V and 325V. At the same time, the cable distance to transfer the maximum power becomes much shorter in 230V. Although it is sufficient for the appliances in the current house, it will be restrictive if some other new appliances with higher power rating implement in the future.

It can be seen that cables in 48V system provide relatively low maximum power and short in cable length. For 1.5mm^2 and 2.5mm^2 cable, they can only satisfy the demand of some low power loads such as lights, TV and laptop. And the 4mm^2 and 6mm^2 cable under 48V are not sufficient to feed their connected loads. Therefore, the voltage level higher than 325V will be sufficient to supply the loads in the household. It is more flexible to use voltage higher than 350V if there are large appliances that will be implemented in the future. And 48V voltage could be used to supply low power loads such as lighting and electronic devices.
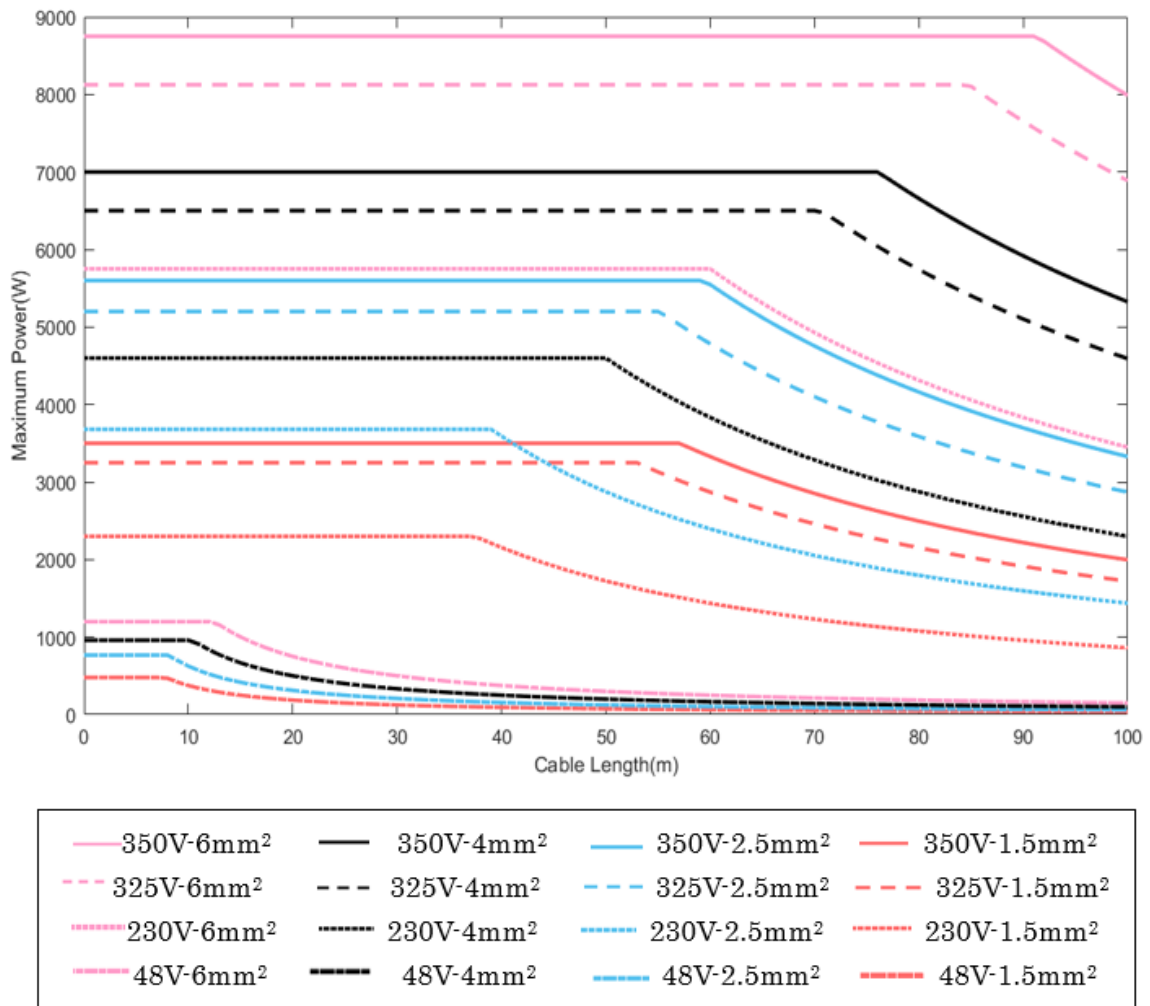
Figure 2-4: Maximum power transfer in a residential house with different cable cross section at different voltage levels

2-4   Solar photovoltaics and battery storage system

The decline of solar photovoltaics price and relatively low impact on the environment of PV system have led to an increase in penetration of rooftop solar photovoltaics in residential home[32]. In the meanwhile, PV generation is highly dependent on solar irradiance, and it does not match with load demands at every instant. There might be residual PV generation in daytime and sunny day, shortage in the night and cloudy day. Therefore, the battery energy storage is needed. By using battery storage, surplus PV generation can be stored on site, and to use it later to supply the load demands.

2-4-1   Architectures of PV and battery storage system

Generally, there are two most common topologies for PV and battery storage system in AC residential system, which are AC-coupled and DC-coupled system[2][33]. The schematic

configurations as shown in figure 2-5.

(a)   (b)
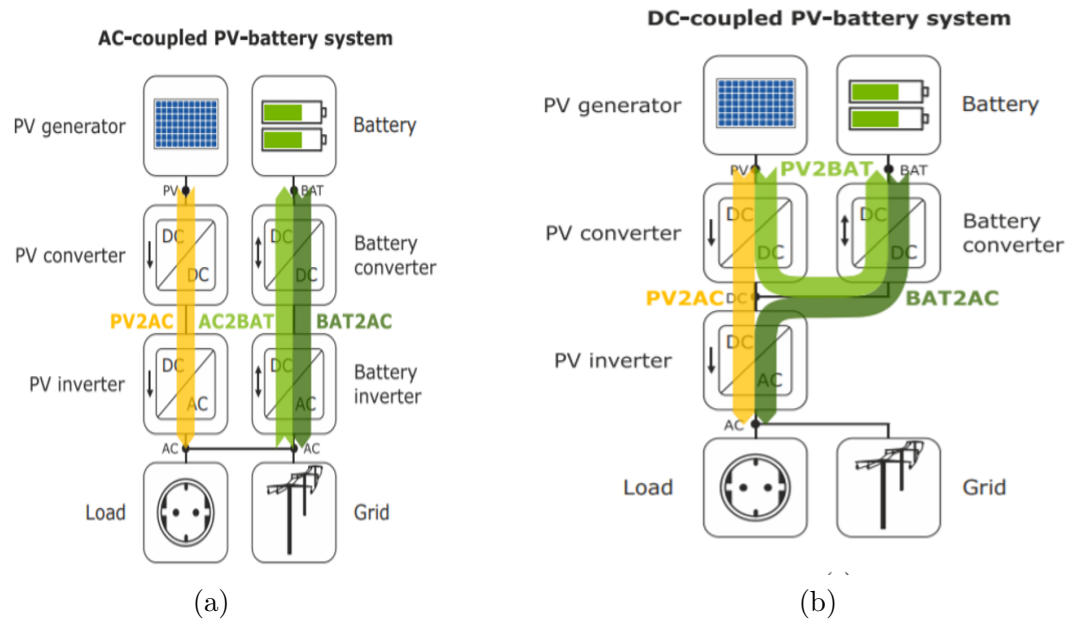
Figure 2-5: Schematic system configuration and relevant power flows of PV-battery storage system[2]

As it can be seen from figure 2-5, the main difference between the two configurations is that there are two distributed inverters for PV and battery respectively in the AC-coupled system, whereas in the DC-coupled system, PV generator and battery storage are connected after their individual DC-DC converter to AC bus via a central inverter. In AC-coupled system, the residual PV generation after feeding loads can be charged to battery storage though PV dc-dc converter, PV inverter, battery inverter and battery dc-dc converter. While in DC-coupled system, there are only PV dc-dc converter and battery dc-dc converter in the route of battery charging from excess PV output power. It seems that AC- coupled system is more flexible since both PV generator and battery have their independent inverter[34]. However, from the perspective of conversion stages, DC-coupled system tends to have higher efficiency since it has no battery inverter in the system, thus, results in lower conversion losses in the process of charging battery when compared to AC-coupled system.

2-4-2   PV and battery storage characteristic

In the PV-battery storage system, several parameters and characteristics of PV and battery storage may affect the performance of the system.

PV system characteristic

In the PV system, one of the significant concepts is the maximum power point tracking(MPPT), which is to ensure that PV modules can be operated to produce maximum power under certain solar irradiance and temperature. Several previous studies modelled the solar cell in

different ways to obtain the I-V characteristic of the solar cells and PV modules[35][36]. The mathematical model can be represented by I-V characteristics curve of PV modules under certain temperature and irradiance by considering standard test conditions(STC)[35]. By implementing maximum power point tracker, the operating point of PV modules at the maximum power point can be maintained. The maximum power point tracker is always connected to the PV dc-dc converter[36].

Battery storage parameters and characteristics

Battery storage is an important element in residential PV system in order to solve the intermittency problem of PV generation. Battery has both proper power density and energy density to meet the storage demand for residential scale PV system[37]. There are numerous type of battery storage system used in combination with renewable energy sources[38]. The commonly used batteries that in combination with residential PV system are lead-acid battery and lithium-ion(Li-ion) battery. Lead-acid battery is a widely used low-cost and mature technology, however, it is lower in lifetime expectancy and round-trip efficiency when compared with Li-ion battery. In this study, the Li-ion battery will be considered in PV-battery storage system.

Battery state of charge and depth of discharge In the operation process of battery, state of charge(SOC) is one of the main factors that indicates the percentage of energy stored in battery that available for discharging. The SOC can be estimated to prevent battery from over charge or over discharge[39]. Several SOC estimation methods have been proposed in previous studies for example open circuit voltage method, Coulomb counting method[40]. In this study, the Coulomb counting method will be used for SOC estimation. Another important factor is depth of discharge(DOD), which describes the percentage that battery discharges. The battery DOD is highly related to the battery lifetime. In addition, SOC and DOD are complementary to each other.

Battery round trip efficiency In the rechargeable battery for residential PV system, the efficiency of battery is characterized by a so-called factor round trip efficiency. It is defined as the ratio of total energy that is fully discharged out of the battery to total energy that is fully charged input the battery.

Battery lifetime cycles and degradation A major concern of battery is the battery life cycles, which is defined as the amount charge and discharge cycles a battery can have before the battery capacity falls to its end of life(EoL). Usually, 80% of the battery original capacity is a typical value as EoL of the battery[41]. Previous studies have discussed the factors that influenced the battery lifetime. [42] has concluded that the main factor that leads to battery capacity fade is ambient temperature, over charge/discharge and cycle depth. For a battery, there might be numerous times of charges and discharges in a day. The battery capacity fade affected by different DooD can be seen from figure2-6[3]. During a low DoD, the life cycle of battery remains unaffected. However, large DoD of the battery results in degradation of battery life.
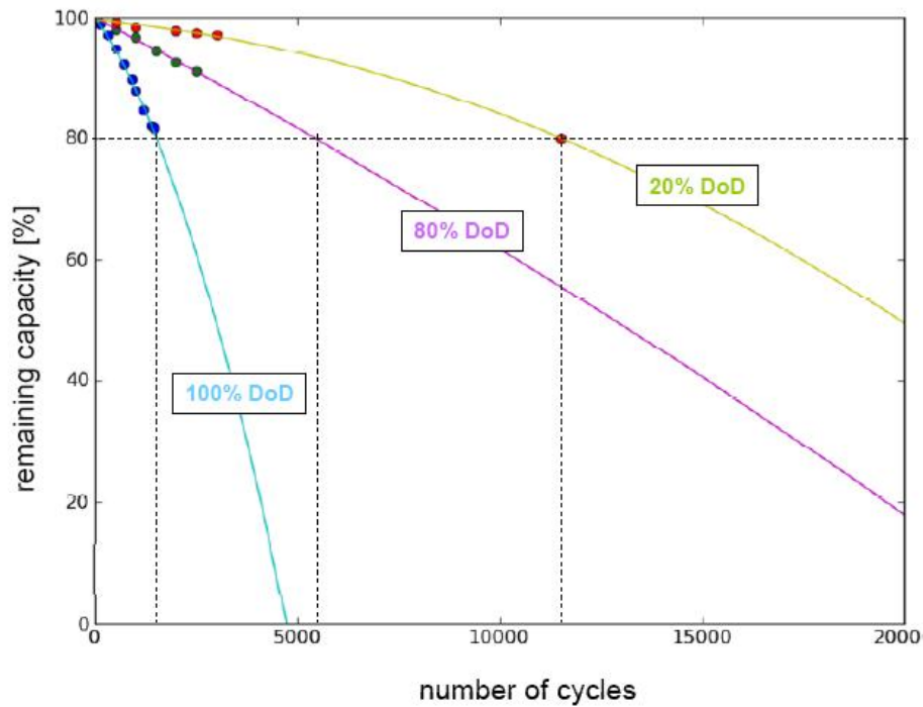
Figure 2-6: Capacity fade of the battery with regards to different DOD ranges[3]

2-5 Conclusion of the chapter

- In this chapter, the basic architecture of AC and DC residential system, as well as the differences between two systems are demonstrated, which are both composed of source side converters, load converters, and cables. At the same time, the typical voltage levels that have been used in DC system were introduced.

- The components in AC and DC residential systems are discussed. Different types of converters that used in systems were listed with their applications. As for cables in the system, the method to calculate cable losses have been shown and the maximum transmissible power in different cables with different voltage levels were calculated, and it demonstrated that voltage level that higher than 325V was sufficient to feed the household loads, and extra voltage level is only enough for electronic loads such as lightings and laptop.

- Furthermore, when it came to PV-battery storage system, the architectures of different PV-battery system were introduced, and it is shown that the DC-coupled system seems more suitable for the study.

Chapter 3

Modelling of the system

This chapter aims to present the modelling of the system. It begins with the overview of both AC and DC residential system and the household load classification. PV and battery system modelling are analyzed followed by the converters and cable modelling. In addition, the power management strategy is introduced in details. The system losses modelling based on the power management is presented. The effects of temperature variation on components are not considered in this study.

3-1   Load category classification

To make a better comparison between AC and DC system, and system with and without PV and battery storage system, both of AC and DC systems will be created. Both AC and DC systems are comprised of various loads and converters. PV and battery storage system will be implemented as well.

The original AC residential system is shown in figure 3-1, and the adopted DC system in figure 3-2 is converted directly from the original AC system with some modifications. It can be seen that the most significant differences between AC and DC system are the load side conversion stages, and the supply side converters.

In the load side of the system, there are two conversion stages of the original AC system, while there is only one conversion stage in DC system. As for supply side, in AC system, there is a centralized PV inverter to convert the DC power from PV and battery system to AC bus. Whereas in DC system, the PV inverter can be removed, In AC system, there is a centralized PV inverter to convert DC power from PV to AC bus. While in DC system, the inverter stage can be removed, which may reduce conversion losses in distributed resources side. However, a grid tied rectifier will be used to interconnect the grid and DC bus.

The load consumption profile will be used as input data to do the simulation and evaluation of systems in the following chapters. In order to make it easier to categorize the load type, the classification of appliances in the residential home is shown in table 3-1. The home appliances
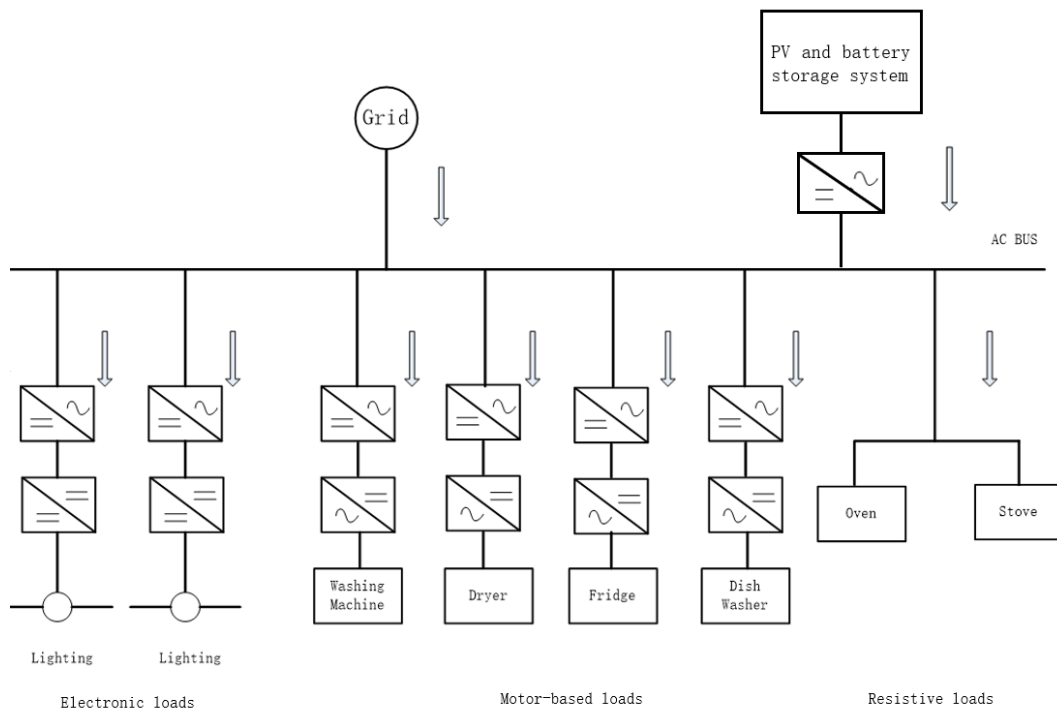
Figure 3-1: Block diagram of original AC residential system
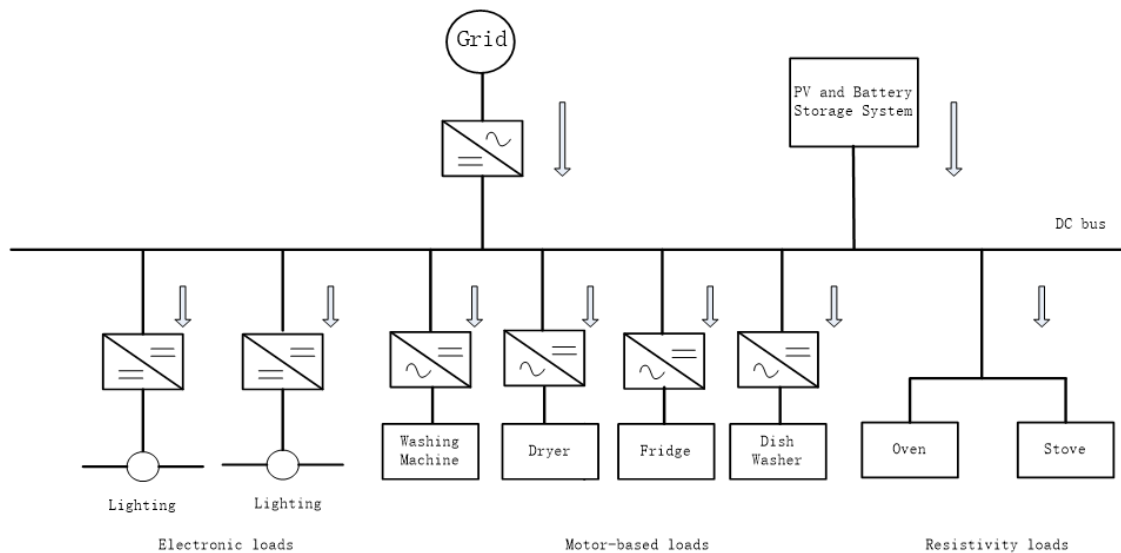
Figure 3-2: Block diagram of adopted DC residential system

has been sorted into three catalogues based on the power supply and load types, which are AC-motor based loads, DC-supply loads and resistance heating loads.

Table 3-1: Classification of appliances in residential home

Load type	AC motor loads	DC loads	Resistance heating loads
Appliances	Washing machine, fridge,dryer, dishwasher.	LED lightings, TV, laptop	Oven, stove.

