Tampere University

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Study of integrated solar PV and municipal energy storage-based power generation system in residential user's context.

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ABSTRACT

Title: Study of integrated solar PV & municipal energy storage-based power generation system in residential user's context.

Cases: Finland and Bangladesh

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Now a days, renewable energy technologies bring revolutionary changes in power systems to meetup electricity load demand to the diverse user levels (i.e. industrial, commercial and residential). Moreover, off-grid PV plants have added a new dimension in energy systems specially in residential user level to serve small scale load demand. Integration of energy storage facilities is helping to bring sustainability by ensuring safe operation of energy technologies, stocking and delivering high performance power generation units to the consumer level with less interruption and fault conditions. Additionally, residential buildings are becoming futuristic energy generation facility by integrating such sustainable energy harvesting technologies. In this thesis, our primary objective is to study on Solar PV integrated building energy infrastructure with the integration of municipal energy storage facility to meet sufficient load demand in residential user level and to test the operation of such systems in different conditions. Moreover, generate optimized models and perform economics analysis for the model. Our plant model has been tested and analyzed for multiple countries aspects which covers developed countries like Finland and developing countries like Bangladesh. This thesis will cover all the necessary analysis for kW range off-grid PV and battery energy-based plants and will help to get insights before projects validation and Initialization.

Keywords: PV, BESS, Off-grid, Residential consumers, Optimization, Performance, Economics, Applications, DR, DSM, CEMS.

Originality of the thesis has been checked using Turnitin originality checking service during thesis writing.

PREFACE

This thesis has been written for the unit of electrical energy engineering under the faculty of information technology and communication sciences at the Tampere University, Finland.

I would like to express my gratitude to my supervisors, Seppo Valkealahti and Pertti Järventausta for their enormous support, guidance towards technical writing and inspiration during my master's studies. I also would like to thank those people who helped and supported me to complete important activities and information acquisition process for my thesis work. Moreover, I am thankful to myself and believe that I have tried myself to reflect all my gained knowledge of MSc coursework studies into my thesis work.

I am dedicating my thesis to my parents who helped me to move forward towards the accomplishment of master's studies and for future endeavors as well.

Tampere, 5th November 2019.

Md. Rayhan Sharif.

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LIST OF ABBREVIATIONS

BESS	Battery Energy Storage System
BD	Bangladesh
CEMS	Community Energy Management System
C1, C2, C3	Condition 01, Condition 02, Condition 03
DR	Demand Response
DSM	Demand Side Management
HLT	High Load Type
LLT	Low Load Type
SOC	State of Charge
LCOE	Levelized Cost of Energy
FIN	Finland
NPC	Net Present Cost
MPPT	Maximum Power Point Tracking
P & O	Perturbation and observation
IC	Incremental Conductance
VSI	Voltage Source Inverter
PWM	Pulse Width Modulation
SPWM	Sinusoidal Pulse Width Modulation
PV	Photovoltaics
GHI	Global Horizontal Irradiation
IDCOL	Infrastructure Development Company Limited
GS	Grameen Shakti
SHS	Solar Home Systems
IED	Intelligent Electronic Device.
MCU	Monitoring and Control Unit
EV	Electric Vehicle

1. INTRODUCTION

Solar energy is regarded as one of the widely used renewable energy resources and major source of inexhaustible free energy. Due to huge potentiality and availability all over the world, harvested solar energy can be utilized to generate several forms of usable energies in wide range of application areas. Moreover, research in solar energy sector are increasing rapidly due to associating with global carbon emissions which has been a major global environmental, social and economic issue in recent years. Installing Photovoltaic (PV) technology in large scale for off-grid and grid-connected utilization managed to help reduction in CO2 emissions at the ranges of millions of tons. Additionally, technologies in solar energy have significant impact to mitigate and alleviate issues which is related with energy security, climate change and unemployment etc.

Comparing other technologies to extract energy from renewable sources, solar energy technologies are the simplest and cheapest one. Such advantages in energy generation leads solar energy to get energy policies, investment and supports from both governmental and non-governmental organizations all over the world. According to statistics, solar PV power has the 2nd largest generation capacity after wind power in recent years. In addition, annual average solar irradiance receives over earth surface is around 350 W/m² which varies from region to region. Some regions which is located southern part of the world have the potential of getting solar irradiation to the earth surface between 1400 W/m² to 3000 W/m² (i.e. region like south-east Asia, Africa etc.). On the other hand, northern part of the world has the lower solar irradiation which is between 60 W/m² to 1000 W/m².

Off-grid solar PV power generation technology is becoming popular among other technologies in solar energy utilization because of it’s high in demand potential for both rural and urban areas of the world. electrification through small scale PV technology implementation helping millions of people to be under the umbrella of electricity where grid power is unavailable and hard to reach. on the other hand, PV power is getting popular among the residential consumers which helps them to play an important role to bring change in energy consumption behavior through net metering protocol by energy sharing policy with the national grid in the developing countries. Moreover, PV power is quite helpful to serve energy demand in both peak and off-peak hour which can bring enormous contributions for change in tariff among energy consumers. Potential integration of PV array and BESS technology will be the future changer for overcoming electrification problems and for all customer area including commercial, industrial and residential in socio-economic development through the establishment of sustainable energy infrastructure. [1]

Several events and purposes will be fulfilled by successfully completing the thesis includes:

- Monitor the affects and behavior of off-grid Solar PV-Municipal BESS plant under several operating conditions to constant power flow to the residential load and charging up municipal BESS system (M-BESS) [i.e. changes in irradiance and temperature in the countries like Finland and Bangladesh etc.]
- Operation of Municipal BESS (M-BESS) systems to delivering power for residential load during peak hours and off-peak hours (i.e. peak hours refer to serving energy demand during outages, peak load shaving and shifting; off-peak hours refers to charging up of energy storage facility to be ready the stock and supply the demand side)
- Analysis of residential load demand for designing off-grid PV and M-BESS model for residential sustainable energy consumers.
- Performing simulation, optimization, and economic analysis for off grid PV-Municipal BESS (M-BESS) implementation in microgrid simulator like HOMER PRO.
- Dynamic application areas analysis for such kind of model including smart EV charging (BESS to EV), Demand Response and Demand side management, Smart ES charging (EV to BESS) etc. for developed countries like Finland. On the other hand, load shedding eradication through off-grid PV & municipal BESS plant, off-grid energy sharing to national grid through net metering protocols and community energy management during peak hours and off-peak hours etc. for developing countries context like Bangladesh.

Figure 1 shows the pie chart representation of our thesis research objective.

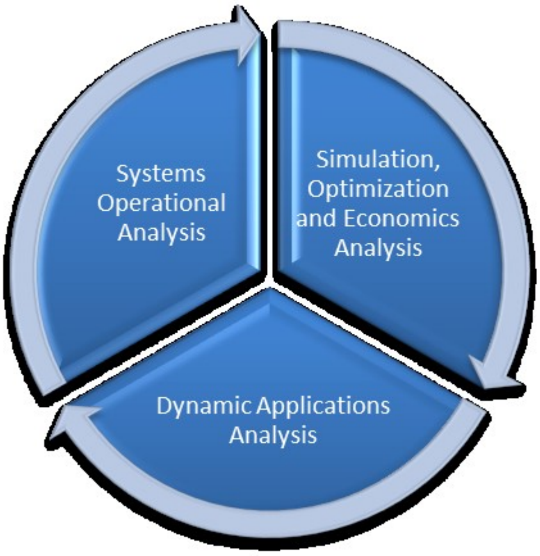


Figure 1: Pie chart representation of Research Objective.

2. BACKGROUND OF SOLAR PHOTOVOLTAICS-ENERGY STORAGE TECHNOLOGY

2.1 Overview of Solar PV power plants

Solar photovoltaic (PV) power system is a technology which is composed of one or more solar panels what converts sunlight (i.e. solar radiation) into direct electricity via an electronic process that occurs naturally in certain types of material, called semiconductors. Electrons in these materials are freed by solar energy and can be induced to travel through an electrical circuit, powering electrical devices or sending electricity to the grid [2] [3]. Such system is comprised of several electrical or mechanical equipment including charge controller, inverter and energy storage device etc. PV systems can vary greatly in size from rooftop or portable systems to massive utility-scale generation plants. Main objective of solar PV plant is to convert solar energy (i.e. solar radiation) from the sun to direct current (DC) and store it in backup storage facility (i.e. electrical energy storage devices). Moreover, DC current can be transformed to AC current using power conversion technologies (i.e. DC-AC power converters) so that it can be supplied to electrical utility grid and AC or DC loads. [4]

Other important components of a solar PV plants include grounding and mounting equipment's (i.e. racks, clamps etc.), combiner box, surge protection, electric meters and instruments, disconnects (i.e. array DC disconnects, inverter AC and DC disconnects, battery disconnects) etc. [5]

2.1.1: Types of Solar Photovoltaic (PV) Power plants:

Based on their functionality and operational requirements, Solar PV power plant are classified in three types:

Grid connected or on-grid PV plant offers parallel operation with the interconnected electric utility grid to serve AC loads with the help of distribution panels. Main components include PV arrays, inverters (i.e. DC-AC converter), distribution panels and electric utilities grid [6]. On-Grid PV systems only generate power when the utility power grid is available, and they must connect to the grid to function [7]. Figure 2.1 shows on-grid model of PV plant.

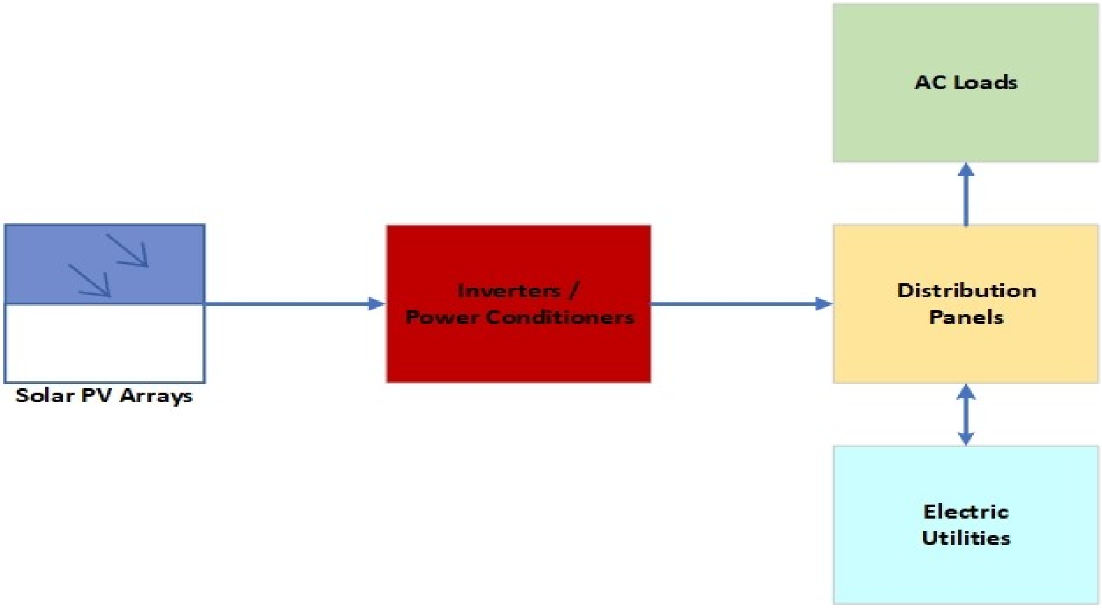


Figure 2.1: Block diagram of On-grid PV [6]

Stand-Alone or off-grid PV plant has been designed to provide electric power without the help of electric utility grid and supplies load areas such as AC and DC loads. This kind of PV plants are consisting of PV arrays, charge controllers, battery energy storage system (BESS) and inverters etc [6]. Such plants allow us to store solar power in BESS for use when the power grid goes down or off-grid scenarios (i.e. not under the grid operation) [7]. Moreover, these plants are sometimes connected with backup generation facilities (i.e. diesel generator /renewable fueled generators). Figure 2.2 shows the off-grid model of PV plant.

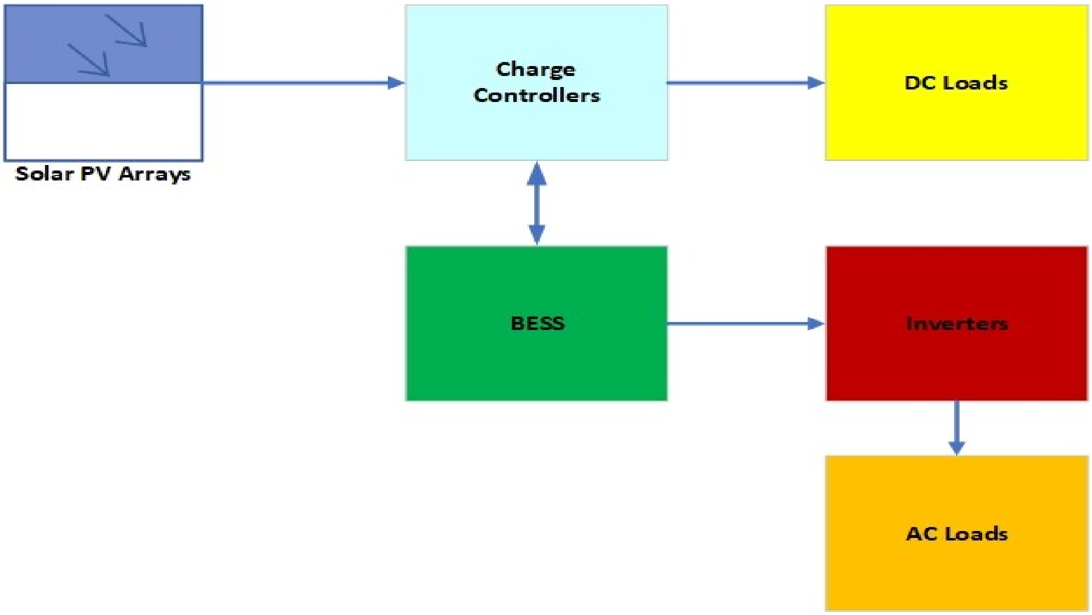


Figure 2.2: Block diagram of Off-grid PV plant [6]

Hybrid PV systems allow solar power to store in the batteries for use when the power grid goes down or off-grid scenarios (i.e. not under the grid operation) [7]. These kind of system uses other energy sources in parallel to the PV array to supply load side. Energy sources include in the hybrid system are wind turbine, hydro turbine, diesel generators or fuel cells etc. Sometimes grid power and battery storage are integrated with the system [8]. Figure 2.3 shows hybrid model of PV plant.

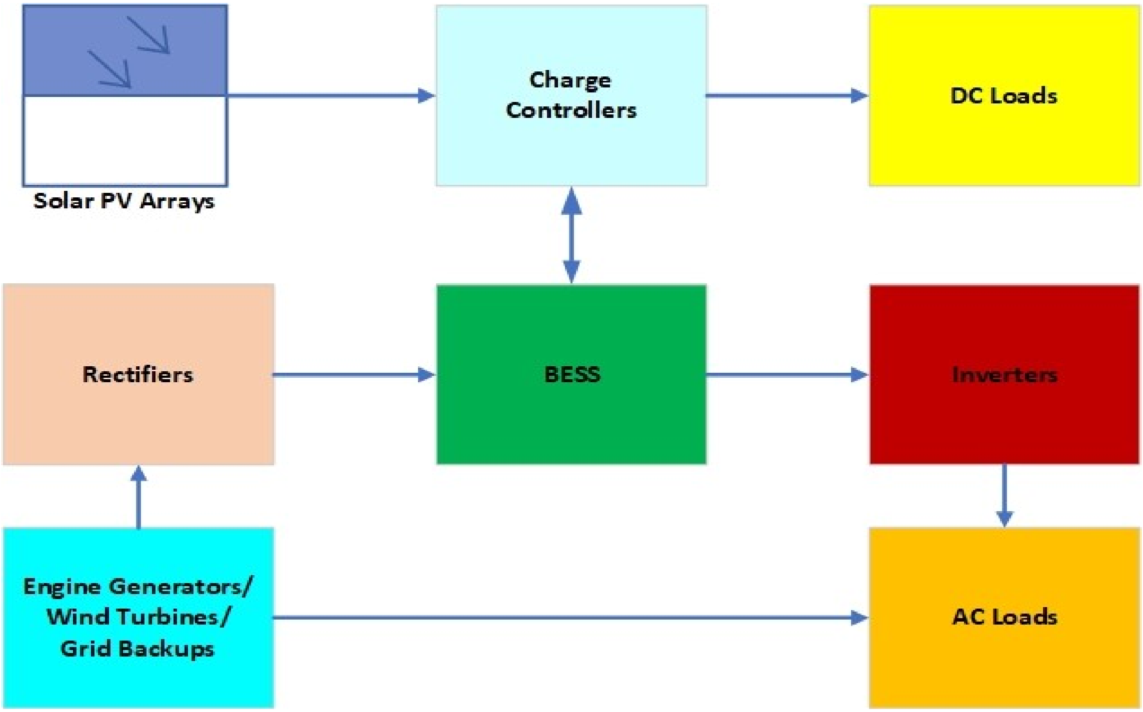


Figure 2.3: Block diagram of Hybrid PV plant [6].

2.1.2: Components of off-grid solar PV power plants:

PV panel also known as photovoltaic panel is a type of electrical generator which captures energy from the solar radiation and convert it into electricity. PV panel consists of small solar cells that are connected with each other. Moreover, PV Cells are developed from semiconducting material, silicone being the most commonly used. Besides, Cells are usually very small but when combined together to form solar panels and solar arrays, they can be very efficient. When the sun shines over the cells, an electric field is created. The more the sunlight is available the more electric energy is produced. Nevertheless, the cells do not need direct sunlight to work, and they can still produce electricity on a cloudy day. [9]

Now a days, PV panels are available in various shapes and sizes and can be easily mounted on top of an existing roof. [9]

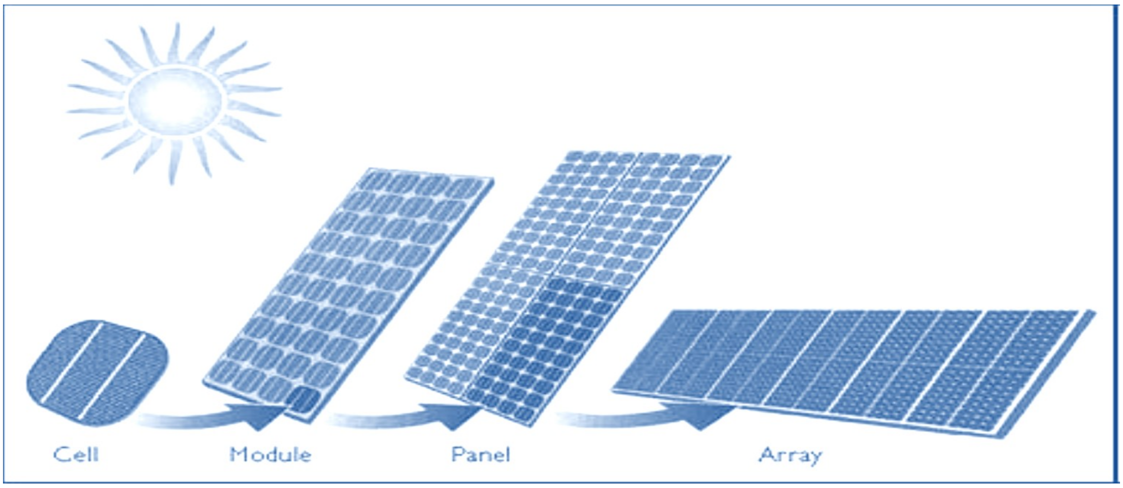


Figure 2.4: Structure of Solar panel. [5]

Based on the availability on the market today, three types of solar panel technology are available today. Those are:

Monocrystalline solar cells are cut from a single, pure crystal of silicon which is cylindrical in shape. Cells of monocrystalline PV is black in color because of how light interacts with the pure silicon crystal. Moreover, to optimize performance and lower costs of a single monocrystalline solar cell, four sides are cut out of the cylindrical ingots to make silicon wafers, which is what gives monocrystalline solar panels their characteristic look. [10] Monocrystalline solar panels have the highest efficiency rates which is typically 15-20%. Other feature of monocrystalline panels includes space efficient and greater lifetime. [11]

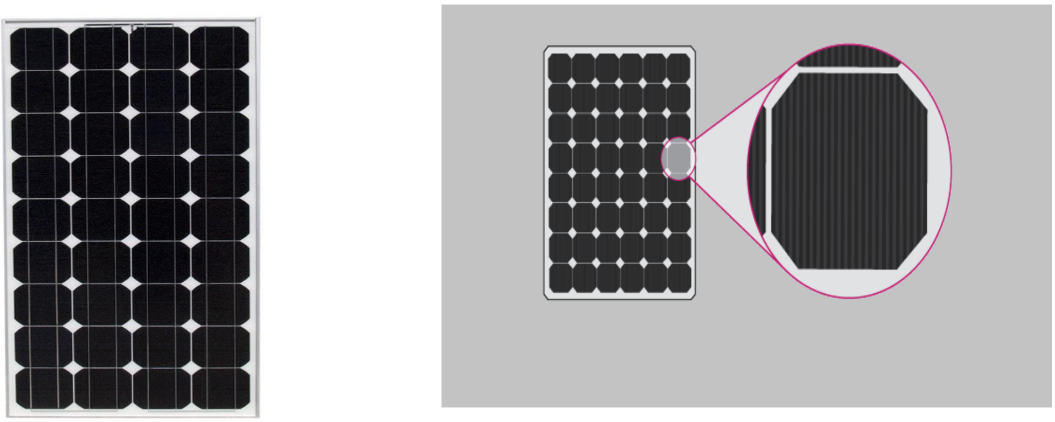


Figure 2.5: Monocrystalline Photovoltaic (PV) panel. [10]

Polycrystalline solar cells are composed of fragments of silicon crystals that are melted together in a mold before being cut into wafers. Reason behind bluish hue of polycrystalline panel are due to light reflecting off the silicon fragments in the cell in a different way than it reflects off a pure monocrystalline silicon wafer. [10] Moreover, polycrystalline solar panels tend to have slightly lower heat tolerance than monocrystalline solar panels. [11]

Typical efficiency of polycrystalline solar panels is between 13-16%. Key feature of polycrystalline panel includes simpler (i.e the amount of waste silicon is less) and cost efficient. [11]

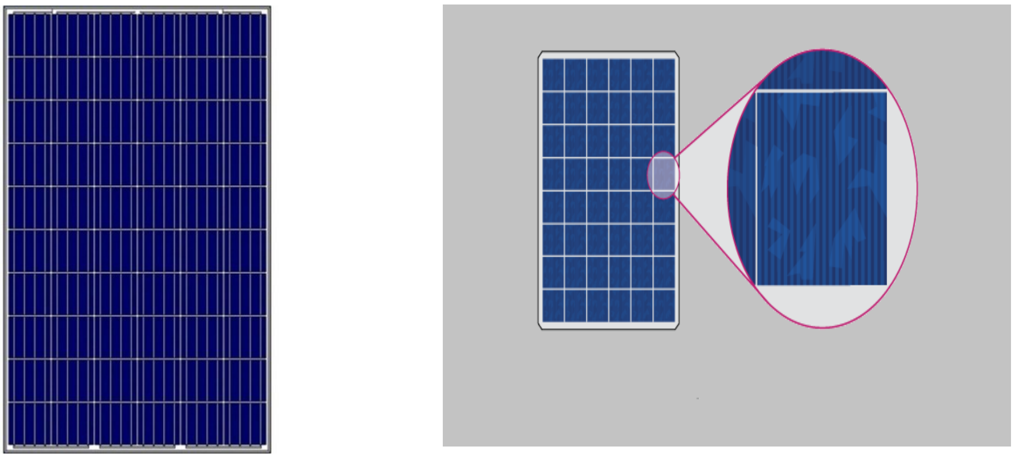


Figure 2.6: Polycrystalline Photovoltaic (PV) panel. [10]

Thin film solar panels are made from a variety of materials where most prevalent type of material is cadmium telluride (CdTe). During manufacturing process of this type of panels, a layer of CdTe is placed between transparent conducting layers that help capture sunlight. Moreover, this type of thin-film technology also has a glass layer on the top for protection. Other possible types of materials from which thin film panels are made includes amorphous silicon (a-Si) and Copper Indium Gallium Selenide (CIGS). In case of panel colouring, thin-film solar panels can come in both blue and black hues, depending on what they're made from. [10]

Depending on the technology, thin-film module prototypes have reached efficiencies between 7–13% and production modules operate at about 9%. Moreover, it can be estimated that, future module efficiencies are expected to climb close to the about 10–16%. [11]

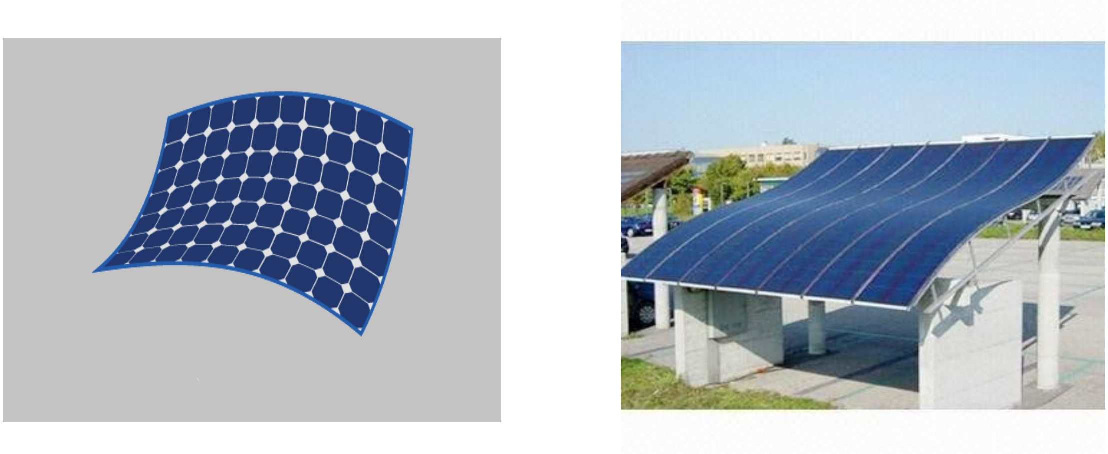


Figure 2.7: Thin Film Photovoltaic (PV) Panel. [10]

Charge controller is a power electronic device, which is used to regulate the charge transfer and prevent the battery from being excessively charged and discharged. The battery storage in a PV system should be properly controlled to avoid catastrophic operating conditions like overcharging or frequent deep discharging. Storage batteries account for most PV system failures and contribute significantly to both the initial and the eventual replacement costs. [12]

For off-grid solar PV systems, solar charge controllers act as a gate to the battery storage system, making sure damage does not occur from overloading it and only necessary in few specific cases. [13]

Charge controllers can be classified in different types based on ranges of cost and capability. Most common types of solar charge controllers for off-grid solar PV systems are:

Pulse width modulation (PWM) charge controllers are solid-state controllers, which are based on more advance three step-charging algorithms than the 1 or 2-stage charge controller. It uses a semiconductor-switching element between the PV array and the battery, which is switched ON/OFF by PWM at a variable frequency determined by the variable duty cycle to maintain the battery at or very close to the voltage regulation set point. This type of trickle charging is ideal for the PV arrays where excess energy is produced for days and weeks and very little of it is consumed. PWM charge controller maintains battery capacities of 90-95% compared to 55-60% of ON/OFF regulated state of the charge and has the ability to recover lost battery capacity. [14]

Advantage of PWM charge controllers includes durable feature with passive heat sink cooling and inexpensive (i.e. good low-cost solution) for small systems when PV panel's cell temperature is moderate to high (i.e. between 45°C to 75°C). Drawback of PWM charge controller is solar input nominal voltage must match the battery bank nominal voltage for the solar systems where PWM controller is used. [14] [15]

Figure 2.8: PWM solar charge controller. (courtesy: sunstore.co.uk)

Below figure illustrates the schematic diagram of PWM charge controller, which is connected with PV array.

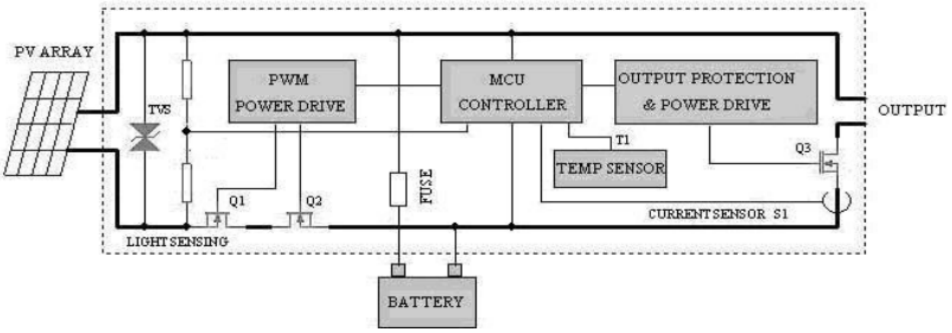


Figure 2.9: Schematic of PV connected PWM charge controller. [16]

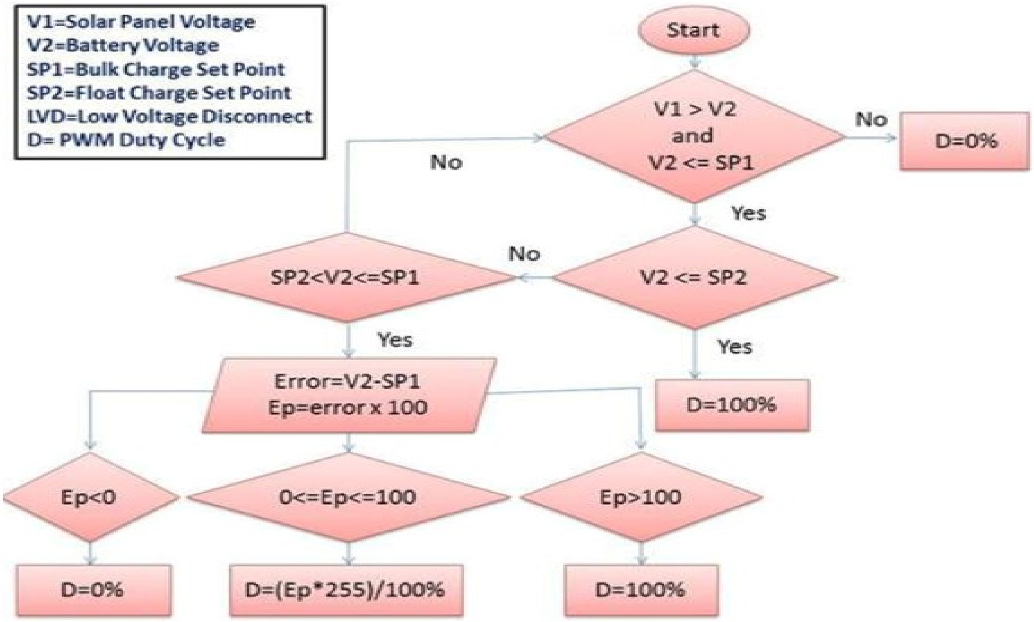


Figure 2.10: Charging algorithm of PWM charge controller. [17]

In PWM charge controller, PWM algorithm is used to control electrical power to a load using square wave pulses at some determined duty cycle. Moreover, Proper control of pulse-width modulation ensures efficiency and accuracy in solar power inverter control, voltage regulation from PV panel and delivering power to the electrical load. [18]

Maximum Power Point Tracking (MPPT) solar charge controller is the charge controller embedded with MPPT algorithm to maximize the amount of current going into the battery from PV module. Typically, MPPT is DC to DC converter which operates by taking DC input from PV module, changing it to AC and converting it back to a different DC voltage and current to exactly match the PV module to the battery.

In MPPT charge controller, Maximum power point tracking (MPPT) algorithm is implemented in photovoltaic (PV) inverters to continuously adjust the impedance seen by the solar array to keep the PV system operating at, or close to, the peak power point of the PV panel under varying conditions, like changing solar irradiance, temperature, and load. Moreover, this algorithms account for factors such as variable irradiance (sunlight) and temperature to ensure that the PV system generates maximum power at all times. MPPT algorithm can be applied to both buck and boost converter depending on system design. Normally, for battery system voltage is equal or less than 48 V, buck converter is useful. On the other hand, if battery system voltage is greater than 48 V, boost converter should be chosen.

MPPTs are the most effective in the weather conditions like cold winter, cloudy and hazy days where it helps to extracts maximum power from the PV module. Moreover, MPPTs can extract more current and charge the battery if the state of charge (SOC) in the battery is lowers during deeply discharged period of the battery storage.

Some advantage of MPPT charge controllers include maximum power extraction at higher efficiency level, integrity and usability in multiple energy sources, reduced complexity in output of the system and brings flexibility in system growth. On the other hand, some disadvantage of such controllers is more expensive than PWM controllers, larger in physical size and complex algorithm for implementation in PV and battery integrated systems.

Most suitable application of MPPT solar charge controllers are off-grid solar power systems like standalone solar power system, solar home system and solar water pump system. [19] [20] [21]

Figure 2.11: MPPT solar charge controller (courtesy: Victron energy USA)

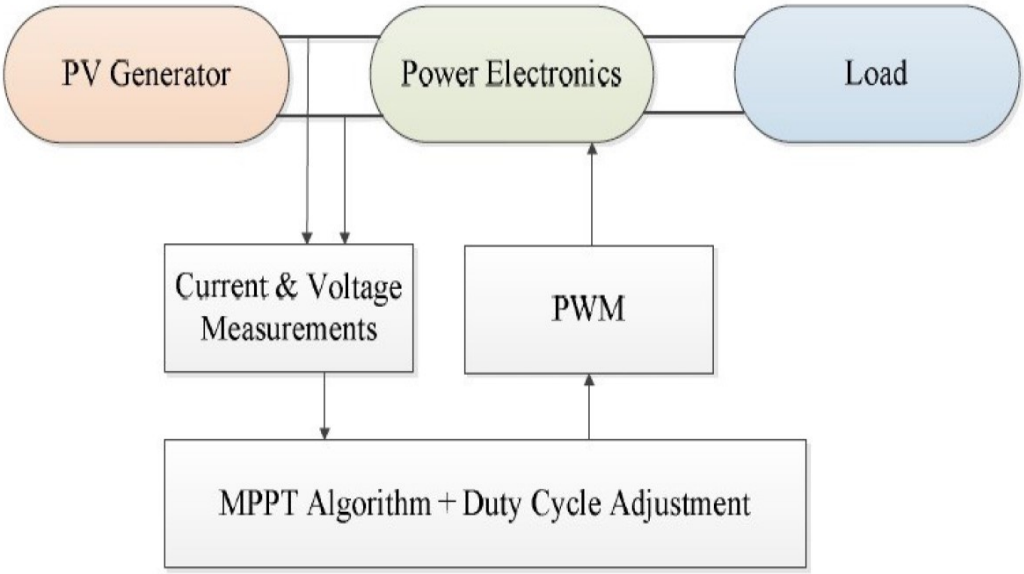


Figure 2.12: Block diagram of PV connected MPPT charge controlling technique. [20]

Two most common types of algorithm used in Perturbation and Observation (P&O) and Incremental Conductance (IC).

