THE ROLE OF GRID-SIZE ENERGY STORAGE IN ENABLING A COMMUNITY-LEVEL ENERGY HUB

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THE ROLE OF GRID-SIZE ENERGY STORAGE IN ENABLING A COMMUNITY-LEVEL ENERGY HUB

CASE STUDY IN ZUID-OOST AMSTERDAM REGION

BY XIANG GAO

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ABSTRACT

To follow the rapid advance of the Energy Transition, the technology and application of the renewable energy resources and energy storage devices have been developed in an unstoppable speed. When the application of energy storage technology starts to prosper gradually over the world, there are some problems showing up while lots of advantages are being advocated. There are plenty of batteries staying unused or being wasted for over half of the lifetime of the system, especially for the behind-the-meter energy storage system. The business models are usually built just for one or two primary services for customers and grid that makes only a limited part of time occupied, leaving the essential untapped values aside. And also, it is common that the energy storage system is coupled with PV panels or wind turbines. In this case, how to increase the on-site solar energy self-consumption becomes an attractive issue considering the sizeable financial benefit it can bring. What is more, when putting the attention on the neighbourhood or community level where there is more than one participator in this picture, how to create the extra value or bonus benefit using the existed system and equipment can be an interesting topic. This report will focus on the grid-size battery installed behind the meter within a commercial community. A methodology of the energy hub with two different lays providing all kinds of services will be proposed. As the result, the value of grid-size energy storage in enabling a community-level energy hub for both battery-owner and neighbours will be explored to cope with all the above problems. There will be a case study conducted in the selected Zuid-Oost Amsterdam region. In the end, how much benefit the energy hub can create for not only the battery-owner but also for the whole community and society will be discussed.

TABLE OF CONTENTS

CHAPTER 1.

INTRODUCTION

1.1 RESEARCH MOTIVATION

To cope with the severity of climate change and the rapid process of the Energy Transition, governments, companies, and individual consumers have been working on finding efficient and economical solutions. The whole Energy Transition addresses the issue concerning the transformation from the current traditional energy system based on fossil fuels to the new one based on sustainable energy resources.

The major challenge of the Energy Transition is about carrying out every step of the transition using the lowest cost with no compromise of the reliability of the whole system [2]. At present, the primary challenge is the intermittence of both renewable energy sources since the most significant and common sustainable energy sources are wind and solar energy. To deal with this intermittency issue, applying multiple types of energy storage seems to be a preferred solution which is reflected by the statistic data and forecasts of many studies and organizations. According to the newest report from one leading research group of BNEF (BloombergNEF), the application of energy storage technology starts to prosper gradually over the world due to the falling cost of all kinds of batteries from the present to the foreseeable future [1]. The whole market of the energy storage system could build up to an aggregated 942GW/2,857GWh over the coming decades while bringing nearly $620 billion investment from now to around 2040 according to [1], also shown in Figure 1. It means the solar and wind energy will be constantly available at all the time in the future when they are needed even during nighttime and a no-wind day.

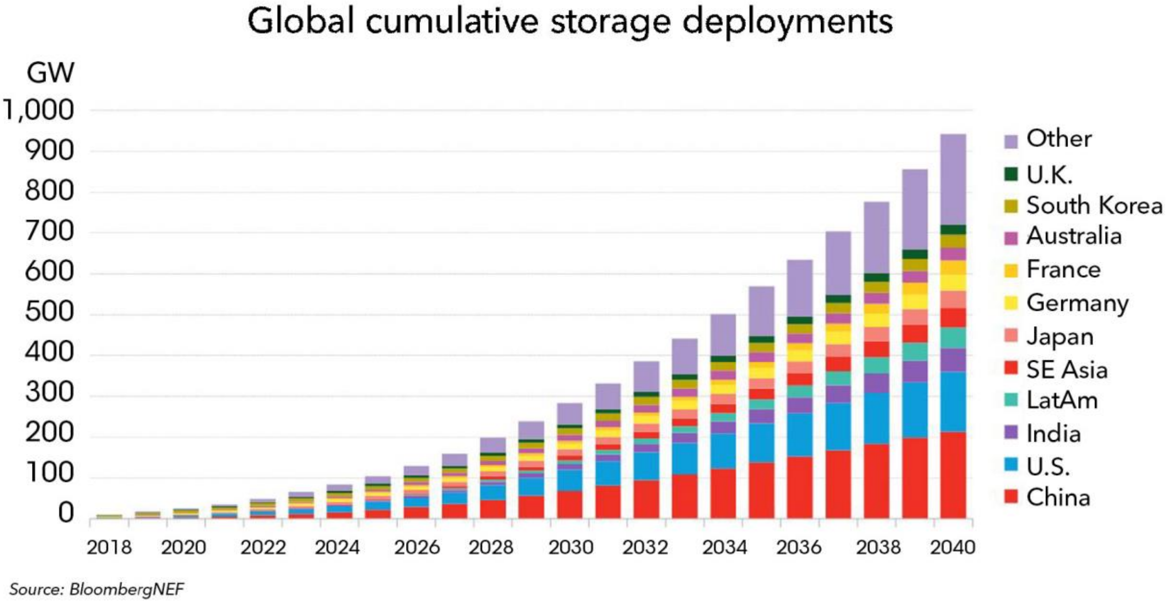


Figure 1 Global cumulative storage deployments

With the unstoppable growth of the energy storage application, there are still some problems following while lots of advantages are being advocated. First, there are plenty of batteries staying unused or being wastes for over half of the lifetime of the system, especially for the behind-the-meter energy storage system. The business models are usually built just for one or two primary services for customers and grid that makes only a limited part of time occupied, leaving the essential untapped values aside [3]. According to [3], for instance, demand charge reduction service only needs a 5-40% usage rate while distribution deferral usually only asks for 1% of the useful lifetime of the storage system. Second, it is common that the energy storage system is coupled with PV panels or wind turbines. In this case, how to increase the on-site solar energy self-consumption becomes an attractive issue considering the sizeable financial benefit it can bring. Increasing self-consumption not only can help consumers manage the electricity bill, but it can also push the local market transformation forward [5]. Third, when putting the attention on the neighbourhood or community level where there is more than one participator in this picture, how to create the extra value or bonus benefit using the existed system and equipment can be an interesting topic. For example, in one district, user A has several PV panels and a storage system, while user B has only PV panels, and user C has two electric vehicles. If they only use their equipment separately, the overall value is limited. However, when a smart energy hub is created, making all roles in the community involved with an appropriate cooperative mechanism, the overall value will be more considerable, and the bonus benefit can be easily gained. Besides, the energy hub can also help it when massive pressure still exists on the grid during peak hours each day.

To take all the above problems into further considerations, exploring the value of grid-size energy storage in enabling a community-level energy hub for both battery-owner and neighbours is necessary and urgent.

1.2 RESEARCH GOALS AND BOUNDARY

The goal of this research is to analyze different viability concepts of the energy hub that revolves around the grid-size battery storage. It will be achieved step by step through several sub-objectives:

- Defining the proposed energy hub methodology.
- Modelling the grid connection of the community with the power demand and supply data in the case study.
- Building five different service cases of the energy hub.
- Integrating five service cases to build a complete energy hub structure.

The boundary of this research report is to treat the electric vehicle (EV) as an average load, which only consumes energy without injecting energy to the grid. Thus, there is no specific consideration of the EV charging in the following report. Moreover, all the assumptions that have been made will be clarified.

1.3 THESIS OUTLINE

CHAPTER 2. BATTERY DEPLOYMENT AND ENERGY UTILIZATION

In this chapter, the popular energy storage technologies and the components of the energy storage system will be introduced. Also, the essential services provided by the batteries will be discussed. At the last of the chapter, the new development regarding energy utilization and energy markets will be indicated, which are the Microgrids and P2P trading Platform.

CHAPTER 3. ENERGY HUB METHODOLOGY

A methodology of the energy hub proposed by this thesis will be defined in details in this chapter. Then, the explanations of every service and a frame structure of the energy hub can be found in this part as well.

CHAPTER 4. A CASE STUDY IN ZUID-OOST AMSTERDAM REGION

Zuid-Oost Amsterdam region is selected as the example community for the further study of the energy hub methodology. The reasons will be explained in this chapter with a description of the grid connection and general situation in this area. And also, the peak moment scenario will be shown to make the energy hub functions more clear.

CHAPTER 5. THE RESULTS OF CASE STUDY

This chapter will introduce four customized service cases for the selected region at first. Then, the integrated energy hub will be built, combining all different service cases with all requirements considered. Finally, how the energy hub can benefit the community will be clarified.

CHAPTER 6. CONCLUSIONS AND FUTURE WORK

This chapter will present the conclusion of the research. Then, the recommendations for future work could be found as followed.

1.4 RESEARCH CONTRIBUTIONS

- This research has developed an integrated energy hub methodology, which consists of two services layers. There are four services on the primary layer, which serves mainly for the battery-owner. Meanwhile, there are five services on the secondary layer serving the whole energy hub. The goal is to minimize the export of the sustainable energy generated internally and maximize the benefit of the energy hub. Moreover, it will contribute to the process of Energy Transition by reducing the carbon emission and motivating the growth of renewable energy usage.
- This research has implemented a case study to realize the methodology into the practice. The case study was carried out in the community located in Zuid-Oost Amsterdam region. The final integrated energy hub model in this community gave the results presenting as the tangible profit to the energy hub members and intangible benefit to the society.

CHAPTER 2.

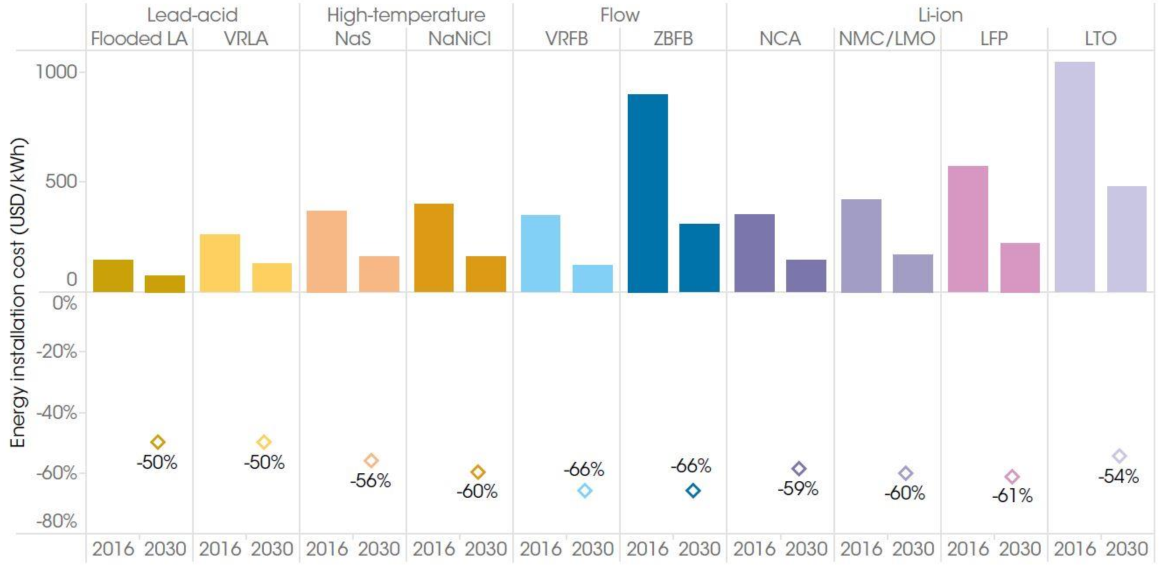
BATTERY DEPLOYMENT AND ENERGY UTILIZATION

In this chapter, the popular energy storage technologies and the components of the energy storage system will be introduced. Also, the essential services provided by the batteries will be discussed. At the last of the chapter, the new development regarding energy utilization and energy markets will be indicated, which are the Microgrids and P2P trading Platform.

2.1 STORAGE TECHNOLOGIES OVERVIEW

Electrical energy storage (EES) is the technology that can store the electrical energy directly from the power grid or generated from renewable energy resources into a specific form that can be converted back to electricity at any time needed [7]. Two essential features of electricity start the rapid development and large numbers of applications of electrical energy storage technologies [6]. The first characteristic is that electricity must be consumed at the same time when it is generated. Thus enough energy should be supplied in time to meet the fluctuating demand; otherwise, it will cause instability and damage the quality of the power grid. Secondly, the location of the traditional power generation plants (using fossil fuels) is far away from the place where consumes mostly the amount of energy [6]. They are connected through transmission lines and cables, sometimes also through the distribution system, which makes up to the whole power system. It highly increases the possibility of any kinds of failure and the congestion on the power grid. With the beginning of the applications of electrical energy storage, renewable energy technologies became popular and widely-used nowadays, which resulted in the further growth of the electricity storage technologies deployment.

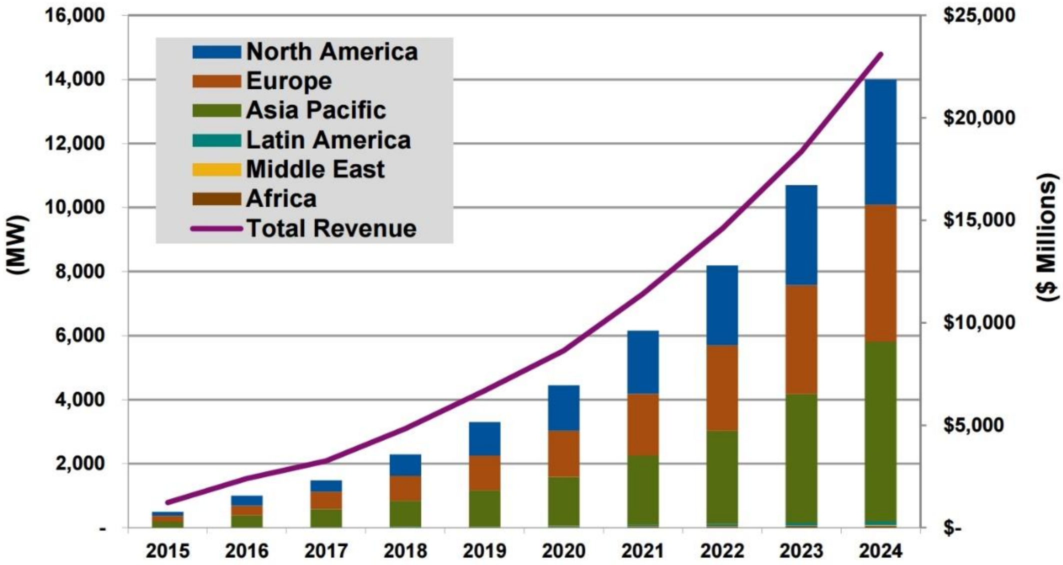
Meanwhile, the cost of electricity storage technologies decreases year by year.



Note: LA = lead-acid; VRLA = valve-regulated lead-acid; NaS = sodium sulphur; NaNiCl = sodium nickel chloride; VRFB = vanadium redox flow battery; ZBFB = zinc bromine flow battery; NCA = nickel cobalt aluminium; NMC/LMO = nickel manganese cobalt oxide/lithium manganese oxide; LFP = lithium iron phosphate; LTO = lithium titanate.

Figure 2 Battery electricity storage system installed energy cost reduction potential, 2016-2030 [8]

According to Figure 2 from [8], there is a noticeable reduction in the installation cost of each popular battery from 2016 to 2030. Using Li-ion battery as an example, the overall cost of the stationary installation of a Li-ion battery may fall by approximately 58% by 2030 [8]. Also, NaS and NaNiCl known as High-temperature sodium sulphur and sodium nickel chloride batteries could be more affordable in 2030, considering 60% drop in the installation cost [8]. Other types of energy storage technologies show a significant decline in the cost of applications as well. Given this sharp and rapid decrease in the cost of investment in the coming years, governments and companies globally speed up the development of the applications of energy storage technologies and services provided by them.



(Source: Navigant Research)

Figure 3. Revenue from the global market for energy storage reaching $23.1 billion in 2024. [9]

As it presents in Figure 3, Asia Pacific, U.S. and the whole Europe will represent most of the energy storage applications of the entire world by in 2024. And the total revenue increases in a fast speed year by year. When it comes to the applications of electrical energy storage technologies, there exists a wide range of popular battery types. According to the different forms of energy used, the electrical energy system can be classified into several categories, which are electrochemical, chemical, electrical, thermal, and mechanical. The most popular kinds of mechanical energy storage technology can be pumped hydro storage (PHS), flywheel energy storage (FES), and compressed air energy (CAES) [6]. One of the most common battery types is Li-ion battery, which is included in Secondary batteries in electrochemical category, while there also are flow batteries, NaS, Lead acid, and NiCd batteries in this category. In Figure 4, a brief categorization is shown, which covers almost all kinds of leading market battery technologies.

With numerous types of battery applications, it is crucial to define the key parameters to evaluate or describe every characteristic of each kind for making a better selection while needed. One way to evaluate battery technologies is to consider the nominal discharge time at rated power, which can cover a wide range from seconds to months. The three major levels are Short Discharge Time (seconds to minutes), Medium Discharge Time (minutes to hours), and Long Discharge Time (Days to months). With this levelling standard, plenty of applications and services can be developed.

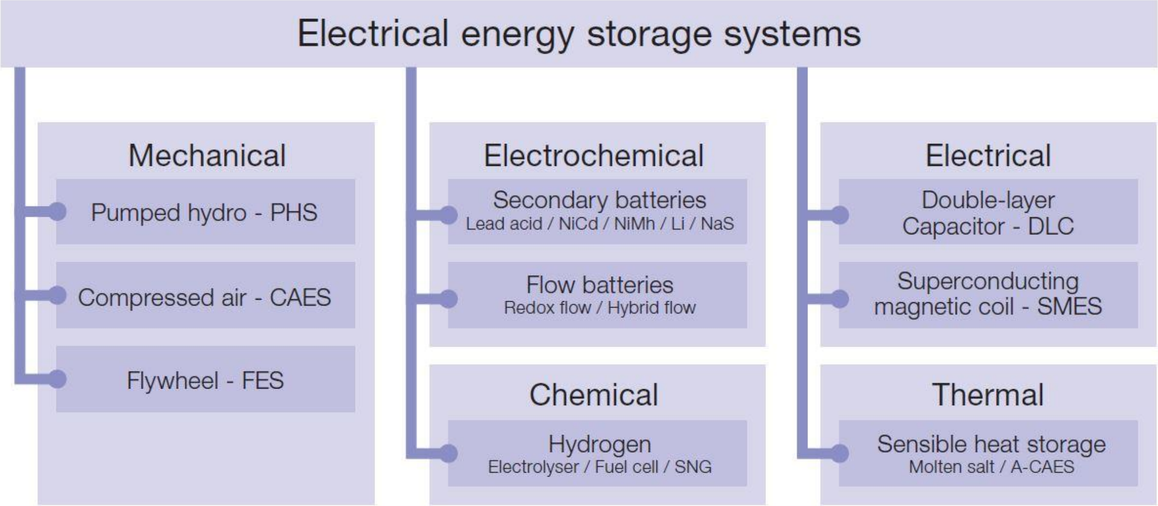


Figure 4 Classification of electrical energy storage systems according to energy form [6]

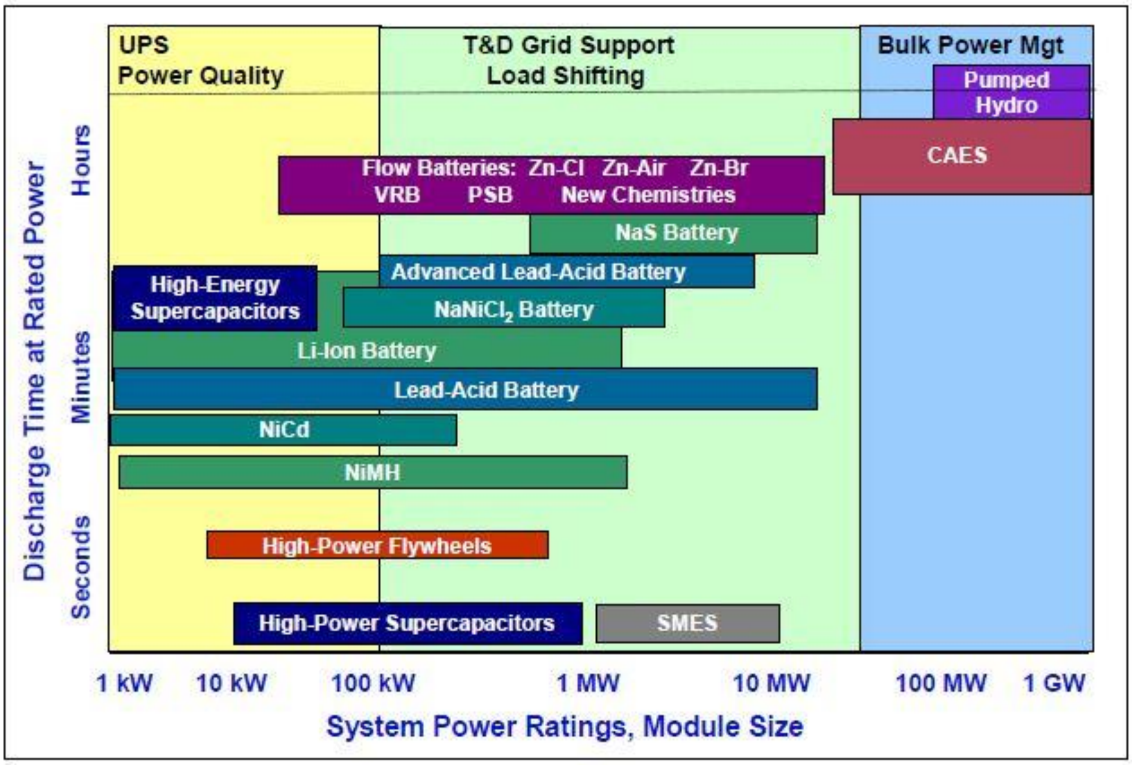
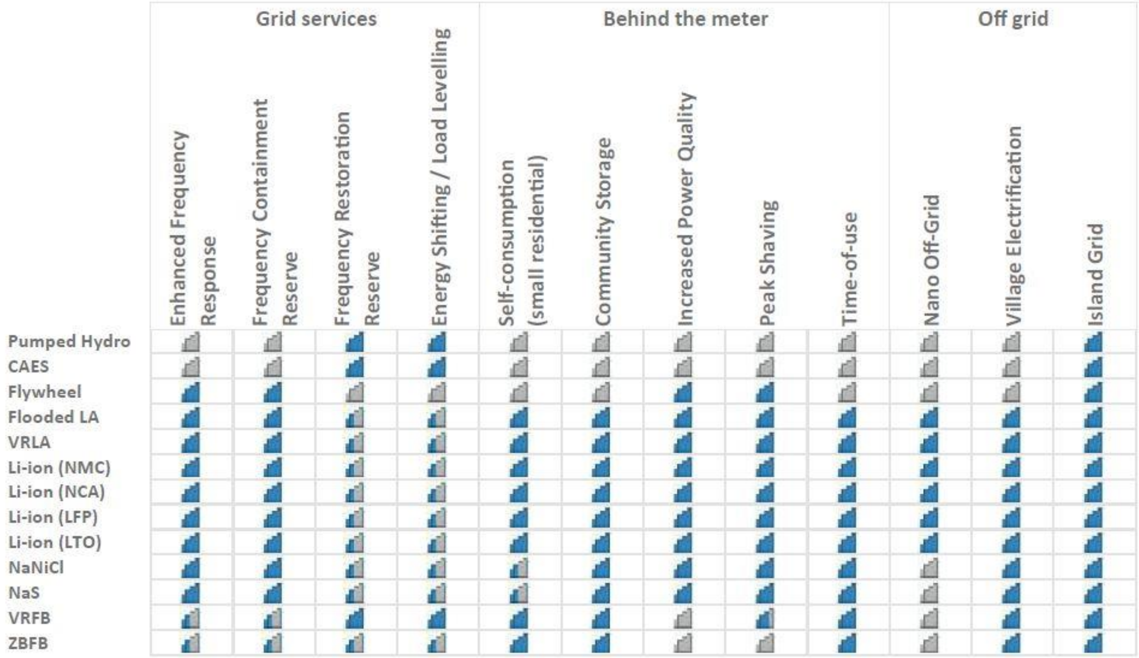


Figure 5 Positioning of Energy Storage Technologies [10]

Generally, the storage time of pumped hydro could be set from 8 to10 hours, and the system power rating is traditionally higher than other. Similarly, CAES also has almost the highest system power rating and long discharge time at rated power. Both of them require ample space to store compressed air or water [10]. By contrast, the group of batteries that usually are in small size clustering around low power rating and rating from seconds to six hours.

According to Figure 5, the system power ratings decide what kind of service that batteries can provide. It can be seen from Figure 6 that different sort of batteries fits in different services.

This research will focus on behind-the-meter services more due to the definition of the energy hub that will be mentioned in the next chapter. According to Figure 6, all the behind-the-meter services can be satisfied by Lithium-ion family of batteries. Therefore, the Lithium-ion batteries could be one of the best choices to apply behind-the-meter service.



	Grid services				Behind the meter					Off grid		
	Enhanced Frequency Response	Frequency Containment Reserve	Frequency Restoration Reserve	Energy Shifting / Load Levelling	Self-consumption (small residential)	Community Storage	Increased Power Quality	Peak Shaving	Time-of-use	Nano Off-Grid	Village Electrification	Island Grid
Pumped Hydro	○	○	●	●	○	○	○	○	○	○	○	●
CAES	○	○	●	●	○	○	○	○	○	○	○	●
Flywheel	●	●	○	○	○	○	●	●	○	○	○	●
Flooded LA	●	●	◐	◐	●	●	●	●	●	●	●	●
VRLA	●	●	◐	◐	●	●	●	●	●	●	●	●
Li-ion (NMC)	●	●	◐	◐	●	●	●	●	●	●	●	●
Li-ion (NCA)	●	●	◐	◐	●	●	●	●	●	●	●	●
Li-ion (LFP)	●	●	◐	◐	●	●	●	●	●	●	●	●
Li-ion (LTO)	●	●	◐	◐	●	●	●	●	●	●	●	●
NaNiCl	●	●	◐	◐	◐	●	●	●	●	○	●	●
NaS	●	●	◐	◐	◐	●	●	●	●	○	●	●
VRFB	◐	◐	●	●	●	●	○	◐	●	○	●	●
ZBFB	◐	◐	◐	◐	●	●	○	○	●	○	●	●

Source: International Renewable Energy Agency.
Note: CAES = compressed air energy storage; LA = lead-acid; VRLA = valve-regulated lead-acid; NMC = nickel manganese cobalt oxide; NCA = nickel cobalt aluminium oxide; LFP = lithium iron phosphate; LTO = lithium titanate; NaNiCl = sodium nickel chloride; NaS = sodium sulphur; VRFB = vanadium redox flow battery; ZBFB = zinc bromine flow battery.

Figure 6 Suitability of storage technologies for different applications [8]

2.2 OTHER COMPONENTS OF THE ENERGY STORAGE SYSTEM

The battery itself can be treated as the most critical part of the energy storage system, but it does not mean that other components of the energy storage system would be less significant. The typical battery storage system is presented below in Figure 7. As it shows clearly, a complete battery storage system consists of several vital elements, which are the battery device, the power conversion system, the monitoring, and control system, switches [7]. Also, the batteries that are based on cells contain single cells that are connected into several modules, and then, modules can be connected into packs [7].

