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Techno-Economic Battery Capacity Estimation for Grid-Connected Building-Integrated Photovoltaic Systems

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Dedicated to the memory of my father

Abdelmotaleb, Mohammed Yassin

Separated by death, together by love

(1944-2010)

Abstract

Among the various applications of Photovoltaic (PV) technology, building-integrated photovoltaic (BIPV) system is one of the most up-and-coming ways of producing on-site electricity silently, without environmental hurt or depletion of resources. These BIPV systems are being used broadly in the development of zero energy buildings (ZEBs). In future, ZEBs are going to play a significant role in the upcoming smart grid development due to their contribution on the on-site electrical generation, energy storage and demand side management.

The main objective of this research is to estimate the appropriate battery energy storage (ES) capacity with consideration of local PV production and load profile taking into account the battery characteristics with minimization of the annual electricity bill. The long-term real-time operational load and PV production are crucial factors in the estimation in addition to the electricity pricing mechanism (tariff). In this study, real-time operational data of BIPV systems from different geographically located nearly zero energy buildings (ZEBs) are used for estimating the capacity of battery energy storage for each building. These buildings are: (i) C6 house in the Smart Village Skarpnes in Southern Norway and (ii) The Energy and Resources Institute (TERI) University in New Delhi, India. In the interest of making the results of this work useful for planning of installing battery energy storage systems for grid-connected BIPV systems, two battery technologies are considered in this estimation. These types are (i) lead-acid type and (ii) lithium-ion type.

In addition, the levelized cost of energy (LCOE) has been calculated for the estimated battery sizes for project frame time of 25 years considering the initial cost as well as the replacement cots of the components based on the operational lifetime and the economic parameters at each geographical location. In addition, a quantitative analysis of the on-site PV production to the local energy load demand has been made for each building with aim of helping with comprehension of how the energy storage may help in achieving nearly zero energy buildings by reducing the grid dependency and increasing the self-consumption of the on-site PV production.

The availability of the hourly real-time PV production as well as load profiles sow the seeds of well accurate sizing of battery capacities. In addition, consideration of two different battery types make the results of this work very useful for planning and installing the battery energy storage systems for grid-connected BIPV systems in smart grid environment in Norway and India.

Key Words: Building-Integrated Photovoltaic (BIPV), Zero Energy Building (ZEB), Energy Storage (ES), Levelized Cost of Energy (LCOE).

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Any weakness or shortcoming found in this work is my own responsibility. Any strengths or useful insights, on the other hand, would have not been possible without the support and help of many people.

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List of Abbreviations

AC	Alternating Current
BIPV	Building-Integrated Photovoltaic
CRF	Capital Recovery Factor
DC	Direct Current
DOD	Depth Of Discharge
DG	Distributed Generators
DSM	Demand Side Management
ES	Energy Storage
ESS	Energy Storage System
FiT	Feed in Tariff
LCOE	Levelized cost of energy
O & M	Operation and maintenance
P-left	Left amount of Power (PV-Load)
P-lack	Lack amount of Power (Load-PV)
PCC	point of common coupling
PCD	Power Conditioning Devises
PV	Photo-Voltaic
SOC	State of Charge
TERI	The Energy and Resources Institute
TOU	Time Of Use
WACC	Weighted Average Cost of Capital
ZEB	Zero Energy Building

List of Research Publication(s)

Paper I: **Mohammed Abdelmotaleb M.Yassin**, Mohan Lal Kolhe and Aimie Nazmin Azmi, ”Battery Capacity Estimation for Building-Integrated Photovoltaic System: Design Study of a Southern Norway ZEB House ”, ***Accepted*** in the peer reviewed 7th IEEE International Conference on Innovative Smart Grid Technologies (IEEE PES ISGT Europe 2017).

Paper II: **Mohammed Abdelmotaleb M.Yassin**, Mohan Lal Kolhe and Arvind Sharma,”Battery Capacity Estimation for Building-Integrated Photovoltaic System: Design Study for Different Geographical Location(s)”, ***Submitted*** (under review) to the 9th International Conference on Applied Energy, ICAE2017, Cardiff, UK.

Chapter 1

Introduction

In this chapter, we attempt to provide background and motivation regarding the concept of estimating the size of the battery energy storage for grid-connected building-integrated PV systems. Thereafter, the objectives and the scope of this thesis are presented. Moreover, the method used for the estimation as well as the key assumptions considered in this study are briefly discussed. The thesis organization is introduced in final section.

1.1 Background

Photovoltaic (PV) power systems are very common clean energy distributed generators (DG) choices, as they are less limited in potential location than small hydro and geothermal, do not emit greenhouse gases (GHGs) after installation, do not require biomass fuel to be delivered, and are economically competitive. The term DG refers to the production of useful energy near or at the location of its use, with power outputs significantly smaller than those typical of central plant. However, these sources of energy are subject to stochastic weather variations, so research has focused on their reliable integration. Since the dawn of exploring innovative ways of incorporating clean energy sources into buildings, PV systems have earned a great attention as clean energy generator. In the early 70^{th}, PV applications for buildings began appearing in remote areas where, access to an electric power grid was unaware of events [4]. However, in 2020 building-integrated Photovoltaic (BIPV) systems will become the primary element of the zero energy building (ZEB) as per European target [5]. The advantage of BIPV systems beside being source of electrical power and reducing pollution is that the initial cost can be offset by reducing the amount spent on building materials and labor that would normally be used to construct the part of the building that the BIPV modules replace. These advantages make BIPV one of the fastest growing technology of the PV industry [4]. Nevertheless, the integration of BIPV systems into existing and future electricity networks represents consequential technical challenges. The widespread development of the grid-connected PV systems requires an analysis of all technical and commercial aspects of renewable energy sources and other decentralized generation units in the distribution network [6]. Due to the nature dependency of the PV systems, the intermittency in the produced power appears [7]. Consequently, problems such as voltage fluctuations, frequency deviations, power quality in the power system network and protections settings may be created [8, 9]. In addition, there is often a considerable mismatch between electricity consumption and electricity supply of PV generators. Such demand-supply mismatch would increase the expense of the grid-connected PV-systems and destabilize the utility network [10].

Due to the unpredictability and the uncontrollability of the load demands, they considered to be very costly as a result of the uncertainty in generation availability. The traditional solution to this issue is by installing new power supply utilities to cover these peaks and variations in the load demands. Reference [11] has concluded that, the investment on the demand side management (DSM) could be more promising, cheaper and more profitable instead of investing in establishing new power supply sources. The grid-connected BIPV systems with energy storage (ES) system can help in reducing the peak demand as well as overcoming the intermittency of the load and the PV production [8, 9]. Grid-connected PV system without ES may not be very useful for improving the power quality as well as control dispatching of the power [12, 13]. ES can help to enhance the profitability of the grid-connected PV-system and also to improve the system efficiency. Thus, proper sizing of ES system is required [14–17]. ES units can be one solution to improve the power supply quality and assure system stability by reducing the fluctuation of the generated power [18]. Moreover, adding a proper size of ES to the grid-connected PV system could reduce the overall investment cost of the combined system through smart and optimized scheduling of the energy flow within the system [19].

In this study, we endeavor to investigate the profitability of adding the proper size of battery energy storage to existing BIPV system in terms of achieving maximum reduction in the annual electricity bill of the building. Many published articles have considered the sizing of battery energy storage for PV systems. In reference [9], the relationship between the PV array and battery storage capacity to supply the required energy at a specified energy load fraction for stand-alone system is proposed and it has not considered the grid-connected system. Reference [20] has determined the capacity of grid-connected PV and battery for residential system, where both PV system and battery sizes have been varied; but it has not considered fixed PV size with real operational load. Reference [21] has proposed the battery capacity sizing for grid-connected PV system for a constant load with limited charging/discharging scales and it has used a simplified PV output model as described in [22]. In many of the published methods for estimating the appropriate battery size [13, 17, 19, 23, 24], the real-time operational data (PV-production and load-consumption) have not been included for estimating the battery storage capacity. These related studies will be discussed in details in Chapter 2.

1.2 Motivation

It is observed through the literature review that the real-time operational load and real-time PV production are crucial parameters for estimating the battery capacity for a ZEB with grid-connected BIPV systems considering minimization of annual electricity bill. In this study, real operational data of BIPV systems from different zero energy buildings are used for estimating the capacity of battery energy storage for each building. These ZEBs are: (i) C6 house in Southern Norway and (ii) TERI University in New Delhi, India. The PV production as well as load profile from these buildings are available at hourly interval for full year (8760 hrs.). Therefore, the estimation of the battery capacity in this study is fairly accurate. In the interest of making the results of this work very useful for planning of installing battery energy storage systems for grid-connected BIPV systems, two battery technologies are considered in this estimation. These types are (i) lead-acid type and (ii) lithium-ion type.

Moreover, the levelized cost of energy (LCOE) has been calculated for the exact estimated battery sizes for long term study (25 years) considering the replacement of the components based on the operational lifetime and the economic parameters at each location. In addition, the quantitative analysis of the on-site PV production to the local energy load demand will help with comprehension of how the energy storage may help in achieving nearly zero energy buildings as well as enhancing the grid-interaction.

1.3 Objectives and Scope

1. The first main objective of this research is to estimate the appropriate battery size with consideration of local PV production and load profile taking into account the battery characteristics with minimization of the annual electricity bill. The real-time operational load and real-time PV production are crucial factors in the estimation of the battery energy storage capacity as well as the electricity pricing mechanism (tariff). Based on these, the research is divided in following topics:

    (a) **Techno-Economic Battery capacity estimation for Norwegian ZEB house**.
    In This case, we attempt to estimate the proper size of battery energy storage for grid-connected BIPV on ZEB house in Smart Village Skarpnes in Southern Norway.

The real-time hourly PV production with real-time operational load have to be used for finding the appropriate lead-acid and lithium-ion battery sizes with minimization of the annual electricity bill. This estimation has to be analyzed under two cases of local electricity tariffs. These cases are:

i. **Flat-rate without feed-in-tariff (FiT)**. This tariff has been used first as a critical scenario of C6 since there is no FiT. In this situation, we considering two main objectives. (i) Minimizing the amount of energy supplied to the grid by charging the battery from the left power of PV system after covering the load and (ii) Minimizing the cost associated with purchasing electricity from the utility grid by discharging the stored energy when there is a lack of PV generation or during nights.

ii. **Spot-price tariff with one-to-one FiT**. This tariff has been examined on the C6 house with more focus since it is the most suitable pricing mechanism for C6 house when considering the benefits of selling the excess of on-site PV generation. In this situation, we considering two main objectives. (i) Maximizing the benefits of selling the energy to the grid. (ii) Minimizing the cost associated with purchasing electricity from the utility grid.

(b) **Techno-Economic Battery capacity estimation for Indian TERI university**.
In this case, we attempt to estimate the proper size of battery energy storage for rooftop grid-connected BIPV at TERI university in New Delhi, India. The university building uses three sources of energy. These sources are: (i) the utility grid, (ii) diesel generators and (iii) BIPV. The real-time hourly PV production with real-time operational load of the university are available for a year (Mar 2016 to Feb 2017). In this case, only half of the total load profile has to be used. As it is assumed that 50 % of the annual load energy from the TERI building will be covered from the PV system, so that this 50 % of the annual load energy will be treated as zero energy building (ZEB). In this situation, we attempt to estimate the proper size of battery energy storage with minimization of the annual electricity bill. By doing this, the university and utility can expect the maximization of self-consumption energy and reducing the dependency on the grid. Accordingly, the university can reduce some of the installed diesel generators capacity and saving some of the fuel cost.

2. The second main objective of this study is to make an economic analysis for calculating the levelize cost of energy (LCOE) for the exact estimated battery capacity in each case. This analysis has to made on the exact estimated battery size considering the cost of the battery and its replacements based on the operational lifetime. In addition, the economic

factors at each geographical location has to be included in the economic analysis.

3. The third objective is to make a quantitative analysis of the nearly zero energy buildings (ZEBs) for investigating on-site energy generation with reference to local load as well as evaluating the performance of the battery energy storage on reducing the dependency on the utility grid and increasing the self-consumption of the on-site PV production.

1.4 Techno-Economic Battery Sizing for BIPV System

1.4.1 Technical part

The sizing of battery capacity extremely depends on the mechanism of the electricity tariff used. Therefore, the estimation strategy model will change from tariff to another and will be discussed in details in later chapters (Chapter 4 and Chapter 5). Figure 1.1 shows the structure of the battery capacity estimation process (main model).

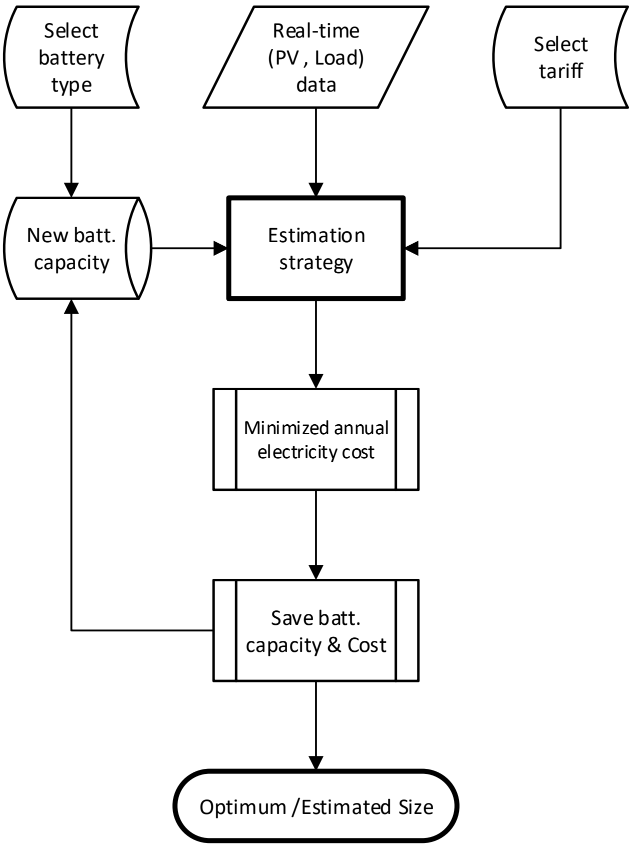


Figure 1.1: Main model structure for battery capacity estimation

As shown in Figure 1.1, the real-time PV and load data are used as inputs in to the model. Then the customer has to select the required electrical tariff and insert the price per unit of energy. Afterwords, the customer has to select the type of battery to be examined either lead-acid or lithium-ion. A suggested range of battery capacities with 50 Ah as interval is introduced the model. For each suggested capacity (interval), the maximum charging and discharging time is assumed to be fixed and the minimum battery state of health is zero to allow the battery to work up to 100 % of its reference capacity. Moreover, the battery capacity loss occurs due to the aging factor only, when the battery is discharging and it has been used for analyzing the lifetime of the battery. For each interval of battery capacity, the model repeats the estimation process and use that battery capacity with the corresponded annual electricity bill. Eventually, the model interprets the annual electricity bill with each battery capacity interval and indicate the optimum-estimated battery capacity responsible for the minimum annual electricity bill.

1.4.2 Economic part

After estimating the size of the battery in the technical part, the levelized cost of energy (LCOE) of the exact estimated battery size has been analyzed considering the cost of the components (battery and inverter) and their replacements based on the operational lifetime. Figure 1.2 exhibits the model structure for LCOE analysis of the estimated battery capacity. In this model, the estimated battery size is the start step in the process. Based on this size and the maximum charging/discharging time (hr), the inverter capacity has been determined. Depending on the Initial & replacement (battery and inverter) cost rate, battery size and battery lifetime, their initial and replacements cost have been projected in the cash flow for the project frame time (25 years). Similarly, the operation & maintenance (O&M) cost rate has been used to determine the (O&M) cost and further escalated through the project frame time using the escalation rate (ER %).

On the other hand, the annual revenue/saving achieved when connecting the estimated battery size is annually escalated with the same ER and deducted from the cost stream. At the end of the project, residue value (salvage) has been calculated based on the last replacement of each component. The projection of all costs, revenues and salvages represents the cash flow.

Thereafter, the cash flow is discounted using weighted average cost of capital (WACC). This index (WACC) is the rate that a company is expected to pay on average to all its security holders to finance its assets and it is dictated by the external market. The summation of this discounted cash flow represents the net present cost/value (NPC). To find the annuity payments, the NPC is annualized over the project frame time using the capital recovery factor (CRF).

Eventually, the annual battery energy production is amused to be the same during the battery lifetime and is has been used together with the annualized payment to find the The levelized cost of energy ($LCOE_{E-out}$) delivered by the estimated battery size. Based on that, the $LCOE_{E-out}$ of each battery size has to be added to the purchasing price of energy for the combined system (PV+ES) after installing each battery capacity to check the long-term profitability of adding that battery energy storage. Hence, the economic parameters and the mathematical formulation of this method will be discussed in details in Chapter 3.

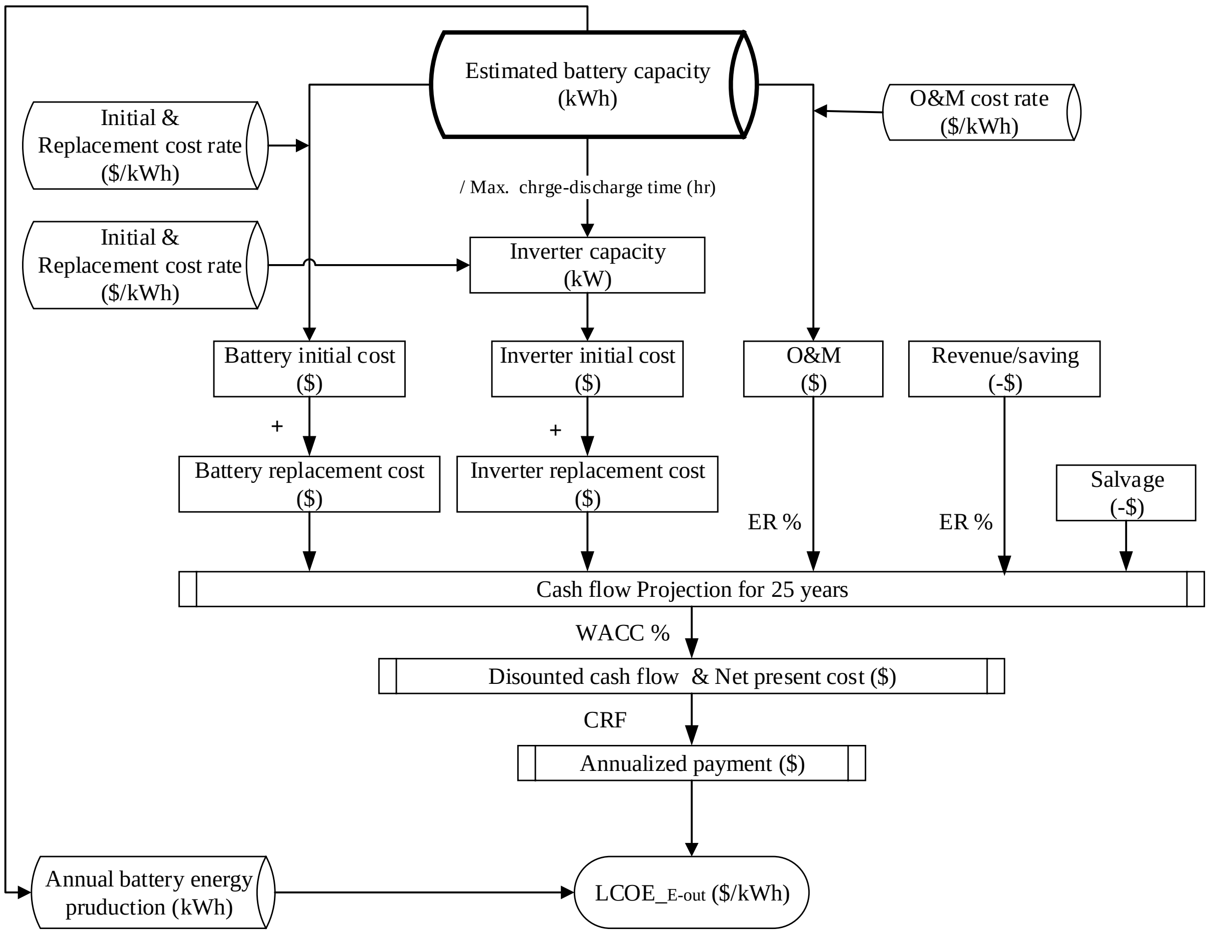


Figure 1.2: Model structure for LCOE analysis of the estimated battery capacity

1.5 Thesis Organization

This thesis is organized as follows:

- **Chapter 2** (***Literature Review***) presents a literature review on grid-connected PV systems, energy storage systems. This is followed by a review on integration of PV systems with battery energy storage. It presents also the collected information regarding the two considered types of batteries with more focus on the required modeling data. Eventually, a brief economic literature review is presented.

- **Chapter 3** (***Mathematical Formulation***) exhibits the definitions and the mathematical modeling of the selected battery characteristics (technical part). In addition, this chapter describes the long term economic analysis approach considering to calculation of the levelized cost of energy (LCOE) of the estimated batteries (economic part).

- **Chapter 4** (***Techno-Economic Battery Capacity Estimation for Norwegian ZEB House***) reveals background about the Smart Village Skarpnes in Southern Norway as well as the grid-connected BIPV on ZEB (C6 house). The real-time operational data as well as the electrical pricing mechanisms are presented before illustrating the estimation strategies in details. Hereafter, the proper battery capacities are estimated for each electricity tariff case and deeply discussed. Eventually, the estimated battery capacities are economically analyzed before concluding the case study.

- **Chapter 5** (***Techno-Economic Battery Capacity Estimation for Indian TERI University***) presents the second case study in this thesis. At the outset, a brief background about TERI University BIPV system is presented. Additionally, the real-time operational data are exhibited along with information on how this building is partially assumed as a ZEB. Consequently, the results are obtained and discussed based on the estimation strategy explained in the same chapter.

- **Chapter 6** (***Quantitative (Per-Unit) Analysis & Relative Comparison***) gives additional value to this thesis by presenting a relative comparison considering the flat price case of Norwegian conditions with the Indian conditions. The quantitative analysis in this chapter reveals the effect of adding energy storage on reducing the dependency of both ZEBs on the utility grid.

- **Chapter 7** (***Conclusions***) summarizes the main conclusions and contributions of this thesis and point out some directions for future research.

Chapter 2

Literature Review

2.1 Summery

In this chapter, presents a literature review on grid-connected PV systems and energy storage systems. This is followed by a review on integration of PV systems with battery energy storage. It presents also the collected information regarding the two considered types of batteries with more focus on the required modeling data. Eventually, a brief economic literature review is presented.

2.2 Grid-connected PV Systems

In an effort to share critical assets, and thus reducing the environmental effects of burning fossil fuels as well as reducing the peak load demands, a significant growth of grid-connected PV systems is being observed during the last decades [25]. Such growth in a clean energy resources is very attractive where, sustainability nowadays is an ethical norm. Since 2000, the grid-connected PV models overtook the stand-alone systems as the largest global market according to the international Energy Agency member countries [12]. Despite the challenges of achieving an efficient grid-interaction with the PV system, the cumulative installed capacity of grid-connected PV modules in 2009 has reached more than 20,000 MW. The applications of solar PV power systems can be split into two main categories based on the installed capacity (size) as:

- Centralized high-capacity PV power generators.
- Distributed small-capacity PV power generators (consumer level).

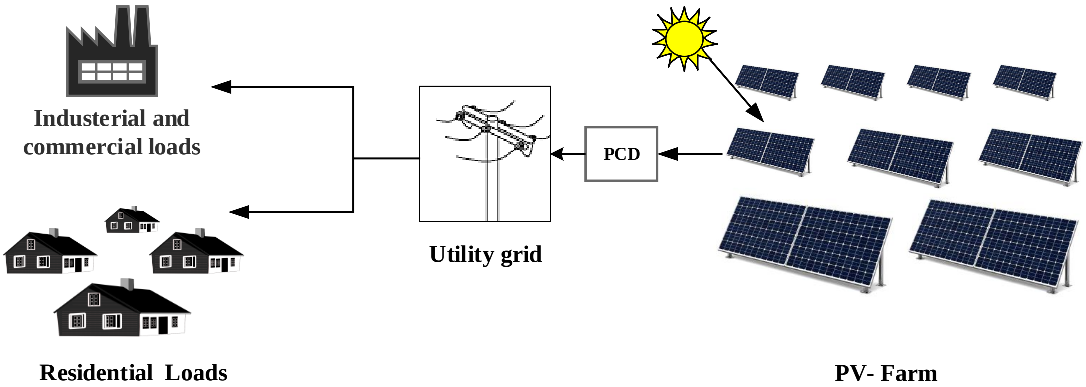


Figure 2.1: Utility-scale PV generation station

2.2.1 Utility-scale PV Generation Stations

The utility-scale PV generation stations contains a large number of PV arrays called usually PV-farms as shown in the example given in Figure 2.1. A utility-scale PV power plant is one which generates solar power and feeds it into the grid, supplying a utility with energy. The integration of intermittent renewable energy resources such grid-connected PV systems into existing and future electricity networks represents consequential technical challenges. The widespread development of the grid-connected PV systems requires an analysis of all technical and commercial aspects of renewable energy sources and other decentralized generation units in the distribution network [6]. In Figure 2.1, the harvested energy from the PV system is sent to the utility grid via power conditioning devices (PCD), DC/DC converters and DC/AC inverters. These PCD have the responsibility of changing the form of the power output of the PV-farm from DC to AC, enhancing the power quality in order to be connected with AC grid without any interruptions. Installing such type of renewable energy DG would gain several benefits [12] such as:

- The cost-effectively displacement of the existing fossil fuel generation plants.
- GHG emission reductions.
- Reducing the thermal overload on transformers and conductors.
- Eliminate more expenses of installing new power stations.
- Eliminate more expenses of reconditioning existing transmission lines, transformers and new circuit constructions.