3-2 Converter efficiency in the system

The types of load converter vary with load types. In AC system, for the AC motor loads, there are a rectifier and an inverter connected in cascade of each load. As for electronic loads, the conversion unit consists of a rectifier and a dc-dc converter. While in DC system, the rectifier stage can be removed in both AC supplied loads and electronic loads. For the resistive loads, there are no conversion losses that need to be considered. The load converter efficiency for different loads is chosen by different power rating of loads, which are shown in figure 3-3[4][5][6][7][8][9][10][11][12]. In this study, it is assumed that different topologies are considered to be presented by the same efficiency curve for each power rating and category of converters.
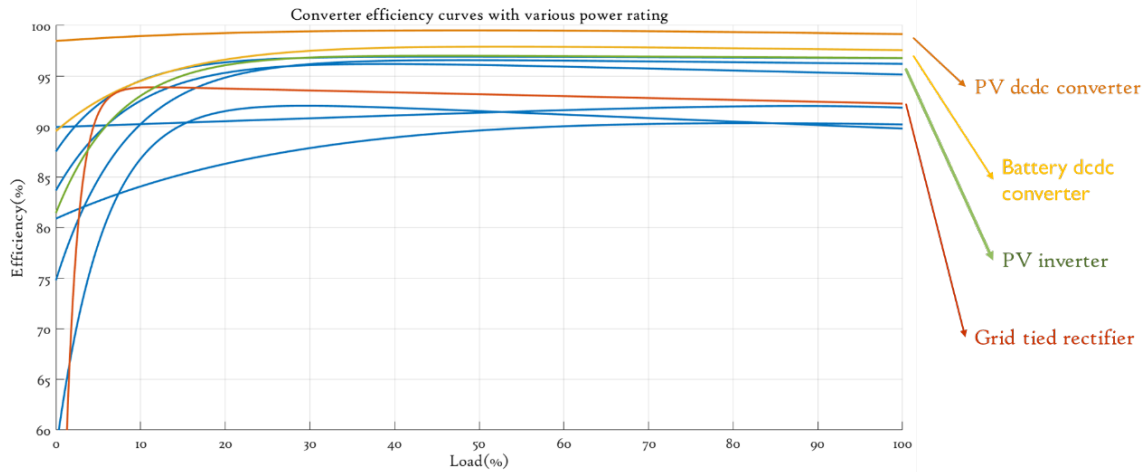
Figure 3-3: Converter efficiency curves used in the system[4][5][6][7][8][9][10][11][12]

For a certain load, the efficiency unit can be obtained by multiplying the efficiency of each converter that connected with the load. For the loads that supplied by AC power as shown in figure 3-4, a rectifier and an inverter are used in AC system, while in the DC system, the rectifier can be removed.

The converter unit efficiency in AC and DC system can be presented as

$$\eta_{conunitAC} = \eta_{rectifier} \cdot \eta_{inverter} \tag{3-1}$$

$$\eta_{conunitDC} = \eta_{inverter} \tag{3-2}$$

For the loads that supplied by DC power as shown in figure 3-5, the interface is composed of a rectifier and a dc/dc converter in the AC system. While in the DC system, the rectifier is removed, and less conversion stage results in higher total efficiency.
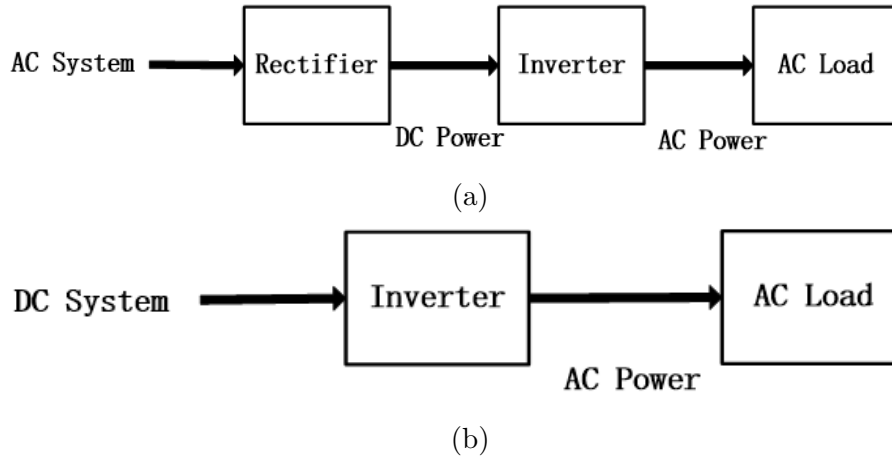
Figure 3-4: AC load with converters in (a)AC and (b)DC residential system
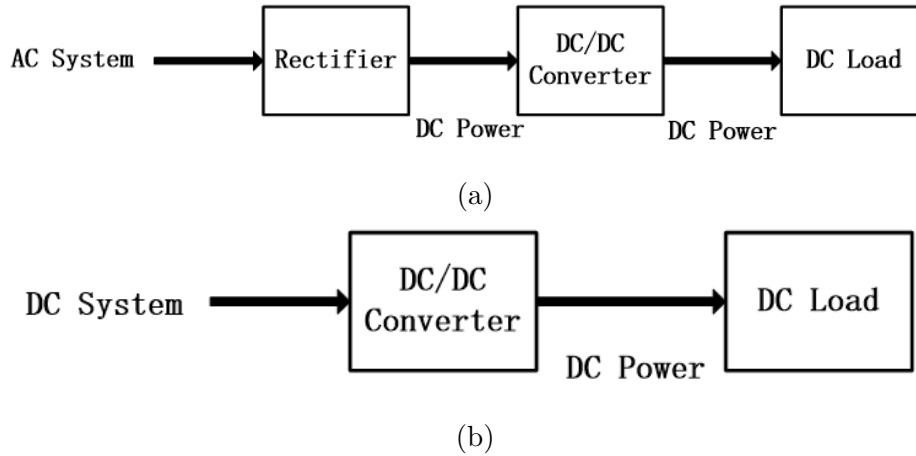
Figure 3-5: DC load with converters in (a)AC and (b)DC residential system

The efficiency of converter unit of DC supplied loads in AC and DC system can be presented as

$$\eta_{conunitAC} = \eta_{rectifier} \cdot \eta_{dc/dc} \tag{3-3}$$

$$\eta_{conunitDC} = \eta_{dc/dc} \tag{3-4}$$

In PV and battery storage system, the main factors that will affect the overall losses are converter losses. The converters that comprised in PV-battery storage systems are PV dc-dc converters, battery dc-dc converter, and PV inverter that only presents in AC system. The efficiency of PV battery system converters can be seen in figure3-3 as well.

The conversion losses of different power flow paths can be modelled by converter unit efficiency on the paths as a function of throughout power. By considering the load profile, the losses that consumed by converters can be calculated as

$$P_{load} = P_{in} \cdot \eta_{conunit} \tag{3-5}$$

$$P_{in} = P_{load} + P_{conlosses} \tag{3-6}$$

$$P_{conlosses} = P_{load} \cdot (1/\eta_{conunit} - 1) \tag{3-7}$$

where P_{load} is the power consumption of loads, P_{in} is the power drawn from supply, $\eta_{conunit}$ is the efficiency of converter unit.

3-3 Cable losses in residential house

The main effective factors that lead to power losses in cable are resistive losses in conductor and dielectric losses in insulating layers[]. Dielectric losses are the dissipation of energy that presents in the insulation material of the conductor. According to the standard [31], it suggests that the dielectric losses could be neglected at low voltage levels. . The resistive losses are caused by the flow of the current I through the conductor of resistance R, which produces heat. It is described by Joule's first law in equation3-8.

$$P_{Joule} = |I|^2 \cdot R \tag{3-8}$$

where R is the resistance of the cable, and I is the current that flow through the cable.

The resistance R is affected by the conductor material and temperature. In AC system, resistance R is influenced by the changing electromagnetic field as well. The phenomena are known as Skin effect and Proximity effect. In previous studies, it was showed that for the single phase system with small cross section cable, the influence of skin effect and proximity effect are not significant, which can be neglected[43]. Therefore, in this study, only resistance losses are taken into account.

To calculate the load side cable losses, the length that connected to the loads, the cross section and operating temperature of cables will be taken into account to calculate the cable resistance by equation 2-2. The calculation of cable losses can be expressed by equation 3-9 and presented in figure3-6.
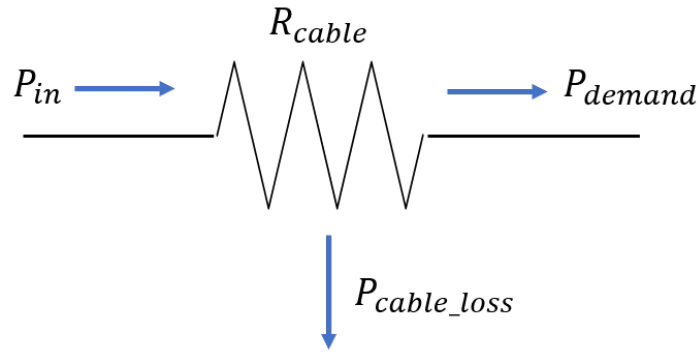
Figure 3-6: Schematic diagram of cable losses calculation

$$P_{cableloss} = P_{in} - P_{demand} = (P_{demand}/U)^2 \cdot R_{cable} \tag{3-9}$$

where P_{demand} is demand power, and U is bus voltage.

The main losses that considered in the system are cable losses and converter losses. A comparison between cable losses and converter losses is carried out to illustrate their contribution

to the overall losses. In DC system, there are lots of voltage levels can be chosen as the bus voltage. Four voltage levels will be chosen in this part to calculate the cable losses and compare cable losses with the conversion losses under the same voltage circumstance. In this case, due to hundreds of thousands of topologies of different converters, the influence of different voltage levels on converters will be ignored. The conversion losses will be seen as the same under each voltage level.

From the calculated results shown in figure 3-7, it can be seen that with voltage level gets higher, the cable losses are much less than the counterpart conversion losses. It is hardly possible to set an extra low voltage level like 48Vdv as the bus voltage. However, except the cable losses under 48Vdc, all of the others are accounted for only less than 5% portion of total losses.
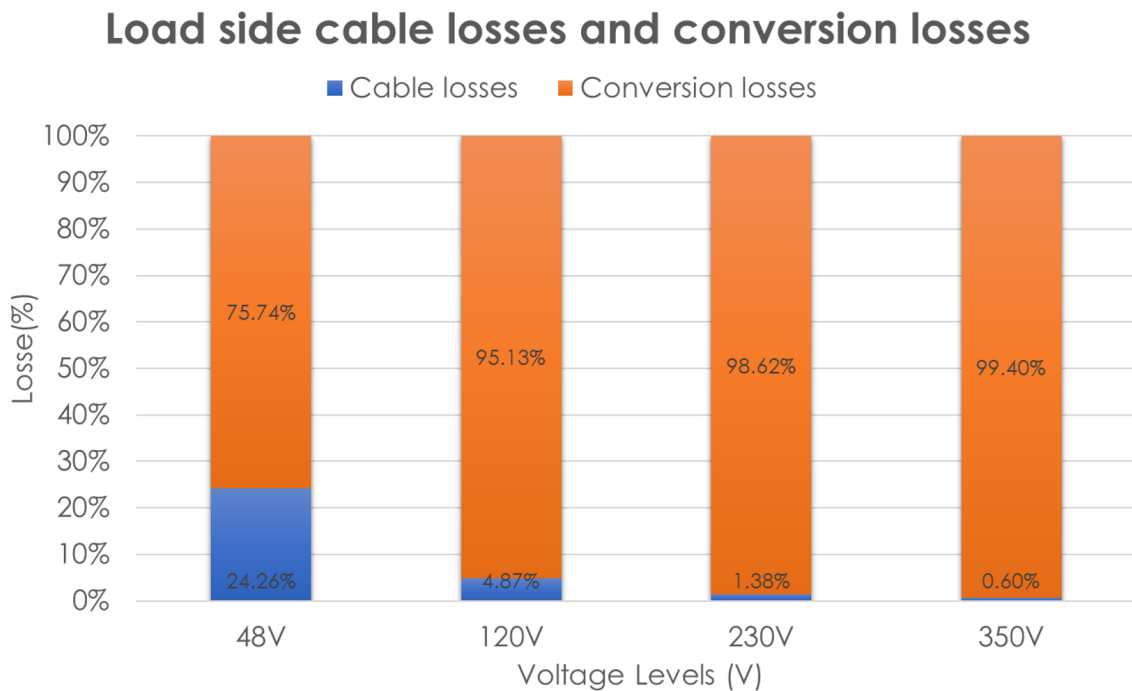
Figure 3-7: Comparison of load side cable losses and conversion losses

A relatively tiny proportion of cable losses is because of the relatively short cable distance, small cross section of cables, and low power rating of demands. Therefore, in a residential system with voltage level higher than 230Vdc, there will be little effect caused by cable losses on total losses.

In AC system, the voltage is 230Vac. And from previous analysis of conversion losses, it can be known that the load side conversion losses are larger than that in DC system. Therefore, it is not difficult to draw the result that the proportion of cable losses in AC system will be much smaller than that in DC system.

Based on the calculation and analysis above, it can be concluded that the cable losses would have little effect on overall system losses of the system. Therefore, the cable losses can be neglected in the following parts.

3-4   PV and battery storage system modelling

The modelling of PV and battery storage system will be introduced in this part. The PV and battery storage system in AC and DC system are shown in figure 3-8 (a) and (b).
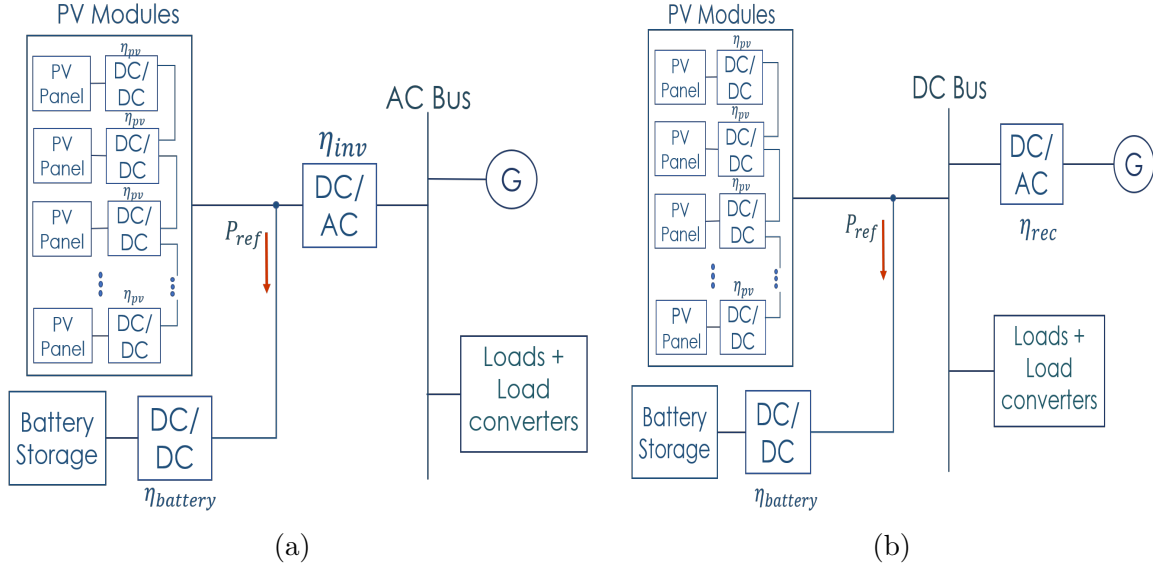
Figure 3-8: PV-battery storage system in (a)AC and (b)DC residential system

3-4-1   Solar photovoltaic modelling

The main components of PV generation modelling part are PV modules and local solar irradiance. To build the system, one dc-dc converter and a PV panel are connected to compose a PV module. Several PV modules are connected to achieve power generation, as seen in figure 3-8. In this way, it is more convenient to add or remove single PV module, therefore, reduce the influence of one panel on overall PV system. The dc-dc converter ofn a PV module is a boost converter aims to step up the PV voltage to the level of DC link.

The output power from N PV panels can be calculated simply by

$$P_{PV} = N_{PV} \cdot \frac{P_{max}}{Irr} \cdot |G| \tag{3-10}$$

where N_{PV} is the number of PV panels, P_{max} is the maximum power rating of PV panel that provided by manufacturer, Irr is the standardized irradiance of 1000W/m^2, and G is real time series local irradiance.

In this study, PV modules are used as the main renewable power source, and it is mainly focused on the general output power from PV. The allocation and control strategy of PV moduels are out of scope. Therefore, it is assumed that PV system is always under MPPT control.

3-4-2   Battery storage modelling

In this study, the lithium-ion battery is considered. The battery storage modelling will be defined by several parameters including battery state of charge(SoC)(%), battery round trip efficiency and battery degradation.

In a battery, SoC is one of the main characters to present the present state of the battery, which can be expressed by the ratio of current battery capacity and the maximum battery capacity over time. The value of SoC is used to control the power flow, that is, to decide whether the energy has to be charged or sold, or have to be discharged or bought from gird. In this study, battery SoC is restricted in the range of 10% to 90%, which is a typical SoC limitation range to protect the battery. When taking battery degradation into account, which will be described in detail in the following part, the prediction state of charge of the battery is defined as

$$SoC(t+1) = SoC(t) + \frac{\Delta(t)}{E_{bat}} \tag{3-11}$$

where $\Delta Q(t)$ is the throughout energy of battery in a time interval, E_{bat} is the maximum usable battery capacity.

The throughout energy $\Delta Q(t)$ in the battery of equation 3-11 can be calculated by

$$\Delta Q = P_{bat}(t) \cdot \Delta t \tag{3-12}$$

where the value of P_{bat} is the predict power that can be charged/discharged inside the battery, which can be decided by the power management that will be analyzed in detail in next section. Here, there is a constraints on the battery throughout power P_{bat}:

$$|P_{bat}(t)| < P_{batmax} \tag{3-13}$$

where P_{batmax} is the maximum battery chargeable/dischargeable power. If the predict charge/discharge power exceed this limitation, then the energy will be sold to or bought from the grid, which will be discussed in power management part. The battery is assumed to be discharge with a 1C-rate, therefore, the maximum chargeable/dischargeable power can be estimated as:

$$P_{nat_max} = \frac{E_{bat}}{T} = \frac{E_{bat}}{1} \tag{3-14}$$

The round trip efficiency of the battery is considered as 90 % in this study, which expresses charging efficiency and discharging efficiency of the battery as showing in equation 3-15.

$$\sqrt{\eta_{rt}} = \eta_{charge} = \eta_{discharge} \tag{3-15}$$

In the battery, the number of cycles is defined as the cycling times of battery charge and discharge cycling. To decide the cycle life and degradation of the battery, a series of parameters such as SoC, depth of discharge (DoD) (%) and end of life (EoL) are used. Usually, the EoL is considered as 80 % of the initial capacity of the battery. In this study, the battery degradation are modelled by using SOC constraints, Rainflow algorithm, battery DOD curve
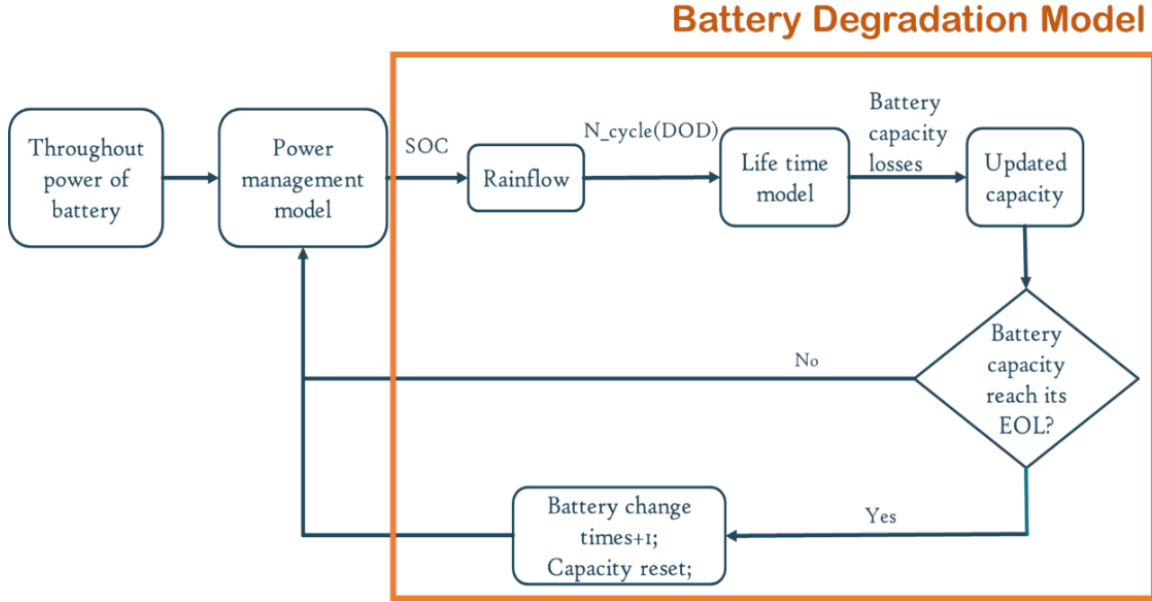
Figure 3-9: Block diagram of battery degradation and change of battery

and EoL, as described in block diagram in figure 3-9. The time step that considered in the modelling of battery degradation is 1-day, and the capacity losses are calculated as one-day accumulated capacity losses.