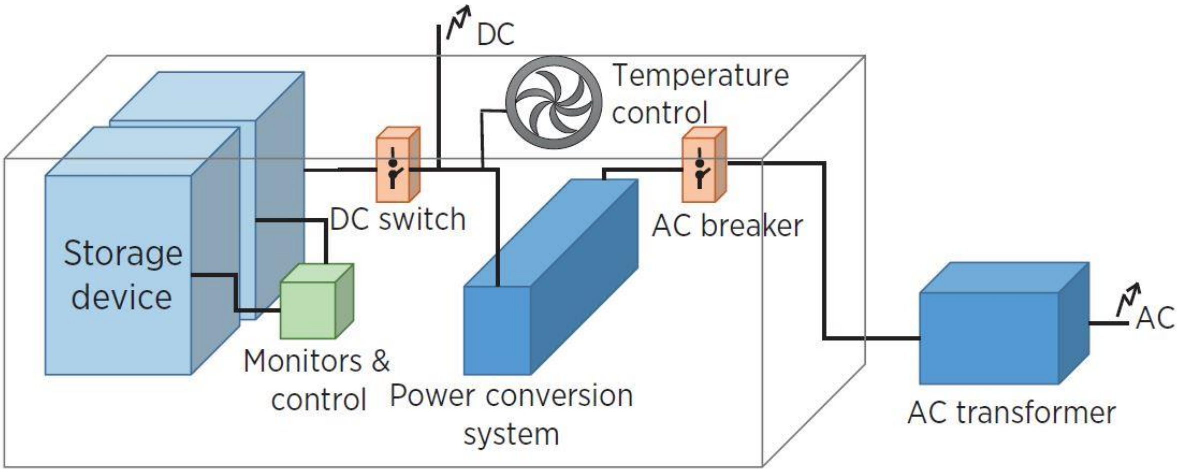


Figure 7 Battery storage system [7]

The monitoring and control system is also known as the Battery Management System (BMS), which is in charge of a rechargeable battery pack (or it can be a single battery cell) via providing safety and maximizing the performance[7]. There are many functions of this Battery Management System, such as communication, computation, monitoring, optimization, protection. For example, the Battery Management System can help control both the individual battery cells and the whole battery pack out of over-charging and monitor the situation inside the system [8]. Moreover, the Battery Management System can be adjusted according to different requirements of different types of battery. For the Lithium-ion battery storage system, the Battery Management System should focus more on the thermal controls [10]. However, the Battery Management System can be relatively expensive and complicated compared to the price of other components of the system.

Except for the internal coordination and management, the battery storage system also needs to communicate with the external distribution system and the local utility. Thus the battery storage system is required to meet the regulations and requirements of the local grid [7]. In a general way, most of regular power electric systems run on alternating current (AC) while the output of the batteries usually is direct current (DC) [7]. It is why the power conversion system should be included in the whole battery storage system. The bi-directional inverters are required to realize both way conversion. For instance, the DC power outputted from the battery needs to be converted into AC power for the utility or grid use. Also, also, AC power can go back to the battery smoothly to charge the battery after converting into DC form [7].

All these components, including all kinds of switches, contribute to build a complete battery storage system taking charge of both internal configuration and external connection.

2.3 SOLAR ENERGY GENERATION

With the boom of the electrical energy storage technologies, a large number of applications in different fields will follow, which are led by several new trends. One of the prevailing trends is the application of renewable energy. In response to the Energy Transition and the 2050 Paris Agreement, the sustainable energy industry started to grow at a rapid speed resulting in the modernization of the power system [7]. Among all kinds of renewable energy resources, wind and solar energy are the most widely used. There is one significant challenge followed after that is the intermittency caused by the varying wind and solar energy generation [6]. This means that electricity supply could be affected by the weather conditions, and the uneven between the demand and supply sides needs to be balanced to ensure the quality and stability of the power system. One of the primary functions of the energy storage system is to keep the balance for the electricity system and provide flexibility for both the generation side and the consumer side [6]. In this research, more attention will be paid on the behind-the-meter side, so the renewable energy resource that is usually applied behind the meter could be solar energy in most instances. So the overall output energy generated by the PV panels over a specific period will be needed for further study.

Equation (1) can be used to calculate the overall energy produced by the PV panels in the case study [44].

$$\mathrm{E} = \mathrm{A} \times \mathrm{r} \times \mathrm{H} \times \mathrm{PR} \tag{1}$$

- E: Energy (kWh) is the total amount of energy that PV panels of a specific area can generate in a specific time.
- A : The overall area of PV panels being used
- r : Solar panel yield given by the ratio: electrical power (in kWp) of one solar panel divided by the area of one panel.
- H : Average solar radiation in a specific period (day, month and year) on tilted PV panels without the shadow part.
- PR : Performance ratio, and it is used to evaluate the quality of a photovoltaic installation, which including all losses from the installation.

When building an energy hub with PV panels and batteries included, this equation can be used to calculate the total output energy using the data of the specific PV system and solar radiation of the corresponding location.

2.4 SERVICES BY BATTERY

During the whole process of the energy transition, the electrical energy storage system will definitely play a crucial role via offering services from the generation sides to the end-customer parts [8]. There have been many studies and researches focussing on what kind of value and services that electrical energy storage can create to the power system for years.

The result of what kind of services and how many services energy storage could offer are different across many studies.

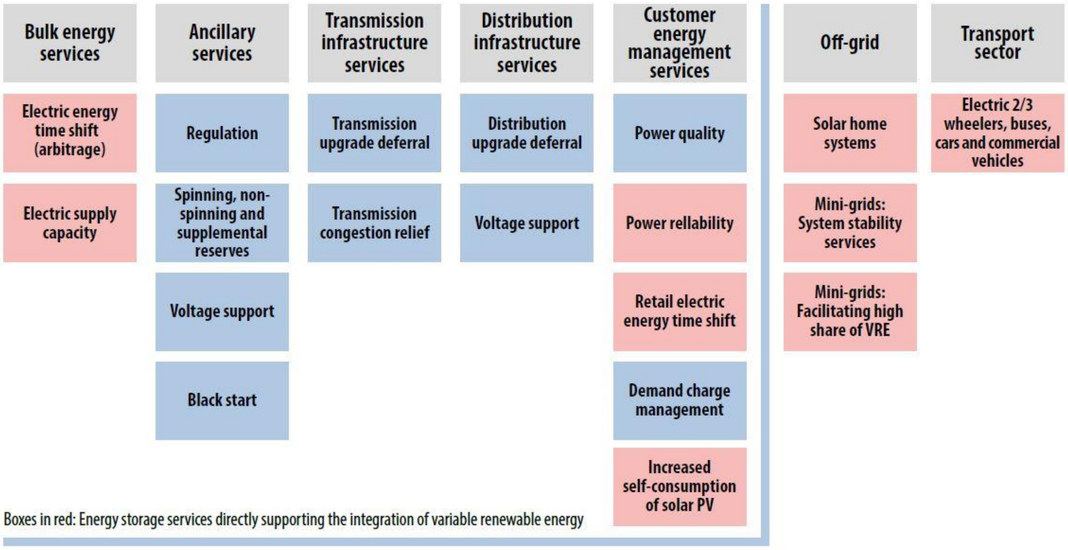


Figure 8 The services that can be provided by electrical energy storage [8]

After going through different reports talking about the services that can be provided by battery storage systems, the essential cores of each report have been found similar. Figure 8 is from the report [8] based in Europe while Figure 9 below is from [15] based in U.S.. After considering both types of research, the services can be categorized into three groups, which are utility services, ancillary services, and customer services.

Ancillary services can be understood as the services that can help grid operators to find the balance between demand and supply sides, keep the power system in a stable and reliable environment, resume from some large-scale energy-consumed events or system accidents [16]. Usually, ancillary services are the operations beyond both generation and transmission to maintain the power flow stably and smoothly. The capacity of the electrical energy storage can help to decrease the restrictions and to slow the congestion on the transmission system, which applies to the distribution network as well [8]. It works well, especially for the growth of applications of renewable energy generation and fluctuating demand profiles. Customer services, or it can be called Behind-the-meter services, can be advantageous for consumers or prosumers to manager the electricity bills and save the money on energy consumption.

For ancillary services, or they are named as ISO/RTO services in Figure 8 [15], Frequency regulation, Voltage support, Black start, and Spin/non-spin reserves are included. These services are distinguished clearly from each other via the time range and the reasons why they are needed [15].

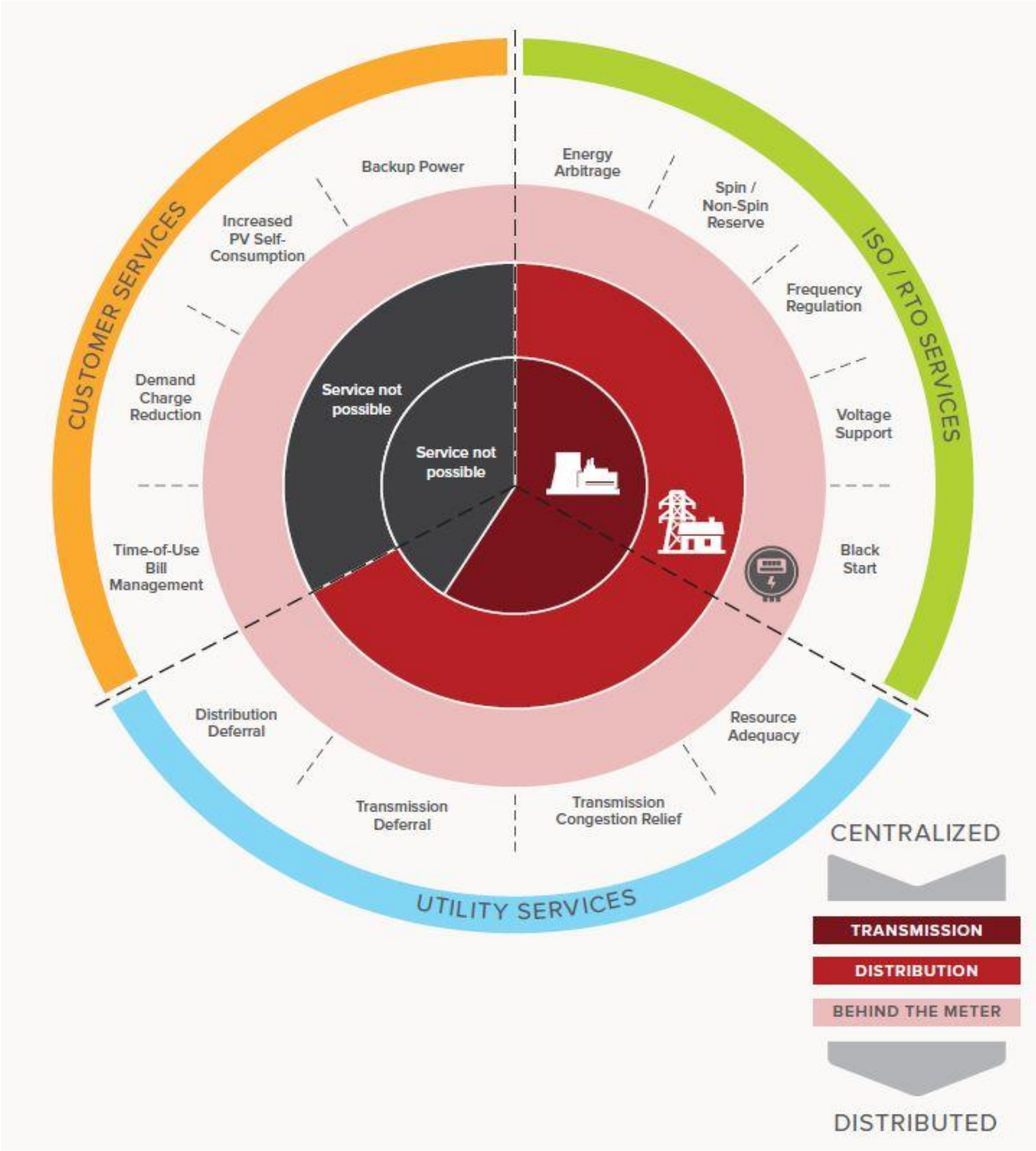


Figure 9 Batteries can provide up to 13 services to three stakeholder groups [15]

- Frequency regulations: It is to ensure grid stability by responding immediately and automatically to a sensed system frequency change, levelling frequency spikes or dips system-wide on a moment-by-moment basis.
- Voltage support: Voltage support contributes to keeping the voltage on the transmission and distribution grids in an acceptable and secure range.
- Black start: If the energy storage system owns the sufficient capacity, it can let the power station or some part of the grid recover rapidly from a shutdown without the external help from other transmission systems to minimize the damage and loss.
- Spin/non-spin reserves: Spinning reserve deals with unplanned generation outage and unexpected contingency event immediately, by using the online reserved generation capacity serve load instantly. The non-spinning reserve serves the same purpose but requires a less than ten minutes responding time.

For utility services, all kinds of services can be put into two main groups serving for two significant objectives. The first one is 'Transmission/Distribution system upgrade deferral'. Usually, the distribution upgrades are needed only for the peak moment produced by some pre-arranged large-scale events while the transmission upgrades are required due to the implementation of new interconnection or severe congestion on the transmission network [15]. The second is about resource adequacy and transmission congestion relief, which are required on a daily basis [15].

- Transmission/Distribution deferral: It helps to downsize or cancelling the cost paid by the utilities in upgrading the distribution or transmission network to satisfy the predicted demand increment on the local grids.
- Resource adequacy: It can be the supervisory construction but to guarantee that there is always going to be enough resources sufficient to meet the demand in all situations, including the most extreme ones. In this context, it can be understood as that utilities can use energy storages to enlarge the capacity and flexibility to decrease the need for building new generation capacity and
- Transmission congestion relief: Electrical energy storage can use the capacity to relocate the demand pattern to some time when the system has no congestion pressure. It can store the surplus energy and release it when the congestion happens to relief the transmission congestion efficiently.

For customer services, they usually can create monetary value directly to the end-users. However, the benefits can be effective only when the energy storage is installed behind the meter [15]. For sure, the outcomes of the service can not only bring income to customers, but it can also benefit the utilities and the society on the sustainable development level. In the following study, the focus will be on the behind-the-meter side since the energy hub will serve the customers and community in the first place.

2.5 MICROGRIDS AND PEER-TO-PEER TRADING

There are many different definitions of an energy hub, and also there are some existing concepts can be categorized as the energy hub under a different name. After extracting and assembling the common from most theories in a nutshell, an energy hub can be described as an integrated energy system with multiple energy carriers containing numerous energy conversion processes, storage operations and network techniques, aiming at advancing energy management at district level [17]. Energy hubs can develop on multiple spatial scales, from the scale of one single building to a community area or even the entire city [17].

When it comes to the Microgrids, a wide range of definitions can be found in the existing literature, and it is worth reminding that this concept has been brought up since decades ago. According to CORDIS Europe, Microgrids can be introduces as a series of electrical loads, power supply devices (PV panels, wind turbines, fuel cells, etc.), storage applications(Li-ion batteries, compressed air, flywheel, etc.) connected together using specific scheme, which, acting as a whole, is connected to the local gird via a single point of linkage [18]. The topology of Microgrids can be briefly shown in Figure 10 [19]. The scheme can control both the power flow within the Microgrid itself and power flow between the supply grids and the Microgrid [18]. One of the most significant characteristics of Microgrids is that they can operate in both grid-connected (on-grid) and stand-alone (off-grid) modes.

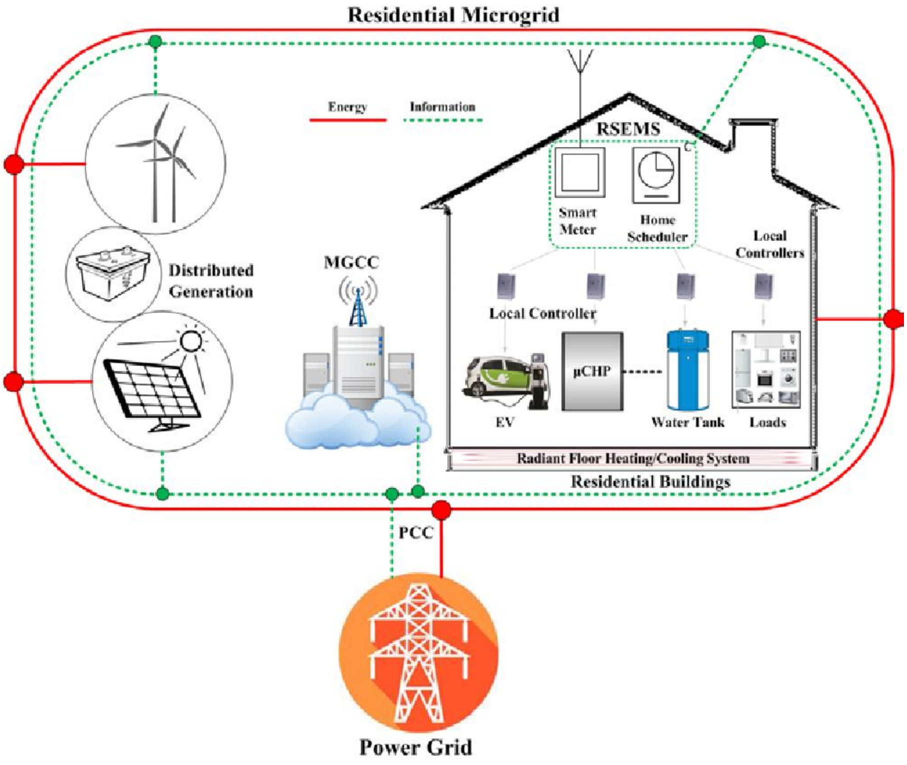


Figure 10 Integrated building and microgrid system [19]

To some degree, Microgrids can be considered as one kind of energy hub. Thus, the coordination mechanism and design concept can be possibly referred to build the other energy hubs according to individual requirements under different conditions. How the renewable sources and battery storage system are integrated into the whole system and how the centered managing and monitoring scheme work to optimize the performance are all excellent examples. When the Microgrid operates on the stand-alone mode, it means that the supply grid has no more contributions at that time, which can be referred for the proposed energy hub during the black start situation. However, the most significant difference between Microgrids and the following proposed energy hub is needed to be clarified. For the energy hub designed in the research, it can be understood as a well-designed independent frame based on the existed local grid connections. It will use the cables, connections, and transforms that are already being used in the local community. Meanwhile, the typical Microgrids are more like an isolated system with one single point linked to the local grids, which can be easily separated from the main supply grids.

Peer-to-peer electricity trading concept, which is based on the idea of the peer-to-peer economy, becomes more and more popular because the PV panels and the battery storage systems are more widely used. With the extensive usage of renewable energy generations, Peer-to-peer energy trading could be an efficient manner to explore the value of the distributed renewable energy resources in the community. On the peer-to-peer trading platform, the surplus electricity from the prosumers will be shared with other participators that can be both prosumers and consumers, which gradually becomes more and more welcomed than the traditional peer-to-grid trading method [20], shown in Figure 11. Currently, there are more and more global studies and projects being carried out on peer-to-peer energy trading. Strictly speaking, there should be no intermedia existing in peer-to-peer trading. It means that a trading platform needs to be created with all the necessary functions to let all consumers and prosumers trade via money and energy with each other freely under specific regulations. In this case, the distributed renewable energy resources can be fully controlled by the owners (or prosumers). Meanwhile, the benefits of the prosumers can be maximized, and the self-consumption of the sustainable energy generations can be increased.

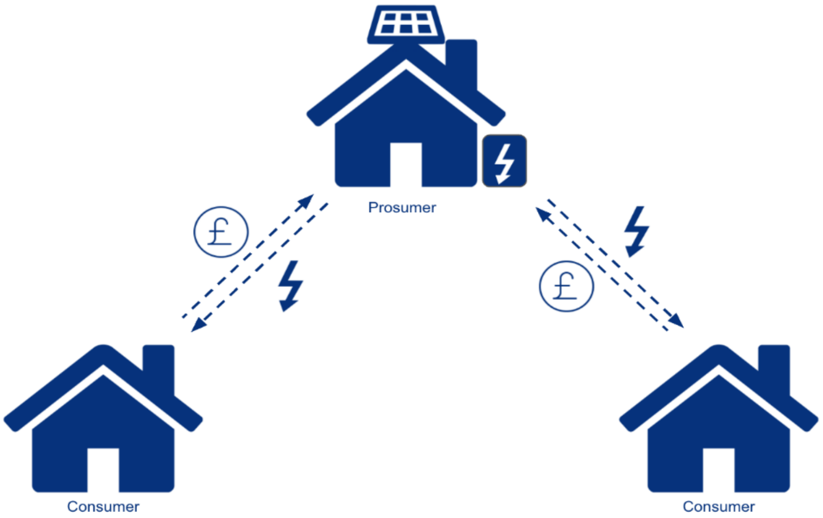


Figure 11 Peer-to-peer trading platform [21]

The idea of the peer-to-peer energy trading platform to explore the monetary value and increase the self-consumption of the distributed energy resources can be a real reference for building the energy hub in this research. What is more, one of the attractive points of this concept is that it is mostly happening or managed to occur within the community area, which means the energy flow and money flow could only be in the full control. When it is necessary to figure out how to calculate the value of the operation of the energy hub and how to encourage the implementation of this energy hub, the outcome of an effective peer-to-peer trading scheme can give a perfect answer.

CHAPTER 3.

ENERGY HUB METHODOLOGY

A methodology of the energy hub proposed by this thesis will be defined in details in this chapter. Then, the explanations of every service and a frame structure of the energy hub can be found in this part as well.

3.1 REQUIREMENTS AND DEFINITION OF THE ENERGY HUB

In order to deal with climate change and cooperate with the Energy Transition, implementation of both renewable energy resources and battery energy storage system gradually become two of the necessary solutions. Battery energy storage system acts as the fundament of all the solutions to improve the stability and reliability of the power system and increase the financial return of renewable energy resources. It is significant for the prosumers to find the practical arrangement of the combined usage of both battery storage system and renewable energy generation to maximize the monetary value and social contributions.

There are plenty of valuable researched discussing the coordination and cooperation of these two applications. For instance, [22] combined the applications of battery energy storage system and large-size PV panels smartly in order to decrease the invested cost and scale down the carbon emission and other kinds of pollution. Besides, [23] obtained a new management method to use an energy storage system to avoid the overvoltage with large-sized PV installed and increase PV hosting capacity of low voltage grids.

Throughout numbers of the literatures available related to the battery storage system and renewable energy resources deployment, many of them focussed on two main directions, which are (1) exploring the value of the battery storage system and/or renewable energy applications only for the owners when the applications are behind-the-meter, and (2) making the arrangement of the battery storage system and renewable energy generations to serve the utility (such as power plants, transmission network operator and distribution system operator). However, it is challenging to get into details of how to apply the battery storage system and renewable energy resources into the community level with more than one participator involved. According to [3], the energy storage system can provide more value if numerous services can be stacked together using the same device or group of devices. Currently, the behind-the-meter battery energy storage systems become more and more popular because they can easily create value for end-users or grid. However, it remains considerable value on the table if the battery storage system is only being used for one service, which may lead to battery storage system staying unused for more than half of its entire lifetime [3]. It is a typical case each individual consumer may own different equipment in the community. For example, end-user A only owns a set of PV panels while end-user B has the wind turbine and the battery energy storage system, and end-user C is only a consumer. If an appropriate arrangement between all prosumers and consumers in the community can be created, the overall value could be much bigger than when each prosumer only apply their devices into their own use and consumers only draw energy from the grid.

In the following, the concept of an energy hub in community-level based on the grid-size energy storage will be defined. The services offered by the proposed energy hub will be categorized into two layers: primary service layer and secondary service layer, shown in Figure 12. The services on the primary layer are to meet the needs of the battery-owner who has the priority to get satisfied while the services on the second layer are meant to serve the neighbours of the battery-owner (or can be described as other participators in the energy hub).

To frame the energy hub, the related requirements need to be set as following:

- It is significant to use the original existed physical devices and connections as much as possible, such as the cables and the transformers. Ideally, the energy hub is preferred to be constructed above the original local electricity grid, and other connections or devices will be added when it has to be.
- The spatial scale of the energy hub is set to the community level with multi-players included. Moreover, it should be a commercial community or a mix-up of the commercial and residential community.
- There can be only one or multiple battery energy storage system in grid size functioning in the energy hub. If multiple batteries are existing, they will be functioning as a whole storage system, which means there is one storage system on the whole.
- There is at least one set of renewable energy resource functioning in the energy hub. Since the battery energy storage system is set to be behind the meter, usually PV panels are used in most cases. Thus, the requirement is limited to at least one set of PV panels working in the proposed energy hub.

- The benefits of battery-owners and PV-owners are supposed to be put in the priority, which means their needs have to be met first and the operations with neighbours are to explore the surplus-value of the battery storage or the PV panels.
- It is significant to minimize the export of electricity generated in the energy hub and try to maximize the economic profit for each member in the energy hub.
- To preserve the lifetime of the battery storage systems, it is suggested to keep the State of Charge of batteries between 20% and 95%. Also, the 95% state of charge could be called sufficiently-charged.

Taking all the requirements into consideration, the definition of the proposed energy hub will be as follows:

- Primary service layer: (only for Battery-owner itself)

  -- Demand charge reduction

  -- TOU bill management

  -- Increased PV self-consumption

  -- Back-up power

- Secondary service layer: (mainly for neighbours)

  -- Demand charger reduction

  -- TOU bill management

  -- Increased PV self-consumption

  -- Back-up power

  -- Flexibility provider

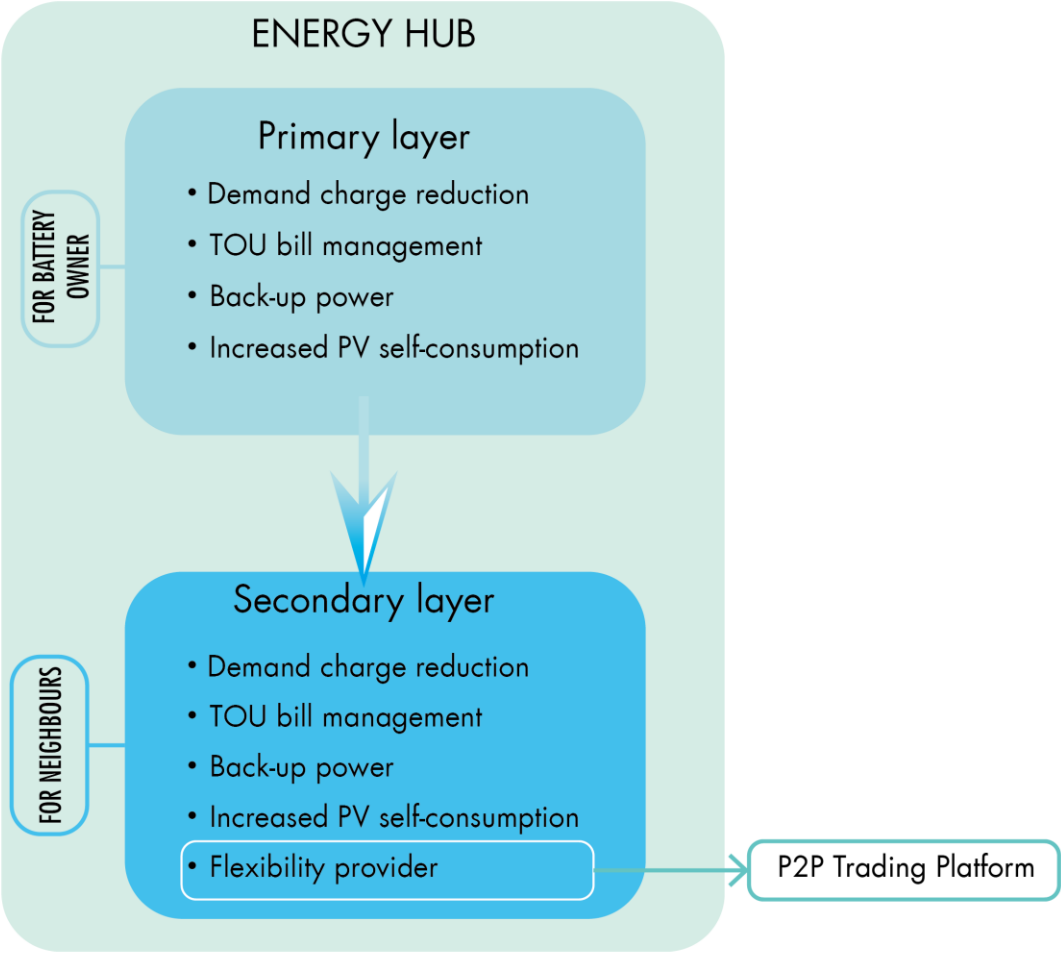


Figure 12 Energy Hub Methodology

3.2 DEMAND CHARGE REDUCTION SERVICE

The first service listed on both primary and secondary layers of the energy hub is the demand charge reduction service. According to the research in [25], the demand charges for those commercial buildings can quickly get to nearly 70 % of the users' monthly electricity bills without even being noticed. Nowadays, the rapid increment of floor space in the commercial buildings is almost two times as quick as the growth of the numbers of commercial buildings according to the study from a recent survey of EIA in 2016 [24]. This data means that a foresee fast growth in the number of the equipment or devices, space area asking for air-conditioning, and other activities consuming more energy is happening in the commercial buildings [24]. It directly can lead to the jumping increment in the electricity consumption of the newly-built commercial building, like hotels, shopping mall, large offices, even though the efficiency of the energy usage of these newly-built commercial architectures has been improved. In this case, the owners of these commercial building may find the problem that they have to pay far more than the electricity fees that they actually consume [24], which is caused by this 'demand charge'. Thus, it is necessary to understand the importance of the role of the demand charges plays in the monthly energy bills, and then, efficient solutions can be found to deal with this kind of problem.