P&O algorithm perturbs the operating voltage to ensure maximum power. In this algorithm perturbation is provided to the PV module or the array voltage. The PV module voltage is increased or decreased to check whether the power is increased or decreased. When an increase in voltage leads to an increase in power, this means the operating point of the PV module is on the left of the MPP hence further perturbation is required towards the right to reach MPP. Conversely, if an increase in voltage leads to a decrease in power, this means the operating point of the PV module is on the right of the MPP and hence further perturbation towards the left is required to reach MPP.

The P&O algorithm compares the previously delivered power with the one after disturbance by periodically varying the voltage of the panel with a minuscule incremental step to reduce the oscillation around the MPP or the desired step. Additionally, this algorithm has a wide application in commercial systems due to its simplicity and involvement of few measured parameters. Figure 2.13 shows flow diagram of P& O algorithm. [22] [23]

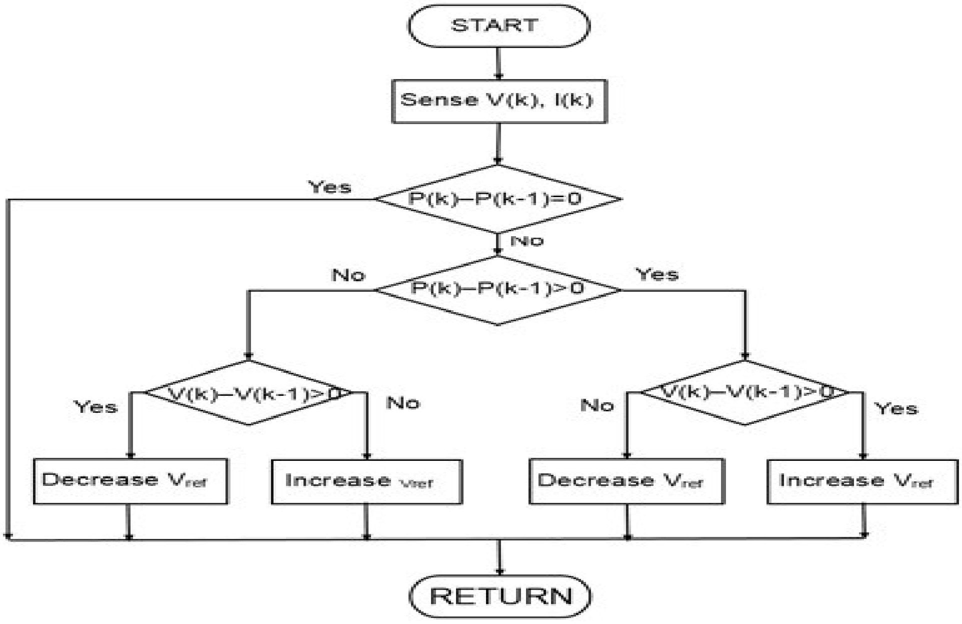


Figure 2.13: Flow chart of Perturbation and observation (P&O) algorithm. [23]

Incremental Conductance (IC) algorithm compares the incremental conductance to the instantaneous conductance in a PV system. Depending on the result, it increases or decreases the voltage until the maximum power point (MPP) is reached. This method was developed to overcome some drawbacks of P&O algorithm and was based on an observation of P-V characteristics curve. This algorithm can determine that the MPPT has reached the MPP and stop perturbing the operating point. If this condition is not met, the direction in which the MPPT operating point must be perturbed can be calculated using the relationship between dI/dV and –I/V. This relationship is derived from the fact that dP/dV is negative when the MPPT is to the right of the MPP and positive when it is to the left of the MPP.

Some advantages of IC algorithm over P&O algorithm is that it can determine when the MPPT has reached the MPP, where P&O oscillates around the MPP. Moreover, incremental conductance can track rapidly increasing and decreasing irradiance conditions with higher accuracy than P&O. The equation of IC method is:

$$\frac{dp}{dV} = \frac{d(V.I)}{dV} = I\frac{dV}{dV} + V\frac{dI}{dV}$$

$$= I + V\frac{dI}{dV}$$

MPP is when $\frac{dp}{dV} = 0$ and;

$$\frac{dI}{dV} = -\frac{I}{V}$$

$\frac{dp}{dV}$>0 then Vp<Vmpp

$\frac{dp}{dV}$=0 then Vp=Vmpp

$\frac{dp}{dV}$<0 then Vp>Vmpp

The MPPT regulates the PWM control signal of the dc – to – dc boost converter until the condition: (dI/dV) + (I/V) = 0 is satisfied. In this method the peak power of the module lies at above 98% of its incremental conductance.

IC based MPPT algorithm offers several advantages such as good tracking efficiency, response in high and well control for extracted power etc. Flowchart of IC algorithm is stated below. Figure 2.14 shows flow diagram of IC algorithm [24] [25]

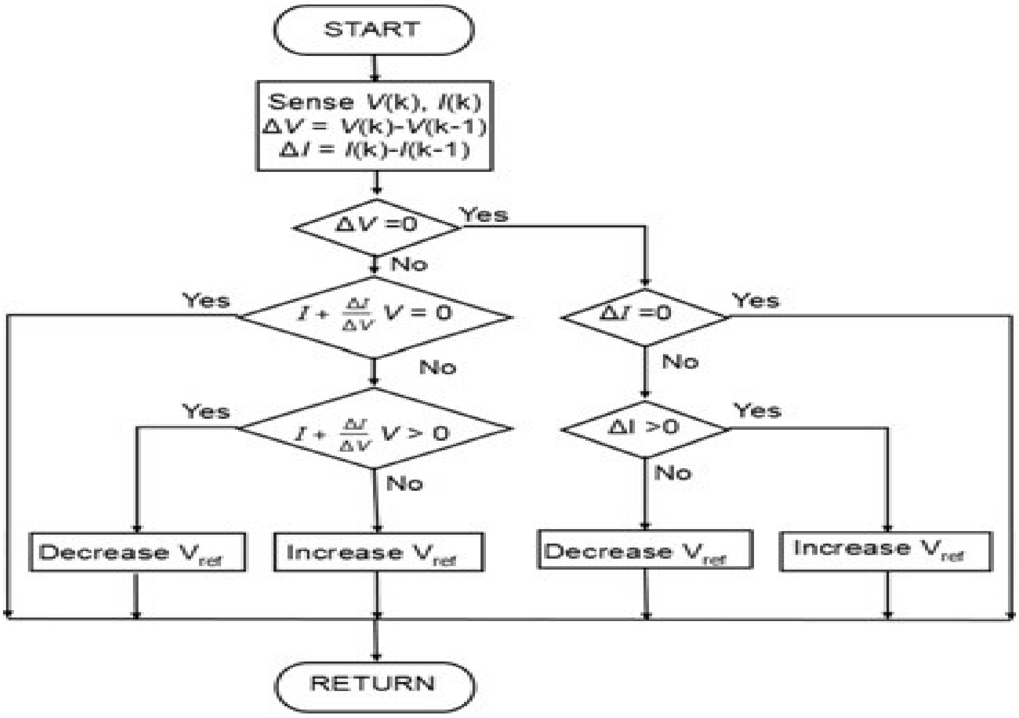


Figure 2.14: Flowchart of Incremental Conductance (IC) algorithm. [24]

Now, we will discuss about DC-AC converter technology used in PV-BESS plant.

DC-AC power inverters in solar system are designed to perform the important function of converting DC voltage to AC voltage. They are used in DC-coupled systems to supply an AC load and in AC–DC systems to facilitate the flow of power from the DC bus to the AC bus. [26]

In terms of the types of power supply, inverters are categorized as voltage-source inverter and current-source inverter. A voltage-source inverter utilizes a DC voltage as the supply, and the Thévenin equivalent resistance of the voltage source is ideally zero. Voltage-source inverters are the second most common power converters, whose DC input voltage can be obtained either from a rectifier or a cell battery or a photovoltaics. On the other hand, a current-source inverter uses a DC current as the supply, and the Thévenin equivalent resistance of the current source is regarded ideally as infinity. [27]

Voltage source inverters are usually used in off-grid applications. They can be single phase or three phases. There are three switching techniques commonly used: square wave, quasi-square wave, and pulse width modulation. Square-wave or modified square-wave inverters can supply power tools, resistive heaters, or incandescent lights, which do not require a high-quality sine wave for reliable and efficient operation.

However, many household appliances require low distortion sinusoidal waveforms. The use of true sine-wave inverters is recommended for remote area power systems. Pulse width modulated (PWM) switching is generally used for obtaining sinusoidal output from the inverters. [28]
Types of inverters used in PV systems are single-phase voltage-source inverters (VSI), three-phase bridge voltage-source inverters and PWM Inverters (i.e. Sinusoidal PWM-SPWM).

Here, we will discuss about three phase VSI technology used in our PV-BESS plant.

Three-phase bridge voltage-source inverters have been widely utilized for AC electric drive and general-purpose AC supplies. The three phase VSI consist of the three inverter legs i.e. three half bridge inverters where three phase voltage is generated by taking the output from each inverter leg.

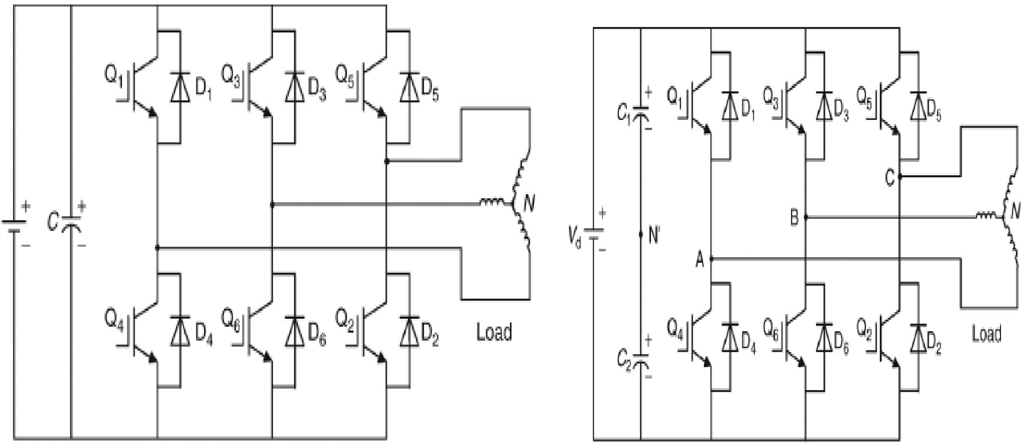


Figure 2.15: Three phase VSI configuration with single and double capacitor-front end

In three phase VSI, there are six switches Q1–Q6, which constitute three bridge legs including the left-hand bridge leg (Q1 and Q4), middle bridge leg (Q3 and Q6), and right-hand bridge leg (Q5 and Q2). The switches at each bridge leg (or at each phase) cannot conduct at the same time but are switched on in turn with a 180° condition period for each. The switches at the three bridge legs (or three phases) have 120° differences at the conduction time. Specifically, the condition time of Q3 delays that of Q1 by 120°, while the trigger time of Q5 has 120° of delay compared with that of Q3. Similar things happen to Q4, Q6, and Q2. In DC side of the inverter, there is one or two capacitors which are connected parallelly to the DC supply. [27] [29]

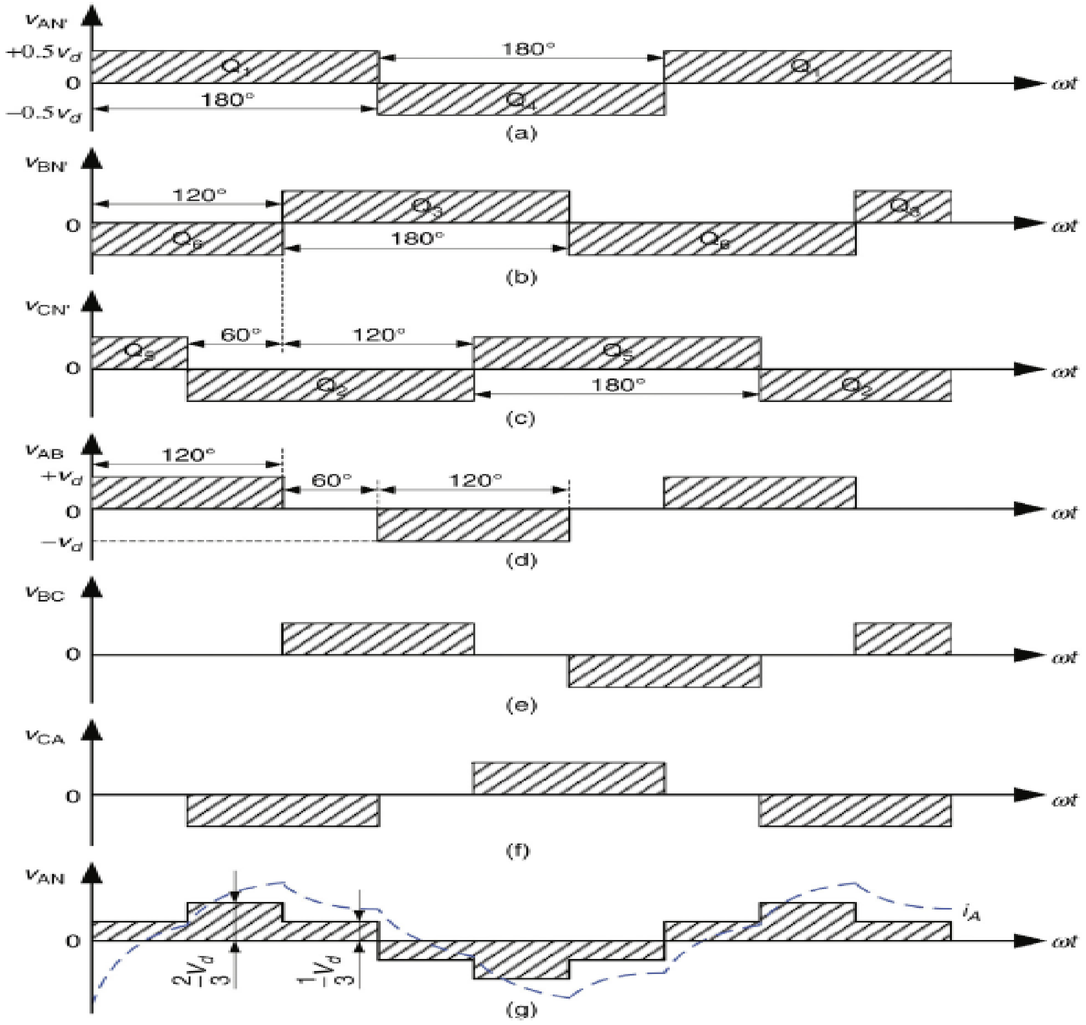


Figure 2.16: Output voltage waveform of three phase VSI at square wave mode.

From figure 2.16 , In 180° mode of conduction; the load voltages are vAN=Vd/3, vBN=-2Vd/3 and vCN=Vd/3. Besides, the line voltages are vAB=vAN-vBN=Vd, vBC=vBN-vCN=-Vd and vCA=vCN-vAN=0 respectively. [30]

In 120° mode of conduction; phase voltages are equal to line voltages. So, line voltages are vAB=Vd, vBC=-Vd/2 and vCA=-Vd/2 respectively. [30]

Now we will discuss DC-DC converter technologies used in PV-BESS plant. Those can be classified as buck converter, boost converter and buck-boost converter.

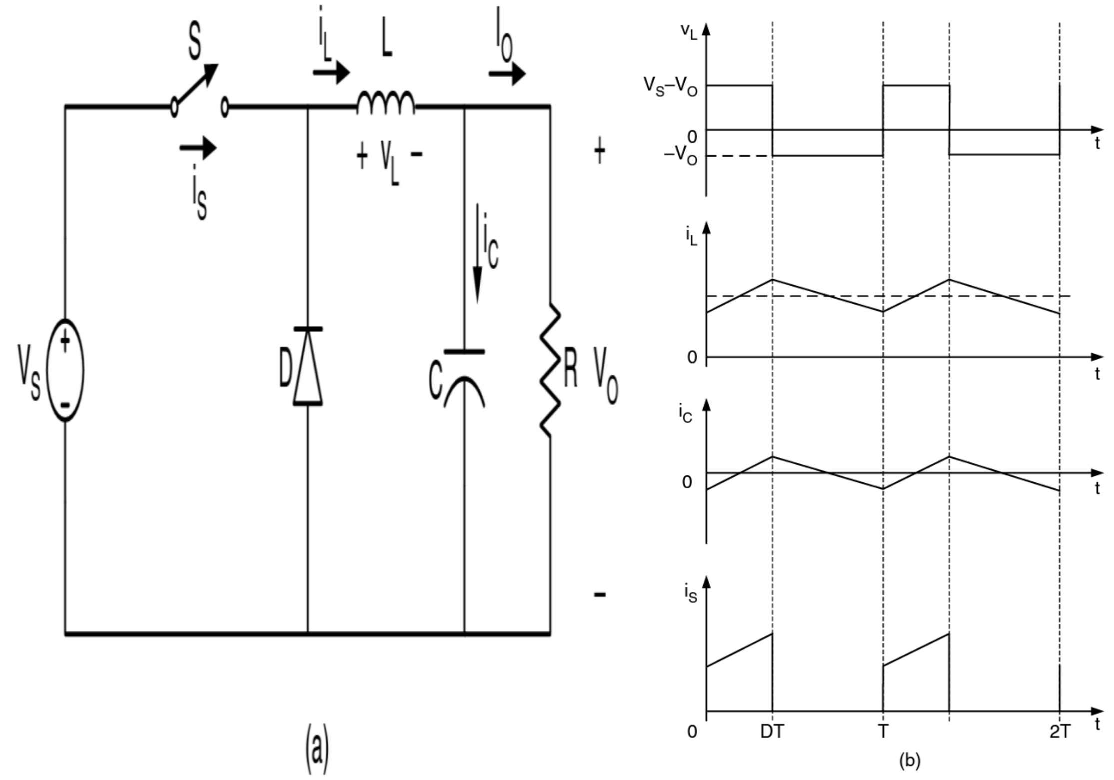
Buck converter or step-down converter is a type of DC-DC converter which reduces the input voltage to get desired output voltage. During CCM mode of operation; the inverter current is above zero all the time then the Converter operates in two switching states. During ON state, the diode is reverse biased and input energy is supplied to charge inductor. On the other hand, during OFF state, the diode is forward biased and inductor current discharge through the diode as shown in figure 2.17.

The transfer function of the buck converter is the ratio of output voltage to the input voltage and written as:

$$D = \frac{Vo}{Vs}$$

Where, Vo is output voltage, Vs is input voltage and D is duty cycle.

The circuit diagram and the output waveforms of the buck converter are shown in figure 2.17. [31]



(a) (b)

Figure 2.17: Buck Converter (a) schematic and (b) output waveforms.

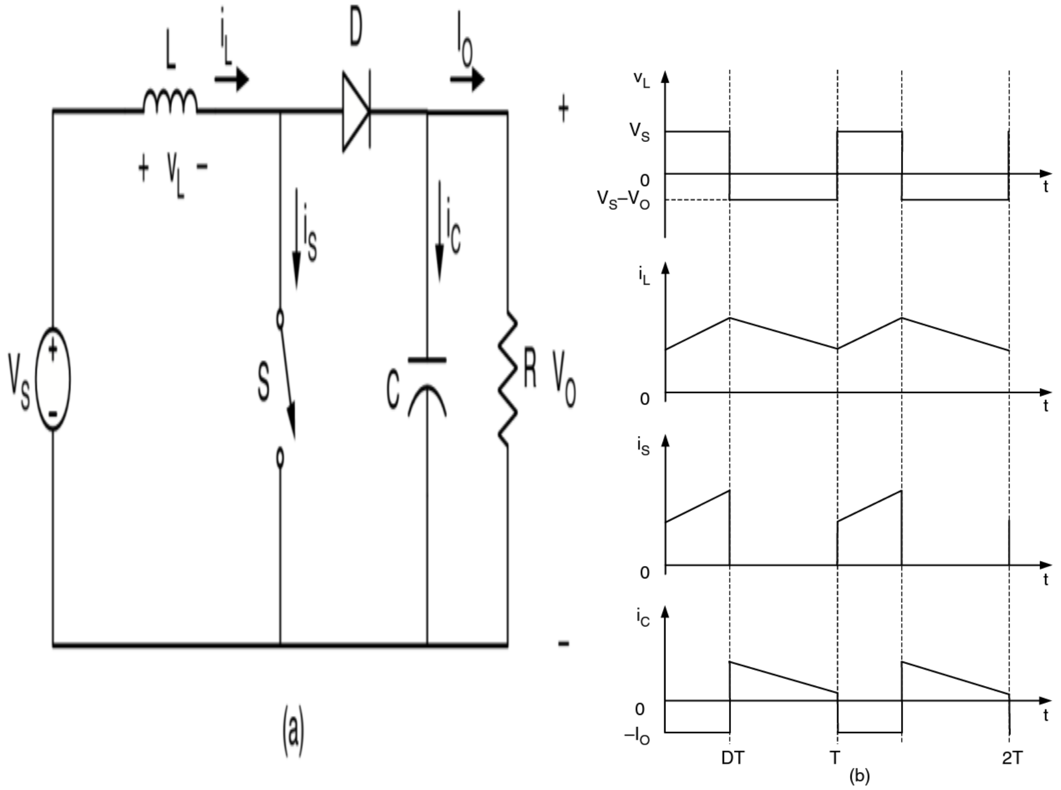
Boost converter or step-up converter DC-DC chopper or converter increases the input voltage to get desired output voltage. Like buck converter, boost converter also operates in two states. During ON state switching, the diode is off and inductor current increases linearly. During OFF state switching, the stored energy in the inductor, as well as the power from input supplies the energy to load.

The transfer function is the ratio of output voltage to the input voltage, it can be given as:

$$\frac{1}{1-D} = \frac{V_O}{V_s}$$

Where Vo is output voltage, Vs is input voltage and D is duty cycle.

The circuit diagram of boost converter and current and voltage waveform are shown in figure 2.18. [31]



(a) (b)

Figure 2.18: Boost Converter (a) schematic and (b) output waveforms.

Buck-boost converter is a kind of converter which perform dual operation of DC-DC buck and boost converters. In this type of converter, cascade arrangement of buck and boost converter enables greater flexibility during operation. Moreover, such converter has the feature of step up and step down the voltage for any given input. Buck-boost converter also incorporates dual operation of inverting and non-inverting mode. In non-inverting mode, the voltage obtained at the output will be of the opposite polarity to that of the input voltage.

The transfer function of buck-boost converter is given below:

$$\frac{Vo}{Vs} = \frac{D}{1 - D}$$

The circuit diagram and output waveform are shown in figure 2.19. [31]

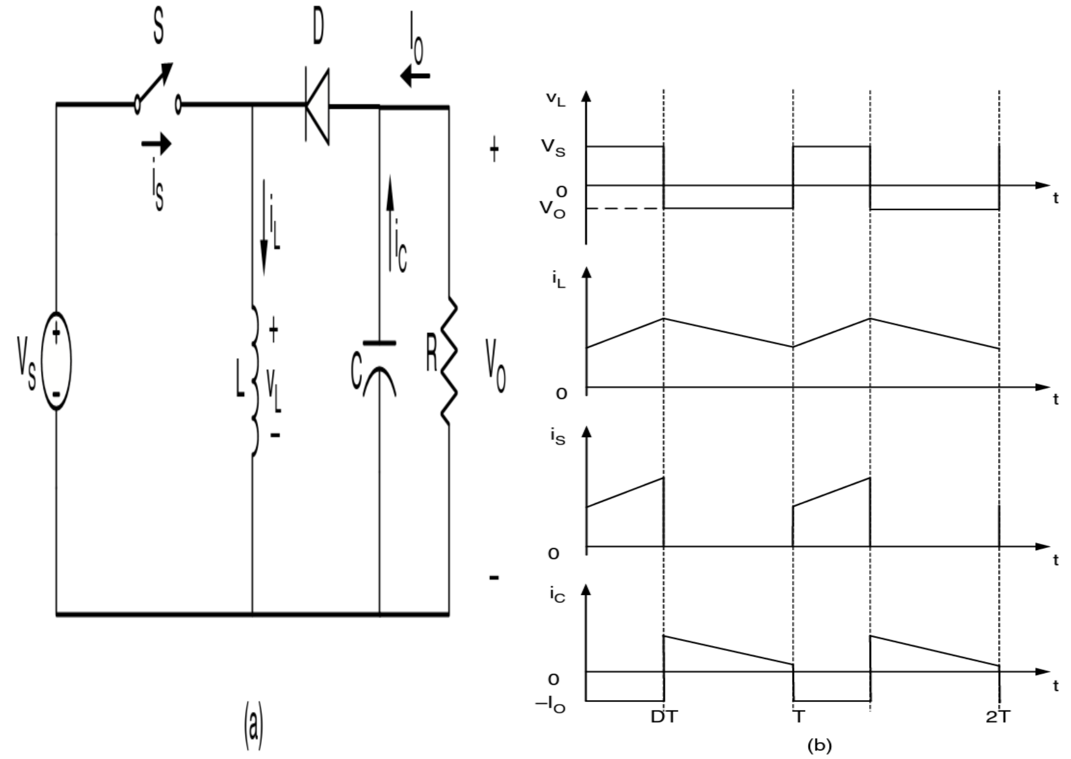


Figure 2.19: Buck- Boost Converter (a) schematic and (b) output waveforms.

Now we will discuss about the battery technology used in PV plants.

Battery Energy Storage System (BESS) is a kind of energy storage technology that can generate electricity with specified level of voltage by using electrochemical reactions on cells of system. Each cell of BESS includes two electrodes, anode and cathode, with a solid, liquid or ropy state electrolytes. [32]

It is a technology which enables the transition to a sustainable and secure energy system based on renewable energy sources with reduced greenhouse gas emissions and enhanced energy independence for the users of electricity. Moreover, BESS can store energy from on-peak renewable energy and release it when it is more needed, in central, de-centralized and off-grid situations. In addition, BESS can also offer grid support services like voltage control and frequency regulation to maintaining grid stability and flexibility. [33]

BESS can be deployed at all levels of the electricity grid including generation level, transmission & distribution level and household level. [33]

Based on battery chemistry, BESS can be classified as several types, but most common types of BESS are using in the generation and household levels are Lead acid and Lithium Ion batteries.

Lead-acid battery (Invented by French physicist Gaston Plante in 1859) is best known as the de facto rechargeable energy storage solution of choice for most cars and vehicle technologies. Moreover, it is a suitable option for household level users to use stored energy from it as a source of backup storage (because of having higher cell voltage and lower cost). In this kind of battery chemistry, battery uses sponge lead and lead peroxide for the conversion of the chemical energy into electrical power. [35] [36]

Some advantages of lead-acid batteries include good performance (i.e. fast response time, approximately 0.3% daily self-charge rate) at high and low temperature, high specific power, capable of high discharge currents, low cost (i.e. 50-600$/KWh) and simple construction. [32] [34]

Disadvantage of lead acid batteries are low specific energy, slow charging (i.e. fully saturated charge takes 14-16 hours), watering requirement for flooded type batteries, adverse environmental impact (i.e. both electrolyte and lead content can lead to environmental damage, which is not environmentally friendly). Figure 2.20 shows the lead acid battery and its internal chemistry (i.e. electrodes and electrolyte. [32] [34]

Figure 2.20: Lead Acid battery and structure of lead acid battery chemistry

Table 2.1. Overview of Types and Applications in Lead-Acid BESS Technology [34]

Technology	**Types of BESS**	**Applications**
Lead-Acid (PbA) Batteries	Sealed lead-Acid (SLA)	Small UPS, emergency lighting, and wheelchairs. Because of its low price, dependable service, and low maintenance requirement, the SLA remains the preferred choice for health care in hospitals and retirement homes.
	Valve-Regulated Lead Acid (VRLA)	Power backup for cellular repeater towers, internet hubs, banks, hospitals, airports, and others.
	Absorbent Glass Mat (AGM)	Starter battery for motorcycles, start–stop function for micro-hybrid cars, as well as marine vehicles and Recreational Vehicle (RVs) that need some cycling.

Lithium Ion battery technology were pioneered by chemist John Goodenough and his colleagues Phil Wiseman, Koichi Mizushima, and Phil Jones at Oxford University in the 1970s. It is a rechargeable storage technology which is made of one or more power generating compartments called cells. In a lithium ion (Li-ion) battery, lithium metal oxide (i.e. $LiCoO_2$) and graphitic carbon will be used as cathode and anode respectively and a non-aqueous organic liquid will be an electrolyte. [37]

Good sides of Li-Ion batteries are high specific energy, long cycle and extended shelf-life, High capacity, low internal resistance, good coulombic efficiency, simple charge algorithm and reasonably short charging time etc. [34]

Shortcomings of Li-Ion batteries include need for protection circuit (i.e. to prevent thermal runway), Degradation at high temperature, Incapability of rapid charge at freezing temperatures and Requirements of transportation regulations during shipping in large quantities etc. Figure 2.21 shows conventional lithium ion battery and its internal chemistry which consists of electrodes and electrolytes. [34]

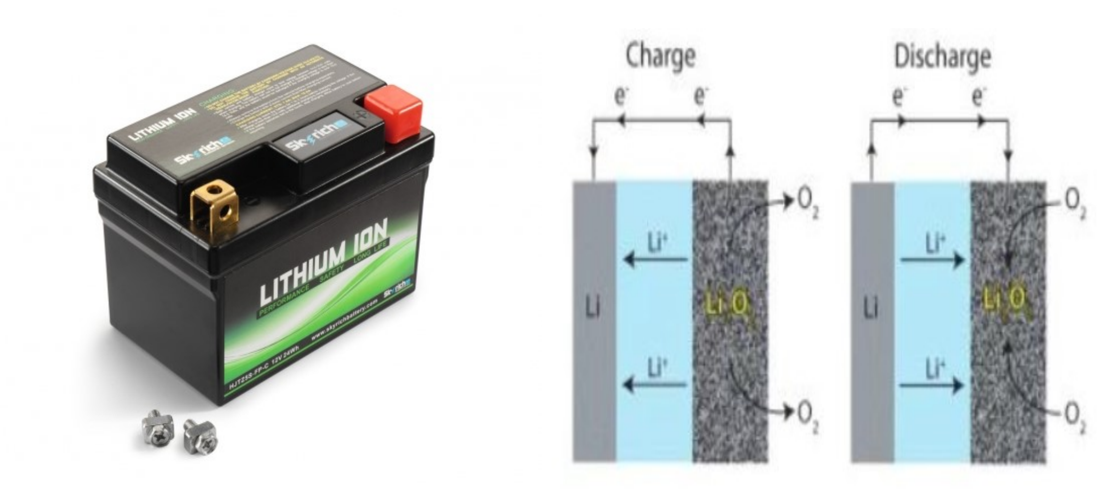


Figure 2.21: Lithium-Ion Battery and structure of Li-Ion battery chemistry

Table 2.2: Overview of Types and Applications in Lithium-Ion BESS Technology [34] [38]

Technology	Types of BESS	Applications
Lithium Ion (Li-Ion) Batteries	Lithium cobalt oxide ($LiCoO_2$) Lithium manganese oxide ($LiMn_2O_4$) Lithium nickel manganese cobalt oxide ($LiNiMnCoO_2$, or NMC) Lithium iron phosphate ($LiFePO_4$) Lithium titanate ($Li_4Ti_5O_{12}$)	• Power backups/UPS • Mobile, Laptops, and other commonly used consumer electronic goods • Electric mobility • Energy Storage Systems 1)Stationary Batteries. 2)Stand-Alone Applications. 3)Solar Applications. 4)Residential Consumptions.

2.2 Overview of PV-BESS systems in Finland

2.2.1 Solar Irradiance in Finland

Finland is northern European country which is located north western part of Europe. In Finland, annual global irradiation is around 1000 kWh/m² and a daily average is nearly 3 kWh/m² [39]. Considering, Tampere which is 3rd largest city by municipality in Finland is geographically located on the latitude of 61.4980214 ° and longitude of 23.7603118 °. Moreover, average temperature lasts about 5°all year round and has annual global irradiation of 876.4 kWh/m² (According to PV-SOL online). PV-SOL online is a free tool for the calculation of PV systems and a full featured market leading PV simulation software. [40]

For getting best year-round performance from the rooftop PV system in Tampere; PV panels should be installed directly to the south at 43° tilt angle position.

Table 2.3: Solar irradiance data based on installation (directing to south at 43° tilt angle position)

Months	Solar Irradiance (kWh/m²/day)
January	0.72
February	1.90
March	3.46
April	4.64
May	5.54
June	5.31
July	5.11
August	4.35
September	3.28
October	1.80
November	1.09
December	0.44
Average (All year round)	3.14

From the table 2.3, it can be seen that, solar irradiance is highest between the month of May to July (varies between 5.54 kWh/m²/day to 5.11 kWh/m²/day). On the other hand, solar irradiance is lowest between the months of November to January (varies between 1.09 kWh/m²/day to 0.72 kWh/m²/day).

All the solar insolation data presented in the table has been collected from the solar electricity handbook which is a simple, practical guide to using electric solar panels and designing and installing photovoltaic PV systems and an online tool to assessing PV panel all year-round performance based on installing and mounting. [41]

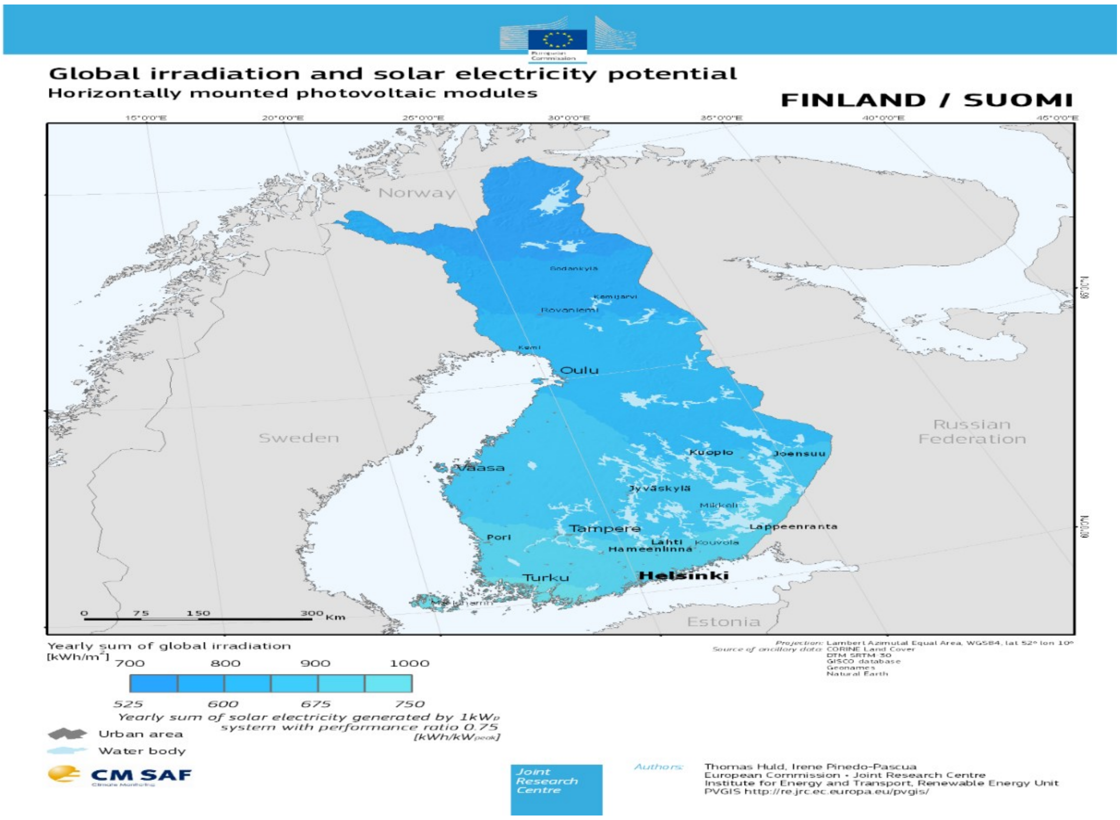


Figure 2.22: Global horizontal irradiation of Finland (courtesy: EU PVGIS).