By using the one-day time-dependent SoC of battery, the discharge depth range and their counterpart cycle numbers (0.5, 1, 1.5, etc.) can be counted through Rainflow. Then, the DoD-life cycles curve of the battery from manufacturer in figure 3-10[13] is used. The Rainflow counted discharge depth, and cycle numbers are used to the DoD curve via look-up table to obtain their counterparts whole life cycles. The deeper the DoD is, the shorter life cycles will be. It is assumed that the battery capacity fade is linear in this study.

By using these three parameters(one-day discharge depth, DoD-related cycling numbers and DoD-related cycle life), the one-day capacity loss $C_{batloss}$ (%) can be obtained, which is expressed by the following equation:

$$C_{batloss}(\%) = (1 - EoL) \cdot \sum_{i=1}^{n} \frac{n_i}{N_i} \qquad (3\text{-}16)$$

where $C_{batloss}$ is the one day capacity loss as percentage of the original battery, i is the number of one day depth of discharge ranges, different i represent different DoD range, n is the one day numbers of cycle of a certain DoD range, N is the whole life cycles of the battery of a certain DoD range.

By using calculated one day battery capacity loss $C_{batloss}$, the updated battery capacity can be obtained by:

$$E_{bat}(d+1) = E_{bat}(d) - C_{batloss} \cdot E_{bat,rated} \qquad (3\text{-}17)$$

where $E_{bat,rated}$ is the rated original battery capacity, $E_{bat}(d)$ is the maximum usable battery capacity, $E_{bat}(d+1)$ is the updated maximum usable capacity after capacity fade.
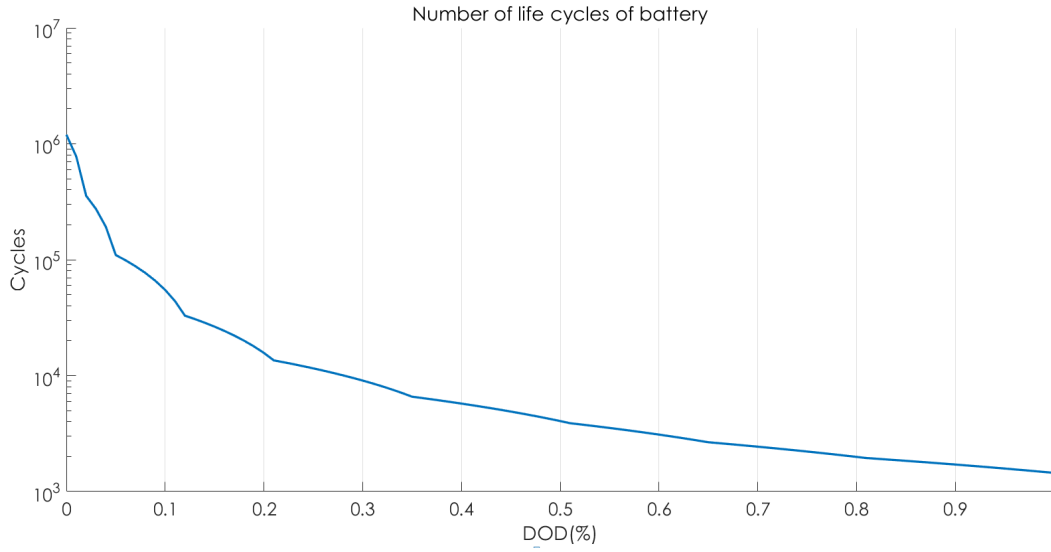
Figure 3-10: Battery DoD ranges with their corresponding life cycles[13]

In this way, when the battery maximum usable capacity of battery goes down to its EoL, the original battery could be replaced by a new one.

3-5   Power management strategy

Based on the previous modelling of the components in the system, the power management strategy can be proposed. In the system, it can be seen that the energy sources in system are PV generator and grid, and the power sinks are loads. By considering possible power flow, the reference point power(P_{ref}) introduced in figure 3-8 is used. It is defined as the difference between PV output power and load demands, as expressed in equation 3-18 for AC system and equation 3-19 for DC system. By determining whether $P_{ref} > 0$ or not, which means if the PV output power is greater than the demands or not, the operation of system can be divided into two main modes as shown in flow chart in figure 3-11. The following parts of this chapter are analyzed according to the divided two modes, and the method of using the reference point will be analyzed as well.

$$AC: \quad P_{ref} = P_{PV} \cdot \eta_{pvdcdc} - \frac{(P_{load} + P_{loadlosss})}{\eta_{inv}} \tag{3-18}$$

$$DC: \quad P_{ref} = P_{PV} \cdot \eta_{pvdcdc} - (P_{load} + P_{loadlosss}) \tag{3-19}$$

Figure 3-11: Flowchart of power management strategy

3-5-1   Mode 1: PV output power > demands

By calculating the reference point power P_{ref}, the direction of power from PV can be decided. If the PV output power outweighs the load demands ($P_{ref} > 0$), it means that there are surplus PV output power after supplying the load demands. Therefore, there are two possible ways for the power flow of surplus power. One is to charge the battery, the other is to sell to the grid.

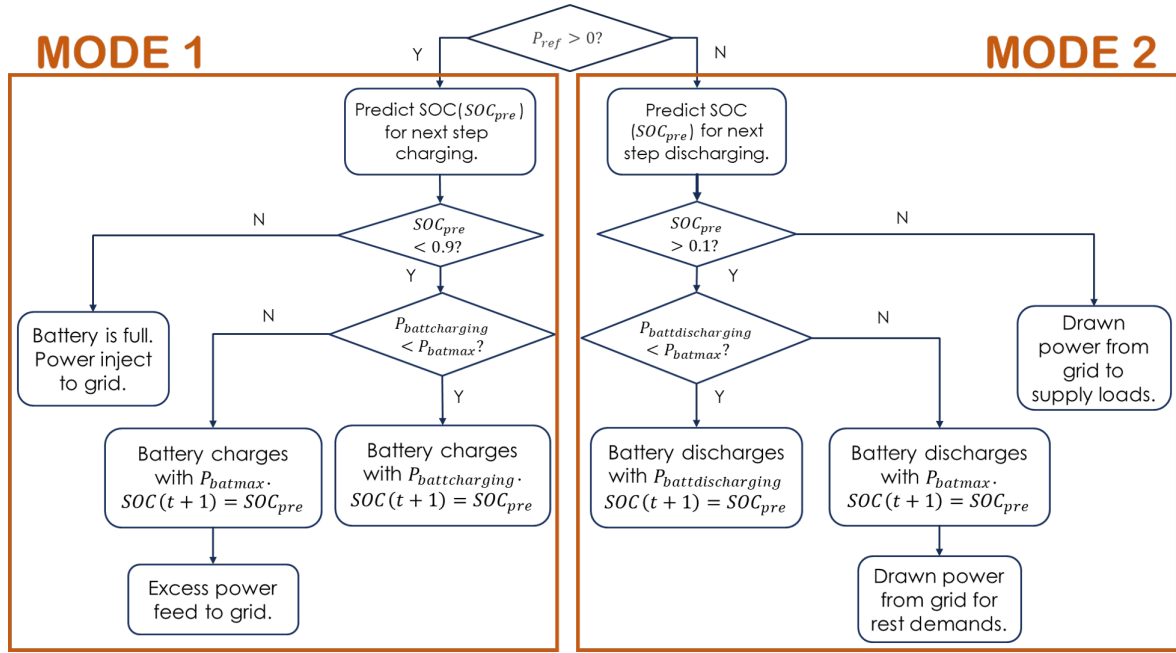To determine the power flow, a prediction SoC (SoC_{pre}) is needed to be estimated by equation 4-5 for next step determination. Since SoC is restricted to the range of 10%to 90 %, the predicted SoC should be compared with its upper limit 90 %. If the value of predicted SoC is no more than 90%, then it means there is available capacity for battery charging. Due to the constraints of battery maximum chargeable/dischargeable power ($\pm P_{batmax}$) as discussed in previous section, the calculated chargeable power $P_{battcharging}$, which is defined as equation 3-20,has to be compared with the P_{batmax}. The first situation is that if $P_{battcharging} < P_{batmax}$, the battery can be charged with $P_{battcharging}$, which is indicated as figure 3-12. The battery chargeable power is calculated by:

$$P_{battcharrging} = P_{ref} \cdot \eta_{charge} \cdot \eta_{batdcdc} \tag{3-20}$$

where η_{charge} is the charge efficiency of battery, and it equals to $\sqrt{\eta_{rt}}$, and η_{bat_dcdc} is the battery connected dc-dc converter efficiency.

If $P_{battcharing} > P_{batmax}$, battery will be charged with the maximum chargeable power P_{batmax}. Further, after supplying load demands and charging battery, the excess PV output power will be fed-in to the grid, as the second situation presented in figure 3-13.
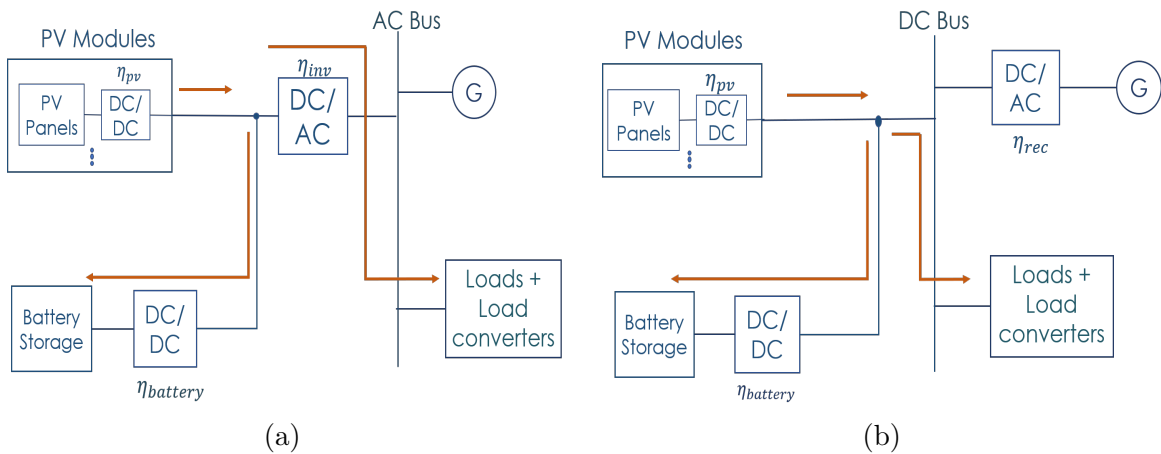
Figure 3-12: Situation1: PV output power supply the load side and charge to battery in (a)AC and (b)DC system
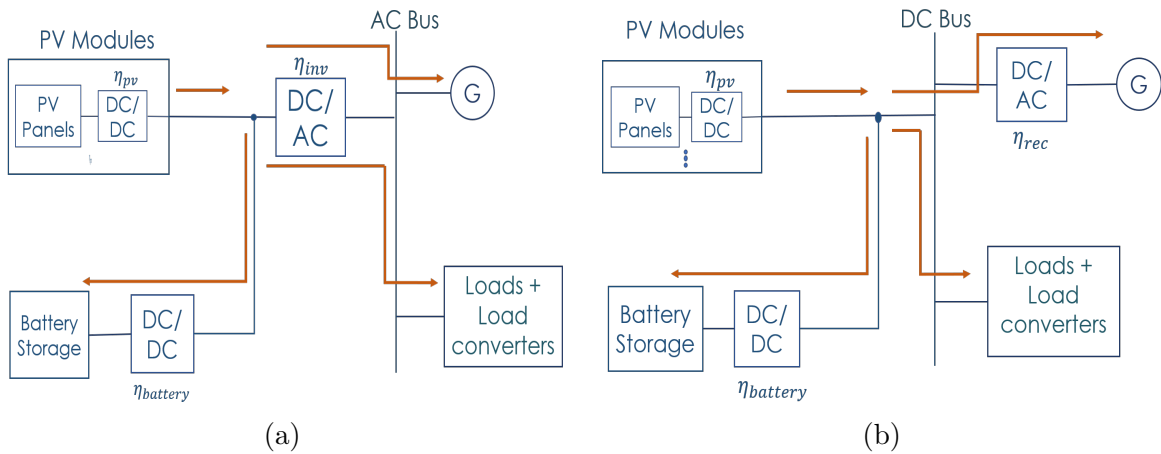
Figure 3-13: Situation2: PV power supply load demands, charge to battery and sell to grid in (a)AC and (b)DC system

If predicted SOC is greater than 90 %, it means that here is no more available capacity of the battery for charging. In this third situation, the PV output power will be first to satisfy the demands and the surplus power will be fed-in the grid, as shown in figure 3-14.
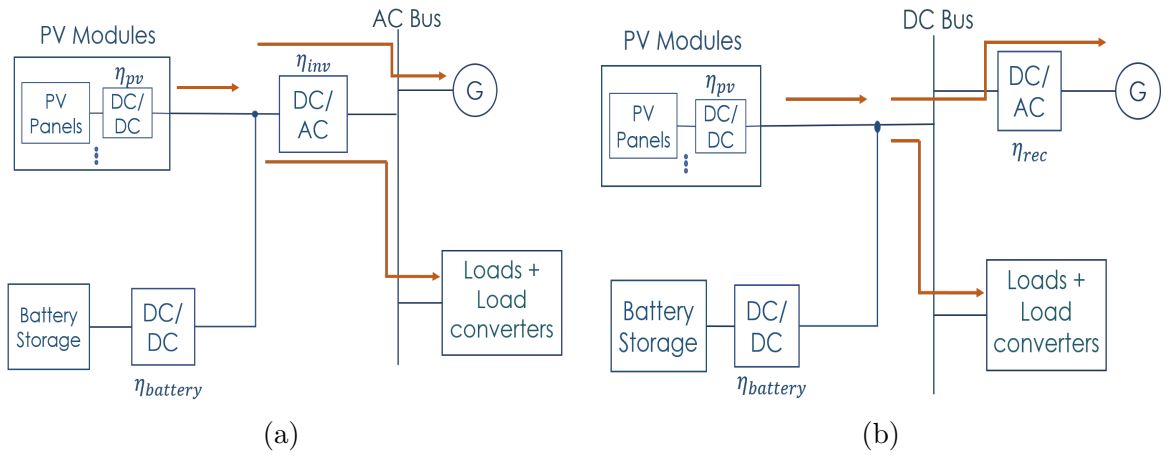
Figure 3-14: Situation3: PV output power supply load demands and sell to grid in (a)AC and (b)DC system

3-5-2   Mode 2: PV output power $<$ demands

If the calculated reference point power P_{ref} is less than 0, which means that the PV output power is not enough to meet the load demands on its own, then more power will be extracted from the other two parts, battery storage or/and grid.

As the same process that described in Mode 1, the prediction SoC (SoC_{pre}) is calculated to compared with its inferior limit 10%. If SoC_{pre} is larger than 10%, that is, power can be discharged from battery. It leads to a further comparison between battery maximum dischargeable power P_{batmax} and the battery dischargeable power $P_{battdischarging}$ that calculated by equation 3-21, to check whether the dischargeable power would beyond the limitation.

$$P_{battdischarging} = -P_{ref}/\eta_{discharge}/\eta_{batdcdc} \tag{3-21}$$
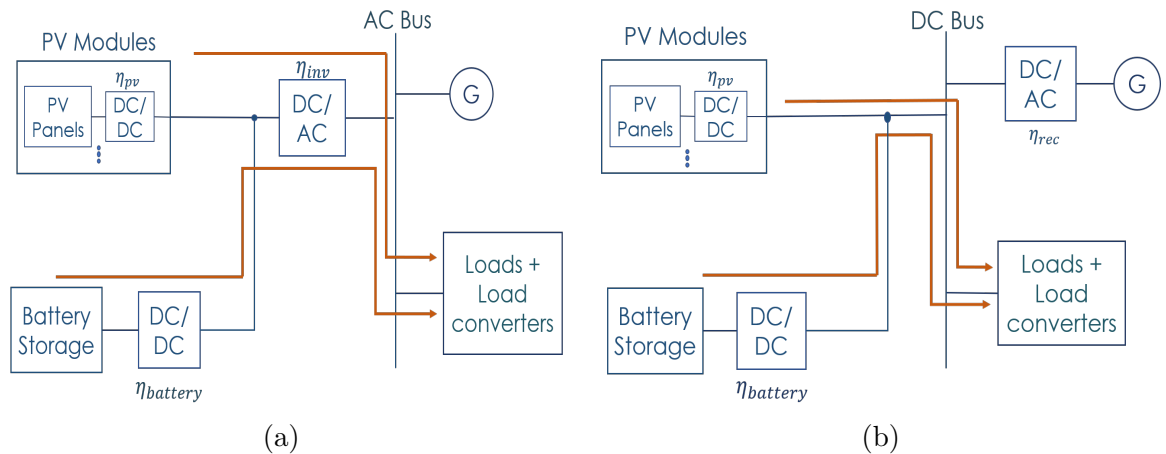
Figure 3-15: Situation4: Load demands are supplied by PV and battery in (a)AC and (b)DC system

As the fourth situation shown in figure 3-15, if $P_{battdischarging} < P_{batmax}$, the battery can be discharged with the calculated $P_{battdischaring}$ to supply the load demands. Under this

operation, the load demands are supplied by PV and battery . On the contrary, the battery has to be discharged with P_{batmax}. In this situation, the grid supply is required to replenish the load demands as indicated in figure 3-16.
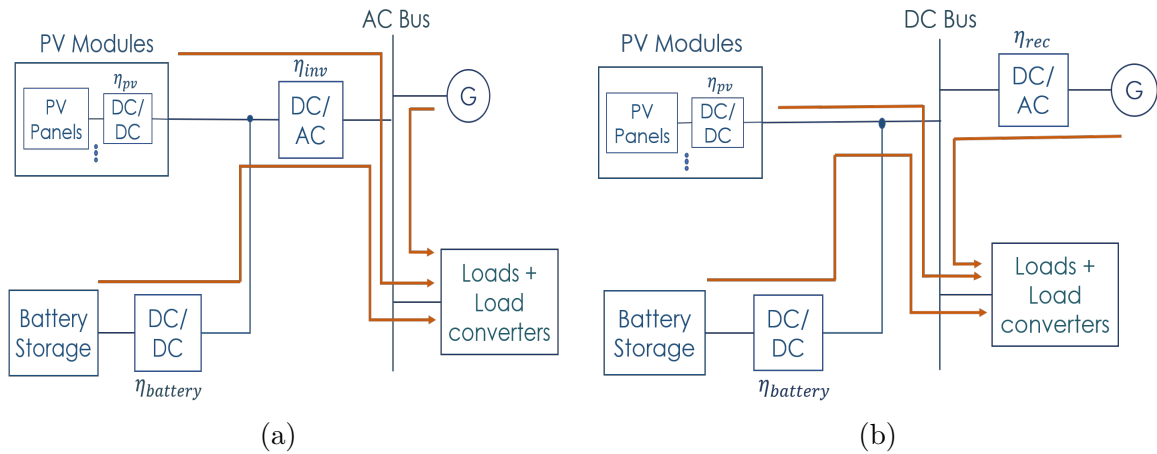
Figure 3-16: Situation5: Load demands are supplied by PV and battery and grid in (a)AC and (b)DC system

Figure 3-17: Situation6: Load demands are supplied by PV and battery and grid in (a)AC and (b)DC system

In the last situation, if $SoC_{pre} < 10$ %, it means that the battery cannot be discharged. Therefore, to meet the requirements of the demands, grid supply is needed besides PV supply. The power flow of this operation can be seen in figure 3-17.