WHAT IS DEMAND CHARGE?

In general, demand charges are acting as a direct penalty reflecting the power demand profile of the commercial buildings, especially for the time when the power demand is over the limited amount. To be more specific, two parts are consisting of the monthly electricity bills of the commercial buildings: (1) Energy charge, and (2) Demand charge [26].

- For the energy charge, it is calculated as energy charge per month equals the total amount of electricity use for the month times the energy rates that might vary in different periods.
- For the demand charge, it is a little more complex to calculate. Usually, it can be decided depending on the highest amount of power that the consumer is going to use per month. In most cases, the demand meter will record the power demand in a 15-minutes time interval through the entire month, and the records from the demand meter will go to the local utility. If the local utility sets the time interval of less than 15 minutes, then the demand charge per month can be even bigger [26]. The recorded the highest power amount multiplying a special rate that is different due to different utilities will become the monthly demand charge. Then the energy charge and the demand charger add up together to become the total electricity bill per month.

WHY IS DEMAND CHARGE CREATED?

As it was discussed, how much the local utility charges the demand charge depends on the peak usage of the electricity among the whole month. This rule is made because the peak amount consumed by any commercial building is a challenging that the electrical utilities are facing, which is to maintain the sufficient capacity continuously to meet the commercial customers' needs immediately at any time they want. For instance, all the air conditioners in one large office may be turned on at the same moment due to the hot weather. Alternatively, a concert is on in a concert hall with thousands of audience. All these situations will require a vast amount of electricity in a short time, and they are not happening regularly. Also, the grid has to satisfy not only one commercial building but a number of those buildings. Keeping this size of capacity available on the grid can be very expensive because the utilities have no choice but to keep many complicated and expensive devices, like generators, transformers, substations, and cables, constantly running standby. The capacity is pretty costly to build and to maintain so that the demand charge can cover these fixed costs of local utilities. What is more, demand charges also can be considered as one method to make consumers aware of the importance of the energy-saving and to advocate the reduction of the power use during the peak time and shut down the unnecessary equipment.

HOW TO REALIZE DEMAND CHARGE REDUCTION IN ENERGY HUB?

Among the literature topic-related, there are four methods used most commonly to reduce demand charges. Firstly, the technology of improving energy efficiency can be helpful on the demand reduction when it is both off-peak and on-peak hours [24]. The second approach is named peak shaving, which helps to decrease the demand during peak periods. The third one is called load shifting, which can relocate the power demand from the peak time to off-peak hours [24]. The last way is to use sustainable energy resources that can generate power behind the meter to reduce the pressure put on the electricity grids [24].

In the proposed energy hub, the second and the forth approaches (peak shaving + renewable energy generation) will be combined to realize the demand charge reduction. The capacity needed to maintain constantly on local grids is the reason for the commercial consumers to pay for the demand charge. In this case, the battery storage systems and the PV panels in the energy hub can work together to create such capacity for the prosumers and consumers participating in the energy hub operations, so that the demand data collected by the meter of the local utilities can be easily controlled under the demand charge tariff threshold. Taking advantage of the flat load profile after using the renewable energy and battery storage system, the consumers can negotiate with their utilities to work out a new agreement to reduce the cost in demand charges.

Usually, the local utility will give several demand charge tariff levels clearly, and it will increase the charge gradually when the peak power jump from a low level to the high level. In the whole operation of an energy hub, the battery storages can be charged by PV panels in the energy hub or during the night off-peak time from the grids when the solar energy is not enough that day. The batteries need to be charged to the sufficient capacity before the moment when the power demand starts to be over the local demand charger tariff. Then, when the power demand is over the tariff threshold, the battery starts to discharge, feeding the partly demand to keep the demand curve under the demand charge tariff threshold constantly. For instance, Figure 13 below shows the concept of this operation. The dark blue curve is the load profile with no help of the solar and the battery, and it is partly beyond the tariff threshold that is shown as the red straight line. After adding the solar and battery storage, the light blue curve is the demand after, which remains below the tariff threshold. In this case, the demand charge can be reduced significantly if this light blue demand pattern can be kept constant.

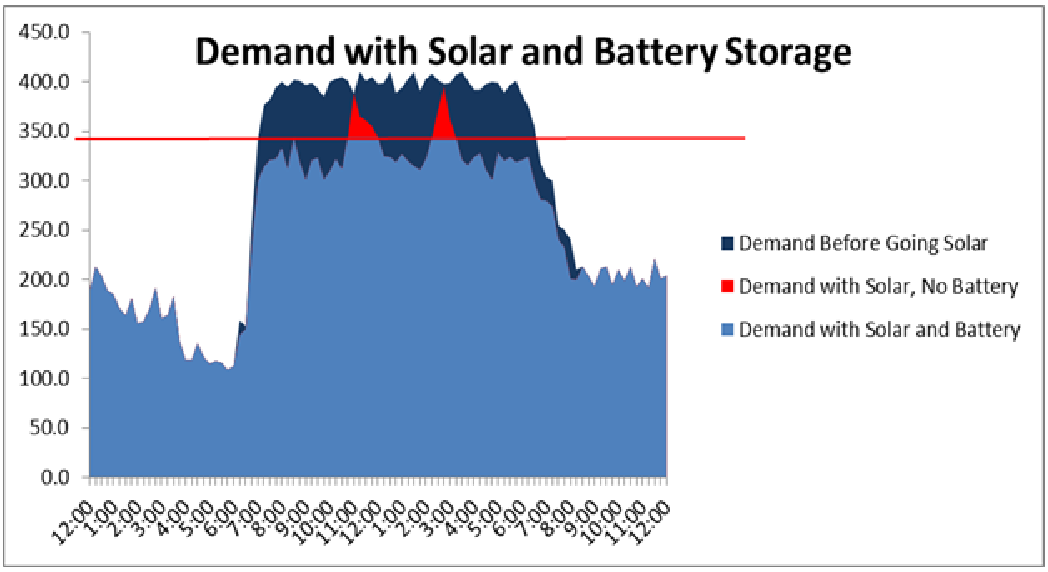


Figure 13 Demand charger reduction using solar and battery storage [27]

In a typical commercial community, there are different types of commercial buildings, such as hotels, cinemas, restaurants, shopping malls, large offices, and hospitals. Different types of commercial buildings will have different peak hours considering their different kinds of services. For instance, the electricity demand of large offices will get to the peak during the working times in the workdays while the cinemas or restaurants may be pretty busy during off-work time and weekends. Hotels might have a similar demand pattern as residential consumers. Different peak hours of these commercial buildings provide the opportunity to realize the demand charge reduction to multiple participators in the energy hub. Besides, different sizes of the commercial buildings could face different levels of the demand charge tariff. A thorough and comprehensive management mechanism is necessary to coordinate the charging and discharging of the battery storage system and to decide who will consume how much energy during what time, which can be achieved easily using current techniques and mathematics.

From a business perspective, the long-term contracts between battery-owners & consumers, energy-hub members & local utilities need to be taken into serious consideration. For battery-owner, the economic benefit can come from two ways. Firstly, when the peak demand is controlled under the tariff threshold, a considerable amount of money and carbon emission will be saved due to the demand charge reduction. Secondly, the capacity of the battery taken by other energy-hub members can be treated as one kind of services. After calculating the original cost of the demand charge paid by the energy-hub members, the price of the battery storage service can be arranged lower, which still can bring a considerable income to the battery-owner. Also, for the other energy-hub members, it can save both the money and the carbon emission through cooperation. On the whole, energy hub contributes to building a greener community and also creates monetary values for most members getting involved.

Also, for the grid operators, the existence of the energy hub will help to release the high pressure on the power system during the peak hours.

WHAT ARE THE CHALLENGES?

One of the challenges that may be faced when designing the demand charge reduction service is that different utilities usually have different demand charge tariff. All the operation rules of this service are built based on the local electricity consumption regulations and tariff of utilities. After managing the demand profile below the demand charge tariff successfully, the following problem is how to keep the demand profile at this status constantly. Because local utilities usually require the customers to keep the peak power demand under the tariff, they set for more than an extended period, and then the demand charge will be cancelled. Otherwise, it will not work even the consumer has already kept the peak demand per month under the tariff for eight months when the local utility asks for nine months. For instance, one of the biggest utilities in Australia called AusNet stipulates that small commercial customers who consume more than 40 MWh pa will be compulsorily labelled as the demand charge tariff customer [28]. Also, in the regulations of AusNet, only when the small commercial customers can keep the total annual consumption below the 40 MWh in the following 12-month periods, the customers can contact the utility to require to cancel the demand charge on their initiative, according to [28]. Therefore, how to use the battery storage and renewable energy to manage the demand pattern smartly could be the key to reduce the demand charge.

3.3 TIME-OF-USE (TOU) BILL MANAGEMENT SERVICE

The second service that shows both on the primary layer and secondary layer is the time-of-use (TOU) bill management service. Nowadays, it has become worldwide for utilities in many countries to use TOU rate structures to charge the electricity bills. As one famous phrase that appears a lot in many electricity-market-related topics, TOU bill management can create benefits directly to the end-users. It can be much more comfortable and cheaper for all kinds of customers to coordinate with the traditional power system operations with a smoother power demand curve with fewer peaks and valleys [6]. This fact motivates the development of the TOU bill management services in order to encourage customers to change their power demand pattern for building a lower-costly power system [6].

WHAT ARE THE TOU RATES?

Time-of-use (TOU) rates are structured as one variable charging standard, which adjusts the electricity price to fluctuate depending on the time of the day, weekdays/weekends or holidays and different seasons [30]. Different utilities may set specific standards accordingly, but usually, they share similar patterns and rules. In general, the rates charged for energy consumption are low when the energy demands are low (that is called off-peak hours), while the rates charged for the electricity usage can be pretty high when there is more energy demand during peak hours [29]. Under normal circumstances, electricity prices are higher in the summertime than in the wintertime. Also, rates may increase a bit during off-work time and weekends for residential consumers while working time on workdays could be the peak hours of the large office buildings. This charging standard delivers the information to all end-users to try to switch the electricity demand from the peak time to the off-peak time as much as possible to save the cost on the electricity bills. For example, it will be cheaper for residential users to use a washing machine or to charge their electric vehicle during off-peak time.

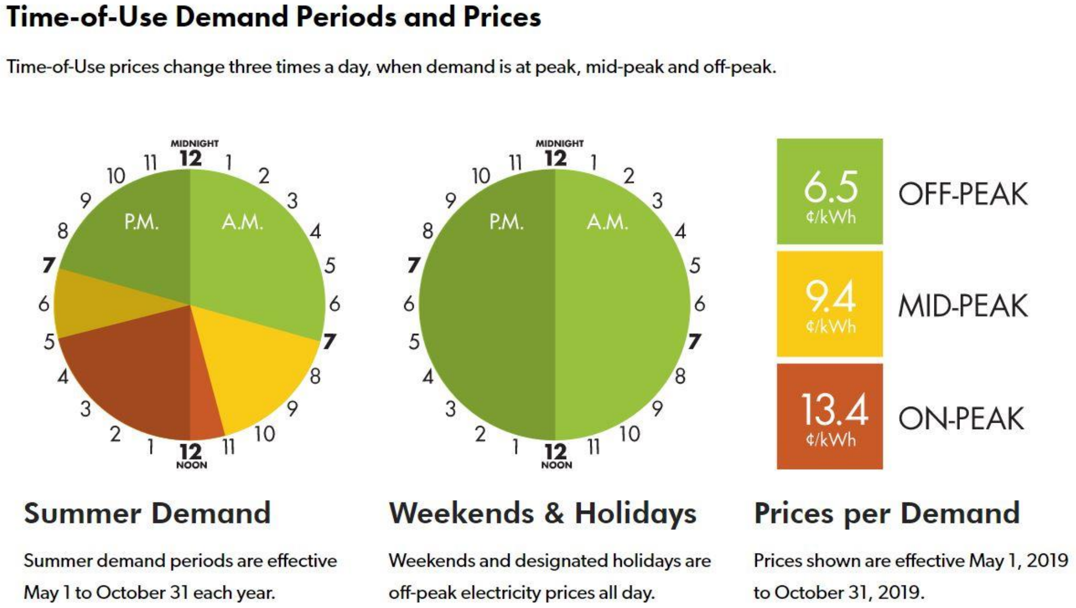


Figure 14 Time-of-use demand periods and prices [31]

There is an example case here to indicate this concept more clearly. Figure 14 indicates the TOU rates standard of Hydroone (one of the most significant utilities in Canada) for some commercial users such as large offices and shopping mall. According to the figure above, there are three main periods: on-peak (red), mid-peak (yellow) and off-peak (green) [31]. On-peak means the electricity demand can be extremely high while the demand in the mid-peak is just moderate, and low power demand exists in the off-peak time. Figure 16 presents clearly when the high-rate time is and how much the three types of rate are.

WHY ARE THE TOU RATES NECESSARY?

Compared to the standard tariff (a fixed rate of electricity), TOU rates structure actually can help to save the cost spent on the energy consumption, even though the rate for the peak hours may be higher than the fixed rate of the standard tariff. The goal of the TOU rates at the first place is to match up the electricity price paid by the consumers with the actual energy generation cost [30]. The standard electricity tariff with a fixed rate could probably blind the customers with no understanding about what is happening behind the meter. This shows up the transparency brought by the TOU rates structure. It is easy for end-users to look through the winder provided by the TOU rates to find out what the real cost of the energy they are currently using and how the cost increases and decreases in every day. After the understanding for this charging system, it could be more comfortable for the customers to arrange their use patterns to lower the total electricity bills and help the pressure on the grids to be reduced. Thus, setting this type of charging system could be win-win for both consumers and utilities.

HOW TO REALIZE TOU BILL MANAGEMENT IN ENERGY HUB?

Taking the characteristics of the TOU rates structure into consideration, if the customers want to shift the power demand from the peak hours to the off-peak hours to save the cost, it is not easy to just shut down the devices during the peak time without affecting the quality of life or the working progress. The battery energy storage applications can be beneficial in solving this problem. Instead of shutting down the critical equipment, customers can discharge the capacity of the pre-charged battery storage for some large-scale or important devices during peak hours. Applying the battery storage can always make the TOU pricing mechanism more cost-efficient for both commercial and residential users.

In the proposed energy hub, the TOU bill management service belongs to both primary and secondary service layers. Firstly, TOU bill management should create benefit for the battery-owner as the primary service. The primary operation needed to consider is how to charge the battery storage system. In this energy hub system, it is recommended to use PV panels (if the battery-owner also has the PV panels on the rooftop or the PV panels from the energy-hub members) or the grid during the off-peak time (mostly night time) to charge the battery. And then, the battery will start to supply power to some devices to shift part of the power demand from the local grid to the battery itself during the peak hours. A thorough and comprehensive management system is required to coordinate the charging and discharging of the battery storage system, to sense the variations between peak time and off-peak time and to calculate how much power is needed to achieve the cost-saving goal.

There exists a balance in the problem related to how much power the battery should discharge during the peak hours.

$$€_1 \times E_1 < €_2 \times E_2 \tag{2}$$

$$E_2 \leq E_1 \tag{3}$$

$$\frac{€1}{€2} E_1 < E_2 \leq E_1 \tag{4}$$

In the above inequation, $€_1$ is the electricity rate during the off-peak time and $€_2$ is the electricity rate during the peak time. And E_1 is the energy amount charged into the battery during the peak hours and E_2 is the energy amount that battery need to discharge during the peak hours. So $\frac{€1}{€2} E_1 < E_2 \leq E_1$ shows the range of the energy amount that battery may offer to the customer to ensure the benefit of the TOU bill management.

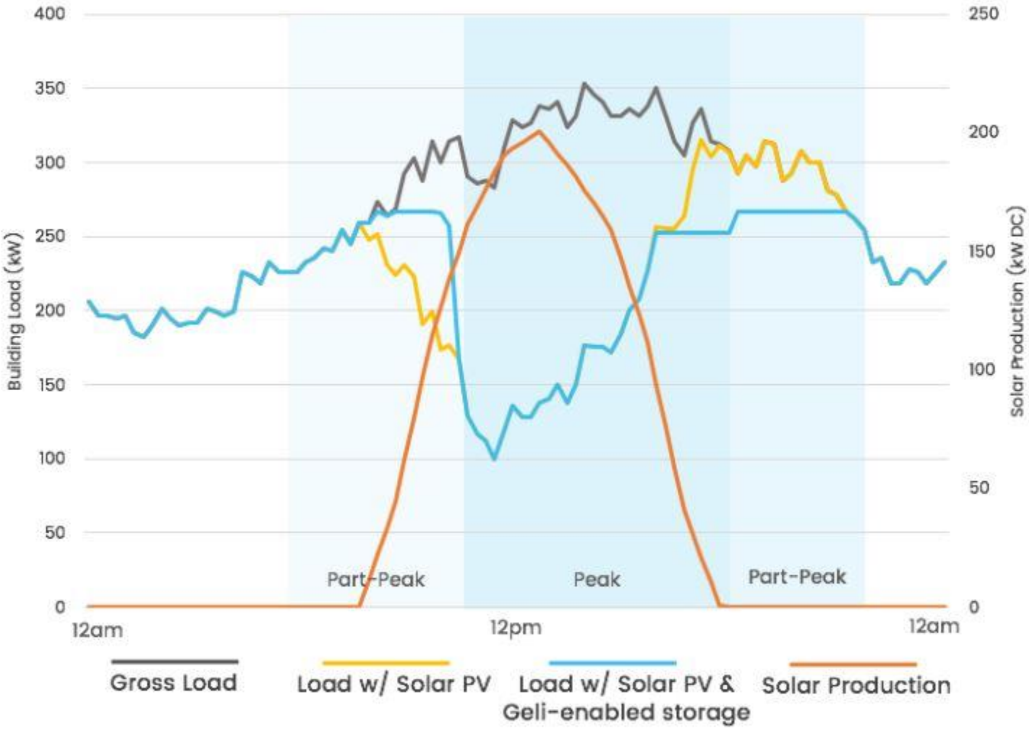


Figure 15 Time-of-use bill management on 12-08-2016 [32]

According to the report of Geli (one of the leading energy software design company in U.S.), Figure 15 shows one example of TOU bill management with the battery storage and solar energy in California [32]. It is clear to see the difference between the blue curve (load profile after using storage and PV panels) and the grey curve (original load profile). During the peak hours (the darker blue region), the solar PV & Geli-enabled storage system starts to work to make the power demand reduce, and also the demand pattern after using the solar PV & Geli-enabled storage system is much lower than the original demand pattern during the part-peak time (mid-peak time).

When considering to use the TOU bill management on the secondary layer of the energy hub, there is one fact needed to be certain that is the scale of this energy hub service. Not like the demand charge reduction service discussed above, even all the commercial buildings in the community have different sizes but they usually share the same partition of peak and off-peak periods. The element that may decide how many members can join in this service is the capacity of the battery storage systems owned by the energy hub. The battery-owners can use the surplus capacity in the battery to provide TOU bill management to the neighbours on the premise of satisfying their own needs. If the battery storage system has enough capacity to support more than one customer to do the TOU bill management, then a long-term contract can be established between the battery-owner and the other members to realize that other members can spent less to buy electricity from the battery than from the grids during peak periods. In this case, the battery-owner can get the direct benefit as well. Also, the TOU bill management service can help the utilities and generation plants to release the high pressure on the electricity network during peak hours.

WHAT ARE THE CHALLENGES?

The challenges that might be faced while executing this service plan can be viewed from subjective and objective perspectives. The objective challenge is about the current technology to enlarge the capacity of the battery system. In this service case, the larger capacity the battery can own, the more benefit it can create for the community. Moreover, the TOU tariff could be updated by utilities according to the seasons and growth in the renewable energy generations so that the update of the software of the managing and monitoring system should be taken care of from time to time. The subjective challenge can be consumer education. A low percentage of customers has been aware of the importance of TOU bill management. It is wide to view this service not only in the way of the monetary value but also in the way of sustainable development.

3.4 INCREASED PV SELF-CONSUMPTION SERVICE

One of the basic ideas of building the energy hub is to minimize the export of the energy produced within the energy hub and reserve the energy for the internal trading process. In the energy hub setting, the PV panels system can generate the electricity for the energy hub, and the battery storage system can reserve the energy for any time needed. These two devices create a practical environment for the idea of minimizing the export of behind-the-meter solar energy and maximizing the benefit of the energy hub members [3].

WHAT IS THE PV SELF-CONSUMPTION?

With the concept ‘self-consumption’, it describes that the electricity generated behind the meter can be consumed on-site directly. Taking the PV solar energy into considerations, it can be explained as the on-site usage of the energy produced by PV panels on the rooftop to minimize the purchase of the energy from the grid or other generation points. With different sizes of PV systems and demand patterns, the ratios of the PV self-consumption can vary in an extensive range, from only a few percentages to almost a hundred percentage [33]. It is beneficial to maximize the ratio of the PV self-consumption because the part of the energy bill could be compensated. Also, the local regulations and tariff due to different regions and countries will determine how much of the bill it can compensate.

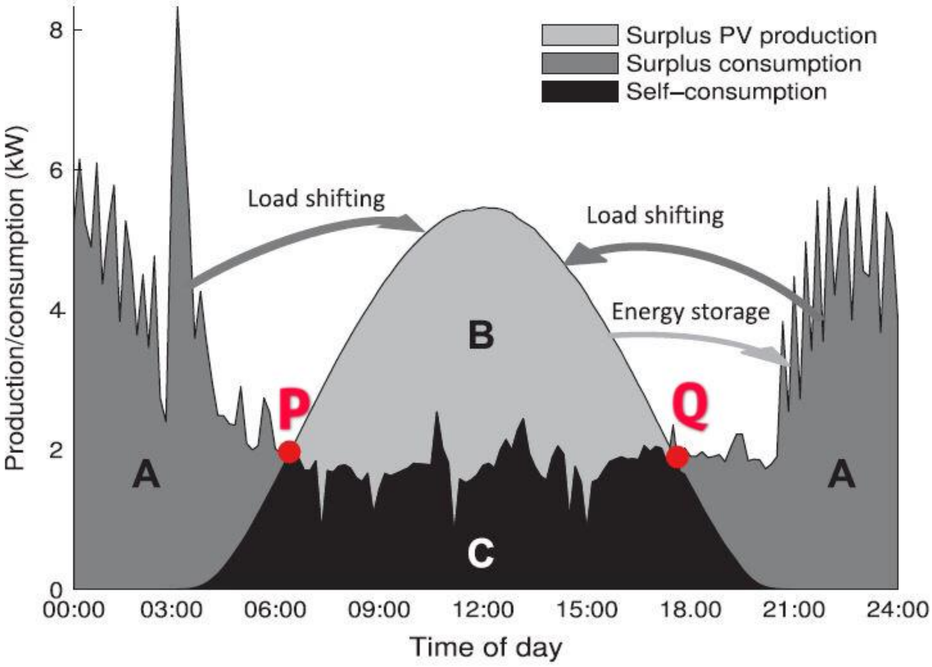


Figure 16 Graphic explanation of load profile, PV generation and self-consumption in a building [33]

Figure 16 above gives a graphic explanation of the demand profile and solar production of a residential building for one day. Area A presents the net energy demand in one day while area B and C together means the total solar energy generation in the same day. Area C shows the solar energy that is consumed directly on site, which is often called absolute self-consumption [33]. Besides, there is also a concept called self-sufficiency, which could be mixed up easily with self-consumption. To simply specify, the self-consumption ratio and self-sufficiency ratio can be both described using one equation according to Figure 16:

$$\text{Self-consumption} = \frac{C}{C+B} \tag{5}$$

$$\text{Self-sufficiency} = \frac{C}{C+A} \tag{6}$$

WHY IS INCREASING THE PV SELF-CONSUMPTION NECESSARY?

According to the research done by the Solar Power Europe Strategy Committee [34], the price of the whole PV panels system has fallen by around 75% in the recent eight years. This attractive price reduction has led to the rapid growth of the competitive power of solar energy in the power sector. Industrial, commercial, and residential end-users gain a more considerable opportunity to use the affordable sustainable energy resource directly on their rooftop.

When it comes to the advantages of increasing PV self-consumption, they can be viewed from two major perspectives. Firstly, it can benefit the local grids and utilities. Increasing the PV consumption on-site by consumers themselves means the expansion of the scale of flexibility on the demand side. Thus, the reliability and stability can be improved, and the peak demand will be reduced, which will benefit the utilities to deal with the grid congestion problem during the peak hours. As can be seen from a broader view, it will help to prevent climate change and to decrease the carbon emission. 4 MWh energy produced by PV panels every year can prevent almost 2,600 Kg of carbon emissions [34]. Secondly, a PV system with maximized self-consumption makes the PV-system owner highly-possible to save the cost spent on the energy bill with its mechanism. In the case of gradually increasing the price of the electricity from the fossil fuel power plant, consumers can use the electricity generated by no-cost sunlight as much as possible to reduce the energy bill. Decreasing the price of the PV system devices not only provide the end-users the cheap energy but also protect them from the increasing price of the traditional-generated electricity [34].

HOW TO INCREASE PV SELF-CONSUMPTION IN ENERGY HUB?

There exists the diversity of regulations and policies in different regions to limit the PV self-consumption. In order to build the scheme of the self-consumption, several parameters need to be considered, which aim to clarify the requirements accordingly in the practice. The scheme requirements used in this service case were referred from the report of the International Energy Agency (IEA) [35].

The total requirments are categorized into three groups, which are PV self-consumption, surplus PV electricity, and other system characteristics.

(1) PV self-consumption:
   - Right to self-consumption: it will determine if the PV-owner can legally connect the PV system to the gird and also can consume directly on-site to compensate the power from the grid.
   - Revenues of the Self-consumed solar energy: it consists of both the cost saved on the electricity bill and extra revenues from the bonus from utilities.
   - Cost charged for total grid costs: it identifies whether the PV-owner needs to cover part of the Distribution and Transmission costs on the self-consumed energy.

(2) Surplus Solar energy:
   - Revenues from surplus solar electricity: it describes how much the conpensated revenue the PV-owner can gain when the PV-generated electricity is exported into the local grids.
   - Geographical compensation: it explains if the production and usage of the PV-generated electricty can be in different locations.

(3) Other system characteristics
   - Reulatoray scheme duration: it shows how long the regulatory scheme will work.