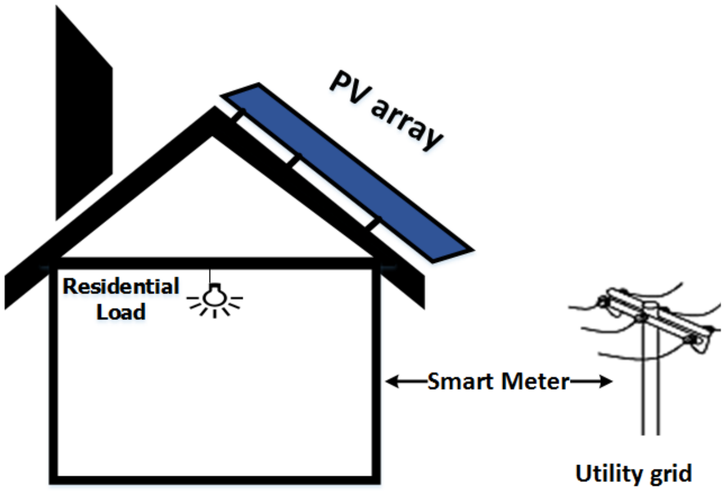


Figure 2.2: Building-integrated PV systems

2.2.2 Distributed Small-capacity PV Power Generators

A Building Integrated Photovoltaic (BIPV) system consists of integrating photovoltaic modules into the building envelope, such as the roof (Figure 2.2) or the facade. These systems are usually installed in a way that taking the priority of satisfying the local loads first before supplying the excess of the generated power to the grid. In this work, the focus is on the grid-connected BIPV systems which as shown in Figure 2.2. The principles of operation are that, during the daytime of sunny days when the solar irradiation fall on the roof mounted PV array, it generates the DC power. Since the residential home's appliances operate with an AC form of energy, the DC/AC grid-interactive inverter is installed between the DC-bus/PV output and the AC-bus. These inverters are responsible also for synchronizing the frequency of the generated power with the frequency of the utility grid. The domestic load is covered during the daytime from the generated energy from the PV array. The surplus of the energy after covering the domestic load is exported to the utility-grid through smart meters and depending on the feed-in-tariff (FiT), the profit of selling this excess of energy can be analyzed. On the other hand, during nights/cloudy days, the shortage/lack of energy is imported from the utility grid. BIPV could be installed with/without ES. Grid-connected BIPV systems without an ES have the drawback of power shortage during nights and cloudy days, variations in the voltage magnitude and consequent deterioration of voltage quality [8]. Additionally, due to the nature dependency of the PV systems, the intermittency in the produced power appears [7]. Consequently, there is often a considerable mismatch between electricity consumption and electricity generation of PV plants. Such demand-supply mismatch would increase the expense of the grid-connected PV systems and destabilize the utility network [10, 26].

2.2.3 Technical Considerations

According to the Australian Standards [12, 27], several issues have to be considered when installing grid-connected PV system. Among these issues, the selection of the grid-interactive inverter has to go through the following requirements:

- **Safety** specially during islanding. The term islanding refers to the period of time when there is a maintenance on the grid or the grid is partially off while the inverter is still sending power to the grid. Such phenomena could be very dangerous the grid workers and the equipment on the network. Thus, isolation transformers are commonly used to prevent this islanding.

- **The efficiency** of the grid-interactive inverter has to be quite high and the losses during the periods where the load is negligible has to be considered.

- **Power quality**. Since the structure of the grid-connected PV system contains power conditioning device, harmonics are tended to appear on the current and voltage on the AC side. These harmonics causes damages to the utility equipment and loads. The limit for the total harmonic distortion (THD) is 5 % for current and 2 % for voltage. Thus, the waveform and the power factor must be commutated with the grid.

- **Compatibility** with the PV-array. The inverter should tolerate the open circuit voltage of the array. The DC input voltage of the inverter should be compatible with array's maximum power voltage in order to achieve the maximum power point. Moreover, the inverter should have very low electromagnetic interference to comply with the local requirements.

2.3 Energy Storage

The general concept behind energy storage (ES) is to capture energy produced at one time for use at a later time. The process of capturing the energy is generally regarded as the charging while the process of releasing the energy to be used is regarded as the discharging. ES units are one solution to improve the power supply quality, assure system stability and help to increase the penetration of renewable generators by reducing the fluctuation of their power generation [14]. There are many technologies used for energy storage purposes. These technologies can be broadly classified according to the purpose for which the energy is stored as:

1. Electrical energy storage.

2. Thermal energy storage.

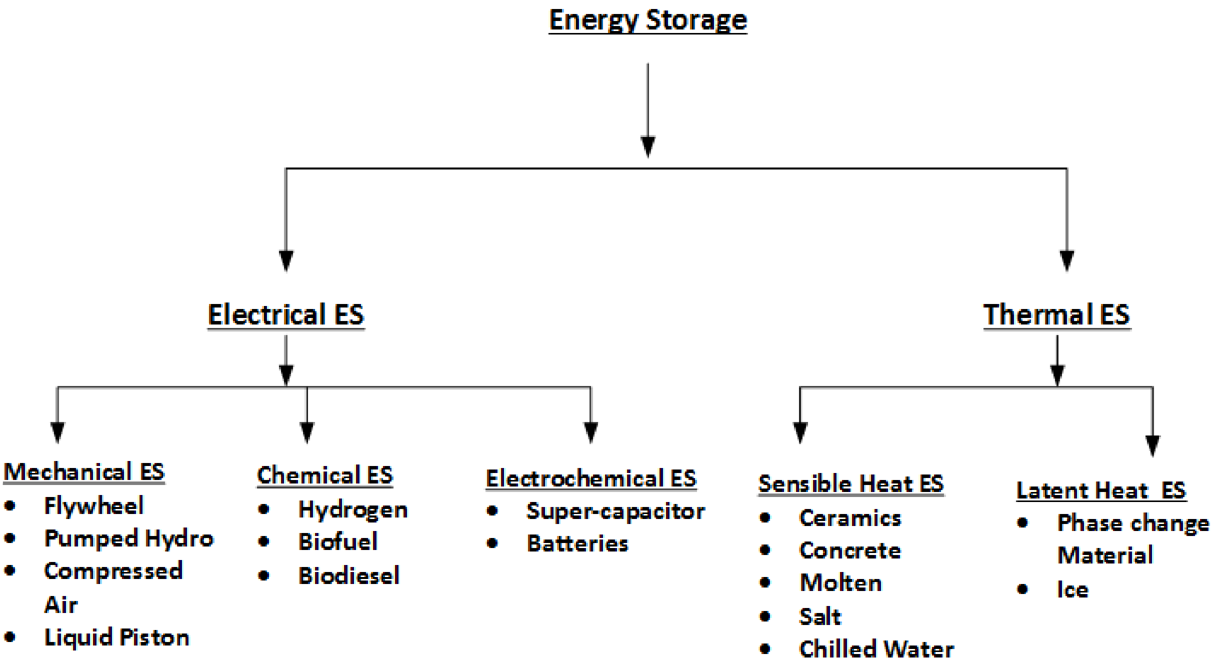


Figure 2.3: Energy storage technologies classification [1]

These two technologies can be detailed further into different technologies. Some of these ES technologies are shown in Figure 2.3. The only way to store the electricity is by converting it into a more stable energy form. Then transforming the electricity form back when needed. Among the various technologies which can be used for this purpose are regarded as electrical energy storage technologies and can be grouped (Figure 2.3) as: mechanical energy storage, chemical energy storage and electrochemical energy storage. In this study, we concern specially about one type of electrochemical ES which is batteries. This study concerns about addressing one of the various benefits of installing this kind of ES to BIPV.

2.3.1 Batteries for BIPV Systems

Batteries in PV-systems applications should be able to supply reasonably steady power when there is a power outage or during the low power generation of the PV-systems. The batteries for PV applications are to be designed to meet the following characteristics [28]:

- Low cost.
- High energy efficiency.
- Long life time.

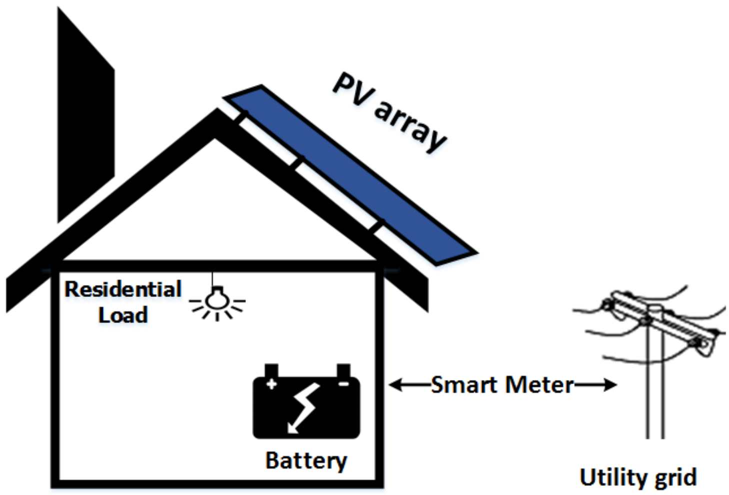


Figure 2.4: Building-integrated PV systems with battery

- Low maintenance and robust construction.
- Good reliability and less self discharge.
- Wide operating temperature.

The rechargeable battery energy storage is considered as the oldest electrical energy storage device which has the ability to store the energy as chemical energy and release the stored energy in the electrical form [29]. The BIPV system with battery is shown in Figure 2.4. The advantages of using an energy storage varies according to the purpose of using it as follow:

- Many applications mostly use the energy storage for demand side management (peak shifting) together with the PV systems to match the generated power from the PV and the load by compensating the load at peak times or when there is a lack of PV [30].
- Another useful use of the energy storage is to buffer/mitigate the fluctuations of the intermittent power output of the renewable energy distributed generators when connecting to the AC grid. If we take the PV systems as an example, we would recognize the nature dependency of the power output on the solar irradiation which would cause several problems in the AC grid and could destroy our appliances [26]. Thus, to get a smooth power or energy curve of the PV, an energy storage should be added to eliminate the destabilizing effect of the solar intermittency [15–17].

Apart from the benefits of adding ES to grid-connected BIPV, ES application covers sectors such as hybrid electric vehicles (HEV), marine and submarine missions, aerospace operation, portable electronic systems and wireless network systems. Nevertheless, many studies have been made considering the sizing of battery energy storage for PV systems depending on the system configuration (stand-alone or grid-connected) such as:

For off-grid (stand-alone) hybrid system of PV/Wind and a battery bank, the dimension of this combination for a given load and a desired loss of power supply probability is analyzed based on the minimum cost of the system [19]. In addition to reference [9] where, the relationship between the PV array and battery storage capacity to supply the required energy at a specified energy load fraction for stand-alone system is proposed and yet it has not considered the grid-connected system.

For on-grid (grid-connected) PV systems, several studies have been made. For suppression of a PV power plant output fluctuation, reference [17] estimated the battery capacity. In their study, they have made a relation between the fluctuation of the PV power plant and the battery capacity over a certain period of time and found the corresponding capacity which can eliminate the destabilizing effect on the PV curve.

Reference [23] concluded that, the dimensioning of batteries for grid-connected PV system highly depends on electricity rates and battery ageing factor. In this work [23], a synthetic load using fuzzy clustering method is used for estimating the battery capacity for grid-connected PV with respect to optimized energy dispatch schedule. The time of use (TOU) and time of use with demand (TOUD) tariffs are used. Similarly, Reference [20] has determined the capacity of grid-connected PV and battery for residential system, where both PV system and battery sizes have been varied; but it has not considered fixed PV size with real operational load. Moreover, and despite the similarity of the current study and the study presented by reference [21], the key difference is that they proposed the battery capacity sizing for grid-connected PV system for a constant load with limited charging/discharging scales and it has used a simplified PV output model as described in [22].

Reference [13] presented a deterministic approach for Energy flow management in grid connected PV systems with storage taking into account the effect of the aging factor of the battery as cost. In their work, The PV output power has been modeled with input values of irradiation and temperature. In addition, they have used a predictive load profile for 24 hrs.

2.3.2 Types of Batteries

Deep cycle batteries for the energy storage system are the common used for renewable energy systems [12]. A battery system should supply reasonably steady power when there is a power outage or during PV system is generating less power output. In this work, two battery types are examined. These types are lead-acid and lithium-ion.

Lead-acid Batteries

Lead acid batteries are the common energy storage devices for PV systems. Due to the reliability, low cost, extended life span and fast response, lead acid batteries are dominating in some applications including household. These batteries known as well with low self-discharge rate and low maintenance [12, 28, 31]. The lead acid batteries can be classified as:

- Flooded cell type battery.
- Sealed /Gel type battery.
- Gelled batteries.
- Absorbed GAS MAT [AGM] batteries.

Lithium-ion Batteries

Lithium-ion is a type of rechargeable battery in which lithium ions move from the negative electrode to the positive electrode during discharge and back when charging. These batteries use lithium metal or lithium compound as anode [1]. This type of battery is used for mainly portable electronics and medical devices [1]. The Li-ion batteries are lighter, smaller and more powerful than other batteries which make it attractive for electronics consumers [1, 12]. The high cost of lithium-ion battery and the fragile with temperature dependent life cycle are the disadvantage of this type of batteries.

2.3.3 Batteries Characteristics

In order to model both batteries, several parameters have to be considered to differentiate between both types. The required characteristics for this study are collected and listed in Table 2.1. In this study, both nominal voltage and the Charge/discharge time are taken to be the same for both batteries. The term Charge/discharge time refers to the hours takes the battery to be fully charged/discharged. The depth of discharge (DoD) is an indication to the maximum amount of energy can be taken from the battery in percentage (%) of the nominal capacity and it is basically the opposite of the state of charge (SOC). For example, if the SOC of the battery is 20 %, that means the DoD is 80 % and the opposite is true. If the battery is fully charged (SOC=90 %), that means the DoD is 10%. Charge/discharge efficiency (%) indicates to the amount of energy supplied to/drained from a cell relative to the amount of energy that is wasted within the cell as a result of its internal impedance [1]. The self-discharge factor (a) represents the loss of capacity

[1] Quora, https://www.quora.com/What-is-charge-discharge-efficiency

Table 2.1: Batteries characteristics

	Lead-Acid	Lithium-ion
Nominal voltage	12 (V)	12 (V)
Depth of Discharge (DoD)	60-80 % [34, 35]	80 % [34]
(Charge/discharge) efficiency	80-90 % [35, 36]	90-95 % [36]
(Charge/discharge) time	10 hrs	10 hrs
Aging factor (Z)	$3e^{-4}$ [13]	$0.17e^{-4}$-$2e^{-4}$ [13]
Self-discharge factor (a)	3-5 % /month [34, 35]	1-2 % /month [34]
Initial Cost rate	100-200 $ /kWh [37]	500-1300 $ /kWh [37, 38]
Replacement Cost rate	50-100 $ /kWh [38]	150-400 $ /kWh [38, 39]
O & M Cost rate	4-5 $ /kWh [37, 39]	5-7 $ /kWh [39]

of a battery while in stored or unused condition without external discharge. The ageing factor (Z) is a crucial parameter in this work that helps to calculate the lifetime of the battery. This factor (Z) is relative indicator of how much in percent's the degradation of the battery relative to the expected cycles of that battery which helps to analyze the battery capacity loss

The capacity loss and the performance reduction of the lead-acid batteries happens commonly if the battery dwells at low charge and never receives a full charge and that's due to the vertical orientation of the plates (electrolyte stratification). In a normal battery, the distribution of the acid is equally from the top to the bottom of the battery. In contrast, a stratified battery has heavier concentration of the acid at the bottom [2]. Another typical disadvantage of these batteries is the corrosion of the external metal parts. This corrosion happens due to the chemical reaction of the battery terminals, lugs and connectors [32]. Moreover, the temperature has a strong effect (rate of mass loss) on the degradation of the battery. Reference [33] has concluded that the cycle-life of the lithium-ion batteries is influenced mainly by the charge/discharge conditions and that the electrochemical oxidation may be the cause of the degradation of these batteries.

2.4 Economic Part

In order to have a complete and solid solution to the problem of battery energy storage sizing, the LCOE from the battery has to be considered. The LCOE is defined as the total lifetime cost of an investment divided by the accumulated generated energy by this investment. The importance of the LCOE is reflected in the inclusion of the initial cost, replacements cost and operation & maintenance cost of the battery. However, reference [40] has provided a new methodology for the calculation of levelized cost of stored energy. Many new terms have been proposed such

[2] Battery University, http://batteryuniversity.com/learn/article/water_loss_acid_stratification_and_surface_charge

as price increase factor and internal transfer cost to calculate the LCOE of the hybrid system. In practice, it is difficult to determine these values. In reference [41], authors have provided a review of LCOE and highlighted the recent developments in large-scale solar PV systems. They proposed a derived model for calculating the LCOE for ES. The proposed methods are evaluated for two types of storage technologies Vanadium Redox Battery (VRB) and Lithium-ion. The results conclude that in the future VRB could potentially substitute Lithium-ion for the energy storage application in PV systems due to the lower LCOE and the falling discount rates for renewable energy systems. In both references [40, 41], estimation of the proper size of the batteries is not included rather than testing fixed sizes.

In this study, real-time operational data from different BIPV systems under different climate conditions are used for estimating the capacity of battery energy storage for each location. The PV production as well as load profile from these locations are available at hourly interval for full year 8760 hrs. This size of battery is estimated for the maximum reduction in the annual electricity bill of that building. In this work, the characteristics of two battery energy storage have been considered. These types are: (i) lead-acid battery and (ii) lithium-ion battery. The batteries characteristics and the electricity tariff are used for the estimation. Moreover, the LCOE is calculated for the exact estimated battery size for long term study (25 years) considering the replacement of the components based on the operational lifetime.

Chapter 3

Mathematical Formulation

3.1 Summery

This chapter consists of two main parts. In the first (technical) part, the selected battery characteristics for this study have been presented. Moreover, the mathematical modeling of these characteristics has been given. In the second (economic) part, we describe the long term economic analysis approach considering to calculation of the levelized cost of energy (LCOE) of the estimated batteries in the first part.

3.2 Selected Battery Characteristics

The considered types of batteries in this project are lead acid battery and lithium-ion battery. Table 3.1 shows the characteristics of the both investigated types of batteries. The PV-Inverter efficiency is taken as 97% [24] while battery-inverter is taken with efficiency of 90% [24] and life time of 15 years with cost rate of 500$/kWh [23, 42]. Hence, in this study the cost of the PV array and PV-inverter are not included.

3.2.1 Mathematical Modeling of Battery system

This section contains the mathematical representation of the battery model. Starting from the time interval (δt) that has been used here, the PV power output can be expressed as:

$$P_{pv,ac}(d,t) = \eta_{pv,inv} \times P_{pv,dc}(d,t) \tag{3.1}$$

where, $P_{pv,ac}$ represents the AC output of the PV inverter (kW), $\eta_{pv,inv}$ represents the efficiency of the PV inverter, $P_{pv,dc}$ represents the DC output of the PV to the inverter (kW) and (d,t)

Table 3.1: Selected batteries characteristics

Characteristics	Lead-Acid	Lithium-ion
Nominal voltage	12 (V)	12 (V)
Depth of Discharge (DoD)	60 %	80 %
Maximum State of Charge SOC_{max}	90 %	90 %
(Charge/discharge) efficiency	85 %	95 %
(Charge/discharge) time	10 hrs	10 hrs
Aging factor (Z)	$3e^{-4}$	$2e^{-4}$
Self-discharge factor (a)	3 % /month	1 % /month
Initial Cost rate	100 $ /kWh	500 $ /kWh
Replacement Cost rate	50 $ /kWh	150 $ /kWh
O & M Cost rate	4 $ /kWh	5 $ /kWh

represents the day and time respectively.

The battery is modeled in a way that, the power transferred to the battery is taken as positive (charging), and negative when the power is transferred from the battery (discharging). In the same way. The energy purchased from the grid is modeled as (positive) and when supplying to the grid as (negative). The charge/discharge power [23] of the battery can be formulated as:

$$P_{dc,batt}(d,t) = \frac{E_{batt}(d,t) - E_{batt}(d,t-\delta t)}{\delta t} \tag{3.2}$$

where, $P_{dc,batt}$ represents the DC the power transferred to/from the battery during time interval (δt) in (kW) and E_{batt} represents the available energy in the battery (kWh). The maximum battery charge/discharge rate (kW) can be represented as:

$$P_{dc,batt,max}(d,t) = \frac{C_{batt}(d,t) \times V}{t_{max}} \tag{3.3}$$

where, $P_{dc,batt,max}(d,t)$ represents the maximum battery charge/discharge rate of the battery, C_{batt} represents the battery capacity (Ah), V represents the battery nominal (rated) voltage and t_{max} represents the maximum time for charge/discharge (hr.). Hence, the maximum charge and the maximum discharge rate of the battery are assumed to be equal in this study. Then through the inverter of the battery, the AC power [23] can be represented as:

$$P_{ac,batt}(d,t) = \begin{cases} \eta_{batt,inv} \times P_{dc,batt}(d,t), & \text{when discharging.} \\ \frac{P_{dc,batt}}{\eta_{batt,inv}}, & \text{when discharging.} \end{cases} \tag{3.4}$$

where, $P_{ac,batt}$ represents the AC the power transferred to/from the battery (kW), and $\eta_{batt,inv}$

represents the efficiency of the battery inverter. The battery capacity loss is very important factor in this study which leads to obtain the lifetime of the battery. These losses occur due to the aging factor of the battery. The battery state of charge (charging/discharging) with time is given as:

$$SOC(d,t) = \begin{cases} SOC(d,t-\delta t)(1-a) - \frac{P_{dc,batt}(d,t)}{\eta_{batt} \times C_{batt}(d,t) \times V}\delta t, & \text{when discharging.} \\ SOC(d,t-\delta t)(1-a) + \eta_{batt}\frac{P_{dc,batt}(d,t)}{C_{batt}(d,t) \times V}\delta t, & \text{when charging.} \end{cases} \tag{3.5}$$

where, SOC represents the state of charge of the battery, η_{batt} represents the efficiency of the battery, C_{batt} represents the capacity of the battery (Ah) and a represents the self-discharge factor. The battery capacity loss due to of the aging factor [23] is described as:

$$\Delta_{BC} = \begin{cases} \Delta_{BC}(d,t-\delta t) - Z \times P_{dc,batt} \times \delta t, & \text{when discharging.} \\ \Delta_{BC}(d,t-\delta t), & \text{when charging.} \end{cases} \tag{3.6}$$

where, Δ_{BC} represents the annual cumulative capacity losses (kWh) during charging/discharging time and Z represents the aging factor of the battery table 2.1. Hence, the cumulative capacity losses ($\Delta_{BC}(0,0)$) at the beginning is taken as zero as it is considered that the battery initially was fully charged. The cumulative capacity losses based on charging/discharging during the specified time has been calculated in equation 3.6. This cumulative capacity losses Δ_{BC} depends on the battery charging/discharging cycles as well as the PV production and load profile during that specified time. Δ_{BC} has to be subtracted in the specified time from the nominal capacity (BC_{nom}) [23] of the selected battery to update the battery capacity as:

$$C_{batt}(d,t) = BC_{nom} - \frac{\Delta_{BC}(d,t)}{V \times 1e^{3}} \tag{3.7}$$

where, C_{batt} represents the updated battery capacity (Ah) and BC_{nom} represents the nominal (rated) battery capacity (Ah). It is important to analyze the bat trey life time considering the cumulative capacity loss Δ_{BC} for the whole year and its given by:

$$B_{life-time} = \frac{BC_{nom} \times V \times 1e^{-3}}{\Delta_{BC,year}} \tag{3.8}$$

where, $B_{life-time}$ represents the life time of the battery (years) and $\Delta_{BC,year}$ represents the cumulative capacity loses for the year (kWh). The annual electricity bill is accumulated for the year and compared with the variation of the battery sizes.

$$AEC = \sum_{d=0,t=0}^{d=365,t=8760} E_{buy/sell}(d,t) \tag{3.9}$$

where, AEC represents the annual electricity cost and $E_{buy/sell}$ represents the electricity cost each time interval (δt) in local currency.

3.3 Economic Analysis

In section 3.2, the variation of the annual electricity cost with respect to the range of examined battery capacities is analyzed. In this section, an economic analysis will be presented to obtain the levelized cost of energy (LCOE) of the estimated battery storage. LCOE is defined as the total lifetime cost of an investment divided by the accumulated generated energy by this investment. It is an economic assessment of the average total cost to build and operate a power-generating asset over its lifetime divided by the total energy output of the asset over that lifetime [41].

3.3.1 Economic Parameters

During the estimated lifetime of the project, there will be two financial streams: one is the cost stream and the other is the revenues (savings after adding the battery) stream. The cost streams contain all costs (battery plus inverter) for the same estimated life frame of the project considering the operational lifetime of these components and their replacements during the project time period. To calculate the LCOE, several economic parameters are required. These parameters are listed in Table3.2 and varies from country to another. Where, weighted average

Table 3.2: Economic parameters

Parameters	Unit
Discount rate (WACC)	%
Escalation rate of energy price (ER)	%
Project life frame	25 years
Local subsidies (if found)	currency
E-out of the battery	KWh

cost of capital (WACC) is the rate that a company is expected to pay on average to all its security holders to finance its assets. It is dictated by the external market and not by management. The escalation rate of energy price is the annual increase in percentages in the energy price. Note that the number of replacements of the batteries will vary per the mechanism of charging/discharging the battery. E-out is the amount of energy released from the battery annually.

3.3.2 Modeling of The Levelized Cost of Energy

After estimating the battery size and obtaining the required economic data, the nominal cash flow can be calculated to have similar view of Figure 3.1. As shown in the figure, the initial cost and the replacement cost of the battery and the inverter is projected for 25 years using the cost rates in Table 3.1. In this work, all costs are modeled with negative values and revenues with positive values. Note that the cost will be presented in the local currency of each geographical location.