Figure 2.22 shows information about global horizontal irradiation (GHI) of Finland. GHI varies from region to region of a country. From the map, it can be seen that, range of irradiance is lower in the northern part (i.e. 700 kWh/m²) and higher in the southern part of Finland (i.e. 1000 kWh/m²). [42]

2.2.2 Potential of Off-Grid PV- BESS plants in Finland

Finland is a Northern European country which is geographically located near arctic region where solar intensity is quite low compared to other regions of the world. Due to having low temperature and heavy snowfalls during the winter times, Finland's has less potential of harvesting massive solar power. Annual global irradiation for horizontally mounted PV modules typically lies between 700 kWh/m² to 1000 kWh/m². On the other hand, Finland has the potential of generating 750 kWh/kWp annually and a daily average of 2.05 kWh/kWp at the southern part of Finland. Moreover, PV output differs from region to region which ranges from 525 kWh/kWp to 750 kWh/kWp annually at a daily average between 1.44 kWh/kWp to 2.05 kWh/kWp.

For optimally inclined PV modules, yearly global irradiation ranges from 900 kWh/ m² to more than 1100 kWh/ m². Besides, for such setup of PV modules, Finland has the potential of generating 675 kWh/kWp annually and a daily average of 1.85 kWh/kWp at the the southern part of Finland. Moreover, PV output differs from region to region which ranges from 675 kWh/kWp to greater than 825 kWh/kWp annually at a daily average between 1.85 kWh/kWp to greater than 2.26 kWh/kWp. (EU PVGIS)

According to statistics 2010; most of the buildings are residential buildings in Finland and total residential area was about 273,420,000 m² where 67% was 1-floor residential buildings, 28% 2-floor and the rest 3-floors or more. Among the available residential rooftop buildings area, one quarter of that roof area could face towards the right direction for solar harnessing which is roughly 61,222,500 m2. Moreover, each region in Finland has a 16.75% potential for rooftop area where solar power can be harvested. Recent studies tell that, Finland has around 80,000 apartment buildings where nearly 2 million peoples are living. Average size of an apartment house is 120 m² and electricity consumption in a single apartment is around 1500 kWh per year. To powering up entire apartment through solar PV system, average sunlight of 5 hour/day is required to extract sufficient power from 52 PV panels of 15% efficiency and an area up to 75.8 m² for installing the PV plant. Performance ratio of solar panels is an important factor which depends on the ratio of area available in rooftop and area required for installing the plant. Typically, in Finland, Performance ratio based on standard operation is around 0.75. [43]

In Finland, technology of off-grid solar PV is based on residential and organizational consumers. Finland has an off-grid PV capacity of around 10 MW with an increase of 0.3 MW on yearly basis. Moreover, Finnish PV market is mainly focusing on small off-grid systems which are mainly operating in recreational or holiday houses like summer cottage (i.e. there are half a million of summer cottages in Finland). In addition, there is around 40 000 Off-grid recreational PV microsystems (Gaia Consulting, 2014). In recent years, rooftop solar PV based plants are increasing in the residential, organizational and sports & recreational places. For example, Helsinki based energy company Helen Oy has been established three biggest rooftop PV plant in Finland and sizes of those plants are 852 kW which comprises of 2992 solar panels and each panel rated 285W located in Kivikko, 500 kW which comprises of 1589 panels and each panel is rated 315 W located in Messukeskus; 340 kW which comprises of 1194 panels and each panel is rated 285W located in Suvilahti respectively. Helen Oy is the largest city-based energy company in Finland, and they are operating such plants through rental services among green energy users. Beside Helen Oy, some private companies like Areva solar have also their off-grid solar PV plant which is operating in Salo (i.e. 4.7 kWp private house) and in Astrum-keskus Salo(i.e. 322.56 kWp) respectively. [44] [45] [46]

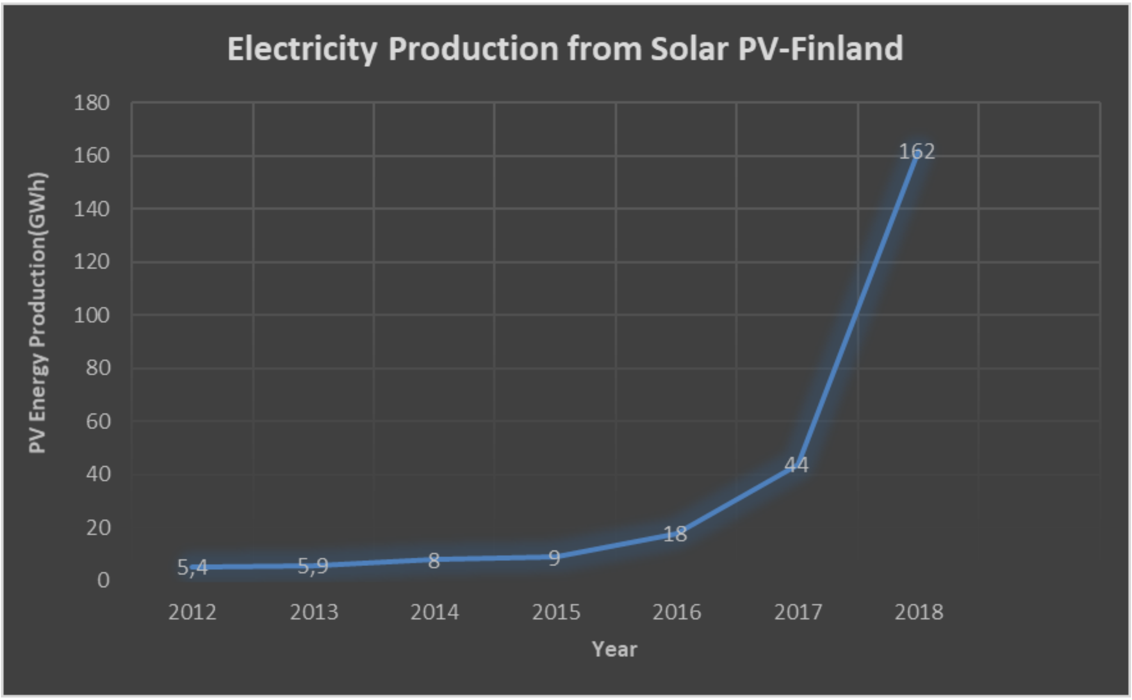


Figure 2.23: Solar PV electricity production volume in Finland (Source: EurObserv'ER)

Due to massive increase in solar energy utilization in Finland, we can see rapid increase in PV electricity production in recent years. Figure 2.23 shows the statistics of PV electricity production from the year of 2012 to 2018. Steady increase in PV electricity is happening from 2012 to 2015. After 2015, we can see rapid growth in PV energy production consistently 18 GWh in 2016, 44 GWh in 2017 and 162 GWh in 2018 which is 30 times more than the production in 2012 and 3.7 times more than the production in 2017. All the data has been collected from them website of EurObserv'ER. It is an EU based institution committed to provide reactive picture of the energy, industry and policy trends for EU 28-member states in renewable energy sectors.

2.3 Overview of PV-BESS systems in Bangladesh

2.3.1 Solar Irradiance in Bangladesh

Bangladesh has on average 4 to 4.5 peak sun hours a day and an average solar insolation of 5 kWh/m² per day [47]. Considering, Dhaka city; capital of Bangladesh which geographic location in on the latitude of 23.7593572° and longitude of 90.3788136° and all year-round average temperature remains around 24.8°. Due to the presence in southern part of the world, Dhaka city has quite higher annual global irradiation which is around 1798.6 kWh/m² (According to PV-SOL online). PV-SOL online is a free tool for the calculation of PV systems and a full featured market leading PV simulation software. [40]

For getting best year-round performance from the rooftop PV system in Dhaka; PV panels should be installed directly to the south at 66° tilt angle position.

Table 2.4: Solar irradiation data based on installation (directing to south at 66° tilt angle position)

Months	Solar Irradiance (kWh/m²/day)
January	5.40
February	5.78
March	5.96
April	5.60
May	4.93
June	4.18
July	3.94
August	4.06
September	4.04
October	4.79
November	5.21
December	5.39
Average (All year round)	4.94

From the table 2.4, it can be seen that, solar irradiance is highest between the month of January to April (varies between 5.40 kWh/m²/day to 5.60 kWh/m²/day). On the other hand, solar irradiance is lowest between the months of June to September (varies between 4.18 kW/m²/day to 4.04 kW/m²/day). All the solar insolation data presented in the table has been collected from The Solar Electricity Handbook which is a simple, practical guide to using electric solar panels and designing and installing photovoltaic PV systems and an online tool to assessing PV panel all year-round performance based on installing and mounting. [41]

Below figure 2.24 illustrates global horizontal irradiation (GHI) of Bangladesh based on the years between 1999 to 2015. GHI varies from region to region of a country. From the map, it can be seen that, range of irradiance is lower in the north part (i.e. 1607 kWh/m²) and higher in the south-east part of Bangladesh (i.e. 1826 kWh/m²).

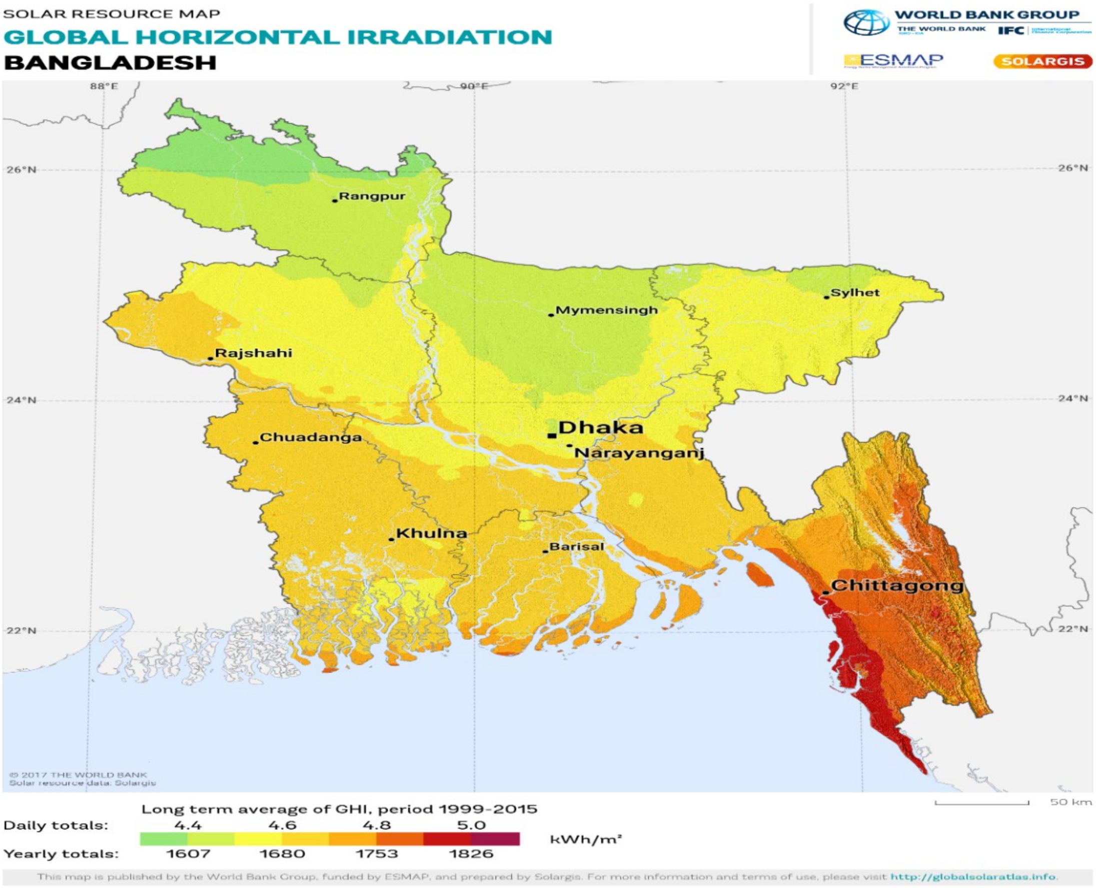


Figure 2.24: Global horizontal irradiation of Bangladesh (courtesy: SOLARGIS).

2.2.2 Potential of Off-Grid PV- BESS plants in Bangladesh

Bangladesh is a South Asian developing country which is geographically located at a viable position to harvest massive solar energy all year round compared to countries located at the northern part of the world. Due to locating at southern part of the world, Bangladesh has the potential of generating 1534 kWh/kWp annually and a daily average of 4.2 kWh/kWp at the south east part of Bangladesh. Moreover, PV output differs from region to region which ranges from 1314 kWh/kWp to 1534 kWh/kWp annually at a daily average between 3.6 kWh/kWp to 4.2 kWh/kWp. (SOLARGIS)

In Bangladesh, technology of solar power generation is mainly based on off-grid PV which is facilitating millions of mini solar home systems (SHS) at rural areas and rooftop

PV power for commercial and residential customers. Moreover, number of SHS installation reached 6.8 million in 2018 (according to 2018 energy statistics, Bangladesh) which provides electricity in the remote areas through off-grid power services.

Infrastructure Development Company Limited (IDCOL) is pioneer in large-scale infrastructure and renewable energy projects in Bangladesh has started their mini SHS in the year of 2003 and managed to installed about 3.5 million mini SHS by the end of year 2014 to electrifying rural life of Bangladesh through its 47 partner organizations funded by world bank. On the other hand, Grameen Shakti (GS) is another key driver in the development of non-profit rural electrification projects through renewables have installed almost 56% of total SHSs. For having SHSs in millions, Bangladesh have the potential of 234 MW electricity generation. As a result, energy dependency based on fossil fuels has been degraded highly due to increase in PV power consumption through SHSs in the rural areas of Bangladesh. [48] [49]

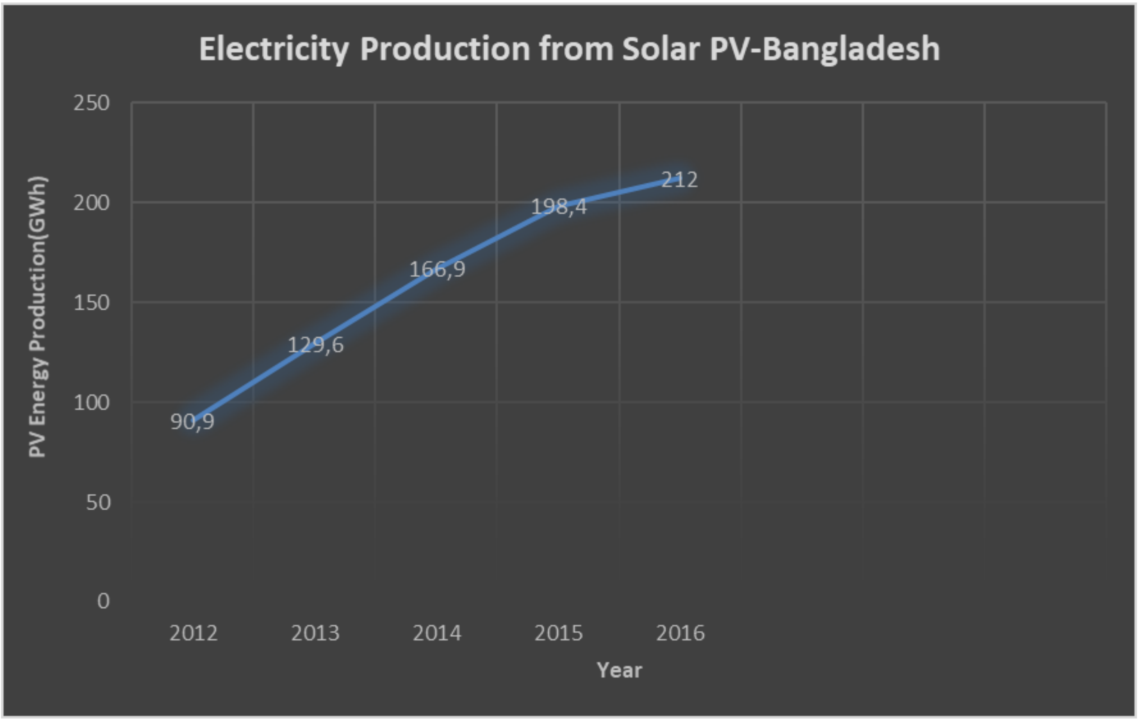


Figure 2.25: Solar PV electricity production volume in Bangladesh (Source: IRENA)

Due to mass increase in mini Solar Home Systems (SHS) and off-grid plants in rooftop and island areas, we can see rapid increase in PV electricity production during the year 2012 to 2016 in figure 2.25. In the year 2016, PV generation is 212 GWh which is 2.4 times more than the year of 2012. Every year PV electricity generation is increasing on average of 30 % more than the previous years.

Off-grid PV is becoming popular among the residential and commercial users in city areas. Cities like Dhaka, dwellers are installing rooftop solar PV system to consume PV power for electrical appliances. moreover, rooftop PV based off-grid systems has the ability to offer net-metering based electricity consumption among the residential and commercial electricity consumers. Based on net-metering protocol, electricity consumers can send excess PV power from their installed rooftop PV panel to the national grid through bi-directional meter installed between residential PV power providers and grid electricity distributors.

Moreover, the tariff of net metering is equal to what a consumer pays for using electricity from the national grid. Additionally, consumer can also export their unused or excessive electricity to the grid, which is later adjusted to the electricity imported from the national grid. Such net metering protocols in PV power utilization will reduce grid power dependency and will be a financially beneficial initiative for the residential PV system owners by minimizing their feed-in tariff. key players for establishing such energy agreement standardization are residential and commercial PV system owners. since, introduction of net metering guidelines, the power generation from industrial rooftop plants has reached to the generation capacity of 18 MW. moreover, government has started motivating and advising to city dwellers and industrial sectors to increase rooftop PV systems which could be helpful to increasing generation capacity up to 300 MW in the next 4 years. As a result, several rooftop projects have entered and will likely to be entered to activating strong energy economy and dependency on renewable PV power through net metering services nationwide. For example, a recent deal has been signed to starting up nation’s largest solar rooftop project with Bashundhara industrial complex and they will host 6,560 monocrystalline panels on the rooftop area of 20,000 m² with generation capacity of 2.46 MW. This project will be financed by IDCOL. [50] [51] [52]

3. MODEL OVERVIEW AND CALCULATION OF SOLAR PHOTOVOLTAICS(PV) and MUNICIPAL – BATTERY ENERGY STORAGE SYSTEMS(M-BESS) PLANT

3.1 Overview of proposed Residential based Rooftop PV-Municipal BESS model

Case-Finland:

For Finland, model of our proposed PV-BESS based plant for residential building includes wiring of components (DC and AC cabling) and PV integrated building blocks. A bus called MCU bus is placed to fetch data from PV integrated building blocks, Municipal energy storage facility (BESS) and EV charging station by Monitoring and control unit which is located near to the residential buildings. Moreover, MCU is responsible to smart monitoring and control through data acquisition process and enables smart energy optimization of the entire system (Off grid plant, Home Energy Management-HEM and EV charging station). Figure 3.1 shows block diagram of PV-BESS model in Finland

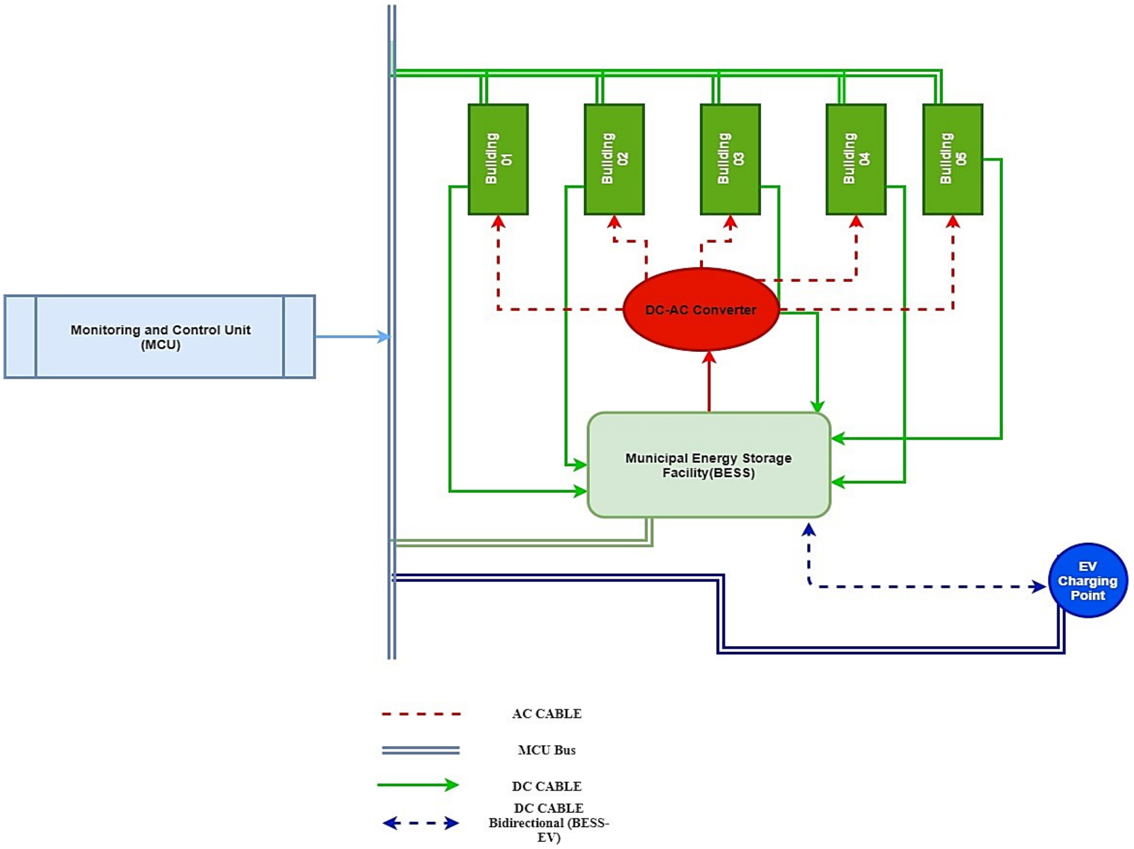


Figure 3.1: Block diagram of Finnish residential based rooftop PV-Municipal BESS model.

Finnish residential buildings are available in different architectural shapes and infrastructure. Moreover, types of rooftop vary in terms of shapes (i.e. rectangular, square, polygon, hexagonal) and position (i.e. flat-horizontal, vertically inclined, dual sided inclined etc.) Since, there is no specific building model of Finnish residential buildings, so we considered rectangular shaped flat-horizontal rooftop based single block detached buildings. Below table illustrates the overview about Finnish building infrastructure.

Table 3.1: Summary of Finnish residential building infrastructure for PV-BESS plant.

No of Buildings : 05

Type of Rooftop: Flat-Horizontal

No of Floors in each buildings: 04

Apartments in each floor: 02

Total no of apartments in each buildings: 08

Totat area in Rooftop: 300 m^2 each building

Estimated rooftop area available for PV plant: Approx. 276 m^2 for each building (Total: 1380 m^2 for 5 buildings)

Area loss: 8%

From the table 3.1, we can see that, rooftop PV plant can be installed based on the available rooftop area of each buildings. There is total five residential detached buildings and each building has total rooftop area of approx. 300 m^2. on the other hand, there is area loss of 8% (estimated) due to the presence of chimney (i.e. through which exhaust heat of houses and excess heats of saunas can pass to the environment). So, for our proposed rooftop plant, available rooftop area is 1380 m^2.

Considering, no of apartments, we can see that, there is 8 apartments in each building and total 40 apartments where PV generated power will be utilized through municipal BESS facility.

More details about PV power generation, residential electrical load profile and other components requirements will be discussed in the chapter in calculation part of off-grid solar PV power plant.

Table 3.2: Apartment architecture and load information (Finland)

	Structure of a single apartment (Finland)					
Type	Living Room	Dining Room	Bed Room	Kitchen	Toilet	Shower place
Area of each place(m^2)	35	25	40	15	10	15
Total Area(m^2)	140					
No of Apartments	40					
Load Type and Ratings	Electrical Home Appliances (EU energy class standardization), AC (230V,50Hz)					

Case-Bangladesh:

Typical model of rooftop-based PV-municipal BESS plant based on Bangladesh residential building infrastructure which represents a wired model includes the presence of DC and AC cabling, Municipal BESS facility and PV integrated residential buildings. here, MCU bus is located to fetch data from PV integrated building blocks and Municipal energy storage facility (BESS).

Since, EVs are very rare in use countries like Bangladesh and EV charging are not available so EV charging hub will not be a part of this proposed model for Bangladesh. Operation of MCU is to optimize smart monitoring and control through data acquisition process for PV integrated building blocks and municipal BESS facility.

Bangladesh residential buildings can be found quite similar in terms of architectural shapes and infrastructure. Moreover, Rooftop types are mostly rectangular and square. So, for proposed PV plant, we will consider square shaped flat-horizontal single blocked multi-storied buildings. Here, figure 3.2 shows block diagram of PV-BESS plant in Bangladesh.

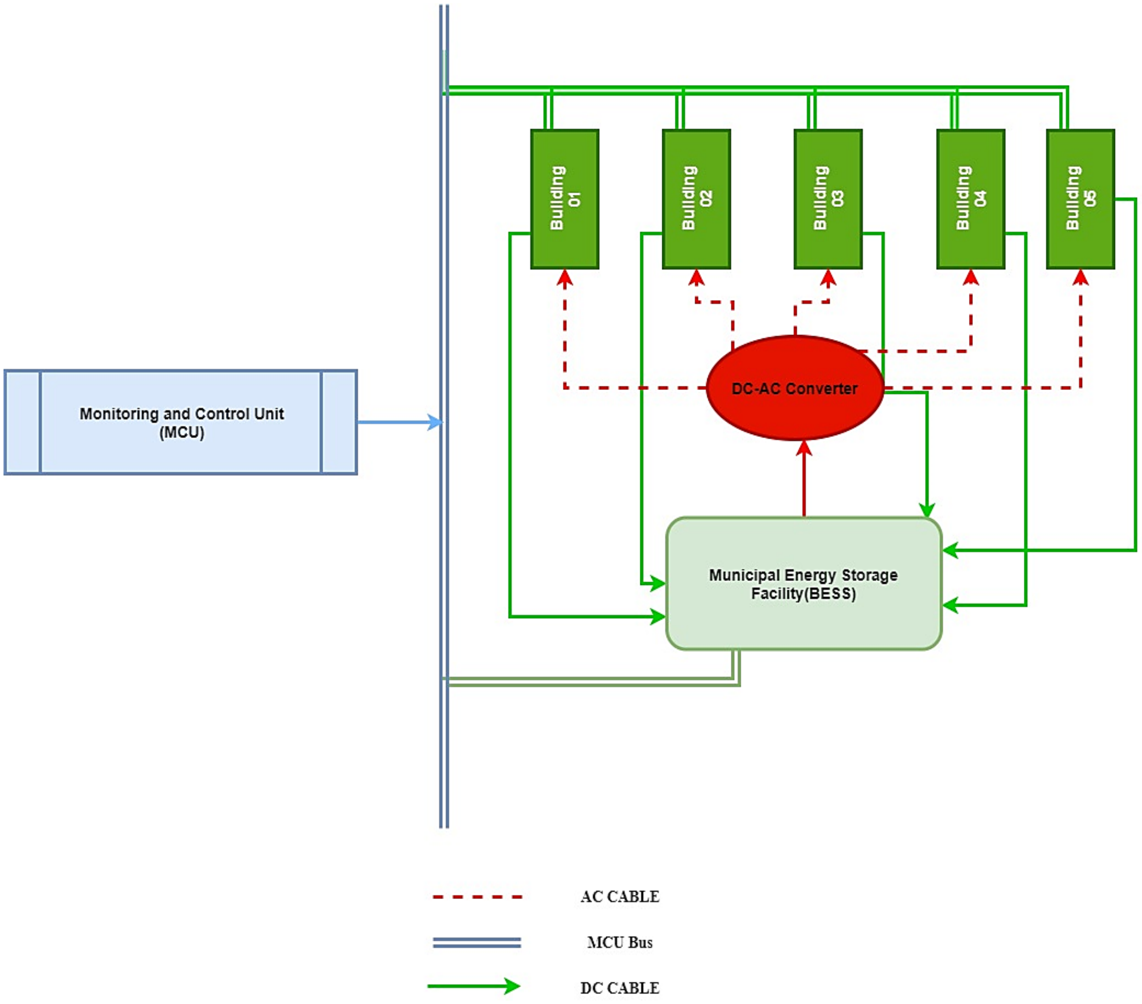


Figure 3.2: Block diagram of Bangladesh residential based rooftop PV-Municipal BESS model

Table 3.3: Summary of Bangladesh residential building infrastructure for PV-BESS plant

- No of Buildings : 05
- Type of Rooftop: Flat-Horizontal
- No of Floors in each buildings: 04
- Apartments in each floor: 02
- Total no of apartments in each buildings: 08
- Totat area in Rooftop: 300 m^2 each building
- Estimated rooftop area available for PV plant: Approx. 255 m^2 for single building (Total: 1275 m^2 for 5 buildings)
- Area loss: 15%

.

From the table 3.3, we can see that, rooftop PV plant can be installed based on the available rooftop area of each buildings. There is total five residential multi-storied buildings and each building has total rooftop area of approx. 300 m^2. on the other hand, there is area loss of 15% (estimated) due to the presence of water tank and rooftop area boundary. So, for our proposed rooftop plant, available rooftop area is 1275 m^2.

Considering, no of apartments, we can see that, there is 8 apartments in each building and total 40 apartments where PV generated power will be utilized through municipal BESS facility.

Table 3.4: Apartment architecture and load information (Bangladesh)

	Structure of a single apartment (Bangladesh)					
Type	**Living Room**	**Dining Room**	**Bedroom**	**Kitchen**	**Toilet+ shower place**	**Toilet+ Shower place**
Area of each place(m^2)	**35**	**25**	**40**	**15**	**15**	**10**
Total Area(m^2)	**140**					
No of Apartments	**40**					
Load Type and Ratings	**Electrical Home Appliances (power rating-based standardization), AC (220V,50Hz)**					

In Bangladesh, Electrical load varies more compared to Finland because of having dissimilarity in electrical appliances from apartment to apartment. Hence, apartments can be categorized based of high and low electrical load profile. For our system, we estimated that, there is 30 apartments which have low electrical load profile and 10 apartments where electrical load profile is high (. i.e. because of the presence of appliances like Air conditioner, washing machine etc.).

3.2 Overview of Steps to off-grid PV & municipal BESS plant

For designing an off-grid solar PV plant, it is necessary to satisfy necessary requirements and process flow to initialize the project work. Moreover, planning and site survey is the very first step to design such plant. Planning helps to determine the total requirement of establishing a PV plant like area requirement, PV array requirements, load demand at customer end, batteries, inverter and equipment requirement for installing such plant in a specific location.

On the other hand, site survey is important because it assures the geographical condition of a specific location which helps to get solar irradiation data, wind speed in that location and temperature variance in the site. Moreover, all these parameters are associated with the performance of PV array operation and efficiency of the plant.

Additionally, site survey also helps to identify shadow-free location so that PV arrays can operate uninterruptedly in an unshaded environment. After satisfying the results of planning and site survey, it is possible to initialize any kind of PV plant to serve a specific location as per energy requirements. Figure 3.3 illustrates the flow diagram of sizing and off-grid solar PV and municipal BESS plant. [5]

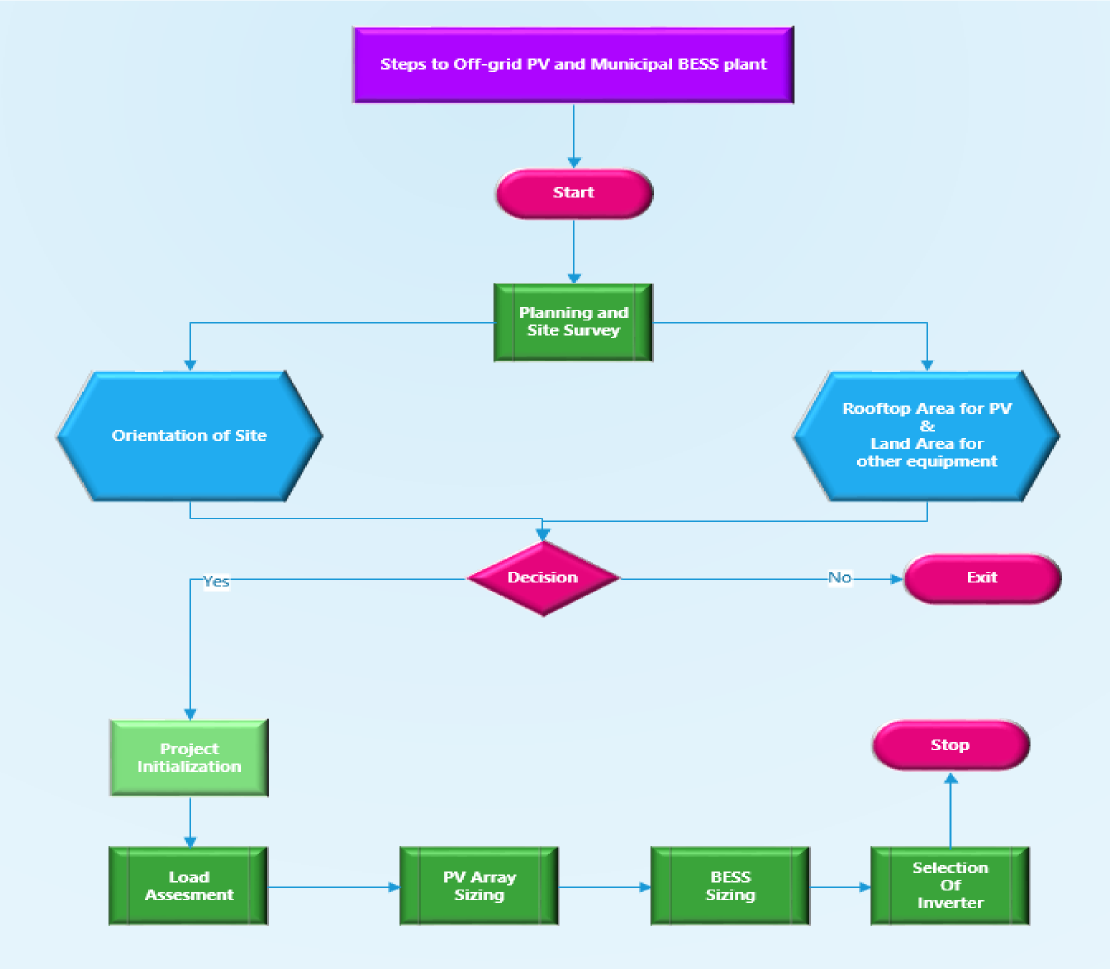


Figure 3.3: Flow diagram of sizing an off-grid solar PV & municipal BESS plant.