- System size limitation: it describes the capacity scale of the PV systems can be allowed according to different consitions.
- Third-party ownership: It states when the consumer is qualified to own some specific kind of the generation assets.
- Other requirements: it means any additional terms that are not mentioned above.

In the proposed energy hub, the increased PV self-consumption service belongs to both primary and secondary service layers. Firstly, the increased PV self-consumption should create benefit for the PV-owner as the primary service. The graphic outline of the demand pattern, PV generation, and self-consumption of a building in one day in Figure 18 will be used to explain the fundamental principles of this service case. Moreover, it is necessary to make the assumptions as to the prerequisite: the regulations of the local utility allow the PV-owner to own the assets, connect to the grid and use the solar energy in different locations with the appropriate size of the system. If there is any condition that could not meet the assumptions, the corresponding adjustment can be easily done accordingly. As can be seen in Figure 16, areas B + C together represents the whole solar energy production for one day from around 04:00 in the morning to around 21:00 in the night. To maximize the self-consumption, the electricity converted by the PV system starts to supply the load in the building since the first second of the production. Also, from the beginning to the point P in Figure 16, the total electricity produced by PV panels will directly supply the consumers, which is not enough for the total power demand. Thus, the rest of the demand will be satisfied by drawing electricity from the local grid. Then, it is known from Figure 16 that PV-produced electricity is much more than the demand needs. In this case, the extra solar energy will be reserved in the battery storage systems of the energy hub instead of exporting into the grids, which is shown as area B. After this, the same situation begins just as the case before the point P. Overall electricity generated by the rooftop PV panels is used for the on-site load demand until the sunset. The rest of the on-site load can be supplied by the local utility, shown as the second area A. Using this service means no reservation of the solar energy to use it as much as possible.

When considering to use the increased PV self-consumption on the secondary layer of the energy hub, one opportunity left from the primary service layer is the extra energy stored in the battery storage system of the energy hub, from point P to point Q. There are two ways to create value from it. The first way is to let the energy hub members use it in the time it is generated. The neighbours could be either battery-owner itself or other neighbours who establish the contract with battery-owners. This method could directly create the monetary value for the PV-owner. The second way is to reserve it in the battery without cashing it out to leave the right of the usage of the electricity in the battery to the battery-owner. However, in return, the battery-owner should reserve the same capacity of the storage for the PV-owner. So, the PV-owner could ask for the withdraw in the future when there is no sun outdoor or during peak hours. These approaches can help to minimize the export of the electricity produced within the energy hub and create their own benefits.

What are the challenges?

The most crucial problem that cannot be ignored is about the regulations and policies of different utilities in every country or region. So it can be challenging to make every aspect of this service plan standardized in details. Even the application of PV systems has been growing rapidly; there is still a long way of the improvement of the related technologies and regulations to explore in the future.

3.5 Back-up power guarantee service

As one of the most basic functionalities of the battery storage system, back-up service seems to be mentioned not that often. However, it is not because this function is not expected by users any more. On the contrary, this back-up service has already been treated by most of the customers as the default function. According to a survey done by [36] in U.S., there have been already more than 1 million PV systems installed on the residential rooftop in U.S., not to mention adding the number of the commercial PV users. Facing the discontinuity of solar energy due to the sunrise and sunset, installation of the battery storage system could be the following step of the PV-users, or the battery storage has already been applied in those buildings with PV panels.

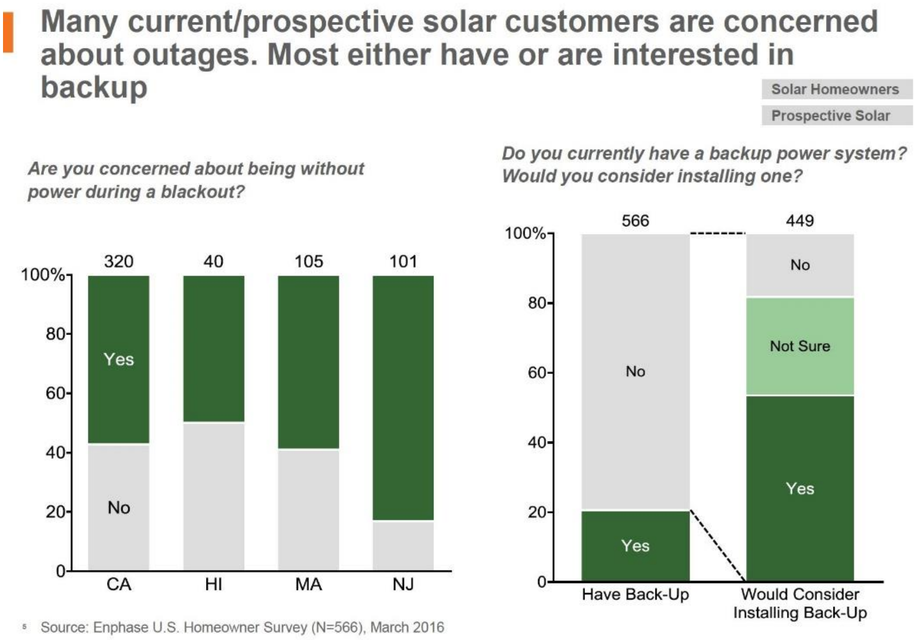


Figure 17 A survey of installation of the back-up battery [36]

According to the Figure 17 from the survey of [35], back-up function still takes its own place as one of the indispensable function while lots of ancillary services are being discussed widely.

WHAT IS THE BACK-UP SERVICE, AND WHY IS IT NECESSARY?

There are usually two different names to call this service in many kinds of literature, which are backup service and black start service. In other words, the backup service can be understood as the service to provide back-up power to the user in order to ensure the regular usage of the electricity during a failure of the local grid. The size of the battery storage system will decide the scale of this backup service, which could vary from power quality maintenance in seconds for industrial operation to keeping power supply for the residential users or one commercial building for days. In this case, it will solve the problem when there could be no electricity supply during the event of grid failure. Also, the consumers will not be affected by the unexpected failure from the beginning of the failure to the power restoration.

In addition to this understanding, there will be another definition added to this service of the energy hub. It can be one kind of service provided by the battery-owner to the other members in the energy hub which is a particular back-up power reservation for one neighbour to cope with any accidents that may happen during any significant events. The details of the operation will be explained in the following context.

HOW TO REALIZE BACK-UP POWER SERVICE IN ENERGY HUB?

As the fourth service that has been included in both service layers of the energy hub, the back-up service might play slightly different roles on two layers. It can be interrupted as two different understanding of the back-up service as the primary service. Firstly, it can be understood as the backup service prepared for the sudden grid failure. Generally, the battery storage will be charged by PV panels when there is sunlight outside and probably by the local grid during off-peak hours in rainy days or night time. One condition that needs to be satisfied is that the battery should be sufficiently charged before some specific time in the morning, and this specific time could be determined by the electricity usage habit in the local regions. It is to make sure if any accident happens in that day, the battery is fully prepared to supply the energy to the battery-owner in a short time. As the second definition of this service, the sufficiently-charged battery is not for the emergence of a grid failure, but it is for some specific significant event hosted by the battery-owner, like a press conference, a concert or a significant surgery. This operation is relatively easier to prepare cause these kinds of the event are usually scheduled in advance, which is to ensure the battery stores enough energy for the event in case any accidents unpredicted occur.

Secondly, the back-up service is provided by the battery-owner to other members in the energy hub. The purpose of this service is similar to the second understanding of the primary back-up service above. The cooperation between the battery-owner and the neighbours could be set in this way: if there is going to be a significant event happening hosted by one of the other energy hub members, the sufficiently-charged battery can be used as one service traded from the battery-owner to the event host with the appropriate price in order to make sure the event can be finished successfully. There could be two different prices of this trade:

one is for the fully-reserved energy without being used during the event, and another one is for the fully-reserved energy with being used during the event. According to these requirements, a short-term contract can be established. Therefore, the event host does not need to worry about any accident of the power supply for the event while the battery-owner can get the benefit directly from this service trade.

WHAT ARE THE CHALLENGES?

One potential challenge that could be faced during the implementation of the back-up power service is how to keep the balance between the daily use of the battery capacity and constant enough reservation for the black start. The tricky problem here is the unpredictability of the event of the grid failure. Moreover, if the total amount of the energy needed for the black start of the consumer is pretty extensive, the reservation of the electricity stored in the battery storage system should always be sufficient, which will limit other usages of the battery.

3.6 PROVIDING FLEXIBILITY TO P2P TRADING PLATFORM

There is a unique service case listed only on the secondary layer of the energy hub, which is acting as the flexibility provider to P2P trading platform. This service case is built on the connections either between the battery owner and the neighbours or between the energy hub and the other trading platform. It is developed to explore the value of the energy hub as much as possible.

WHAT IS THE FLEXIBILITY PROVIDER TO P2P TRADING PLATFORM AND WHY IS IT NECESSARY?

Traditional energy trading is usually in a unidirectional way with electricity transported from far-away generators to the end-users over a long distance, when the cash flow is in the other way round. On the contrary, the peer-to-peer (P2P) energy trading develops the multiple-directional energy trading in a geographical region [49]. So this new trading form has attracted more attention from different industries and disciplines. There already have been several trials of the concept of the energy trading platform being developed over the world, for example, Powerpeers and Vandebron in Netherlands and Piclo in the UK [49]. How to keep the balance between the supply and demand sides is also a significant issue that needs to be coped with carefully in order to make the operation of the whole P2P energy trading platform smoothly and successfully. When the imbalance is happening, there should be a role providing the flexibility to participate in the P2P energy trading in order to erase the imbalance, which could be the generators or the battery storages with enough capacity.

HOW TO REALIZE PROVIDING FLEXIBILITY TO P2P TRADING PLATFORM FROM THE BATTERY?

There are two different aspects to view the role that battery can play as the flexibility provider to P2P energy trading platforms.

1. There exists a P2P energy trading platform in the energy hub, in which the battery storage system acts as the main element and the foundation of the platform.

2. When the existing P2P energy trading platform is outside of the energy hub, the battery can act as the third party to partly be involved with the platform to provide flexibility when an imbalance occurs.

The market design of the first perspective of this service case is shown in Figure 18. There exists a P2P energy trading platform in the energy hub, and it applies one centralized battery to the P2P energy trading platform to let the prosumers and consumers trade locally. The battery system can be owned by the community or any energy hub member as long as it is built behind the meter and can be fully controlled by the energy hub.

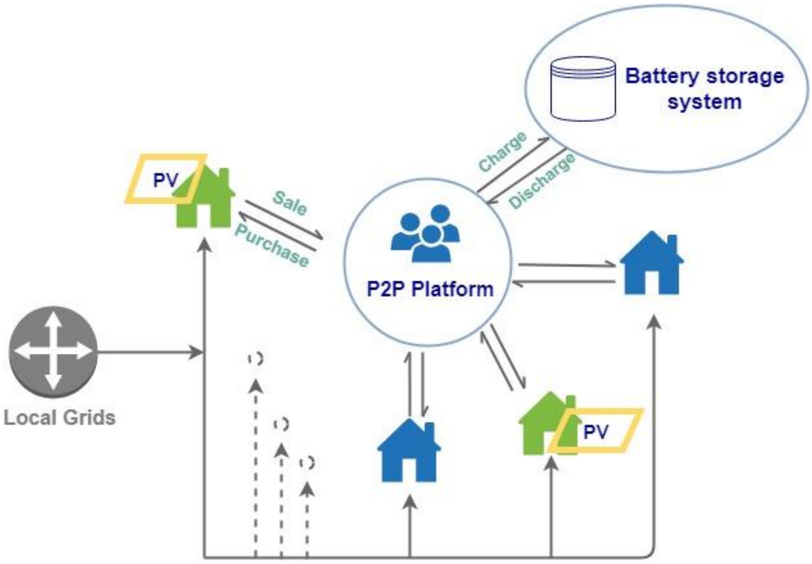


Figure 18 Local P2P platform with centralized battery

Since the energy hub is connected to the grid, then the major or partly energy demand of each consumer could still be satisfied by the grid. It is set that the battery can only be charged by the renewable energy generation of the prosumers in the energy hub, and the prosumers will get the compensation. Meanwhile, discharging from the battery is available for each user with the rate that can be a bit higher than the compensation rate. It is important to leave some margin capacity in the battery for the small-size flexibility in case when the demand in total suddenly increases in a short time. And after the small-size flexibility provided by the battery runs out, the local grid can participant in at the last. In this case, because the whole P2P platform and each member are connected to the grid, the imbalance will not be such a serious problem for all the consumers and prosumers.

The second perspective of this service case is quite unique, of which the service range is already out of the energy hub expanding to the third party. The P2P energy trading platform operates outside of the energy hub, instead of existing within it. When there are no needs from the other service cases for the battery storage system at that time and there are still sufficient capacity left in the batteries to deal with the imbalance, then the request from the external P2P trading platform can be satisfied by the battery storage system of the energy hub. And the battery-owner could get the compensation as the payback, as can be seen in Figure 19. A short-term contract could be established between the battery-owner and the operator of the P2P trading platform. In this case, the cooperation mode can be more adaptable and flexible accordingly.

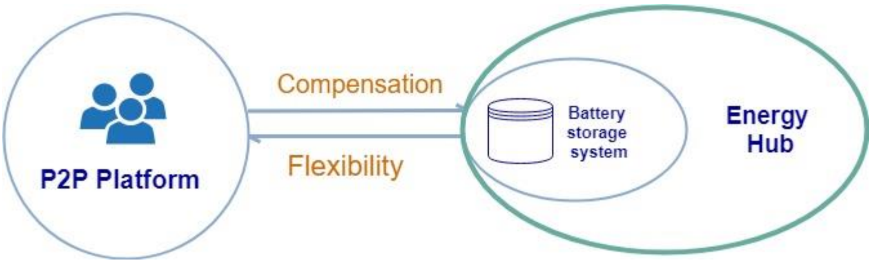


Figure 19 Battery acts as flexibility provider to the P2P trading platform

WHAT ARE THE CHALLENGES?

As one of the most popular forefront topics, the service case covers the subjects of renewable resources, behind-the-meter grid-size battery, P2P trading, and flexibility. Thus, there are limited pieces of literature that could be references or guides. And considering both technology development and related regulations of different regions, there is ample space for the growth and improvement. Whether the behind-the-meter battery can play the role is depending on the local regulations and the local electricity market.

3.7 INTEGRATION OF DIFFERENT SERVICE CASES

In this whole chapter, different service cases on both layers have been discussed. Each service case explores the value of the battery storage system in distinguishing aspects, and also they occupy different time duration of the battery storage system. Challenges are existing for every service. When developing an energy hub for a specific community in reality, it is not necessary and practical to put all service cases together. Instead, it is significant to select the service cases smartly and make them working together as the whole to realize ‘1+1 $>$ 2’, which means to find a smart arrangement among each service cases and make appropriate sacrifices in order to create the highest value for the energy hub and contribute to the society. In most cases, local regulations of the utilities and electricity market can play a crucial role in it.

CHAPTER 4.

CASE STUDY IN ZUID-OOST AMSTERDAM REGION

Zuid-Oost Amsterdam region is selected as the example community for the further study of the energy hub methodology. The reasons will be explained in this chapter with a description of the grid connection and general situation in this area. And also, the peak moment scenario will be shown to make the energy hub functions more clear

4.1 RATIONALE BEHIND CHOOSING THIS AREA

A fundamental concept has been given in Chapter 3, indicating how two service layers form the energy hub in the community level with the grid-size battery storage system. In this chapter, a case study will be established to put the proposed energy hub methodology into practice. The site of the case study will be located in the Zuid-Oost Amsterdam region. To be more specific, the location will be on the western side of Bijlmer-Centrum, as shown in the bigger red circle in Figure 20.

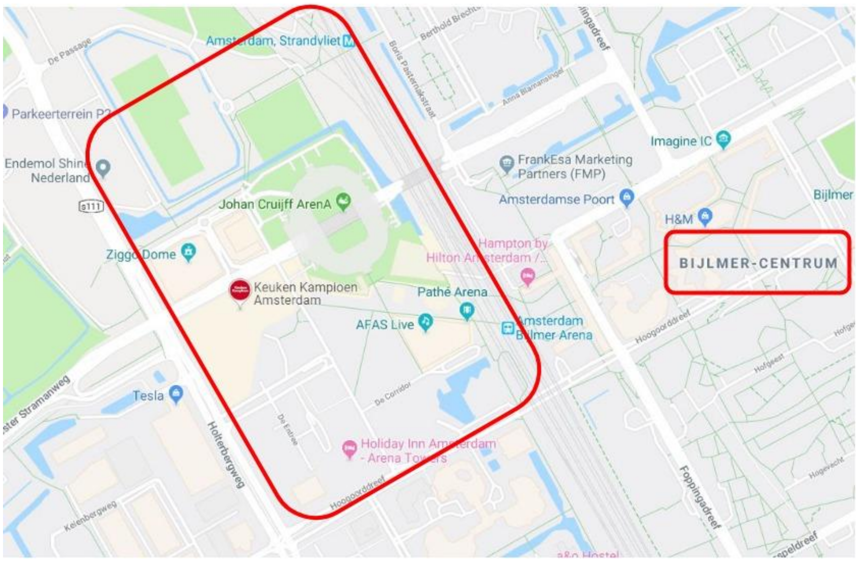


Figure 20 Site selection of the case study using https://www.google.nl/maps

The location of the case study is set on the western side of Bijlmer-Centrum due to three major reasons.

- In the region within the bigger red circle in Figure 20, it is a commercial community including one ArenA, two concert halls, several large offices, restaurants, cinema, etc. They are all connected together with the battery-owner on the grid.
- There is a grid-size battery storage system buried under the football field of Johan Cruijff ArenA (used to be Amsterdam ArenA), which is in the centre of this selected region [37].
- The grid-size battery storage system consists of the 280 second-hand Nissan LEAF batteries, in which way it recycles the electric vehicles' batteries and brings out the largest value of them.
- There is a PV system on the rooftop of Johan Cruijff ArenA, consisting of 4200 PV panels and other components [37].

4.2 INTRODUCTION OF THIS REGION

The selected Zuid Oost Amsterdam region, shown in Figure 20, is a comprehensive business community containing energy consumers with different functions. Among them, Johan Cruijff ArenA, Ziggo dome, and AFAS Live are three buildings that always schedule large-scale events.

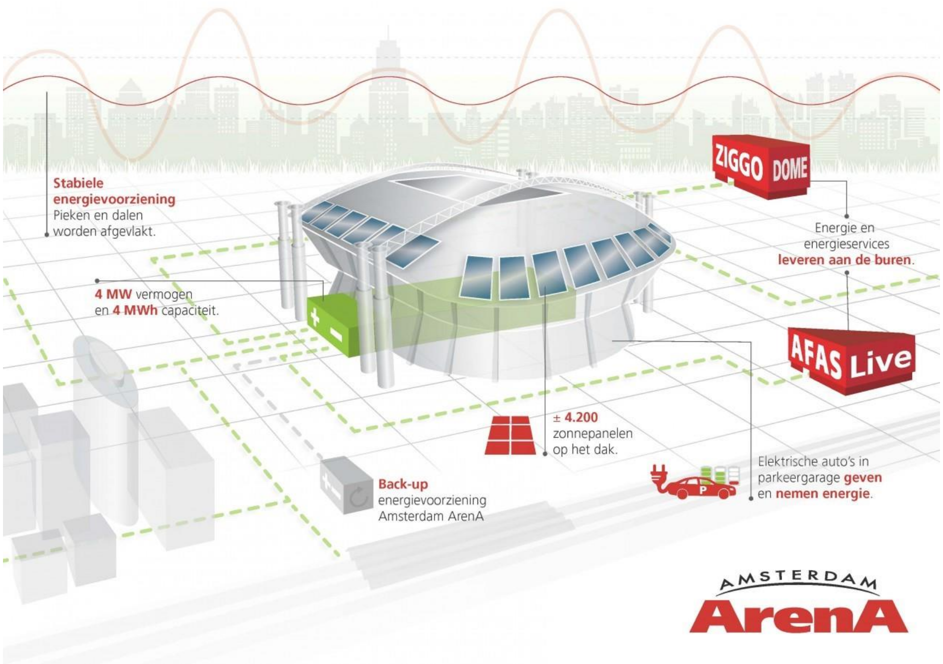


Figure 21 Installations of Johan Cruijff ArenA [37]

For Ziggo dome and AFAS Live, many scheduled musical events are going on in both of them. For Johan Cruijff ArenA, lots of football matches and concerts are hosted every year in it. Three of them could be the top three electricity consumers during the event night in this region, compared to other neighbours, like the Pathe cinema, the strip malls, and several hotels. And, the whole neighbourhood is supplied by Bijmer Noord substation at present.

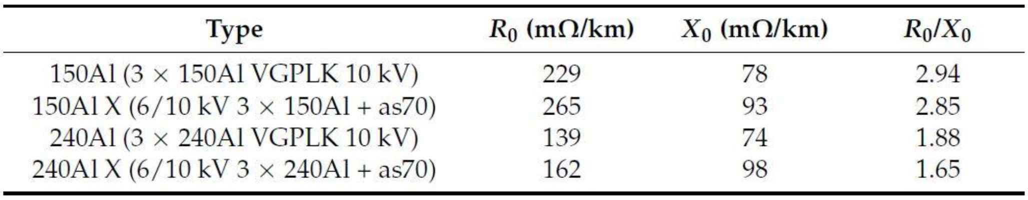
What is more, the implementation of one unique project aroused lots of attentions from multiple industries recently, which is the installation of the extensive battery storage system below the football field in the Johan Cruijff ArenA. It is an outcome of the cooperation among the Johan Cruijff ArenA, Nissan, Eaton, BAM and The Mobility House, which is supported by the Amsterdam Climate and Energy Fund (AKEF) and the Interreg SEEV-City projects (a sister project of EV ENERGY), as the Figure 21 presents. The current capacity of this battery storage system is 3 MW/2.8 MWh, and it could be expanded to 4MW/4MWh in the future comprising 280 second-hand Nissan LEAF batteries, according to [38]. The Nissan LEAF battery consists of air-cooled, stacked laminated lithium-ion manganese oxide batteries manufactured by Automotive Energy Supply Corporation (AESC), which means the whole battery storage system is using Lithium-ion storage technology that is an excellent arrangement for extensive size capacity storage system for the energy hub application. Meanwhile, there are four bi-directional inverters provided from Eaton, and the whole system is managed by the control system from The Mobility House. It is called the largest energy storage system powered by second-life batteries used by a commercial business in Europe. The current installed capacity of the battery storage system is enough to supply several thousand households [37]. This system is believed to provide a more effective and stable electricity supply environment for the stadium itself, the audients, even the neighbourhood and the whole grid.

This whole project could act as the pioneer of the application of the grid-size battery storage installed behind the meter, used by a commercial business in Europe. Combining the proposed energy hub methodology in Chapter 3 and this project idea together could provide a brand-new perspective to explore the values that a grid-size battery could bring to the whole community.

4.3 LOCAL GRID CONNECTION

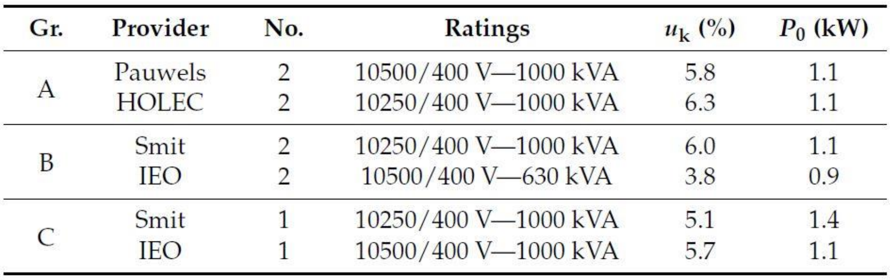
After the site selection, it is necessary to get the local network topology for the power flow simulation. The grid connection used in the following study is referred to the network topology given in [39], as presented in Figure 22. There are 30 outgoing feeders in this topology, which is currently controlled by Liander. It can be observed that the neighbourhood currently is supplied via two relevant feeders coming from 150/10.5 kV Bijlmer Noord substation. Also, the relevant feeders are all underground cables, according to [39], of which the type and the length of each section is also shown in Figure 22. To be more detailed about the cables used to connect every consumer and each feeding bus, the specification of the main conductors of the cables are given in Table 1. According to the relevant information in [39], the battery-owner, Johan Cruijff ArenA itself is powered through eight 1000 kVA and two 620 kVA transformers, of which the parameters are shown in Table 2. The network shows that the transformers used to support the ArenA are divided into three groups (A, B and C) probably based on the physical locations. The data related to the exact reconfiguration of this network is not available online. Thus, the topology is assumed to be fixed in the following simulation [39].

Table 1Specifications of the cables used in the Johan Cruijff ArenA network [39]



Type	R_0 (mΩ/km)	X_0 (mΩ/km)	R_0/X_0
150Al (3 × 150Al VGPLK 10 kV)	229	78	2.94
150Al X (6/10 kV 3 × 150Al + as70)	265	93	2.85
240Al (3 × 240Al VGPLK 10 kV)	139	74	1.88
240Al X (6/10 kV 3 × 240Al + as70)	162	98	1.65

Table 2 Specifications of the transformers used to support the Johan Cruijff ArenA from grid [39].



Gr.	Provider	No.	Ratings	u_k (%)	P_0 (kW)
A	Pauwels	2	10500/400 V—1000 kVA	5.8	1.1
	HOLEC	2	10250/400 V—1000 kVA	6.3	1.1
B	Smit	2	10250/400 V—1000 kVA	6.0	1.1
	IEO	2	10500/400 V—630 kVA	3.8	0.9
C	Smit	1	10250/400 V—1000 kVA	5.1	1.4
	IEO	1	10500/400 V—1000 kVA	5.7	1.1

Considering all the references on hand, both the network topology and the relevant parameters of cables and transformers used in the local power system, they are not enough to simulate the operation of the grid in that whole area with all consumers getting involved. Therefore, several necessary assumptions are going to be made in the following context in order to get the simulation result.

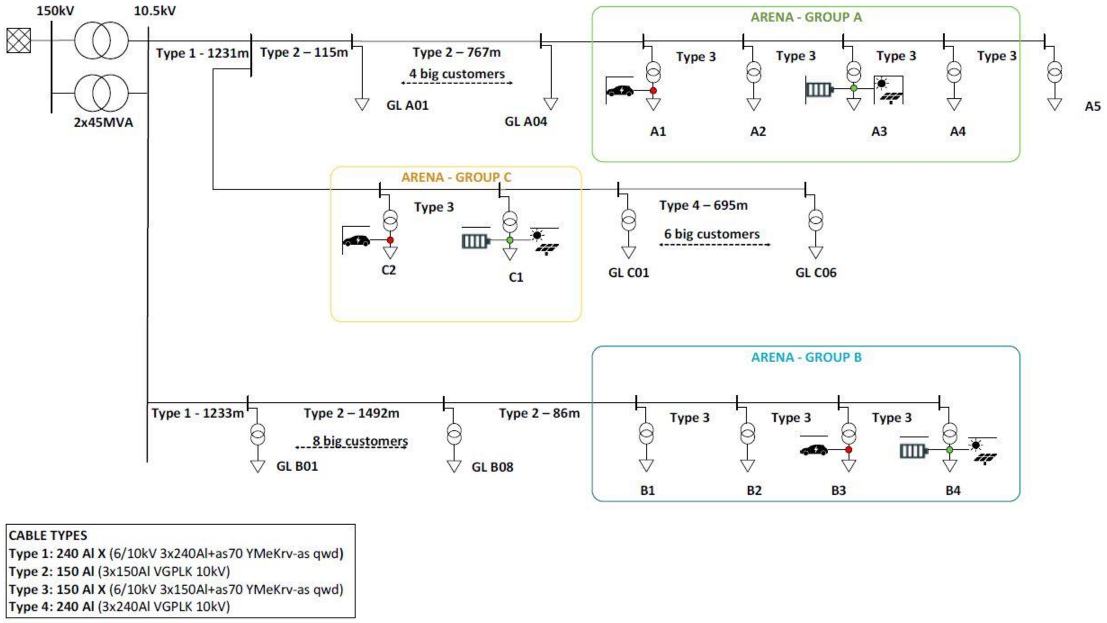


Figure 22 Single line diagram of the network supplying the ArenA [39]

Assumption 1 :

To complete all the consumers on each feeder, the assumptions in Figure 24 and Table 3 are made based on the google map and the fact that usually the cables take the directions of the roads buried under the roads and streets, as shown in Figure 23.