3-6 System losses modelling

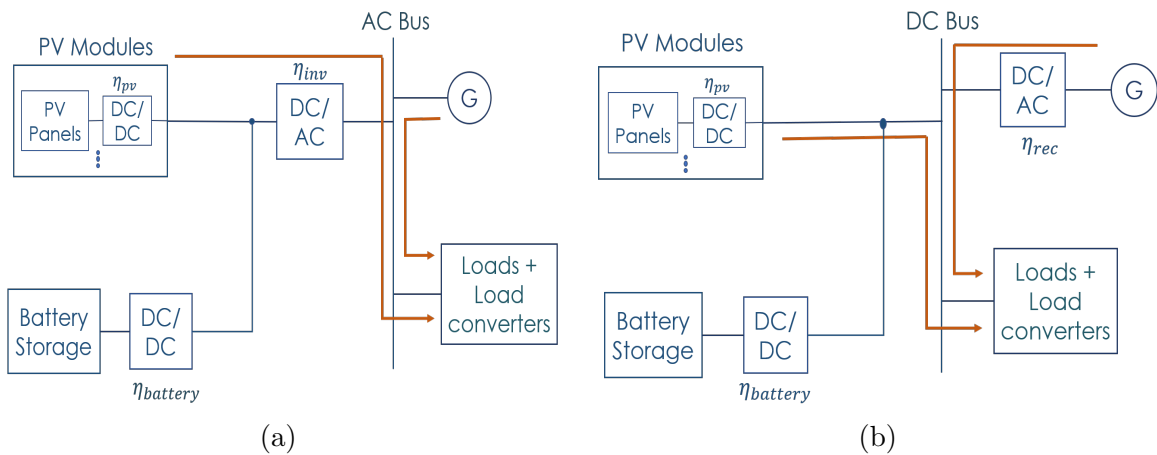In this section, the losses will be analyzed in both AC and DC systems in terms of different operation modes that have been discussed in previous section. The losses modelling will be built based on the previous analysis that cable losses are so tiny when compared to conversion losses that can be neglected. The main losses difference between two systems is considered due to different conversion stages.

3-6-1 AC system losses modelling

As for overall losses in AC system, it is varied with the operations of system which have been discussed in the last section. In each of the situations, the losses components that would not be affected by others are load converter losses $E_{loss_{load\_converters}}$ and PV dc-dc converter losses $E_{loss_{pvdc-dc}}$. The load converter efficiency $\eta_{conunit}$ includes two conversion stages. All the energy losses of the system in different situations, can be calculated by:

$$E_{loss} = \int P_{loss} dt \tag{3-22}$$

Situation 1: PV output power supply the load demands and charge to the battery

$$P_{loss} = P_{loss_{pvdc-dc}} + P_{loss_{load\_converters}} + P_{loss_{bat\_charge}} + P_{loss\_inv} \tag{3-23}$$

where,

$P_{loss_{load\_converters}} = P_{load} \cdot (\frac{1}{\eta_{conunit}} - 1)$;

$P_{loss_{pvdc-dc}} = P_{PV} \cdot (1 - \eta_{pvdcdc})$;

$P_{loss_{bat\_charge}} = P_{ref} \cdot (1 - \eta_{batdcdc} \cdot \eta_{charge})$;

$P_{loss\_inv} = P_{res} \cdot (1 - \eta_{inv})$;

$P_{res} = P_{PV} \cdot \eta_{pvdcdc} - P_{ref}$;

P_{res} is defined as the power output from PV-battery storage system through inverter.

Situation 2: PV power supply the load demands, charge to the battery and sell to the grid

$$P_{loss} = P_{loss_{pvdc-dc}} + P_{loss_{load\_converters}} + P_{loss_{bat\_charge}} + P_{loss\_inv} \tag{3-24}$$

where,

$P_{loss_{bat\_charge}} = P_{bat\_max} \cdot (\frac{1}{\eta_{batdcdc} \cdot \eta_{charge}} - 1)$;

$P_{loss\_inv} = P_{res} \cdot (1 - \eta_{inv})$;

$P_{res} = P_{PV} \cdot \eta_{pvdcdc} - \frac{P_{bat\_max}}{\eta_{batdcdc} \cdot \eta_{charge}}$.

Situation 3: PV output power supply the load demands and sell to the grid

$$P_{loss} = P_{loss_{pvdc-dc}} + P_{loss_{load\_converters}} + P_{loss\_inv} \tag{3-25}$$

where,

$$P_{loss\_inv} = P_{res} \cdot (1 - \eta_{inv});$$

$$P_{res} = P_{pv} \cdot \eta_{pvdcdc}.$$

Situation 4: Load demands are supplied by PV generator and battery storage

$$P_{loss} = P_{loss_{pvdc-dc}} + P_{loss_{load-converters}} + P_{loss\_inv} + P_{loss_{bat\_discharge}} \tag{3-26}$$

where,

$$P_{loss_{bat\_discharge}} = -P_{ref} \cdot (\frac{1}{\eta_{batdcdc} \cdot \eta_{discharge}} - 1);$$

$$P_{loss\_inv} = P_{res} \cdot (1 - \eta_{inv});$$

$$P_{res} = P_{pv} \cdot \eta_{pvdcdc} + P_{ref}.$$

Situation 5: Load demands are supplied by PV generator, battery storage and the grid

$$P_{loss} = P_{loss_{pvdc-dc}} + P_{loss_{load\_converters}} + P_{loss\_inv} \tag{3-27}$$

where,

$$P_{loss_{bat\_discharge}} = P_{bat\_max} \cdot (1 - \eta_{batdcdc} \cdot \eta_{discharge});$$

$$P_{loss\_inv} = P_{res} \cdot (1 - \eta_{inv)};$$

$$P_{res} = P_{pv} \cdot \eta_{pvdcdc} + P_{bat\_max} \cdot \eta_{bat\_dcdc} \cdot \eta_{discharge}.$$

Situation 6: Load demands are supplied by the PV generator and the grid

$$P_{loss} = P_{loss_{pvdc-dc}} + P_{loss_{load\_converters}} + P_{loss\_inv} \tag{3-28}$$

where,

$$P_{loss\_inv} = P_{res} \cdot (1 - \eta_{inv});$$

$$P_{res} = P_{pv} \cdot \eta_{pvdcdc}.$$

3-6-2 DC system losses modelling

Similar to the AC system losses analysis, the DC system losses with will be calculated with different operation modes of system. In the modelling of DC system losses, the load converter efficiency $\eta_{conunit}$ presents only one conversion stage.

Situation 1: PV output power supply the load demands and charge to battery

$$P_{loss} = P_{loss_{pvdc-dc}} + P_{loss_{load\_converters}} + P_{loss_{bat\_charge}} \tag{3-29}$$

where,

$$P_{loss_{bat\_charge}} = P_{ref} \cdot (1 - \eta_{batdcdc} \cdot \eta_{charge}).$$

Situation 2: PV power supply load demands, charge to battery and sell to grid

$$P_{loss} = P_{loss_{pvdc-dc}} + P_{loss_{load\_converters}} + P_{loss_{bat\_charge}} + P_{loss\_rec} \tag{3-30}$$

where,

$P_{loss_{bat\_charge}} = P_{bat\_max} \cdot (\frac{1}{\eta_{bat_{dcdc}} \cdot \eta_{charge}} - 1);$

$P_{loss\_rec} = P_{feedin} \cdot (1 - \eta_{rec});$

$P_{feedin} = P_{pv} \cdot \eta_{pvdcdc} - \frac{P_{load}}{\eta_{conunit}} - \frac{P_{bat\_max}}{\eta_{batdcdc} \cdot \eta_{charge}}.$

Situation 3: PV output power supply the load demands and sell to the grid

$$P_{loss} = P_{loss_{pvdc-dc}} + P_{loss_{load\_converters}} + P_{loss\_rec} \tag{3-31}$$

where,

$P_{loss\_rec} = P_{feedin} \cdot (1 - \eta_{rec});$

$P_{res} = P_{pv}\eta_{pvdcdc}.$

Situation 4: Load demands are supplied by the PV generator and battery storage

$$P_{loss} = P_{loss_{pvdc-dc}} + P_{loss_{load-converters}} + P_{loss_{bat\_discharge}} \tag{3-32}$$

where,

$P_{loss_{bat\_discharge}} = -P_{ref} \cdot (\frac{1}{\eta_{bat\_dcdc} \cdot \eta_{discharge}} - 1).$

Situation 5: Load demands are supplied by the PV generator, battery storage and the grid

$$P_{loss} = P_{loss_{pvdc-dc}} + P_{loss_{load\_converters}} + P_{loss\_rec} + P_{loss_{bat\_discharge}} \tag{3-33}$$

where,

$P_{loss_{bat\_discharge}} = P_{bat\_max} \cdot (1 - \eta_{bat\_dcdc} \cdot \eta_{discharge});$

$P_{loss\_rec} = P_{feedout} \cdot (\eta_{rec)-1};$

$P_{feedout} = \frac{P_{load}}{\eta_{conunit}} - P_{PV} \cdot \eta_{pvdcdc} - P_{bat\_max} \cdot \eta_{bat\_dcdc} \cdot \eta_{charge},$

where $P_{feedout}$ is the power drawn from the grid to meet the load demands(on the bus).

Situation 6: Load demands are supplied by the PV generator and the grid

$$P_{loss} = P_{loss_{pvdc-dc}} + P_{loss_{load\_converters}} + P_{loss\_rec} \tag{3-34}$$

where,

$P_{loss\_rec} = P_{feedout} \cdot (\frac{1}{\eta_{rec}} - 1);$

$P_{feedout} = \frac{P_{load}}{\eta_{conunit}} - P_{PV} \cdot \eta_{pvdcdc}.$

A summarized comparison between AC and DC system losses is concluded in table 3-2 and table 3-3.

Table 3-2: AC system losses in different operation modes

MODE 1	System losses	MODE 2	System losses
Situation 1	$Loss_{system} = Loss_{pv-dcdc}+$ $Loss_{inv} + Loss_{bat-dcdc}$ $+Loss_{load\_converters}$ $+Loss_{bat-charging}$	Situation 4	$Loss_{system} = Loss_{pv-dcdc}+$ $+Loss_{inv} + Loss_{bat-dcdc}$ $+Loss_{load\_converters}$ $+Loss_{bat-discharging}$
Situation 2	$Loss_{system} = Loss_{pv-dcdc}+$ $Loss_{inv} + Loss_{bat-dcdc}$ $+Loss_{load\_converters}$ $+Loss_{bat-charging}$	Situation 5	$Loss_{system} = Loss_{pv-dcdc}+$ $Loss_{inv} + Loss_{bat-dcdc}$ $+Loss_{load\_converters}$ $+Loss_{bat-discharging}$
Situation 3	$Loss_{system} = Loss_{pv-dcdc} +$ $Loss_{load\_converters} + Loss_{inv}$	Situation 6	$Loss_{system} = Loss_{pv-dcdc} +$ $Loss_{load\_converters} + Loss_{inv}$

Table 3-3: DC system losses in different operation modes

MODE 1	System losses	MODE 2	System losses
Situation 1	$Loss_{system} = Loss_{pv-dcdc}$ $+Loss_{load\_converters}$ $+Loss_{bat-charging}$ $+Loss_{bat-dcdc}$	Situation 4	$Loss_{system} = Loss_{pv-dcdc}$ $+Loss_{load\_converters}$ $+Loss_{bat-discharging}$ $+Loss_{bat-dcdc}$
Situation 2	$Loss_{system} = Loss_{pv-dcdc}$ $+Loss_{load\_converters}$ $+Loss_{bat-dcdc} + Loss_{rec}$ $+Loss_{bat-charging}$	Situation 5	$Loss_{system} = Loss_{pv-dcdc}$ $+Loss_{load\_converters}$ $+Loss_{bat-dcdc} + Loss_{rec}$ $+Loss_{bat-discharging}$
Situation 3	$Loss_{system} = Loss_{pv-dcdc} +$ $Loss_{load\_converters} + Loss_{rec}$	Situation 6	$Loss_{system} = Loss_{pv-dcdc} +$ $Loss_{load\_converters} + Loss_{rec}$

3-7   Conclusion of the chapter

- In this chapter, overview of the two systems were introduced firstly. Based on the overview, the system was divided into four main parts for modelling, which are loads, converters, PV generator and battery storage. The one year based load profile was obtained online, which is the real world measurement data to make the study more comprehensive.

- Next, the converters of the systems were modeled as the converter efficiency curves, which are obtained from the converter datasheet in the market. The choice of the converter efficiency curves was based on the power rating of converter-connected source/demand.

- Then, as for the PV and battery system, the local solar irradiance was regarded as the input to calculate the PV output power, and one panel with one dc/dc converter topology was used due to easily replacement. When designing the battery system, the one day based SOC was used with the DOD related life cycles to estimate the capacity

degradation of the battery.

- Finally, by implementing power management, the system losses were calculated based on different operation of system. The AC and DC system losses could be compared with a same method and conditions. The difference between these two system losses comparison was due to the differences between the converters that caused by the systems themselves.

Chapter 4

AC and DC system evaluation and comparison with varying PV and battery sizing

This chapter aims to analyze the PV and battery system energy generation, battery degradation, and the grid side net energy, energy saving and overall system losses based on the system models. The modelled residential system will be evaluated with different sizes of PV generator and battery storage. The period for the evaluation is set to be 20 years, which is the same as the PV lifetime.

4-1 Load profile

A typical daily load consumption of a residential home can be seen as figure4.1. The loads in residential home can be modelled as real time loads profile with 1-min resolution, which can be obtained from website Pecan Street [34]. The one year load profile and daily load profile in June and December can be seen from figure 4-1 and figure 4-2 separately. The load consumption in a year is 3423.5kWh, the peak power of the house along the whole year can reach over 8kW. The peaks of load profile mainly come from the utility of kitchen appliances like oven and stove, which are not used every day.

4-2 PV and battery storage system generation

PV and battery storage system is assumed to be same in both AC and DC systems. In this part, energy generation from PV with different sizes and battery control and degradation that may affect the system performance will be presented.
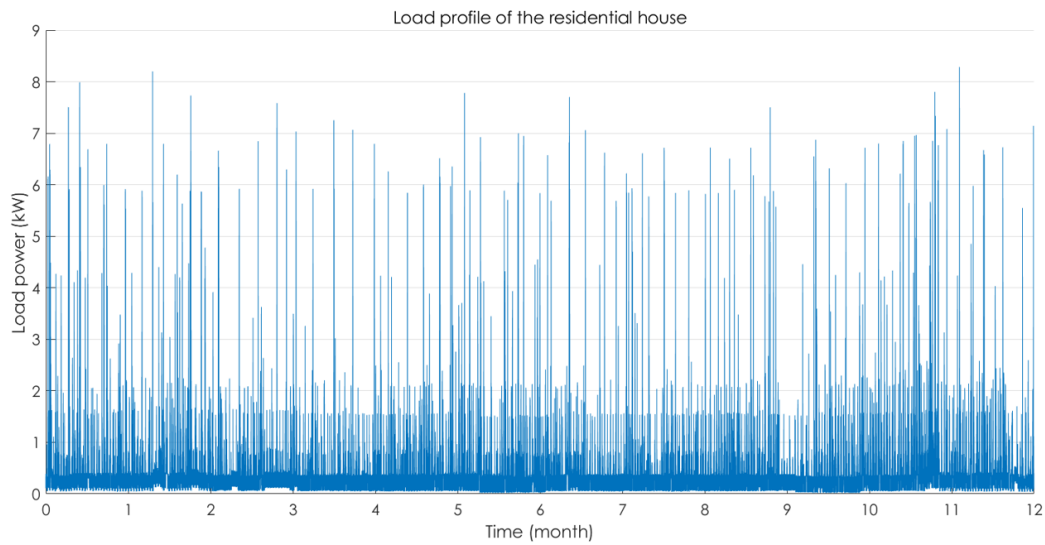
Figure 4-1: Residential load profile in one year
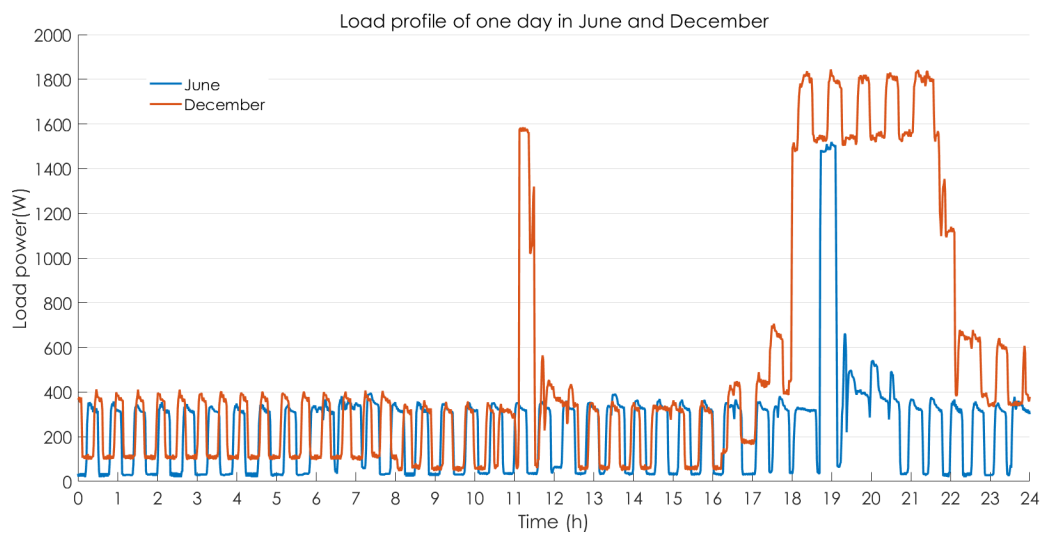
Figure 4-2: Load profile of 1-day in June and December

4-2-1   PV generation

From the previous chapter, it can be known that to calculate the energy generation from PV panels, there are two main parameters should be considered. The first one is the maximum power of PV panel from datasheet, the other is local irradiance. The required data we used in this study are shown in table 4-1. Furthermore, the PV panels lifetime is assumed to be 20 years, which is a general PV lifetime in market. It is assumed that the accidents like damage of PV panels will not happen in this study.

By implementing the input data, the output power from PV panels can be obtained. Figure 4-3 shows the one-year PV power generation of two different sizes of PV. The red one is 2kWp and blue one is 6kWp PV. The PV generation is highly depends on local solar irradiance.