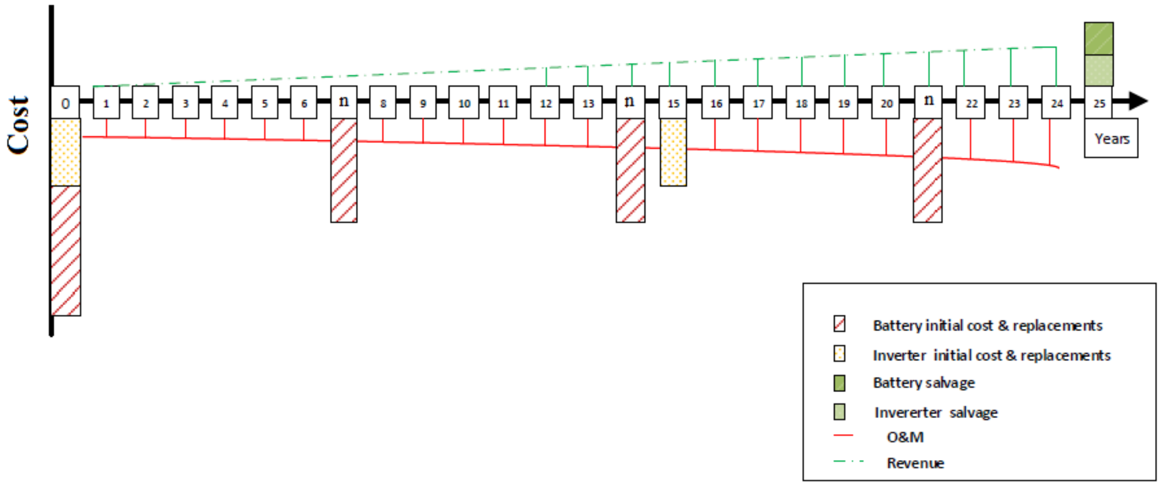


Figure 3.1: Example of nominal cash flow

The O & M cost stream and the revenues are escalated annually with the escalation rate (Equation3.10) as:

$$O\&M_{n+1} = O\&M_n \times (1+ER) \tag{3.10}$$

where, n represents the number of the year and ER represents the escalation rate. At the end of the project life frame, the residual value (salvage) of the components are calculated according to equation 3.11

$$Salvage = \frac{Cost_{rep} \times (n_{rep} - (n_{end} - n_{rep}))}{n_{rep}} \tag{3.11}$$

where, $Cost_{rep}$ represents the cost at the last year of replacement, n_{rep} is the year of replacement and n_{end} represents the last year of the project. In this work, annuitizing method is used for calculating the LCOE. In order to do that, the discounted cash flow and the net present cost

(NPC) are calculated using the discount rate WACC as shown in equation 3.12

$$NPC = \sum_{n=0}^{n=25} \frac{Cost_n}{(1+WACC)^n} \tag{3.12}$$

where, $Cost_n$ represents the total annual cost. Next, the annuity value (payments) is calculated using the annuity factor as expressed in equation 3.13.

$$A = NPV \times \frac{WACC(1+WACC)^n}{(1+WACC)^n - 1} \tag{3.13}$$

where, A represents the equal amount of money to be paid annually (annualized) as shown in the example Figure 3.2.

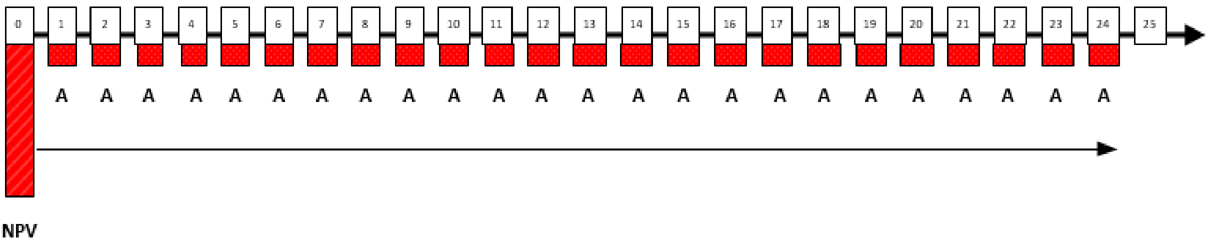


Figure 3.2: Example of the annuity value (payments)

The levelized cost of energy ($LCOE_{E-out}$) delivered by battery is calculated using the annuity value (payments) and the energy delivered by the battery for full year as shown in equation 3.14

$$LCOE_{E-out} = \frac{A}{E_{out}} \tag{3.14}$$

where, $LCOE_{E-out}$ is the levelized cost of energy delivered by battery (currency/kWh) and E_{out} represents the energy delivered by the battery for full year (kWh). In order to calculate the total LCOE, the cost of the energy supplied to the battery should be considered. This cost is expressed as:

$$POE = \frac{E_{AEB}}{Total_{load}} \tag{3.15}$$

where, POE is the net purchasing price of energy (currency/kWh), E_{AEB} represents the annual electricity bill after adding the battery (currency) and $Total_{load}$ is the total served domestic load for the full year (kWh). Finally, the total POE (currency/kWh) is calculated as shown in equation 3.16

$$Total_{POE} = POE + LCOE_{E-out} \tag{3.16}$$

Chapter 4

Techno-Economic Battery Capacity Estimation for Norwegian ZEB House[1]

4.1 Summery

In this chapter, we endeavor to apply the knowledge of estimating the battery energy storage for BIPV system. In such a context, a real case study has been presented in this chapter. The BIPV system is installed at ZEB (C6 house) located in Smart Village Skarpnes in Southern Norway. The estimation of the battery size has been done considering two different electrical pricing mechanisms and two battery types (lead-acid and lithium-ion). Thereafter, the LCOE has been analyzed under each tariff case before concluding the chapter in the final section.

4.2 Introduction

The Smart Village Skarpnes (58.43°N, 8.72°E) is located close to the city of Arendal, Southern Norway. Several houses in the smart village are built in according to the passive house standard NS3700 [2]. The village will have a total of 17 detached single family houses and 3 apartment blocks with 20 units. Five houses are built as zero energy buildings (ZEBs) with BIPV systems on the roof. Each house is fully instrumented for data collection of electricity production and consumption, grid quality parameters and indoor climate conditions. Large number of ABB electricity meters are installed on the main electrical circuits in the households to evaluate energy consumption patterns and peak power demands as well as measurement of the PV power generation data [3]. The map of the five BIPV houses in the Smart Village Figure 4.1 where PV

[1]Modified from the paper accepted in the peer reviewed 7th IEEE International Conference on Innovative Smart Grid Technologies (IEEE PES ISGT Europe 2017)

Figure 4.1: Map of the five BIPV houses in the smart village [2]

Figure 4.2: Picture of the specific studied house (C6) [3]

systems are indicated with blue and a real picture of the specific studied house (C6) is shown in Figure 4.2.

4.3 C6 House

The C6 house is a typical Norwegian house with an area of 154m^2 located in the Smart Village Skarpnes. The usable area of the roof is 57.43m^2 and it is facing south west as shown in fig 4.1. The PV panels that has been installed is Sunpower SPR 230NE-BLK-I and covering only 39.9m^2 of the roof area. The system has crystalline silicon PV modules and arranged in 16 strings as shown in Figure 4.2. Table 4.1, presents the parameters of the installed system.

Table 4.1: Installed PV-parameters at C6 house

PV system size	7.36 (KWp)
Array type	Fixed roof mount
Tilt angle	32°
Azimuth	48°

4.3.1 Real-Time Annual PV and Load Curves for C6 House

For the C6 house, The PV system is monitored for the solar irradiation and temperature through sensors placed on the roof to help for collecting data and the performance of the house being zero energy building. The individual load consumption monitored and measured by ABB electricity meters. The power quality measurements as well as power flow from/to grid is measured by ElSPEC power quality instrument. Figure 4.3 shows the generation profile of the PV system, Figure 4.4 shows the load consumption profile. Hence, all data profiles are for full year (8760) hrs. starting from Sep-2015 to Aug-2016 [43]. It is observed that there are considerable

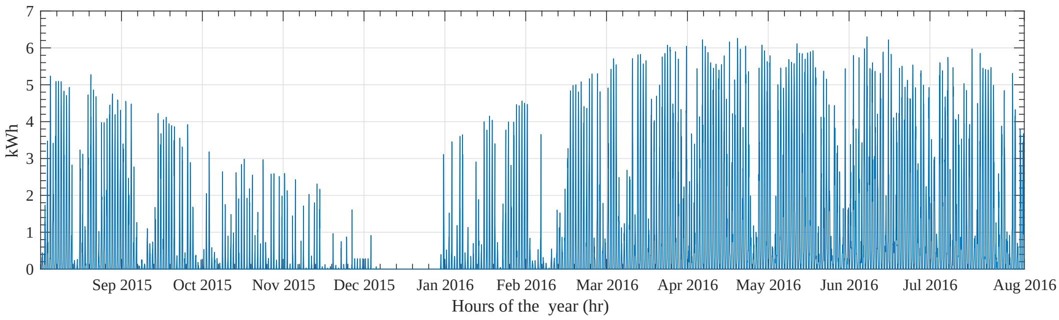


Figure 4.3: C6 house hourly PV profile for full year

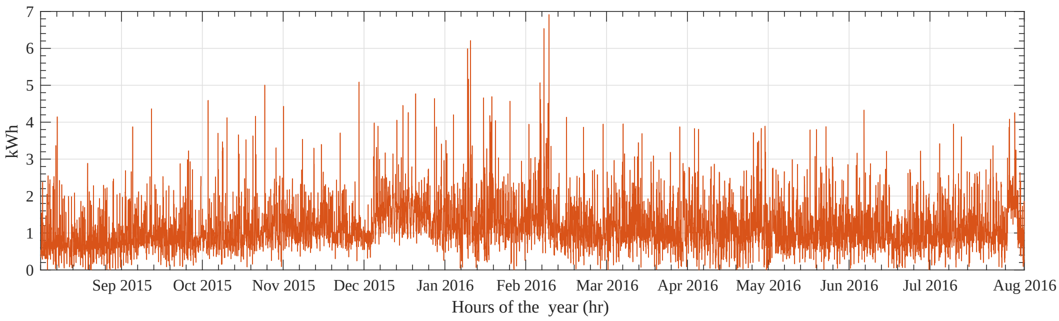


Figure 4.4: C6 house hourly load profile for full year

variations with intermittency of PV production ranging from 0 kWh to 6.5 kWh hourly (Figure

4.3). The total PV production for the year is 7132.2 kWh with lowest production in December and the house may have more electricity demand in this month. From Figure 4.4, it is observed that the highest net demand is coming in the mid of February with net hourly energy demand of 7 MWh. The minimum net load consumption is 1000 kWh in December. The total load consumption for the full year is 10335.73 kWh.

4.3.2 Electricity Tariff for C6 House

According to Agder Energy Nett [2], the customer can choose between three types of electricity tariffs. These types are: seasonally differentiated tariff, flat-rate tariff and ahead/spot-price. In this work, flat rate tariff and spot-price are chosen.

1. Table 4.2 shows the flat rate tariff specifications in Norwegian krone (NOK)[3]. Additionally, there is an extra charge for NOK/kW-month, which is the one time in the month where the customer has to pay for the max kW consumption. Thus, in this tariff the excess of the PV generated power after covering the domestic load and charging the battery will be supplied to the grid without benefits.

Table 4.2: Flat Electricity tariff without FiT

Description	Fixed charge NOK/month	Consumption NOK/KWh	Extra NOK/KW/month
Flat-rate	62.50	0.2515	41(summer), 125 (winter)

2. Figure 4.5 shows the second chosen tariff which is the spot-price that varies hourly throughout the year according to the energy market price from Nord Pool [4]. In this tariff mechanism, the customer is able to sell the excess of on-site PV generated power to the utility grid with the same purchasing price (one-to-one FiT). In Figure 4.5, the energy price is for 8760 hours from September 2015 to August 2016.

[2] Agder-Energy-Nett, http://www.aenett.no/kundeforhold/kundebetingelser/kundebetingelser-privatkunde/tariffer/

[3] 1 USD = 8.6 NOK

[4] NordPool, http://www.nordpoolspot.com/historical-market-data/

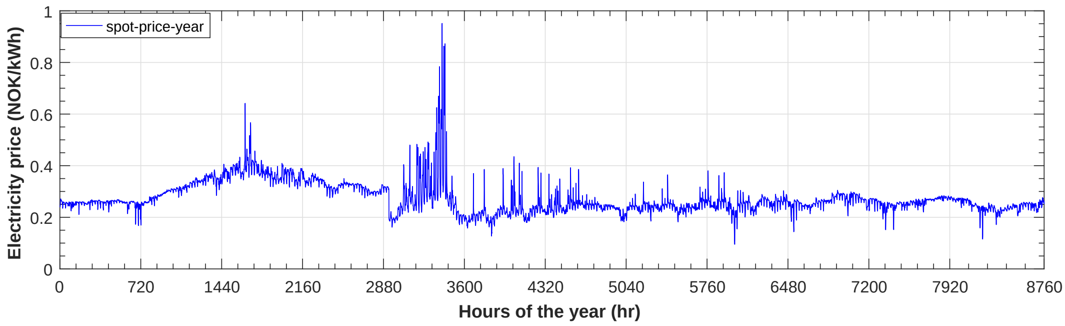


Figure 4.5: Spot-price for full year with one-to-one FiT

4.4 Battery Sizing for C6 House

As mentioned in Section 1.4, the estimation strategy will change from location to another or from tariff to another. In the case of C6 house which locates in Norway, two tariffs have been used. Flat rate and spot-price. Accordingly, two strategies have been proposed.

4.4.1 Under Flat-rate Tariff

According to Agder Energy Nett, the feed-in-tariff (FiT) is not activated when the customer chooses this kind of electricity tariff (i.e., flat-rate). Thus, the excess of the generated PV power will be supplied to the grid without getting any profits. In this situation, we concern to find the optimum size of the battery which will lead to the maximum reduction in the annual electricity cost considering two main objectives. (i) Minimizing the amount of energy supplied to the grid by charging the battery from the left power of PV system after covering the load and (ii) Minimizing the cost associated with purchasing electricity from the utility grid by discharging the stored energy when there is a lack of PV generation or during nights.

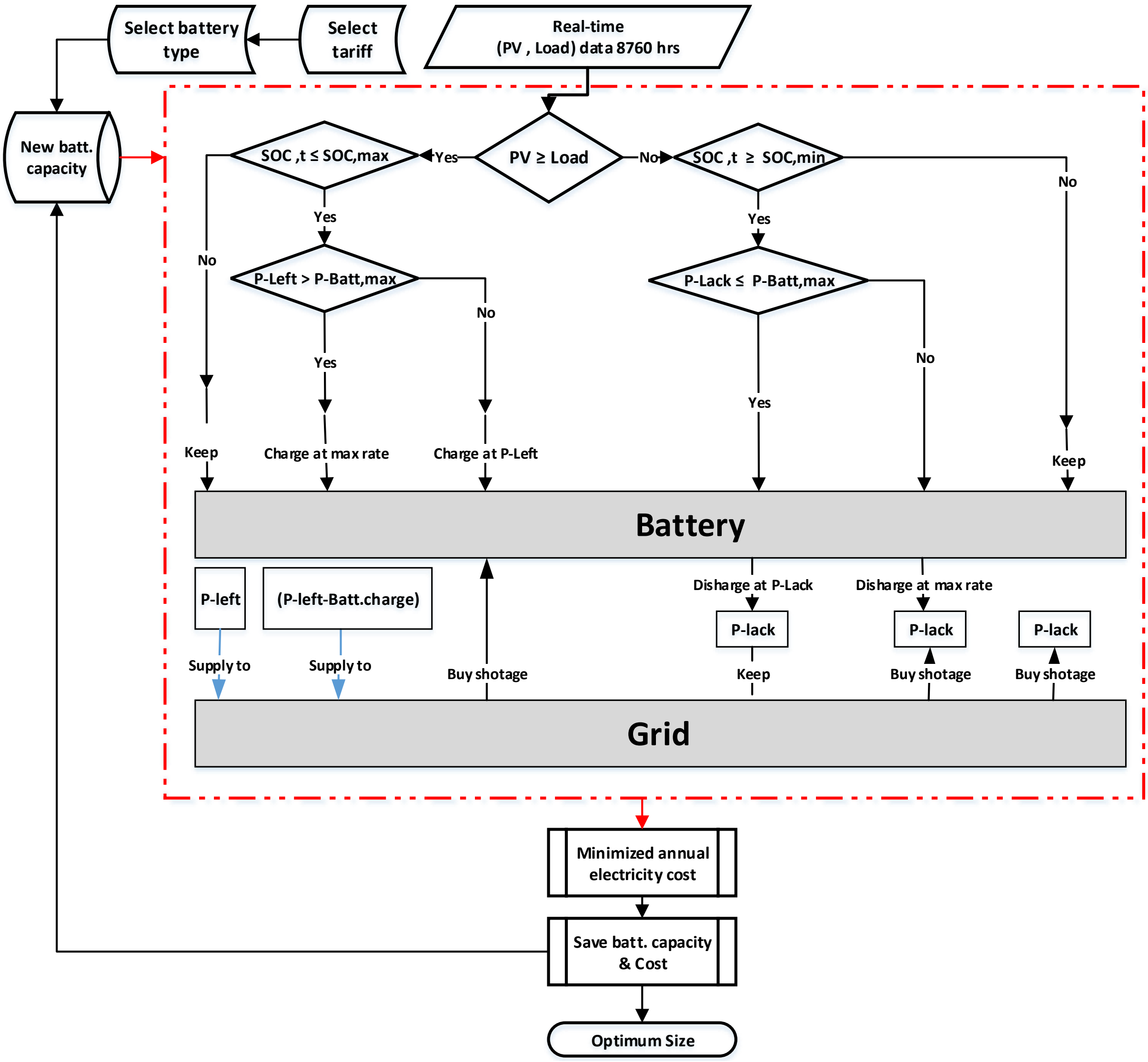


Figure 4.6: Estimation strategy of Flat rate tariff for C6 house

As shown in the model structure Figure 4.6, the hourly real-time PV profile, load profile, the electricity price and a range of suggested battery capacities from (0-3000) Ah with interval of 50 Ah are used as inputs to the estimation strategy process. Since there are no defined peak/off peaks hours by the utility, the optimization process first *checks* hourly if the PV generation is higher than the load. Then if the battery is fully charged, the left PV power after covering the load $(P_{PV} - P_{load})$ will be supplied to the utility grid. Else if the state of charge of the battery is less than the maximum, the left power will be compared with the maximum charge rate of the battery $P_{dc,batt,max}(d,t)$. If the left power $(P_{PV} - P_{load})$ is higher, then the battery will be charged at maximum rate first and the rest of the left power will be supplied to the grid. Otherwise, The

PV left power $(P_{PV} - P_{load})$ will be used to charge the battery only. Second, the estimation strategy process *checks* if load is higher than the generated power of the PV, if the state of charge is at the minimum, then the battery will be kept as its and the lack of power $(P_{load} - P_{PV})$ will be purchased from the utility. Else if the state of charge of the battery is higher than the minimum, the lack power $(P_{load} - P_{PV})$ will be compared with the maximum discharge rate of the battery $P_{dc,batt,max}(d,t)$. If lack power is less, then the battery will discharge to cover the lack of power $(P_{load} - P_{PV})$ without purchasing from the grid. Otherwise, the battery will discharge at the maximum rate towards the lack power $(P_{load} - P_{PV})$ and the rest will be purchased from the utility grid. For each interval of battery capacity, the model repeats the estimation process and use that battery capacity with the corresponded annual electricity cost. At the end, the model analyzes the annual electricity bill against each battery capacity interval and indicate the optimum capacity responsible for the minimum annual electricity bill.

4.4.2 Under Spot-Price Tariff

The mechanism of the spot-price allows the consumer to sell the excess of the generated PV energy to the utility grid. The price of purchasing and selling the energy from/to the utility is the same price (one-to-one) which varies each hour Figure 4.5 and determined by Nord Pool. Hence, spot-price profile is for full year (8760) hrs starting from Sep-2015 to Aug-2016. In this situation, we considering two main objectives. (i) Maximizing the benefits of selling the energy to the grid. (ii) Minimizing the cost associated with purchasing electricity from the utility grid.

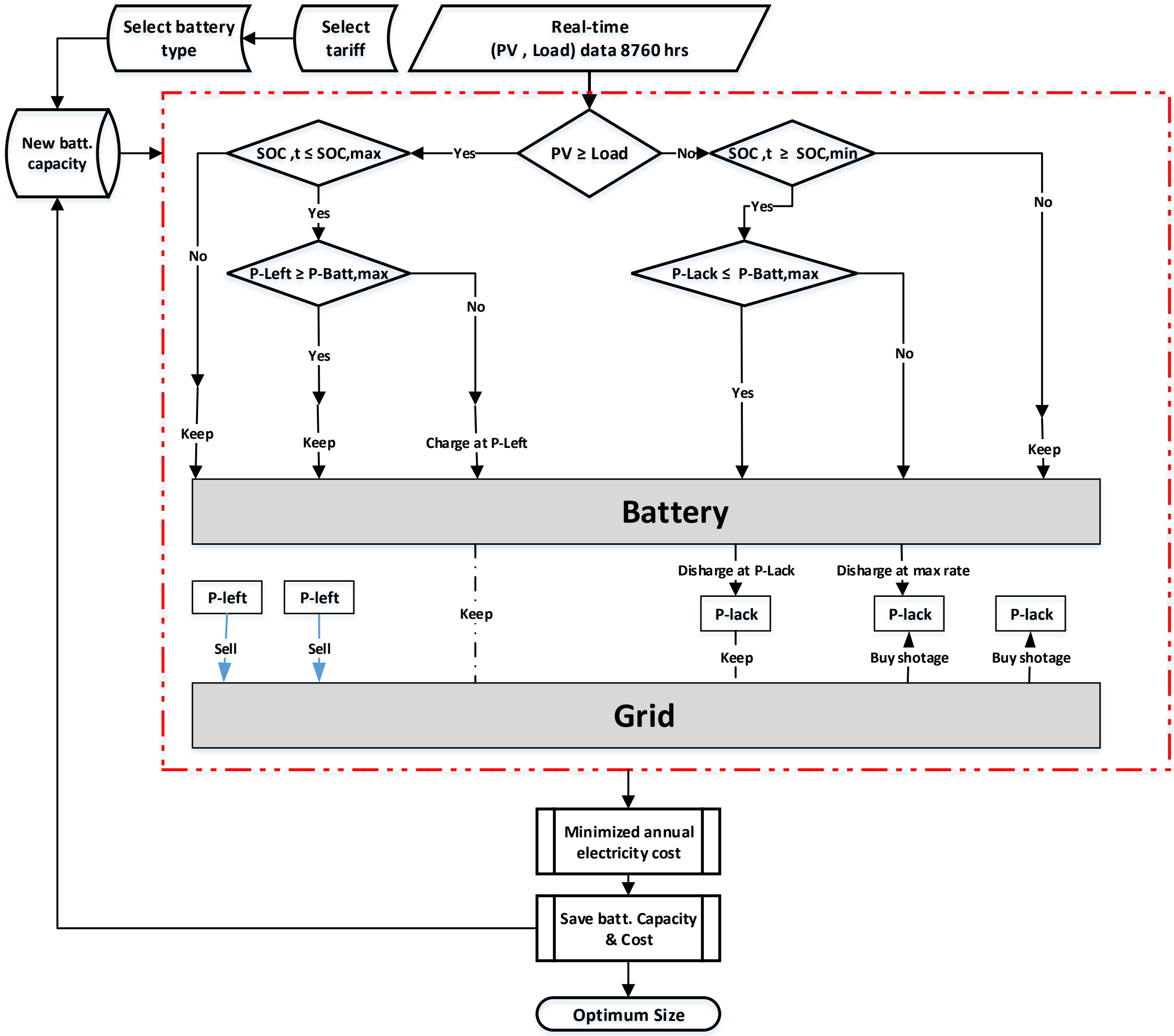


Figure 4.7: Estimation strategy of spot-price for C6 house

According to Figure 4.7, the hourly real-time PV profile, load profile, the electricity price and a range of suggested battery capacities from (0-3000) Ah with interval of 50 Ah are used as inputs to the estimation strategy process. The model first *checks* the period where the PV generation is higher than the load. Then if the battery is fully charged, the left PV power after covering the load $(P_{PV} - P_{load})$ will be sold to the utility grid. Else if the state of charge of the battery is less than the maximum, the the left power will be compared with the maximum charge rate of the battery $P_{dc,batt,max}(d,t)$. If the left power is less or equal, then, the battery will be charged at this left power $(P_{PV} - P_{load})$ and keep the grid at rest. Otherwise, the left power will be sold to the grid to maximize the profits. Second, the model *checks* periods where the load is greater than the generated power of the PV. If the state of charge is at the minimum, then the battery will be kept as it is and the lack of power $(P_{load} - P_{PV})$ will be purchased from the utility. Else if the state of charge of the battery is higher than or equal to the minimum state of charge, the lack power $(P_{load} - P_{PV})$ will be compared with the maximum available power of the battery $P_{dc,batt,max}(d,t)$ (maximum discharge rate). If the lack power $(P_{load} - P_{PV})$ is less, the battery will cover the lack of power $(P_{load} - P_{PV})$ without purchasing from the grid. Otherwise, the battery will discharge at the maximum rate towards the lack power $(P_{load} - P_{PV})$ and the rest will be purchased from the utility grid.

4.5 Results and Discussion

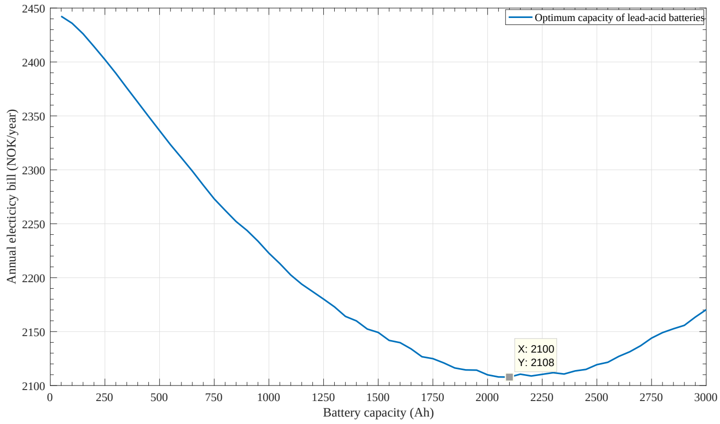
In this work, real operational results of C6 house from the Skarpnes Smart Village in Southern Norway is used for estimating the capacity of battery energy storage for that house. Based on the type of the electricity tariff selected, the observed results are presented.

4.5.1 Flat-Rate Tariff Case

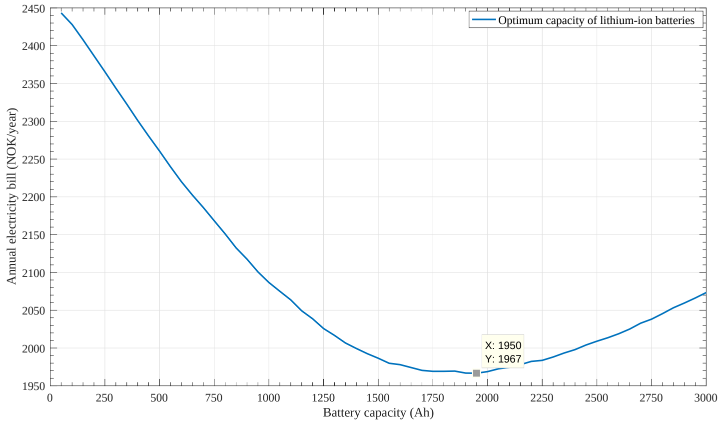
In this section, we present the results from the technical and economic parts under the flat-rate tariff.