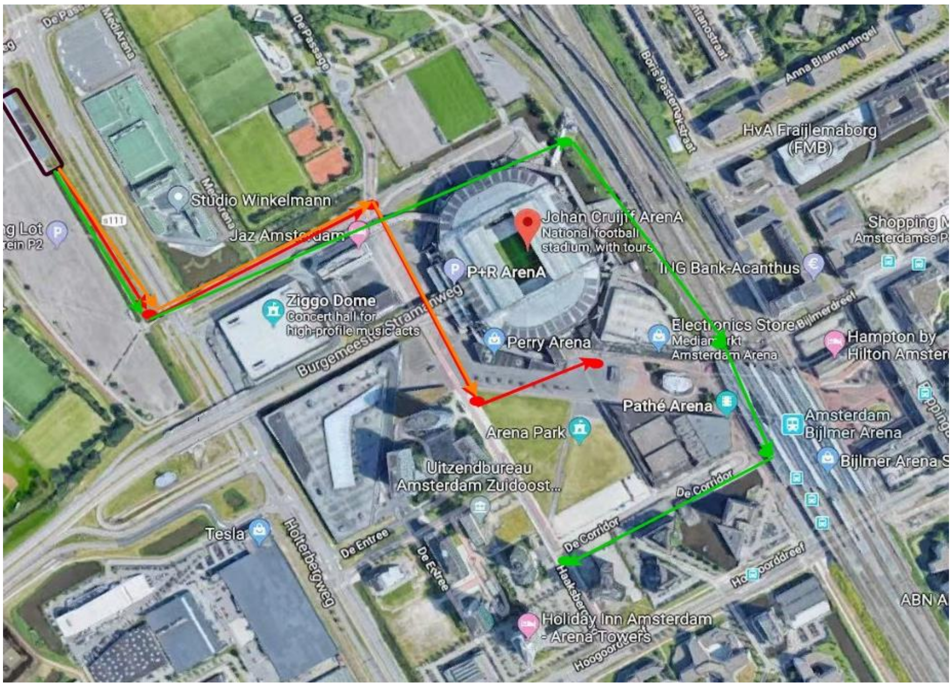


Figure 33 Assumptions of the grid connections based on Google map [39]

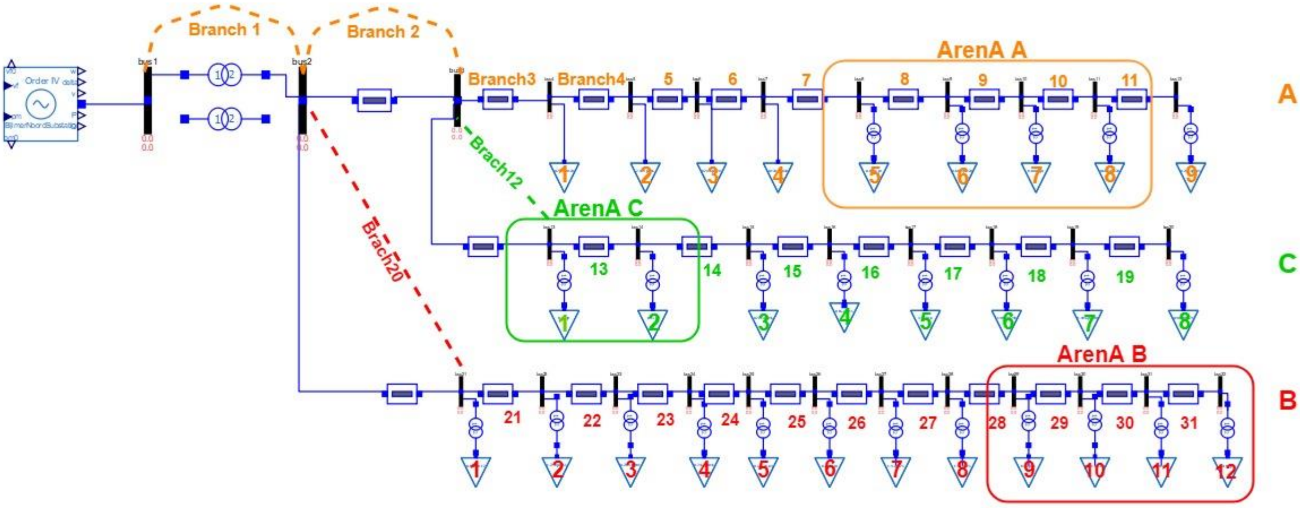


Figure 24 Assumptions of the grid connections based on Google map

Table 3 All consumers on each feeder in the selected area

Feeder A	**Feeder B**	**Feeder C**
A1: Large Office1 Part I (1114BC)	B1: Large Office1 Part II (1114BC)	C1: Johan Cruijff ArenA C
A2: Ziggo Dome Part I	B2: Ziggo Dome Part II	C2: Johan Cruijff ArenA C
A3: Jaz Amsterdam Part I	B3: Jaz Amsterdam Part II	C3: MediaMarkt
A4: L.T.C. Strandvliet Part I	B4: L.T.C. Strandvliet Part II	C4: Pathe Cinema
A5: Johan Cruijff ArenA A	B5: Villa ArenA	C5: ASAS Live
A6: Johan Cruijff ArenA A	B6: Deutsche Bank Nederland	C6: Large Office2 (1101BE)
A7: Johan Cruijff ArenA A	B7: ICCA	C7: Emerald Investment
A8: Johan Cruijff ArenA A	B8: Restaurants group (1101DL)	C8: Holiday Inn
A9: Johan Cruijff ArenA A	B9: Johan Cruijff ArenA B	
	B10: Johan Cruijff ArenA B	
	B11: Johan Cruijff ArenA B	
	B12: Johan Cruijff ArenA B	

Figure 24 shows the complete network topology of the selected community that is made using OpenModelica software, which is remade and improved from Figure 22. The basic idea of making the assumptions are shown in Figure 23, which is based on the physical road connections. And the orange, red and green colours in both Figure 23 and 24 are corresponding while orange represents feeder A, red represents feeder B and green represents feeder C.

4.4 ENERGY CONSUMPTION DURING PEAK MOMENT

In order to explore the feasibility of putting the proposed energy hub methodology into the practice in the selected location, the energy consumption during the peak moment will be evaluated. In other words, the worst scenario of power demand side that might happen during one day in the community will be simulated using MATPOWER. To be more specific, the Johan Cruijff ArenA, Ziggo Dome and AFAS Live are all hosting the large-scaled events, and all the restaurants, all strip malls and the cinema are full of customers, which basically means all the buildings are busy during the peak hours. In general, this peak period is around from 7:00 pm to 9:00 pm in a day.

First, the load profile of the battery-owner, Johan Cruijff ArenA, is simulated via MATPOWER, which is referred to [39]. According to Figure 25, it is evident that the load profile covers two days demand pattern when there is an event hosted in the stadium on the first day making the highest power demand get to around 2.5 MW.

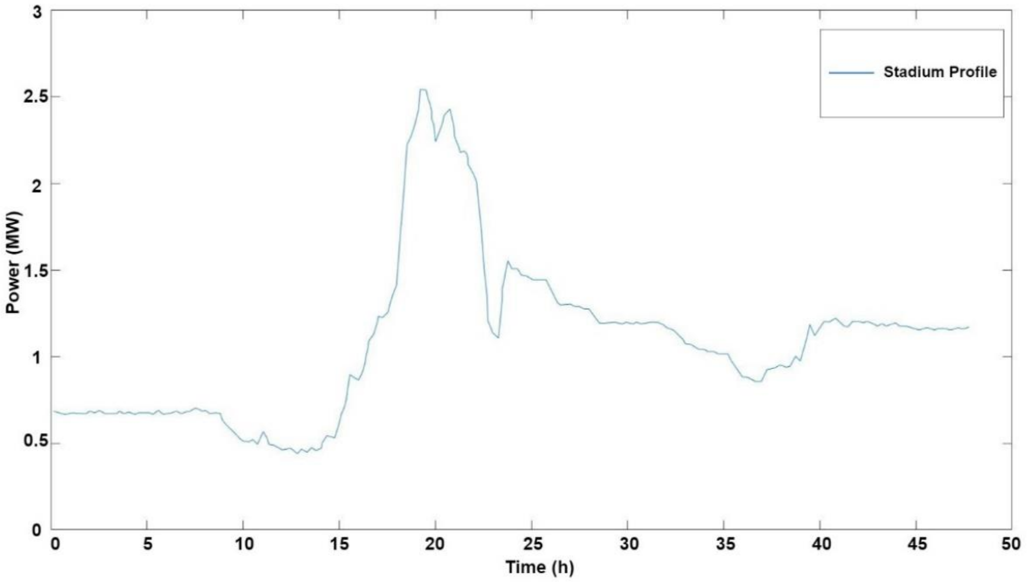


Figure 25 Load profile of the battery-owner in two days used in the simulation [39]

After getting the two-day load profile of the battery owner, demand patterns of other consumers connected on the same feeders with the battery-owner are needed to calculate the power flow during the peak period.

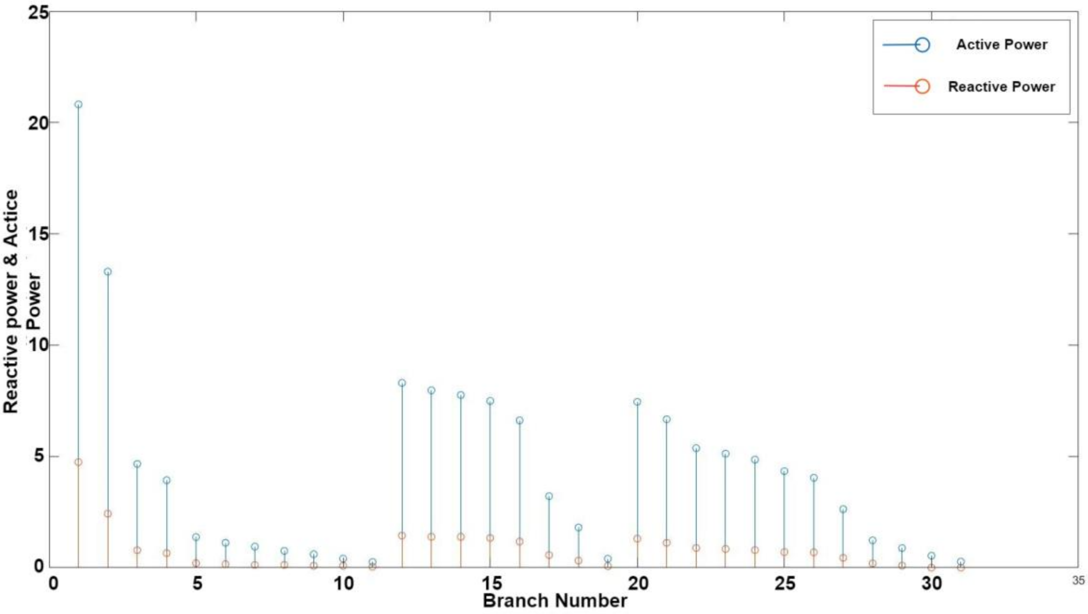


Figure 26 Active Power & Reactive Power of each branch on the peak moment

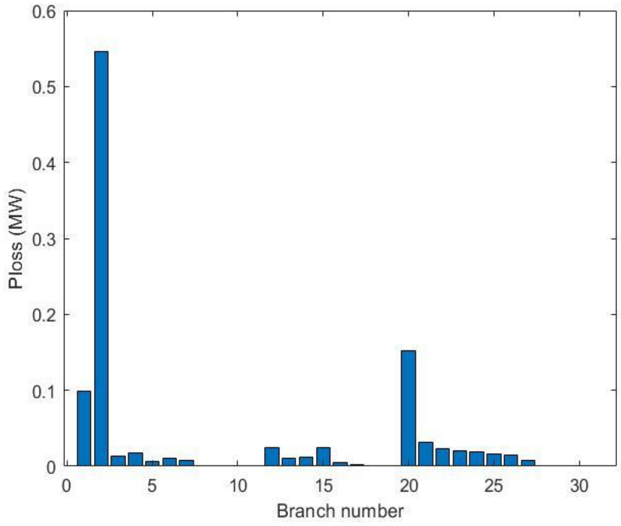


Figure 27 Power loss of each branch on the peak moment

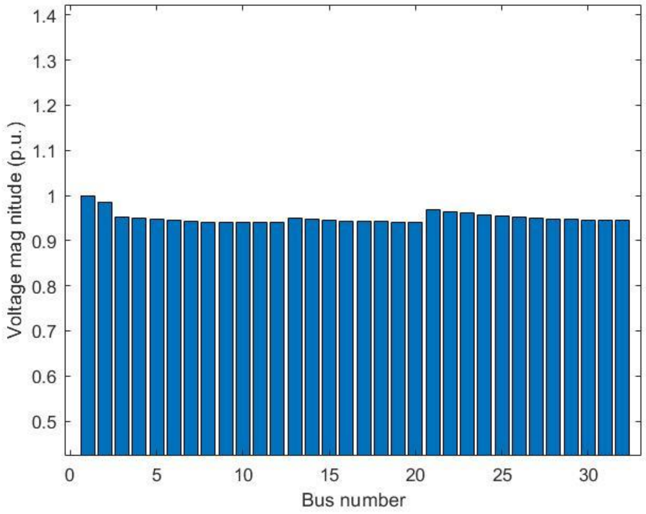


Figure 28 Bus voltage magnitude on the peak moment

Due to the limited data on hand, the assumptions are made as follows:

Assumption 2 :

The highest power demand of all the consumers on the Feeder A, B and C are happening on the same moment.

Assumption 3 :

When it comes to the energy consumption data needed to put into simulation, the Chicago load profile could be applicable among the limited resources [40]. It contains load profiles of full-service and quick-service restaurants, offices and hotels in large, medium and small size, stand-alone retail, strip malls and many other types of buildings. To be more accurate, the data of big shopping mall is from one detailed case study report in Netherlands that can be found in [41]. And then, the data of Ziggo dome and AFAS Live will take the load profile of the Johan Cruijff ArenA as the reference given in [39]

Assumption 4 :

The power factor of each outgoing feeder that has reactive power demand is assumed to be 0.8, which is a common power factor rate.

And also, the parameters of the substation transformer are referred to the parameters of 'High voltage be created for other situations under better conditions if the outcome of the case study positive. Figure 26, 27, 28 indicate the apparent power and power loss of each branch and voltage magnitude of each bus on the peak moment. The outgoing feeders with large commercial consumers, such as the Johan Cruijff ArenA, Ziggo Dome and AFAS Live, have high demand for the reliable power and stable voltage supply. And the total power demand of the entire community could be pretty big during peak time, which puts enormous pressure on the power grid.

4.5 SOLAR RADIATION

In the case study, there are 4200 PV panels on the roof of the battery-owner, and the energy generated by the PV system can be stored in the battery storage system to be used for creating higher value. To push forward the process of the case study, how much energy the whole PV system could produce in one day, and how the solar radiation varies in one day are significant to figure out.

$$E = A \times r \times H \times PR \tag{1}$$

Equation (1) can be used to calculate the overall energy produced by the PV panels in the case study. First, the overall area of the entire 4200 PV panels on the stadium's roof is around 7200 square meter, according to [43]. And then, the efficiency (r) of the commercial PV panels nowadays varies from 0.15 to 0.2 and the performance ratio (PR) could be about 0.85 for the commercial PV panels at present [44].

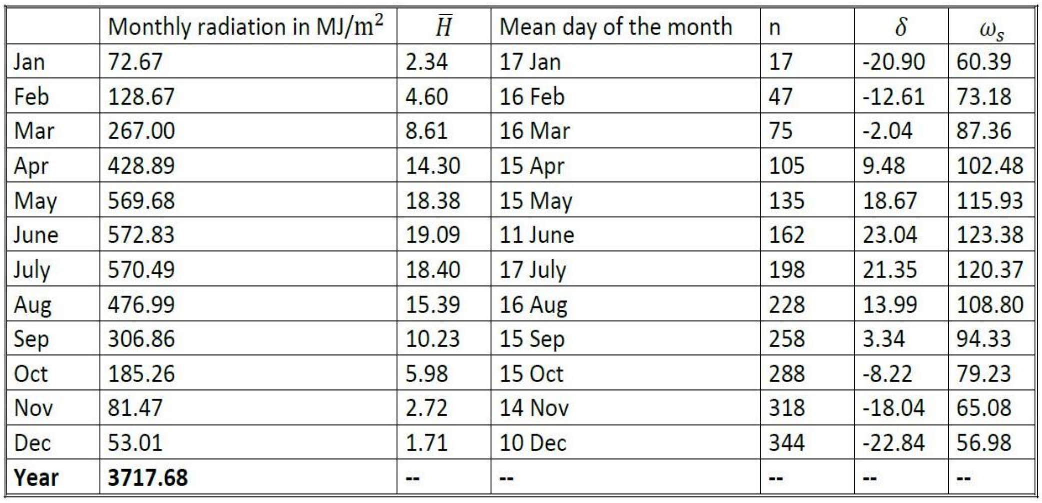
Assumption 5 :

The active area of the PV panels is the overall area of 4200 PV panels. The positioned angles will not be taken into considerations.

Efficiency (r) is assumed to be 0.18 while performance ratio (PR) is assumed to be 0.85

For further study, it is necessary to analyse the situation in two cases separately that are winter case and summer case due to the totally different sunlight conditions. Thus, June 11th and January 11th will be selected to continue the case study. These two days should have almost the most and the least solar radiation in one year while the solar radiation of other days should fluctuate in between.

Table 4. Monthly average radiation on a horizontal surface between 1990-2010 in MJ/ m 2 at Schiphol airport [44]



	Monthly radiation in MJ/m^2	$\overline{H}$	Mean day of the month	n	δ	ω_s
Jan	72.67	2.34	17 Jan	17	-20.90	60.39
Feb	128.67	4.60	16 Feb	47	-12.61	73.18
Mar	267.00	8.61	16 Mar	75	-2.04	87.36
Apr	428.89	14.30	15 Apr	105	9.48	102.48
May	569.68	18.38	15 May	135	18.67	115.93
June	572.83	19.09	11 June	162	23.04	123.38
July	570.49	18.40	17 July	198	21.35	120.37
Aug	476.99	15.39	16 Aug	228	13.99	108.80
Sep	306.86	10.23	15 Sep	258	3.34	94.33
Oct	185.26	5.98	15 Oct	288	-8.22	79.23
Nov	81.47	2.72	14 Nov	318	-18.04	65.08
Dec	53.01	1.71	10 Dec	344	-22.84	56.98
Year	**3717.68**	--	--	--	--	--

And for the annual average solar radiation on both selected days, the data will be referred to the Table 4, which indicates the monthly and daily average radiation at Schiphol airport that is quite close to the community selected for the case study. The unit will be changed from MJ/m 2 to kWh/m 2. Therefore, all the parameters are taken into considerations to get the overall energy production in the picked days.

Summer time, June 11th. $E = A \times r \times H \times PR = 5846.21$ kWh (7)

Winter time, January 11th. $E = A \times r \times H \times PR = 741.66$ kWh (8)

For the next step, the daily radiation curves are needed to be drawn. The data used for making the daily radiation curve is from [45]. The daily PV radiation of recent years in the whole Netherlands has been recorded by PVMD group of TU Delft with the data of Noord Holland province included. The hourly solar radiation data on the January 11^{th} 12^{th} and June 11^{th} 12^{th} in 2018 in Noord Holland province were input into MATLAB to get the daily solar energy generation curves together with the load profiles battery-owner, as shown in Figure 29 and Figure 30.

As can be seen in Figure 29 and 30, the PV-generated energy during the summertime can be higher than the peak power demand of the stadium, which means that it could be possible for the stadium to avoid the peak time if there is an appropriate arrangement of the battery and the PV system. And, the stadium may need the help from the off-peak grid and the battery to reduce the demand during the peak period due to the not sufficient sunlight in the wintertime. To see it in a bigger picture, Table 5 gives the energy output of the PV system on the roof of the stadium in different months over the year. As can be seen, the solar energy is totally enough to sufficiently charge the battery from April to August.

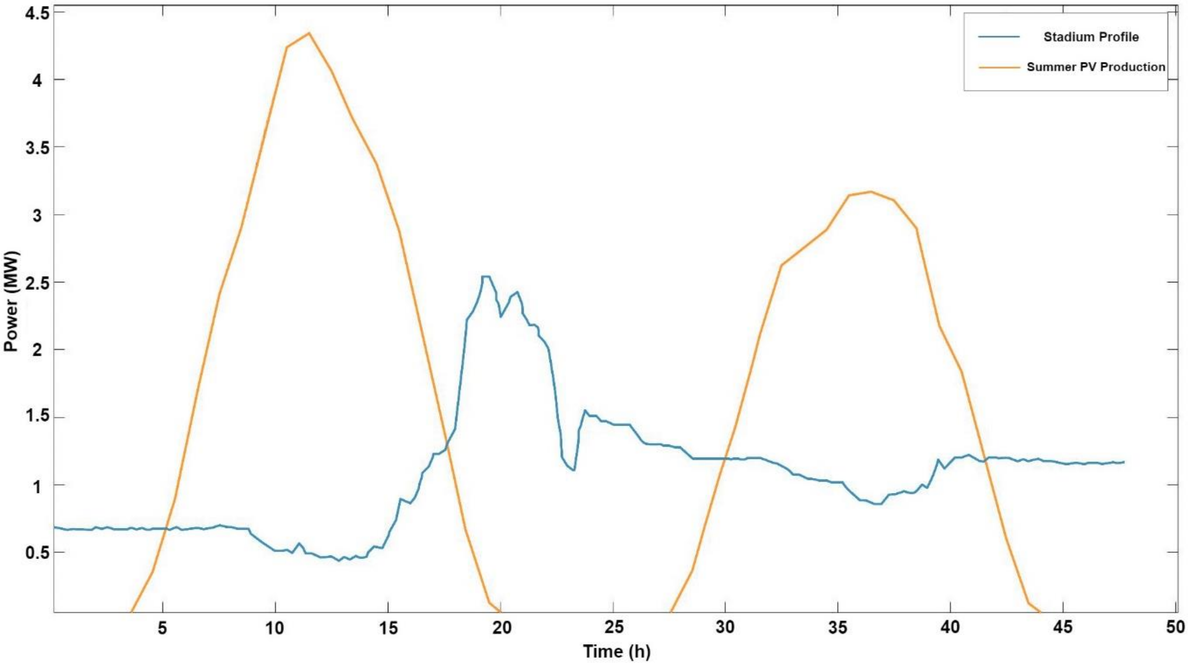


Figure 29 Daily solar radiation on 11 & 12-06-2018 in Noord Holland with the stadium load profile

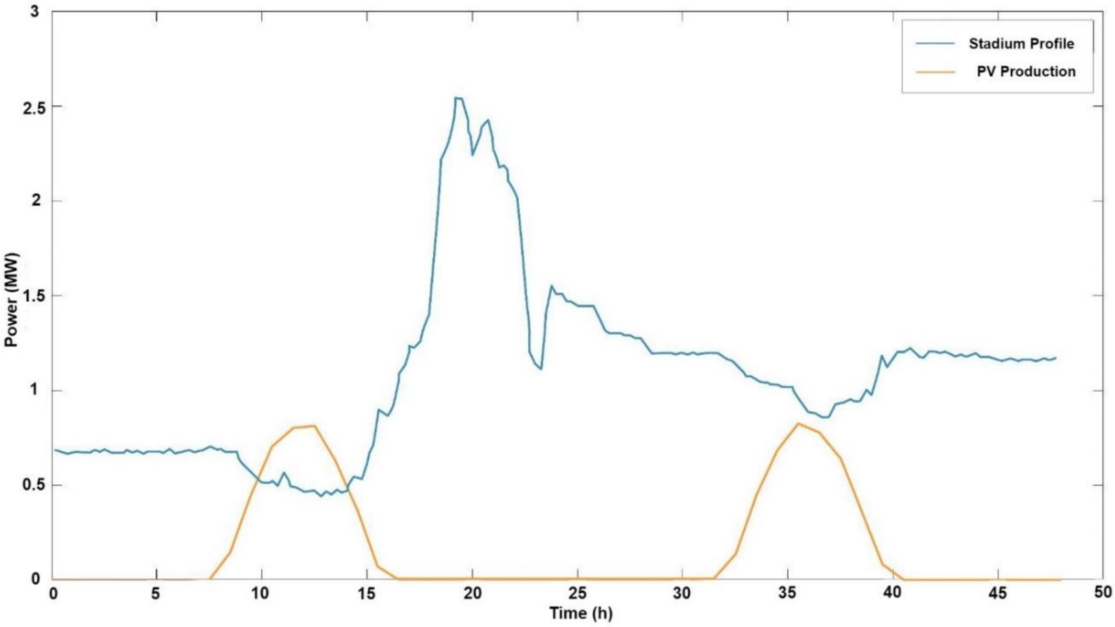


Figure 30 Daily solar radiation on 11 & 12-01-2018 in Noord Holland with the stadium load profile

Table 4 Energy generated by PV system of the battery owner in the whole year.

Month	Output Energy (kWh) / Day	Output Energy (kWh) / Month
Jan	716.6	22,254.8
Feb	1408.7	39,404.5
Mar	2636.8	81,767.4
Apr	4379.3	131,345.4
May	5628.5	174,461.7
Jun	5846.2	175,426.3
Jul	5634.9	174,709.7
Aug	4713.1	146,075.8
Sep	3132.9	93,974.34
Oct	1831.4	56,734.95
Nov	833.0	24,949.78
Dec	523.7	16,234.05

CHAPTER 5.

RESULT OF THE CASE STUDY

In this chapter, the outcomes of the case study using the proposed energy hub methodology will be given. The outcomes of the demand charge reduction service and the increased PV self-consumption service will be shown via cost saved and the carbon emission reduced while the other services can be performed by the explanation of the operation principles since the battery-owner and other neighbours are not using the TOU bill structure based on the tariff rates provided by the Liander below and the assumptions of no customized contracts between them and Liander. And each service case will firstly operate separately without considering other services. Finally, an integrated energy hub will be discussed considering all the services at the same time.