Table 4-1: PV panel data

P_{max}	305W
V_{mp}	36.8V
I_{mp}	8.3A
$Lifetime$	20 Years

A daily PV generation in different month can be seen from figure 4-4, it is obvious that PV generation is even 5 times higher in mid-year than that in begin/end of the year. Longer day time and more sunny days lead to wider time range and higher peak value of solar irradiance in mid-year period than in winter time.
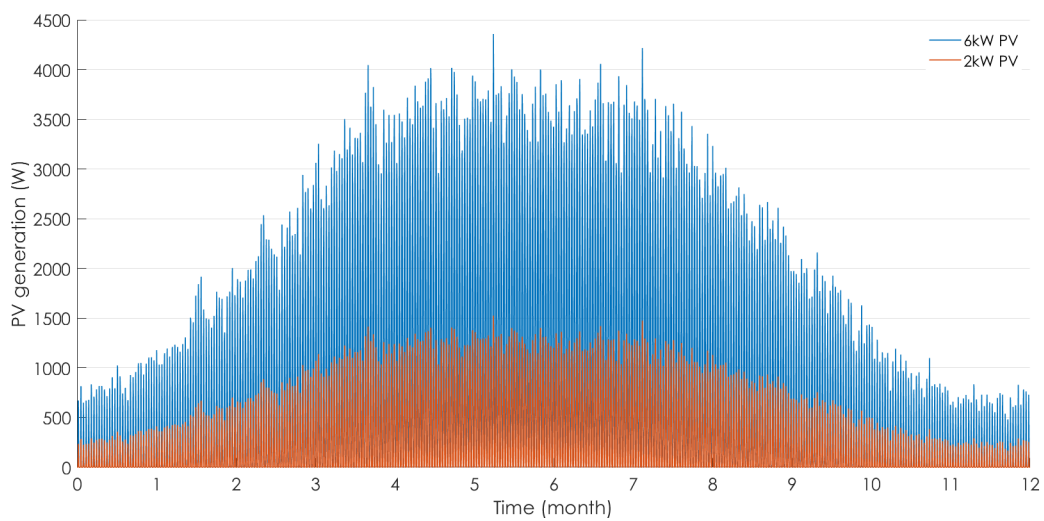
Figure 4-3: PV output power for one year in size of 2kWp and 6kWp
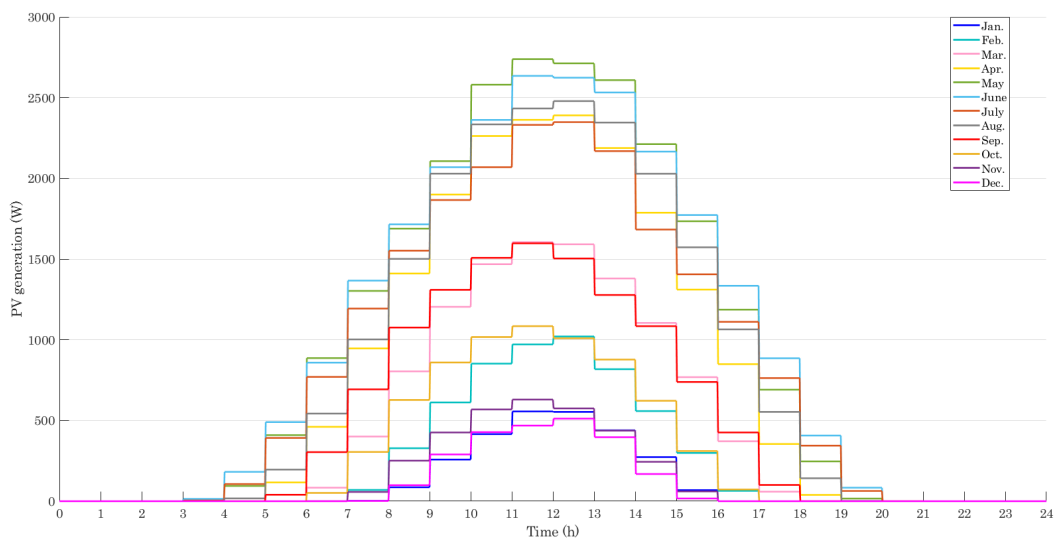
Figure 4-4: PV generation in one day of each month

4-2-2   Battery SoC and degradation

The battery used in this study is Li-ion battery. The SoC is one of the main characters of the battery. The size of PV and battery will have obvious influence on the SoC. For a certain size of PV, if the storage has a relatively large capacity, the battery will not be fully charge/discharge, which has a low DoD and extend the battery life time. In the meantime, too much larger capacity will lead to resource wasting. In contrary, if the storage capacity is too low, there will be a cut-off in the process of charge/discharge.

By implementing power management strategy, the SoC of a 3kWh battery SoC with 3kWp PV generation can be presented in figure4-5 as an example. The SoC is restricted to the preset range of 10%-90% of the minimal battery capacity. It can be seen from the figure that from March to mid-October period, the battery can be fully charge/discharge almost all the time due to long day hours in duration and relatively high irradiation. While in late autumn and winter months, the battery is low in exploitation because of shorter day time and low irradiation.

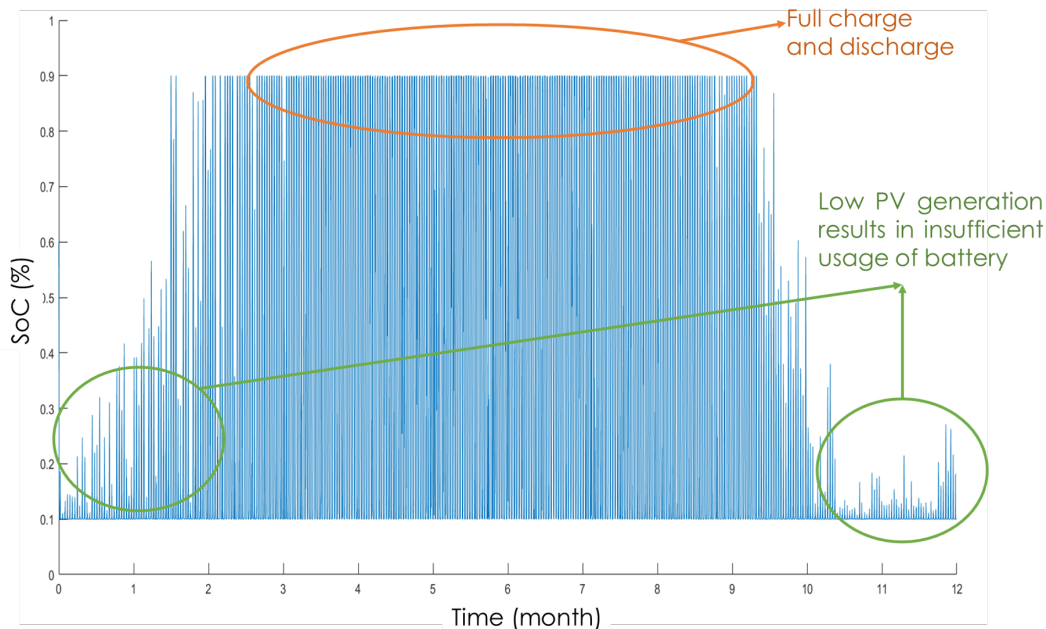**Figure 4-5:** Battery storage SoC for one year with 3kWp PV and 3kWh battery

By analyzing the SoC of battery, the DoD of battery can be obtained. DoD is the parameter that closely related to the battery degradation. As the previous statement of battery degradation model, with SoC, power management strategy, rainflow algorithm and DoD and battery lifecycles from datasheet, the battery degradation process can be obtained.
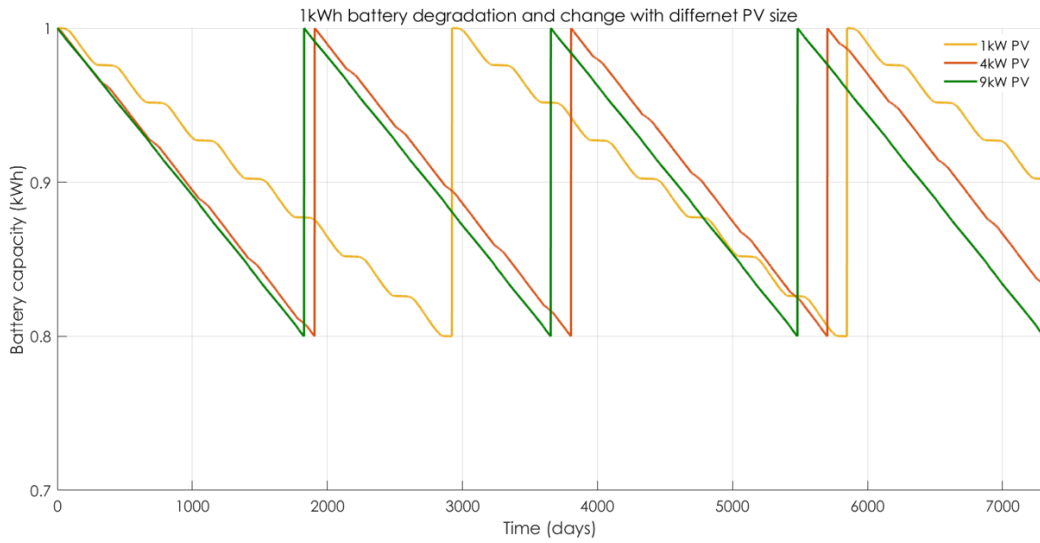
Figure 4-6: 1kWh battery degradation with different sizes of PV
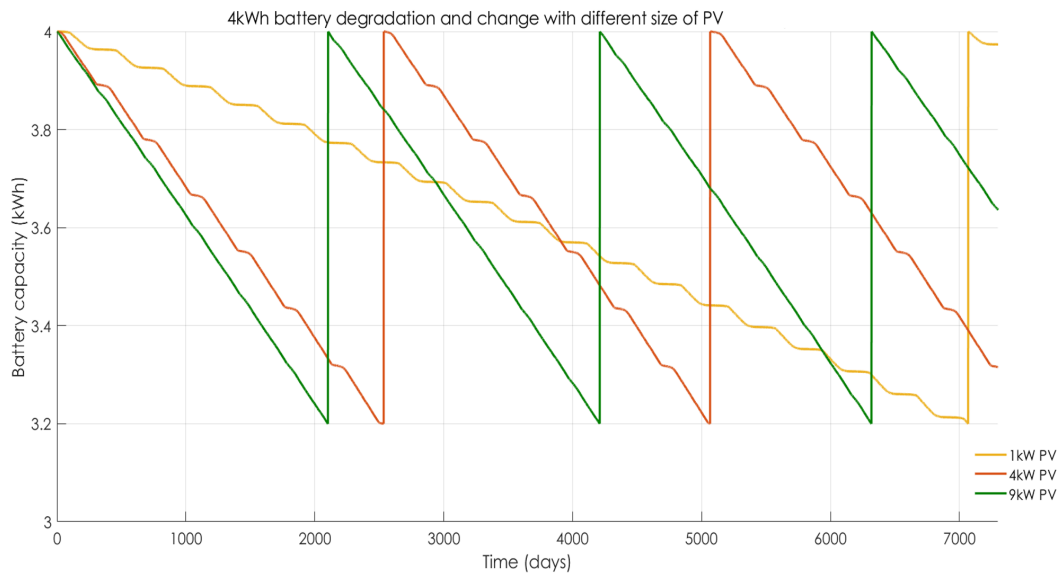
Figure 4-7: 4kWh battery degradation with different sizes of PV

It can be seen from figure 4-6 to 4-8, where 3 different sizes of battery are picked with three different size of PV, to illustrate the battery degradation and battery change that influence by size of PV generator and battery in the period of 20 years that is the same as PV lifetime. For a certain nominal capacity of battery storage, the capacity fades relatively rapid and battery changes more frequent with larger size of PV generator. While with smaller size of PV, the capacity is slower in degradation and battery changes less. It is mainly because that the battery will charge/discharge more frequent with large PV generation, and battery is easy to be fully charge/discharge, so that almost all of the DoD of the battery in this situation are relatively higher, which also leads to decrease in its life cycles. As for a lower PV generation, there will be various possibility of DoD range. Small DoD leads to extension
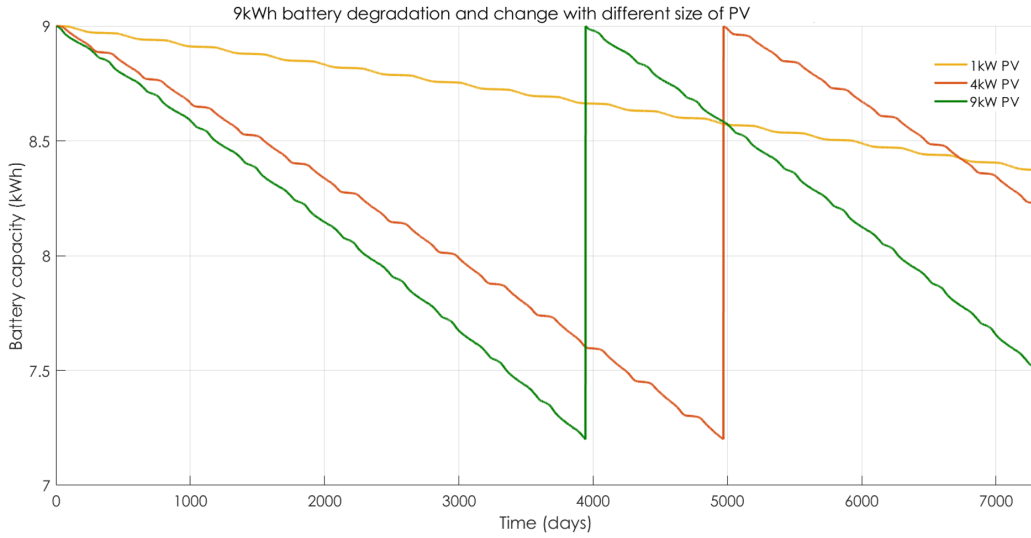
Figure 4-8: 9kWh battery degradation with different sizes of PV

in lifecycles, thus increases lifetime. And battery charge and discharge processes are not so frequent with low PV generation as that with high penetration of PV. In addition, there is fluctuation in the blue curve, which is due to change of season. In the season with more sunlight, battery capacity is faded with a higher rate, while in the season with less sunlight, degradation becomes slowly due to lower PV output power.

4-3   System energetic analysis

After analyzing PV and battery storage system, the energetic analysis of both AC and DC residential system will be evaluated. In this part, the grid side net energy and energy saving will be analyzed with sizing of PV and battery storage.

4-3-1   Net energy in AC and DC system

Net energy is defined as the difference between the feed-out energy from gird and the feed-in energy to grid in both of AC and DC systems, shown as

$$P_{net}(t) = P_{feedout}(t) - P_{feedin}(t) \tag{4-1}$$

$$E_{net} = \int P_{net} dt \tag{4-2}$$

Results and analysis: The results of net energy in AC and DC residential system are shown in figure 4-9(a) and (b).

1. It can be seen that PV generator is the dominant factor in deciding system net energy. Battery storage has little influence on the variation of net energy. Since there is no energy generation from the battery, therefore, the distributed generation is only related to PV generation in overall.

(a)

(b)
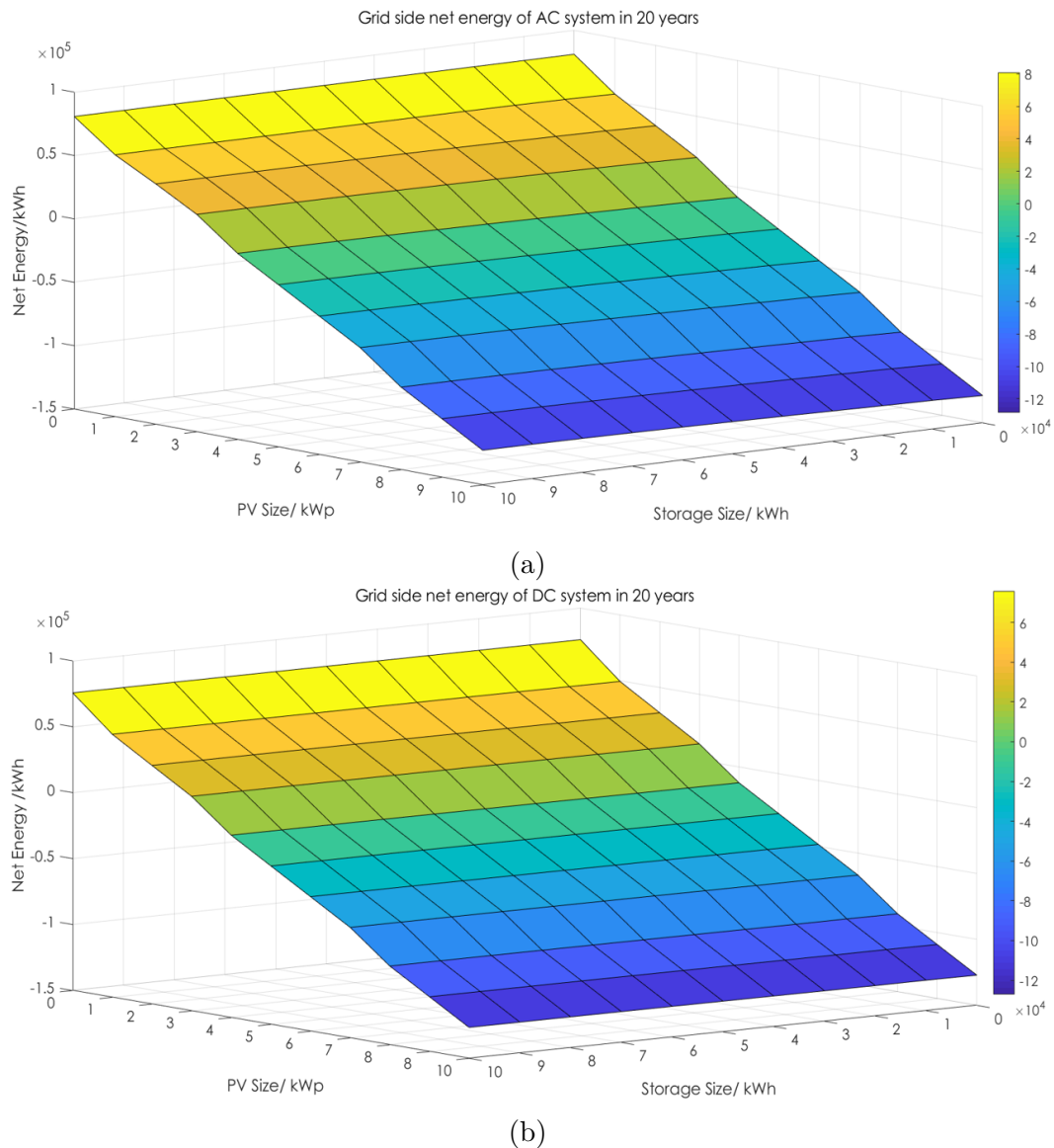
Figure 4-9: Net energy in grid connected side in (a)AC and (b)DC system in 20 years

2. The tiny net energy variation that caused by the increase of battery storage size is that for a certain PV size, with the battery storage capacity increases, the total net energy gets higher in a small range. It is due to the charge and discharge process losses. Large storage leads to larger losses, which consume more PV generation. At the same time, there are more power drawn from the grid. Therefore, larger value of net energy is obtained.

3. When comparing net energy in AC and DC, a similar net energy amount can be found in both of the systems. If the effect of battery is assumed to be same in both systems, for simplified analysis, it can be ignored in comparing two systems. When net energy>0, the net energy in DC system is relatively lower than that in AC system under the same PV and battery condition, which means there is lower feed-out or higher feed-in

energy in DC system. In AC system, the output energy from PV generator supplies the load demands via three conversion stages in total, PV inverter and two stages of load converters. While in DC system, the amount of PV output energy is the same, however, it passes only one load side conversion stage, which results in less losses. Therefore, to supply the same loads, there will be more power drawn from grid in AC system than that in DC system.

As for net energy<0, the absolute value of net energy in DC system is relatively larger than that in AC system. The reason for this situation is similar to the case of net energy>0. A conclusion can be drawn for net energy evaluation of systems, which is that DC system has lower net energy than AC system in the period of 20 years, with different PV and battery sizes combination. It means that DC system drawn less energy from grid and feed in more to the grid than that of AC system.

4-3-2   Energy saving from grid in AC and DC system

One of the significant potential benefits from implementing PV-battery storage is to save electricity energy purchase from grid. The amount of energy saving in 20 years can be calculated with different size of PV and battery storage penetration to evaluate the benefits from implementation of PV-battery system. The difference between AC and DC residential system can be compared to evaluate the potential advantages of DC as well. Energy saving in this study is defined as how much energy can be saved from grid by using PV and battery storage system generation. It can be expressed as

$$E_{saving} = E_{org} - E_{net} \tag{4-3}$$

where, $E_{o}rg$ is the energy consumption without PV and battery storage, and $E_{n}et$ is the net energy in the system.

The energy saving of AC and DC residential system are shown in figure 4-10(a) and (b), respectively. The range of battery size used in the evaluation is from 0 to 10kWh, three sizes 0kWh,4kWh and 10kWh are picked with entire sizes of PV as demonstration shown in figure 4-11.

Results and analysis:

1. It is obvious that in both systems, energy saving is highly affected by the changing of PV size. With PV generator gets larger, electricity that have to be drawn from grid will reduce. PV generator has higher effect on overall energy saving than battery storage because that PV generation can cover load demands and reduce grid supply, however, battery does not generate or dissipate energy except losses.