4.5.1.1 Battery Sizing Analysis

In the analysis, a range of battery capacities up to 3000 Ah is examined for finding the appropriate capacity. The annual electricity bill before connecting any battery is 2651 Norwegian Kroner (NOK). The variation of the annual electricity bill after considering up to 3000 Ah of lead-acid battery capacities is shown in Figure 4.8(a). It is observed that a capacity of 2100 Ah of lead-acid battery is the optimum capacity (Figure 4.8(a)) and the reduction in the annual electricity cost after adding this exact capacity is 453 NOK/year to be 2108 NOK/year. Figure 4.8(b) shows that a capacity of 1950 Ah of lithium-ion battery is the optimum-estimated capacity. The reduction in the annual electricity cost after installing this exact capacity (1950 Ah) is 684 NOK/year to be 1967 NOK/year as shown in Figure 4.8(b). Due to the better characteristics of the lithium-ion battery, it is observed that the reduction in the annual electricity bill is higher when using the lithium-ion battery (22.6 %) than installing the lead-acid battery (17.6 %) even though, the capacity of the lithium-ion battery energy storage is lower than the lead-acid battery energy storage.



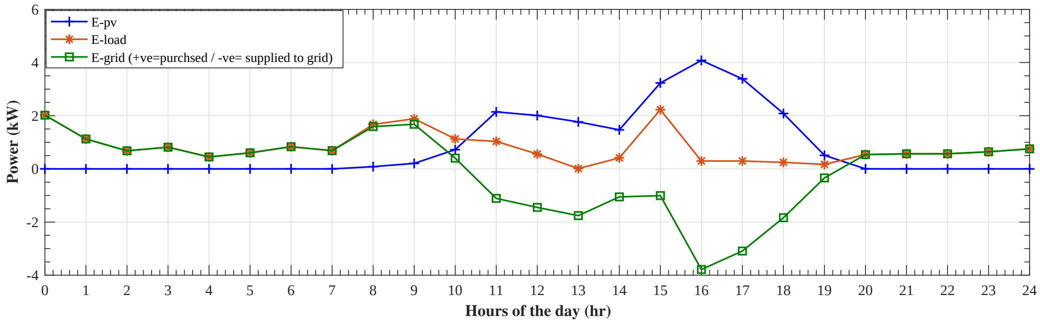
(a) Annual electricity bill variation with (0-3000) Ah lead-acid battery capacities



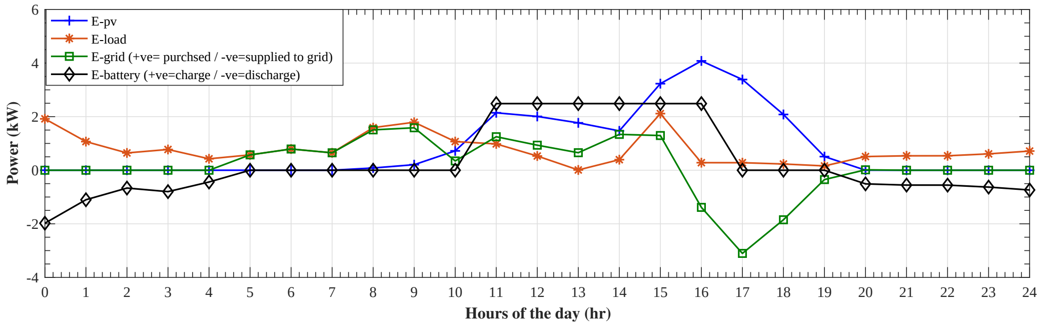
(b) Annual electricity bill variation with (0-3000) Ah lithium-ion battery capacities

Figure 4.8: Annual electricity bill variation with (0-3000) Ah battery capacities (C6, flat-rate tariff)

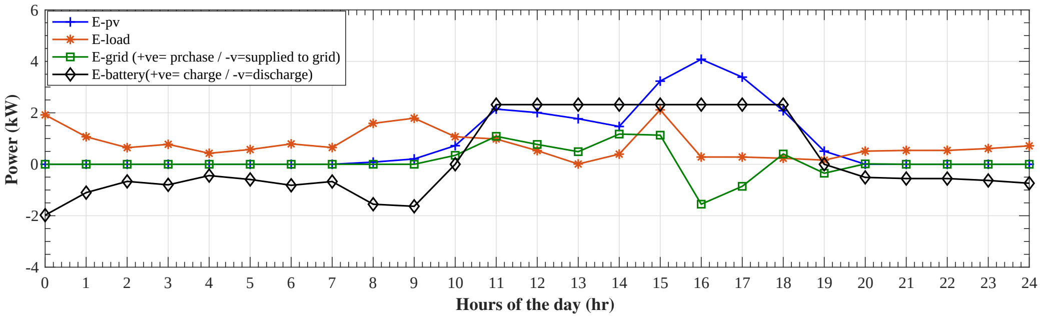
The power flow from PV (E-PV), load (E-load), the grid supply (E-grid) and (E-battery) of C6 house for a typical day (25^{th} Sep-2015) are given in Figure 4.9. Figure 4.9(a) shows the power flow before connecting battery where, the positive values of the grid supply (E-grid) represents the purchased power from the utility grid and the negative values represents the supplied power to grid. It is observed that the load is supplied form the utility grid until 08:00 and after this time the PV production starts. It is observed that the excess energy from the PV after covering the load is supplied to the grid from 10:00 to 19:00. For the same day, as per defined strategy in Section 4.4.1, after connecting 2100 Ah battery capacity the load is completely covered from the battery from midnight to 04:00 and from 20:00 to 24:00 (Figure



(a) Power flow variation for the 25^{th} Sep without battery



(b) Power flow variation for the 25^{th} Sep with 2100 Ah lead-acid battery

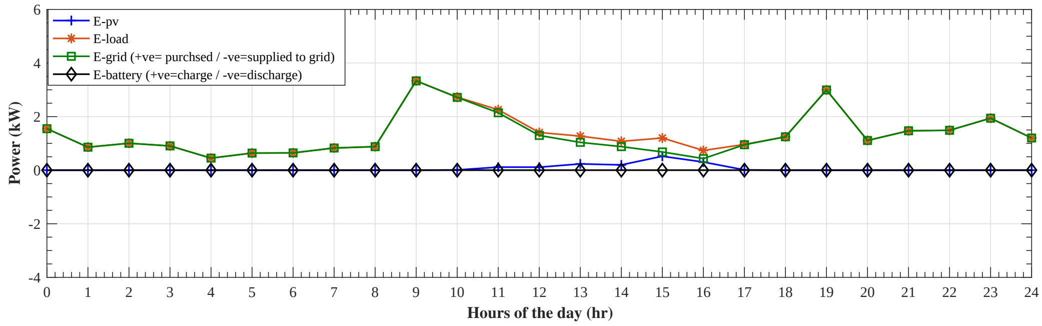


(c) Power flow variation for the 25^{th} Sep with 1950 Ah lithium-ion battery

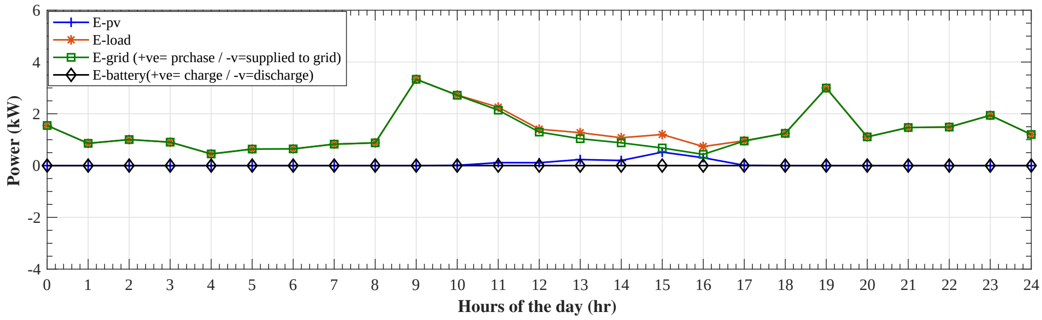
Figure 4.9: Power flow variation of the system components for the 25^{th} Sep 2015 (C6, flat-rate tariff)

4.9(b)). Note that the negative values of (E-battery) represents the discharging and positive values for charging. Only from 05:00 to 08:00, the load is completely supplied from the utility grid. Moreover, its observed that the left/excess energy after covering the load is used for charging the battery from 11:00 to 16:00. Thus, the supplied energy to the grid occurred only between 16:00 to 19:00. Figure 4.9(c) shows the power flow for the same typical day when connecting 1950 Ah lithium-ion battery. It is observed that the lithium-ion battery is able to cover the load consumption the whole night time from 00:00 to 09:00 and from 20:00 to 24:00

where no energy purchasing occurred in these time periods. Due to the higher depth of discharge of the lithium-ion battery, more energy is used to charge the battery (Figure 4.9(c)) resulting in less supply of the excess PV power production (only between 16:00 to 17:00).



(a) Power flow variation for the 1^{st} Jan with 2100 Ah lead-acid battery

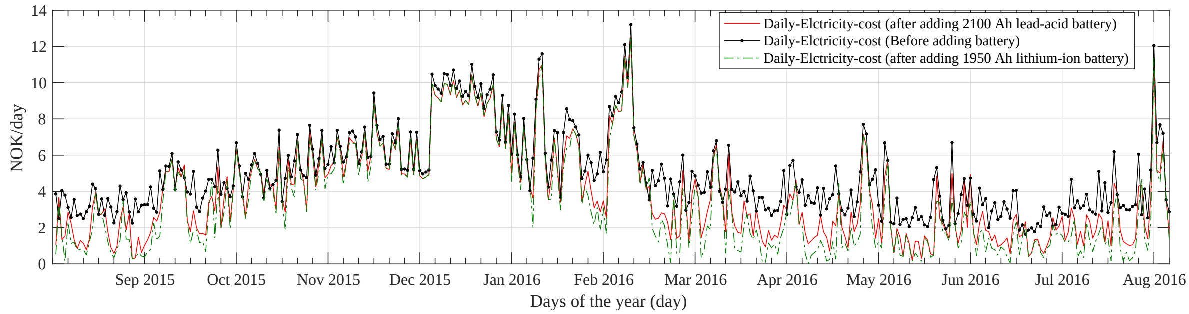


(b) Power flow variation for the 1^{st} Jan with 1950 Ah lithium-ion battery

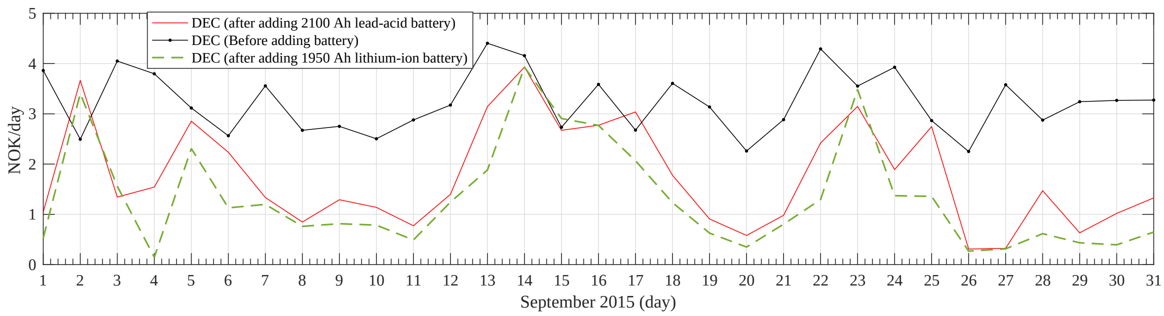
Figure 4.10: Power flow variation of the system components for the 1^{st} Jan 2016 (C6, flat-rate tariff)

As expected, the C6 house will purchase more energy from the utility grid during winter season due to the low PV production and high load demand. Figure 4.10 shows the power flow variation of the grid-connected BIPV after adding 2100 Ah lead-acid battery capacity (Figure 4.10(a)) and 1950 Ah lithium-ion battery capacity (Figure 4.10(b)) for a typical winter day (1^{st} Jan-2016). As it observed in Fig.4.10, the load is completely covered from the utility grid almost all the day since the PV production is very low. Only from 11:00 to 17:00, the PV system is able to cover small part of the load. Such mismatch of the PV power production and load consumption may lead us to state that the C6 house is unhealthy to be zero energy building. As per claimed in Section 1.1, installing an energy storage to BIPV system will help to reduce such mismatch and accordingly help to achieve ZEB.

The daily electricity cost (DEC) variation before and after adding the estimated battery capacities has been shown in Figure 4.11. It is observed from Figure 4.11(a) that the batteries (lead-acid and lithium-ion) are able to reduce the daily electricity bill from Sep to Oct and from Mar to Aug. This energy bill saving can be more attractive when considering the demand side management (DSM) and future implementation of demand limits on the residential load from the network or the power tariff. During winter season from November 2015 to February 2016, the PV production is low therefore the electricity bill almost remained the same except for the last days of Feb (Figure 4.11(a)). For clear visualization, Figure 4.11(b) shows the daily electricity cost (DEC) variation before and after adding the estimated battery capacities for the month of September 2015. It is clear to see that both batteries can achieve remarkable reduction in the electricity bill when installed. In the context of achieving higher reduction, it is observed that the capacity of 1950 Ah of lithium-ion is able to achieve more reduction in the electricity bill.



(a) Daily electricity cost before and after adding the estimated battery capacities (Sep 2015 to Aug 2016)



(b) Daily electricity cost before and after adding the estimated battery capacities for September 2015

Figure 4.11: Daily electricity cost before and after adding the battery (C6, flat-rate tariff)

4.5.1.2 LCOE Analysis

To decide which battery capacity is more beneficial to install, the capital cost of the two estimated batteries will be considered. The operational lifetime of the 2100 Ah lead-acid battery is as 7 years while, the operational lifetime of the 1950 Ah lithium-ion battery capacity is found as 9 years. The economic parameters used for C6 house under flat-rate case are listed in Table 4.3. The local subsidies in Norway is given by Enova [5] for users who produce their own energy only if the tariff used is spot-price. Therefore, in this case of flat-rate tariff the incentives are not included in the analysis.

Table 4.3: Economic parameters (C6 house under flat-rate tariff)

Parameters	Unit
Discount rate (WACC)	4 %
Escalation rate of energy price (ER)	2 %
Local subsidies	0 NOK

Table 4.4: Results of the economic analysis (C6 house under flat-rate tariff)

Battery type	Lead-acid	Lithium-ion
Size	25.2 kWh	22.8 kWh
Number of replacements	3	2
Net present cost (NPC)	56666.87 NOK	101051.0 NOK
Annual E-out of the battery	2492.098 kWh/year	3049.23 kWh/year
Annualized payments (A)	4020.65 NOK/year	7169.81 NOK/year
Purchasing price of energy **before** adding battery (POE)	0.248 NOK/kWh	0.248 NOK/kWh
Purchasing price of energy **after** adding battery (POE)	0.204 NOK/kWh	0.1916 NOK/kWh
$LCOE_{E-out}$	1.613 NOK/kWh	2.351 NOK/kWh
Total POE	1.817 NOK/kWh	2.543 NOK/kWh

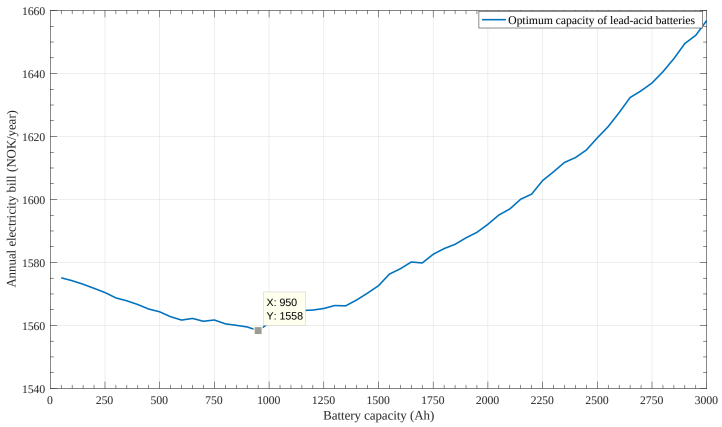
Considering the lifetime of the batteries and the mathematical approach explained in Section 3.3.2, the LCOE of each estimated battery capacity is analyzed. Table 4.4 shows the results of the long term economic analysis of the two estimated battery capacities (2100 Ah lead-acid and 1950 Ah lithium-ion) under the flat-rate pricing mechanism case. It is observed that even though, the lithium-ion battery has lower size (22.8 kWh), lower number of replacements (2) and higher energy output (3049.23 kWh/year), the total net present cost (NPC) of the lead-acid battery is almost 44 % lower than the lithium-ion. Similarly, the reduction of the purchasing price of energy (POE) after adding battery is higher when adding 1950 Ah lithium-ion, but when considering the $LCOE_{E-out}$ of each battery, we find that the total POE is lower when installing a capacity of 2100 Ah lead-acid battery with 1.1621 NOK/kWh. The high cost of the lithium-ion batteries is the drawback that led to this high total POE (2.543 NOK/kWh).

[5] Enova, https://www.enova.no/privat/alle-energitiltak/solenergi/el-produksjon-/

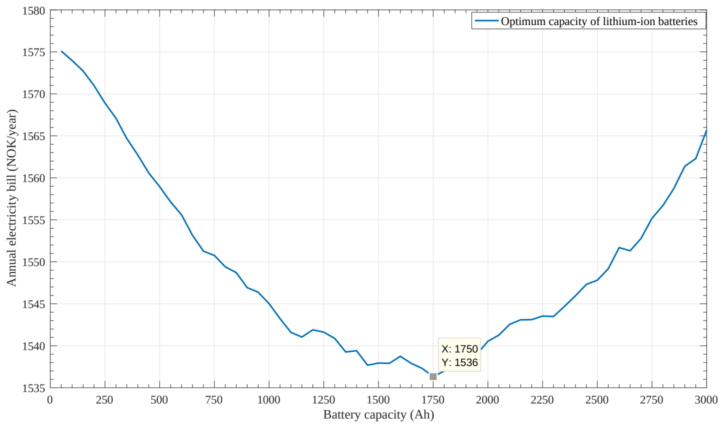
4.5.2 Spot-Price Tariff Case

In this section, we present the results from the technical and economic parts under the dynamic spot-price tariff.

4.5.2.1 Battery Sizing Analysis



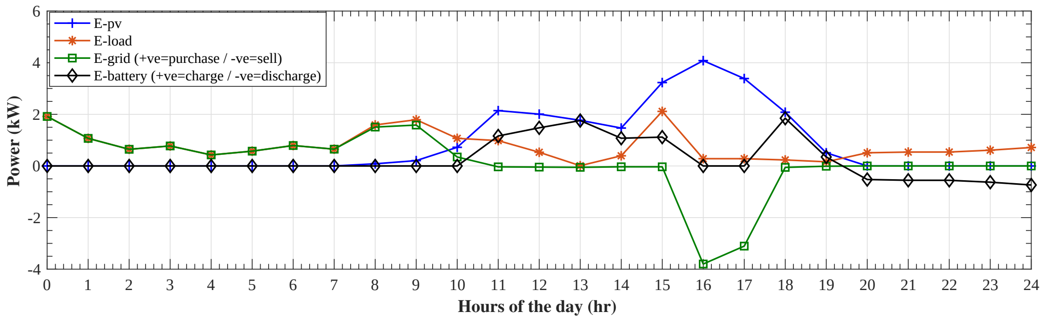
(a) Annual electricity bill variation with (0-3000) Ah lead-acid battery capacities



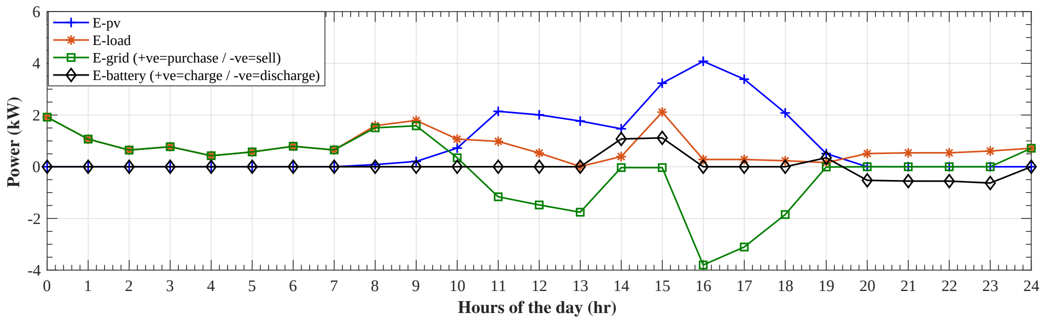
(b) Annual electricity bill variation with (0-3000) Ah lithium-ion battery capacities

Figure 4.12: Annual electricity bill variation with (0-3000) Ah battery capacities (spot-price tariff)

As per the mechanism of this tariff (Figure 4.5), the annual electricity bill before connecting any battery is 1712.8 Norwegian Kroner (NOK). The variation of the annual electricity bill after considering up to 3000 Ah of lead-acid battery capacities is shown in Figure 4.12(a). It is observed that a capacity of 950 Ah of lead-acid battery is the optimum capacity (Figure 4.12(a)) and the reduction in the annual electricity cost after adding this exact capacity is 154.9 NOK/year to be 1558 NOK/year. Figure 4.12(b) shows that a capacity of 1750 Ah of lithium-ion battery is the optimum-estimated capacity. The reduction in the annual electricity cost after installing this exact capacity (1750 Ah) is 176.9 NOK/year to be 1536 NOK/year as shown in Figure 4.12(b). It is observed that the reduction in the annual electricity bill is almost the same when using the lithium-ion battery (10 %) and the lead-acid battery (9 %) even though, the capacity of the lithium-ion battery is almost as twice as the capacity of the lead-acid battery.



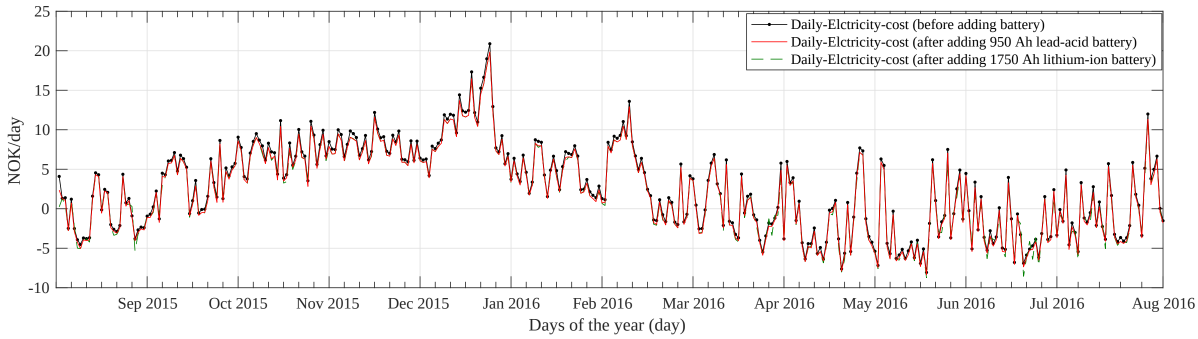
(a) Power flow variation for the 25^{th} Sep with 1750 Ah lithium-ion battery



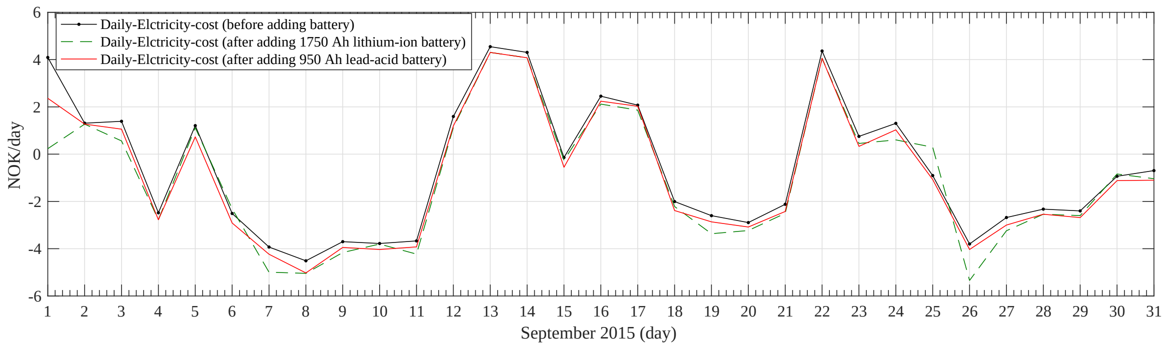
(b) Power flow variation for the 25^{th} Sep with 950 Ah lead-acid battery

Figure 4.13: Power flow variation of the system components for the 25^{th} Sep 2015 (C6, spot-price tariff)

For the same typical day (25^{th} of Sep 2015), the power flow from PV (E-PV), load (E-load), the grid supply (E-grid) and (E-battery) of C6 house are given in Figure 4.13. In this case, the positive values of the grid supply (E-grid) represents the purchased/imported power from the utility grid and the negative values represents the sold/exported power to grid via FiT. Figure 4.13(a) exhibits the power flow variation for the 25^{th} Sep when adding 1750 Ah lithium-ion battery. Figure 4.13(b) exhibits the power flow variation for the 25^{th} Sep with 950 Ah lead-acid battery. It is observed from Figure 4.13 in both cases, the load is completely covered from the utility grid until 08:00 where the PV starts taking over. Between 10:00 to 19:00, the on-site PV power production is in a position to supply the domestic load completely. From Figure 4.13(a), it is observed that the lithium-ion battery started to charge after 10:00 to 16:00 and between 17:00 and 19:00 from the left power. From 20:00 to midnight, the battery started to discharge covering the load to minimize the purchased/imported power from the grid. On the other hand, the left power is sold/exported to the grid between 15:00 and 18:00. From Figure 4.13(b), due to the different characteristics of the lead-acid battery, the battery has been charging between 13:00 and 16:00 and from 18:00 to 19:00 using the left power after supplying the load. From 20:00 to 23:00, the 950 Ah lead-acid battery has been discharging towards the load to minimize the purchased/imported power from the grid.



(a) Daily electricity cost before and after adding the estimated battery capacities (Sep 2015 to Aug 2016)



(b) Daily electricity cost before and after adding the estimated battery capacities for September 2015

Figure 4.14: Daily electricity cost before and after adding the battery (C6, flat-rate tariff)

The daily electricity cost (DEC) variation before and after adding the estimated battery capacities has been given in Figure 4.14. It is noticed from Figure 4.14(a) that the batteries (lead-acid and lithium-ion) are able to reduce relatively the same amount of the daily electricity bill during the year as well as maximizing the profit of selling more energy to the grid. In this figure, the positive values represent the purchasing cost and the negative ones represent the selling cost. For clear visualization, Figure 4.14(b) shows the daily electricity cost (DEC) variation before and after adding the estimated battery capacities for the month of September 2015. It is clear to see that both batteries are in a position to slightly reduce the purchasing electricity cost when installed. However, the maximization of the profit of selling more energy (negative values) to the grid is relatively higher, when considering the 1750 Ah lithium-ion battery. This difference appears clearly between the (7^{th} and 11^{th}), (18^{th} and 21^{st}) and (26^{th} and 27^{th}).