3.3 Calculation of Residential based Rooftop PV-Municipal BESS power plant:

3.3.1 Assessment of Residential Load

In this part of the chapter, we will perform residential load assessment for 24 hours period for Finland and Bangladesh case.

Case: Finland

For Finland case, residential load assessment has been done by collecting electrical appliances power consumption data from retailers of electrical and electronics appliances like Gigantti, power and Verkokauppa etc. Operating hours of appliances has been estimated based on the yearly average operations of appliances (i.e. summer and winter times). Table 3.5 shows electrical load profile of a single apartment of Finnish residential building.

Table 3.5: Electrical load profile for single apartment-Finland

Appliances	Power Rating(W)	Quantity	Operating Hour	Total Load (kW)	Total Energy (kWh)
LED Lamp	8	5	3	40	120
Flurocent lamp	18	1	2	18	36
Suspension type lamp	15	2	3	30	90
PC	570	1	2	570	1140
Laptop	60	1	3	60	180
Microwave Oven	700	1	0.5	700	350
LED TV	71	1	5	71	355
Electric Cooker	31.94(EU energy class)	1	3	31.94	95.82
Gaming Console	110	1	3	110	330
Coffee Machine	1100	1	0.5	1100	550
Washing Machine	19.74(EU energy class)	1	1	19.74	19.74
Refrigerator and Freezer	26.81(EU energy class)	1	24	26.81	643.44
Dishwasher	27.40(EU energy class)	1	1	27.40	27.40
Ceiling lamp	12	2	3	24	72
Juicer	400	1	0.1	400	40
Total:				3.3 kW	4.1 kWh

From table 3.5, it can be seen that, peak load (i.e. total load in kW) for a single apartment is around 3.3 kW and total energy requirements of an apartment per day is around 4.1 kWh. High rated power appliances like electric cooker, washing machine, refrigerator &

freezer and dishwasher's daily energy requirement has been calculated from EU energy class standardization data.

Table 3.6: Electrical load and energy information PV-BESS plant (Finland).

Total Energy for single apartment	4.1 kWh/ day
Total Power for single apartment	3.3 kW
No of Apartments in building blocks	40
Total Energy for 40 apartments	164 kWh/day
Total Power for 40 apartments	132 kW

Table 3.6 depicts the information about energy requirements per day and peak load for a single apartment and all 40 apartments. all the load and energy information has been calculated based on yearly average instead of seasonal variance in load and energy requirements for the apartments of building blocks.

Case: Bangladesh

Unlike Finland, electrical appliances in the apartments of Bangladesh can be different (i.e. in terms of number and type of appliances) due to the categorization among inhabitants (i.e. low wage earners and high wage earners) in a residential area. As a result, electrical load profile might be different for different user level. For this case, we calculated load profile based on the appliance's usability of low wage inhabitants and high wage inhabitants. Information of electrical load profiles are stated below.

Table 3.7: Electrical load profile for single apartment-Bangladesh (Low Load Type-LLT apartment)

Appliances	Power Rating(W)	Quantity	Operating Hour	Total Load (kW)	Total Energy (kWh)
CFL bulb	30	7	3	210	630
Tube Light	40	4	4	160	640
Fan	75	4	8	300	2400
Desktop PC	300	1	4	300	1200
Laptop	120	1	3	120	360
Exhaust Fan	45	1	2	45	90
Refrigerator and Freezer	250	1	24	250	6000
LED TV	120	1	8	120	960
Total:				1.6 kW	12.30 kWh

From table 3.7, it can be seen that, single apartment of low load type requires total energy of around 12.30 kWh per day where peak load (i.e. total load) is around 1.6 kW. all the appliances data has been taken from the load calculator of Dhaka Electric Supply Company Ltd (DESCO) and electronic manufacturer Walton's websites. Moreover, appliances energy and load data has been calculated based on power ratings (W)

Table 3.8: Electrical Load Profile for single apartment-Bangladesh (High Load Type-HLT apartment)

Appliances	Power Rating(W)	Quantity	Operating Hour	Total Load (kW)	Total Energy (kWh)
CFL bulb	30	7	3	210	630
Tube Light	40	4	4	160	640
Fan	75	4	8	300	2400
Desktop PC	300	1	4	300	1200
Laptop	120	1	3	120	360
Exhaust Fan	45	1	2	45	90
Refrigerator and Freezer	250	1	24	250	6000
LED TV	120	1	4	210	840
Air Conditioner (AC)	3520	2	4	7040	28160
Washing Machine	750	1	0.3	750	225
Juicer/Mixer	400	1	0.1	400	40
Microwave Oven	900	1	0.4	900	360
Total:				11 kW	41 kWh

From table 3.8, single apartment of high load type requires total energy of around 41 kWh (Approx.) per day where peak load (i.e. total load) is around 11 kW (Approx.). High load apartment has been initialized due to the presence of high-power rating appliances like air conditioner, washing machine, microwave oven etc.

Table 3.9: Electrical Load and Energy information for PV-BESS Plant (Bangladesh)

Total Energy for single apartment (Low Load Type-LLT)	12.30 kWh/day
Total Power for single apartment (Low Load Type-LLT)	1.6 kW
Total Energy for single apartment (High Load Type-HLT)	41 kWh/day
Total Power for single apartment (High Load Type-HLT)	11 kW
No of Apartments in building blocks	30 LLT & 10 HLT = 40
Total Energy for 30 LLT apartments	369 kWh/day
Total Energy for 10 HLT apartments	410 kWh/day
Total Power for 30 LLT apartments	48 kW
Total Power for 10 HLT apartments	110 kW
Total Energy for 40 apartments	775 kWh/day
Total Power for 40 apartments	158 kW

Table 3.9 illustrates the information about the daily energy requirements (kWh/day) and peak power (kW) for a single apartment and all 40 apartments. Apartments are categorized based on the terminology of LLT (i.e. Low Load Type) and HLT (i.e. High Load

Type). All the energy and power requirements information has been calculated based on yearly average load data and requirements.

So, from the above information, it is cleared that rooftop PV-BESS plant will be designed based on the load (kW) and daily energy requirements (kWh/day) data of Finland and Bangladesh. Due to categorization and variability in electric appliances, Bangladesh's electrical energy requirement (i.e 775 kWh/day) is quite high compared to Finland's electrical energy requirements (i.e. 164 kWh/day). Moreover, Bangladesh's peak load demand (i.e 158 kW) is also higher in comparison of Finland's peak load demand (i.e. 132 kW).

3.3.2: Sizing of Rooftop solar PV array

Rooftop PV array is one of the most important and basic component of an off-grid solar PV plant. A photovoltaic array is a complete power-generating unit comprising of any number of PV modules and panels. Several factors should be considered before installing PV arrays in roof top space which includes size of single PV module(m^2), rooftop area(m^2) requirement for installing PV array and installed plant capacity (W or KW).

Generally, Performance of PV modules and arrays are rated based on their maximum DC power output (watts) under Standard Test Conditions (STC). Standard Test Conditions are defined by a module (cell) operating temperature of 25˚C (77˚F), and incident solar irradiance level of 1000 W/m2 and under Air Mass 1.5 spectral distribution. Moreover, actual performance of PV array is usually 85 to 90 percent of the STC rating. Typical service lifetime of a PV module varies between 20 to 30 years and increased temperature may degrade module output and lifetime. [53]

For our rooftop PV system, we considered a 250 W base panel (length of 1.64 m and width of 0.998 m) which requires an area around 1.63 m^2. Our PV plant will be designed based on the peak load of residential building apartments which varies countries to countries (i.e. for Bangladesh, peak load is 158 kW and for Finland, peak load is 132 kW). So, installed plant capacity should be 180 kW for Bangladesh and 150 kW for Finland respectively (since, there will be loss of PV array power due to using DC-AC converter between generation and load, cabling and temperature). Such conversion loss could vary between 0% to 10% by converters. [54]

Case-Finland:

In Finland, PV panels will be installed on flat rectangular shaped rooftop based residential building blocks. Each Buildings has an area of 300 m² and a total of 1380 m² of area is available from 5 building blocks. Moreover, installed plant capacity is 150 kW which consists of several rooftop array formed by 250 W PV panel.

Considering size of base panel 250 W, total 600 pcs of PV panels are required for implementing 150 kW Finnish PV-BESS plant. Since, base panel requires 1,63 m² of rooftop space, so total area requirement of our plant $978\ m^2$ in the rooftop area.

So, it is clear that, we need a total area of 978 m² for installing 600 pcs of PV panel for our desired 150 kW Finnish residential rooftop PV- BESS plant.

Case- Bangladesh:

For Bangladesh, we are considering squared shaped flat rooftop buildings for installing PV panels. Each building has rooftop area of 300 m² consisting 5 buildings where a total of 1275 m² area is available from the buildings. Besides, installed plant capacity is 180 kW which consists of several rooftop array formed by 250 W panel.

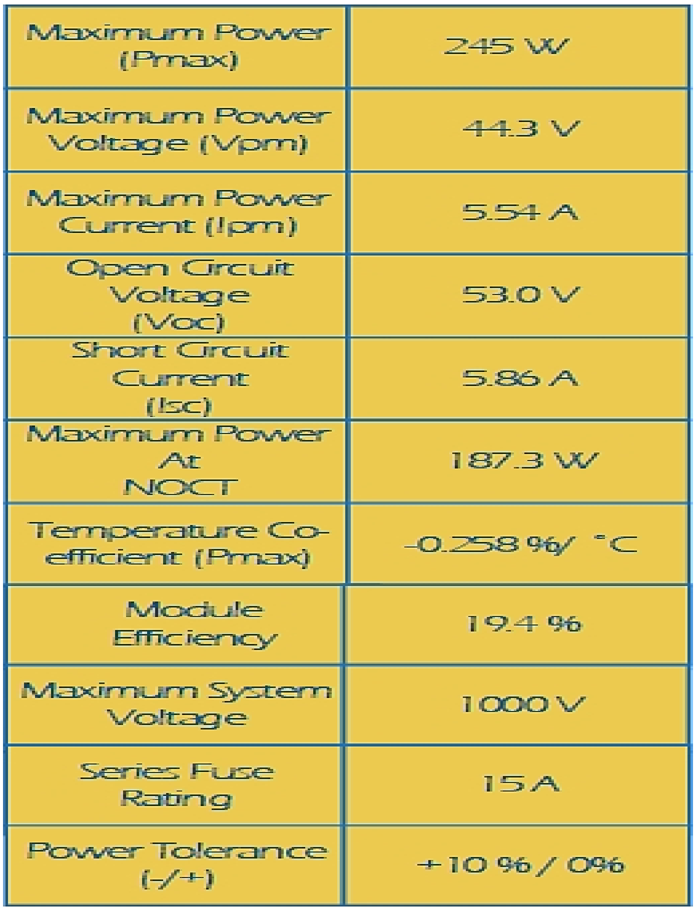
Considering size of base panel 250 W, total 720 pcs of PV panels are required for implementing 180 kW Bangladesh PV-BESS plant. Since, base panel requires 1,63 m² of rooftop space, so total area requirement of our plant $1174\ m^2$ in the rooftop area.

So, it is estimated that, we need a total area of 1174 m² for installing 720 pcs of PV panel for our desired 180 kW Bangladesh residential rooftop PV- BESS plant.

For our plant we can use, solar PV module of Panasonic brand VBHN245SJ25 which has a rated power of 245 W at STC and efficiency of 19.4%. Moreover, it is quite area efficient and requires only 1.26 m² per module. [55]

For Finland, using Panasonic VBHN245SJ25 245 W monocrystalline module to install 150 kW solar PV plant requires a total of around 771.12 m² for 612 pcs PV module. As a result, it will save 206.88 m² of rooftop space (i.e. 26% of total space requirement for installed plant).

For Bangladesh, using Panasonic VBHN245SJ25 245W monocrystalline module to install 180 kW solar PV plant requires a total of around 926.1 m² for 735 pcs PV module. As a result, it will save 247.9 m² of rooftop space (i.e. 26% of total space requirement for installed plant).



Maximum Power (Pmax)	245 W
Maximum Power Voltage (Vpm)	44.3 V
Maximum Power Current (Ipm)	5.54 A
Open Circuit Voltage (Voc)	53.0 V
Short Circuit Current (Isc)	5.86 A
Maximum Power At NOCT	187.3 W
Temperature Co-efficient (Pmax)	-0.258 %/ °C
Module Efficiency	19.4 %
Maximum System Voltage	1000 V
Series Fuse Rating	15 A
Power Tolerance (-/+)	+10 % / 0%

Figure 3.4: Panasonic VBHN245SJ25 panel and electrical specifications. [55]

3.3.3: Sizing of Municipal BESS(M-BESS) technology

BESS is one of the most important component of off grid solar power plant. Moreover, Batteries are the most expensive components of the solar panel systems. Before, installing an off-grid plant it is important to select the right battery technology to satisfy the customer demand in terms of operation and performance. Selection of BESS should be made based on the factors such as cost, depth of discharge, efficiency, maintenance and lifespan etc.

Lithium Ion based BESS are way ahead compared to Lead Acid based BESS because of having higher DoDs (i.e. typically 80% or more), longer cycle life (i.e. minimum 2000 to 4000 cycles), better and quicker charging efficiency, robustness and compact in size. On the other hand, pricing of Lithium Ion based BESS is the only drawbacks compared to Lead acid-based BESS.

Case-Finland:

Considering, off grid PV-municipal BESS plant in Finland, sizing of the BESS will be determined based on the energy consumption (i.e. in kWh) at peak hour periods. Below bar diagram shows electrical load profile for 24 hours in Finland's case.

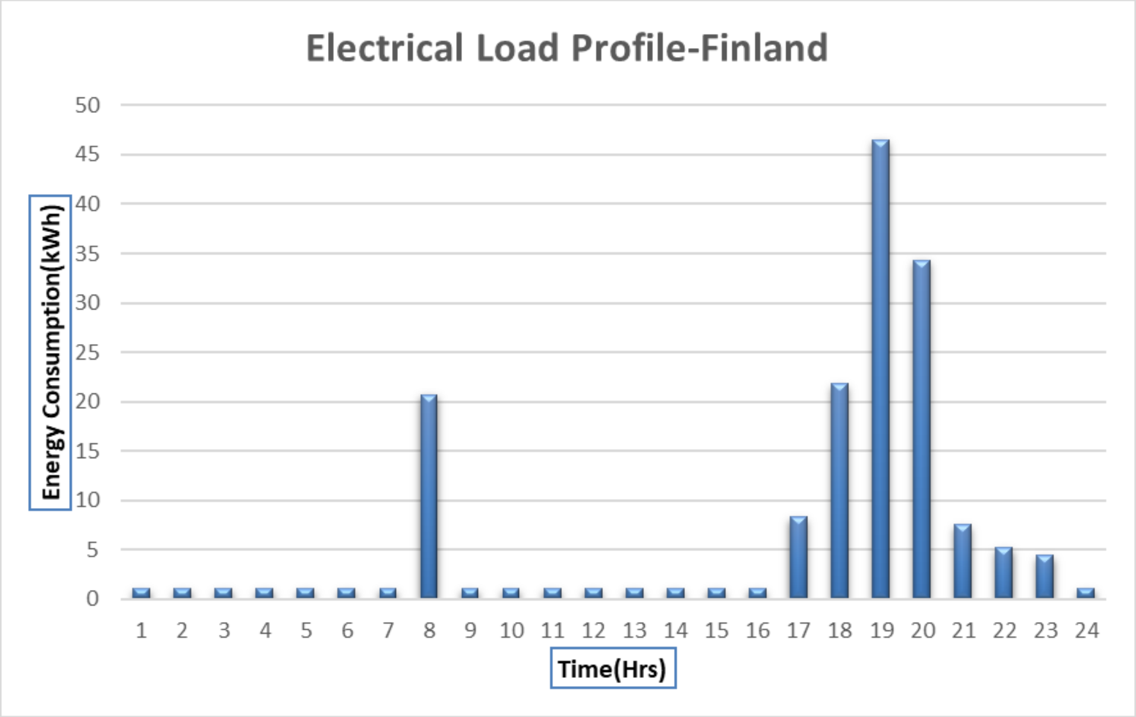


Figure 3.5: Electrical load profile for all 40 apartments in Finland-24 hrs

Figure 3.5 shows, electrical load profile for 40 apartments which is in 5 buildings block of Finland. From the graph, Peak hours in terms of energy consumption are 17:00 to 20:00 and morning at 8:00. On the other hand, off-peak hours are between 01:00 to 7:00, 09:00 to 16:00 and 21:00 to 24:00 respectively. Energy consumption in peak load hours ranges from 8.312 kWh to 46.5 kWh. Electrical load profile for Finland has been calculated based on the power rating data stated in table 3.5 for the period of 24 hours.

Table 3.10: Load summary of peak and off-peak hours for BESS sizing (Finland)

No of Peak Hours	5
No of Off-Peak Hours	19
Total Energy Consumption(peak hours)	132 KWh/day
Total Energy Consumption (off-peak hours)	32 KWh/day

Based on the information of table 3.10, sizing of BESS based on peak hours energy consumption will be an optimal solution to fulfil energy demand in the customer end at residential users' point of view. As a result, BESS will able to deliver power during both peak and off-peak hours while energy demands at peak hours will be reduced.

Since, it is more than 100 kW PV-BESS plant so our desired BESS nominal voltage should be 48 V. So, our BESS size should be 2,750 Ah at 48 V nominal voltage to deliver energy demand of 132 kWh/day for Finnish residential buildings.

Case-Bangladesh:

For Bangladesh, sizing of BESS will be determined based on the electrical energy consumption during peak hours in a day of 24 hours period. Below bar diagram illustrates electrical load profile of all 40 apartments of 5 building blocks of Bangladesh. Electrical load profile has been calculated based on the energy consumption of both HLT and LLT apartments.

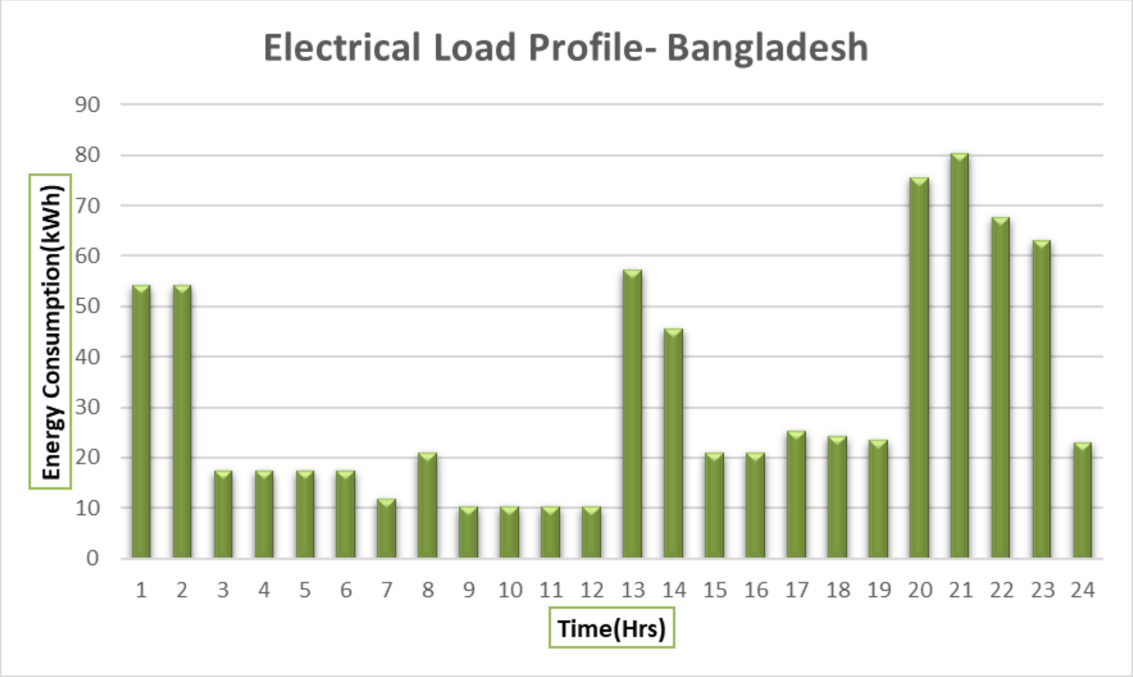


Figure 3.6: Electrical load profile for all 40 apartments in Bangladesh

From figure 3.6, it is seen that, peak hours of energy consumption lie between night to midnight time, and afternoon to evening time. Energy consumption in peak load hours ranges from 20.8 kWh to 80.2 kWh. Electrical load profile for Bangladesh has been calculated based on the power rating data stated in table 3.7 and 3.8 for the period of 24 hours.

Table 3.11: Load summary of peak and off-peak hours for BESS sizing (Bangladesh)

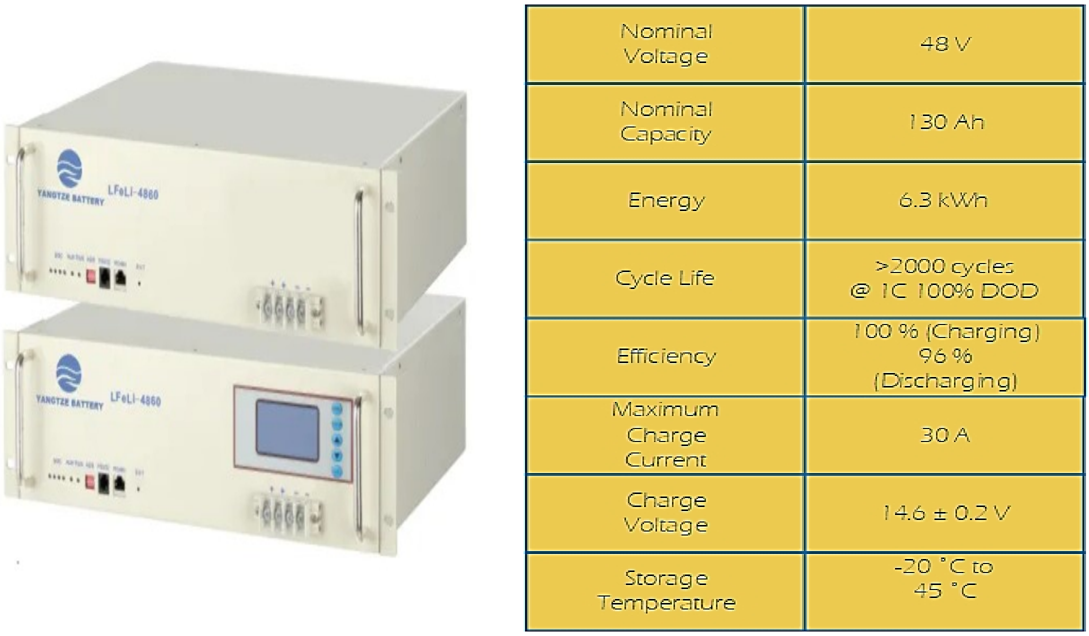
No of Peak Hours	15
No of Off-Peak Hours	9
Total Energy Consumption (Peak Hours)	654.03 KWh/day
Total Energy Consumption (Off-Peak Hours)	120.4 KWh/day

Based on information of table 3.11, sizing of BESS based on peak hours energy consumption will be an optimal solution to fulfill energy demand in the customer end at residential users' point of view. As a result, BESS will able to deliver power during both peak and off-peak hours while energy demands at peak hours will be reduced.

Since, it is more than 100 kW PV-BESS plant so our desired BESS nominal voltage should be 48 V. So, our BESS size should be 13,625 Ah at 48 V nominal voltage to deliver energy demand of 654.03 kWh/day for Bangladesh residential buildings.
Formula used to calculate the BESS sizing is stated below:

$$BESS\ Capacity, Bcap\ (Ah) = \frac{Required\ Energy\ (Wh)}{BESS\ Nominal\ Voltage} \tag{3.1}$$

Considering Base Battery 48V 130 Ah Li-Ion technology, we need 22 pcs of battery to form our BESS for PV-BESS plant in Finland. On the other hand, we need 105 pcs of battery to form our BESS for PV-BESS plant in Bangladesh.



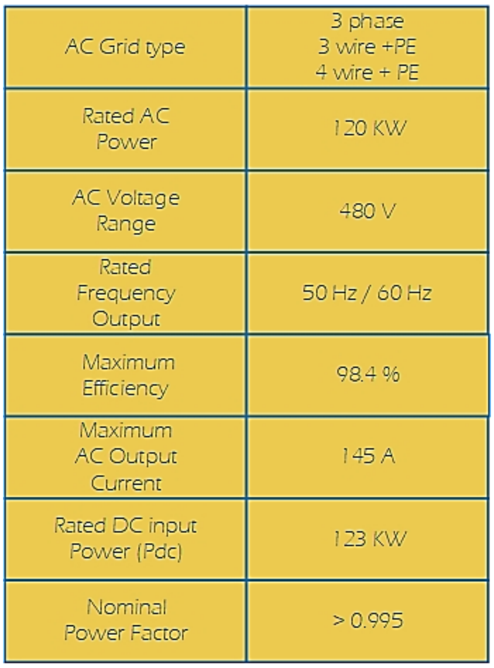
Nominal Voltage	48 V
Nominal Capacity	130 Ah
Energy	6.3 kWh
Cycle Life	>2000 cycles @ 1C 100% DOD
Efficiency	100 % (Charging) 96 % (Discharging)
Maximum Charge Current	30 A
Charge Voltage	14.6 ± 0.2 V
Storage Temperature	-20 °C to 45 °C

Figure 3.7: Yangtze Co. 48 V 130 Ah battery and electrical specification [56]

3.3.4: Selection of Inverters

For designing an off-grid PV and municipal BESS plant, Inverter plays a vital role in PV power conversion and regulating voltage from DC to AC. Moreover, Inverter system is needed to power up all the AC electric loads consisting of different appliances. During inverter sizing, it is important to consider a situation where all the appliances and loads are running simultaneously, and the inverter should be able to handle the highest continuous power load. The inverter must have extra capacity to start for these surges which can be two to three times higher than the continuous load. Moreover, there are also additional loads which is needed to accommodate with surge loads that occur at the start of electric pumps or electric motors for air conditioning, wells, and machine tools. To handle the AC load, the inverter size must be enlarged by 25–30% of the total AC load. For surge requirement, the capacity of an inverter should be increased to a minimum of three time the capacity of AC load and must be added to the total inverter capacity. Inverter size can be calculated by following equation: [14]

For off-grid PV & municipal BESS plant, inverter capacity should be 165 kW (i.e. 1.25 times of peak load) for Finland and 198 kW (i.e. 1.25 times of peak load) for Bangladesh. Here, 1.25 is the value for inverter safety factor.



AC Grid type	3 phase 3 wire +PE 4 wire + PE
Rated AC Power	120 KW
AC Voltage Range	480 V
Rated Frequency Output	50 Hz / 60 Hz
Maximum Efficiency	98.4 %
Maximum AC Output Current	145 A
Rated DC input Power (Pdc)	123 KW
Nominal Power Factor	> 0.995

Figure 3.8: ABB PVS 120 KW inverter and electrical specification. [57]

4. SIMULATION AND RESULT ANALYSIS

4.1. PART A: MATLAB-SIMULINK

In this part, we will cover simulation and result analysis of MATLAB-SIMULINK implementation which will cover PV-BESS plant's operational and performance analysis.

4.1.1 Overview of MATLAB-Simulink Tool

MATLAB is a dynamic simulation and program-based platform which offers wide range of applications like data analyzing, algorithms developments and model creation & system simulation based on several programming language like C, C++, java script and python etc. Moreover, MATLAB has its own language called MATLAB language which is matrix-based language allows natural expression of computational mathematics to solve complex mathematical problems in engineering sciences research and development-based project and studies.

Simulink is an integration feature of MATLAB based graphical programming environment for modeling, simulation and dynamic system's multidomain analysis. Additional feature of Simulink is to generate graphical block diagram of system's implementation. Common applications of using Simulink software to perform automatic control design, signal processing and model design & simulation in the field of electrical and electronics engineering. [58]

4.1.2 Purpose of MATLAB-Simulink Tool

Since, MATLAB-Simulink can be utilized in several research and studies purpose so for this thesis we have used this software for implementing proposed model in graphical form and generate necessary outcome of PV-BESS plant operation in varying operating conditions like changes in temperature & irradiation and changing switching conditions of charge controller to see the behavior and operation of PV-BESS plant during charging of BESS from PV, discharging of BESS to Residential load and delivering power from PV to Residential load etc. key purposes include:

- Modeling of off-grid PV-BESS plant components (i.e. sizing of PV, BESS, residential loads and converter), charge controller design (i.e. through switches and SOC estimation of BESS) and graphical implementation of the proposed model for Finland (i.e. 150 KW PV-BESS plant) and Bangladesh (i.e. 180 KW PV-BESS plant).
- Initialize varying temperature and irradiation ramp signal for PV array.

- Charge controlling algorithm integration at MATLAB function block to control charging and discharging behavior of PV-BESS plant.
- Monitor the output voltage, current and power of the main components of the model (i.e. PV array, BESS and Residential load).
- Monitor the operation of PV-BESS due to changes in temperature & irradiance and due to charge controller operating based on supply demand requirements for the proposed plant.

4.1.3 Systems Operational Analysis-MATLAB SIMULINK

Simulink model of off-grid PV-BESS plant has been tested based on the variations in irradiation and temperature and has been inserter to PV array as inputs. Values of irradiation and temperature has been designed in the signal builder according to PV plant test conditions in Bangladesh and Finland. In this chapter, we will discuss plant operations based on environment conditions (i.e. irradiance and temperature) and by controlling change controllers switching among PV, BESS and Residential load.

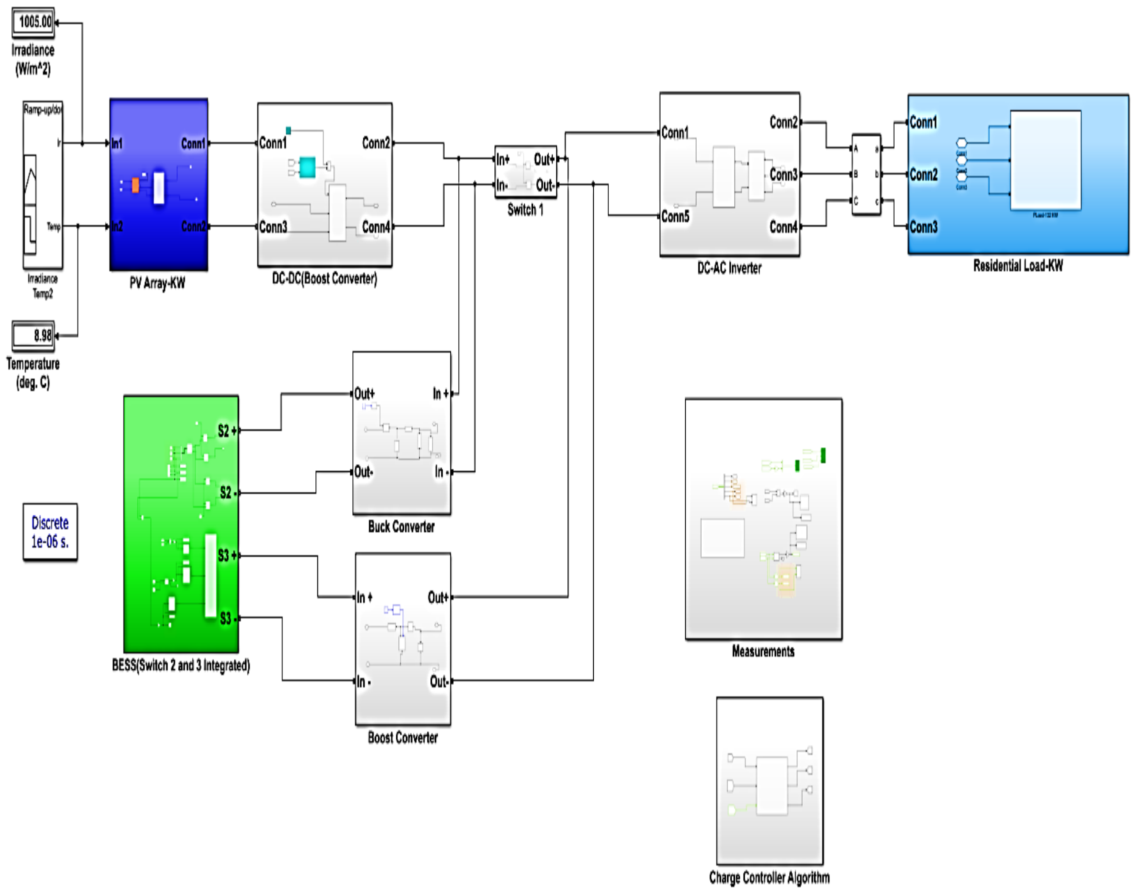
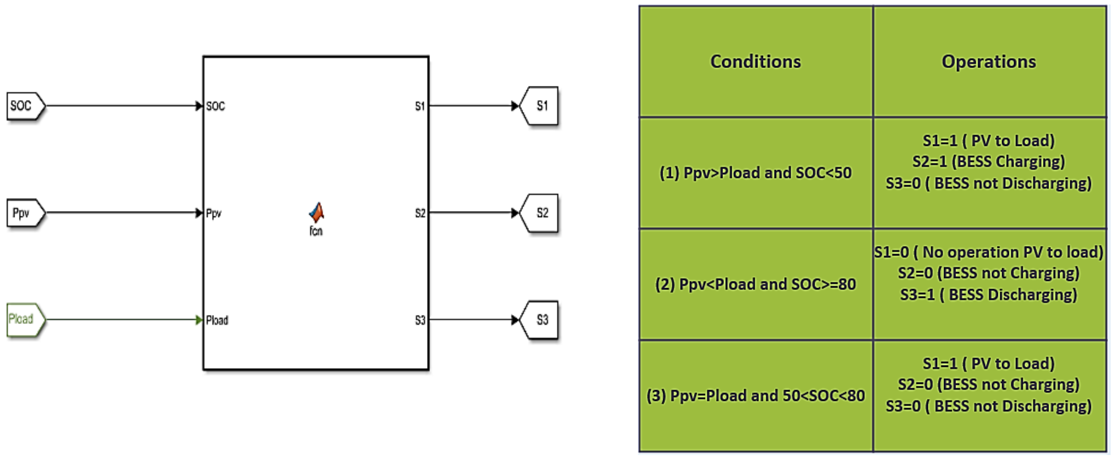


Figure 4.1: Simulink implementation of off-grid PV-BESS power plant.

Figure 4.1 shows base model implementation of our proposed PV-BESS power plant for residential buildings. Operation of the PV-BESS plant has been controlled by implementing charge controlling algorithm which has been encoded in MATLAB function. Moreover, such charge controlling technique has been designed based on the sensing of SOC level of battery, PV power and residential load power. During plant operation, all the simulation results has been generated based on T= 2.4 minute of operation. So, X-axis in each time series plot has a timeframe of T= 2.4 minutes.