2. Battery storage has much less influence on total energy saving when compared with the influence of PV generator. With battery capacity increases, in a certain PV generator, the energy saving decreases in both systems. In addition, the decrease rate caused by battery size variation in AC system is higher than that in DC system. The tiny effect on overall energy saving that influenced by battery storage capacity change is mainly because that larger battery has ability to store more energy, that is to say, there are more throughout power of the battery. Therefore, more losses dissipate in the process of battery charge and discharge, which leads to decrease in energy saving.
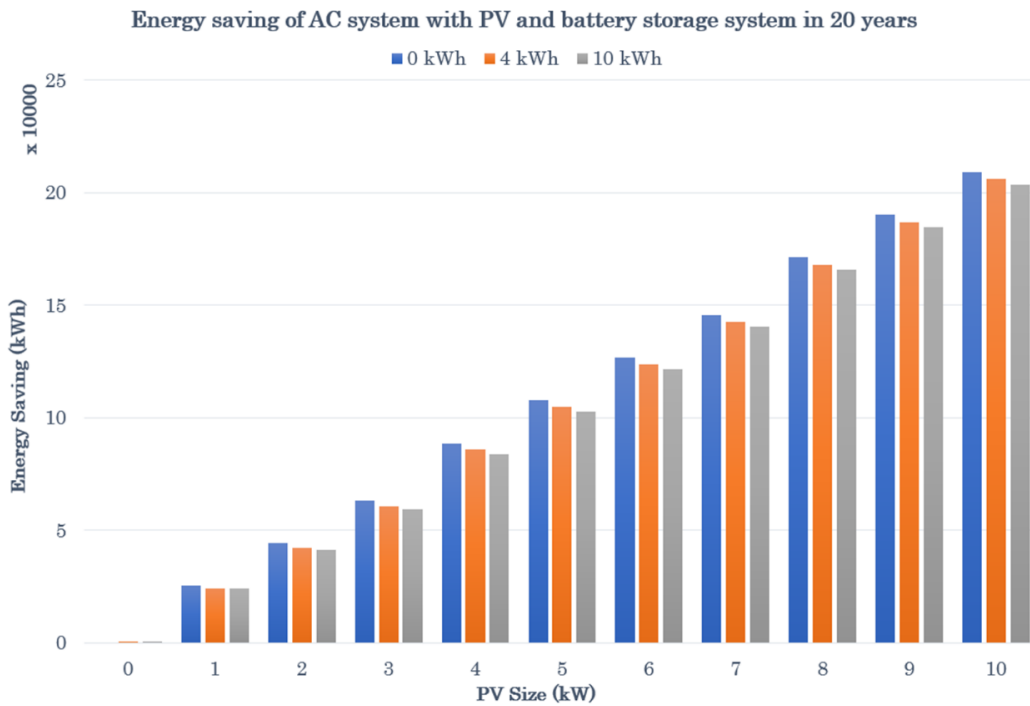
(a)
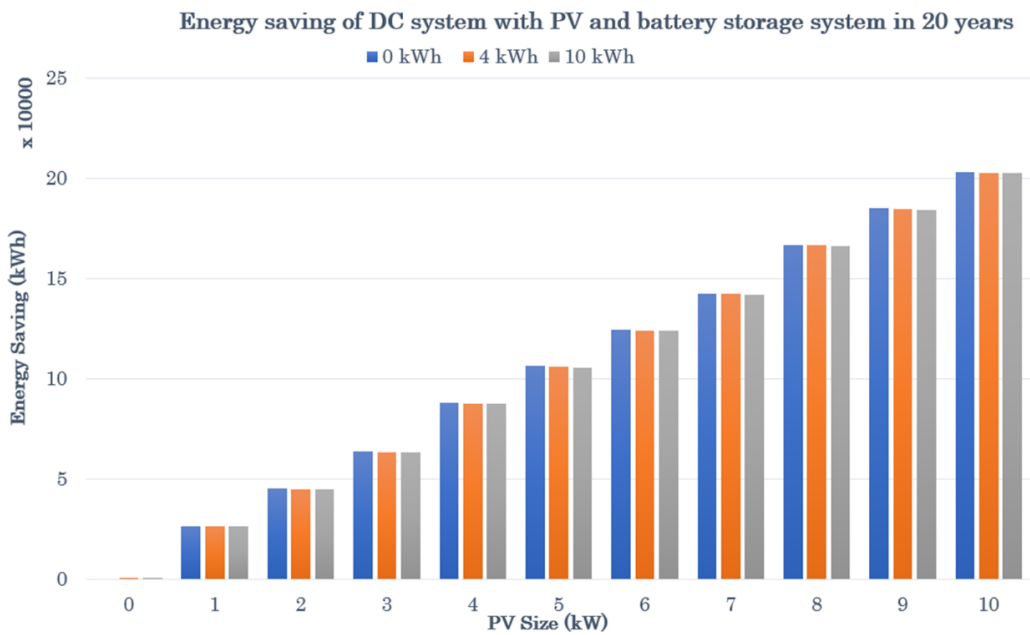
(b)

Figure 4-10: Energy saving of (a)AC and (b)DC residential system with varying PV sizes and three picked battery sizes

3. Since battery has less effect on energy saving than PV generator, when comparing AC and DC residential system, main focus can be put into the influence that caused by
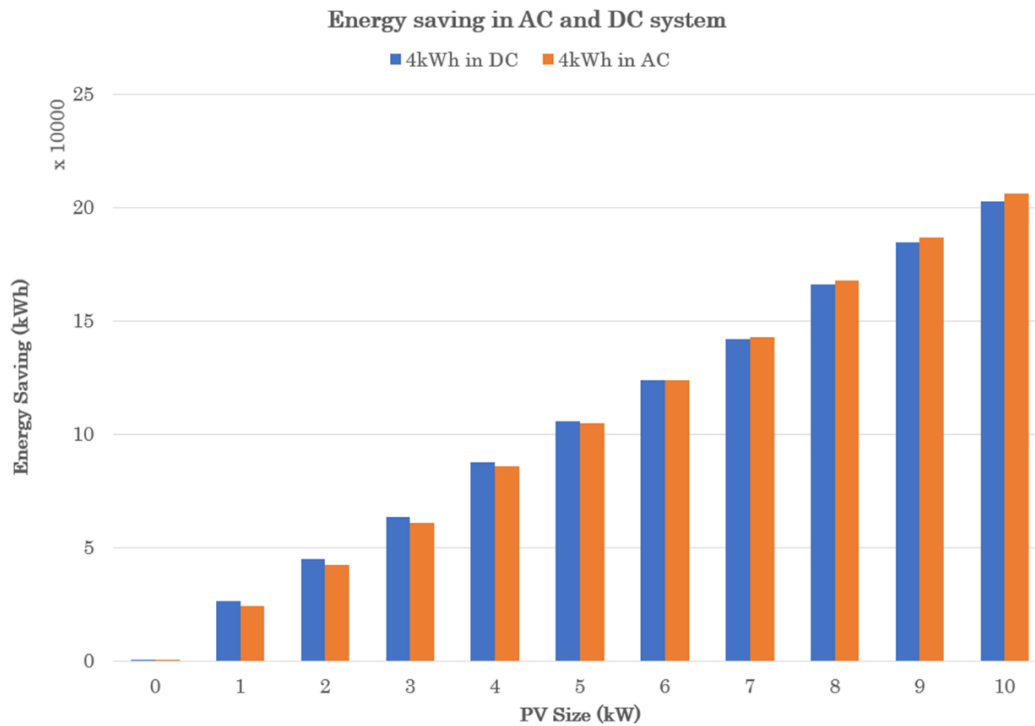
Figure 4-11: Energy saving comparison between AC and DC residential system

PV generation changes. And a certain size of battery is picked for comparison. Figure 4-11 indicates that in lower PV size range, DC residential system performs better in energy saving than that of AC system. As for 1kW PV generator, DC system performs 8.55% higher in energy saving than AC system. For 4kW PV generator, 1.88% higher in energy saving of DC system than that of AC system. The difference between AC and DC system is decreasing. With the PV gets larger, the capability in saving energy of AC system overweight that of DC system. For example, AC system with a 10kW PV generator saves 1.7% higher in energy than DC system. In the situation that lower sizes of PV generator are used, PV generation mainly flows to cover the load demands. In AC system , conversion losses dissipate on PV inverter and load converters. Whereas in DC system, conversion losses are lower than that in AC system due to reduction in conversion stages. Therefore, more energy saving in DC system when compared with AC system. When the implementation of PV generator increases, besides the PV output power that required to supply the load demands, surplus PV generation will feed to grid. Number of conversion stages in the way of feed-in process are the same in AC and DC system. However, the efficiency of grid-connected rectifier in DC system is lower than the PV inverter in AC system, which leads to a reduction in energy saving increasing rate in DC system. When PV generator becomes relatively large, DC system loses its advantage in saving energy.

4-4   System losses in AC and DC residential system

The system losses are calculated based on the losses modelling that introduced in last chapter. Both of the AC and DC system losses are compared under the same situation. In AC system, the PV and battery storage system connect the AC bus via an PV inverter, therefore, all power from PV and battery storage system will go through the inverter, consequently, losses dissipated. In contrast to that in AC, there is no PV inverter in DC system, while a grid tied rectifier is needed in the grid interface. In this situation, only feed-in grid power will go through the rectifier.

The system losses are calculated by different system operation in the period of 20 years for different sizes of PV and battery, which is shown in figure 4-12. When there is no PV and battery in the residential system, the calculated system losses in one year of AC and DC system are listed in table 4-2.

Table 4-2: Energy consumption and system losses with no PV or no battery in a year

	AC residential system	DC residential system
Load comsumption(kWh)	3423.5	3423.5
System losses(kWh)	619	366.3

Results and analysis of AC system:

In AC system, it can be detected from figure 4-12(a) that system losses are increased with the PV and battery size rises. The results can be analyzed in following parts.

1. As for the low sizes of either PV or battery, the losses are increased in a relative low rate. With both of PV and battery storage sizes become larger, the system losses become higher with an increasing rate. When there is low PV generation, the PV energy will be used to supply load demands. Therefore, although the battery storage capacity becomes larger, there is no notable difference in system losses.

2. With the PV size increases, there will be residual energy to charge the battery after supplying loads, and battery will also discharges to load demands, where the system losses will be increased by charging/discharging processes.

3. Furthermore, the trend of energy losses increase caused by PV generation rises is sharper than that of changing battery storage capacity.

Results and analysis of DC system:

In DC system as shown in figure 4-12(b), the trend of system losses caused by PV is much more obvious than that of battery storage.

1. When there is no PV generation, the system losses is always the same in different battery storage capacity. With the generation of PV becomes higher, the system losses will be larger whatever the battery size is. Since with increasing PV size, PV output will not only supply the load demands, but also will charge to battery and sell to grid, which will definitely increase system losses.
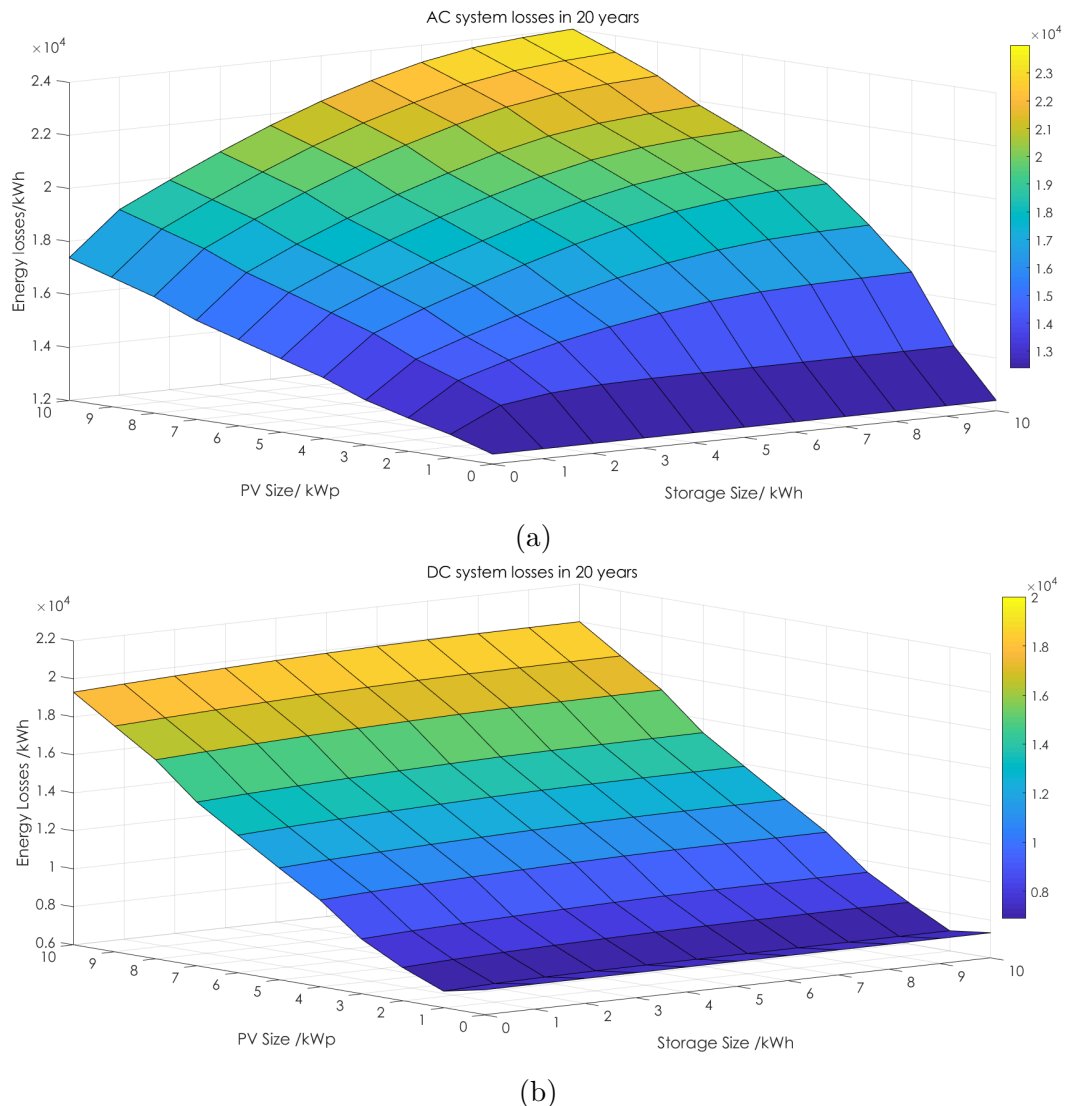
(a)

(b)

Figure 4-12: Total system energy losses in (a)AC system and (b)DC system in 20 years

2. When it comes to the effect of battery storage size, for a certain PV generation over 0, with the battery storage capacity increases, there is tiny growth in system losses with a higher increase rate at first and then become nearly steady. The reason of this losses increase trend is similar to that in AC system.

3. When the battery storage capacity is too large, there will be less, even no feed-in energy to grid, which will decrease the growth rate of system losses on grid tied rectifier, thus, energy losses become almost steady.

Results and analysis in comparison of AC and DC system:

1. When there are no PV and battery storage, DC residential system shows a higher benefit in losses reduction. It is mainly because that in DC system, a modular grid tied rectifier is used. Even in light load condition that lower than 10% power rating, the rectifier

efficiency will not be too low, thus, there are not much losses produced in rectification stage. While in AC system, the rectifier is connected with individual load. When the load operates in lower power rating, the rectifier efficiency could be relatively low, thus, the resulting losses will increase.

2. When comparing energy losses in AC and DC systems, it can be seen that the losses change caused by PV generation is much more obvious in DC system than that in AC system. At the same time, the effect of battery storage on energy losses in DC system is less than that in AC system. When both of PV and battery storage sizes are in low range, the system losses in AC system is almost two times of that in DC system. PV generation can only supply parts of energy demands to loads, most of the energy are drawn from grid. In this situation, to supply the loads, power from PV and grid will go through more conversion stages in AC system than that in DC system, thus, results in more energy losses.

3. When PV gets higher and battery storage stay in low capacity, energy losses in DC system increase more rapid than that in AC system. More PV generation with low storage capacity means more energy feed in to grid. In AC system, there is no additional conversion stage in the route of grid feed-in process, however, as for DC system, there is a grid-connected rectifier.

4-5   Conclusion of the chapter

In this chapter, AC and DC residential system was compared in terms of net energy, energy saving and system losses with the effect of varying PV and battery sizing in 20 years. Conclusion of the energetic evaluation can be drawn as follows.

- Firstly, the simulation of distributed sources, PV generator and battery storage, has shown that the amount of PV generation has an obvious influence on battery degradation and lifetime. With the same battery capacity, a large PV size results in a more battery changing times.

- Then, as for system net energy, which showed highly depends on PV generation rather than battery storage in both AC and DC residential system. It is concluded that DC system drawn less energy from grid due to less conversion stages in grid feed-out process than AC system. In feed-in process, the slight advantage of DC system over AC system mainly as a result of efficiency difference between PV inverter in AC system and grid-connected rectifier in DC system.

- Finally, the overall system losses have been analyzed based on different system operation modes. It has been found that the losses change caused by PV generation is much more obvious in DC system than that in AC system. And the effect of battery storage on energy losses in DC system is less than that in AC system. In low PV generation with small battery, power from PV and grid will go through more conversion stages in AC system than that in DC system, thus, results in more losses. With higher PV generation, more feed-in energy to grid, which results in more rapid increase in DC system losses than AC system due to grid-connected rectifier.

Chapter 5

Economic analysis

The purpose of this chapter is to assess the potential of both AC and DC residential system that use varying sizes of rooftop PV and battery storage to lower electricity bills and benefit from feed-in energy. The required data for economic analysis of the whole system that have been considered in this study contained grid electricity prices and PV and battery storage investment costs. In recent years, it has shown a rapid decrease in the costs of PV panels[44]. At the same time, there is a similar decline in the costs of battery storage as well[45]. These have been a positive motivation for installing the PV and battery storage system in household. By increasing the penetration of PV and battery storage system, consumers will pay less for grid electricity bills, and even may benefit from feed-in electricity energy. In this chapter, the electricity pricing, PV costs and battery storage costs will be given to calculate the payback time and evaluate the cost-benefit of the system with varying PV and battery sizes. This will demonstrate the feasible of the PV-battery storage system in connect with residential home. Comparing of AC and DC system will show how much potential benefit can be obtained from each of the system.

5-1 Electricity price

The electricity price has relatively large effect on obtaining the evaluation results regarding the cost-benefit of AC and DC systems. There are several electricity pricing schemes in market such as time-of -use, real time pricing, fixed pricing and net energy metering[46][47][48].

Table 5-1: Utility grid electricity price[15]

	Normal	Off-peak
Feed-out Tariff(€/kWh)	0.2283	0.2075
Feed-in Tariff(€/kWh)	0.05	0.03

The feed-in tariff will be applied with a time-of -use pricing in this study, which are listed in table 5-1[15]. The time periods will be divided into two parts, the normal period is from 7am to 23pm of a day, and the off peak period is from 23pm to next day 7am of a day. The feed-in tariff here does not includes the tax. The electricity price in the evaluation is assumed to be constant in the period of 20 years. According to the statistics[49][50], the electricity prices for household consumers were almost stable in recent years. And [51] has shown an small fluctuation in retail electricity price for residential.

5-2   Investment costs of PV and battery storage

In the past, the most significant economic barrier for installing PV and battery storage system of household is their high investment costs. With the falling of costs of both PV and battery storage system, and sustained increasing retail price of electricity, the PV and battery storage system that can be used in household becomes more attractive since the electricity bills can be reduced.

5-2-1   PV investment costs

In residential rooftop PV system, the capital costs generally takes a high portion in its whole lifetime costs, and the operating and maintenance costs takes only around 1%/year of installation costs[33]. The maintenance costs of PV system will not be taken into account in the study. As for the investment costs of rooftop residential PV system, an average investment costs will be used according to the report "Nationaal solar trendapport 2018", which is 1.33€/Wp [52]. The investment costs of PV system include the price of modules, installation, and conversion components.

5-2-2   Battery storage investment costs

The considered battery storage system is Li-ion battery system. The battery price showed a considerable decline these decades, and previous literature also showed a prediction for future reduction of battery storage price from between170€/kWh and 1071€/kWh in 2016 to between 65€/kWh and 488€/kWh by2030 [36]. In this study, the battery storage price of 200€/kWh will be used[53].