Figure 4.15 shows the battery state charge (SOC) variations of both estimated battery capacities (950 Ah lead-acid and 1750 Ah lithium-ion) for the 25^{th} Sep 2015. This figure helps with the understanding of the power flow variation that exhibited in Figure 4.13 and reveals the proposed estimation strategy model explained in Section 4.4.2. It is observed from the Figure 4.15 that the left power $(P_{PV} - P_{load})$ is compared with the maximum available power of the batteries (maximum charge rate) during the periods where PV generation is higher than load consumption. Due to the higher capacity of the 1750 Ah lithium-ion battery storage, it starts to charge before the 950 Ah lead-acid battery storage (11:00 and 14:00 respectively). After 15:00, the generation of the PV starts to increase and the load starts to decrease (Figure 4.13).

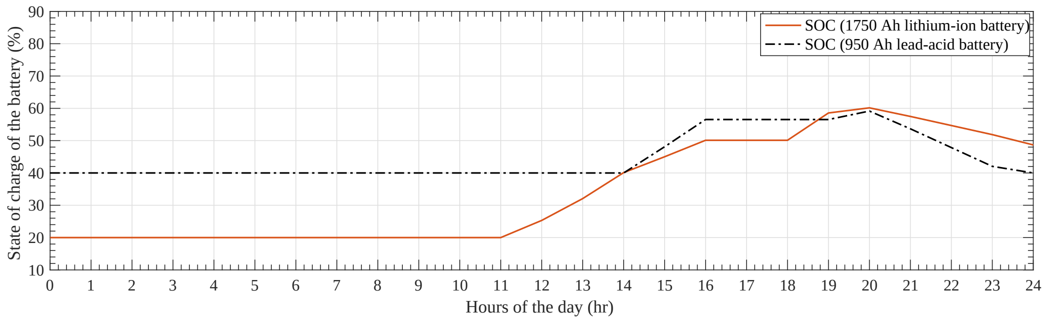


Figure 4.15: State of charge variation of the batteries for the 25^{th} Sep 2015 (C6, spot-price tariff)

Therefore, the priority has been given for selling the left power $(P_{PV} - P_{load})$ to the utility grid by keeping both batteries idle at SOC 50 % for lithium-ion and around SOC 58 % for lead-acid. Just before the end of the daytime (sunset), the amount of left power $(P_{PV} - P_{load})$ has been less than maximum charge rate of the batteries. Accordingly, between 18:00 and 20:00, the lithium-ion battery capacity has been charging again up to SOC=60%. Similarly, the lead-acid battery storage has been charged to SOC around 60 %. AT 20:00, the load becomes higher due to the absence of PV power generation. Consequently and according to the strategy, both batteries start to cover the lack of power $(P_{load} - P_{PV})$ at maximum rate of discharging. It is observed that the 950 Ah lead-acid battery reaches the minimum state of charge at around 24:00. On the other hand, the 1750 Ah lithium ion battery has been supplying the load completely during the night and starts the next day (26^{th}) with SOC around 50%.

As per the defined estimation strategy (Section 4.4.2), both batteries can achieve the two main priorities of the estimation strategy by (i) maximizing the benefits of selling the energy to the grid and (ii) minimizing the cost associated with purchasing electricity from the utility grid. Figure 4.16 shows the power flow from/to the utility grid for the same typical day (25^{th} Sep 2015). It is observed that more power (11.7 kW) has been sold/exported to the utility grid between 10:00 to 19:00 when 950 Ah lead-acid is connected comparing to 7.15 kW when connecting 1750 Ah lithium-ion. On the other hand, it is observed from Figure 4.9(a) that total imported power from the utility grid for the whole day (25^{th} Sep 2015) before connecting any battery is 14.25 kW. As per Figure 4.16, the total imported power from the utility grid for the whole day (25^{th} Sep 2015) after installing a capacity of 1750 Ah lithium-ion battery storage is minimized to 10.2 kW. On the other hand, the capacity of 950 Ah lead-acid has achieved a minimization of the total imported power from the utility grid of around 11 kW. The higher compensation of the imported power after installing the capacity of 1750 Ah lithium-ion battery appears on the figure after 23:00 and continue for early hours of the next day's morning.

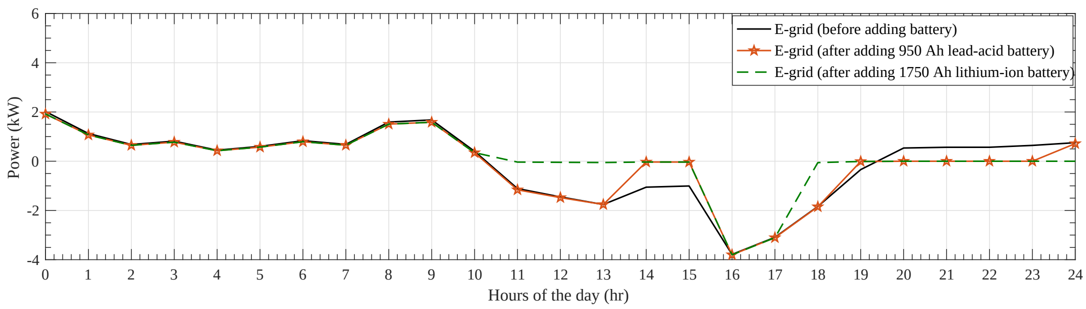
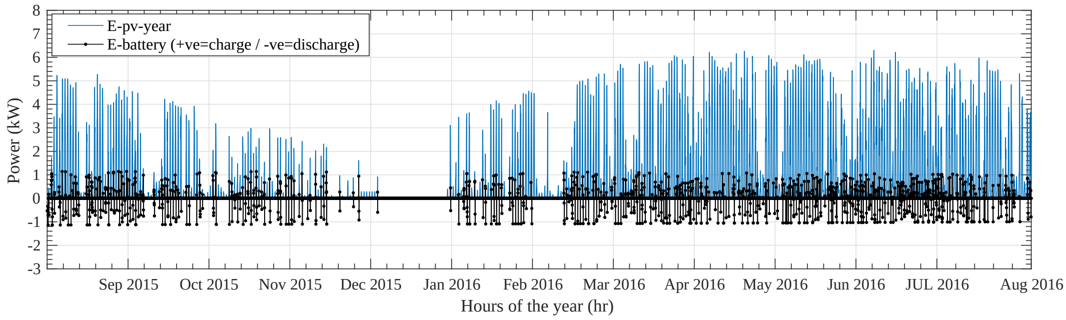
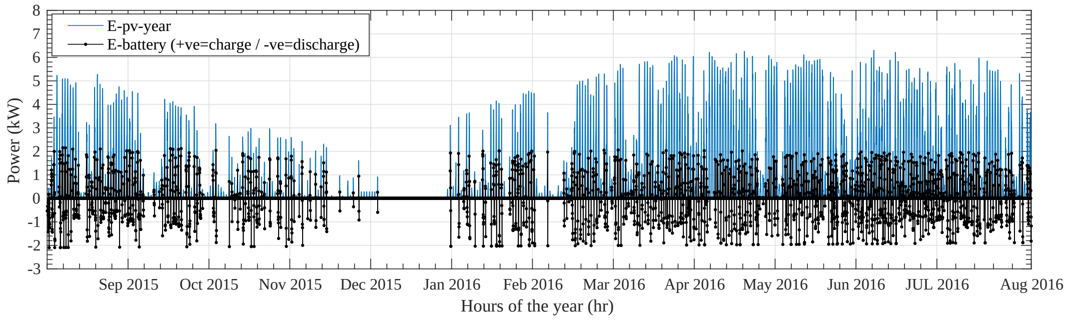


Figure 4.16: Power export/import with the grid for the 25^{th} Sep 2015 (C6, spot-price tariff)

Figure 4.17 shows the Power flow of the batteries (charging/discharging) with PV power production for 12 months (Sep2015 to Aug 2016). The power flow of the 950 Ah lead-acid and 1750 Ah lithium-ion for the full year with respect to the PV power production are given in Figure 4.17(a) and Figure 4.17(b) respectively. It is observed that both batteries are able to follow the power production of the PV system through the estimation strategy given in Figure 4.7. Due to the higher capacity and efficiency of the lithium-ion, more power is stored in it than the lead-acid battery. It is clear to see that both batteries have been at rest during winter season particularly, in January 2016 and the first few days of March 2016. This is due to the very low PV power production in this period. Consequently, the cumulative capacity loses of the batteries have been idle in these periods. These loses is very important when calculating the lifetime of the batteries. For the lead-acid battery storage (950 Ah, 12 V), the annual cumulative capacity loses ($\Delta_{BC,year}$) is found as 1.4061 kWh. For the lithium-ion (1750 Ah, 12 V), the annual cumulative capacity loses ($\Delta_{BC,year}$) is found as 2.19 kWh. Based on these annual loses and Equation 3.8, the lifetime of these two battery capacities are 8 years for the lead-acid battery capacity and 10 year for the lithium-ion battery capacity.



(a) Power flow of the 950 Ah lead-acid battery with PV power production



(b) Power flow of the 1750 Ah lithium-ion battery with PV power production

Figure 4.17: Power flow of the batteries with PV power production for the full year (C6, spot-price tariff)

4.5.2.2 LCOE Analysis

The economic parameters used for C6 house under spot-price case are listed in Table 4.5. Due to the utilization of this pricing mechanism, the subsidies maybe granted by Enova[6]. In this study, it is assumed that C6 house will have the maximum amount of the incentives. This amount of money will be deducted from the net present cost in the calculation of the cost of energy storage.

Table 4.6 shows the results of the long term economic analysis of the two estimated battery capacities 950 Ah lead-acid and 1750 Ah lithium-ion for C6 house under the spot-price pricing

[6]Evova subsidies, https://www.enova.no/privat/alle-energitiltak/solenergi/el-produksjon-/

Table 4.5: Economic parameters (C6 house under spot-price tariff)

Parameters	Unit
Discount rate (WACC)	4 %
Escalation rate of energy price (ER)	2 %
Local subsidies	max 28750 NOK

Table 4.6: Results of the economic analysis (C6 house under spot-price tariff)

Battery type	Lead-acid	Lithium-ion
Size	11.4 kWh	21 kWh
Number of replacements	3	2
Net present cost (NPC) (before subsidies)	20069.34344 NOK	114398.30 NOK
Net present cost (NPC) (after subsidies)	0 NOK	85648.30 NOK
Annual E-out of the battery	542 kWh/year	1049 kWh/year
Annualized payments (A)	0 NOK/year	6076.95 NOK/year
Purchasing price of energy **before** adding battery (POE)	0.166 NOK/kWh	0.166 NOK/kWh
Purchasing price of energy **after** adding battery (POE)	0.151 NOK/kWh	0.149 NOK/kWh
$LCOE_{E-out}$	0 NOK/kWh	5.79 NOK/kWh
Total POE	0.151 NOK/kWh	5.94 NOK/kWh

mechanism. It is observed that the lithium-ion battery has approximately twice the size of the lead-acid battery even though, the reduction in the annual electricity bill is almost the same for the two batteries. The annual energy output of the lithium-ion battery is almost double of that from the lead-acid battery. The purchasing price of energy after adding battery (POE) is almost the same for both sizes but; when considering the $LCOE_{E-out}$ of each battery and the subsidies, we find that it is more financially beneficial to install 950 Ah lead-acid battery since the total POE is lower (0.151 NOK/kWh). This result will remain the percentage of the reduction in the annual electricity bill the same (9 %) for the 950 Ah after considering the capital and replacements costs. Note, the $LCOE_{E-out}$ of the 950 Ah lead-acid battery without considering the subsidies is found as 2.62 NOK/kWh

4.6 Conclusion

This chapter reports the estimation of energy storage capacity for grid-connected BIPV on ZEB house in Smart Village Skarpnes in Southern Norway. The real time hourly PV production with real time operational load of C6 house of a year (Sep 2015 to Aug 2016) are used for finding the appropriate capacities of lead-acid and lithium-ion batteries with minimization of the annual electricity bill. The local electricity tariff (flat-rate without FiT) is used first as a critical scenario of C6 since there is no FiT. Then, spot-price tariff with one-one FiT is examined on the C6 house considering both batteries as well. Based on the tariffs used, different battery sizes have been found for this typical PV and load profiles of C6 house as shown in Table 4.7 where, AEC-Reduction is the reduction in annual electricity bill after adding the battery.

Table 4.7: Conclusion (C6 house)

Flat-rate tariff			
Battery type	Estimated size	Lifetime	AEB-Reduction
Lead-acid	25.2 kWh	7 years	17.6 %
Lithium-ion	22.8 kWh	9 years	22.6 %
Spot-price tariff			
Battery type	Estimated size	Lifetime	AEB-Reduction
Lead-acid	11.4 kWh	8 years	9 %
Lithium-ion	21 kWh	10 years	10 %

The results show that the estimation of the battery capacity for grid-connected BIPV depends extremely on the mechanism of the electricity tariff. When the flat-rate tariff is used, the highest reduction in the annual electricity bill is achieved by a size of 22.8 kWh lithium-ion battery. Despite the absence of the subsidies and the FiT, this energy bill saving can be more attractive when considering the demand side management (DSM) and future implementation of demand limits on the residential load from the network or the power tariff. On the other hand, when the spot-price tariff is used, only 11.4 kWh lead-acid battery can achieve almost the same reduction in the annual electricity bill achieved by 21 kWh lithium-ion battery.

After estimating the size of the battery to be installed under each electrical pricing mechanism, an economic analysis has been made on the exact estimated battery size considering the cost of the battery and its replacements based on the operational lifetime. The subsidies are included in the analysis only when the spot-price pricing mechanism is used. Based on that, the LCOE of each battery size is analyzed and added to the purchasing price of energy for the combined system (PV+ES) after installing each battery capacity. Based on the economic analysis, the best scenario for the C6 house is to utilize the spot-price tariff with one-to-one FiT. Depending on the subsidies, the profit of installing battery energy storage can be analyzed. Therefore, for this case where, the maximum subsidies of 28750 NOK are assumed. It is observed that adding a size of 11.4 kWh lead-acid battery will reduce the annual electricity bill by 9 % if only 69% of the maximum subsidies is granted.

Chapter 5

Techno-Economic Battery Capacity Estimation for Indian TERI University [1]

5.1 Summery

In this chapter, we attempt to estimate the battery energy storage for BIPV system installed at TERI university in New Delhi, India. The estimation of the battery size has been done considering the applied electrical pricing mechanism (flat-rate tariff) at the building and two battery types (lead-acid and lithium-ion). Thereafter, the LCOE has been analyzed for the exact estimated batteries before concluding the chapter in the final section.

5.2 Introduction

The TERI university (28.54°N, 77.14°E) is located in New Delhi, India. The university was established in 1998. Recently, the university added a rooftop grid-connected PV system. The system has been set up under solar leasing model. The main motive for the University to install the solar rooftop system was to bolster its philosophy of practicing what it preaches, besides having something that physically manifests the theory that is taught, thereby providing students an actual feel [2]. Figure 5.1 shows PV system installed on the rooftop of the building of the TERI university on the map.

[1] Modified from the paper submitted (under review) to the 9th International Conference on Applied Energy, ICAE2017, Cardiff, UK

[2] TERI University, http://www.teriuniversity.ac.in/index.php?option=com_content&view=article&id=181

Figure 5.1: TERI university (28.54°N, 77.14°E)

5.3 TERI University BIPV

This grid-connected system comprises polycrystalline PV modules and SMA inverters. It is expected to generate about 1.5 million units of electricity over 25 years, offsetting 15 % of the grid electricity. It would also result in mitigating around 1400 MT of CO2 emissions. The PV panels that has been installed are 158 modules of JKM305P-72 with annual production of approx. 65.057 kWh. Table 5.1, presents the parameters of the installed system.

Table 5.1: Installed PV-parameters at TERI university

PV system size	48.19 (kWp)
Array type	Fixed rooftop
Tilt angle	28°

5.3.1 Real-Time Annual PV and Load Curve for TERI University

The PV system is monitored for the solar irradiation and temperature through Sunny Sensor-box placed on the roof to help for collecting data. The average annual solar radiation per day at TERI university is around 5.98 $kWh/m^2/day$ [3]. Figure 5.2 shows the generation profile of the

[3] PVGIS, http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php?map=africa&lang=en

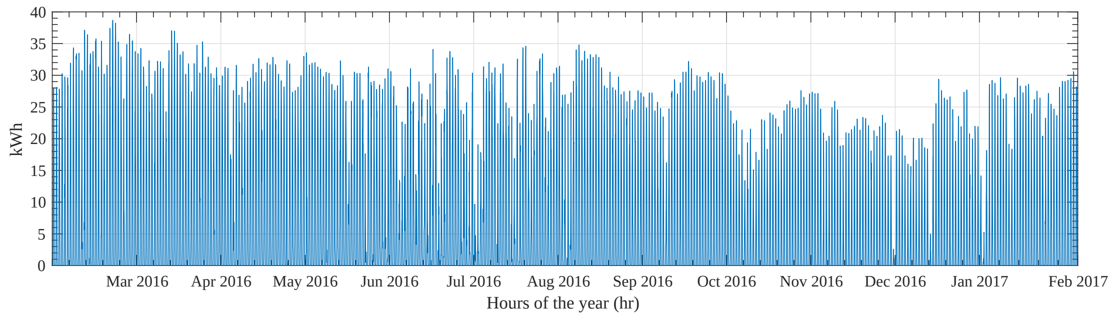


Figure 5.2: TERI university hourly PV profile for full year

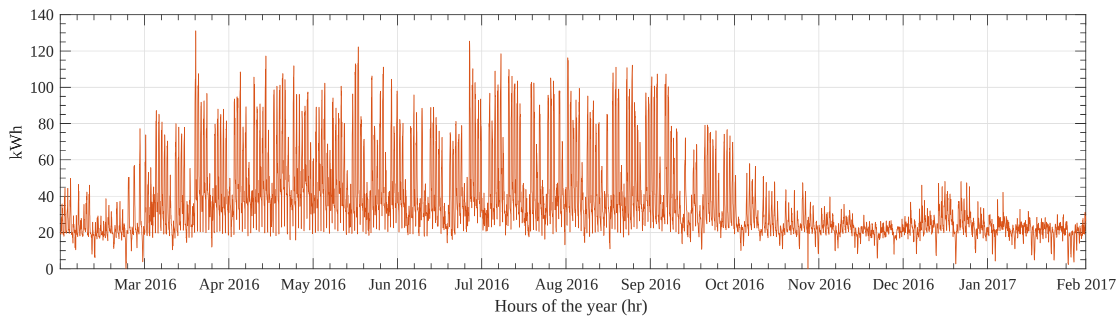


Figure 5.3: TERI university hourly load profile for full year

PV system. It seems that the PV power generation is highest during Mar 2016 and Apr 2016 with peak output of 39 kWh on the 22^{nd} March 2016. The total PV production for the full year is around 65 kWh. Figure 5.3 illustrates the hourly load consumption profile for 12 months which represents 50 % of the total load of the university building with a peak demand of 131.1324 kWh on the 19^{th} April 2016. As it is assumed that 50 % of the annual load energy from the TERI university building will be covered from the PV system, so that this 50 % of the annual load energy will be treated as zero energy building (ZEB). This PV system with battery energy storage can also work as an active generator by using an innovative management and operation strategies as given in reference [43]. It is observed that the university building consumes more energy from April to October than other months. The net load consumption during the year is approximately 317.28 MWh. Hence, both profiles are for full year (8760) hrs. starting from Mar-2016 to Feb-2017 [44].

5.3.2 Electricity Tariff for TERI University

As per the power purchase agreement signed with the Renewable Energy Supply Company (RESCO), the solar-tariff is, and will remain, substantially lower than the grid-tariff. The RESCO would also take care of the operation and maintenance of the system. Therefore, the tariff used in this study is 6 Indian rupee (INR)[4] per unit of energy (6 INR/kWh) without FiT.

5.4 Battery Sizing for TERI University

As mentioned in Section 5.3.2, the electricity tariff applied at the TERI university in New Delhi is flat-rate tariff without FiT. That means the university is buying the energy from the utility at a fixed price. The excess of the PV power production is exported to the utility grid without financial benefits. Therefore, the estimation strategy to use in this situation is the same strategy used in the case of the Flat-rate tariff for C6 house Figure 4.6. Due to the absence of the FiT, the priority of the estimation model is minimizing the cost associated with purchasing electricity from the utility grid by discharging the stored energy when there is a lack of PV generation or during nights. The amount of the left power of PV system after covering the load is used to supply the remaining 50 % of the total load. In this case, 24 V is used as the nominal (rated) voltage for both batteries.

5.5 Results and Discussion

In this section, we present the results from the technical and economic parts under the TERI case study under flat-rate tariff.

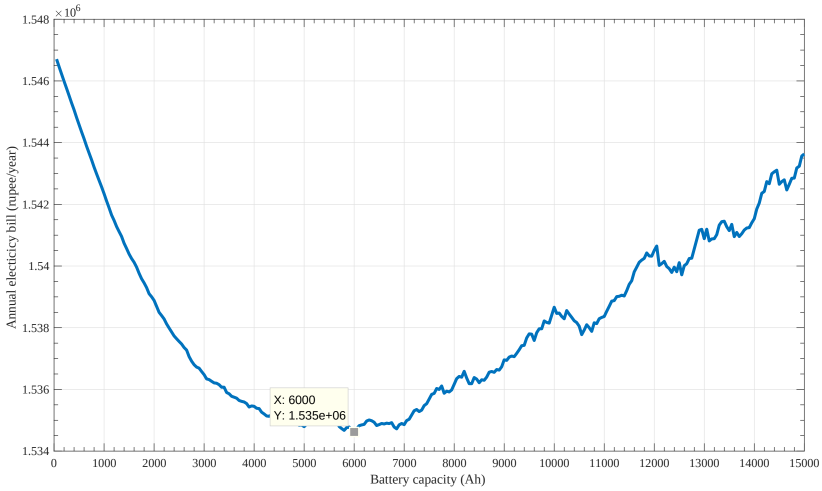
5.5.1 Battery Sizing Analysis

The real-time PV output of TERI university BIPV system and real-time load profile of the university in New Delhi, India are available at hourly interval. In this case, 50 % of the total load consumption of the university building and the flat-rate tariff are used for the estimation. Two batteries have been considered in this study: (i)lead-acid. (ii) lithium-ion.

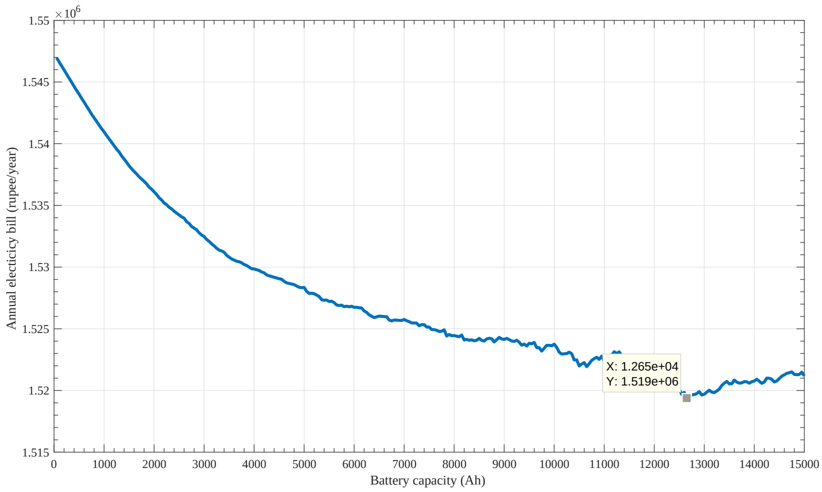
The annual electricity bill before connecting any battery is 1.5401×10^6 Indian Rupee (INR). To analyze the variation of the annual electricity bill with battery capacities, a range

[4] 1 USD=65 INR

of capacities between (0-15000) Ah with 50 Ah as an interval is used. Figure 5.4 shows the change of the annual electricity bill with 0-15000 Ah capacities of lead-acid and lithium-ion batteries. It is observed that, installing a capacity of 6000 Ah lead-acid battery storage (Figure 5.4(a)) will reduce the annual electricity bill by 5500 INR. On the other hand, installing a capacity of 12650 Ah lithium-ion battery storage resulting in reduction in the annual electricity bill by 21000 INR (1.4 %) as shown in Figure 5.4(b).