Conditions	Operations
(1) Ppv>Pload and SOC<50	S1=1 (PV to Load) S2=1 (BESS Charging) S3=0 (BESS not Discharging)
(2) Ppv<Pload and SOC>=80	S1=0 (No operation PV to load) S2=0 (BESS not Charging) S3=1 (BESS Discharging)
(3) Ppv=Pload and 50<SOC<80	S1=1 (PV to Load) S2=0 (BESS not Charging) S3=0 (BESS not Discharging)

Figure 4.2: MATLAB function block of charge controller algorithm and operating conditions.

Case-Finland:

For Finland, 150 KW PV-BESS model has been modeled in Simulink tool which can be able to meetup residential load demand up to 132 KW.

Table 4.1: Model Specification of 150 kW Off-grid PV- BESS power plant.

Components	Specifications
Solar PV	150 KW (Base panel 305.226 W SunPower SPR 305E, Voc-64.2 V, Isc=5.96 A, Temp Co-eff of Voc=-0.27269) Parallel strings- 62 Series connected module per strings- 8
Residential Load	132 KW, 415 V, 50 Hz (Δ- Configuration)
BESS	48 V 2750 Ah (132 KWh)
DC-DC Converter	Boost (PV to Load); Control- MPPT Incremental conductance. Buck (PV to BESS); Control- PWM based Duty Cycle Control (DCC). Boost (BESS to Load); Control- PWM based Duty Cycle Control (DCC).
Charge Controller Control	SOC, PV power and Load power-based estimation.
DC-AC Inverter	3-Φ VSI (Gain of Duty Ratio- 72%)
Measurements	PV Array- Vpv, Ipv, Ppv BESS- SOC, Ib,Vb Residential Load- Pload, Va,Ia

Based on the component's specifications stated in table 4.1, we have designed off-grid PV-BESS plant in Simulink tool. Information about irradiation and temperature inputs of PV array has depicted in table 4.2.

Table 4.2: Plant Operational Inputs- PV array (Finland)

Parameter	Values
Temperature	10°C to 30°C
Irradiance	750 W/m^2 to 1010 W/m^2

From table 4.2, we can see, operational inputs of PV array which has been generated using a signal builder. Timeframe for inputs operation in the signal builder has been initiated to 2.4 minutes. Modelling of such data has been initiated based on the environmental test conditions of PV-BESS power plants in Finland. Graphical representation of time-based irradiance and temperature data for 150 KW off-grid PV-BESS plant in Finland which has been stated below in figure 4.3.

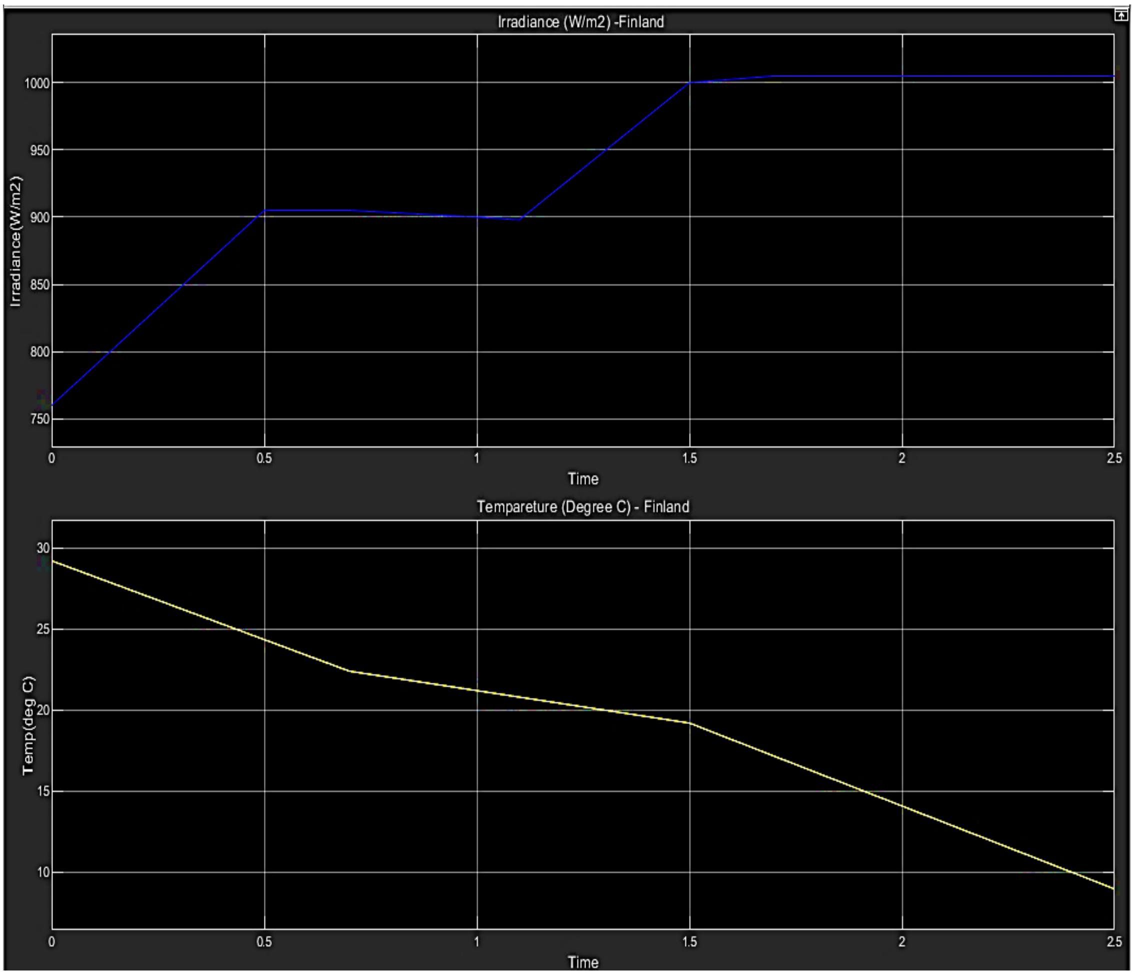


Figure 4.3: Time series plot of irradiance and temperature for 150 kW PV-BESS Plant.

In Simulink tool, we are performing PV-BESS plant based on the PV and Load power sensing and the estimation of SOC level of BESS. Simulation results based on such conditions is discussed below. We tried to model temperature and irradiation signal as performance parameter under typical weather condition of Finland (i.e. practically, it can be different during 24-hour period) to show the performance and operation of PV-BESS plant under weather variations.

Condition (1) [C1-FIN]: When, PV power (Ppv) is greater than Residential load Power (Pload) and SOC of BESS is less than 50 then PV is supplying power to the load (i.e. S1 is ON) and BESS is also charging from the PV array (i.e. S2 is ON) and no discharge is happening from BESS (i.e. S3=0). The results of PV-BESS plant based on the condition is below:

In figure 4.4, PV power has started increasing based on the changes in temperature and irradiance from 0.4 minutes whereas load power is also start increasing according to PV power and this phenomenon exits till 1.5 minutes. After, 1.5 minutes PV power and load power becomes constant till the end of operation. Moreover, having enough power from PV is allowing BESS to charge (i.e. after 0.5 minutes) and delivering to load demand side during the time period and no power is drawing from BESS. So, BESS power remains constant within the period of operation.

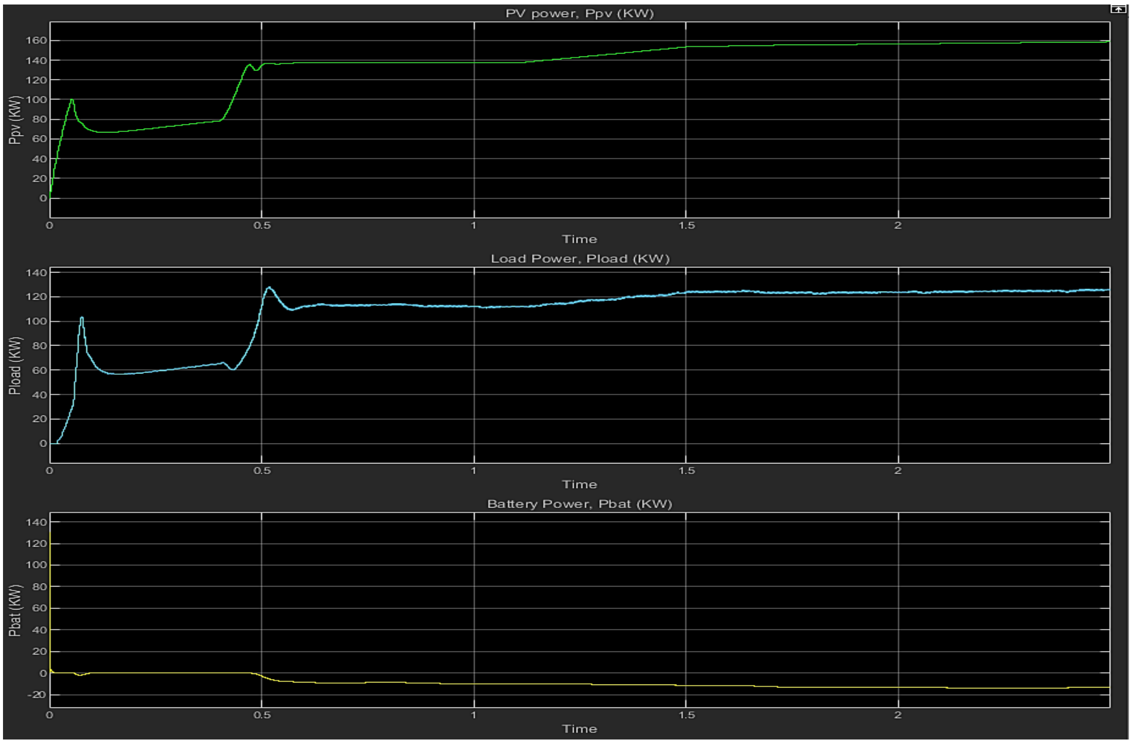


Figure 4.4: Time series plot of PV power, load power and BESS power. [C1 - FIN]

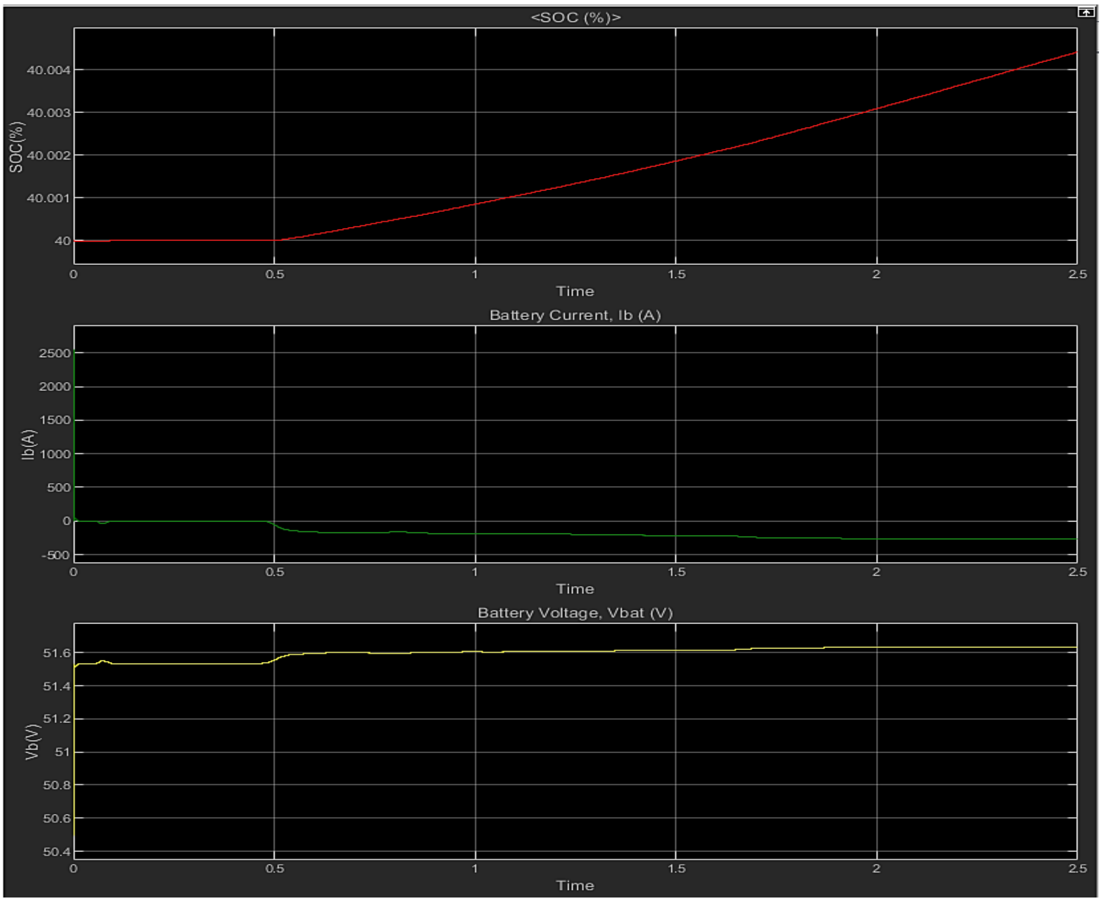


Figure 4.5: Time series plot of SOC, BESS current and BESS voltage. [C1 - FIN]

Figure 4.5 shows that, BESS remains constant till 0.5 seconds of operation and after it starts charging till the end of operation. During charging phase, BESS current is decreasing, and BESS voltage is increasing.

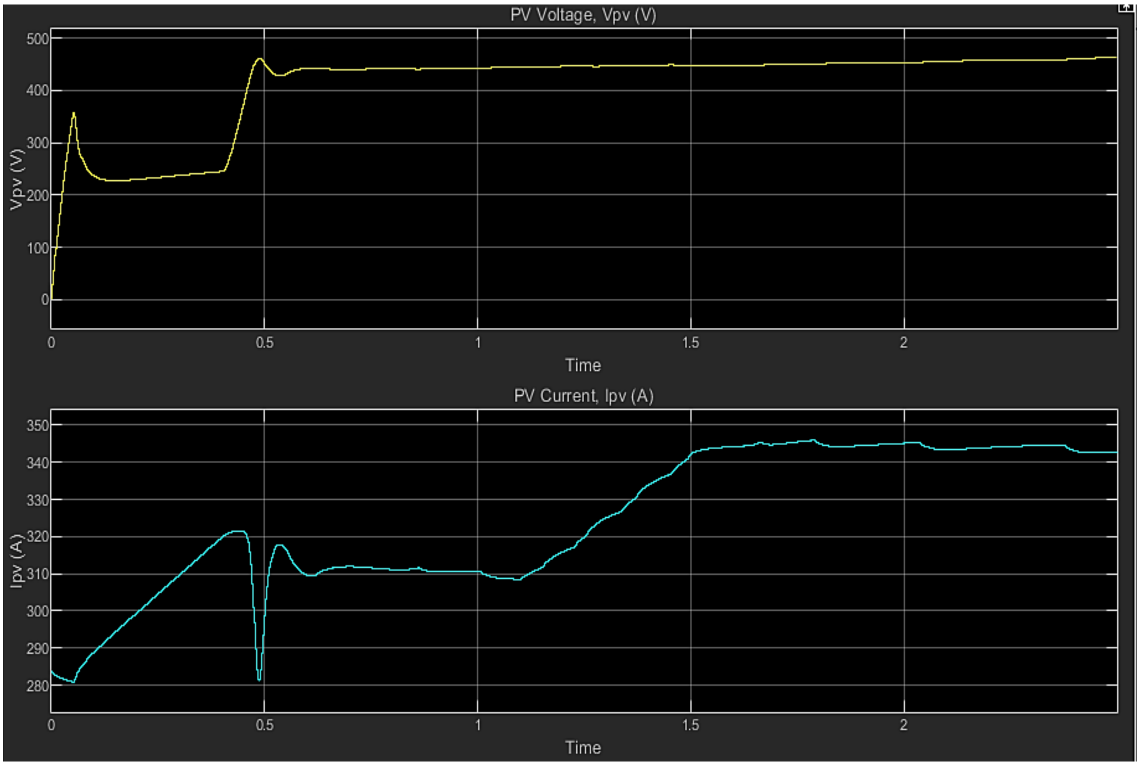


Figure 4.6: Time series plot of PV voltage and PV current. [C1 - FIN]

In figure 4.6, we can see the changes in PV voltage and current according to change in irradiation and temperature with respect to time. Vpv remains constant after 0.5 minute where Ipv is fluctuating till 1 minute and after that it start increasing till 1.5 minute. Finally, Ipv remains constant after 1.5 minute to till the end of operation.

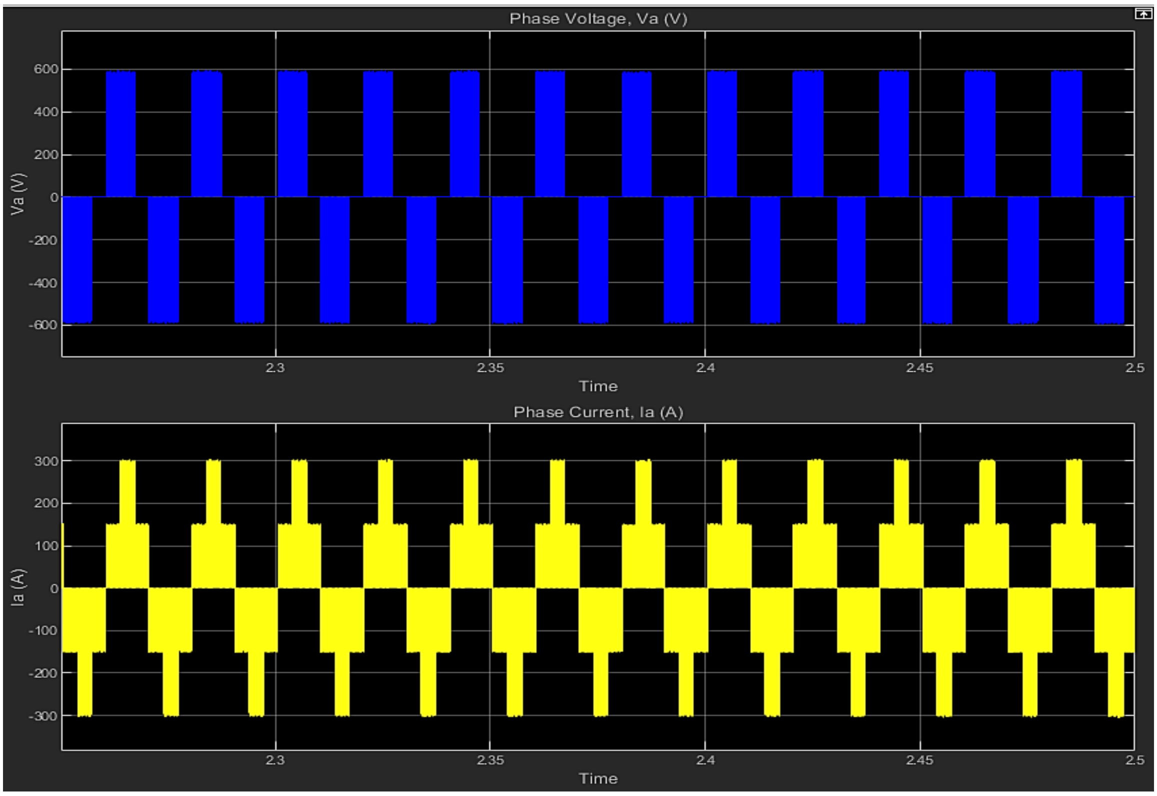


Figure 4.7: Time series plot of load voltage and load current. [C1- FIN]

From figure 4.7, we can see that, voltage and current of load is following the same manner and maintain constant values and sinusoidal waveshapes with respect to time. Time series plot has been taken the between time period of 2.25 and 2.50 minutes.

Condition (2) [C2-FIN]: When, PV power (Ppv) is less than Residential load Power (Pload) and SOC of BESS is greater than and equal to 80 then PV has stopped power to the load (i.e. S1 is OFF) and BESS is discharging to load (i.e. S3 is ON) and no charging of BESS is happening (i.e. S2 is OFF). The results of PV-BESS plant based on the condition is as follows:

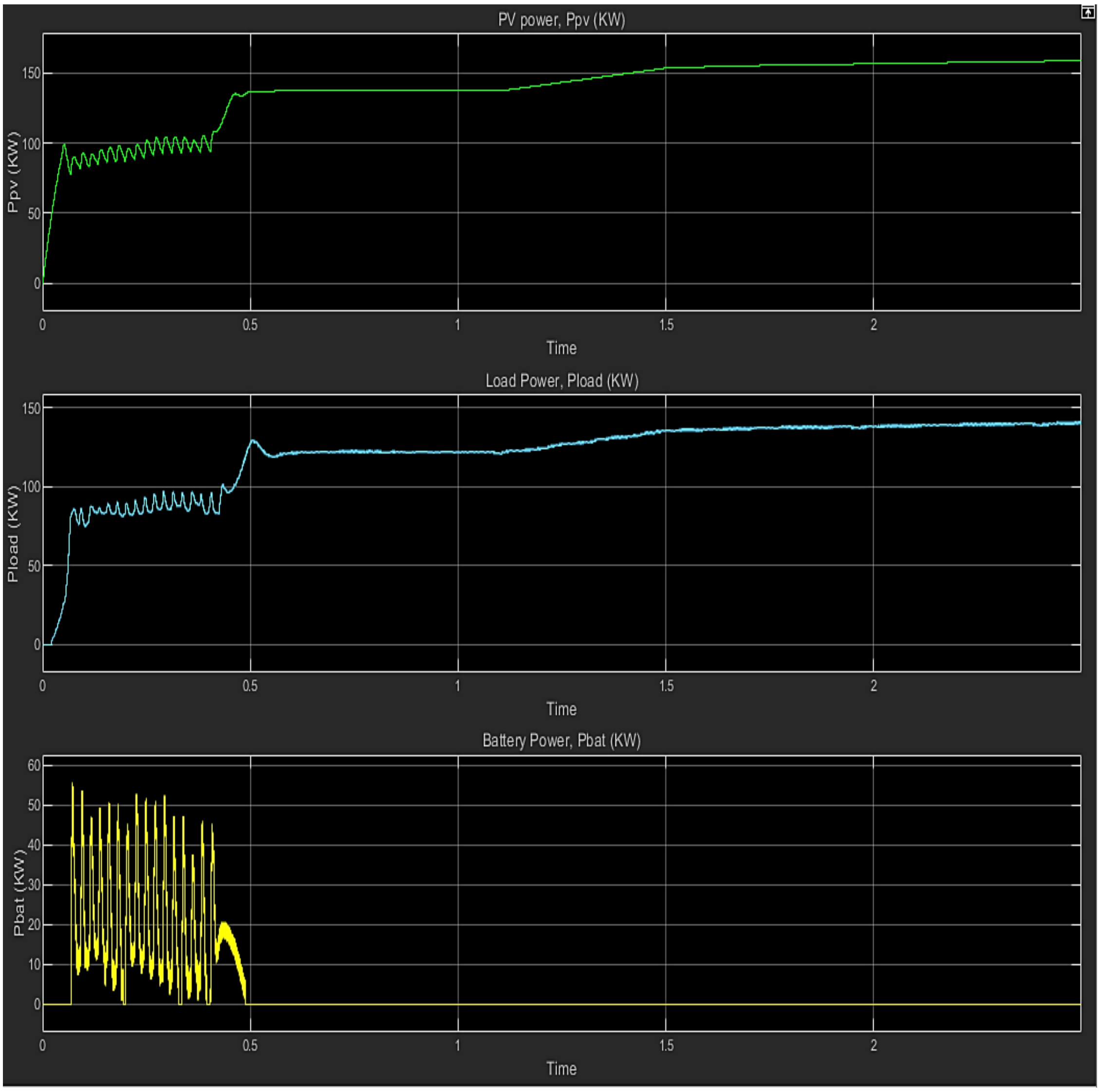


Figure 4.8: Time series plot of PV power, load power and BESS power. [C2 – FIN]

In figure 4.8, it can be noticed that, BESS is discharging between 0 to 0.5 minutes and after that PV power starts increasing with respect to increase in irradiance and supplying the load side constantly after 0.5 minute. BESS has fully discharged at 0.5 minute and PV is delivering to load side because the initial state of switch between PV and load (i.e. S1) is ON for reliability purposes. On the other hand, BESS may run out of supplying demand of load side. That’s why, PV power is delivering uninterruptedly when BESS has emptied and PV start generating more power.

In figure 4.9, SOC tells that, BESS is discharging from 90% of its SOC state till 0.5 minute and after that BESS is emptied. Over that period, we can see increase in current, Ib and decrease in voltage, Vb. From 0.5 minute, current, Ib becomes zero and voltage, Vb becomes constant.

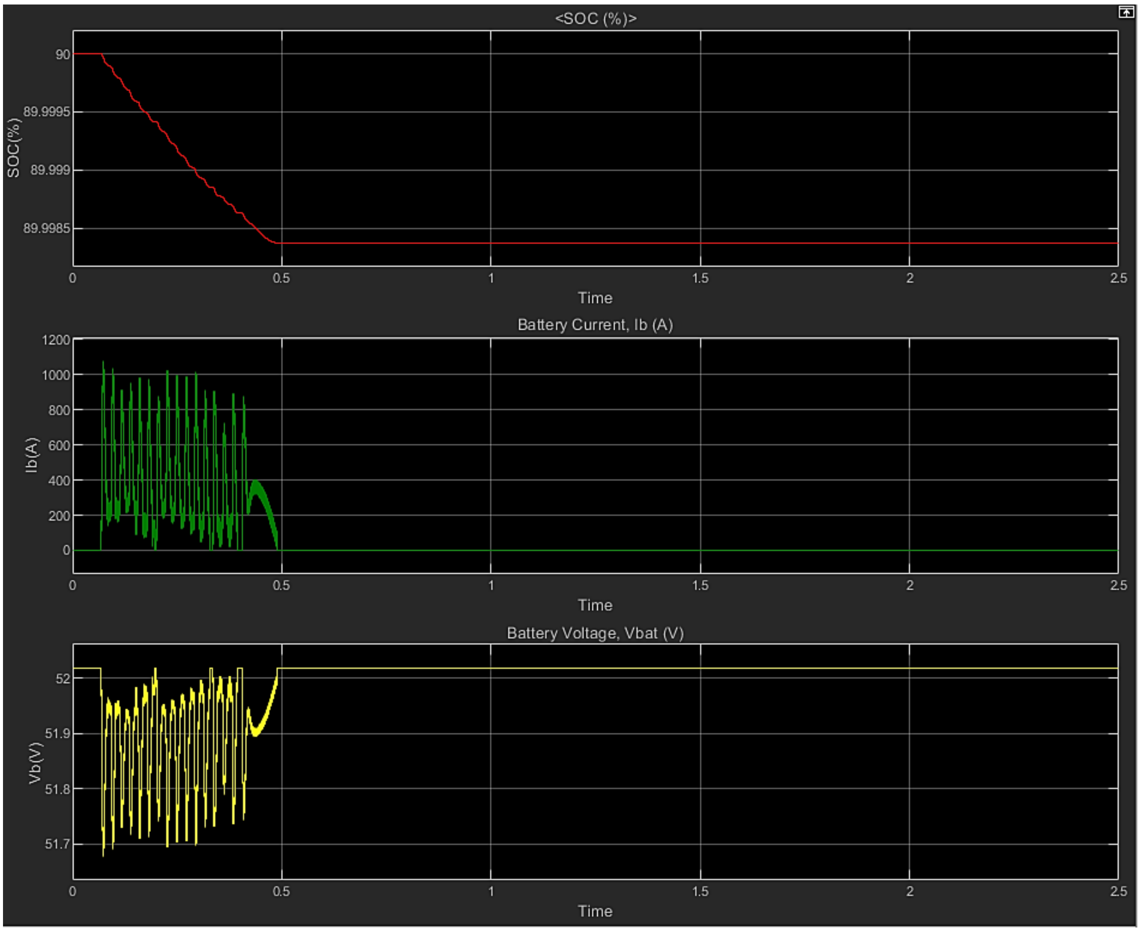


Figure 4.9: Time series plot of SOC, BESS current and BESS voltage. [C2 – FIN]

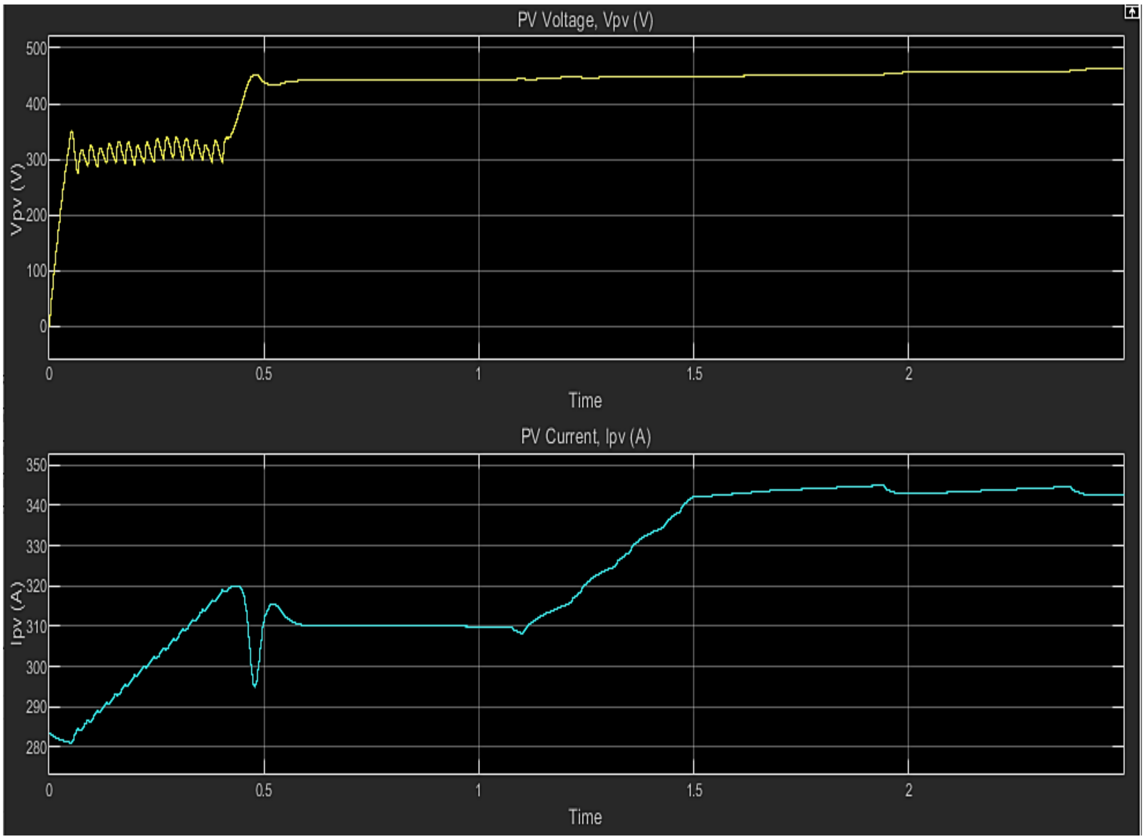


Figure 4.10: Time series plot of PV voltage and PV current. [C2 – FIN]

From figure 4.10, PV voltage is fluctuating till 0.4 minute and increased till 0.5 minute. After, 0.5-minute PV voltage, Vpv stabilizes and remains constant till the end of operation. On the other hand, PV current, Ipv is behaving the same as condition 1 during the operation which stabilizes after 1.5 minute. Sudden drops in PV current occurs at 0.4 minute is lower compared to PV current drops in condition 1.

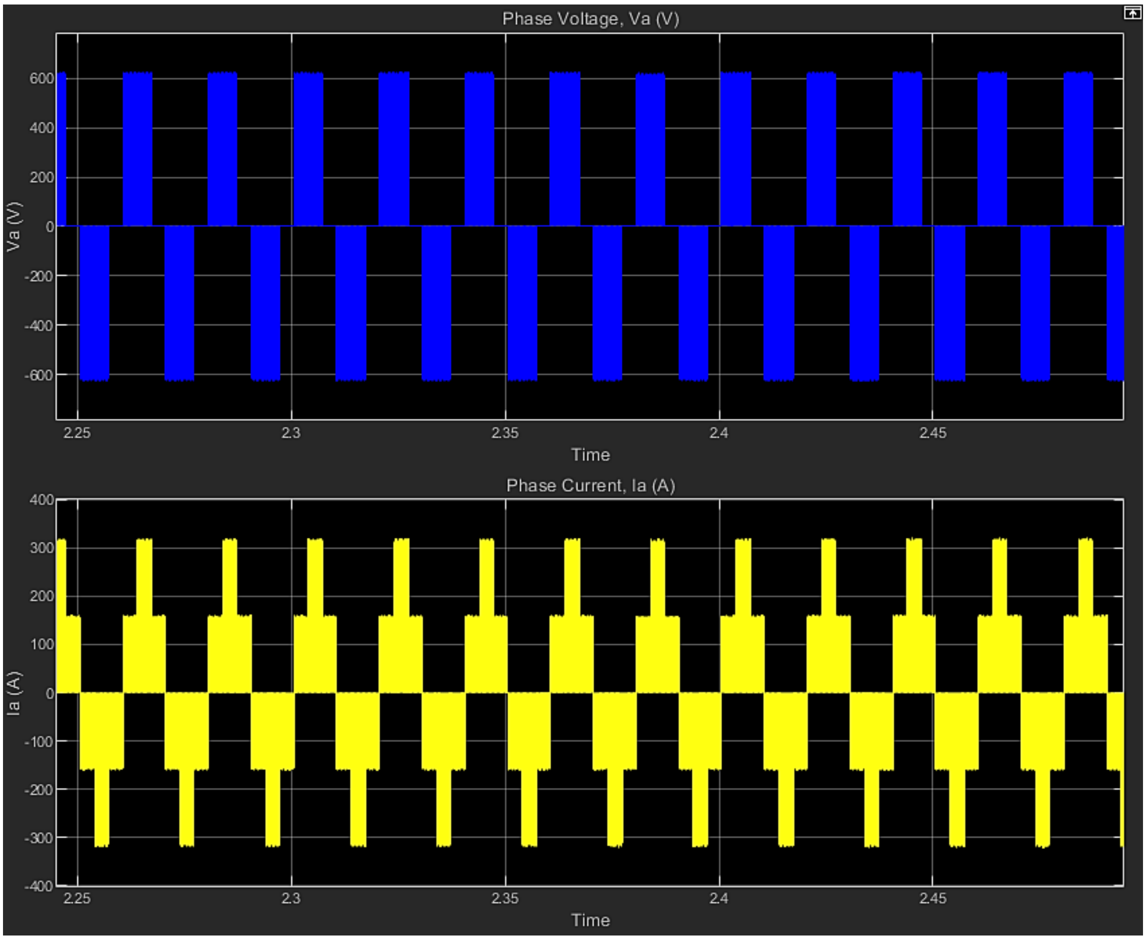


Figure 4.11: Time series plot of load voltage and load current. [C2 – FIN]

From figure 4.11, we can see sinusoidal operation over the operation time. Based on load power behavior, load voltage, Va and current, Ia is maintaining continuity. For this condition, time series plot has been taken between 2.25 and 2.50 minutes.