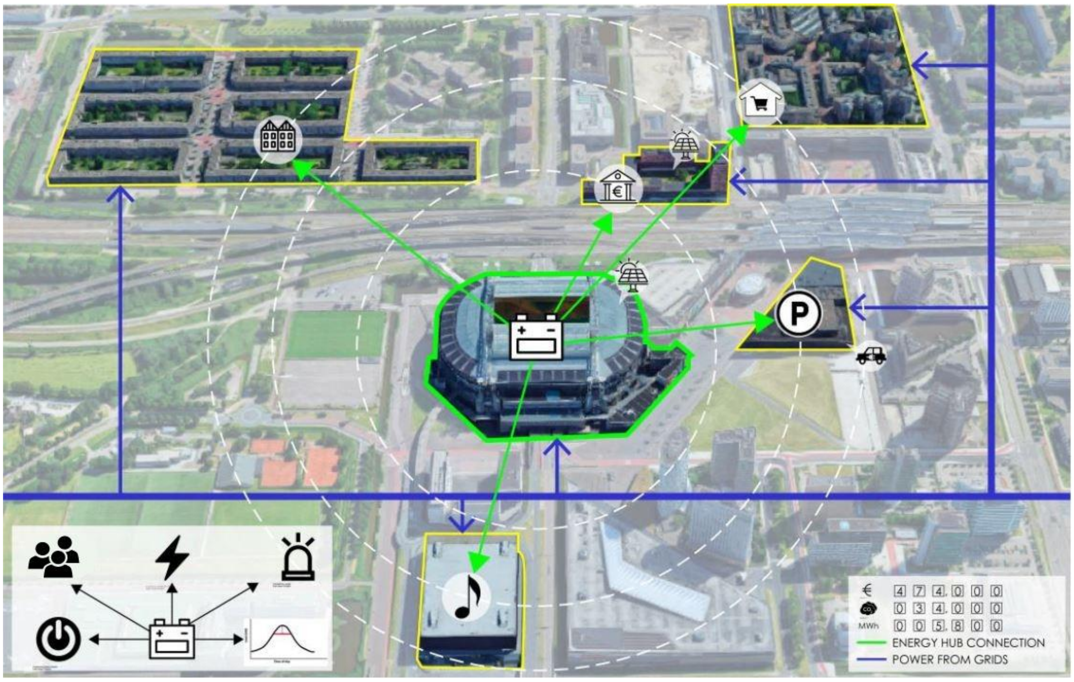


Figure 31 The energy hub with the integration of available services

5.1 ELECTRICITY TARIFF RATES OF THE LOCAL UTILITY

The first thing needed to realize different service cases of the energy hub into practice is the relevant tariff regulated by the local utility. It is found that Liander manages the power grid of the selected community. On the official website of Liander [46], the different categories of standard electricity rates can be found, and the 'Transport rates 2016 for large consumers' among all rates charging standard applies to the situation of the case study.

The large consumers here are defined as the consumers who have the connection larger than 3x80 Ampere, which is large business users by the great chance. According to Liander [46], the connection rates take charge of new connection building and maintenance. In addition to the charged connection rates, the transport of electricity is also charged with different market segments. The different market segments are divided based on the contracted capacity of the transport electricity. Every consumer should hold a contract with Liander, in which states how much the capacity is that Liander will reserve for the consumer in the power grid, which is named 'contracted transport capacity' [46]. The defined 'contracted transport capacity' indicates the maximum power demand that the consumer could request at any time in one year.

- For Sub-markets medium voltage (MS) and medium / low voltage (MS / LS)

The contracted transmission capacity applies indefinitely and can be increased at any time if it could fit the customer's connection capacity while decreasing the contracted capacity is also possible, but it needs some certain conditions. (1) The increment of the contracted capacity requested by the consumer itself will take effect on the first day of the month after the month in which the request is submitted. And the request for decreasing the contracted capacity will be only possible when the consumer has not increased the contracted capacity in the last 12 months. (2) If the consumer exceeds the contracted transmission capacity during one certain month, the contracted capacity will be automatically increased on the first day of the month of the excess. (3) If the consumer already made the contracted capacity adjusted downwards successfully, then the consumer still exceeds the reduced contracted capacity within twelve months after the request. In this case, the contracted capacity will be retroactively adjusted upwards. This retroactive adjustment takes effect on the date that the request for the reduction was first made

- For Sub-markets between medium / medium voltage (TS / MS), high / medium voltage (HS / MS), intermediate voltage (TS) and high voltage (HS)

The contracted transmission capacity applies for one calendar year. The customer could request the increment and reduction once in the meantime. However, only if there are some severe unexpected circumstances, it can be treated as the expectation [46]. When the consumer exceeds the contracted capacity, this capacity will then be increased to the value automatically [46]. This new contract will take effect on the whole year in which the excess happens.

Thus in total, the entire transport rate of one consumer contains:

- a rate for fixed transport
- a rate for contracted capital
- a rate for the actually transported power
- a rate for the maximum transport capacity that was measured that month
- a rate for the amount of blind energy purchased

Table 5 Transport rates for large consumers by Liander [46]

Transport rates 2016 for large consumers

Share market	Contracted transport capacity	Fixed-rate tax per month in € excl. VAT	Per kWh - high in € excl. VAT	Per kWh - low in € excl. VAT	per kWh per month - kW contract in € excl. VAT	kW max. month in € excl. VAT
LS	up to 50 kW	1.50	0.0334	0.0154	0.43	-
MS / LS	greater than 50 up to and including 136 kW	36.75	0.0088	0.0088	1.83	1.47
MS	greater than 136 to 2,000 kW	36.75	0.0088	0.0088	1.21	1.47
TS / MS or HS / MS	greater than 2,000 kW	230.00	-	-	1.77	1.98
TS	greater than 2,000 kW	230.00	-	-	1.59	1.91
HS [1]	greater than 2,000 kW	230.00	-	-	0.83	0.91

In the share market column of Table 6, LS stands for the low voltage that is up to and including 1KV, and MS represents medium voltage (from 1 kV to 20 kV). And the peak time of the LS market segment is from 7 a.m. to 11 p.m. from Monday to Friday. TS stands for intermediate voltage (50 kV), and HS is the high voltage that is higher than 50 kV.

5.2 DEMAND CHARGE REDUCTION SERVICE

The demand charge reduction service that was described in Chapter 3 can apply to the selected community in the Zuid-Oost Amsterdam region. Firstly, this demand charge reduction service of the primary layer will be discussed, which is only for the battery-owner. Now, it is assumed that the battery-owner, Johan Cruijff ArenA, mentioned in Chapter 4 is following the standard transport rates charged by Liander, instead of having a customized contract. According to the information collected in Chapter 3, the battery-owner in the case study should be included in the MS market share, and the contracted power capacity should be more than 2000 kW, as shown in the red circle. It is clear to notice that the fixed-rate tax per month for the stadium is 230 Euro, and the contracted power is 1.77Euro per kWh per month. In addition to the mentioned payments, the stadium still needs to pay the highest power consumption at any time in a month that is 1.98 Euro per kW. The demand charge reduction provided by the energy hub is aiming to decrease the contracted capacity from the range of 'greater than 2000 kW' (the red circle) to the range of '136 kW to 2000 kW' (the blue circle). And according to the regulation, the large consumers have to keep the highest power demand of the whole calendar year under 2000 kW to make this reduction request take effect. Thus, the demand patterns of not only the summertime but also the wintertime all need to make some adjustments. In this case, the difficulty for the battery-owner is when the big event is ongoing in the stadium, which can consume the largest amount of energy compared to other ways of consumption.

The operation of the demand charge reduction is presented in Figure 32 and 33. On the 11th and 12th June, the solar energy generation started at around 4:00 am and ended at around 08:30 pm, meanwhile the battery was being charged by the PV systems. And there was a large-scale event happening on the first day showed by the load profile, so the power demand was more than the tariff threshold for a while. Thus, the battery started to discharge when the power demand was approaching 2000 kW and kept the power supplied by the local grid at 2000 kW. This could be done by the control and monitoring system. Then when the control system could sense that the supply of the grid started to reduce from 2000 kW, the battery ended discharging. Since the battery storage system consists of 280 second-hand Nissan LEAF batteries, it is possible to both charge and discharge at the same time using different batteries.

The part of the original energy demand over the tariff threshold is estimated by MATLAB, which is about 1.13MWh. And the total energy consumption of Figure 25, the two-day load profile, is calculated by MATLAB as 7.3838 MWh. Also, the energy demand of one normal day with no event ongoing is assumed on the basis of the two-day load profile (Figure 25), which is estimated using MATLAB to be 1.0363 MWh. The capacity of the whole battery system is 4 MW/ 4 MWh.

The calculation of the total solar radiation per day shows: (1). Summer time, June 11th E = A × r × H × PR = 5846.21 kWh = 5.846 MWh. (2). Winter time, January 11th E = A × r × H × PR = 741.66 kWh = 0.74166 MWh The solar radiation is sufficient to charge the battery system to get 95% State of Charge on 11th June. And on 11th January, the battery system needs to charge partly from the power grid during the night time and partly from the PV system.

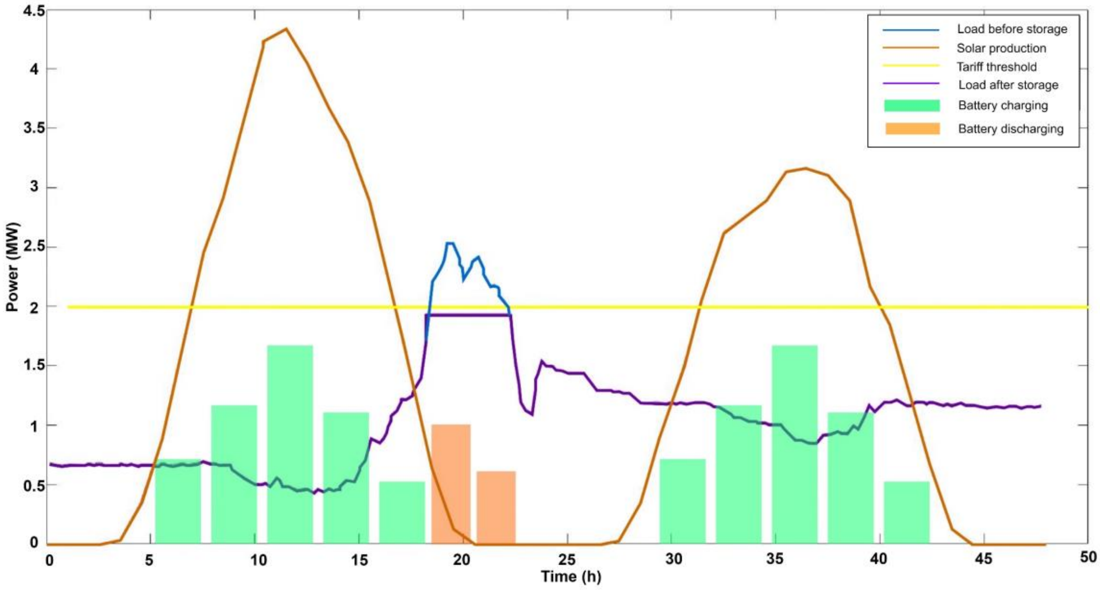


Figure 32 Demand charge service via battery storage on 11 & 12-06-2018

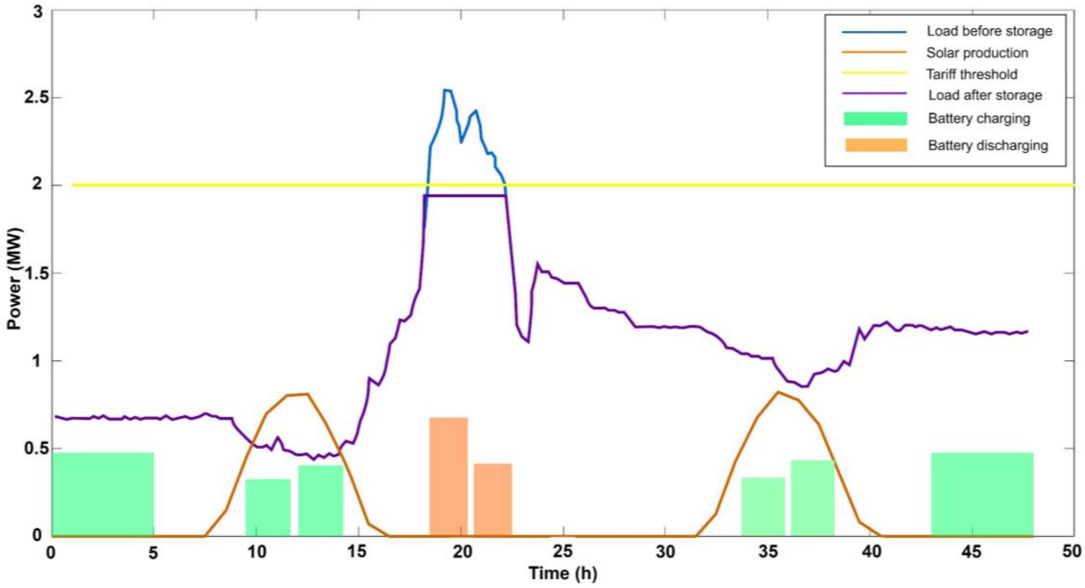


Figure 33 Demand charge service via battery storage on 11 & 12-01-2018

Table 6 Cost saved and Carbon emission reduction of battery owner by demand charge reduction

	Jan	Feb	Mar	Apr	May	Jun
Number of events in arena	1	2	3	2	2	3
PV Output (kWh) /Day	716.60	1,408.70	2,636.80	4,379.30	5,628.50	5,846.20
Energy Saved (kWh)	716.60	2,260.00	3,390.00	2,260.00	2,260.00	3,390.00
Electricity Bill Before(€)	71,523.80	75,421.90	90,325.40	79,090.40	80,924.60	88,491.20
Electricity Bill After (€)	47,319.50	48,116.90	56,937.90	50,624.70	51,878.70	55,684.00
Money Saved (€)	24,204.30	27,305.00	33,387.50	28,465.70	29,045.90	32,807.20
Carbon Emission Reduction (tons)	0.57	1.8	2.6	1.8	1.8	2.6
	Jul	Aug	Sep	Oct	Nov	Dec
Number of events in arena	1	1	3	2	3	2
PV Output (kWh) /Day	5,634.90	4,713.10	3,132.90	1,831.40	833.00	523.70
Energy Saved (kWh)	1,130.00	1,130.00	3,390.00	2,260.00	2,499.00	1,047.40
Electricity Bill Before(€)	71,523.80	71,523.80	88,491.20	80,924.60	88,491.20	80,924.60
Electricity Bill After (€)	46,819.40	46,819.40	55,684.00	51,878.70	56,762.00	53,345.90
Money Saved (€)	24,704.40	24,704.40	32,807.20	29,045.90	31,729.20	27,578.70
Carbon Emission Reduction (tons)	0.89	0.89	2.6	1.8	1.9	0.83
			Total saved cost (€) / year:			**345,785.40**
	Total Carbon Emission Reduction (tons) / year:					**20.1**

The benefits that the primary demand charge reduction service can create for battery-owner with the combined action of the battery storage system and local solar radiation and limitation of the tariff regulation are given in Table 7. The reduction of the electricity bill can directly indicate the monetary value provided by this demand charge reduction, which is € 345,785.40 over the year. This amount of bill reduction accounts for 35.7% of the original electricity bill (€967,656.5).

To calculate the electricity bill before and after, it is assumed there are *n* events occurring in the month with *N* days in that month. And it is calculated by MATLAB using the Johan Curijff ArenA load profile that the normal daily consumption with no event going on is around 1036.3 kWh. Moreover, the highest power demands with the service case and without the service case during the event ongoing are 1965 kW and 2541 kW. When the event occurs, the first day with event ongoing and the second day after in total consume 7383.8 kWh. Every demand charge reduction service needs 1130 MWh (shown as E_{demand}) and the daily energy of the PV system will be represented by E_{pv}. To simplify the calculation, it is assumed that each event will have the same load profile, so as the normal daily consumption. Moreover, €1.77/kWh, €1.21/kWh are the rates for the contracted capacity of different market segments, and €1.98/kWh, €1.47/kWh are the rates for the highest demand per month, and €230, €36.75 are the fixed payment. Under the condition that only this service case is applied without considering using the surplus solar energy, the electricity bills per month can be calculated as:

$\text{Bill}_{\text{before}} = 1.77€/\text{kWh} \times [1036.6(N-2n) + 7383.8\times n]\ \text{kWh} + €230 + 2541\text{kW} \times 1.98€/\text{kW}$ (9)

(1) When $E_{pv} < E_{demand}$

$\text{Bill}_{\text{after}} = 1.21€/\text{kWh} \times [1036.6(N-2n) + (7383.8-E_{pv})\times n]\text{kWh} + €36.75 + 1965\text{kW}\times 1.47€/\text{kW}$ (10)

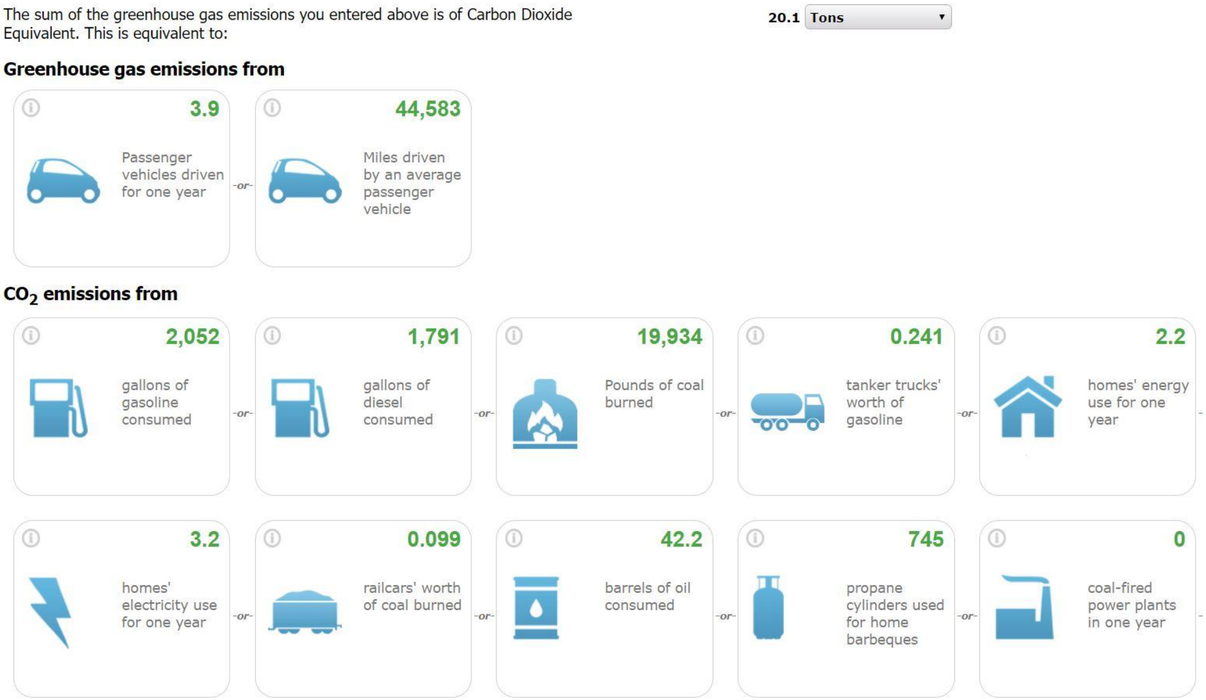
(2) When $E_{pv} > E_{demand}$

$\text{Bill}_{\text{after}} = 1.21€/\text{kWh} \times [1036.6(N-2n)+(7383.8-1130)\times n]\text{kWh} + €36.75+1965\text{kW}\times 1.47€/\text{kW}$ (11)

Also, another meaningful outcome brought out by this operation is the reduction of Carbon Dioxide emission. (1) When $E_{pv} < E_{demand}$, every event will save E_{pv} amount of energy; (2) when $E_{pv} > E_{demand}$, every event will save E_{demand} amount of energy.

It can be calculated using a ‘Greenhouse Gas Equivalencies Calculator’ that realizing this demand charge reduction service, the battery-owner can reduce at least 20.1 tons of Carbon Dioxide emission per year [47]. It means this amount of carbon dioxide emission reduction could save 19,934 pounds of coal burned and it also can be equal to the same amount of the greenhouse gas exhausted by an average vehicle after driving 44,583 miles or almost four average vehicles together driven for one entire year. According to the analysis of the Greenhouse Gas Equivalencies Calculator, different kinds of equivalencies of 18.7 tons of Carbon Dioxide emission can be seen in Figure 34. It is a meaningful contribution to sustainable development and the whole Energy Transition process.

With the view to a bigger picture, the demand charge reduction service of the secondary layer will be explored, which is for the neighbours around and for the energy hub. After looking through all types of the commercial consumers connected to the same outgoing feeders with the stadium, there are many large offices that usually have the similar demand pattern on workdays, according to Table 3. They can get involved in the demand charge reduction services.


The sum of the greenhouse gas emissions you entered above is of Carbon Dioxide Equivalent. This is equivalent to:

20.1 Tons

Greenhouse gas emissions from

3.9 Passenger vehicles driven for one year -or-

44,583 Miles driven by an average passenger vehicle

CO$_2$ emissions from

2,052 gallons of gasoline consumed -or-

1,791 gallons of diesel consumed -or-

19,934 Pounds of coal burned -or-

0.241 tanker trucks' worth of gasoline -or-

2.2 homes' energy use for one year

3.2 homes' electricity use for one year -or-

0.099 railcars' worth of coal burned -or-

42.2 barrels of oil consumed -or-

745 propane cylinders used for home barbeques -or-

0 coal-fired power plants in one year

Figure 34 Equivalencies of the 20.1 tons of the Carbon Dioxide emission reduction [47]

What is more, there are two commercial end-users who may have a similar load profile of the stadium, which is Ziggo Dome and AFAS Live. They are both concert halls connected to the same outgoing feeder to the battery-owner. The highest power demand for them will always happen during a large event, like a concert. The audience capacity of Ziggo Dome is around 17,000, which is a bit smaller than Johan Cruijff ArenA. To make the further analysis operable, the load profile of Ziggo Dome is assumed to use the same load profile of the stadium. In this case, if the battery storage system could satisfy the assumption case, it will also be workable for the situation in reality, which may consume less energy from the battery through energy hub methodology. However, the capacity of AFAS Live is only 6,000, which is much smaller than the stadium, so it can be possible that AFAS Live is not in the same market segment with the stadium when coming to the electricity transport tariff. Then, it may be categorized to the same market segment with the large office buildings, which is the range of ‘136 kW to 2000 kW’ (the blue circle). And it indicates that when the market segment changes from the range of ‘136 kW to 2000 kW’ (the blue circle) to the range above (the green circle), the rates of the contracted capacity are raised from €1.21 per kWh to €1.83 per kWh and others remain the same. Afterward, it will be discussed as another case under another assumption.

Thus, it is suggested to take Ziggo Dome into the demand charge reduction service case on the secondary layer. The capacity of the demand charge reduction service of the energy hub is Johan Cruijff ArenA and Ziggo Dome together. Since the load profile of Ziggo Dome is assumed to use the same load profile of the stadium, Ziggo Dome needs 1130 kWh energy for each event to reduce the demand charge, which will come from the battery storage system of the Johan Cruijff ArenA. And it is feasible for the battery to support two events ongoing in both the stadium and Ziggo Dome due to its 4MWh capacity. Therefore, the operating conditions will be set as:

- The battery needs to be sufficiently charged before the beginning of each event.
- The battery should be charged via both the supply of local grid during night time and the PV system during the day time. When the solar radiation during the day time is not sufficient to charge the battery till enough capacity, for example during the wintertime, then it is time to use the supply of the power system during the night time.
- There should be a long-term contract established between Johan Cruijff ArenA and Ziggo Dome to clarify all the conditions and the service price. The price of the electricity from the battery to the Ziggo Dome could be a bit higher than the price of the electricity from the grid to the battery (between €1.21 per kWh and € 1.77 per kWh).

In this case, the demand charge reduction service will make Ziggo Dome’s market segment change from the range of ‘greater than 2000 kW’ (the red circle) to the range of ‘136 kW to 2000 kW’ (the blue circle). Even though, Ziggo dome might spend a bit more on electricity of the peak time, and it does not need to pay the high demand charge. On the whole, Ziggo dome will make a considerable saving on the electricity bill. Meanwhile, the battery owner could gain direct monetary value from this service case.

For instance, there are n events happening this month in Ziggo dome and the price charged by the battery owner is set as €1.6 per kWh.

(1). Before using the energy hub service, the electricity bill per month:

$$\text{Bill}_1 = 1130\ \text{kWh} \times n \times €1.77/\text{kWh} + E_{rest} \times €1.77/\text{kWh} + 2541\ \text{kWh} \times €1.98/\text{kWh} + €230 \quad (12)$$

(2). After using the energy hub service, the electricity bill per month:

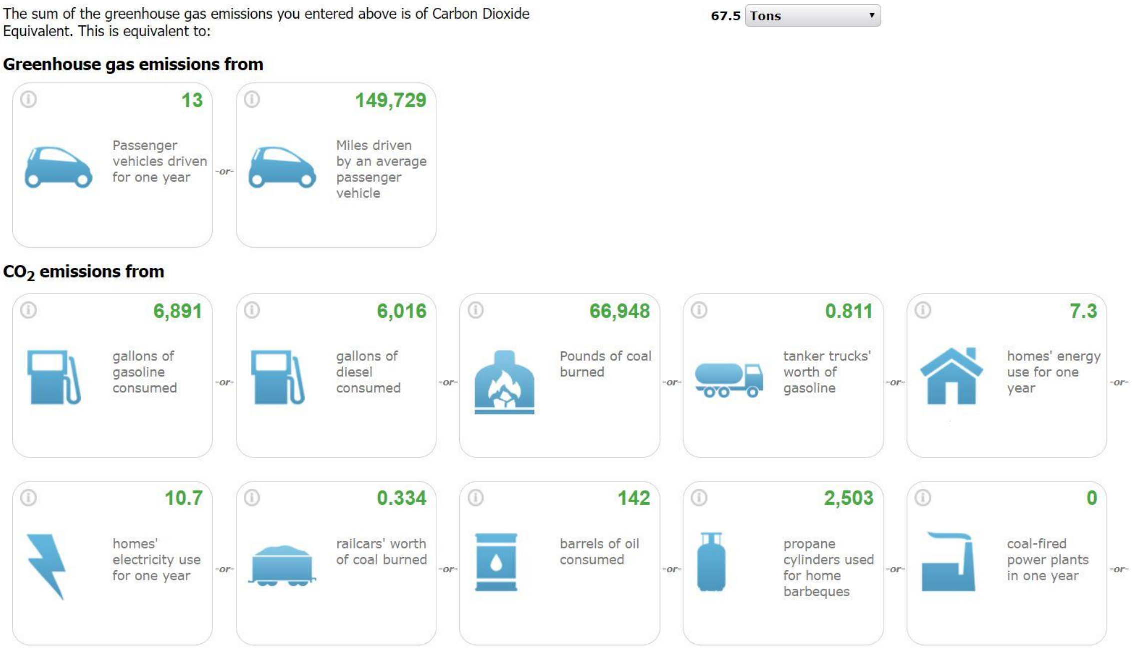
$$\text{Bill}_2 = 1130\ \text{kWh} \times n \times €1.6/\text{kWh} + E_{rest} \times €1.21/\text{kWh} + 1965\ \text{kWh} \times €1.47/\text{kWh} + €36.75 \quad (13)$$

E_{rest} is the amount of the energy of every month except the part over the tariff threshold (2000kW) consumed by Ziggo Dome. Obviously, $\text{Bill}_1 > \text{Bill}_2$. And in this case, the Johan Cuijff ArenA can earn the profit, € 112,096, from providing this service to the energy hub. To add it up, the Johan Cruijff ArenA could get the financial return € 345,185.40 per year plus the extra profit from the price difference of the demand charge contract with Ziggo Dome, for instance, it is € 112,096 when the price is set as €1.6. Thus, the overall profit of this service case per year that the battery-owner can gain is € 457,281.4.

In addition to the economic benefit, the reduction of carbon dioxide emission is also a meaningful outcome produced by this service case. In total, 67.5 tons of Carbon Dioxide can be reduced over the year with the efforts of the energy hub. This considerable amount of carbon dioxide emission reduction could save 66,948 pounds of coal burned. According to the analysis of the Greenhouse Gas Equivalencies Calculator, different kinds of equivalencies of 67.5 tons of Carbon Dioxide emission can be seen in Figure 35.