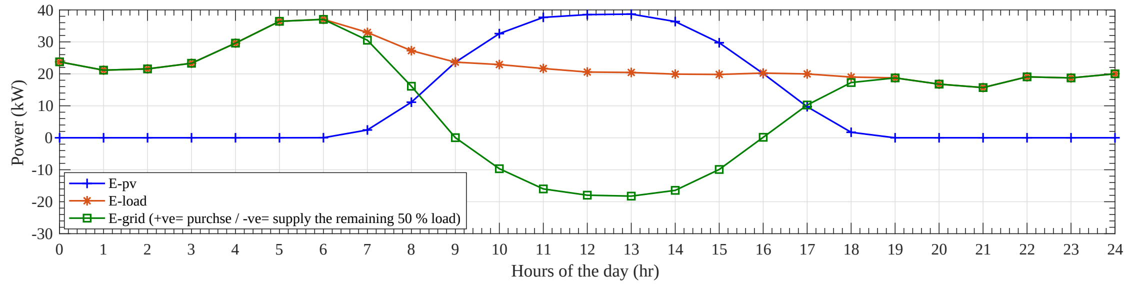


(a) Annual electricity bill variation with (0-15000) Ah lead-acid battery capacities

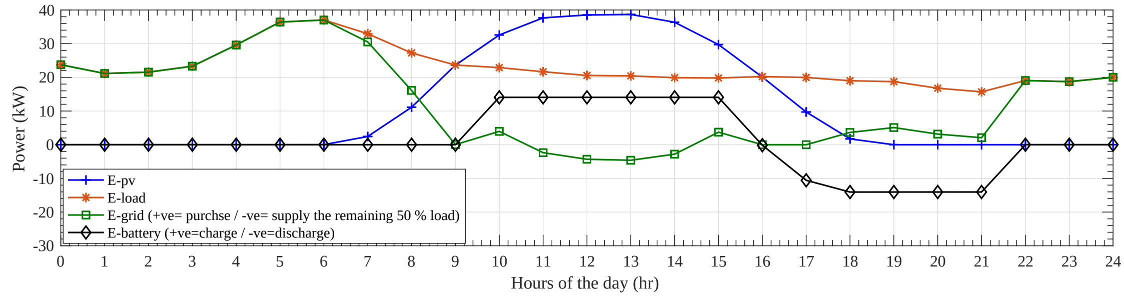


(b) Annual electricity bill variation with (0-15000) Ah lithium-ion battery capacities

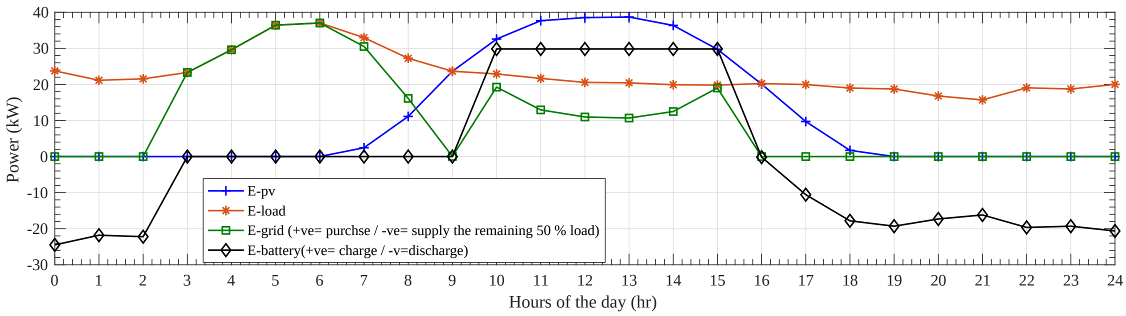
Figure 5.4: Annual electricity bill variation with (0-15000) Ah battery capacities (TERI university)



(a) Power flow variation for the 22^{nd} Mar without battery



(b) Power flow variation for the 22^{nd} Mar with 6000 Ah lead-acid battery



(c) Power flow variation for the 22^{nd} Mar with 12650 Ah lithium-ion battery

Figure 5.5: Power flow variation of the system components for the 22^{nd} Mar 2016 (TERI university)

Figure 5.5(a) shows the power flow before connecting battery where, power flow from PV (E-PV), load (E-load), the grid supply (E-grid) and (E-battery) of C6 house for a typical day (22^{nd} Mar-2016) are given. The positive values of the grid supply (E-grid) represents the purchased/import power from the utility grid and the negative values represents the supplied/export power to grid. It is observed that the load is supplied form the utility grid until 06:00 and after this time the PV production starts. It is observed that the excess power from the PV after covering the load is supplied to the remaining 50 % of he total load between 09:00 and 16:00 with peak power of around 20 kW at 12:00 and 13:00. For the same day, as per defined strategy in Section 4.4.1, after connecting 6000 Ah lead-acid battery storage the excess power from the PV after covering the load is reduced to approximately 5 kW by utilizing it for charging the battery energy storage (Figure 5.5(b)). Note that the negative values of (E-battery) represents the discharging and positive values represent the charging. From 17:00 to 21:00, the battery discharges the stored energy at the maximum rate to cover the lack of power $(P_{load} - P_{PV})$. It is observed that in the time period (18:00 to 21:00), part of the load demand has been purchased from the utility grid. Thus, the battery is not able to cover the load 100 % in this specific time period. Figure 5.5(c) shows the power flow for the same typical day when connecting a capacity of 12650 Ah lithium-ion battery. It is observed that the lithium-ion battery requires more energy to be fully charged. From 10:00 to 15:00, the amount of the excess/left power plus power from the utility grid have been used to charge the battery storage. In contrast, from 17:00 to 24:00 the battery storage can supply the domestic load completely without purchasing from the utility grid (E-grid=0).

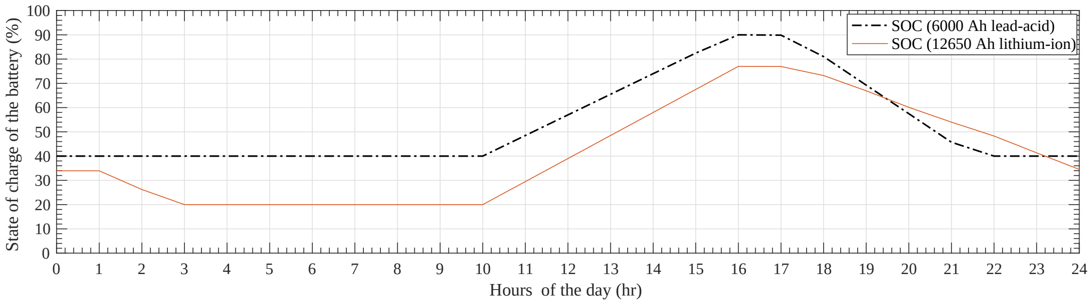


Figure 5.6: State of charge variation of the batteries for the 22^{nd} Mar 2016 (TERI university)

Figure 5.6 shows the battery state charge (SOC) variations of both estimated battery capacities for the 22^{nd} Mar 2016. Knowing that the maximum state of charge for both batteries is 90 % (Table 3.1), it is observed that the lithium-ion battery storage has been discharging the stored energy from the previous day until 03:00 where, it reaches the minimum state of charge (20 %). on the other hand, the lead-acid battery storage is at the minimum state of charge (40 %) from the beginning of the day. As per the defined estimation strategy (Figure 4.6), until 09:00, both batteries have been at the minimum SOC due to high load demand. At 10:00, both batteries start to charge from the left power $(P_{PV} - P_{load})$ and the utility grid (Figure 5.5). It seems that at 16:00 the lead-acid battery storage is fully charged (SOC_{max}=90%) while, the lithium-ion battery storage is at around only SOC=80 %. Starting from 17:00, both batteries start to discharge the stored power at maximum rate to supply the lack of power $(P_{load} - P_{PV})$ until they reach the SOC_{min}. As shown in Figure 5.6 and Figure 5.5, the 6000 Ah lead-acid battery storage reaches the SOC_{min} at 22:00 where, the lack of power is purchased from the utility grid. In contrast, due to the higher capacity of the lithium-ion battery storage (12650 Ah), the load is covered completely by the discharged power from the battery until the early hours of the next day's morning where, the SOC is around 35 %.

The cumulative battery capacity losses (Δ_{BC}) of the battery is a crucial parameter in this work. Based on this parameter the lifetime of the batteries is obtained. As explained in Equation 3.6, the cumulative capacity losses based on charging/discharging during the specified time has been calculated. This cumulative capacity losses depends on the battery charging/discharging cycles as well as the PV production and load profile during that specified time. Figure 5.7 shows the annual cumulative battery capacity loss of the estimated capacities (6000 Ah lead-acid and 12650 lithium-ion). At the beginning, both batteries are assumed to be fully charged and the cumulative capacity loses is zero. When the battery discharges the stored power, theses loses starts to accumulate. It is observed from Figure 5.7 that the lithium-ion battery storage has higher loses throughout the year with 33.56 kWh at the end of the year ($\Delta_{BC,year}$). For the lead-acid battery storage, ($\Delta_{BC,year}$) is 22.23 kWh. Both batteries have been at rest from the middle of Apr 2016 to the middle of Jun 2016 where, no charging/discharging cycles occurred. Consequently, the cumulative battery capacity loss is kept idle. The reason behind that is the high load demand (higher than the PV production) where, there is no left/excess power from the PV production to charge the battery with. Similarly, from the end of Oct 2016 to almost the middle of Nov 2016.

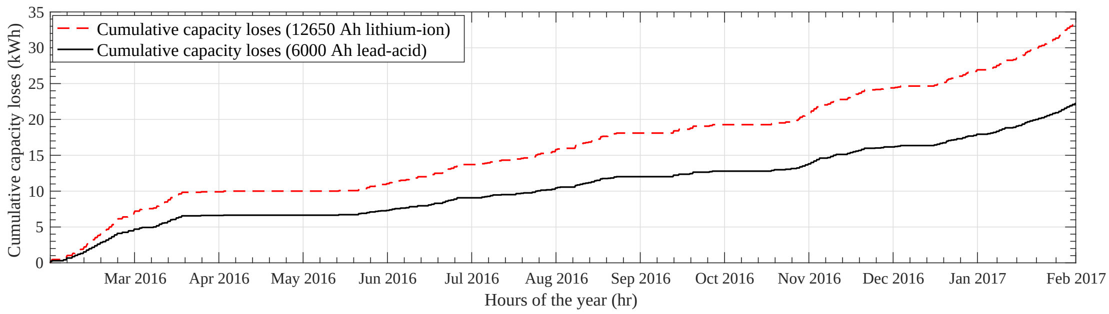


Figure 5.7: Annual cumulative capacity loss variations during the year (TERI university)

The daily electricity cost (DEC) variation for the month of March 2016 before and after adding the estimated battery capacities is given in Figure 5.8. This month (March) has been chosen to visualize the reduction in the electricity cost due to high PV power production in that month. It is observed that by installing the estimated battery capacities (6000 Ah lead-acid and 12650 Ah lithium-ion), we are in a position to achieve the objective of the study by reducing the electricity bill. In the context of achieving higher reduction, it is observed that the capacity of

12650 Ah of lithium-ion can achieve more reduction in the electricity bill than the capacity of 6000 Ah lead-acid battery storage. This higher performance of the lithium-ion battery storage appears clearly between 13^{th} and 24^{th} of Mar 2016 (Figure 5.8). In contrast, both batteries have not been able to reduce the electricity bill in some days (i.e, 26^{th} to 28^{th}) and thats due to the high load consumption (higher than PV power production) so that no left power to be stored in the batteries.

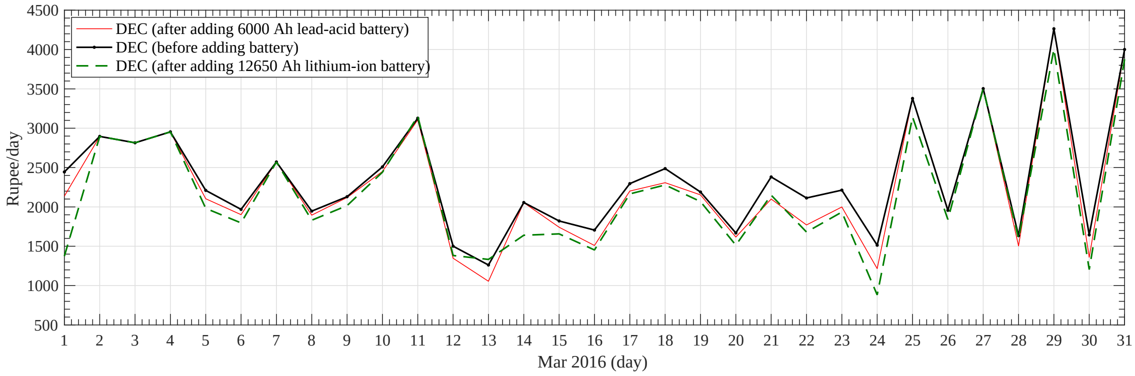


Figure 5.8: Daily electricity cost before and after adding the battery for March 2016 (TERI university)

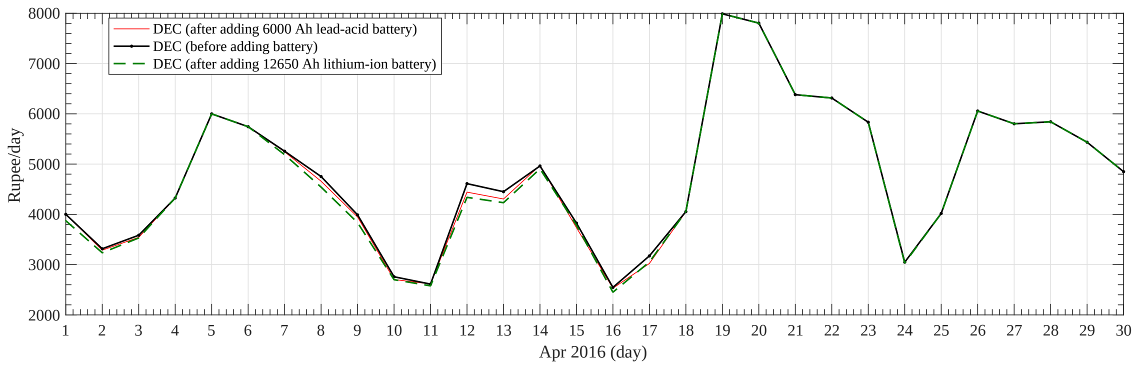


Figure 5.9: Daily electricity cost before and after adding the battery for April 2016 (TERI university)

In contrast, Figure 5.9 illustrates the daily electricity cost (DEC) variation for the month of April 2016 before and after adding the estimated battery capacities where, the load consumption is high comparing to the relative low PV production. The highest energy load consumption is on the 19^{th} of the month with cost of 8000 INR and the lowest daily electricity cost is observed on the 16^{th} with around 2500 INR. It is observed from the Figure 5.9 that both batteries have been in a position to reduce the daily electricity cost only in the period between the 7^{th} and 14^{th}

of the month with relatively higher amount of reduction for the case of lithium-ion. For the other days of the month, the PV production is lower than the energy load demand. Therefore, the shortage $(P_{load} - P_{PV})$ of on-site PV power production is supplied from the utility grid.

5.5.2 LCOE Analysis

Based on the annual cumulative battery capacity losses ($\Delta_{BC,year}$), the lifetime of both estimated battery capacities analyzed. It has been found that the lifetime of the 6000 Ah lead-acid battery capacity is 6 years and 9 years for the capacity of 12650 Ah lithium-ion battery. The economic parameters used for TERI university BIPV case [45] are listed in Table 5.2

Table 5.2: Economic parameters (TERI university case)

Parameters	Unit
Discount rate (WACC)	10 %
Escalation rate of energy price (ER)	7.5 %
Local subsidies	0 INR

Table 5.3: Results of the economic analysis (TERI university case)

Battery type	Lead-acid	Lithium-ion
Size	144 kWh	303.6 kWh
Number of replacements	4	2
Net present cost (NPC)	6738941.72 INR	8703779.01 INR
Annual E-out of the battery	6350.129 kWh/year	15803.5 kWh/year
Annualized payments (A)	742416.218 INR/year	958878.55 INR/year
Purchasing price of energy **before** adding battery (POE)	4.854 INR/kWh	4.854 INR/kWh
Purchasing price of energy **after** adding battery (POE)	4.836 INR/kWh	4.77 INR/kWh
$LCOE_{E-out}$	116.91 INR/kWh	60.67 INR/kWh
Total POE	121.75 INR/kWh	65.46 INR/kWh

The LCOE of each estimated battery capacities are analyzed. Table 5.3 shows the results of the long term economic analysis of the two estimated battery capacities (6000 Ah lead-acid and 12650 Ah lithium-ion) under the flat-rate pricing mechanism. It is observed that the lithium-ion battery storage has almost twice the size of the lead-acid battery storage 144 kWh & 303.6 kWh respectively. This difference in the sizes leads to higher annual energy production of the lithium-ion battery storage. Even though, the NPC of the lithium-ion battery storage is higher than the lead-acid battery storage, the $LCOE_{E-out}$ of the lithium-ion battery is almost half of the $LCOE_{E-out}$ of the lead-acid battery. Consequently, lower total POE when installing a size of 303.6 kWh (12650 Ah, 24V) lithium-ion battery.

5.6 Conclusion

This chapter reports the capacity estimation of energy storage for rooftop grid-connected BIPV at TERI university in New Delhi, India. The university building uses three sources of energy. These sources are: (i) the utility grid, (ii) diesel generators and (iii) BIPV. The real time hourly PV production with real time operational load of the university are available for a year (Mar 2016 to Feb 2017). Due to the high load consumption profile, only 50 % of the total load are used for finding the appropriate capacity of lead-acid and lithium-ion battery energy storage with minimization of the annual electricity bill. The electricity tariff (flat-rate without FiT) as well as the characteristics of the lead-acid and lithium-ion batteries are used for the estimation. For this typical PV and load profiles of TERI university, Table 5.4 shows the results found.

Table 5.4: Conclusion (TERI university case)

Battery type	Estimated size	Lifetime	$LCOE_{E-out}$
Lead-acid	144 kWh	6 years	116.91 INR/kWh
Lithium-ion	303.6 kWh	9 years	60.67 INR/kWh

Based on the economic analysis, the results show that the highest reduction in the annual electricity bill is achieved by a size of 303.6 kWh lithium-ion battery with a $LCOE_{E-out}$ of 60.67 INR/kWh. Even though, only half of the total load profile has been used in this study, installing this size of lithium-ion battery increases the self-consumption of the on-site PV production as well as offsetting 21000 INR of the annual electricity bill and accordingly reduce some of the fuel cost and CO_2 emissions. In order to include the total load profile of the university, the size of the PV system has to be modified. Consequently, the size of the battery storage will be changed.

Chapter 6

Quantitative (Per-Unit) Analysis & Relative Comparison

6.1 Summery

In this chapter, the real-time hourly PV production and load consumption for both buildings (TERI university and C6 house) have been used for normalizing the on-site PV generation as well as the imported energy from the grid with reference to local load consumption. The relative comparison has been done considering the flat price case of Norwegian conditions with the Indian conditions, where PV production is more and also the load is institutional. This per-unit analysis is going to help with the comprehension of how the battery energy storage confers the possibility of achieving nearly zero energy buildings by reducing the grid dependency of each building.

6.2 C6 House of Skarpnes Smart Village

Considering the real-time PV and load profiles of C6 house, the ratio of cumulative energy supplied by on-site PV generation to the load during a specific time period (hourly, monthly and yearly) is normalized as:

$$PV_{P.U.} = \frac{PV_{production},(t)}{Load_{consumption},(t)} \tag{6.1}$$

where, $PV_{P.U.}$ represents the per-unit index of the on-site PV production normalized to the load consumption in P.U. or %, $PV_{production},(t)$ and $Load_{consumption},(t)$ represent the on-site energy generation and consumption for the same time period respectively. If this value ($PV_{P.U.}$) is higher than unity, the PV production is higher than load consumption at that time. Thus, the excess of this generation will be exported to grid most of the time.

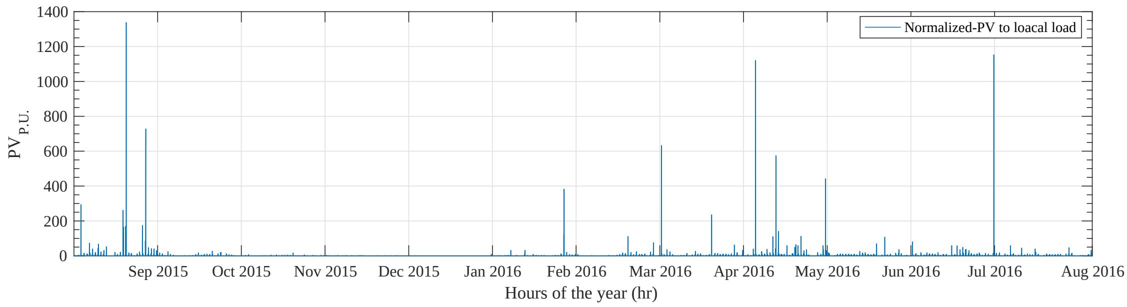


Figure 6.1: Normalized on-site PV production for each specific time (hourly) for C6 house

A presentation of Equation 6.1 is given in Figure 6.1 where, on-site PV production is normalized with respect to the local load consumption for each specific time (hourly) for 12 months (Sep 2015 to Aug 2016). It is noticed from Figure 6.1 that C6 experiences high energy mismatch on the hourly bases analysis. The high P.U. values of the PV production on the graph shows that on that specific hour the load is very low comparing with the on-site PV production. For instance, on the 18^{th} Sep 2015 at hour 19:00, the load consumption was the lowest with 0.00217 kWh with PV production of 2.95 kWh. Thus, it appears on the graph around 1382 $PV_{P.U.}$, which means that the on-site PV production on that specific time has not been consumed locally on C6 house. This phenomenon appears several times during the summer seasons, where PV production is high and the load demand is relatively lower.

For clear visualization, Figure 6.2 shows the normalized on-site PV production with the load demand as a reference for C6 house on monthly bases. It is observed from the yearly analysis

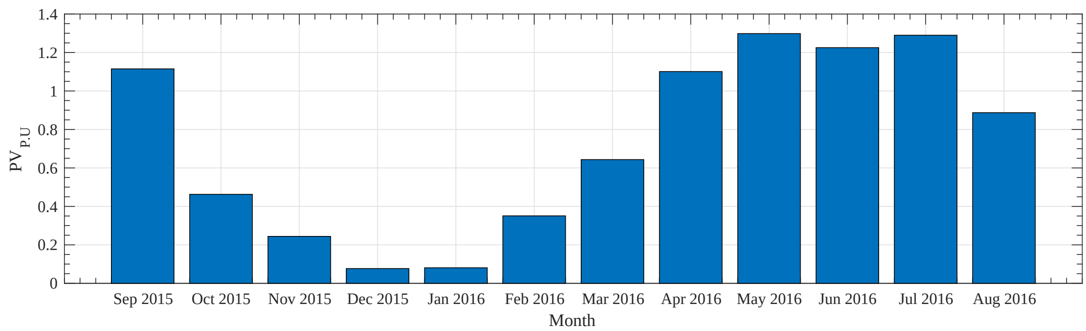


Figure 6.2: Monthly normalized on-site PV production for C6 house

that $PV_{P.U.,year}$ is 0.690 P.U. (69 %). This value means that the net annual production of the BIPV system installed at C6 house represents 69 % the net annual load demand. As given in Figure 6.2, the PV production at C6 hose is low during winter season and lowest during Dec 2015 - Jan 2016 with around 0.074 P.U. On the other hand, the PV production is high enough during summer season (Sep 2015, Apr-Jul 2016) to supply the local load demand with excess of energy that has been supplied to the utility grid. The highest value of the normalized PV production to the load consumption is observed in May 2016 with around 1.23 P.U.

To show the grid dependency of the C6 house as well as illustrating the effect of adding battery energy storage on reducing the dependency on the utility grid, the imported energy from the grid (E_{grid}) is normalized to the load consumption as:

$$E_{grid,P.U.} = \frac{E_{grid},(t)}{Load_{consumption},(t)} \tag{6.2}$$

where, $E_{grid,P.U.}$ represents the dependency on the grid in P.U. or percentages. The monthly imported energy from the grid (E_{grid}) for C6 house is normalized to the load consumption over daily, monthly and yearly time period using Equation 6.2. It is observed from the yearly analysis that the $E_{grid,P.U.,year}$ is 0.7414 P.U. That means the net annual load demand of C6 house is 74.14 % supplied from the utility grid due the high-energy mismatch as well as high exported energy to the utility grid. However, it is noticed that $E_{grid,P.U.,year}$ has been reduced to 0.5912 P.U. (59.12 %) when installing of 25.2 kWh lead-acid battery.

In Figure 6.3, the monthly normalized imported energy from the grid has been shown before and after installing the estimated lead-acid battery size (25.2 kWh) considering the flat

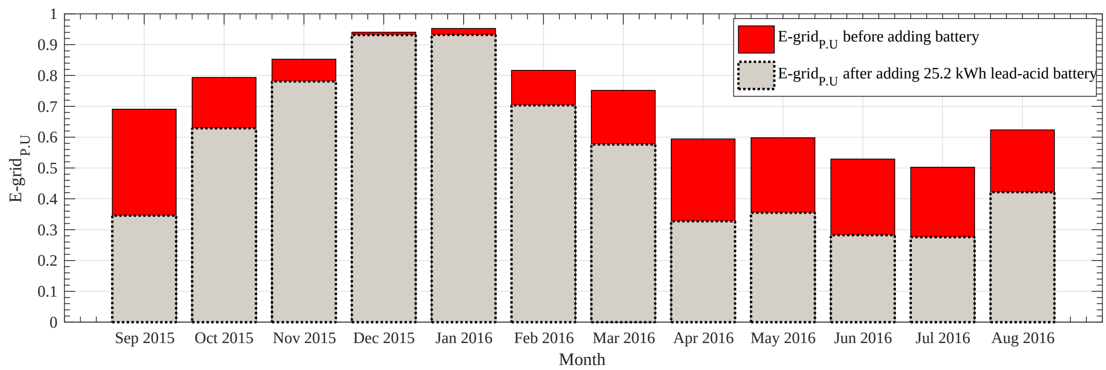


Figure 6.3: Monthly normalized imported energy from the grid before/after considering the battery, (C6 house)

price case of Norwegian conditions (Chapter 4). As illustrated, the battery has achieved remarkable reduction during summer season (Apr-Aug) 2016 with highest reduction in Sep 2015. Minor reduction is observed during Oct-Nov 2015 and Feb-Mar 2016. However, inconsiderable reduction is observed during the cold Norwegian winter (DEC 2015 - Jan 2016) due to the low PV production.

6.3 TERI University

Considering the local load consumption of TERI university ZEB (50 % of the net load) as a reference, the same analysis (Equations 6.1 and 6.2) used for the C6 house is repeated considering TERI University. A presentation of Equation 6.1 is given in Figure 6.4 where, on-site PV production is normalized with respect to the local load consumption for each specific time (hourly) for 12 months (March 2016 to February 2017). Note that, the excessive amount of the PV production in this case is supplied to the remaining 50 % of the total load. Moreover, it is noticed that most of the on-site PV production is locally consumed comparing with C6 house (Fig. 6.1).

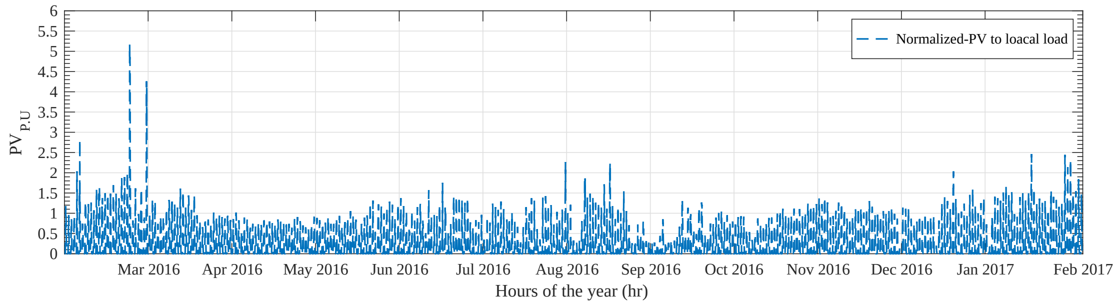


Figure 6.4: Normalized on-site PV production for each specific time (hourly) for TERI university

For clear visualization, Figure 6.5 illustrates the monthly normalization of the PV production to the load consumption. It is observed that the local energy load demand has been supplied from the PV production mostly in Mar 2016 and Feb 2017 with 0.366 P.U. and 0.352 P.U. (36.6 % and 35.2 %) respectively. In the months of July and Aug 2016, the On-site energy supply-demand is the lowest (0.146 P.U./14.6 %) compared to other months. For the whole year (Mar 2016 - Feb 2017), this ratio of the on-site PV production to the load consumption is observed as 0.197 P.U. That means the PV system installed at TERI university is able cover the load demand only by 19.7 %. These results show that TERI university is not in a good shape to achieve ZEB comparing with C6 house ($PV_{P.U.,year}$ = 0.690 P.U. (69 %)).