Condition (3) [C3 – FIN]: When, PV power (Ppv) is equal to Residential load Power (Pload) and SOC of BESS is between 50% and 80% then PV is supplying power to the load (i.e. S1 is ON) and BESS is not charging and discharging (i.e. S2 and S3 is OFF). The results of PV-BESS plant based on the condition is as follows:

In figure 4.12, PV power and load power are behaving same as condition 1. For this condition, PV is fully operational to load. As a result, no BESS power is charging from the PV and a no discharging to the load is happening.

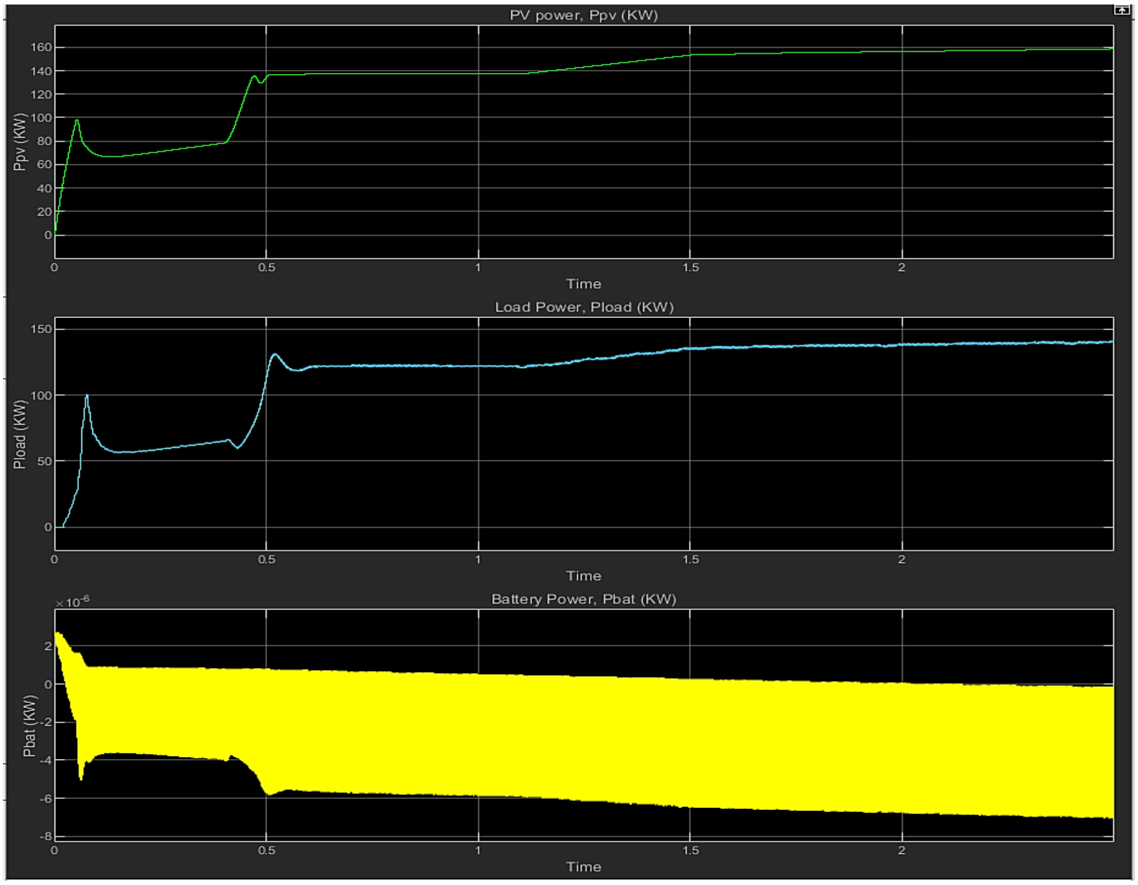


Figure 4.12: Time series plot of PV power, load power and BESS power. [C3 – FIN]

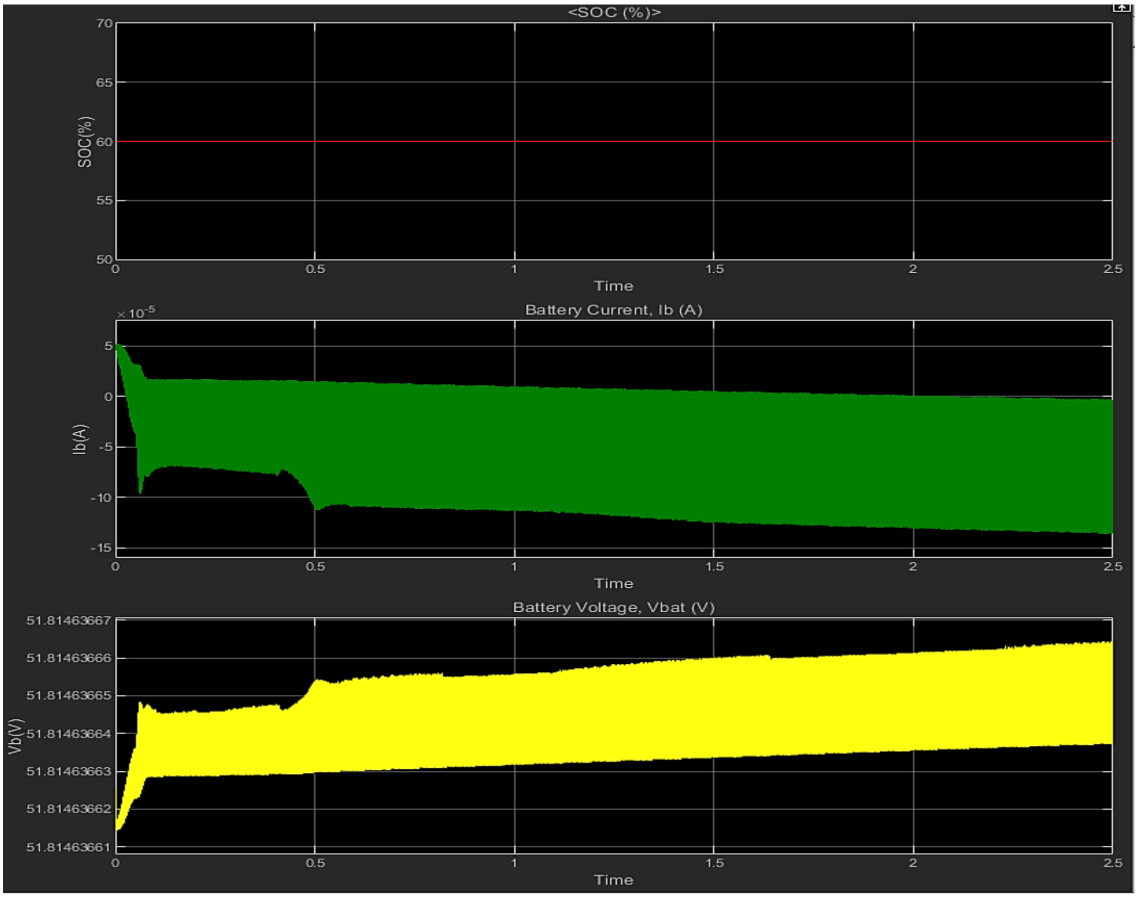


Figure 4.13: Time series plot of SOC, BESS current and BESS voltage. [C3 – FIN]

From figure 4.13, it is clear that, SOC remains constant at 60%. As a result, BESS voltage, Vb and current, Ib is constant as well. So, no BESS operation is happening.

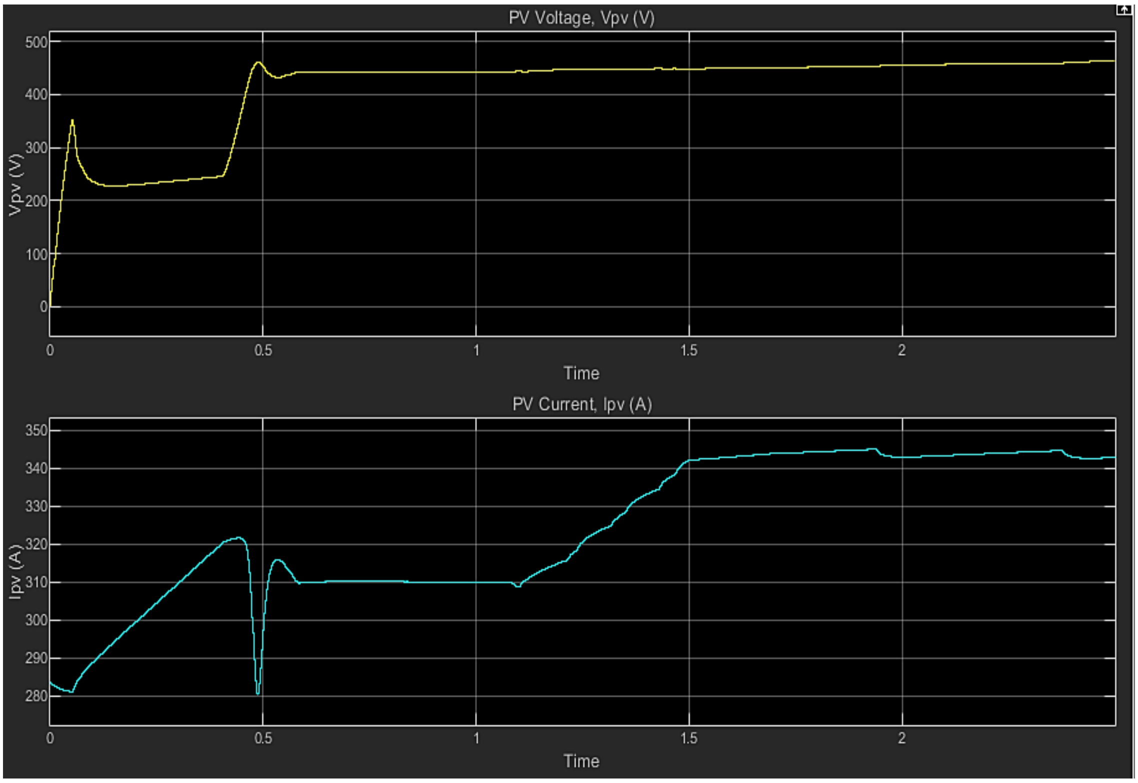


Figure 4.14: Time series plot of PV voltage and PV current. [C3 – FIN]

From figure 4.14, we can see similar scenario of PV voltage, Vpv and current, Ipv like condition 1. Here, PV is supplying to the load side constantly by maintaining constant voltage where current is increasing between 1.2 minute to 1.5 minute and stabilizing after 1.5 minute.

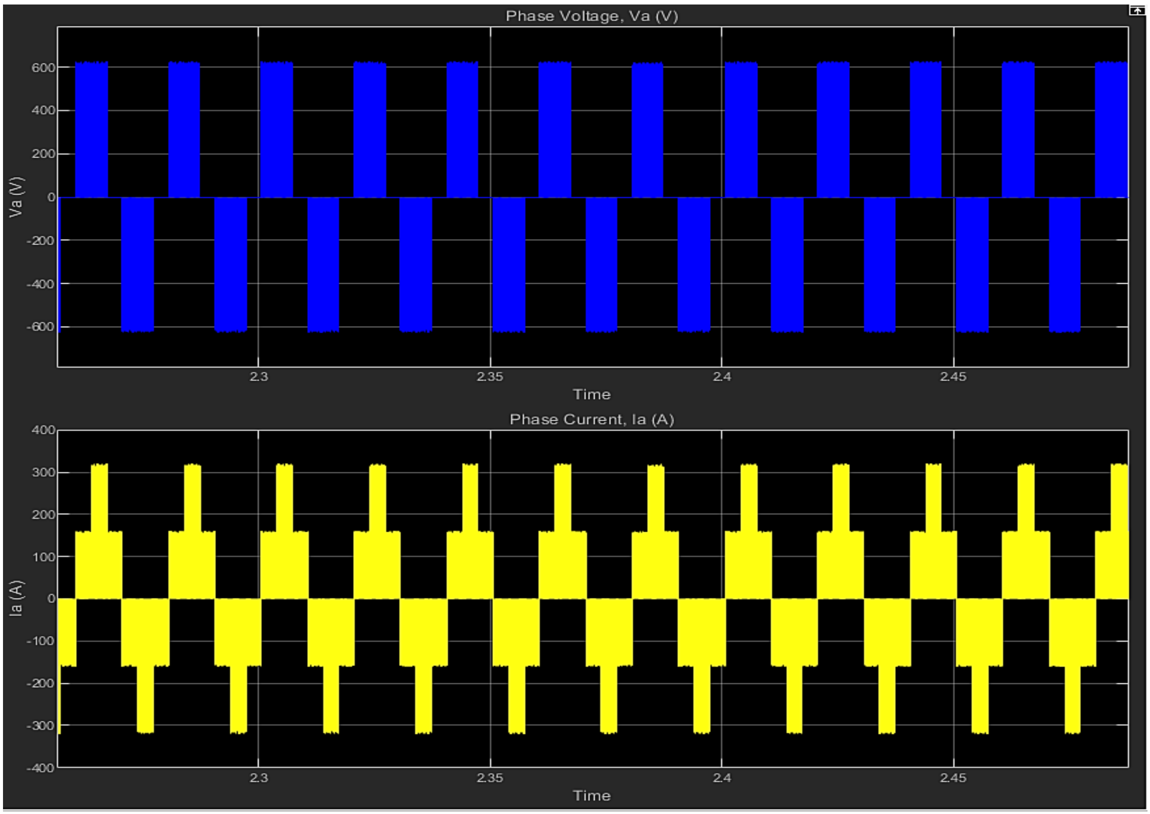


Figure 4.15: Time series plot of load voltage and load current. [C3 – FIN]

At figure 4.15, we can see no variations in phase voltage and current of load. Operation of voltage and current has taken between 2.25 and 2.50 minutes.

Case-Bangladesh:

For Bangladesh, 180 KW PV-BESS model has been modeled in Simulink tool which can be able to meetup residential load demand up to 158 KW.

Table 4.3: Model Specification of 180KW Off-grid PV- BESS power plant.

Components	Specifications
Solar PV	180 KW (Base panel 305.226 W SunPower SPR 305E, Voc-64.2 V, Isc=5.96 A, Temp Co-eff of Voc=-0.27269) Parallel strings-59 Series connected module per strings-10
Residential Load	158 KW, 415 V, 50 Hz (Δ- Configuration)
BESS	48 V 13626 Ah (654 KWh)
DC-DC Converter	Boost (PV to Load); Control- MPPT Incremental conductance. Buck (PV to BESS); Control- PWM based Duty Cycle Control (DCC). Boost (BESS to Load); Control- PWM based Duty Cycle Control (DCC).
Charge Controller Control	SOC, PV power and Load power-based estimation.
DC-AC Inverter	3-Φ VSI (Gain of Duty Ratio-72%)
Measurements	PV Array- Vpv, Ipv, Ppv BESS- SOC, Ib,Vb Residential Load- Pload, Va,Ia

Based on the component's specifications stated in table 4.3, we have designed off-grid PV-BESS plant in Simulink tool. Information about irradiation and temperature inputs of PV array has depicted in table 4.4.

Table 4.4: Plant Operational Inputs- PV array (Bangladesh)

Parameter	Values
Temperature	20°C to 40°C
Irradiance	700 W/m^2 to 1050 W/m^2

From table 4.4, we can see, operational inputs of PV array which has been generated using a signal builder. Timeframe for inputs operation in the signal builder has been initiated to 2.4 minutes. Modelling of such data has been initiated based on the environmental test conditions of PV-BESS power plants in Bangladesh. Graphical representation of time-based irradiance and temperature data for 180 KW off-grid PV-BESS plant in Bangladesh which has been stated below in figure 4.16.

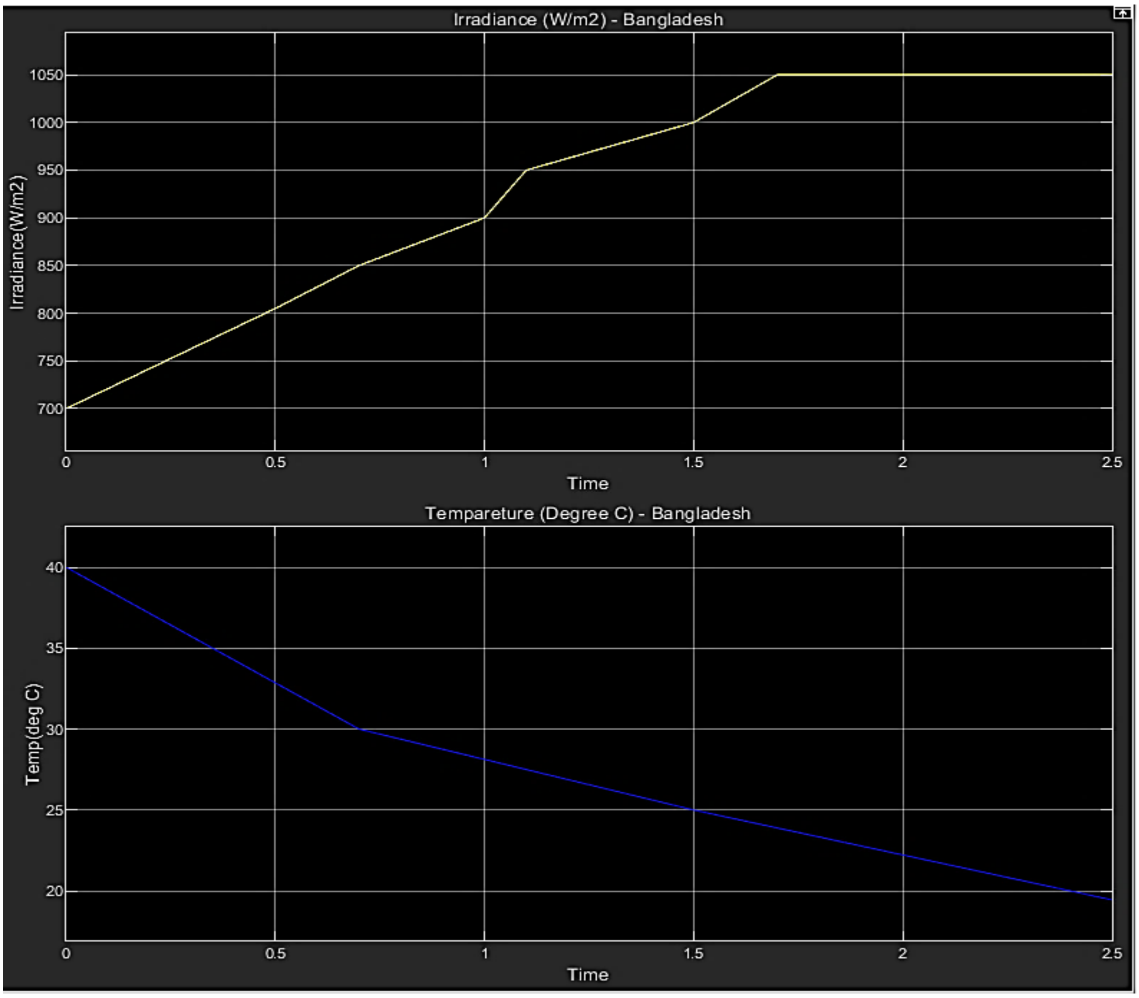


Figure 4.16: Time series plot of irradiance and temperature for 180 KW PV-BESS Plant.

In Simulink tool, we are performing PV-BESS plant based on the PV and Load power sensing and the estimation of SOC level of BESS. Simulation results based on such conditions is discussed below. We tried to model temperature and irradiation signal as performance parameter under typical weather condition of Bangladesh (i.e. practically, it can be different during 24-hour period) to show the performance and operation of PV-BESS plant under weather variations.

Condition (1) [C1-BD]: When, PV power (Ppv) is greater than Residential load Power (Pload) and SOC of BESS is less than 50 then PV is supplying power to the load (i.e. S1 is ON) and BESS is also charging from the PV array (i.e. S2 is ON) and no discharge is happening from BESS (i.e. S3=0). The results of PV-BESS plant based on the condition is below:

Below figure 4.17 shows the power outputs of PV, load and BESS. During this operation, PV power starts increasing linearly from 0.4 minute and stabilizes after 1.6 minute. On the other hand, BESS starts charging after 0.5 minute when PV power start increasing. Moreover, load power is also increasing as the load is feeding power from generated PV power.

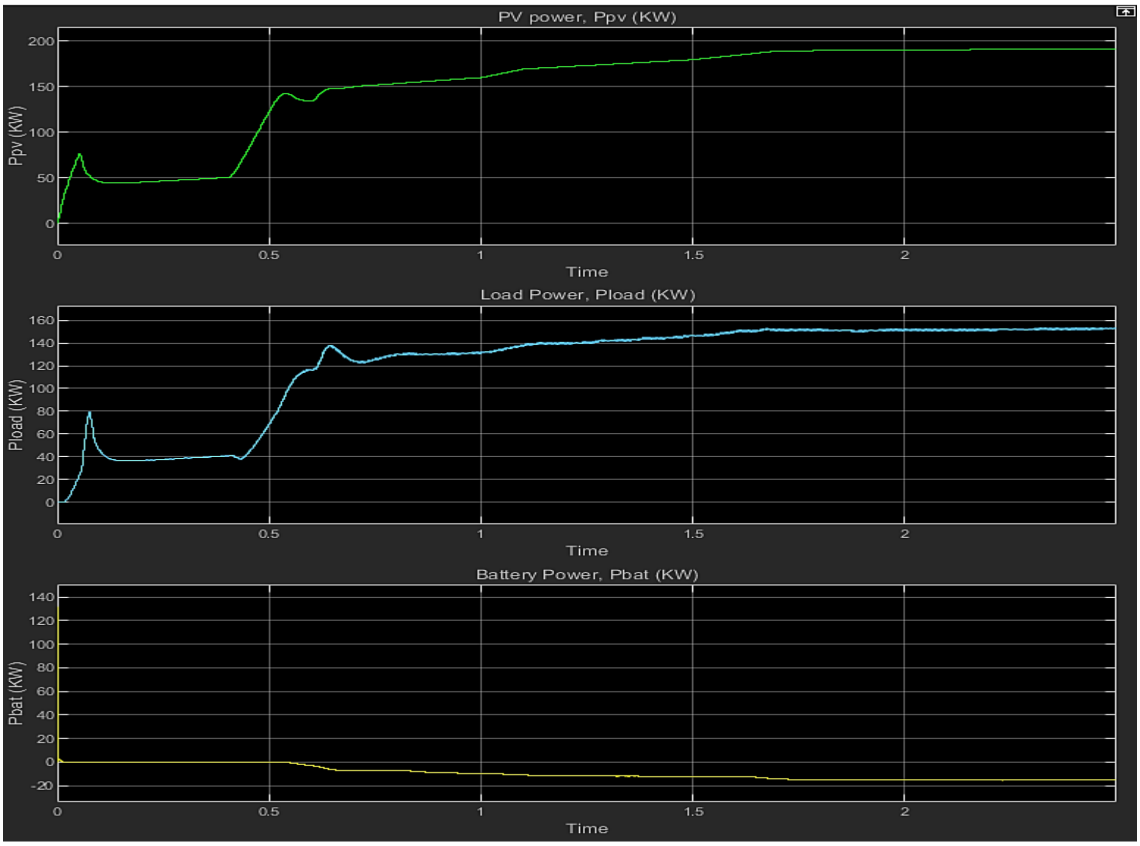


Figure 4.17: Time series plot of PV power, load power and BESS power. [C1 - BD]

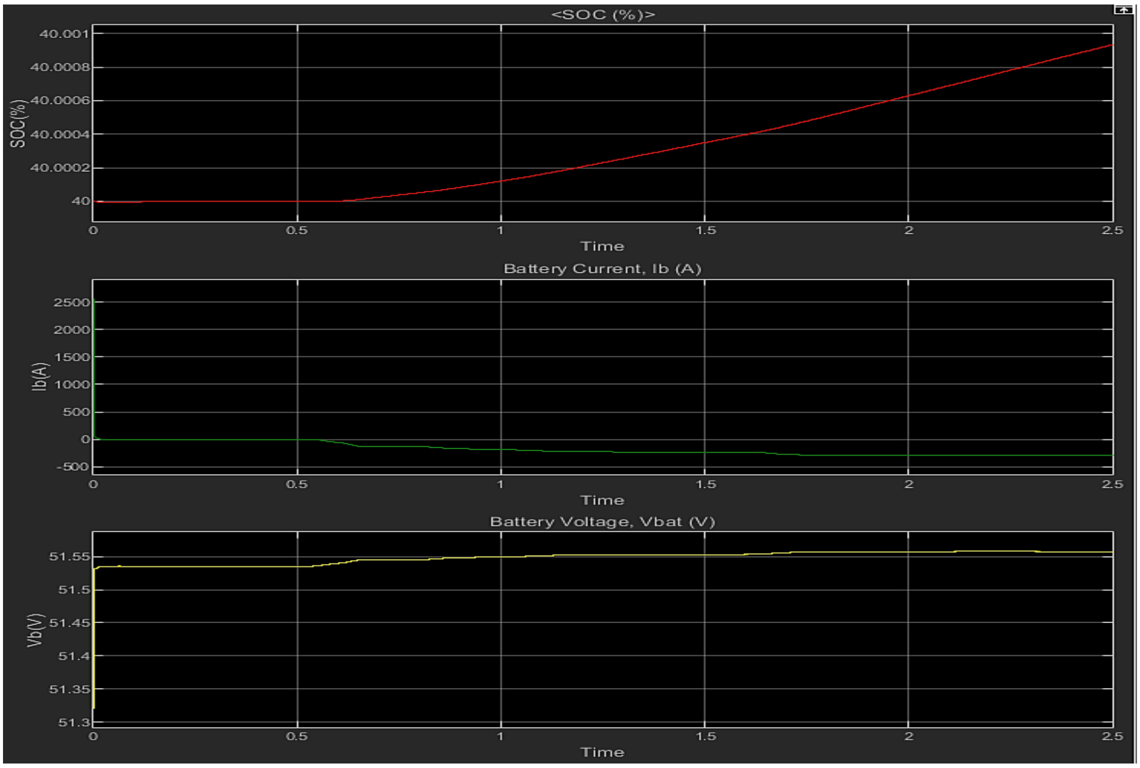


Figure 4.18: Time series plot of SOC, BESS current and BESS voltage. [C1 - BD]

From figure 4.18, we can that, BESS start charging from SOC state of 40 % after 0.6 minute to till the end of operation time. As a result, BESS current remains constant near zero and BESS voltage starts increasing slowly by maintaining charging voltage over the time period.

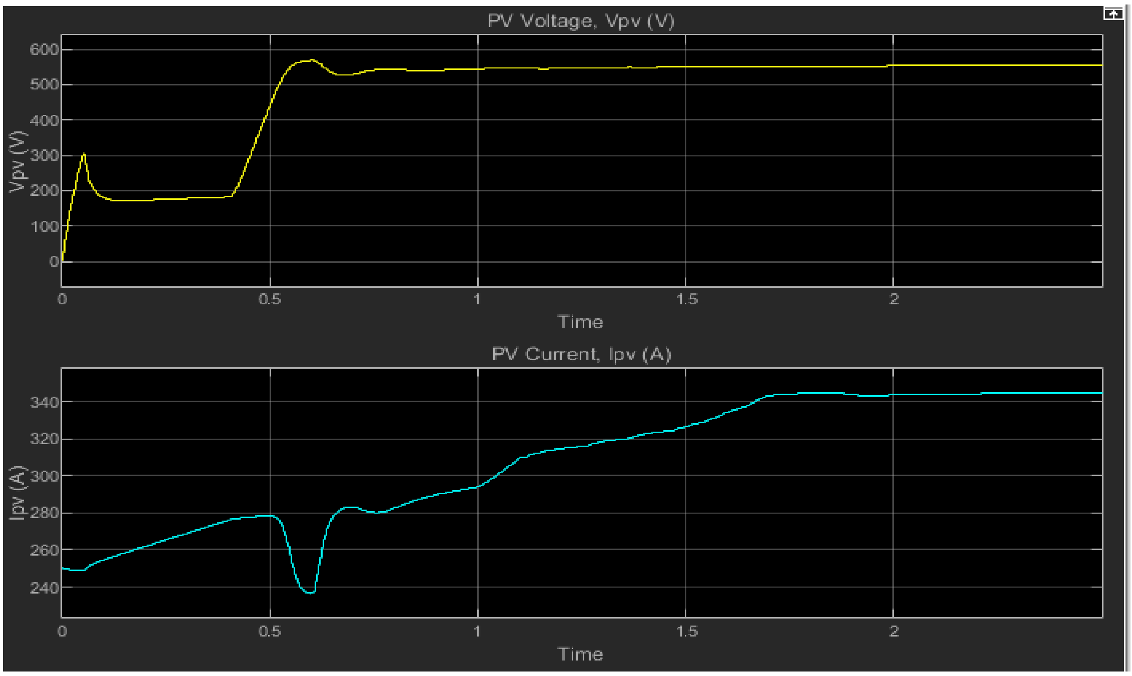


Figure 4.19: Time series plot of PV voltage and PV current. [C1 - BD]

In figure 4.19, PV voltage is increasing linearly from 0.4 minute to 0.6 minute and stabilizes after 0.6 minute. On the other hand, PV current increasing linearly where sudden drop happened in current at 0.6 to 0.7 minute. Finally, PV current stabilizes after 1.6 minute to till the end of operation.

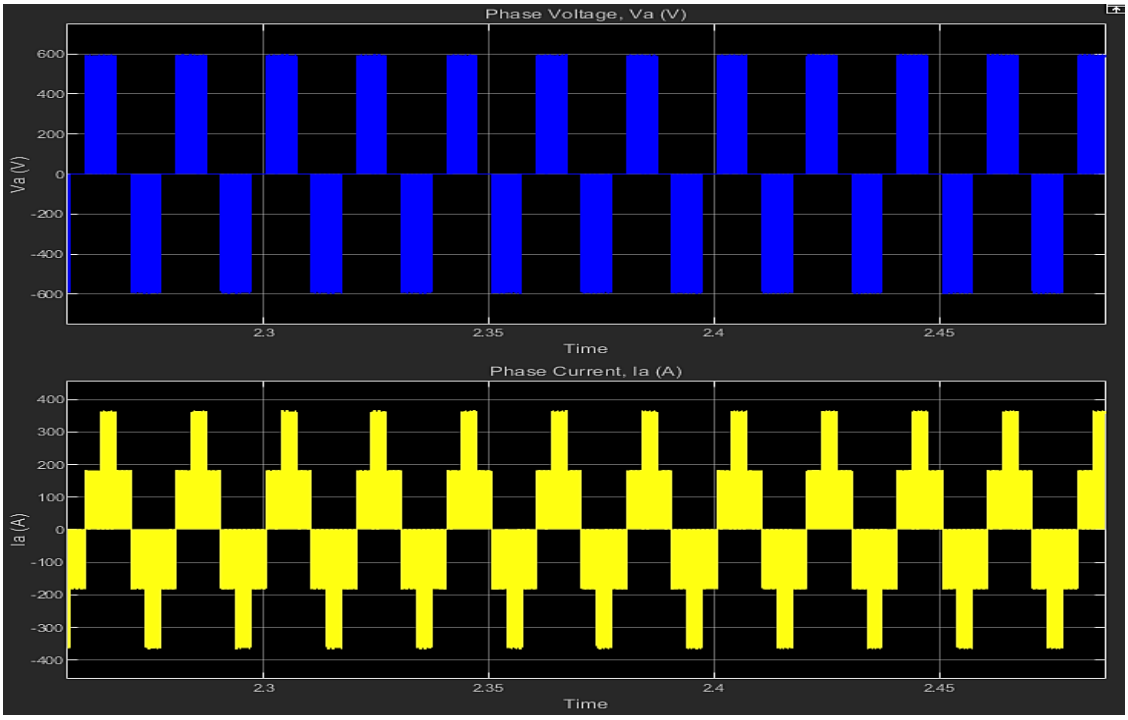


Figure 4.20: Time series plot of load voltage and load current. [C1 - BD]

Figure 4.20 shows continuous sinusoidal operation of phase voltage and current over the operation time. For this condition, time series plot has been taken between 2.25 and 2.50 minutes.

Condition (2) [C2-BD]: When, PV power (Ppv) is less than Residential load Power (Pload) and SOC of BESS is greater than and equal to 80 then PV has stopped power to the load (i.e. S1 is OFF) and BESS is discharging to load (i.e. S3 is ON) and no charging of BESS is happening (i.e. S2 is OFF). The results of PV-BESS plant based on the condition is as follows:

In figure 4.21, we can see that, BESS start draining from 0 minute to 0.6 minute because in that time PV power is less than load power which allows BESS to operate. After 0.6-minute, PV power start increasing and supplying to the load side. As a result, load power is also increasing with respect to time. Both PV and load power stabilizes after 1.5 minute and remains constant till the end of operation. On the other hand, BESS stops working after 0.6 minute.

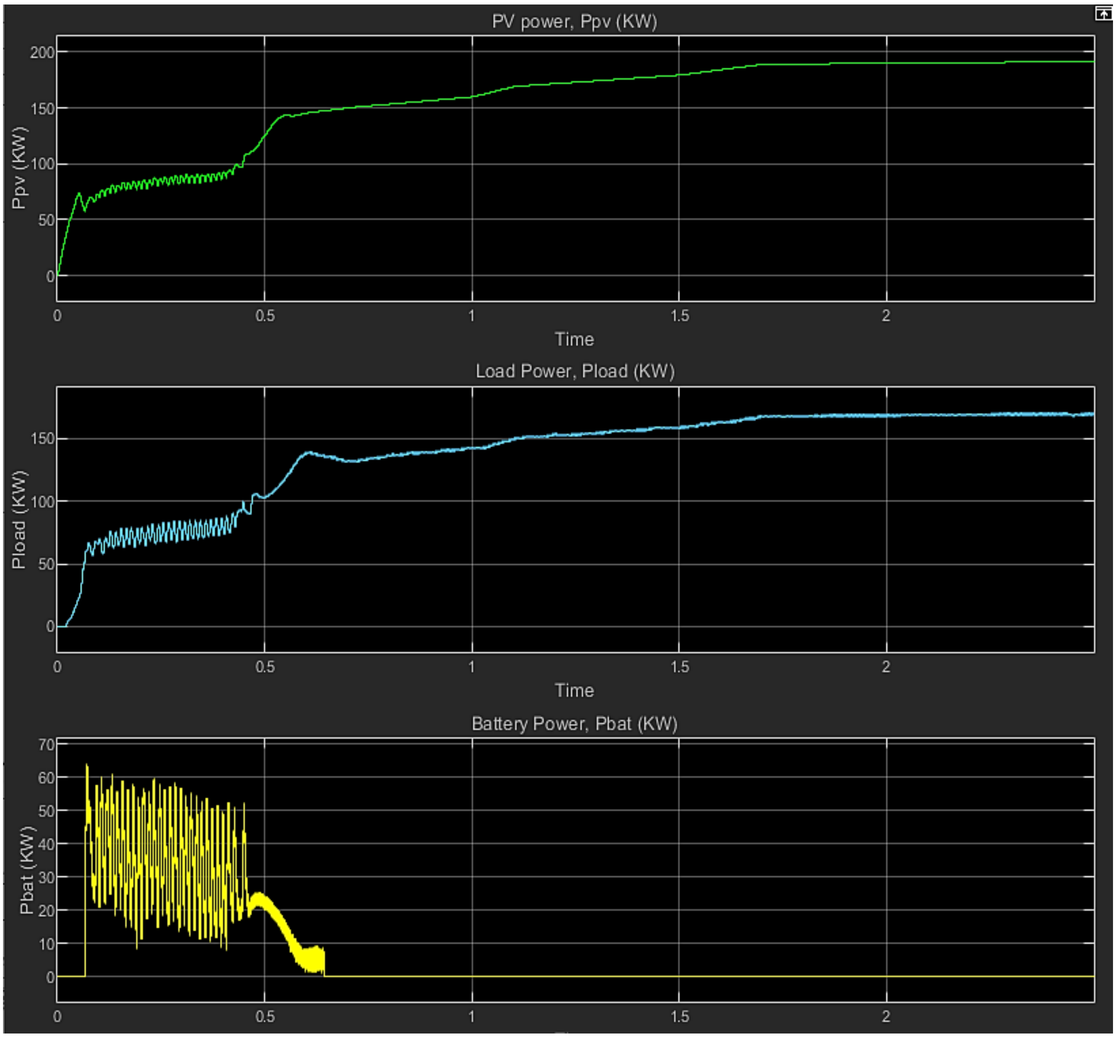


Figure 4.21: Time series plot of PV power, load power and BESS power. [C2-BD]

In figure 4.22, BESS is discharging from 90 % SOC level till 0.6 minute. Besides, BESS current is increasing and fluctuating over the time period and voltage behaves the same and discharging by maintaining discharge voltage. After 0.6-minute, BESS current becomes zero and voltage remains constant at maximum discharge value till the end of operation (i.e. BESS stops supplying after 0.6 minute).