Table 7 Carbon emission reduction of the energy hub by demand charge reduction

	Jan	Feb	Mar	Apr	May	Jun
Number of total events	3	7	10	5	5	6
Number of events in ArenA	1	2	3	2	2	3
Number of events in ZiggoDome	2	5	7	3	3	3
PV Output (kWh) /Day	716.60	1,408.70	2,636.80	4,379.30	5,628.50	5,846.20
PV Output (kWh) /Month	22,254.80	39,404.50	81,767.40	131,345.40	174,461.70	175,426.30
Energy Saved (kWh)	2,148.90	7,910.00	11,300.00	5,650.00	5,650.00	6,780.00
Battery capacity (kWh)for ZiggoD	2,260.00	5,650.00	7,910.00	3,390.00	3,390.00	3,390.00
Carbon Emission Reduction (tons)	1.8	6.2	8.8	4.4	4.4	5.3
	Jul	Aug	Sep	Oct	Nov	Dec
Number of total events	4	3	8	13	12	10
Number of events in ArenA	1	1	3	2	3	2
Number of events in ZiggoDome	3	2	5	11	9	8
PV Output (kWh) /Day	5,634.90	4,713.10	3,132.90	1,831.40	833.00	523.70
PV Output (kWh) /Month	174,709.70	146,075.80	93,974.34	56,734.95	24,949.78	16,234.05
Energy Saved (kWh)	4,520.00	3,390.00	9,040.00	14,690.00	9,996.00	5,237.00
Battery capacity (kWh)for ZiggoD	3,390.00	2,260.00	5,650.00	12,430.00	10,170.00	9,040.00
Carbon Emission Reduction (tons)	3.5	2.7	7	11.5	7.8	4.2
		Total Carbon Emission Reduction (tons) / year:				**67.5**



The sum of the greenhouse gas emissions you entered above is of Carbon Dioxide Equivalent. This is equivalent to:

67.5 Tons ▾

Greenhouse gas emissions from

13 Passenger vehicles driven for one year -or-

149,729 Miles driven by an average passenger vehicle

CO$_2$ emissions from

6,891 gallons of gasoline consumed -or-

6,016 gallons of diesel consumed -or-

66,948 Pounds of coal burned -or-

0.811 tanker trucks' worth of gasoline -or-

7.3 homes' energy use for one year -or-

10.7 homes' electricity use for one year -or-

0.334 railcars' worth of coal burned -or-

142 barrels of oil consumed -or-

2,503 propane cylinders used for home barbeques -or-

0 coal-fired power plants in one year -or-

Figure 35 Equivalencies of the 67.5 tons of the Carbon Dioxide emission reduction[47]

Another case is to consider the possibility to apply the demand charge service case to other consumers in the energy hub. After considering the general demand pattern of other types of end-user, it is assumed that office buildings in the energy hub have the highest possibility to realize the demand charge reduction. Most of the office buildings are generally included in the range of '136 kW to 2000 kW' (the blue circle). It indicates that when the market segment changes from the range of '136 kW to 2000 kW' (the blue circle) to the range above (the green circle), the rate of the contracted capacity is raised from €1.21/kWh to €1.83/kWh and others remain the same, according to the Table 6. It does not act as a common case. However, it is still possible for the owners of those office buildings to have the specific customized agreement of the electricity transport rates if they could negotiate with Liander holding a long-term contract of the demand charge reduction that is signed with the Johan Cruijff ArenA. In that agreement with Liander, the office buildings could have a cheaper choice if they can keep the highest power demand of the month under the tariff threshold. In this case, a load profile of the office buildings with the similar size is referred to [48]. As the Figure 36 indicates, the part of the load profile over the tariff threshold is around 200.98 kWh calculated by MATLAB. Thus, the battery will discharge over the period that is above the tariff threshold to keep the demand under the 136 kW. Taking the sufficient capacity margin remained in the battery dealing with the errors that might exist during the calculation, the capacity of the demand charge reduction service case is the Johan Cruijff ArenA itself plus ten (10) more office buildings. Considering the local grid connection, it is possible that the large office 1 (A1+B1), Deutsche Bank Nederland (B6), ICCA (B7), Large office 2 (C6) and Emerald Investment (C7) could all use this service case to save the electricity bill and help reduce the carbon emission.

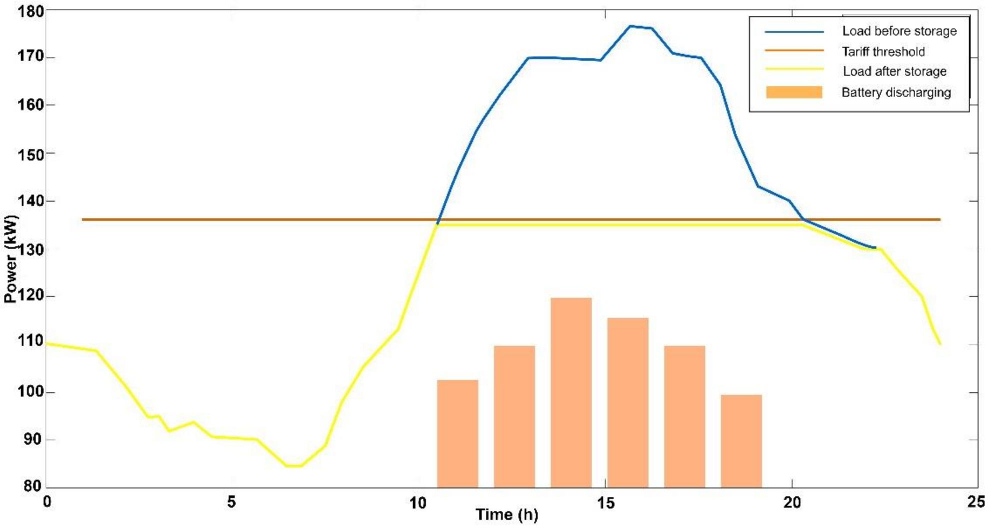


Figure 36Demand charge service via battery storage for the large office

In order to satisfy the needs of all office loads or some of them, the battery should be sufficiently charged before around 10 PM using the night-time grid. And during part of the battery packs are discharging to the office buildings, another part of the battery packs could be charging from the PV system during the day time in case the evening event in the stadium needs it as well. And the long-term contract between the stadium and office buildings should clarify a suitable price to make both sides benefit from it, which could also let Liander get involved in deciding the relevant electricity transport rates and the emergency plans.

5.3 INCREASED PV SELF-CONSUMPTION SERVICE

The fundamental operation idea of the increased PV self-consumption service is to minimize the export of the energy produced in the energy hub and reserve the energy for the internal trading process.

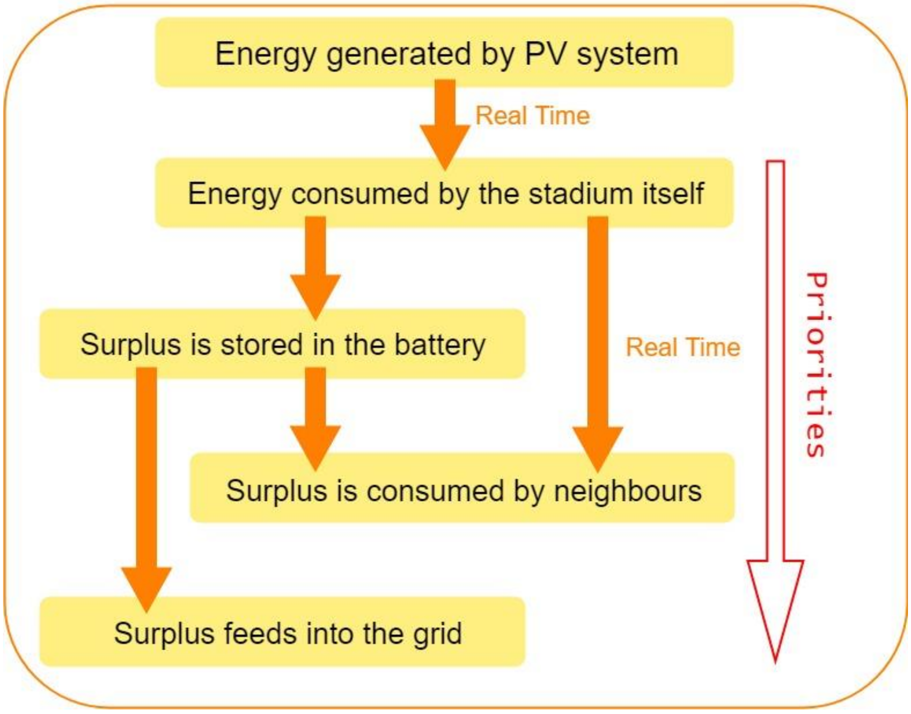


Figure 37 Operation Principle of Increased PV Self-consumption Service

Priorities should be set for every operation in order to realize the maximization of the PV self-consumption, as shown in Figure 37. When the solar radiation is converted into electricity, it will be consumed directly by the stadium first to supply its current load.

- If the power demand is more than the electricity supply generated by PV system, then the stadium should consume the overall solar energy plus the electricity drawn from the grid partly. In this case, no more solar energy could be left for the battery or the energy hub.
- If the electricity supply generated by PV system is more than the power demand of the stadium, then the entire demand of the stadium will be covered by the PV-generated energy. The usage of surplus energy will be divided into two ways accordingly. If there is

a direct request of the electricity supply from the neighbours at that time, the surplus could be sold to the neighbours of the energy hub directly with a decent price. Otherwise, the surplus will be stored in the battery for the later use. The stadium reserves the right to make the decision of how to use the surplus energy, which usually depends on how much energy will be, when the electricity generated by PV system on one day in the summertime is much more than the demand pattern of the stadium, and the battery is already sufficiently charged with no energy trade request from the neighbours at the present, the surplus will be fed back into the power system.

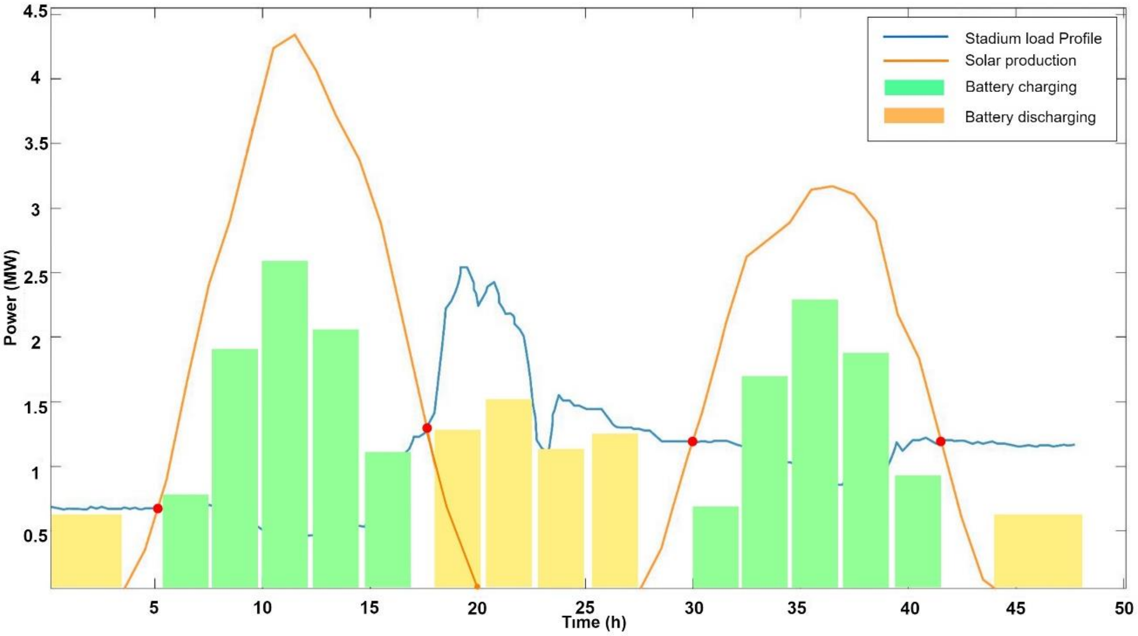


Figure 38 PV Self-consumption service for the stadium via battery storage on 11 & 12-06-2018

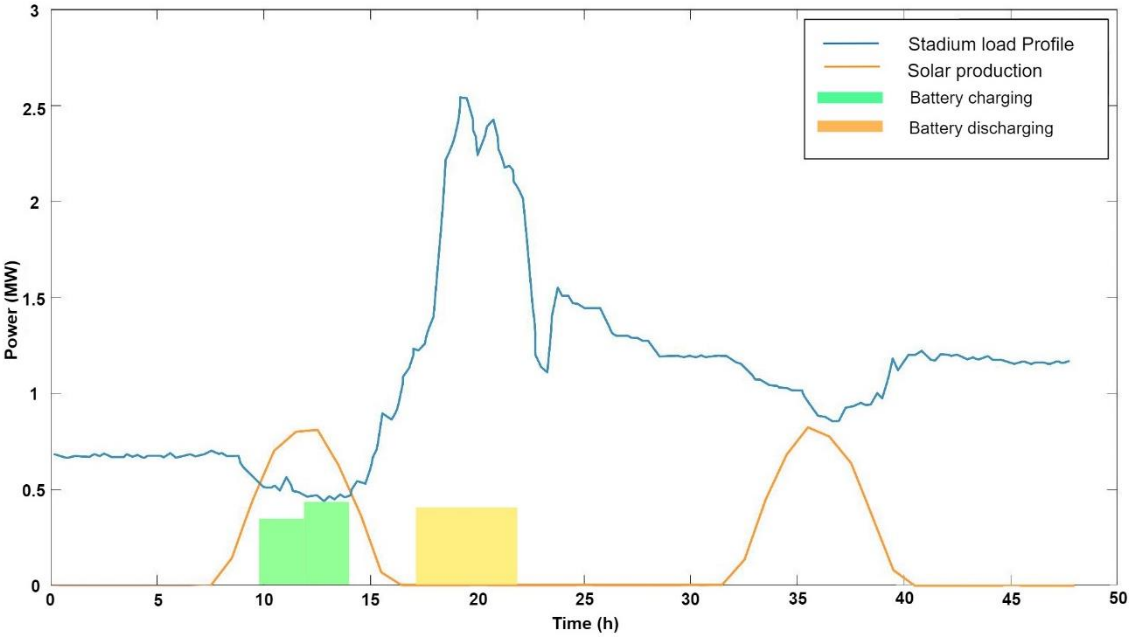


Figure 39 PV Self-consumption service for the stadium via battery storage on 11 & 12-01-2018

As an example, Figure 38 indicates how the battery storage system operates for the increased PV self-consumption service for the stadium on 11 & 12-06-2018 with the large-scale event ongoing on the first day. When solar energy is much more than the power demand from 6:00 am to 6:00 pm, the battery is being charged. And the period after 7:00 pm until 2:00 am of the next day, and the battery keeps discharging to supply the big event that can help to reduce the pressure of the power system. And on the second day, the operation mode runs in a similar way. Figure 39 shows the operation of this service via the battery for the stadium on 11 & 12-01-2018. The solar radiation is far less than sufficient to supply the stadium and then charge the battery during the wintertime. Thus according to the priorities set for this service case, the limited amount of energy produced by PV system will serve the stadium firstly in this case.

Considering all the parameters that could be the no-event daily energy demand and energy demand of the large-scale event day, solar radiation data, local energy transport tariff, and service operation principles, it can be approximately calculated by MATLAB to get the final results, shown in Table 9. The 'PV Energy self-consumed(kWh)/Month' means the PV-generated energy consumed by the stadium each month, and the row of 'PV Energy for Energy Hub (kWh)/Month' represents the surplus of the solar energy that can be used for the energy hub, with assuming that there is zero export of the solar energy to the power system. Therefore, the amount of the electricity bill of the Johan Cruijff ArenA will be saved €399.968.32 every year. This amount does not include the potential profit gained from the energy trade between the stadium and energy hub members, using the energy from the PV system directly or reserved in the battery storage system. The price is suggested to set a bit lower than the electricity price at the moment. Thus, the entire monetary value created by the increased PV self-consumption service is the €399.968.32 per year plus the extra profit from the energy trade in the energy hub.

To calculate the electricity bill saved, it is assumed there are *n* events occurring in the month with *N* days in that month. As mentioned above, the normal daily consumption of the stadium with no event going on is around 1036.3 kWh (E_{daily}).When the event occurs, the first day with event ongoing and the second day after separately consume 3017.9 kWh (E_1) and 4365.9 kWh (E_2), and in total consume 7383.8 kWh. Daily output energy of the PV system will be represented by E_{pv}. To simplify the calculation, it is assumed that each event will have the same load profile, so as the normal daily consumption. Moreover, €1.77/kWh is the rates for the contracted capacity of different market segments. Under the condition that only this service case is applied, the electricity bill saved per month can be calculated as:

(1) When $E_{pv} < E_{daily}$ (1036.3 kWh)

$$Bill_{saved} = 1.77€/kWh \times E_{pv} \times N \tag{14}$$

(2) When E_2 (4365.9 kWh) $> E_{pv} > E_1$ (3017.9 kWh)

$$Bill_{saved} = 1.77€/kWh \times [\, E_{daily} \times (N-2n) + (E_1 + E_{pv}) \times n] \tag{15}$$

(3) When E_2 (4365.9 kWh) $< E_{pv}$

$$Bill_{saved} = 1.77€/kWh \times [\ E_{daily} \times (N-2n) + (E_1 + E_2) \times n] \quad (16)$$

In addition to the economic benefit, the reduction of carbon dioxide emission also endows this service case significant meaning in the perspective of sustainable development and environment protection. To calculate the surplus solar energy per month (E_{hub}) contributed to the energy hub,

(1) When $E_{pv} < E_{daily}$, the stadium will put its own electricity consumption at first priority, thus there is no surplus left for the energy hub;

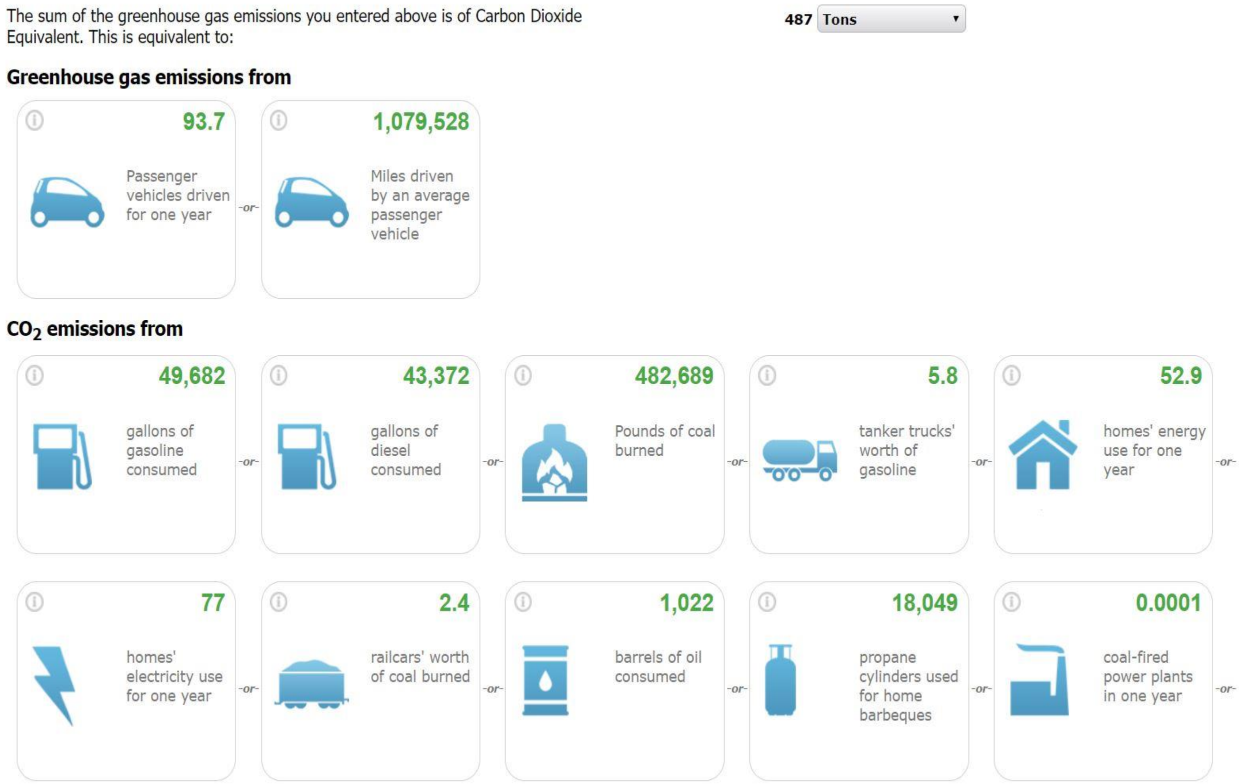
(2) When $E_2 > E_{pv} > E_1$, $E_{hub} = (E_{pv} - E_{daily}) \times (N-2n) + (E_{pv} - E_1) \times n$ (17)

(3) When $E_2 < E_{pv,}$, $E_{hub} = (E_{pv} - E_{daily}) \times (N-2n) + [(E_{pv} - E_1) + (E_{pv} - E_2)] \times n$ (18)

Then, the total energy saved for the whole energy hub over the year can be understood as the whole yield of the PV system over the year, because the increased PV self-consumption service will help the energy hub to consume almost all solar energy. There could be around 487 tons of Carbon Dioxide reduced over the year with the efforts of the increased PV self-consumption service of the energy hub. This amount of the reduction of carbon dioxide emission equals preventing the pollution of 482,689 pounds coals burned, as Figure 40 indicates. This amount also can be equivalent to the carbon dioxide emission from the energy consumption that supplies the whole 53 residential houses for the entire one year, or 1,079,528 miles driven by an average passenger vehicle. It is a pretty considerable number to reflect the contributions made by all members of the energy hub to the Energy Transition process.

Table 8 Carbon emission reduction of the energy hub by increasing PV self-consumption

	Jan	Feb	Mar	Apr	May	Jun
Number of events	1	2	3	2	2	3
PV Output (kWh) /Day	716.60	1,408.70	2,636.80	4,379.30	5,628.50	5,846.20
PV Output (kWh) /Month	22,254.80	39,404.50	81,767.40	131,345.40	174,461.70	175,426.30
PV Energy self-consumed(kWh)/Month	22,254.80	30,506.00	41,728.30	41,711.40	42,747.70	47,022.60
PV Energy for Energy Hub (kWh)/Month	0.00	8,898.50	40,039.10	89,634.00	131,714.00	128,403.70
Electricity Bill Reduction (€)/Month	39,391.00	53,995.62	73,859.09	73,829.18	75,663.43	83,230.00
Carbon Emission Reduction (tons)/Month	17.3	30.7	63.7	102	136	137
	Jul	Aug	Sep	Oct	Nov	Dec
Number of events	1	1	3	2	3	2
PV Output (kWh) /Day	5,634.90	4,713.10	3,132.90	1,831.40	833.00	523.70
PV Output (kWh) /Month	174,709.70	146,075.80	93,974.34	56,734.95	24,949.78	16,234.05
PV Energy self-consumed(kWh)/Month	37,436.50	37,436.50	43,323.60	35,305.70	24,949.78	16,234.05
PV Energy for Energy Hub (kWh)/Month	137,273.20	108,639.30	50,650.74	21,429.25	0.00	0.00
Electricity Bill Reduction (€)/Month	66,262.61	66,262.61	76,682.77	62,491.09	44,161.11	28,734.27
Carbon Emission Reduction (tons)/Month	136	114	73.3	44.5	19.4	12.7
		Total Electricity Bill Reduction(€)/year:				**399,968.32**
		Total Carbon Emission Reduction (tons) / year:				**487**



The sum of the greenhouse gas emissions you entered above is of Carbon Dioxide Equivalent. This is equivalent to:

487 Tons

Greenhouse gas emissions from

93.7 Passenger vehicles driven for one year -or-

1,079,528 Miles driven by an average passenger vehicle

CO_2 emissions from

49,682 gallons of gasoline consumed -or-

43,372 gallons of diesel consumed -or-

482,689 Pounds of coal burned -or-

5.8 tanker trucks' worth of gasoline -or-

52.9 homes' energy use for one year -or-

77 homes' electricity use for one year -or-

2.4 railcars' worth of coal burned -or-

1,022 barrels of oil consumed -or-

18,049 propane cylinders used for home barbeques -or-

0.0001 coal-fired power plants in one year -or-

Figure 40 Equivalencies of the 487 tons of the Carbon Dioxide emission reduction [47]

5.4 BACK-UP POWER SERVICE

As one of the most basic functionalities of the battery storage system, back-up service case acts as the fourth service on both primary and secondary layers of the energy hub. In Chapter 3, the energy hub methodology describes two different possible definitions of the back-up service, which are the back up for a grid failure and the back-up for some certain significant event hosted by the members of the energy hub, like a press conference, a concert or a very important surgery. According to the original appeal of the battery owner when building the whole battery storage system [37], the power back-up service case will focus more on the second definition of this service. And the total amount of the energy needed for the stadium to host a large event can be calculated using the load profile provided by [39], which is around 4.2 MWh and is almost the amount that fully-charged battery could supply.

As shown in Figure 41, it can be viewed from two different perspectives. Firstly, the backup service will only be used for the battery-owner itself on the day when there is going to be a big event today in the stadium. During the days when there is no event ongoing in the stadium, the other members can apply for a short-term back-up service for the certain significant events. And also, the amount of the capacity of the battery that is needed to reserve for the event should be provided. When providing the back-up service to the energy hub, there are two kinds of the payment that are the maintenance cost and the payment of is the electricity used. If there is no take of the electricity from the battery during the whole process of the event, then the applicant of this backup service needs to pay a certain amount bill of the maintenance to the battery-owner, which should be clarified in the contract. And if the certain amount of the electricity is used during the ongoing event, the applicant needs to pay another amount bill for the energy used plus the maintenance cost.

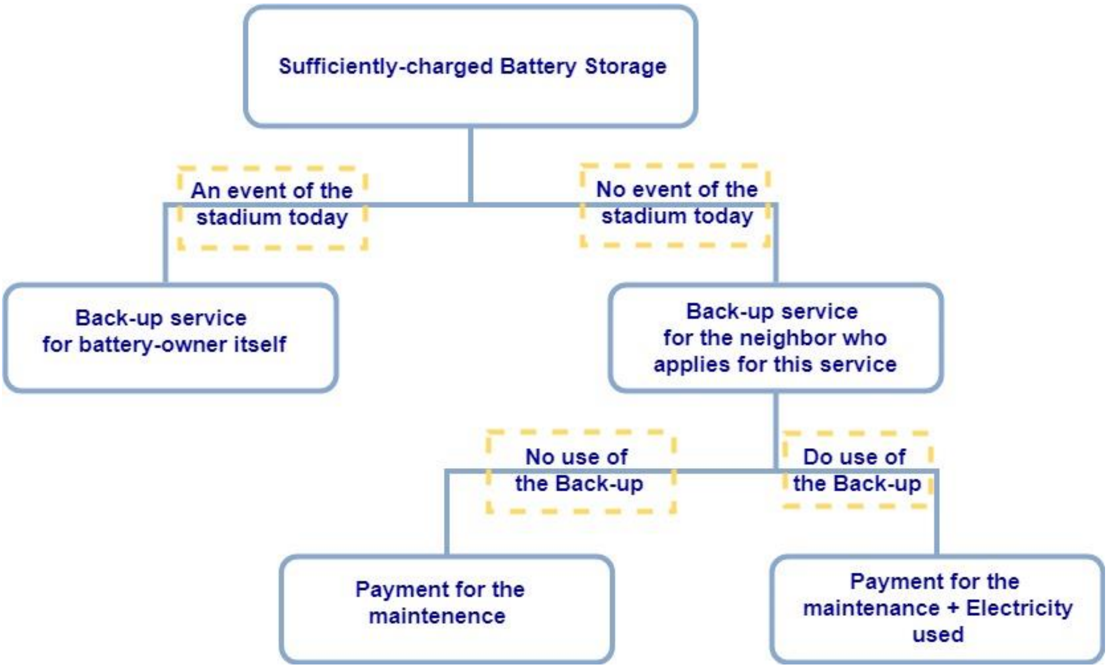


Figure 41 Power back-up service case operation principle

Usually, the battery storage will be charged by PV panels when there is sunlight outside and by the local grid during off-peak hours in rainy days or night time. This service case requires to make sure that the battery has been charged to the level that is enough for the holding of the event before the beginning of the event.