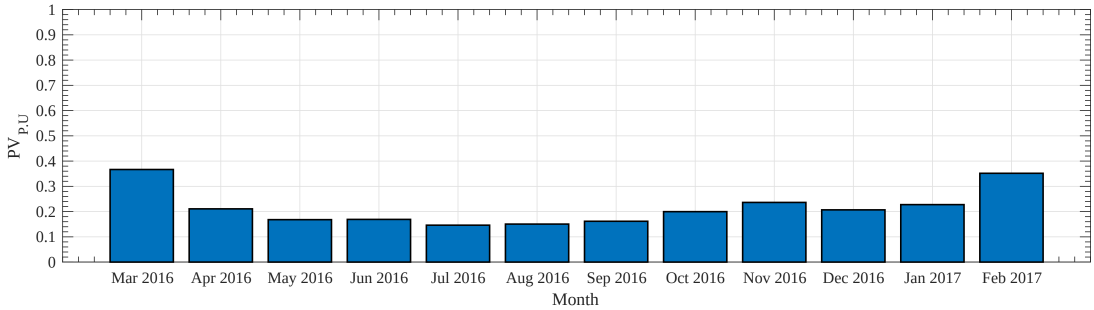


Figure 6.5: Monthly normalized on-site PV production for TERI university

From the normalization of the imported energy from the grid for the whole year, it is observed that the $E_{grid,P.U.,year}$ is 0.813 P.U. That means the net annual load demand of TERI university ZEB is supplied by 81.3 % from the utility grid. On the other hand, $E_{grid,P.U.,year}$ has been reduced to 0.78 P.U. (78%) when considering the installation of 303.6 kWh lithium-ion battery. To exhibit the monthly share of this reduction, Figure 6.6 shows the annualized imported energy from the utility grid before and after installing the optimum estimated battery size (303.6 kWh) in Chapter 5.

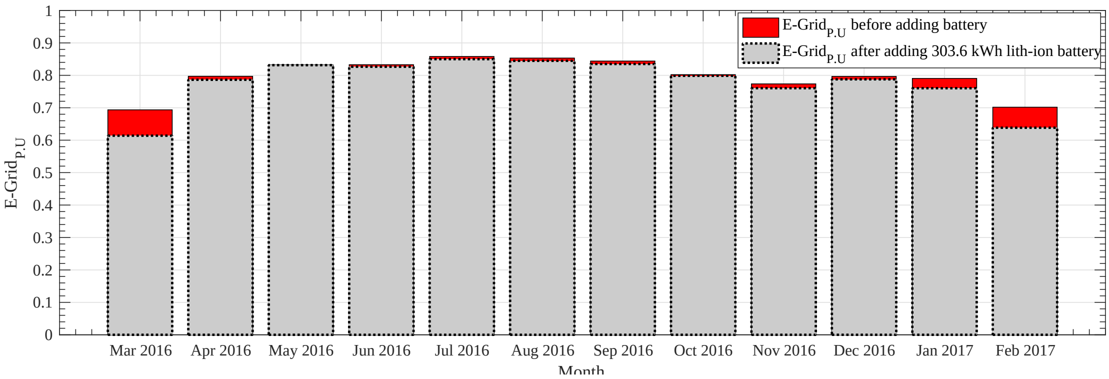


Figure 6.6: Monthly normalized imported energy from the grid before/after considering the battery, (TERI university)

It is observed that the highest reduction achieved by the battery on the monthly grid dependency is in Mar 2016 and Feb 2017 where, the $PV_{P.U.}$ is the highest. Smaller reduction in the imported energy is observed in Nov 2016 and Jan 2017. In May, Jun and Oct 2016, the PV production is low as shown in Figure 6.4 that is why the battery has not been able to reduce the imported energy from the grid (Figure 6.6). Almost the same amount of monthly reduction is achieved in Jul, Aug and Sep 2016.

6.4 Conclusion

In addition to the main objective of this thesis, this chapter has presented a brief analysis of both (C6, Teri) ZEBs status as well as the effect of installing battery energy storage on the grid dependency. The real-time energy produced by the on-site PV system and the imported energy from the grid are normalized with referenced to the real-time load consumption for the same time period (hourly, monthly and yearly). This quantification is defined as per-unit index. The yearly per-unit $PV_{P.U.,year}$ index of the on-site PV production should have higher values to ensure better coincident with on-site PV generation and the load. In contrast, the yearly per-unit $E_{grid,P.U.,year}$ index of the imported energy from the utility grid should have lower values to ensure lower-grades of grid dependency as well as energy supply-demand mismatch.

Table 6.1: Results of P.U. analysis

Parameter	TERI university	C6 house
$PV_{P.U.,year}$	19.7 P.U.	0.69 P.U.
$E_{grid,P.U.,year}$	0.813 P.U.	0.7414 P.U.
$E_{grid,P.U.,year}$ after adding battery	0.78 P.U.	0.5912 P.U.

It is observed from Table 6.1 that C6 house is in a better position in terms of achieving zero energy house even though, the grid dependency indicated by $E_{grid,P.U.,year=}$0.7414 P.U is relatively high taking into account the high on-site PV production (0.69 P.U.). Moreover, the battery energy storage has shown a superb performance on minimizing the grid dependency of both buildings. For C6 house, 15 % of the annual imported energy from the grid is reduced when 25.2 kWh of lead-acid battery is installed. 3.3 % reduction in the annual imported energy from the grid is achieved by 303.6 kWh lithium-ion battery when installed at TERI university building. Note that the relative comparison is done considering the flat price case of Norwegian conditions with the Indian conditions, where PV production is more and also the load is institutional.

Chapter 7

Conclusions

7.1 Conclusions

The main focus of this research study is to develop a strategy for estimating the capacity of the battery energy storage (ES) for grid-connected building-integrated photovoltaic (BIPV) systems installed at different nearly zero energy buildings (ZEBs) in different geographical locations. The scope of this strategy is to estimate the optimum battery capacity with consideration of minimum reduction in the annual electricity bill of the buildings. The characteristics of two different battery types (lead-acid and lithium-ion) as well as the local electricity tariff have been used in the estimation process.

In addition, the levelized cost of energy (LCOE) of each estimated battery capacity has been analyzed and added to the purchasing price of energy for the combined system (PV+ES) after installing each battery capacity to check the long-term profitability of adding that battery energy storage. Based on the typical PV and load profiles of each ZEB, the following conclusions are achieved.

- **For the C6** house of Skarpnes Smart Village in Southern Norway, the analysis of estimating the capacity of the battery energy storage (ES) for grid-connected (BIPV) system as well as the LCOE have been determined under two electrical tariffs. Based on these tariffs, the following findings are achieved (Table7.1).

  Based on these types of tariffs, it is found that the best scenario for the C6 house is to utilize the spot-price tariff with one-to-one FiT. Depending on the subsidies, the profit of installing battery energy storage can be determined. In Norway, the subsidies may be granted only, if the consumer is being charged through the spot-price tariff. Therefore, for this case of C6 house where, the maximum subsidies of 28750 NOK are assumed. It has

Table 7.1: Findings 1

Flat-Rate Tariff					
Battery type	Estimated size	Lifetime	AEB-Reduction	Subsidies	$LCOE_{E-out}$
Lead-acid	25.2 kWh	7 years	17.6 %	✗	1.613 NOK/kWh
Lithium-ion	22.8 kWh	9 years	22.6 %	✗	2.543 NOK/kWh
Spot-Price Tariff					
Battery type	Estimated size	Lifetime	AEB-Reduction	Subsidies	$LCOE_{E-out}$
Lead-acid	11.4 kWh	8 years	9 %	✓	0 NOK/kWh
Lithium-ion	21 kWh	10 years	10 %	✓	5.94 NOK/kWh

been found that a size of 11.4 kWh (950 Ah, 12 V) lead-acid battery is most profitable size to be installed at C6 ZEB with reduction in the annual electricity bill (AEB-Reduction) of 9 % if only 69 % of the maximum subsidies is granted. The total purchasing price of energy (Total POE) is 0.151 NOK/kWh. This total POE represents the price per unit of energy the consumer should pay after installing this size of lead-acid battery which is 9 % lower then the POE before installing the battery. Note, the $LCOE_{E-out}$ of the 950 Ah lead-acid battery without considering the subsidies is found as 2.62 NOK/kWh.

- **For the TERI** university in New Delhi, India, the analysis of estimating the capacity of the battery ES for grid-connected BIPV system as well as the LCOE have been determined under flat-rate electrical tariff. As it is assumed that 50 % of the annual load energy from the TERI university building will be covered from the PV system, so that this 50 % of the annual load energy, will be treated as zero energy building. This PV system with battery energy storage can also work as an active generator by using an innovative management and operation strategies. Based on the technical and economic analysis, the following findings (Table 7.2) are observed.

Table 7.2: Findings 2

Battery type	Estimated size	Lifetime	AEB-Reduction	Subsidies	$LCOE_{E-out}$
Lead-acid	144 kWh	6 years	0.35 %	✗	116.91 INR/kWh
Lithium-ion	303.6 kWh	9 years	1.4 %	✗	60.67 INR/kWh

The results show that the highest reduction in the annual electricity bill is achieved by a size of 303.6 kWh lithium-ion battery with a $LCOE_{E-out}$ of 60.67 INR/kWh. Even though, half of the total load profile has been used in this study, installing a size of 303.6

kWh (12650 Ah, 24 V) lithium-ion battery increases the self-consumption of the on-site PV production as well as offsetting 21000 INR of the annual electricity bill and accordingly reduce some of the fuel cost and CO_2 emissions. In order to include the total load profile of the university, the size of the PV system has to be modified. Consequently, the size of the battery storage will be changed.

- **For different geographical located buildings** (TERI university and C6 house), a quantitative analysis and relative comparison considering the flat price case of Norwegian conditions with the Indian conditions has been done. The real-time hourly PV production and load consumption for both buildings have been used for quantifying the on-site PV generation as well as the imported energy from the grid with reference to local load consumption. This analysis has been made before and after installing the estimated battery capacity in each case to show the impact of this inclusion from grid point of view. Based on that, the following findings are achieved.

  1. It has been found that C6 house is in a better position in terms of achieving zero energy house even though, the grid dependency indicated by $E_{grid,P.U,year=}0.7414$ P.U is relatively high taking into account the high on-site PV production (0.69 P.U). For TERI university, the load is institutional and much higher than the PV capacity. Thus, the grid dependency is quiet high ($E_{grid,P.U,year=}0.813$).
  2. The battery energy storage has shown a superb performance on minimizing the grid dependency of both buildings and incresing the self-consumption of the on-site PV production.
     (a) For C6 house, 15 % of the annual imported energy from the grid is reduced, when 25.2 kWh of lead-acid battery is installed.
     (b) For TERI university, 3.3 % reduction in the annual imported energy from the grid is achieved by installing 303.6 kWh lithium-ion battery.

Among the two examined battery types, it has been found that the on-going problem is the outstandingly high initial cost of the batteries especially for the lithium-ion battery types. Given the available technology nowadays, there is no doubt that battery energy storage systems may turn into a primary element for ZEBs one day with a proper design, higher equipment efficiency, and better planning. From ZEB designing angle, the per-unit analysis of nearly zero energy buildings (ZEBs) is important for investigating on-site PV generation as well as the imported energy from the grid with reference to local load as well as help for understanding the effect of adding energy storage on reducing the dependency on the utility grid and thus helping in achieving nearly zero energy buildings.

7.2 Future Work

This research will be more interesting to be extended further. Recommendations for future research are divided into two parts. They are:

- It would be interesting to estimate the battery energy storage capacity for the both ZEBs with consideration of mitigation the fluctuation of the PV power output to enhance the grid-interaction.
- In the case of the availability of smaller time interval of the real-time operational data, it would be attractive to evaluate the operational performance of the battery energy storage based on the peak loads variations. This performance evaluation would be attractive when considering the demand side management (DSM) and future implementation of demand limits on the residential load from the network or the power tariff.

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Appendix A

Paper I

Title:	Battery Capacity Estimation for Building-Integrated Photovoltaic System: Design Study of a Southern Norway ZEB House
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Battery Capacity Estimation for Building-Integrated Photovoltaic System: Design Study of a Southern Norway ZEB House

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***Abstract*—Building-integrated Photovoltaic system (BIPV) with energy storage (ES) can help in reducing the peak demand as well as overcoming the intermittency of the load and PV production. In Southern Norway, a Smart Village Skarpnes is developed for zero energy buildings (ZEBs). In this Smart Village, five houses are built with BIPV system. Its important to estimate the appropriate battery sizing with consideration of local PV production and load profile taking into account the battery characteristics with minimization of the annual electricity bill. In this study, real operational results of house (C6) from the Skarpnes Smart Village is used for estimating the capacity of battery energy storage for that house. The size of battery storage is estimated considering the maximum reduction in the annual electricity bill. In this work, the lead-acid battery characteristics and the flat-rate electricity tariff are used for the analysis of the annual electricity bill. Based on the results, it is found that for this typical PV and load profiles of ZEB house, installation of a of 25.2 kWh (2100 Ah) lead-acid battery will reduce the annual electricity bill by 17.6 % of the bill before installing the battery.**

I. Introduction

The grid-connected PV systems with energy storage (ES) can help in reducing the peak demand as well as overcoming the intermittency of the load and the PV production [1], [2]. ES can also help in demand side management (DSM) as well as for improving system stability. Grid-connected PV system without ES may not be very useful for improving the power quality as well as control dispatching of the power [3], [4]. ES can help to enhance the profitability of the grid-connected PV-system and also to improve the system efficiency, proper sizing of ES system is required [5]–[8]. ES units can be one solution to improve the power supply quality and assure system stability by reducing the fluctuation of the generated power [5], [8]. Moreover, adding a proper size of ES to the grid-connected PV system could reduce the overall investment cost of the combined system through smart and optimized scheduling of the energy flow with in the system [9].

In reference [10], the relationship between the PV array and battery storage capacity to supply the required energy at a specified energy load fraction for stand-alone system is proposed and it has not considered the grid-connected system. Reference [11] has determined the capacity of grid-connected PV and battery for residential system, where both PV system and battery sizes have been varied; but it has not considered fixed PV size with real operational load. Reference [12] has proposed the battery capacity sizing for grid-connected PV system for a constant load with limited charging/discharging scales and it has used a simplified PV output model as described in [13]. It is observed through the literature review that battery estimation for a ZEB with BIPV is needed to use the real operational load with real time PV production considering minimization of annual electricity bill.

In this study, the real operational load and real time PV production of C6 house from the Skarpnes Smart Village in Southern Norway are used for estimating the capacity of battery energy storage for that particular house. The real time operational results of a year are used for estimating the battery size with maximum reduction in the annual electricity bill of that house. In this work, The considered battery is lead-acid battery type and the flat rate electricity tariff without any feed-in-tariff (FiT).

Section II presents background of the Smart Village Skarpnes and the analysis of annual real time load with PV production of house C6. Section III discuss about ES with battery model and optimization strategy which are used for finding the optimum battery size. Section IV analyze the results of this study. In Section V, the results are concluded.

II. Background of the Smart Village Skarpnes

The Smart Village Skarpnes (58.43°N, 8.72°E) is located close to the city of Arendal, Southern Norway. Several houses in the Smart Village are built in according to the passive house standard NS3700 [14]. The village will have a total of 17 detached single family houses and 3 apartment blocks with 20 units. Five houses are built as nearly ZEB with roof mounted BIPV systems. Each house is fully instrumented for data collection of electricity production and consumption, grid quality parameters and indoor climate conditions. Large number of ABB electricity meters are installed on the main electrical circuits in the households to evaluate energy consumption

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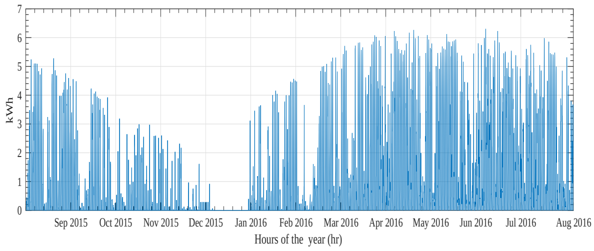
(a) Map of the five BIPV houses in the Smart Village [16]

(b) Construction face picture of the specific studied house (C6) [14]

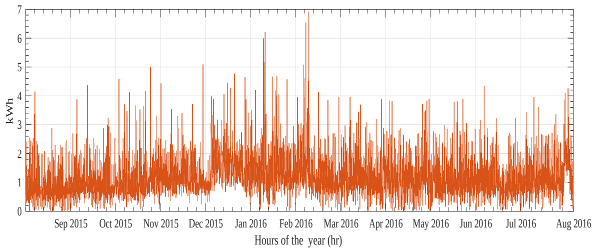
Fig. 1. Smart Village Skarpnes map and the studied house C6

TABLE I
PV ARRAY ORIENTATION

PV system size	7.36 (kWp)
Array type	Fixed roof mount
Tilt angle	32°
Azimuth	48°



(a) The hourly PV profile for full year



(b) The hourly load profile for full year

Fig. 2. PV and load profiles

patterns and peak power demands as well as measurement of the PV power generation data [14]. Fig.1 shows the Smart Village Skarpnes map and the studied house C6. The map of the five BIPV houses in the Smart Village is shown in Fig.1(a) where PV systems are indicated with blue, and a construction face picture of the specific house (C6) is shown in Fig.1(b).

In this work, the lead-acid battery characteristics and the flat rate electricity tariff are used for the analyzing of the bill. The size of battery is estimated considering the maximum reduction in the annual electricity bill. The electricity pricing mechanism in addition to the operational load with on-site PV production are going to influence battery sizing. Moreover, and according to the Agder Energy Nett [15], the feed-in-tariff (FiT) is not activated at when the customer chooses this kind of electricity tariff (i.e., flat-rate). Thus, the excess of the generated PV power will be supplied to the grid without getting any profits. In this situation, we concern to find the optimum size of the battery which will lead to the maximum reduction in the annual electricity cost considering two main objectives: (i) Minimizing the amount of energy supplied to the grid by charging the battery from the left power of PV system after covering the load and (ii) Minimizing the cost associated with purchasing electricity from the utility grid by discharging the stored energy, when there is a lack of PV generation or during nights.

A. House C6 data

The house C6 is a typical Norwegian house with an area of 154m^2 located in the Smart Village Skarpnes. The usable area of the roof is 57.43m^2 and it is facing South-West as shown in Fig.1(a). The installed crystalline silicon PV panels are manufactured by Sunpower SPR 230NE-BLK-I and they are covering only 39.9m^2 of the roof area. PV array orientation is given in Table I.

1) PV power production and load data: The terms PV and data data refer to the generated power from the PV system and the load demand from the house appliances all together that collected hourly. For the house C6, The PV system is monitored for the solar irradiation and temperature through sensors placed on the roof to help for collecting data and the performance of the house being zero energy building. The individual load consumption monitored and measured by ABB electricity meters. The power quality measurements as well as power flow from/to grid is measured by Elspec power quality instrument. The collected PV and load profiles from the house C6 is shown in Fig.2. Fig.2(a) shows the generation profile of the PV system, Fig.2(b) shows the load consumption profile. Hence, all data profiles are for full year (8760) hrs starting from Sep-2015 to Aug-2016 [17].

2) Electricity tariff: According to the Agder Energy Nett [15], the customer can choose between three types of electricity tariffs. These tariffs are: seasonally differentiated tariff, flat rate tariff and ahead/spot-price. In this work, the flat rate tariff is chosen. Table II shows the tariff specifications in Norwegian krone (NOK) [15]. Additionally, there is an extra charge for

TABLE II
FLAT ELECTRICITY TARIFF

Description	Fixed charge NOK/month	Consumption NOK/kWh	Extra NOK/kW/month
Flat-rate	62.50	0.2515	41(summer), 125 (winter)

TABLE III
BATTERY CHARACTERISTICS

Battery type	Lead-Acid
Nominal voltage	12 (V)
Depth of Discharge (DoD)	60 % [21]
(Charge/discharge) efficiency	85 % [22], [23]
(Charge/discharge) time	10 hrs
Aging factor (Z)	$3e^{-4}$ [4]
Self-discharge factor (a)	3 % /month [21]

NOK/kW-month, which is the one time in the month where the customer has to pay for the max kW consumption.In this work, it is considered that the excess of the PV generated power after covering the domestic load and charging the battery will be supplied to the grid without benefits.

III. SYSTEM MODELING

The general concept behind energy storage is to capture energy produced at one time for use at a later time. The process of capturing the energy is generally regarded as the charging while the process of releasing the energy to be used is regarded as the discharging [5]. Batteries in PV-systems should be able to supply reasonably steady power when there is a power outage or when PV system is generating less power output. Battery should have low cost, high energy efficiency, long life time, low maintenance, good reliability and less self-discharge [18]. Table III shows the battery characteristics which are used in this study. The PV-inverter efficiency is taken as 96% [19] and the battery inverter is taken with efficiency of 90% [20]. In this study the cost of the PV array, PV-inverter and capital cost of the battery are not included and they will be considered in future work for estimating the levelized energy cost from the system.

1) Battery characteristics: This section describes the considered battery model. The PV power output at a particular day (d) and at time (t) is expressed as:

$$P_{pv,ac}(d,t) = \eta_{pv,inv} \times P_{pv,dc}(d,t) \tag{1}$$

where, $P_{pv,ac}$ represents the AC output of the PV inverter (kW), $\eta_{pv,inv}$ represents the efficiency of the PV inverter, $P_{pv,dc}$ represents the DC output of the PV to the inverter (kW) and (d,t) represents the day and time respectively.

The battery is modeled in a way that, the power transferred to the battery is taken as positive (charging), and negative when the power is transferred from the battery (discharging). In the same way. The energy purchased from the grid is modeled as (positive) and when supplying to the grid as (negative). The charge/discharge power [20] of the battery can be formulated as:

$$P_{dc,batt}(d,t) = \frac{E_{batt}(d,t) - E_{batt}(d,t-\delta t)}{\delta t} \tag{2}$$

where, $P_{dc,batt}$ represents the DC the power transferred to/from the battery during time interval (δt) in (kW) and E_{batt} represents the available energy in the battery (kWh). The maximum power of the battery (kW) can be represented as:

$$P_{dc,batt,max}(d,t) = \frac{C_{batt}(d,t) \times V}{t_{max}} \tag{3}$$

where, C_{batt} represents the battery capacity (Ah), V represents the battery nominal (rated) voltage and t_{max} represents the maximum time for charge/discharge (hr). Then through the inverter of the battery, the AC power [20] can be represented as:

$$P_{ac,batt}(d,t) = \begin{cases} \eta_{batt,inv} \times P_{dc,batt}(d,t), \\ \text{(when discharging).} \\ \frac{P_{dc,batt}}{\eta_{batt,inv}}, \text{(when discharging).} \end{cases} \tag{4}$$

where, $P_{ac,batt}$ represents the AC the power transferred to/from the battery (kW), and $\eta_{batt,inv}$ represents the efficiency of the battery inverter. The battery capacity loss is very important factor in this study which leads to obtain the lifetime of the battery. Thees losses occur due to the aging factor of the battery. The battery state of charge (charging/discharging) with time is given as:

$$SOC(d,t) = \begin{cases} SOC(d,t-\delta t)(1-a) \\ -\frac{P_{dc,batt}(d,t)}{\eta_{batt} \times C_{batt}(d,t) \times V}\delta t, \\ \text{(when discharging).} \\ SOC(d,t-\delta t)(1-a) \\ +\eta_{batt}\frac{P_{dc,batt}(d,t)}{C_{batt}(d,t) \times V}\delta t, \\ \text{(when charging).} \end{cases} \tag{5}$$

where, SOC represents the state of charge of the battery, η_{batt} represents the efficiency of the battery, C_{batt} represents the capacity of the battery (Ah) and a represents the self-discharge factor. The battery capacity loss due to of the aging factor [20] is described as:

$$\Delta_{BC} = \begin{cases} \Delta_{BC}(d,t-\delta t) - Z \times P_{dc,batt} \times \delta t, \\ \text{(when discharging).} \\ \Delta_{BC}(d,t-\delta t), \\ \text{(when charging).} \end{cases} \tag{6}$$

where, Δ_{BC} represents the annual cumulative capacity losses (kWh) during charging/discharging time and Z represents the aging factor of the battery table III. Hence, the cumulative capacity losses $(\Delta_{BC}(0,0))$ at the beginning is taken as zero as it is considered that the battery initially was fully charged. The cumulative capacity losses based on charging/discharging during the specified time has been calculated in equation 6. This cumulative capacity losses Δ_{BC}

depends on the battery charging/discharging cycles as well as the PV production and load profile during that specified time. Δ_{BC} has to be subtracted in the specified time from the nominal capacity (BC_{nom}) [20] of the selected battery to update the battery capacity as:

$$C_{batt}(d,t) = BC_{nom} - \frac{\Delta_{BC}(d,t)}{V \times 1e^{3}} \tag{7}$$

Where, C_{batt} represents the updated battery capacity (Ah) and BC_{nom} represents the nominal (rated) battery capacity (Ah). It is important to analyze the battery life time considering the cumulative capacity loss Δ_{BC} for the whole year and its given by:

$$B_{life-time} = \frac{BC_{nom} \times V \times 1e^{-3}}{\Delta_{BC,year}} \tag{8}$$

Where, $B_{life-time}$ represents the life time of the battery (years) and $\Delta_{BC,year}$ represents the cumulative capacity loses for the year (kWh). The annual electricity bill is accumulated for the year and compared with the variation of the battery sizes.