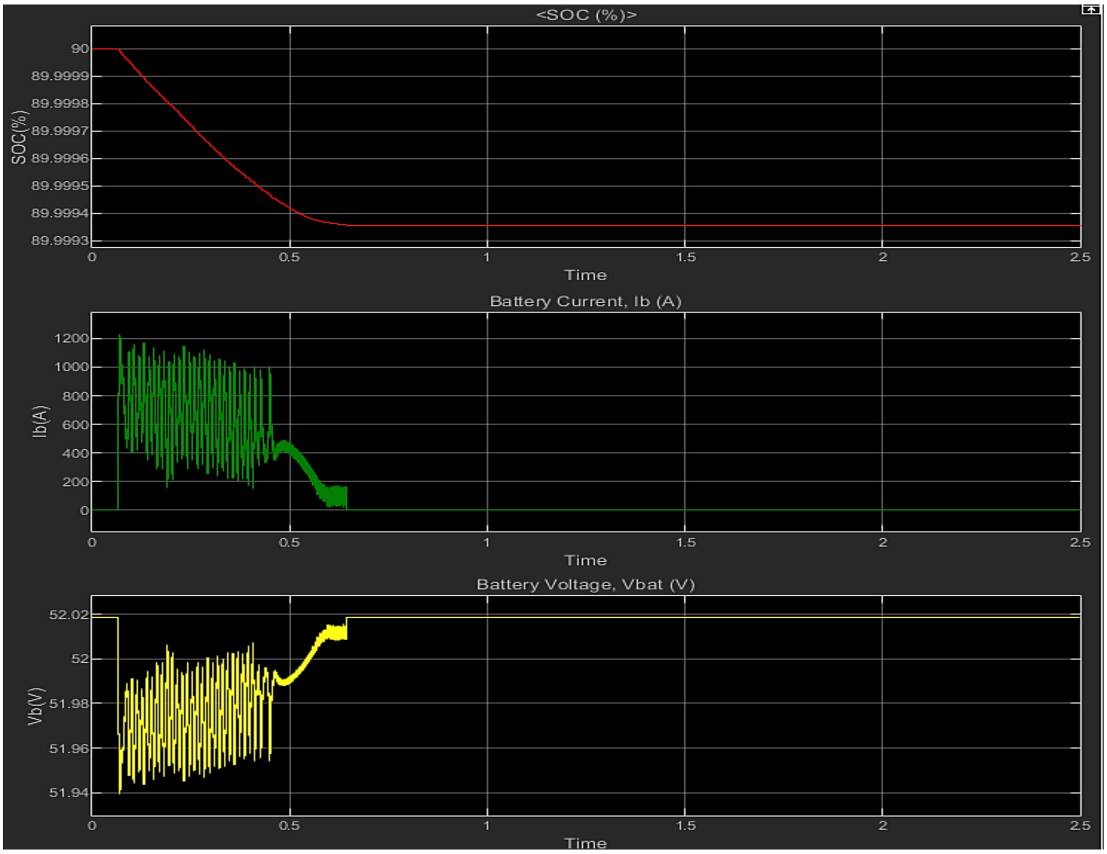


Figure 4.22: Time series plot of SOC, BESS current and BESS voltage. [C2 - BD]

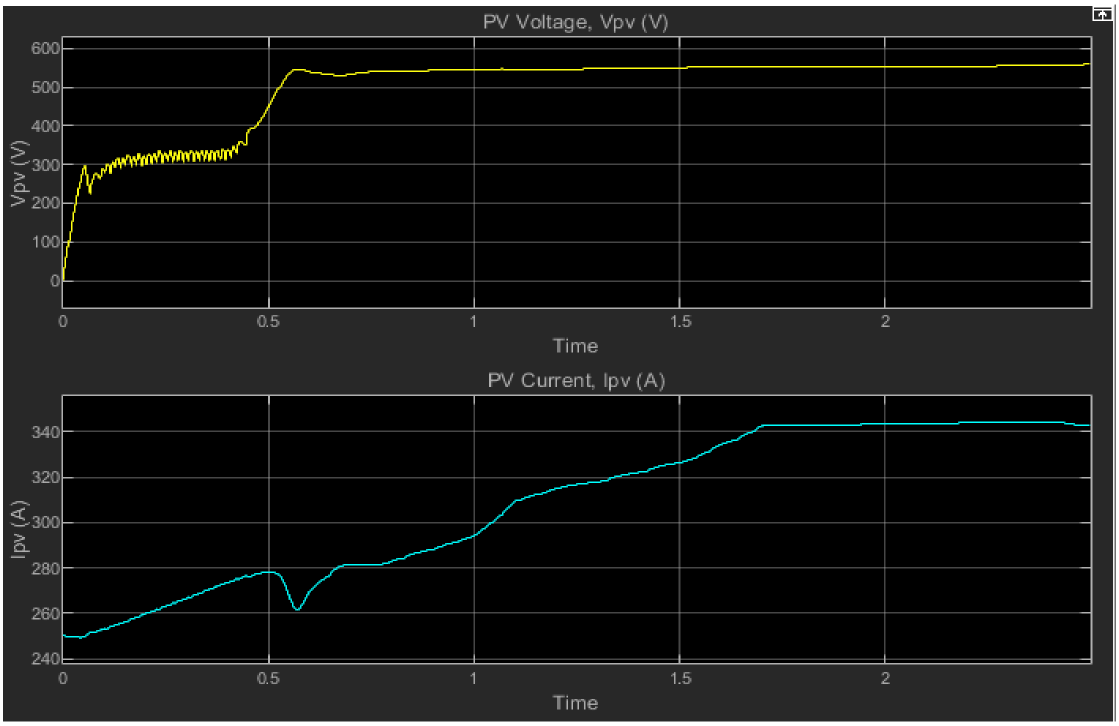


Figure 4.23: Time series plot of PV voltage and PV current. [C2 - BD]

From figure 4.23, PV voltage is fluctuating till 0.4 minute and increased till 0.6 minute. After, 0.6-minute PV voltage, Vpv stabilizes and remains constant till the end of operation. On the other hand, PV current, Ipv is behaving the same as condition (1) during the operation which stabilizes after 1.6 minute. Sudden drops in PV current occurs at 0.6 minute is lower compared to PV current drops in condition 1.

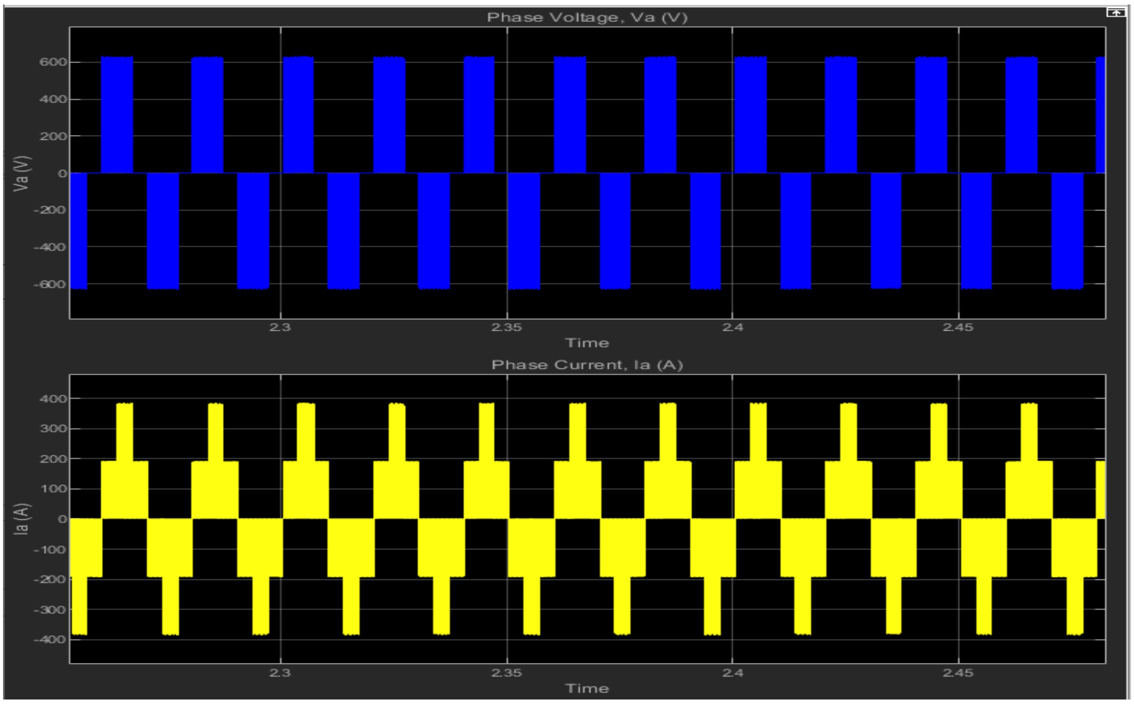


Figure 4.24: Time series plot of load voltage and load current. [C2 - BD]

At figure 4.24, no variations in phase voltage and current of load (i.e. continuous operation). Operation of voltage and current has taken between 2.25 and 2.50 minutes.

Condition (3) [C3 – BD]: When, PV power (Ppv) is equal to Residential load Power (Pload) and SOC of BESS is between 50% and 80% then PV is supplying power to the load (i.e. S1 is ON) and BESS is not charging and discharging (i.e. S2 and S3 is OFF). The results of PV-BESS plant based on the condition is as follows:

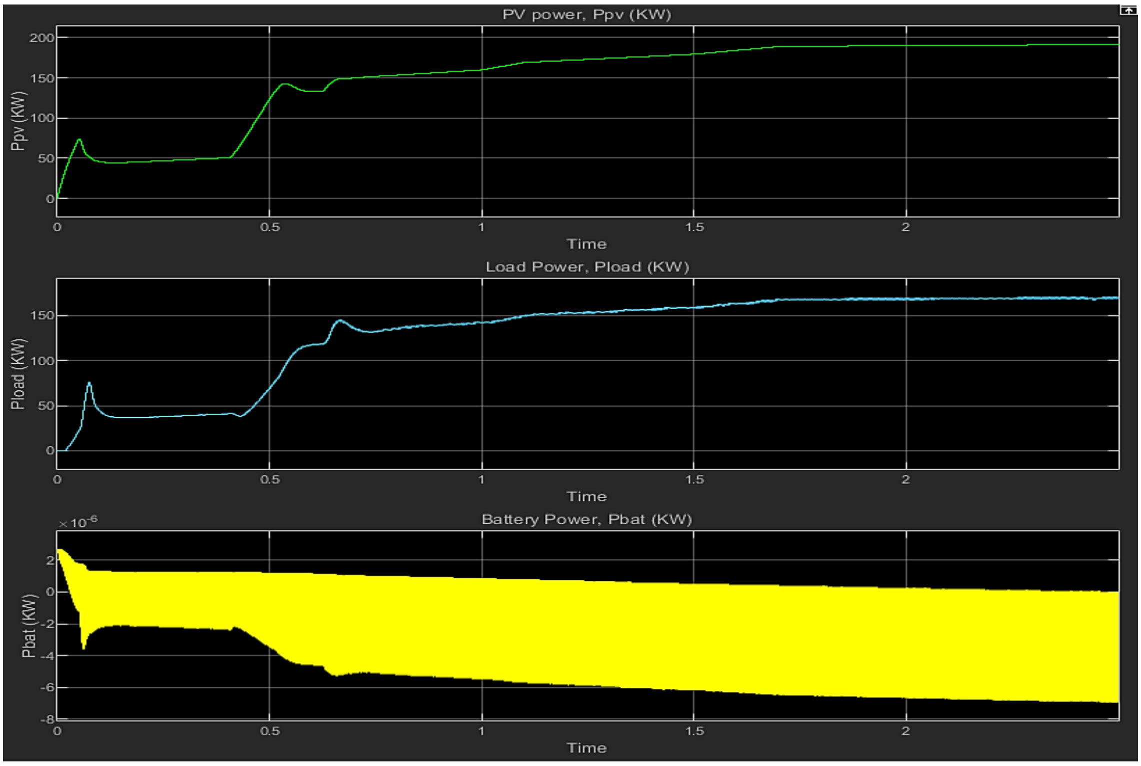


Figure 4.25: Time series plot of PV power, load power and BESS power. [C3 - BD]

Figure 4.25 shows PV power and load power are behaving same as condition 1. For this condition, PV is fully operational to load. As a result, no BESS power is charging from the PV and a no discharging to the load is happening.

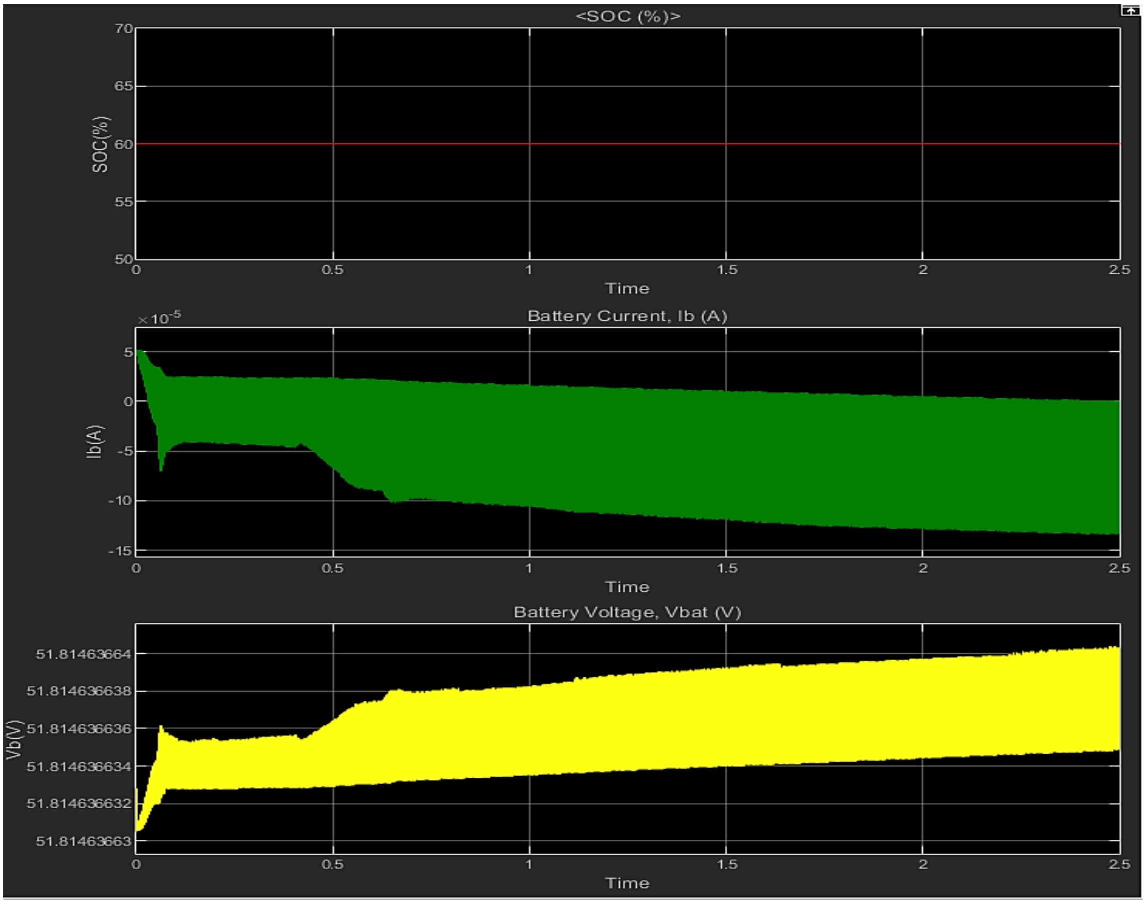


Figure 4.26: Time series plot of SOC, BESS current and BESS voltage. [C3 - BD]

In figure 4.26, SOC remains constant at 60%. As a result, BESS voltage, Vb and current, Ib is constant as well. So, no BESS operation is happening.

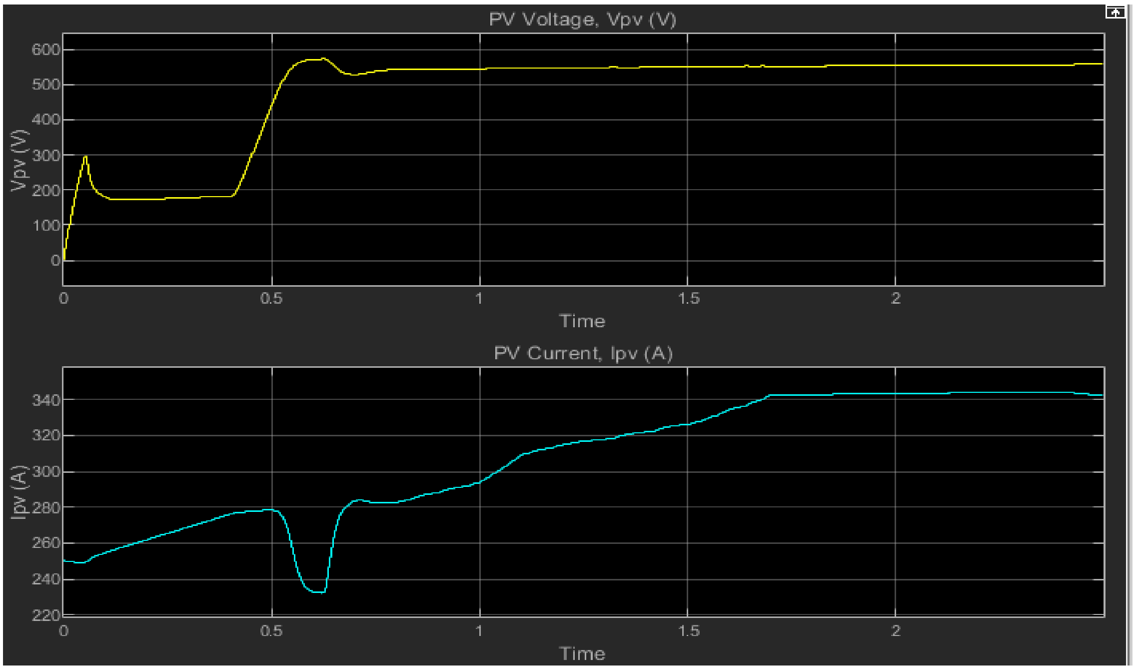


Figure 4.27: Time series plot of PV voltage and PV current. [C3 - BD]

In figure 4.27, PV voltage is increasing linearly from 0.4 minute to 0.6 minute and stabilizes after 0.6 minute. On the other hand, PV current increasing linearly where sudden drop happened in current at 0.6 to 0.7 minute. Finally, PV current stabilizes after 1.6 minute to till the end of operation. So, scenario of PV current and voltage is same in condition 3 and condition 1.

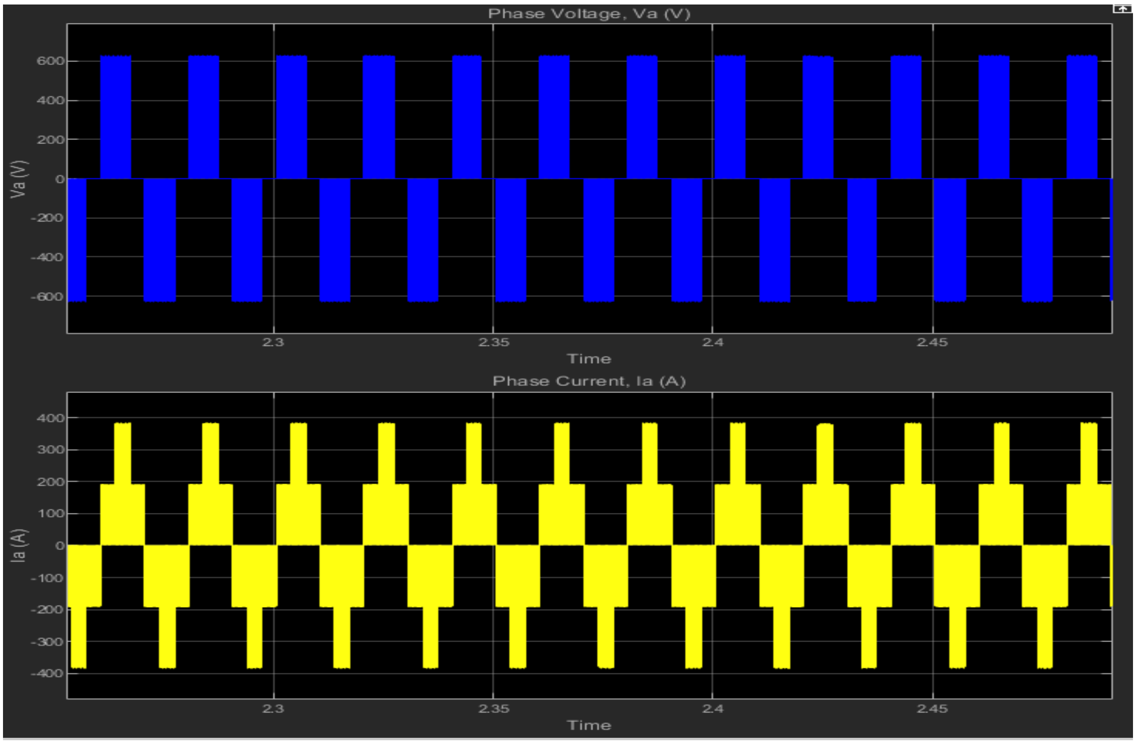


Figure 4.28: Time series plot of load voltage and load current. [C3 - BD]

In figure 4.28, we can see continuous operation of phase voltage and current. Moreover, phase voltage and current are maintaining the same behavior in all three conditions.

Finally, we can conclude that, 150 KW PV-BESS and 180 KW PV-BESS plant operations are quite similar for all the charge controlling conditions. Due to intermittent behavior of solar energy, irradiation and temperature (i.e. air temperature) are changing with respect to time. Most common thing to notice in the simulation results is to changes in PV current behavior. Since, boost converter is controlling by MPPT based incremental conductance method and sudden changes in irradiation value might cause some tracking error to the boost converter output (i.e. MPPT based incremental conductance algorithm is extracting PV power at maximum power points for any given irradiation input in PV array). Another reason might be sudden switching to heavy load initiated by charge controller algorithm causing such PV current drops phenomenon. [59] [60]

Since, we are concentrating on system's operation and performance analysis which demonstrates system-based research rather than component-based research (i.e. inverter control / Battery performance / PV power control etc.) so it can be said that we tried to generate desired output of proposed generation capacity and consumption demand based on charge controller operating modes and variations in PV inputs (i.e. temperature and irradiance). Moreover, isolation and stabilization are possible to bring in waveshapes of power, voltage by varying amplitude of PV side DC link capacitor and load side DC link capacitor (i.e. we varied during our simulation to get low fluctuation and variations in outputs).

Additionally, some limitations in our simulation can be overcome by integrating time-based and battery power estimation-based mechanisms in our designed charge controlling technique and by implementing regulated and optimized voltage control technique in the DC-AC inverter.

4.2 PART B: HOMER Pro

In this part of the thesis, we will cover simulation, optimization, economics analysis for our proposed model in both Finland and Bangladesh.

4.2.1 Overview of HOMER Pro Software

HOMER (Hybrid Optimization Model for Electric Renewable) Pro is a microgrid simulator by homer energy which is the global standard for optimizing microgrid design in all applications (i.e. both off-grid and grid connected solutions) for commercial, industrial and residential customers. This software has been developed by National Renewable Energy Laboratory (NREL) USA.

HOMER pro allows a number of energy technologies option which accounts for both renewable and non-renewable energy sources. moreover, this software has been standardized within the recent years with more advanced and resourceful features to initializing and developing modern smart grid infrastructure by integrating several energy resources under a micro-grid platform.

For our simulation, we have used Homer pro version 3.11.2 which was released in the year of 2017. [61] [62]

4.2.2 Objective of HOMER Pro Software

HOMER Pro offers wide range of activity based on microgrid simulation for public and private sectors. Moreover, this software helps to generate feasible and optimized model for grid development projects by performing necessary calculations of system's components, system's economy and sensitivity variables of system's components. For our thesis, Homer pro software has been used for following outcomes:

- **Simulation:** HOMER Pro has been used to simulate renewable based residential micro-grid model by integrating energy resources like solar and energy generation & conversion technologies like PV, batteries and inverters. In the software, simulation has been performed for a whole year (i.e 8760 Hours) and shows the outcome of electrical power generation data and consumption data. Moreover, HOMER performs calculations of energy balances for the implemented model.

- **Optimization:** Based on simulation results, HOMER sort out the optimized model of the implemented micro-grid which are based on cost inputs and constraints used for the system. Moreover, optimized model among simulated results offer the most economic advantage for the system (i.e. cost efficient among all the simulated result)

- **Economics:** HOMER perform all the necessary economics analysis which covers net present cost (NPC), operating cost, levelized cost of electricity (LCOE) of the project during its lifetime. Moreover, it compares the economics of sensitive and optimized model of the micro-grid and tells which option has a project value in terms of payback, rate of return and return on investment.

4.2.3 Simulation, Optimization and Economics Analysis-HOMER Pro

Case-Finland:
In HOMER pro software, we performed the microgrid simulation for our desired PV-BESS model in Finland. All the economics analysis and calculation of system's component has been initialized in euro. In figure 4.29 we show the microgrid model designed in the software.

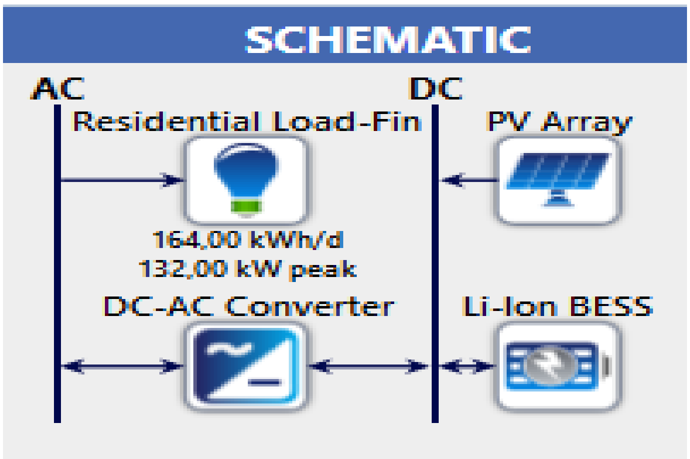


Figure 4.29: Homer Schematic of Off-grid PV-BESS plant - Finland

Figure 4.29 represents the implemented microgrid model of off-grid PV-BESS model for Finnish residential users. The model has been implemented based on component's sizes and cost information as an input to perform necessary data analysis for generating optimized and sensitive model in terms of economics parameter like NPC, Operating cost, LCOE and initial capital. In table 4.5, we can see the necessary component's sizes and cost information for our off-grid PV-BESS plant.

Table 4.5: Summary of cost and size information of PV-BESS plant components - Finland

Components	Model and Specifications	Base Component Price		Sizes	Unit		Prices	
			Quantity			Capital (€)	Replacement (€)	O & M (€)
Solar PV Array	Panasonic VBHN325SJ47 (Base Panel-325 W)	€209/pcs	306	100	kW	€63,954	€31,977	€0
			382	125	kW	€79,838	€39,919	€0
			459	150	kW	€95,931	€47,966	€0
Li-Ion BESS	Yangtze Battery (China Manufacturing Co.) Base Battery: 48 V 130 Ah (6,6 KWh)	€1,350/pcs	20	125	kWh	€27,000	€15,000	€0
			40	250	kWh	€54,000	€30,000	€0
			60	375	kWh	€81,000	€45,000	€0
DC-AC Converter	ABB PVS-120 Base Converter-120 kW	€7,500/pcs	1	120	kW	€7,500	€5,000	€100
			1	140	kW	€10,000	€6,000	€150
			1	160	kW	€12,000	€8,000	€200

Table 4.5 depicts brief information regarding components' size and costs which has been used to perform optimization and economics analysis in Homer Pro software. All the components information has been collected from the components company website. To perform optimization and economics analysis for our model, we used three inputs for each component. Moreover, PV array and BESS has maintenance free advantage over the period of their operational lifetime. As a result, there is no costs during their operation and maintenance period. Information about PV array inputs like solar irradiance and temperature data has been illustrated in figure 4.30 and 4.31.

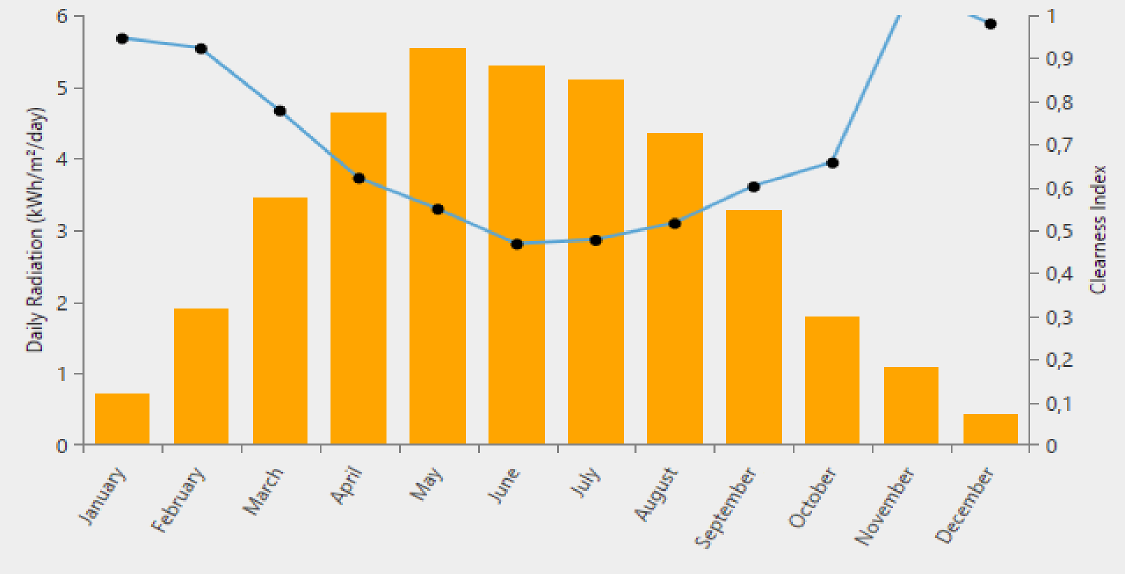


Figure 4.30: Homer representation of annual irradiation data of Finland.

Data's used in figure 4.30 has been used as an input for PV array operation to generate necessary electrical energy during 12-month period (i.e. 365 days). Inputs for irradiance has set based on the orientation of PV panel directly facing to the south at 43° tilt angle position (i.e. same irradiation data from chapter 2). For Finland, Annual average radiation is 3.14 kWh/m²/day.

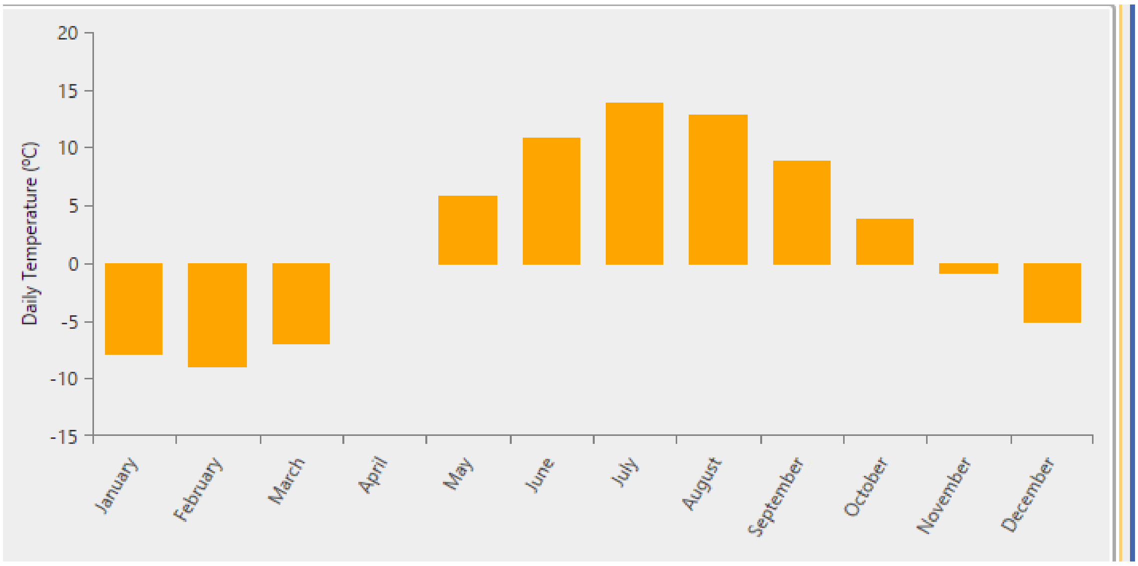


Figure 4.31: Homer representation of annual temperature data of Finland.

Figure 4.31 is showing the annual average temperature of Finland over the 12 months period. Temperature ranges between -8°C to 14°C. Data used for analysis has been collected from National Centres for Environmental Information. For Finland, annual average temperature 2.25 °C.