In this case, both sides can benefit from this service case. On one hand, the energy hub members could get the guarantee from the battery-owner to ensure the event ongoing successfully. On the other hand, the battery-owner could gain the economic benefit directly using the battery when it is idle.

5.5 PROVIDING FLEXIBILITY TO P2P TRADING PLATFORM

As the unique service case on the secondary layer of the energy hub, providing flexibility to P2P energy trading platform is the only service case of the energy hub that could expand the service range to the outside of the energy hub. Considering the two perspectives of the role that battery can play in this service case mentioned in Chapter 3 and the geographic conditions of the case study, the second one with the slight adaption can be more suitable in order to apply this service to the Zuid-Oost Amsterdam region. Since there is no existing P2P trading platform in the selected community, it is still possible to figure out an appropriate cooperation model between the battery storage system of the energy hub and the external P2P trade platform. As it has been discussed in Chapter 3, the battery storage system of the energy hub can act as an external back-up for the P2P trading platform to provide the surplus energy stored as the flexibility to fix the imbalance that might happen between the demand and supply sides on the platform.

There are two leading P2P energy trading platforms currently operating in the Dutch electricity market, which are *Powerpeers* and *Entrnce*.

- *Entrnce* is the independent local P2P market platform for energy trading supported by Dutch grid company Alliander. According to [51], Entrnce as the trading platform provides the opportunity for all electricity connections (large and small consumers) to purchase and sale their energy easily, with no limitation of the locations.
- *Powerpeers* is a P2P electricity trading platform with fixed price, supported by Vattenfall. It can be considered as the main competitor of Entrnce in the Netherlands. Instead of buying the energy from the platform, users of Powerpeers can directly purchase electricity from the prosumers on the platform. It's worth mentioning that it triggers the growth of the investment in sustainable energy since the platform encourages trading of behind-the-meter sustainable energy.

Taken the conditions of both the case study and the current Dutch electricity market into considerations, Entrnce is more suitable to be used as the example platform to cooperate with the energy hub in the case study. Because, the network manager of the Zuid-Oost Amsterdam is Liander, which belongs to the same company that sponsors the Entrnce.

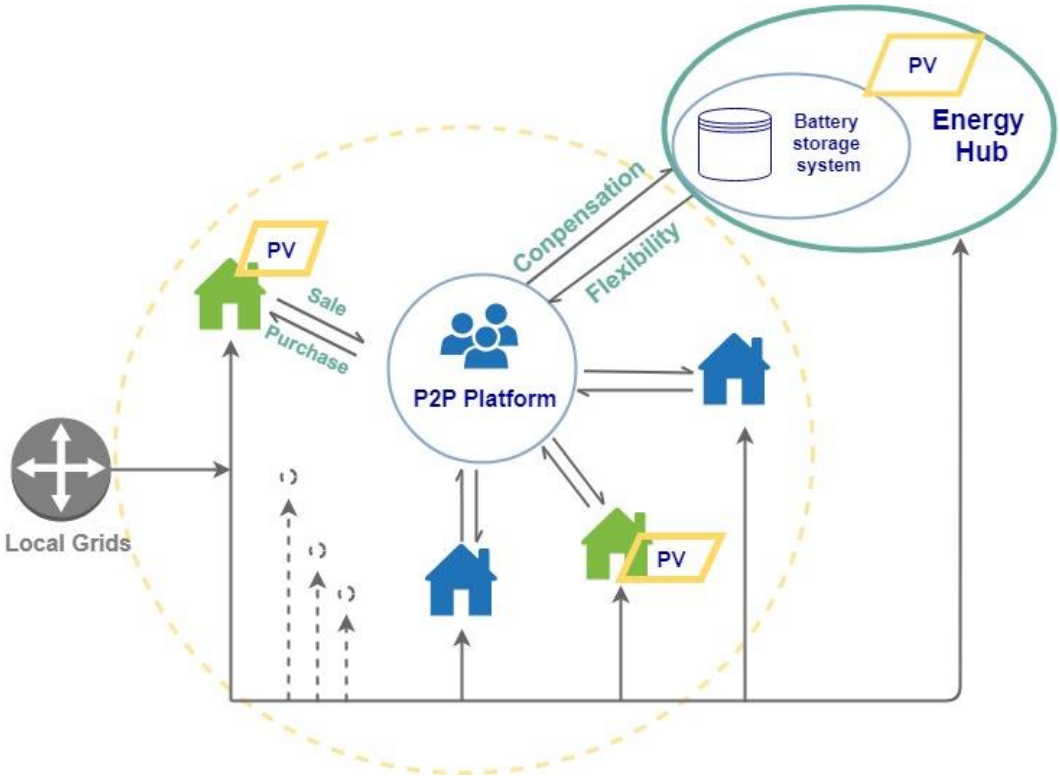


Figure 42 Battery plays the role of flexibility provider to the P2P trading platform

Thus, the suggested cooperation mode between Entrnce and energy hub is briefly described in Figure 42. The prosumers and consumers on the P2P energy trading platform are all connected to the local grid, so as the energy hub. The role that battery can play during the whole operation of the platform can be understood as one of the 'peers'. However, it is a pure producer, instead of being either the consumer or the prosumer. Therefore, the battery storage system follows almost the same rules that other prosumers and consumers are following. When there is extra energy reserved in the battery with no other usages, the operator of the energy hub (or the battery-owner) can put the available amount of the energy on the table to notice the whole P2P trading platform. Then the consumers and prosumers no matter who needs this energy could start to bid. The battery-owner can get the correspondent amount of compensation as the payback. According to [51], ENTRNCE deals with all transactions totally automated on a quarterly basis, which is done both financially and energy technically. What is more, all transactions are strictly settled following the rules of the Dutch energy market.

Among all the service cases, the service of providing flexibility to P2P energy trading platform is put to the last in the list of the priorities, which means the energy hub should focus on the internal value realization first and then contribute to the external. Therefore, when all the energy stored in the battery has been arranged to different services, and there is zero kWh left for the external use that day, the energy hub operator can inform the P2P trading platform that it will not participate in today's trading process. This kind of the cooperation mode makes the energy hub proceed or step back freely and flexibly. What's more, it can help the battery-owner cash out all the energy stored in one day, and the battery could be sufficiently charged by the night-time grid and the PV systems in the next day.

5.6 INTEGRATION OF DIFFERENT SERVICE CASES

For the utilisation of the Energy hub to different communities in the future, it is possible only to apply one service case or combine two of them, which shows the characteristics of customization as one of the advantages. However, in the case study of the Zuid-Oost Amsterdam region, the integration of all possible service cases will be discussed as the followed in order to maximize the profit of both the battery-owner and the energy-hub members. The battery will be charged by both PV systems on the stadium's roof and the night-time local grid. The amount of the energy of the night-time charging can be calculated using the prediction of the solar radiation of the next day from the history data and weather broadcast. And the battery storage system consists of more than one hundred battery packs so that it is operational to be charged and discharged at the same time. It is assumed that battery will always be sufficiently- charged and it will try to cash out all the energy capacity before the end of the day.

Considering all the practical service cases explored above, the final integration version of the energy hub is shown in Figure 43.

- If there is going to be an event in the stadium and also an event in Ziggo Dome today, the demand charge reduction will work for both of them as the first priority. It will take around 2.26 MWh capacity out from the battery. On the premise that enough capacity is well reserved for the demand charge reduction service, the remaining energy could be used for either the stadium self-consumption to save the electricity bill or the energy trading in the energy hub. The energy trading is not a specific service case, but it can be included in the increased PV self-consumption service in the energy hub. After this, the remaining capacity can be sold to the P2P trading platform as the flexibility for other peers to bid if there is still remaining in the battery storage system. In this case, there is no back-up service that can be provided to the energy hub.
- If there is going to be an event in the stadium but no event in Ziggo Dome today, or if there is going to be no event in the stadium but an event in Ziggo Dome today, the demand charge reduction service will work for the stadium as the top priority, which will occupy about 1.13 MWh capacity of the battery. Then, it is necessary to see whether Ziggo Dome or the stadium itself requests for a back-up service for the event, the total capacity will be reserved if either of them asks for it due to the activity scale. How to use the remaining energy in the battery will follow the same steps mentioned above.
- On the normal day with no events going on in both the stadium and Ziggo Dome, it is significant to check if there is a request from other neighbours for the back-up service. If so, the requested amount of the energy will be reserved in the battery and the remaining

capacity will be used in the same method mentioned in the first point. If there are no back-up service requests in the energy hub, then the whole battery will serve the stadium's self- consumption and the energy trading in the energy hub first. If there is any surplus energy after, it will be provided to the P2P trading platform to earn the compensation.

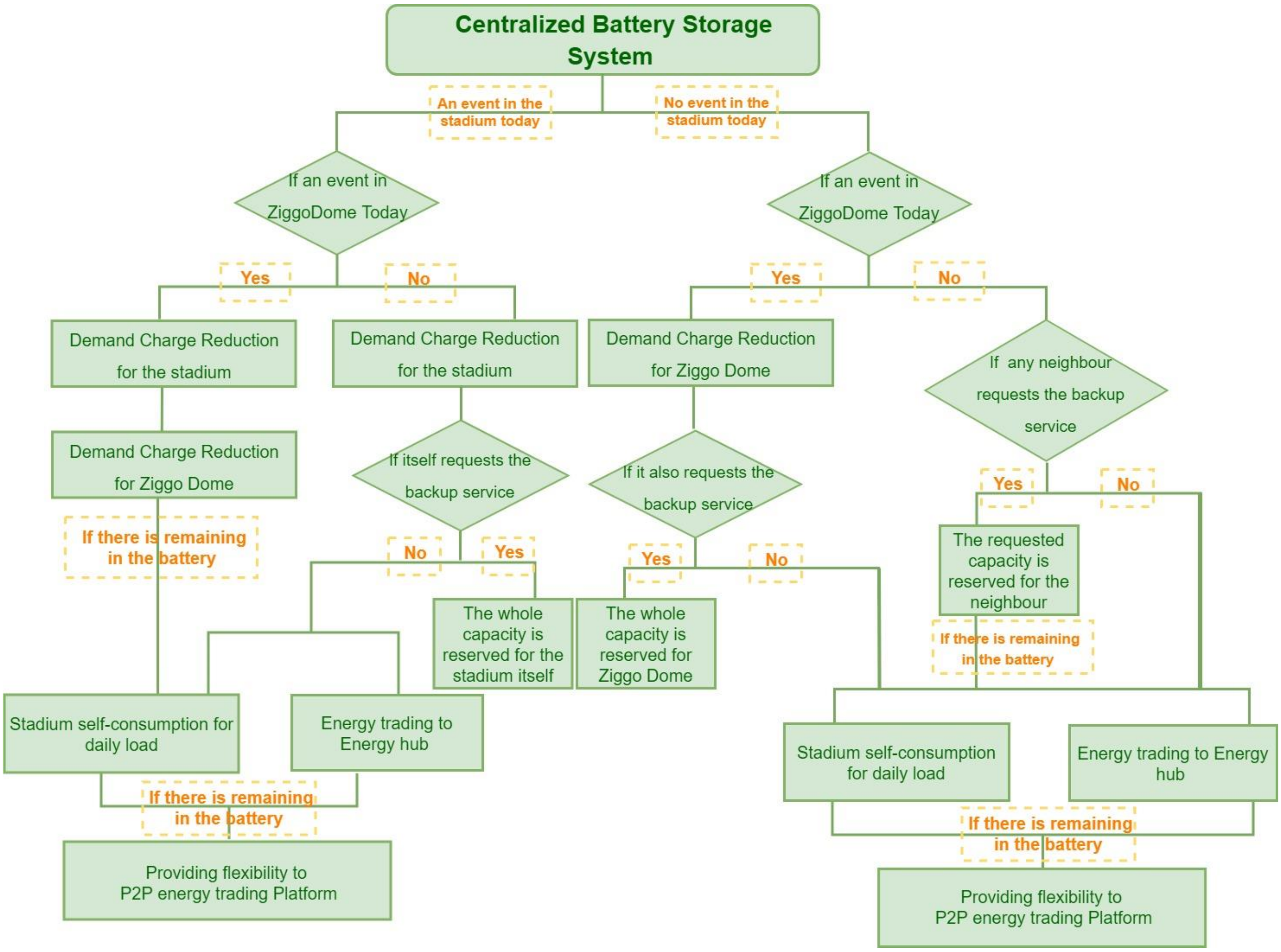


Figure 43 Integration of service cases of Energy Hub

After the application of the energy hub, the load profile of the stadium on event days can be improved, shown in Figure 44 and 45. With the battery storage, the demand charge can be easily saved a lot, and tariff threshold will be adjusted from 2000 kW to 136 kW. Moreover, the daily use of electricity can be reduced by using solar energy, and the extra will be stored in the battery, even in the wintertime in Figure 45.

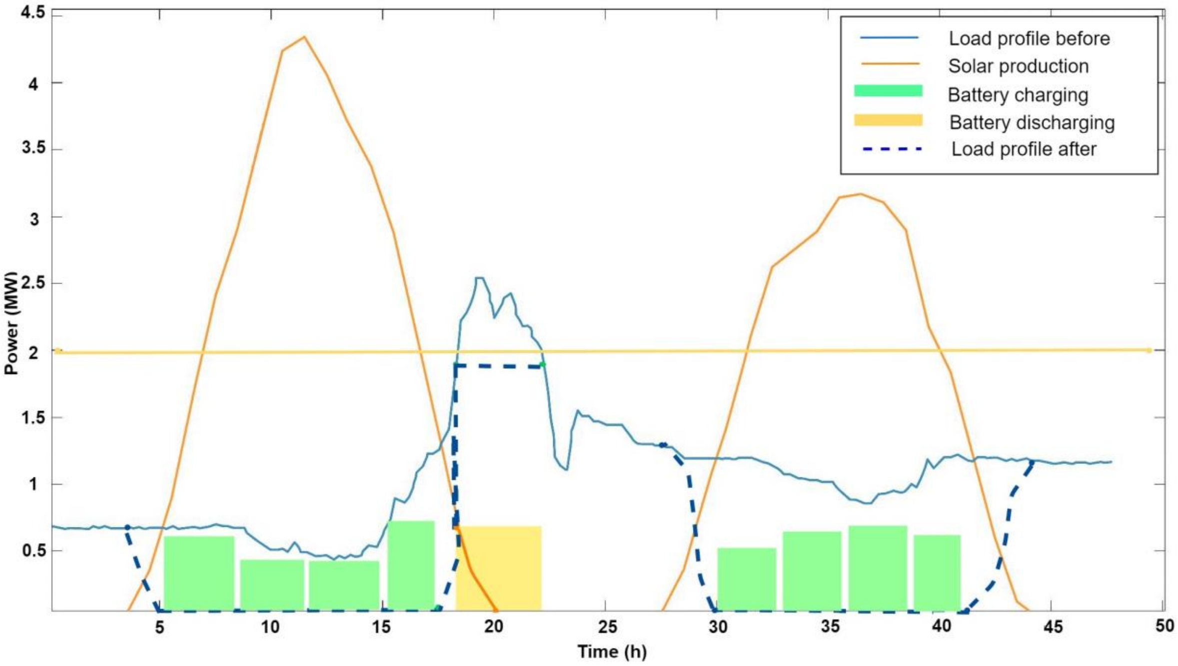


Figure 44 Integration of service cases applied on the stadium on 11 & 12-06-2018

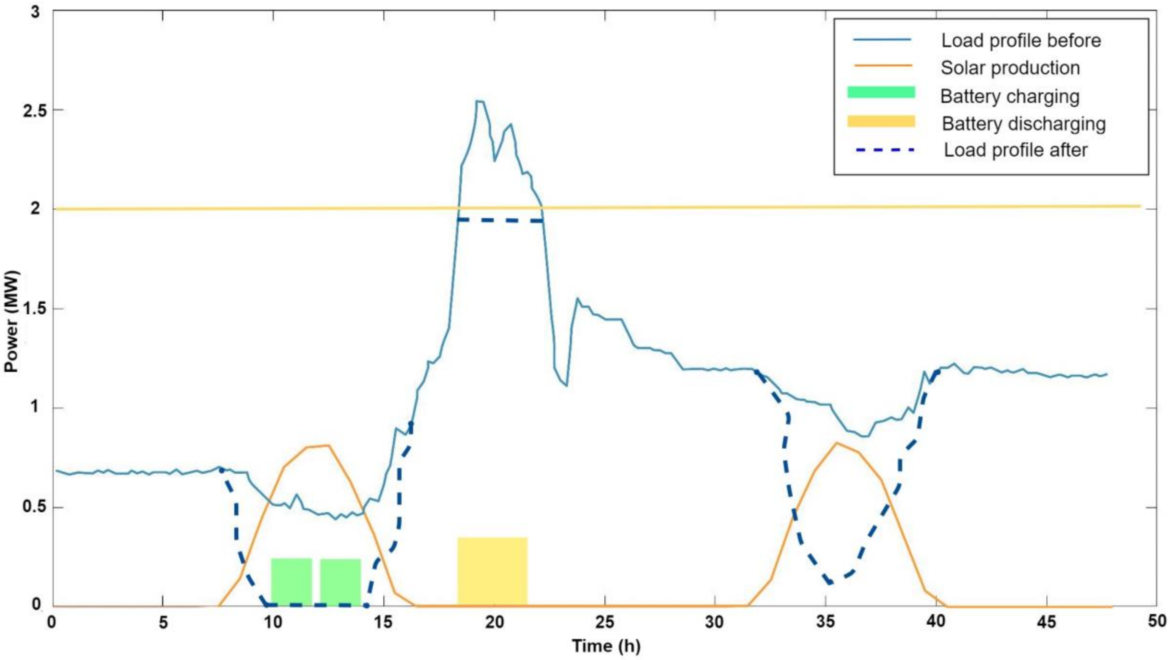


Figure 45 Integration of service cases applied on the stadium on 11 & 12-01-2018

The application of the energy hub with the integration of all available services can bring the considerable result to the table. The result can be viewed from two aspects, which are the tangible profit and the intangible benefit.

- The economic benefit for the battery-owner that is the Johan Cruijff ArenA in the case study can be gained from five different approaches:
  1. The first way is to apply the demand charge reduction for both the stadium itself and the neighbour Ziggo Dome. The Johan Cruijff ArenA could save € 345,185.40 per year from the electricity bill plus the extra profit from the price difference of the demand charge reduction contract with Ziggo Dome, for instance, it can be around € 112,096 per year when the contract price is set as € 1.6. Thus, the overall profit of this service case per year that the stadium can gain is € 457,281.4.
  2. Self-consuming the solar energy on-site for the daily load profile could save the part of the electricity bill, especially when it is the summer and the solar radiation can be super intense.
  3. The energy trade with the members of the energy hub using the surplus solar energy could bring the respectable income to the battery-owner. How to allocate the amount of surplus energy to the energy trade and the self-consumption depends on the conditions of the time, for instance, how is the price the neighbours offer and whether the self-consumption is already satisfied.
  4. The profit can also be gained from the back-up power service provided to the energy hub. Any member of the energy hub that requests the use of the back-up service will pay for the cost of the reservation and maintenance of the battery storage system. And if the back-up energy is used during the service process, another payment for the energy consumption will be charged in addition.
  5. The compensation of the P2P energy trading platform is another approach to cash out the surplus energy when the battery of the energy hub provided the flexibility to the P2P platform.

     The specific amount of profit of the approaches (2), (3), (4) and (5) is difficult to estimate because the contract price and the specific amount of the energy involved could fluctuate accordingly. However, the summation of all the five profit approaches can be the total economic benefit for the battery-owner. And for the other members of the energy hub, the payment for the different services will be lower than the cost of traditional electricity consumption from the local grid. In this case, applications of the energy hub can be a win-win for all the participators in the energy hub.

- The intangible benefit here is regarding the contributions that the energy hub can make to the sustainable development and the Energy Transition, which can be represented by the total Carbon Dioxide emission reduction. There can be around 716,682 MWh renewable energy contributed to all neighbours from the battery of the energy hub, and this number does not include the capacity reserved for the back-up service and the stadium's maximal solar electricity consumption. What is more, the whole renewable energy consumption over the year for the whole energy hub including the stadium equals around 487 tons of Carbon Dioxide reduced, shown in Table 10. This amount of the reduction of carbon dioxide emission equals decreasing the pollution of 482,689 pounds coals burned, as Figure 46 shows. It is also equivalent to the carbon dioxide emission from the energy consumption that supplies the whole 53 residential houses for the entire year, or 1,079,528 miles driven by an average passenger vehicle. It is a meaningful movement that can be done by all members of the energy hub to play the leading roles in the sustainable development and contribute to the Energy Transition process.

	Jan	Feb	Mar	Apr	May	Jun
Number of events	1	2	3	2	2	3
PV Output (kWh) /Day	716.60	1,408.70	2,636.80	4,379.30	5,628.50	5,846.20
RE Consumption of Energy Hub	22,254.80	39,404.50	81,767.40	131,345.40	174,461.70	175,426.30
Carbon Emission Reduction (tons)/Month	17.3	30.7	63.7	102	136	137
	Jul	Aug	Sep	Oct	Nov	Dec
Number of events	1	1	3	2	3	2
PV Output (kWh) /Day	5,634.90	4,713.10	3,132.90	1,831.40	833.00	523.70
RE Consumption of Energy Hub	174,709.70	146,075.80	93,974.34	56,734.95	24,949.78	16,234.05
Carbon Emission Reduction (tons)/Month	136	114	73.3	44.2	19.4	12.7
		Total Carbon Emission Reduction (tons) / year:				**486.7**

Table 10. Carbon emission reduction of the energy hub in total per year

The sum of the greenhouse gas emissions you entered above is of Carbon Dioxide Equivalent. This is equivalent to:

487 Tons

Greenhouse gas emissions from

93.7 Passenger vehicles driven for one year -or-

1,079,528 Miles driven by an average passenger vehicle

CO_2 emissions from

49,682 gallons of gasoline consumed -or-

43,372 gallons of diesel consumed -or-

482,689 Pounds of coal burned -or-

5.8 tanker trucks' worth of gasoline -or-

52.9 homes' energy use for one year -or-

77 homes' electricity use for one year -or-

2.4 railcars' worth of coal burned -or-

1,022 barrels of oil consumed -or-

18,049 propane cylinders used for home barbeques -or-

0.0001 coal-fired power plants in one year -or-

Figure 46 Equivalencies of total Carbon Dioxide emission reduction of the energy hub per year [47]

5.7 LIMITATIONS OF THE ENERGY HUB APPLICATION

In addition to lots of benefits, there still could be some limitations and risks when applying the integrated energy hub to the commercial community in Zuid-Oost Amsterdam region.

First, it is totally a trade-off when selecting the proper services and building the energy hub. In the case study, there is a conflict existing between the demand charge reduction service on the secondary layer and the back-up power service on the primary layer. The demand charge reduction service on the secondary layer should serve the Ziggo Dome to keep its highest power demand under the tariff threshold (2000 kW) during every event. And this is a long-term cooperation according to the regulations of Liander. One of the regulations states when the consumer exceeds the contracted capacity, this capacity will then be increased to the value automatically and this new contract will take effect on the whole year in which the excess happens [46]. However, the back-up power service on the primary layer is aiming to provide the back-up service for the stadium for every large-scale event. According to the load profile of the Johan Cruijff ArenA, most events that are usually hosted by the stadium need around 4 MWh energy from the very beginning to the end of the event. Thus, the fully-charged battery just meets the need to support the whole event ongoing successful if a black-out occurs. The conflict appears when Ziggo Dome and Johan Cruijff ArenA hold the events on the same day. Under the limitation of the long-term contract with Ziggo Dome, Johan Cruijff ArenA, as the battery-owner, is not able to reserve the enough capacity for itself as the back-up in case the black-out happens. In the final result of the case study, the demand charge reduction service for Ziggo Dome is selected for the energy hub while the battery-owner takes the risk of the sudden black out. The decision is made after considering the extremely low possibility of the sudden black-out of the power system and the considerable profit brought by the cooperation with the Ziggo Dome. However, if the battery-owner prefer the 100% safety of the electricity consumption instead of the economic profit, the back-up service for itself can be added with the removal of demand charge reduction service for neighbours.

Secondly, the TOU bill management service is not used in the integrated energy hub due to the fixed transport rates of the electricity according to Liander. Moreover, the stadium has a special peak period compared to the other large consumers since the event does not happen every day and it usually happens during the night-time

CHAPTER 6.

CONCLUSIONS AND FUTURE WORK

This chapter will present the conclusion of the research. Then, the recommendations for future work could be found as followed.

6.1 CONCLUSIONS

In this thesis, an energy hub methodology has been defined on the basis of the existing service provided by the grid-size battery storage system in order to deal with the intermittency issue of sustainable energy generation. Considering that the battery is set behind the meter, the efficient services have been decided as demand charge reduction, TOU bill management, increased PV self-consumption, and back-up power service. In addition to these four, there is one more unique service that has been created, especially for the energy hub, which is the flexibility provider service to the P2P energy trading platform. And, the energy hub is defined as a two-layer structure with primary service layer and secondary service layer. The primary service layer is mainly for the battery-owner itself while the secondary layer contributes to the whole energy hub. The four common service cases are all contained into the two service layers of the energy hub. Moreover, the flexibility provider service to the P2P energy trading platform is only listed on the secondary layer since it concerns with the connection between the battery in the energy hub and the external third party. It is quite flexible and dynamic for the energy hub operators to select and integrate the available services to build their own customized energy hub. It means that not every service needs to be involved and there is no such a priority order of the service cases, which are all depending on the actual operations and requirements.

Secondly, a specific case study in the Zuid-Oost Amsterdam region was explored. One stadium, the Johan Cruijff ArenA, owns a 4 MWh battery storage system in a commercial community with lots of large electricity-consumers involved. Also, the local grid connections and the peak demand moment have been modelled using MATPOWER and OpenModelica. The proposed energy hub methodology in the previous chapter was applied in the case study to get an integrated energy hub. Based on the electricity transports rates provided by the local utility Liander, four service cases were selected to coordinate together to work for the energy hub, except the TOU bill management service due to the fixed electricity price for the commercial users in the tariff regulations. At first, four separate service cases were built without considering the effects of the others. The demand chare reduction service could help the stadium save € 345,185.40 per year on the electricity bill and earn the € 112,096 pear year as the profit from the energy hub. In addition to the economic benefit, this service case can also reduce 67.5 tons of carbon emission per year. Moreover, the increased PV self-consumption service can save €399.968.32 per year on the electricity bill, and this number does not add the extra profit from the energy trade in the energy hub yet. In total, this service case can prevent 487 tons of Carbon Dioxide emission per year, which is a large contribution to the whole Energy Transition process. For both the back-up service and flexibility provider for the P2P trading platform, operation procedure and cooperation mode were suggested, and enough space was left for the adjustment of the operation of the energy hub since there is some uncertainty lying at how often these two services could occur and how much capacity they may need.

The last step of building the energy hub is to integrate all available service cases to form a comprehensive energy hub to make different services operate together to maximize the benefit of both the members of the energy hub, local grid and development of Energy Transition.

6.2 FUTURE WORK

To consummate the realization of the energy hub on the basis of the present research, the related further improvements are needed in two main aspects.

- Business model perfection

Based on the current work, further refinement of the business models of each service case of the energy hub could be done in the future, such as the prices in different contracts and the customized agreement with the local utility.

- Management mechanism accomplishment

At the technical level, there are several things waiting for the development, such as how to coordinate the charging and discharging statuses of the battery storage system and the monitoring and control system of the entire energy hub.

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