2) Optimization strategy: The real time PV production and real time operational load profile are used with taking battery capacity rage (0-3000) Ah with interval of 50 Ah for minimizing the annual electricity bill. Since there are no defined peak/off peaks hours by the utility, the optimization process first *checks* in the specific time $((\delta t))$ interval if the PV generation is higher than the load. Then if the battery is fully charged, the left PV power after covering the load $(P_{PV} - P_{load})$ will be supplied to the utility grid. Else if the state of charge of the battery is less than the maximum, the left power will be compared with the available power of the battery $P_{dc,batt,max}(d,t)$. If the left power $(P_{PV} - P_{load})$ is higher, then the battery will be charged at maximum rate first and the rest of the left power will be supplied to the grid. Otherwise, The PV left power $(P_{PV} - P_{load})$ will be used to charge the battery only. Second, the optimization process *checks* if load is higher than the generated power of the PV, if the state of charge is at the minimum, then the battery will be kept as its and the lack of power $(P_{load} - P_{PV})$ will be purchased from the utility. Else if the state of charge of the battery is higher than the minimum, the lack power $(P_{load} - P_{PV})$ will be compared with the maximum available power of the battery $P_{dc,batt,max}(d,t)$. If lack power is less, then the battery will discharge to cover the lack of power $(P_{load} - P_{PV})$ without purchasing from the grid. Otherwise, the battery will discharge at the maximum rate towards the lack power $(P_{load} - P_{PV})$ and the rest will be purchased from the utility grid. For each interval of battery capacity, the model repeats the optimization process and use that battery capacity with the corresponded annual electricity cost. At the end, the model analyzes the annual electricity bill as shown in Equation 9 against each battery capacity interval and indicate the optimum capacity responsible for the minimum annual electricity bill.

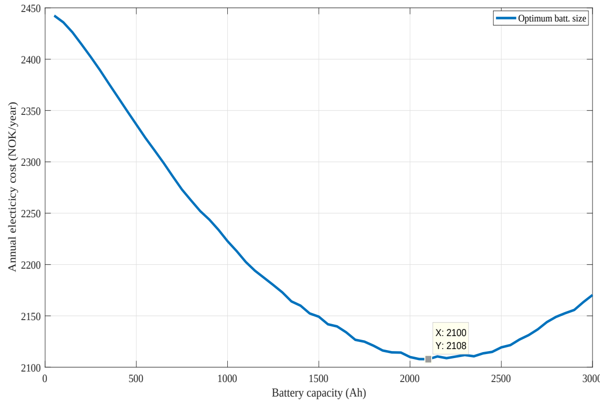


Fig. 3. Variation of the annual electricity bill with (0-3000)Ah battery capacities

$$AEC = \sum_{d=0,t=0}^{d=365,t=8760} E_{buy}(d,t) \tag{9}$$

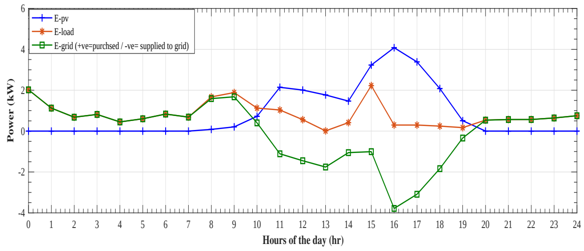
Where, AEC is the annual electricity cost and E_{buy} represents the electricity purchasing cost in Norwegian Krone (NOK/year).

IV. Results and Discussion

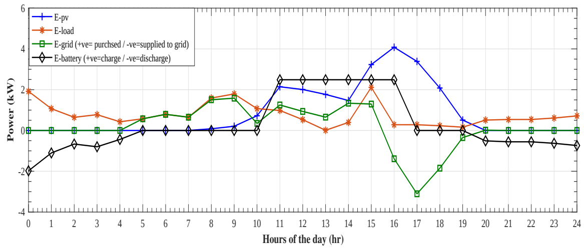
In this work, real operational results of C6 house from the Skarpnes Smart Village in Southern Norway is used for estimating the capacity of battery energy storage for that house. This house load profile and PV production are available at hourly interval, therefore, the specified time interval (δt) is considered 1 hour. In this study, lead-acid battery (Tabel III) is considered for finding the appropriate battery size. It is assumed in this study that the maximum charging and discharging time are fixed and the minimum battery state of health is zero to allow the battery to work up to 100 % of its reference capacity.

The annual electricity bill before connecting any battery energy storage is 2651 Norwegian Kroner (NOK) as per defined electricity pricing (Table II). The variation of battery capacities from 0-3000 Ah with 50 Ah interval is considered and hourly power flow is calculated using the methodology explained in Section III. Based on that, the annual electricity bill is calculated and it is given in Fig.3. It is observed that the annual electricity bill is minimum for a size of 2100 Ah. If this battery capacity (2100 Ah) is added, then the annual electricity bill is reduced by 453 NOK.

The power flow from PV (E-PV), load (E-load) and the grid supply (E-grid) of C6 house without battery are given in Fig.4(a) for a typical day (25^{th} Sep-2015). For the same day, if the battery capacity of 2100 Ah is connected then the PV power, load and the variation of grid supply are given in Fig.4(b). Fig.4(a) shows that the load is supplied form the utility grid until 08:00 and after this time the PV production starts. It is observed that the excess energy from the PV



(a) Power flow variation for the 25^{th}-Sep without battery



(b) Power flow variation for the 25^{th}-Sep with battery

Fig. 4. power flow variation of the system components

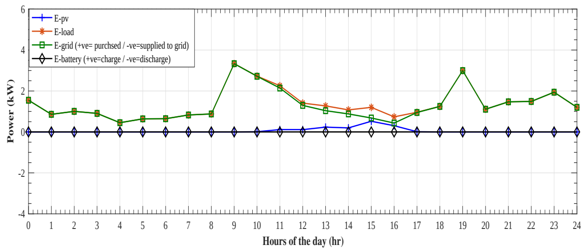


Fig. 5. Power flow variation for the 1^{st}-Jan with battery

after covering the load is supplied to the grid from 10:00 to 19:00. As per defined strategy in Section III-2, after connecting 2100 Ah battery size the load was completely covered from the battery from midnight to 04:00 and from 20:00 to 24:00 (Fig.4(b)). Only from 05:00 to 08:00, the load is completely supplied from the utility grid. Moreover, its observed that the left/excess energy after covering the load is used for charging the battery from 11:00 to 16:00. Thus, the supplied energy to the grid occurred only between 16:00 to 19:00.

As expected, the house C6 will purchase more energy from the utility grid during winter season due to the low PV production and high load demand. Fig.5 shows the power flow variation of the grid-connected BIPV after adding 2100 Ah battery size for a typical winter day (1^{st} Jan-2016). As it observed in Fig.5, the load is completely covered from the utility grid almost all the day since the PV production is very low. Only from 11:00 to 17:00, the PV system was able to cover small part of the load.

The daily electricity cost variation before and after adding the battery has been shown in Fig.6 throughout the year. It is observed from Fig.6 that the battery is able to reduce the daily electricity bill from Sep to Oct and from Mar to Aug. This

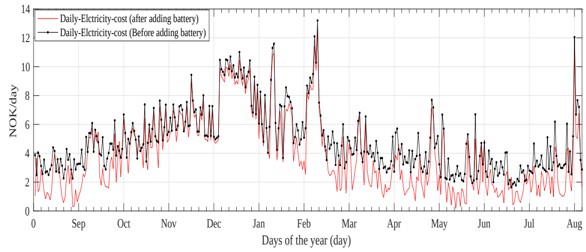


Fig. 6. Daily electricity cost before and after adding the battery

energy bill saving can be more attractive when considering the demand side management (DSM) and future implementation of demand limits on the residential load from the network or the power tariff. During winter season from Nov to Feb, the PV production is low therefore the electricity bill almost remained the same except for the last days of Feb (Fig.6).

The reduction in the annual electricity bill seems to be promising, even though the capital cost of the battery is not included in this study. This work considers the most critical scenario for the house C6 since the flat tariff has been selected without FiT. Moreover, local subsidies and tax reduction maybe guaranteed if the customer is charged with the spot-price tariff mechanism and maybe one-to-one FiT. Analysis on such type pricing mechanism is continuing.

V. Conclusion

This paper reports the estimation of energy storage sizing for grid-connected BIPV on ZEB house in Smart Village Skarpnes in Southern Norway. The real time hourly PV production with real time operational load of C6 house of a year (Sep 2015 to Aug 2016) are used for finding the appropriate lead-acid battery size with minimization of the annual electricity bill. The local electricity tariff (flat rate with out FiT) is used as a critical scenario of C6 since there is no FiT.

Based on the results, it is found that for this typical PV and load profiles of C6 house, the lead-acid battery size should be 25.2 kWh. The operational lifetime of this battery is found as 7 years. More importantly, the annual reduction in the electricity bill after adding the battery is 17.6 %.

This work is continuing with consideration of different types of battery technologies and electrical pricing mechanisms. It will also cover the levelized cost of energy (LCOE) from energy storage systems. Hence, the battery lifetime will be a key factor for calculating the LCOE in the continuation of this study.

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Appendix B

Paper II

Title:	Battery Capacity Estimation for Building-Integrated Photovoltaic System: Design Study for Different Geographical Location(s)
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Battery Capacity Estimation for Building Integrated Photovoltaic System: Design Study for Different Geographical Location(s)

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Abstract

Building Integrated Photovoltaic system (BIPV) with energy storage (ES) can help in reducing the peak demand, improving the power quality and control dispatching of the power. Adding a proper size of battery ES to the grid-connected PV system could reduce the overall investment cost as well as reducing the grid-dependency. A typical battery energy storage capacity is going to be determined by considering the real-time operational (PV production as well as load consumption) data. In this study, real-time operational data of a residential load (C6 house) with BIPV system located Southern Norway as well as institutional load (Teri university) with BIPV located in New Delhi, India are used for estimating the size of the battery energy storage considering the maximum reduction in the annual electricity bill. The estimation of battery capacity is done considering the characteristics of lead-acid battery technology and the electrical pricing mechanism. Based on the results, it is observed that for these typical PV and load profiles, installation a capacity of 2100 Ah lead-acid battery to C6 house will reduce the annual electricity bill by 17.6 % of the bill before installing the battery. Similarly, the annual electricity bill is minimum for a battery capacity of 6000 Ah for Teri university. If this battery capacity (6000 Ah) is added, then the annual electricity bill is reduced by 5500 Indian rupee INR.

Keywords: Building-Integrated Photovoltaic System (BIPV); Energy Storage;

1. Introduction

Energy storage (ES) units are one solution to improve the power supply quality, assure system stability and help to increase the penetration of renewable generators by reducing the fluctuation of their power generation [1], [2]. Moreover, adding a proper size of energy storage (ES) to the grid-connected PV system could reduce the overall investment cost of the combined system through smart and optimized scheduling of the energy flow [3]. ES can also help in demand side management (DSM) as well as for improving system stability [4].

Reference [5] presented a deterministic approach for Energy flow management in grid connected PV systems with storage considering the effect of the aging factor of the battery as cost. In their work, The PV output power has been modeled with input values of irradiation and temperature. In addition, they have used a predictive load profile for 24 hrs. only. In [6, 7], dimensioning of batteries for grid-connected PV system has been analysed. In both studies, real-time operational data of a fixed PV size with real-time operational load have not been considered. In reference [8], tecno-economic analysis is made for the possibilities of battery energy storage for BIPV considering PV production based on the global tilted irradiance.

In this study, the real-time operational load and real-time PV production from two different building-integrated PV system are used for estimating the capacity of battery energy storage for these BIPV. One of these systems is C6 house from the Skarpnes Smart Village in Southern Norway and the other one is at Teri university in New Delhi, India. The real-time operational results of a year for both systems are used for estimating the battery size with maximum reduction in the annual electricity bill of each building. In this work, the electricity tariff is crucial factor for the estimation as well as the characteristics of the battery (lead-acid battery type).

2. Background

2.1. The Smart Village Skarpnes, Agder, Norway

The Smart Village Skarpnes (58.43°N, 8.72°E is located close to the city of Arendal, Southern Norway. The village will have a total of 17 detached single family houses and 3 apartment blocks with 20 units. Five houses are built as nearly zero energy buildings (ZEBs) with roof mounted BIPV systems. Each house is fully instrumented for data collection of electricity production and consumption, grid quality parameters and indoor climate conditions. Large number of ABB electricity meters are installed on the main electrical circuits in the households to evaluate energy consumption patterns and peak power demands as well as measurementt of the PV power generation data [9]. The C6 house is a typical Norwegian house with an area of 154 m^2 located in the Smart Village Skarpnes. The usable area of the roof is 57.43m^2 and it is facing Southwest. The PV panels that have been installed are Sunpower SPR 230NE-BLK-I and covering only 39.9m^2 of the roof area. The system has crystalline silicon PV modules and arranged in 16 strings with a size of 7.36 kWp and tilt angle of 32°.

2.2. Teri University, New Delhi, India

Teri university (28.54°N, 77.14°E) is in New Delhi, India. The university was established in 1998. Recently, the university added a rooftop grid-connected PV system. The main motive for the University to install the solar rooftop system was to bolster its philosophy of practicing what it preaches, besides having something that physically manifests the theory that is taught, thereby providing students an actual feel [10]. This grid-connected system comprises polycrystalline PV modules and SMA inverters. It is expected to generate about 1.5 million units of electricity over 25 years, offsetting 15 % of the grid electricity. It would also result in mitigating around 1400 MT of CO2 emissions. The PV panels that has been installed are 158 modules of JKM305P-72 with a size of 48.19 kWp, tilt angle of 28° and annual production of approx. 65.057 kWh.

2.3. Real-time PV power production and load data for C6 house

The PV system is monitored for the solar irradiation and temperature through sensors placed on the roof to help for collecting data and the performance of the house being zero energy building. The individual load consumption monitored and measured by ABB electricity meters. The power quality measurements as well as power flow from/to grid is measured by Elspec power quality instrument. Fig. 1. shows the real-rime operational PV and load profiles for full year (8760) hrs. starting from Sep-2015 to Aug-2016 [11].

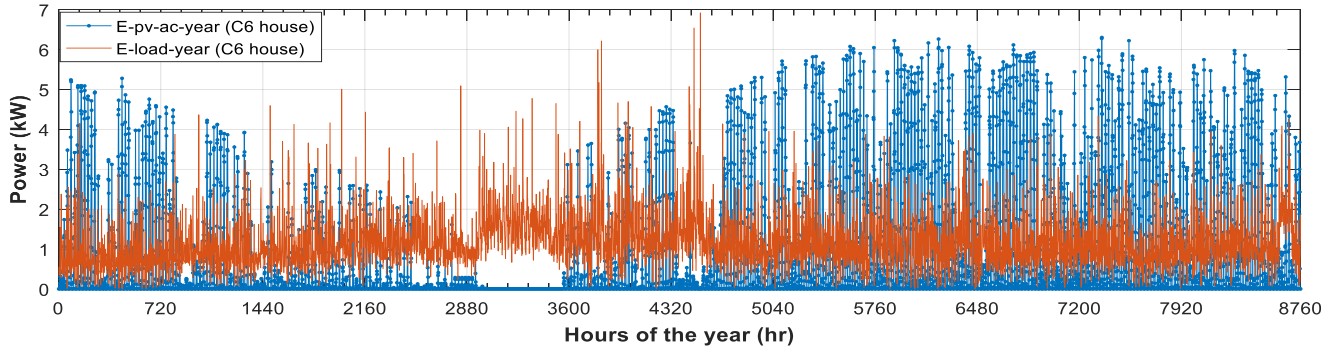

Fig. 1. Hourly PV and load profile for full year, C6 house

2.4. Real-time PV power production and load data for Teri university

The PV system is monitored for the solar irradiation and temperature through Sunny Sensor-box placed on the roof to help for collecting data. Fig. 2. shows the generation profile of the PV system and the load consumption profiles. The load profile represents 50 % of the total load of the university building. Hence, all data profiles are for full year (8760) hrs starting from Mar-2016 to Feb-2017

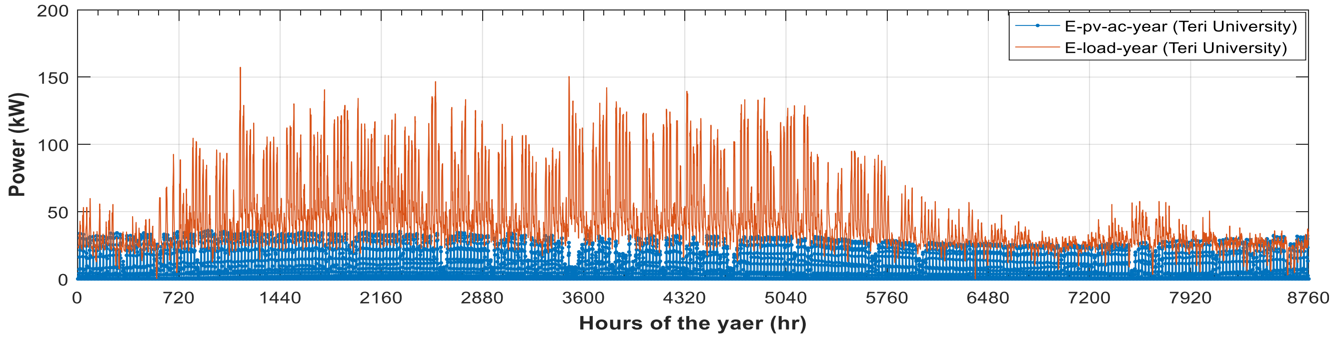

Fig. 2. Hourly PV and load profiles for full year, Teri university

2.5. Electricity tariff for C6 house

According to the Agder Energy Nett [12], the customer can choose between three types of electricity tariffs. These tariffs are: seasonally differentiated tariff, flat rate tariff and ahead/spot-price. In this work, the flat rate tariff is chosen. Table 3 shows the tariff specifications in Norwegian krone (NOK). Additionally, there is an extra charge for NOK/kW-month, which is the one time in the month where the customer has to pay for the max kW consumption. In this work, it is considered that the excess of the PV generated power after covering the domestic load and charging the battery will be supplied to the grid without benefits.

Table 3. Flat-rate electricity tariff for house C6 [12]

Description	Fixed charge NOK/month	Consumption NOK/kWh	Extra NOK/Kw/month
Flat-rate	62.5	0.2515	41 (summer), 125 (winter)

2.6. Electricity tariff for Teri university

As per the power purchase agreement signed with the Renewable Energy Supply Company (RESCO), the solar-tariff is, and will remain, substantially lower than the grid-tariff. The RESCO would also take care of the operation and maintenance of the system [10]. Therefore, the tariff used in this study is 6 Indian rupee (INR) per unit of energy (6 INR/kWh) without FiT. Thus, the excess of power will be supplied to the utility grid without financial benefits.

3. Modelling structure

Batteries in PV-systems should be able to supply reasonably steady power when there is a power outage or when PV system is generating less power output. Table 3 shows the battery characteristics which are used in this study. The battery inverter is taken with efficiency of 90% [7]. In this study the cost of the PV array and capital cost of the battery are not included and they will be considered in future work for estimating the levelized energy cost from the system.

Table 3. Battery characteristics

Battery type	Lead-Acid
Nominal voltage	12 V
Depth of Discharge (DoD)	60 % [13]
(Charge/discharge) efficiency	85 % [14, 15]
Max (Charge/discharge) time	10 hrs
Aging factor (Z)	$3e^{-4}$ [5]
Self-discharge factor (a)	3 % /month [13]

3.1. Estimation strategy

The real-time PV production and real time operational load profile are used with battery wide capacity rage with interval of 50 Ah for minimizing the annual electricity bill. As per the tariffs used, the feed-in-tariff (FiT) is not activated. Thus, the excess of the generated PV power will be supplied to the grid without getting any profits. In this situation, we concern to find the optimum size of the battery which will lead to the maximum reduction in the annual electricity cost considering two main objectives. (I) minimizing the amount of energy supplied to the grid by charging the battery from the left power of PV system after covering the load and (II) Minimizing the cost associated with purchasing electricity from the utility grid by discharging the stored energy when there is a lack of PV generation or during nights. Since there are no defined peak/off peaks hours by the utility, the estimation process first checks in the specific time (δt) interval if the PV generation is higher than the load. Then if the battery is fully charged, the left PV power after covering the load (P_{PV} - P_{load}) will be supplied to the utility grid. Else if the state of charge of the battery is less than the maximum (90%), the left power will be compared with the maximum charge rate of the battery. If the left power (P_{PV} - P_{load}) is higher, then the battery will be charged at maximum rate first and the rest of the left power will be supplied to the grid. Otherwise, The PV left power (P_{PV} - P_{load}) will be used to charge the battery only. Second, the estimation process checks if the load is higher than the generated power of the PV, if the state of charge is at the minimum (40%), then the battery will be kept as its and the lack of power (P_{load} - P_{PV}) will be purchased from the utility. Else if the state of charge of the battery is higher than the minimum, the lack power (P_{load} - P_{PV}) will be compared with the maximum discharge rate of the battery. If lack power is less, then the battery will discharge to cover the lack of power (P_{load} - P_{PV}) without purchasing from the grid. Otherwise, the battery will discharge at the maximum rate towards the lack power (P_{load} - P_{PV}) and the rest will be purchased from the utility grid. For each interval of battery capacity, the model repeats the estimation process and use that battery capacity with the corresponded annual electricity bill and calculate the lifetime of the battery based on the accumulated losses due to the aging factor during discharging process. At the end, the model analyzes the annual electricity bill against each battery capacity interval and indicate the optimum capacity responsible for the minimum annual electricity bill.

4. Results and discussion

In this work, real operational results of C6 house from the Skarpnes Smart Village in Southern Norway and Teri university in New Delhi, India are used for estimating the capacity of battery energy storage. In this study, lead-acid battery (Table 3) is considered for finding the appropriate battery size. The annual electricity bill before connecting any battery energy storage for house C6 is 2651 Norwegian Kroner (NOK) and $1.5401e^6$ Indian rupee (INR) for Teri university as per defined electricity tariffs (Sections 2.5. and 2.6.). The variation of battery capacities from (0-3000) Ah for house C6 and from (0-15000) Ah for Teri university with 50 Ah intervals is considered and hourly power flow is calculated using the methodology explained in Section 3.1. Based on that, the annual electricity bill is calculated and it is given in Fig. 3 and Fig. 4 It is observed that the annual electricity bill is minimum for a battery capacity of

2100 Ah for C6 house (Fig. 3). If this battery capacity (2100 Ah) is added, then the annual electricity bill is reduced by 453 NOK. On the other hand, the annual electricity bill is minimum for a battery capacity of 6000 Ah for Teri university (Fig. 4). If this battery capacity (6000 Ah) is added, then the annual electricity bill is reduced by 5500 INR.

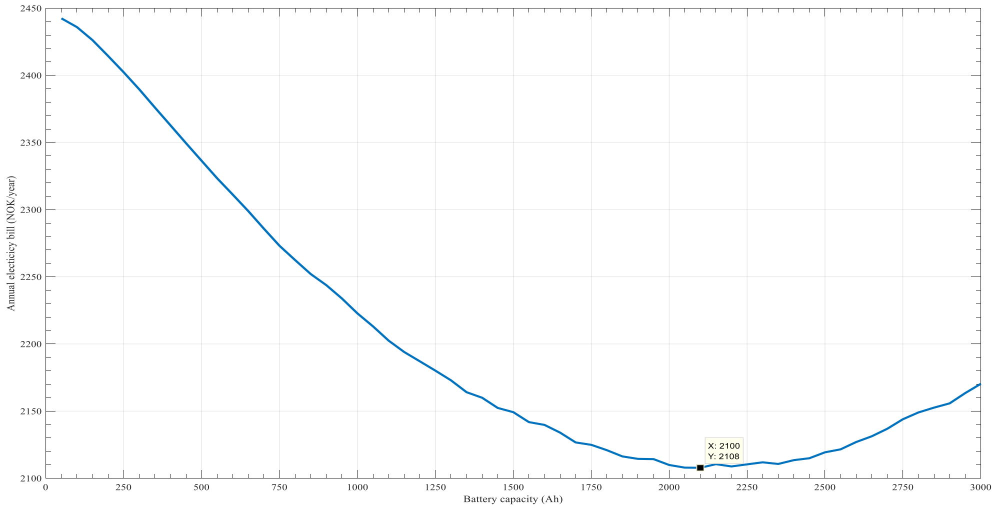

Fig.3. Variation of annual electricity bill with 0-3000 Ah battery capacities, C6 house

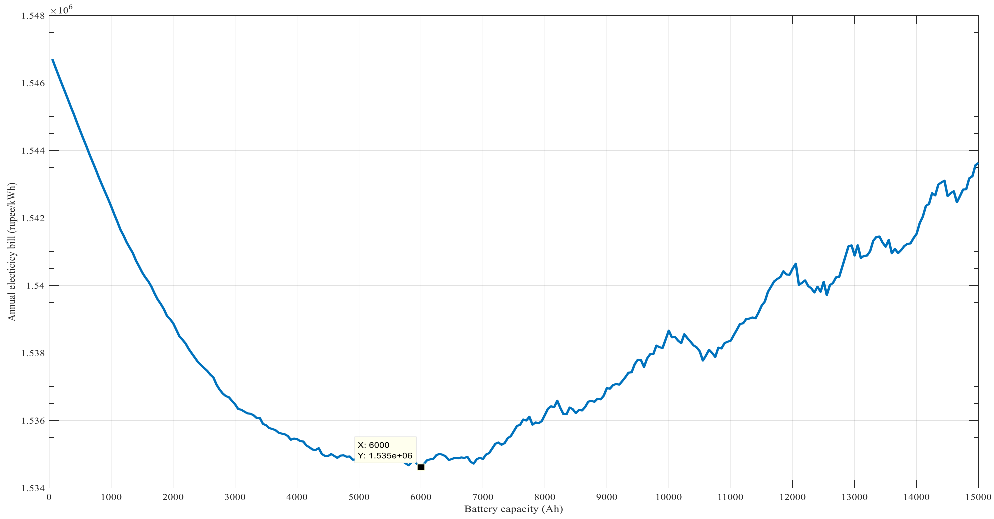

Fig. 4. Variation of annual electricity bill with 0-15000 Ah battery capacities, Teri university

5. Conclusion

In this work, typical battery energy storage capacity is estimated by considering the real-time operational (PV production as well as load consumption) data. In this study, real-time operational data of a residential load (C6 house) with BIPV system located Southern Norway as well as institutional load (Teri university) with BIPV located in New Delhi, India are used for estimating the size of the battery energy storage with consideration in the maximum reduction of the annual electricity bill. The estimation of battery capacity is done considering the characteristics of lead-acid battery technology and the electrical pricing mechanism.

Based on the results, it is observed that for these typical PV and load profiles, installation a capacity of 2100 Ah lead-acid battery to C6 house will reduce the annual electricity bill by 17.6 % of the bill before installing the battery.

Similarly, the annual electricity bill is minimum for a battery capacity of 6000 Ah for Teri university. If this battery capacity (6000 Ah) is added, then the annual electricity bill is reduced by 5500 Indian rupee INR.

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