5-3   Economic analysis model

In order to compare the AC and DC system in the aspect of economic and highlight the attractiveness of using residential PV and battery storage system, an economic evaluation will be presented to show the potential benefit. In the following analysis, the analysis of AC and DC system will be discussed with varying sizes of PV and battery.

In residential sector, installation of the residential PV and battery storage system has potential to lead to less grid electricity bill. However, investment costs of PV and battery storage system

maybe too high to covered by the saving bills from grid. Therefore, in this study, a cost and benefit analysis will be performed as the net expenditure to evaluate the system.

The costs associated in this study is the electricity feed-out costs and investment costs of PV and battery storage. It should be noted that the investment costs of battery storage is not restricted to the battery investment cost at beginning, but all the expenditures due to battery replacement over system operating periods should be considered. The benefits of the system mainly come from the feed-in tariff that export from PV system. Therefore, the system net expenditure that contains the electricity bills and investment costs of PV modules and battery storage can be expressed as equation 5-1

$$C_{Net} = C_{Bills} + C_{PV} + C_{Battery} \tag{5-1}$$

where, C_{Net} represents the net expenditure of the system, C_{bills} is the electricity bills, C_{PV} is the capital costs of PV system, and $C_{Battery}$ is the investment costs of battery storage system.

The electricity bill C_{Bills} is defined as the difference between the costs that pay for electricity drawn from grid and the benefits obtained from feed-in energy, which can be presented as equation 5-2

$$C_{Bills} = C_{Feedout} - B_{Feedin} \tag{5-2}$$

In the equation 5-2, the feed-out costs is calculated by

$$C_{Feedout} = E_{nor} \cdot C_{nor} + E_{off-peak} \cdot C_{off-peak} \tag{5-3}$$

where E_{nor}, $E_{off-peak}$ are electricity energy drawn from grid in normal time period and off-peak time period, respectively. And C_{nor}, $C_{off-peak}$ are feed-out tariff in normal time period and off-peak time period, respectively.

Further, the feed-in benefits can be expressed as

$$B_{Feedin} = E_{in-nor} \cdot C_{in-nor} + E_{in-offpeak} \cdot C_{in-offpeak} \tag{5-4}$$

where E_{in-nor}, $E_{in-offpeak}$ represent the electricity energy feed in to the grid in the period of normal time and off-peak time, respectively. And C_{in-nor}, $C_{in-offpeak}$ represent the feed-in tariff in the period of normal time and off-peak time, respectively.

As for PV costs, the parameter C_{PV} in equation 5-1 represents the investment costs of installation PV modules, which can be calculated by equation

$$C_{PV} = C_{module} \cdot N_{modules} \tag{5-5}$$

where C_{module} is the unit price of PV modules in W_p, $N_{modules}$ is the number of PV modules.

And, the parameter $C_{Battery}$ represents the investment costs of battery storage, which can be obtained by the all the battery storage investment costs, which can be expressed as

$$C_{Battery} = C_{perbattery} \cdot N_{change} \tag{5-6}$$

where $C_{perbattery}$ is the investment costs per battery, N_{change} represents the battery replacement times due to battery degradation.

5-4   Economic evaluation in AC and DC residential system

Based on the economic model that introduced in last section, both AC and DC system net expenditure with varying sizes of PV and battery are shown in figure 5-1 and figure 5-2, respectively.
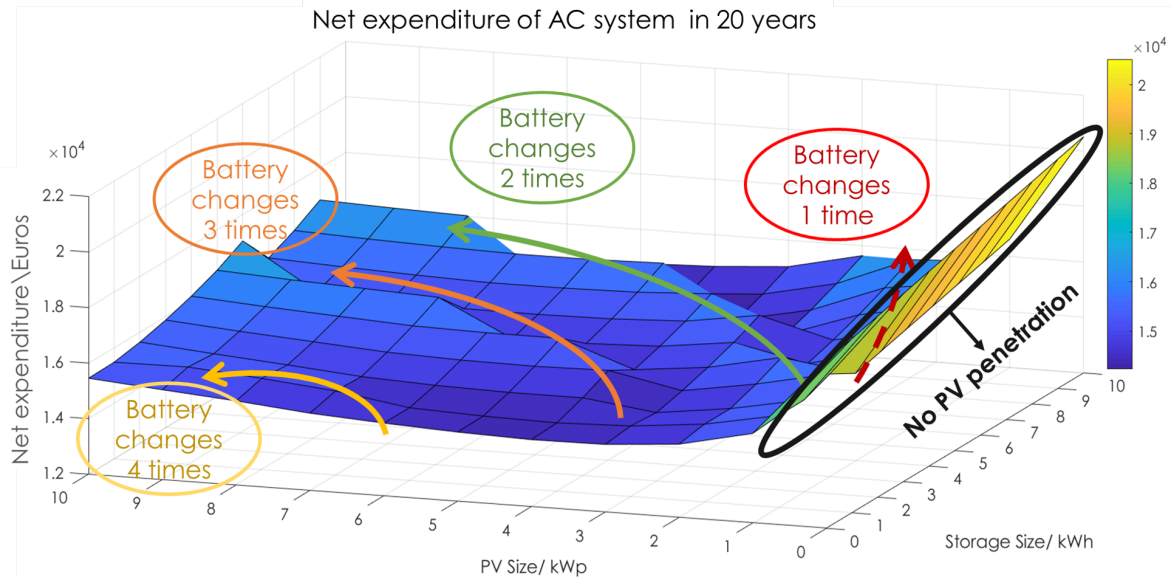

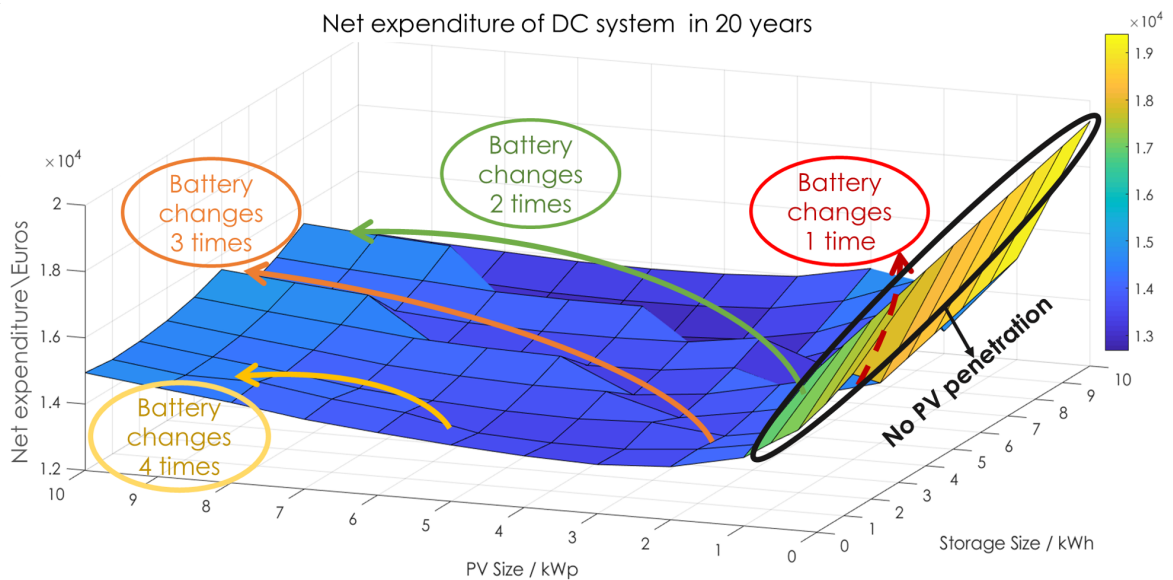**Figure 5-1:** Net expenditure of AC system in 20 years with varying PV and battery storage sizes

Figure 5-2: Net expenditure of DC system in 20 years with varying PV and battery storage sizes

Results and analysis:

1. It can be seen from the above figures that with the penetration of PV and battery

storage system, consumers pay less when compared to the electricity bills with no PV and battery storage system. The colored lines with arrow in the two figures represent the different times of battery replacement. Along with the direction of the arrow of each line, there are same battery changing times occur. It indicates that with the size of PV increases, there are more replacement of battery because of deep discharge.
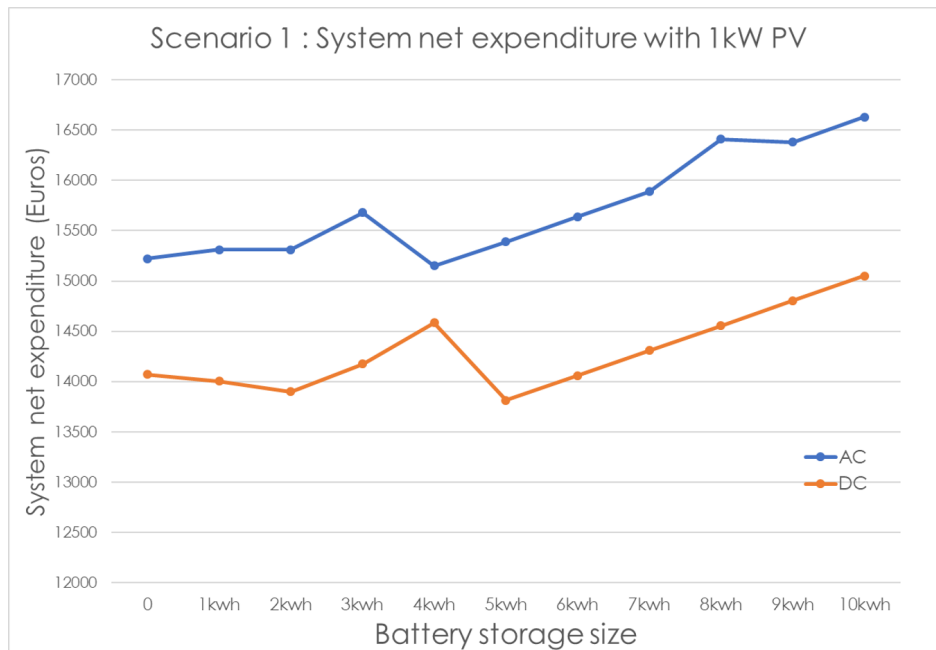

Figure 5-3: AC and DC system net expenditure in 20 years with 1kW PV and varying sizes of battery storage
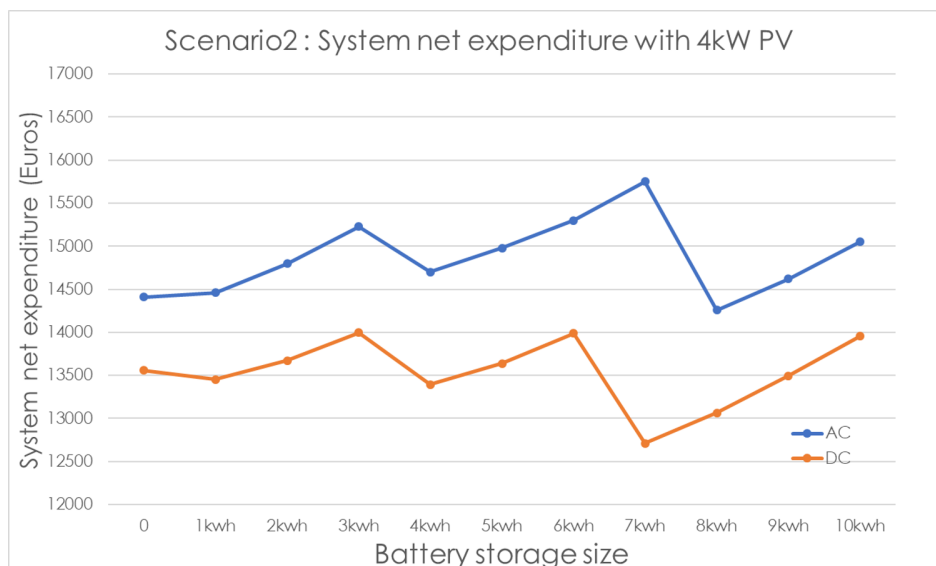

Figure 5-4: AC and DC system net expenditure in 20 years with 4kW PV and varying sizes of battery storage
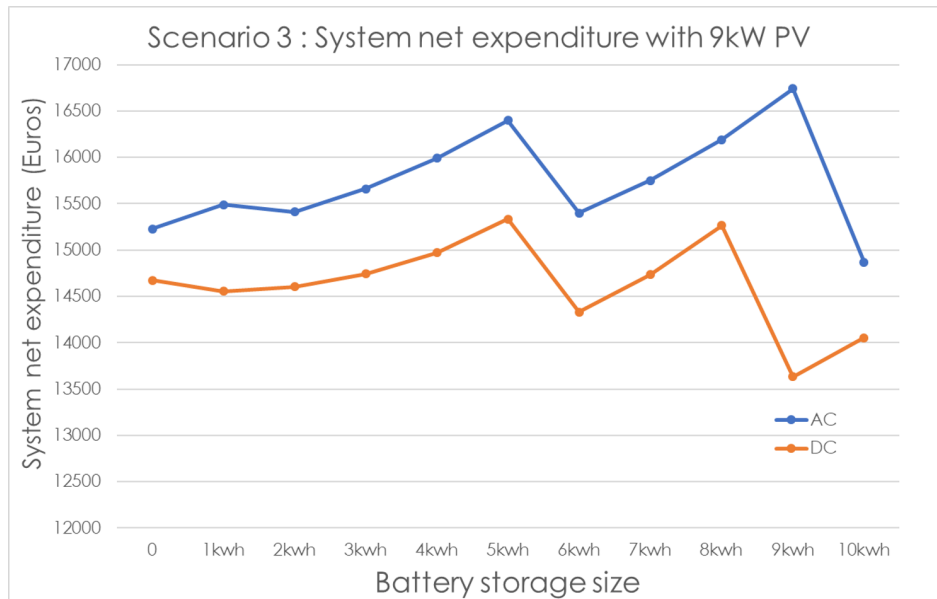
Figure 5-5: AC and DC system net expenditure in 20 years with 9kW PV and varying sizes of battery storage

2. In order to make it easier to analyze the costs difference between AC and DC system, three sizes of PV are chosen as examples to present the differences, as shown in figure 5-3,5-4 and 5-5. It can be seen from the figures that with the same PV and battery size, the total net expenditure of DC system always advantageous over that of AC system. However, it is obvious to find that the net costs are higher in both AC and DC system with relatively small size(1kW) and relatively large size(9kW) of PV. While the system with 4kW PV, whose generation is proper to cover the load demands, has a relatively lower costs than the others.

3. Since if small size of PV is installed, although there are lower investment costs of PV generator, most of load demands have to be drawn from the grid, which results in high electricity bills. As for large size of PV, for example 9kW PV generator in scenario 3, it leads to more energy from PV generator export to grid, thus, more profit can be obtained by feed-in tariff. However, large size of PV also results in higher installation costs than that of smaller size of PV. Due to relatively low feed-in tariff, it is not easy to compensate the high installation costs of PV by feed-in benefits. Furthermore, there will be more replacement for the battery with relatively low capacity, which leads to a higher investment costs.

5-5 Payback period

The payback time can be defined as the time period that required to recover the costs of investment according to [37], and it can be expressed as

$$PaybackPeriod = \frac{InvestmentCost}{AnnualBenefit} \tag{5-7}$$

The annual benefit can be presented by how much PV generates to cover the demands in addition to the benefits that obtained from the PV generation export to the grid. The payback period of different scenarios discussed in last section are shown in figure 5-6,5-7 and 5-8 to present how the size of PV and battery affect the payback period, and the difference of payback period between AC and DC system. The trends of payback period are related to the total system costs.
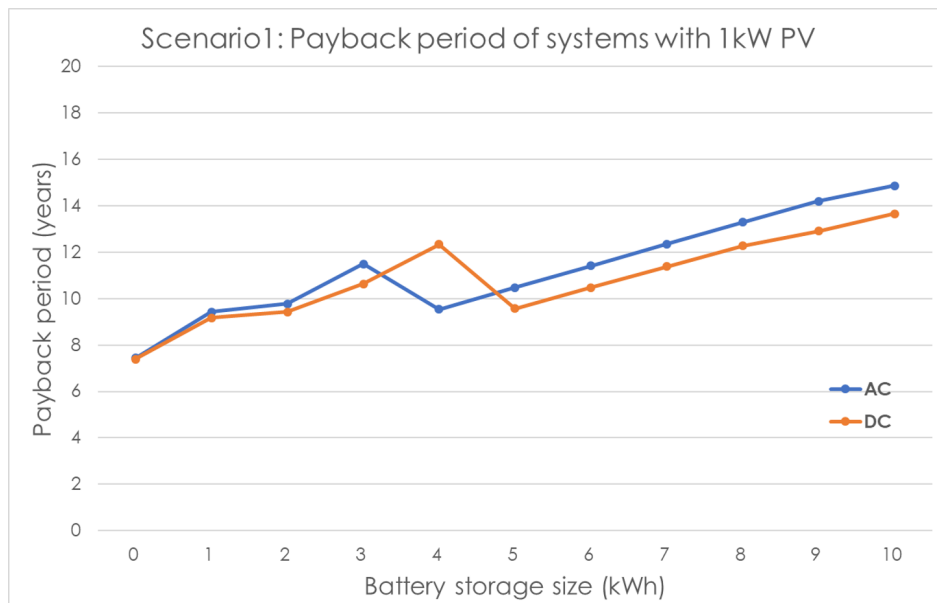

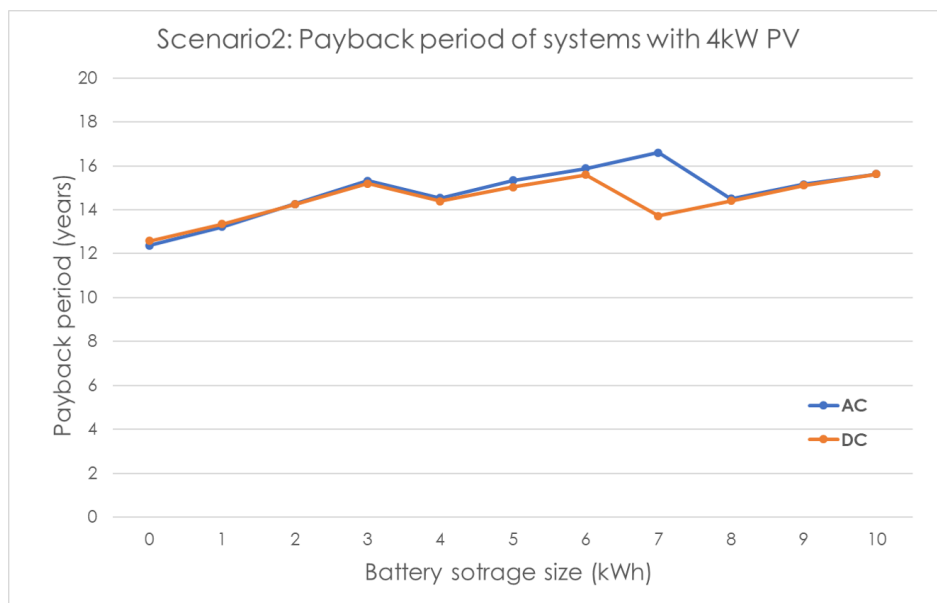**Figure 5-6:** Payback period of AC and DC system with 1kW PV and varying sizes of battery storage

Figure 5-7: Payback period of AC and DC system with 4kW PV and varying sizes of battery storage
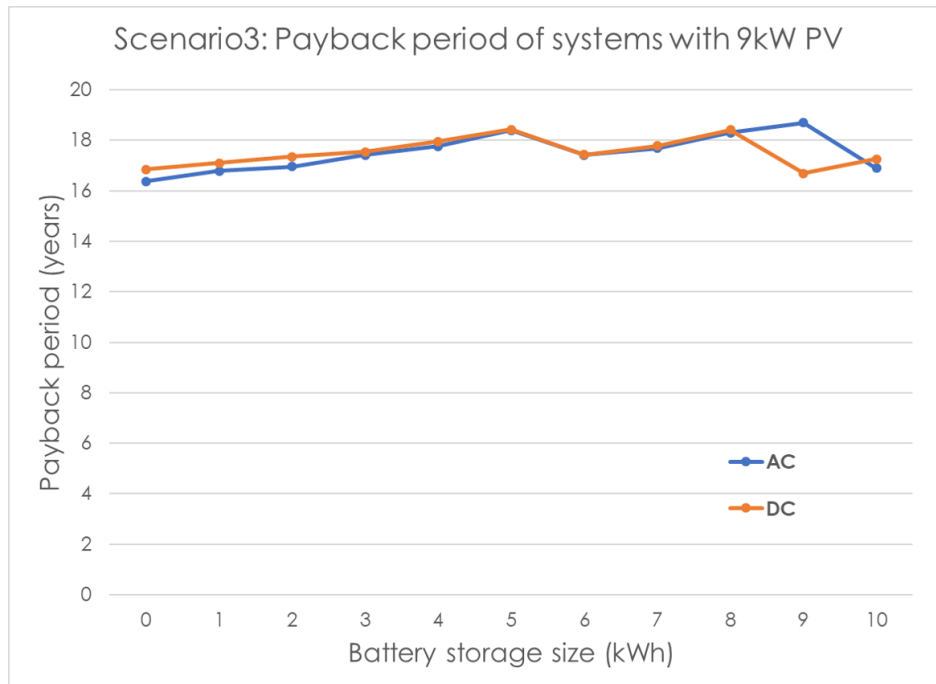
Figure 5-8: Payback period of AC and DC system with 9kW PV and varying sizes of battery storage

It can be detected from the figures above that the DC system tends to have shorter payback time on average when compared to AC system, especially in relatively small and medium size of PV generator as shown in figure 5-6and 5-7. In the point of 1kW PV with 4kWh battery, where AC system shows shorter payback years mainly due to the difference of battery changing times with DC system. However, in scenario 3 with 9kW PV, DC system does not perform a superiority over AC system, which is considered as the results of similar tradeoff between system capital costs and system benefits in both of AC and DC system.

5-6   Conclusion of the chapter

The economic analysis of AC and DC system with varying PV and battery storage size were evaluated by calculating the total costs that consumers have to pay during 20 years. From the analysis, it can be concluded as follows.

- The net expenditure of DC system is lower than that of AC system with varying size of PV and battery system.

- A proper size of PV is important for minimizing the system total expenditure since the feed-in tariff is relatively lower than investment costs of PV-battery system. If a larger size of PV was used, the profit from feed-in tariff would be lower when compared with the investment costs. In addition, the total costs with feed-in benefits of both systems are significantly affected by the replacement of battery.

- Finally, AC and DC residential system were compared in terms of feedback period of different sizes of PV and battery storage. Larger size of PV-battery system has a longer payback period in both residential systems. Meanwhile, with different size of PV, DC residential system has a relatively shorter payback years than that of AC system, especially with small and medium PV sizes. When it comes to large size of PV, DC system does not have apparent advantage over AC system. It is considered as the result of similar tradeoff between system capital costs and system benefits in both systems.

Chapter 6

Conclusion and future work

In this thesis, the AC and DC residential system with varying size of PV generator and battery storage were compared in terms of energetic and economic aspect. Both of AC and DC system were comprised with three parts, PV-battery storage system, household loads, and grid utility.

6-1 Conclusion of thesis

The conclusion of the thesis will be drawn in terms of three parts, modelling part, energetic evaluation part and economic evaluation part as follows.

Modelling part: In the modelling part, based on the overview of AC and DC residential system, it was divided into four components for system modelling, which are loads, power converters, PV generator and battery storage. The load profile was the real world measurement data obtained online to make the study more comprehensive. And the power electronic converters were performed by converter efficiency curves with power rating of their converter-connected source/demand. Then, as for the PV and battery system, the local solar irradiance was regarded as the input to calculate the PV output power, and one panel with one dc/dc converter topology was used due to easily replacement. When designing the battery storage, the one day based SOC was used with the DOD related life cycles to estimate the capacity degradation of the battery. In addition, by implementing power management strategy, the system losses based on different operation of system were figured out.

Energetic evaluation: In the results of energetic evaluation part, the simulation of PV generator and battery storage shown that the amount of PV generation has an obvious influence on battery degradation and lifetime. Then, the evaluation showed that system net energy is highly depends on PV generation rather than battery storage in both systems. It is concluded that DC system drawn less energy from grid due to less conversion stages in grid feed-out process than AC system. Furthermore, the energy saving in both systems is mainly dominant by PV generator. In lower range of PV size, DC system showed its advantage in saving energy, while when PV generation is relatively larger than load demands, AC system

saves more energy. Finally, the overall system losses have been analyzed based on different system operation modes. The losses change caused by PV generation is much more obvious in DC system than that in AC system, the effect of battery storage on energy losses in DC system is less than that in AC system. In low PV generation with small battery, power from PV and grid will go through more conversion stages in AC system than that in DC system, thus, results in more losses. With higher PV generation, more feed-in energy to grid, which results in more rapid increase in DC system losses than AC system due to grid-connected rectifier.

Economic evaluation: The economic analysis was carried out in order to perform a more intuitive variation in and between two residential systems. It was carried out by calculating the total costs that consumers have to pay in the period of 20 years, which contains electricity bills, feed-in tariff, and investment costs of PV-battery system. From the analysis, it can be concluded that the total costs of the DC system is lower than that of AC system with varying size of PV and battery system. Furthermore, a proper size of PV is important for minimizing the system costs since the feed-in tariff is relatively lower than investment costs of PV-battery system. If a larger size of PV was used, the profit from feed-in tariff would be lower when compared with the investment costs. In addition, the total costs with feed-in benefits of both systems are significantly affected by the replacement of battery. Finally, AC and DC residential system are compared in terms of feedback period of different size of PV and battery storage. Larger size of PV-battery system has a longer payback period in both residential systems. Meanwhile, with different size of PV, DC residential system has a relatively shorter payback period than that of AC system, especially with small and medium PV sizes.

6-2   Future work

Some future works can be considered with recommendation in the following.

1. In this study, the effects of temperature are not considered. Therefore, the temperature effect can be taken into consideration in the parts for example PV cells, batteries and converters.

2. Sensitive analysis can be taken into consideration in the future work.

3. In the economic analysis part, the price uncertainty of battery and electricity are not considered. In the future work, a reduction in battery price and increase in electricity tariff can be taken in to consideration.

Appendix A

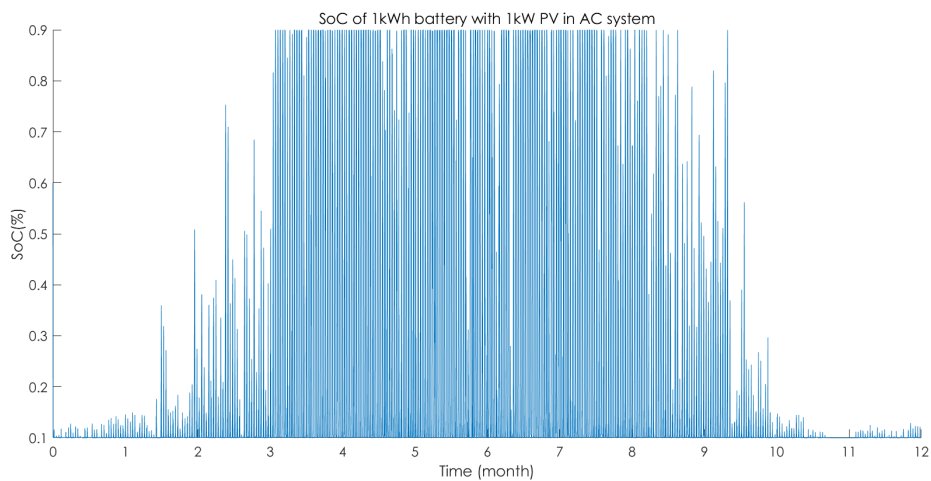# Battery SoC with different sizes of PV and battery storage

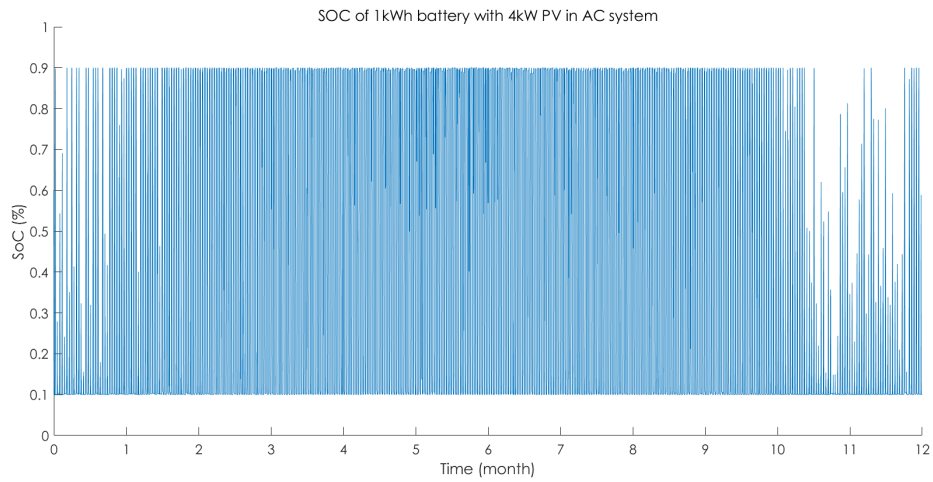**Figure A-1:** 1kWh battery with 1kW PV
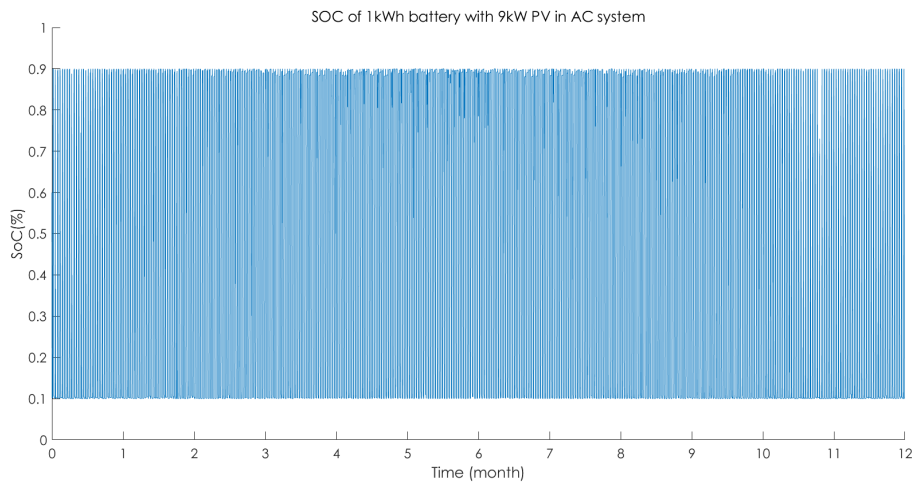
SOC of 1kWh battery with 4kW PV in AC system

Figure A-2: 1kWh battery with 4kW PV

SOC of 1kWh battery with 9kW PV in AC system

Figure A-3: 1kWh battery with 9kW PV

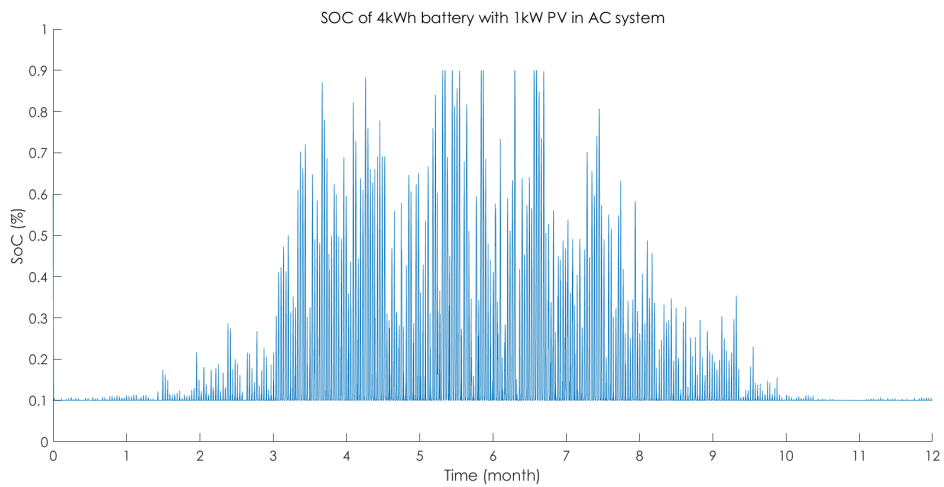SOC of 4kWh battery with 1kW PV in AC system

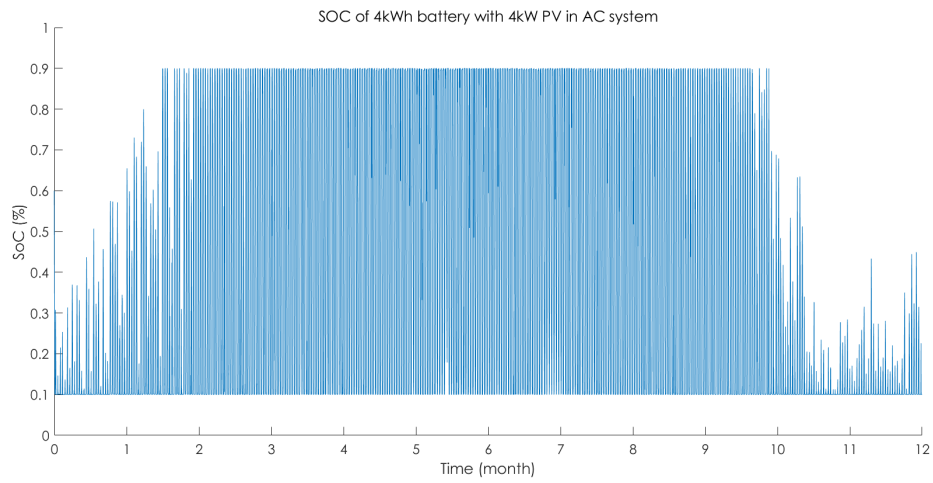**Figure A-4:** 4kWh battery with 1kW PV

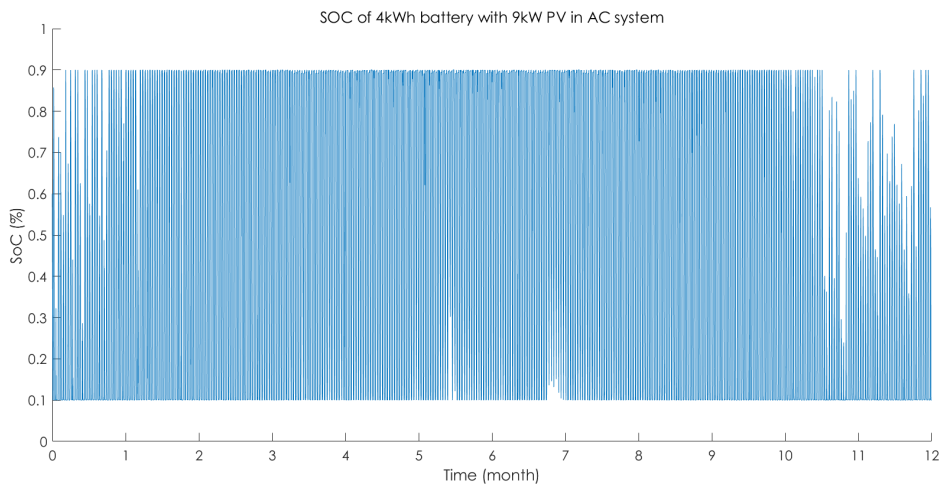**Figure A-5:** 4kWh battery with 4kW PV

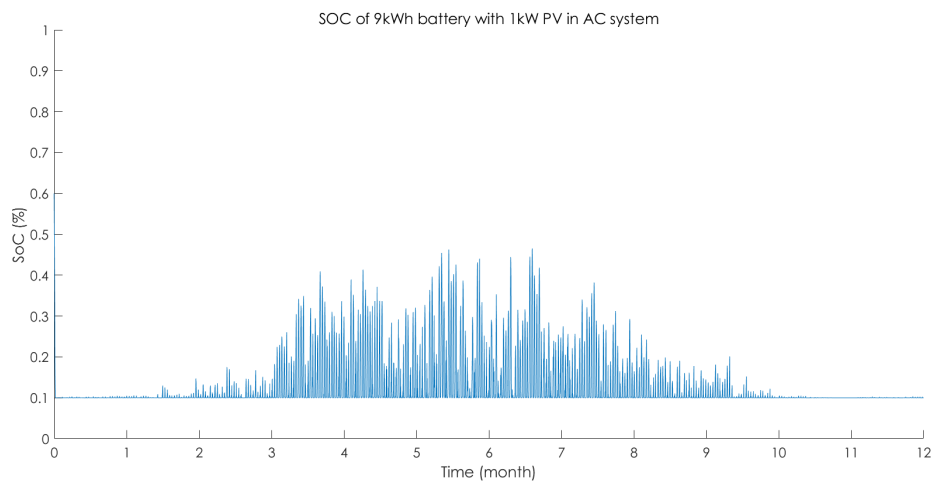**Figure A-6:** 1kWh battery with 9kW PV

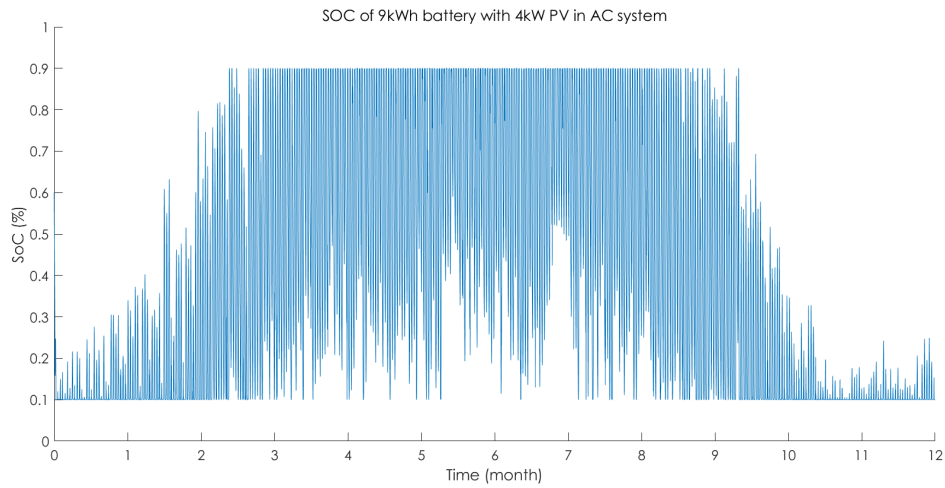
Figure A-7: 9kWh battery with 1kW PV

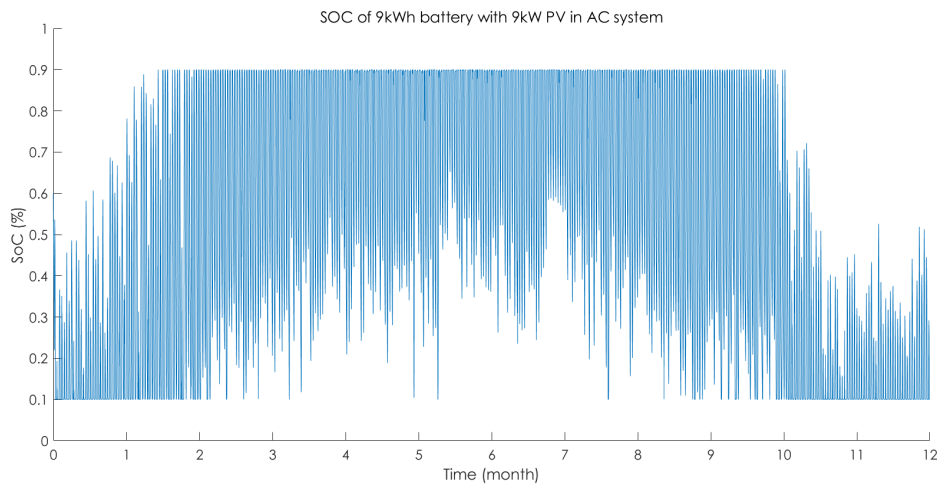**Figure A-8:** 9kWh battery with 4kW PV

Figure A-9: 9kWh battery with 9kW PV

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