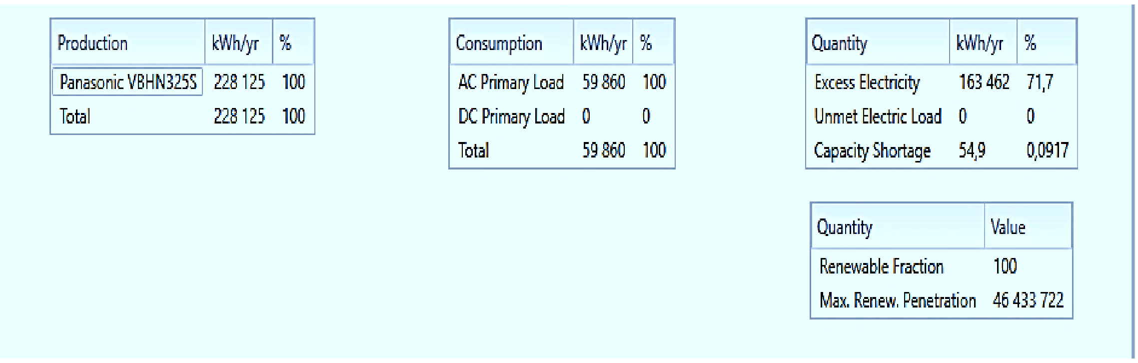
For Finnish case, temperature and irradiance data have been used for the city of Tampere in Finland case.

Table 4.6: Summary of optimized system of PV-BESS plant - Finland

PV	**142 kW**
BESS	382.8 kWh
Converter	**173 kW**
Dispatch	Homer Cycle Charging (CC)
Levelized COE	**0.145 €/kWh**
NPC	265,234 €
Operating Cost	**2,059 €/yr.**
Initial Capital	2,02,501 €

In table 4.6, we can see the overview of optimized PV-BESS model of Finland. This model has been generated based on the lowest LCOE, NPC and operating cost among the several results generated by Homer. For optimization analysis, Homer optimizer based on cycle charging has been initiated by the software. Homer cycle charging is a dispatch strategy which is based on operation of generator at full output power to serve the needs of primary load.

Table 4.7: Electrical Generation & Consumption of PV-BESS plant components – Finland



Production	kWh/yr	%
Panasonic VBHN325S	228 125	100
Total	228 125	100

Consumption	kWh/yr	%
AC Primary Load	59 860	100
DC Primary Load	0	0
Total	59 860	100

Quantity	kWh/yr	%
Excess Electricity	163 462	71,7
Unmet Electric Load	0	0
Capacity Shortage	54,9	0,0917

Quantity	Value
Renewable Fraction	100
Max. Renew. Penetration	46 433 722

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From table 4.7, we can see that yearly generation and consumption of PV energy where 142 kW optimized PV array is sufficient enough to generate power to meetup customer demand over the entire year. Consumption of PV energy is based on to serving load side and charging of BESS of the plant. For the model, renewable fraction is 100 % because of using only PV based power generation technology for the residential load. On the other hand, excess electricity is the excess energy produced by PV array over the entire year and it has been un-utilized for the plant and capacity shortage is defining the shortcoming which occurs between required operating capacity and actual amount of the operating capacity that the system can provide. Here, capacity shortage is only 55 kWh/ year which is negligible for our operational case.

Table 4.8: Cost summary of Optimized PV-BESS system components -Finland

Component	Capital (€)	Replacement (€)	O&M (€)	Fuel (€)	Salvage (€)	Total (€)
ABB PVS-120	13 280,35 €	11 585,46 €	7 069,91 €	0,00 €	-4 477,38 €	27 458,33 €
Other	20 000,00 €	0,00 €	15 237,97 €	0,00 €	0,00 €	35 237,97 €
Panasonic VBHN325S	90 920,18 €	0,00 €	0,00 €	0,00 €	0,00 €	90 920,18 €
Yangtze Battery 6.6kWh 48VDC w/Xanbus	78 300,00 €	54 304,78 €	0,00 €	0,00 €	-20 986,95 €	111 617,83 €
System	202 500,53 €	65 890,23 €	22 307,88 €	0,00 €	-25 464,33 €	265 234,31 €

From table 4.8, we can see the information regarding PV-BESS model components costs which includes initial capital cost, replacement cost, O & M cost and NPC of the total models. Here, salvage value in the cost summary defines value remaining in a component of the power plant at the end of project lifetime. For project lifetime of 25 years, we can see the salvage value remains for Inverter and batteries because such component has been changed once during their project lifetime and still some value is left for both of the components (i.e. 5 years each) after the 25 year of project lifetime.

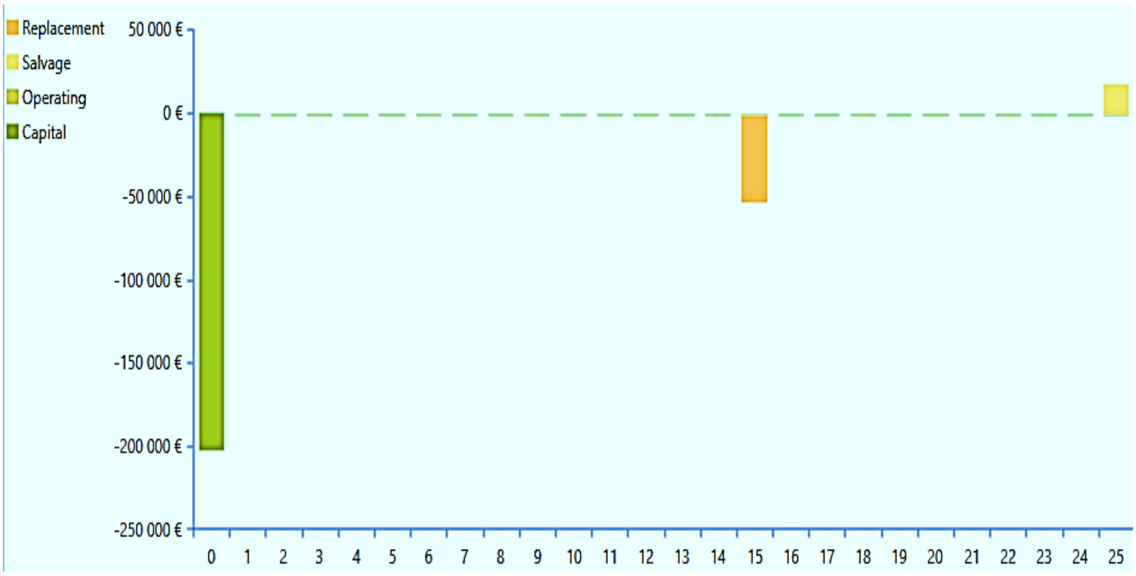


Figure 4.32: PV-BESS plant nominal cash flow by cost type.

From figure 4.32, we can see cash flow result of optimized model for PV-BESS plant of Finland where X-axis represent project lifetime (i.e. T= 25) and Y-axis presents cost data of the plant. During first year of project, initial capital for investment generates outflow (i.e. negative value) for the project has not started generating any income or salvage value for the components. In the year of 15, we can see outflow again because of replacement of system components (i.e. inverter and BESS). Finally, In the year of 25, we can see inflow (i.e. positive value) from the project as components like BESS and inverter value is still left for five more years at the end of 25 years project lifetime. So, Salvage value or inflow for the project is €17,594 after all the addition and deduction of system components price, discount rates and additional costs.

Table 4.9: Summary of sensitive system of PV-BESS plant-Finland

PV	**139 kW**
BESS	389.4 kWh
Converter	**175 kW**
Dispatch	Homer Load Following (LF)
Levelized COE	**0.146 €/kWh**
NPC	265,796 €
Operating Cost	**2,090 €/yr.**
Initial Capital	2,02,102 €

Table 4.9 shows the information of sensitive case (base model) of PV-BESS plant in Finland. Sensitivity analysis is important to perform because based on range of values (i.e. costs, sizes and constrains) as inputs it helps to determine us how important each value is and how the changes are happening with respect to changes in those values. Moreover, sensitive analysis is performed to make a single analysis applicable to more than one installation and comparing the optimized results with several sensitive results. In sensitive case, we can see that, reduced size of PV array is required for our plant and initial capital cost for the plant is € 202,102. Moreover, cost of LCOE, NPC and operating costs are more compared to optimized system. By comparing with optimized system, we can say that, sensitive system has the advantage of having efficient system's component size (i.e. PV array), initial capital costs and project value (i.e. in terms of payback time, return on investment and initial rate of return etc.) at the end of project lifetime. Economics summary of the sensitive system is showing in table 4.10.

Table 4.10: Economics summary of PV-BESS plant -Finland (sensitive system)

Present worth (€)	**561**
Annual worth (€/yr)	18
Return on investment (%)	**4.3**
Internal rate of return (%)	6.5
Simple payback (yr)	**14,31**
Discounted payback (yr)	14,24

Economics analysis has been performed based on the constrains of real discount rate, expected inflation rate, system fixed costs and system fixed O & M cost. For Finland, inflation rate has set 1.49 % (According to EU inflation rate statistics 2019) and real discount rate is -1.47 % (i.e. real discount rate has been calculated based on the information of nominal discount rate and inflation rate). Increasing nominal discount rate increases real discount rate. On the other hand, increases inflation rate decreases real discount rate. Generally, LCOE for PV applications ranges from 0.033 €/kWh (i.e. for bigger PV plant near 1000KW) to 0.11 €/kWh (i.e. for smaller rooftop PV plants) in Finland. The LCOE prices decreases with increasing inflation rate and increasing nominal discount rate. For PV-BESS plant in Finland, Nominal discount rate has initiated to zero. NPC is the main economic output in the homer pro because it helps to rank all the system configuration in the optimization results and the basis from which it calculates the total annualized cost and LCOE. [63] [64] [65]

Case-Bangladesh:

In homer pro software, we performed the microgrid simulation for our desired PV-BESS model in Bangladesh. All the economics analysis and calculation of system's component has been initialized in euro. In figure 4.33 we show the microgrid model designed in the software.

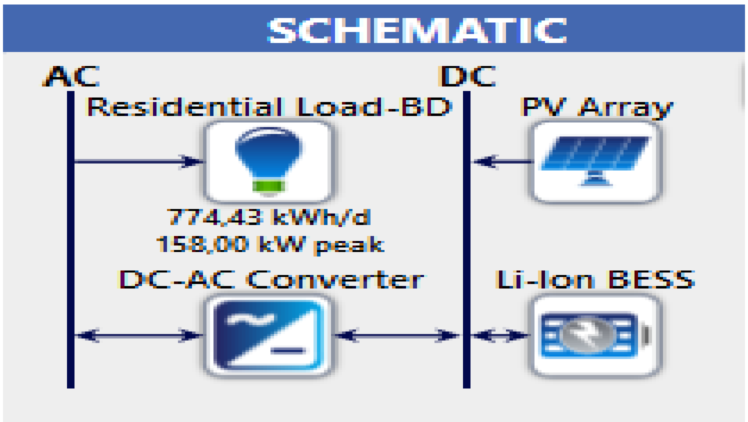


Figure 4.33: Homer schematic of off-grid PV-BESS plant – Bangladesh.

Figure 4.33 shows microgrid model of off-grid PV-BESS model for Bangladesh implemented in homer. The model has been implemented based on component's sizes and cost information as an input to perform necessary data analysis for generating optimized and sensitive model in terms of economics parameter like NPC, Operating cost, LCOE and initial capital. In table 4.11, we can see the necessary component's sizes and cost information for our off-grid PV-BESS plant.

Table 4.11: Summary of cost and size information of PV-BESS plant components – Bangladesh.

Components	Model and Specifications	Base Component Price	Quantity	Sizes	Unit	Prices		
						Capital (€)	Replacement (€)	O & M (€)
Solar PV Array	Panasonic VBHN325SJ47 (Base Panel-325 W)	€209/pcs	431	140	kW	€90,079	€45,040	€0
			492	160	kW	€102,828	€51,414	€0
			554	180	kW	€115,786	€57,893	€0
Li-Ion BESS	Yangtze Battery (China Manufacturing Co.) Base Battery: 48 V 130 Ah (6,6 kWh)	€1,350/pcs	40	264	kWh	€54,000	€30,000	€0
			80	528	kWh	€108,000	€60,000	€0
			120	792	kWh	€162,000	€90,000	€0
DC-AC Converter	ABB PVS-120 Base Converter-120 kW	€7,500/pcs	1	120	kW	€7,500	€5,000	€100
			1	160	kW	€12,000	€8,000	€150
			1	160	kW	€15,000	€10,000	€200

Table 4.11 tells summary components' size and costs which has been used to perform optimization and economics analysis in Homer Pro software. All the components

information has been collected from components company website. To perform optimization and economics analysis for our model, we used three inputs for each component. Moreover, PV array and BESS has maintenance free advantage over the period of their operational lifetime. As a result, there is no costs during their operation and maintenance period. Information about PV array inputs like solar irradiance and temperature data has been illustrated in figure 4.34 and 4.35.

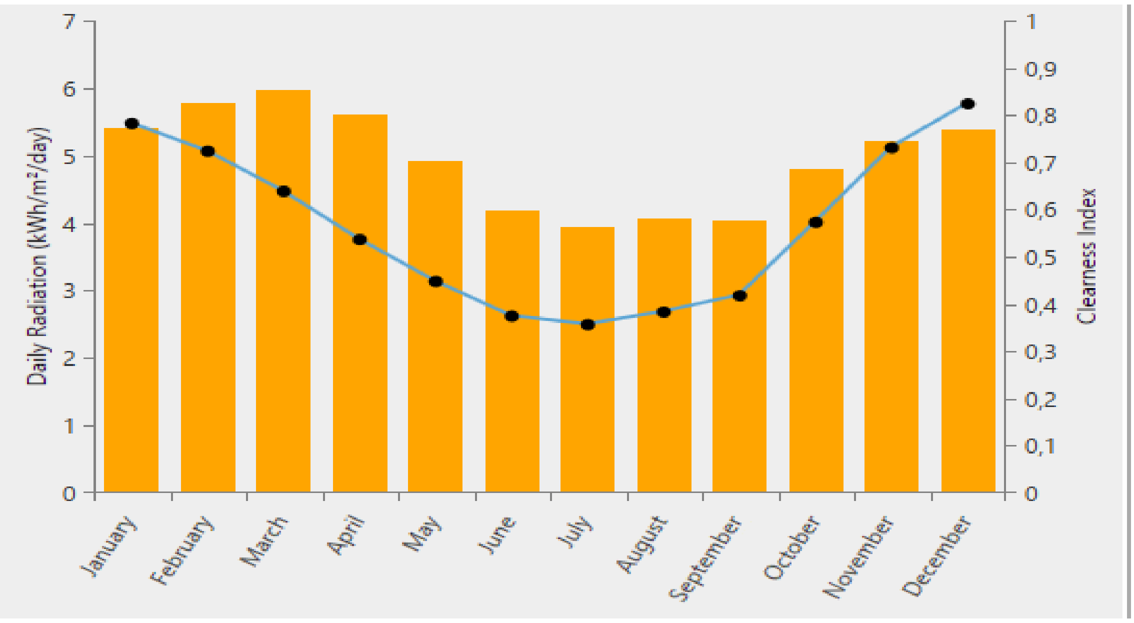


Figure 4.34: Homer representation of annual irradiation data of Bangladesh.

Data's used in figure 4.34 has been used as an input for PV array operation to generate necessary electrical energy during 12-month period (i.e. 365 days). Inputs for irradiance has set based on the orientation of PV panel directly facing to the south at 66° tilt angle position (i.e. same irradiation data from chapter 2). For Bangladesh, Annual average radiation is 4.94 kWh/m²/day.

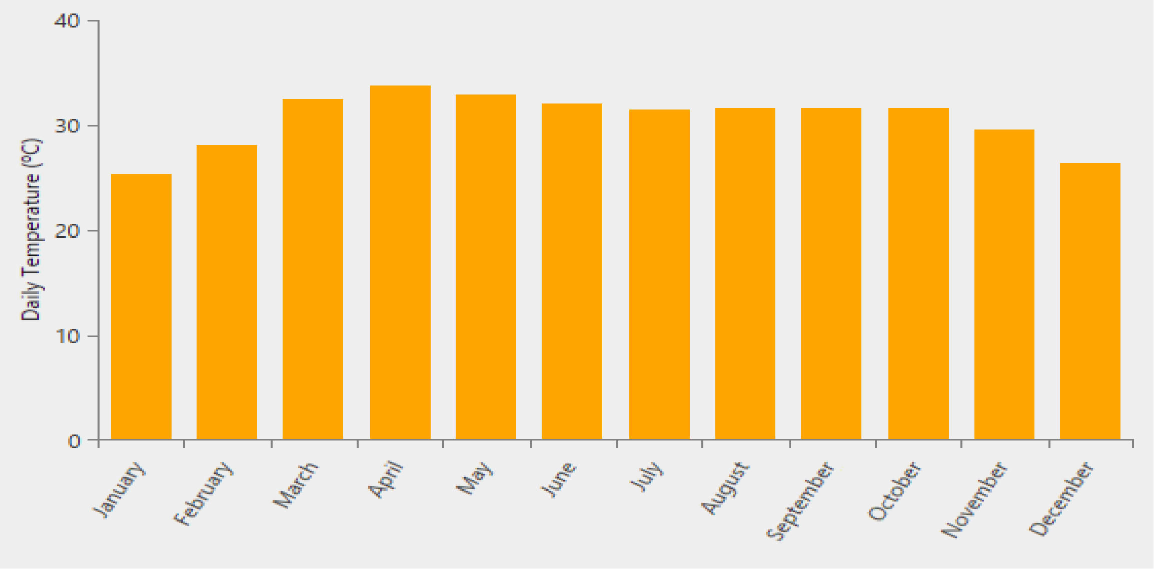


Figure 4.35: Homer representation of annual temperature data of Bangladesh.

Figure 4.35 is showing the annual average temperature of Bangladesh over the 12 months period. Temperature ranges between 25.4 °C to 33.7 °C. Data used for analysis has been collected from National Centres for Environmental Information. For Bangladesh, annual average temperature is 30.58 °C.

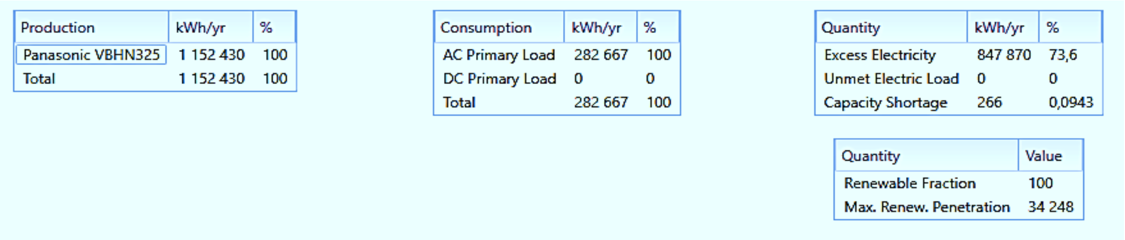
Temperature and irradiance data have been used for the city of Dhaka in Bangladesh case.

Table 4.12: Summary of optimized system of PV-BESS plant - Bangladesh

PV	**686 kW**
BESS	1590.6 kWh
Converter	**178 kW**
Dispatch	Homer Cycle Charging(CC)
Levelized COE	**0.135 €/kWh**
NPC	1,01 Million €
Operating Cost	**8,313 €/yr.**
Initial Capital	**7,93,500 €**

In table 4.12, we can see the summary of optimized PV-BESS model of Bangladesh. This model has been generated based on the lowest LCOE, NPC and operating cost among the several results generated by Homer. For optimization analysis, Homer optimizer based on cycle charging has been initiated by the software. Homer cycle charging is a dispatch strategy which is based on operation of generator at full output power to serve the needs of primary load.

Table 4.13: Electrical Generation & Consumption of PV-BESS plant components – Bangladesh.



Production	kWh/yr	%
Panasonic VBHN325	1 152 430	100
Total	1 152 430	100

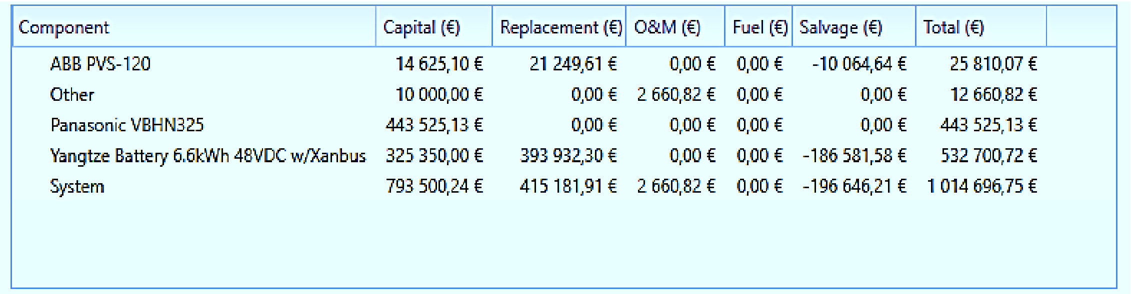
Consumption	kWh/yr	%
AC Primary Load	282 667	100
DC Primary Load	0	0
Total	282 667	100

Quantity	kWh/yr	%
Excess Electricity	847 870	73,6
Unmet Electric Load	0	0
Capacity Shortage	266	0,0943

Quantity	Value
Renewable Fraction	100
Max. Renew. Penetration	34 248

From table 4.13, we can see that yearly generation and consumption of PV energy where 686 kW optimized PV array is sufficient enough to generate power to meetup customer demand over the entire year. Consumption of PV energy is based on to serving load side demand and charging of BESS of the plant. For the model, renewable fraction is 100 % because of using only PV based power generation technology for the residential load. On the other hand, excess electricity is the excess energy produced by PV array over the entire year and it has been un-utilized for the plant and capacity shortage is defining the shortcoming which occurs between required operating capacity and actual amount of the operating capacity that the system can provide. Here, capacity shortage is only 266 kWh/ year which is negligible for our operational case.

Table 4.14: Cost summary of Optimized PV-BESS plant components - Bangladesh



Component	Capital (€)	Replacement (€)	O&M (€)	Fuel (€)	Salvage (€)	Total (€)
ABB PVS-120	14 625,10 €	21 249,61 €	0,00 €	0,00 €	-10 064,64 €	25 810,07 €
Other	10 000,00 €	0,00 €	2 660,82 €	0,00 €	0,00 €	12 660,82 €
Panasonic VBHN325	443 525,13 €	0,00 €	0,00 €	0,00 €	0,00 €	443 525,13 €
Yangtze Battery 6.6kWh 48VDC w/Xanbus	325 350,00 €	393 932,30 €	0,00 €	0,00 €	-186 581,58 €	532 700,72 €
System	793 500,24 €	415 181,91 €	2 660,82 €	0,00 €	-196 646,21 €	1 014 696,75 €

In table 4.14, we can see the information about PV-BESS plant components costs which includes initial capital cost, replacement cost, O & M cost and NPC of the whole model. Here, salvage value in the cost summary defines value remaining in a component of the power plant at the end of project lifetime. For project lifetime of 25 years, we can see the salvage value remains for Inverter and batteries because such component has been changed twice during their project lifetime and still some value is left for both of the components (i.e. 1 year each) after the 25 year of project lifetime.

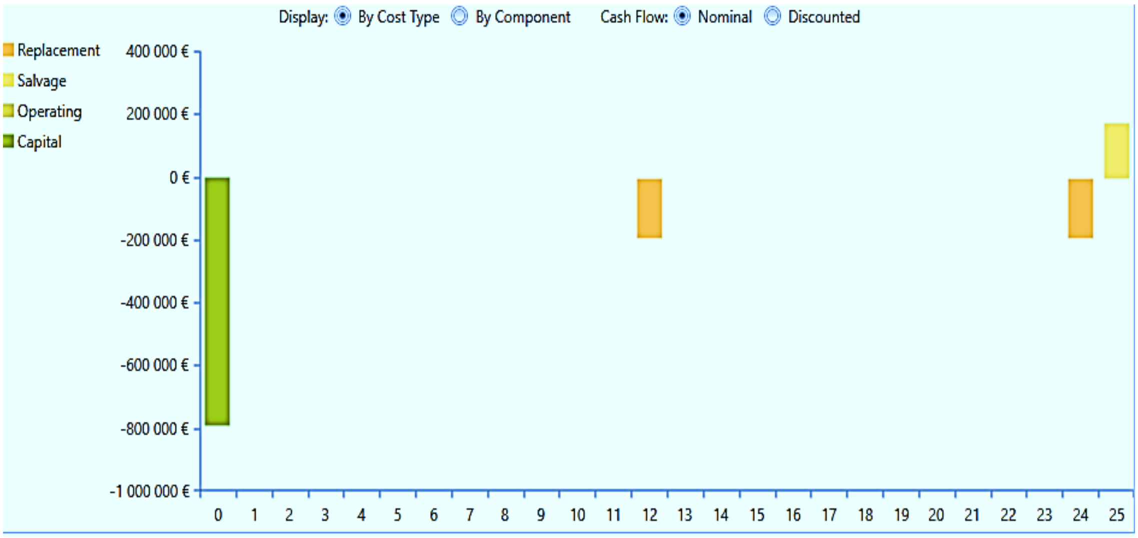


Figure 4.36: PV-BESS plant nominal cash flow by cost type – Bangladesh.

From figure 4.36, we can see cash flow result of optimized model for PV-BESS plant of Bangladesh where X-axis represent project lifetime (i.e. T= 25) and Y-axis presents cost data of the plant. In first year of project, initial capital for investment generates outflow (i.e. negative value) for the project because it has not started generating any income or salvage value for the components. In the year of 12, we can see outflow again because of replacement of system components (i.e. inverter and BESS). Moreover, in the year 24, we again experience outflow for the replacement of BESS and inverter. Finally, In the year of 25, we can see inflow (i.e. positive value) from the project as components like BESS and inverter value is still left for one more year at the end of 25 years project lifetime. So, Salvage value or inflow for the project is €174,625.06 after all the addition and deduction of system components price, discount rates and additional costs.

Table 4.15: Summary of sensitive system of PV-BESS plant-Bangladesh

PV	549 kW
BESS	1920.6 kWh
Converter	**226 kW**
Dispatch	Homer Load Following (LF)
Levelized COE	**0.140 €/kWh**
NPC	1,05 Million €
Operating Cost	**10,138 €/yr.**
Initial Capital	7,79,727 €

Table 4.15 shows the information of sensitive case (base model) of PV-BESS plant in Bangladesh. Sensitivity analysis is important to perform because based on range of values (i.e. costs, sizes and constrains) as inputs it helps to determine us how important each value is and how the changes are happening with respect to changes in those values. Moreover, sensitive analysis is performed to make a single analysis applicable to more than one installation and comparing the optimized results with several sensitive results.

In sensitive case, we can see that, reduced size of PV array (i.e. 549 kW) is required for our plant and initial capital cost for the plant is € 7,79,727. Moreover, LCOE, NPC and operating costs are more compared to optimized system. By comparing with optimized system, we can say that, sensitive system has the advantage of having efficient system's component size (i.e. PV array), initial capital costs and project value (i.e. in terms of payback time, return on investment and initial rate of return etc.) at the end of project lifetime. Economics summary of the sensitive system is showing in table 4.16.

Table 4.16: Economics summary of PV-BESS plant - Bangladesh (sensitive system)

Present worth (€)	34,789
Annual worth (€/yr)	1,307
Return on investment (%)	**9.3**
Internal rate of return (%)	10.3
Simple payback (yr)	**11,33**
Discounted payback (yr)	11,31

Economics analysis has been performed based on the constrains of real discount rate, expected inflation rate, system fixed costs and system fixed O & M cost. For Bangladesh, inflation rate has set 5.50 % (According to Bangladesh Bank statistics 2019) and real discount rate is -0.47 % (i.e. real discount rate has been calculated based on the information of nominal discount rate and inflation rate). Increasing nominal discount rate increases real discount rate. On the other hand, increases inflation rate decreases real discount rate. The LCOE prices decreases with increasing inflation rate and increasing nominal discount rate. For PV-BESS plant in Bangladesh, Nominal discount rate has initiated to 5.00 %. NPC is the main economic output in the homer pro because it helps to rank all the system configuration in the optimization results and the basis from which it calculates the total annualized cost and LCOE. [65]

Finally, it can be concluded that, sensitive model wins for both the PV-BESS plant cases because of having efficient microgrid model, return on investment and reduced initial investment compared to optimized model.

5. DYNAMIC APPLICATIONS ANALYSIS

5.1 Case-Finland

In this part of chapter, we will discuss few application areas with analytical aspects for our PV-BESS plant in Finland.

5.1.1 Demand Response Program for PV-BESS plant

Demand response (DR) is the future of electricity market which ensures safe operation of electricity consumption and brings grid reliability played by consumers during peak period in response to time based rates or other form of financial incentives. Our proposed PV- BESS plant will be key actor for playing DR program both in price-based and incentive-based options.

Considering price-based option of DR; Helen energy oy (i.e. one of the largest energy producers in Finland) offers time-based rates for residential electricity consumers where their daytime (i.e. from 7 a.m. to 10 p.m.) rate is 0.0867 €/kWh and night-time (i.e. from 10 p.m. to 7 a.m.) rate is 0.0742 €/kWh. Since, BESS of our plant has been designed based on the peak hour energy demand (i.e. 132 kWh) which is about 80 % of our total energy demand (i.e. 164 kWh) for Finnish residential buildings (discussed in chapter 3). So, we can say that, BESS activation to perform DR program during peak hours will reduce dependency on grid power which helps to save around 11.5 € (i.e. 132 kWh priced at night tariff 0.0867 €/kWh) per day and 345 € per month of electricity bill for 40 Finnish residential apartment inhabitants. So, we can say that, performing DR program among residential customers through their PV-BESS plant will help to save 132 kWh of energy from national or regional grid per day and 3960 kWh per month during peak hour period. [66]

Considering incentive-based option of DR; Our PV-BESS can be able to play to ancillary and curtailment services. Here, ancillary services are all about dispatching our BESS energy based on daily load demand and scheduling to operate as per demand (i.e. off-peak or peak hours). Moreover, excess energy produced by PV-BESS plant can be utilized where energy imbalances is occurring. Our PV-BESS plant has the potential to provide many of the potential services to the national or regional grid because inverter using for our distributed generation plant can be used as spinning generator and voltage regulators for initializing voltage control, flicker control, active power filtering and harmonic cancellation. Curtailment service can be played by activating our PV-BESS plant to deliver to the load side demand during peak hour or off-peak hour which will curtail energy consumption during peak hours from the grid power. As a result, grid reliability and resiliency will increase, and it will ensure optimal operation of grid power during peak curtailment for a certain electricity consumers area. [67]

Figure 5.1 shows the possible application areas of DR program for PV-BESS plant in Finland.

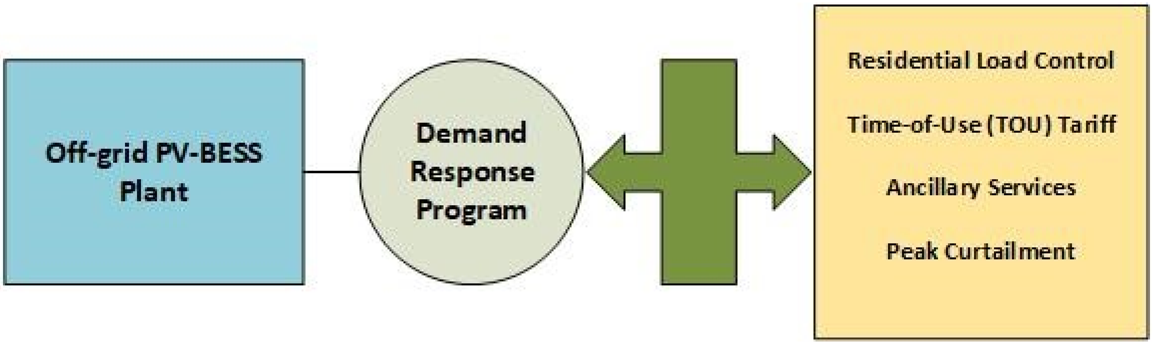


Figure 5.1: Applications of DR program for PV-BESS plant of Finland

5.1.2 Demand Side Management of Residential Consumers

Demand side management (DSM) is a kind of energy management mechanism which refers to initiate a group of actions for efficiently managing energy consumption in a certain customer area with the aim of consuming cost-efficient energy by cost cutting from grid charges (i.e. incurred for supplied grid electricity) and general system charges including taxes [3].This kind of program may bring revolutionary changes for optimized energy consumption in residential context. Integrity and reliability of PV power in such consumer area might be a game changer for establishing futuristic demand side management protocol. Implementing demand side management though PV-BESS plant in residential energy distribution point will bring optimal performance in energy consumption and help to reduce grid dependency. As a result, grid purchase costs will be minimized, and grid reliability will increase during peak hour operation. [68]

DSM for residential consumers will include control of grid power consumption, PV power consumption, BESS power consumption, time-based operation of PV-BESS and grid, energy management of BESS etc.

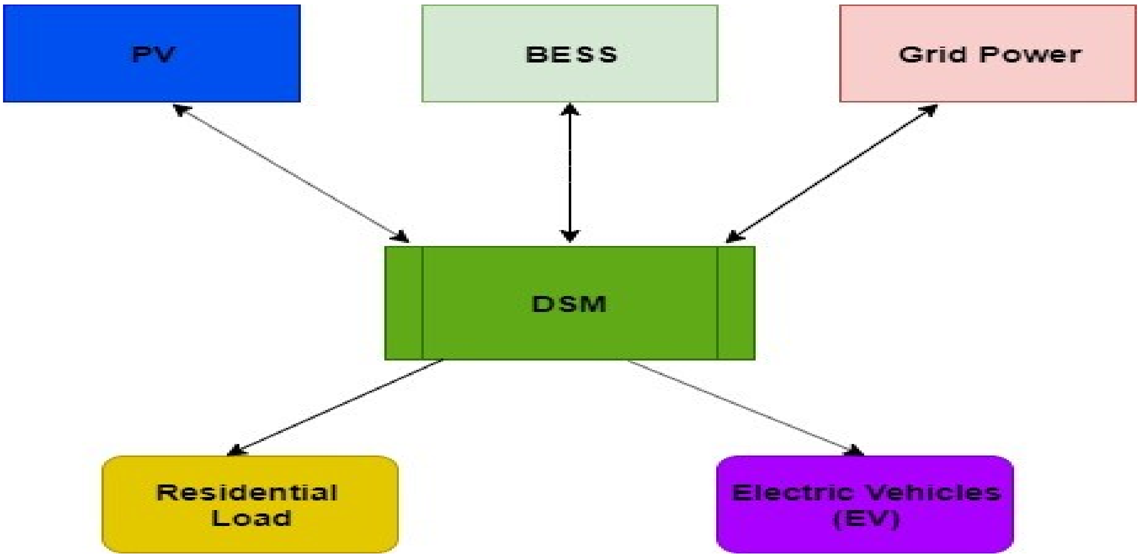


Figure 5.2: Overview of PV-BESS based DSM architecture for residential consumers

Above figure 5.2 shows typical layout of a PV-BESS based DSM for residential consumers. DSM consists of computers, software and Intelligent Electronic Devices (IEDs) which is responsible for all kind of operation, monitoring and control of energy management among PV-BESS, grid and residential consumers (i.e. load and their EVs).

5.1.3 Smart BESS to EV and EV to BESS charging

Now a days, electric vehicles (EV) are becoming popular not only in transportation sector but also in electricity market as well. Integrated power train of EV is playing a vital role for electrifying car industry and brings robustness in modern grid management system. EV could operate as a multi-tasker to provide backup power to the demand side (i.e. EV to BESS) and storing energy (i.e. BESS to EV) to play as a long ranger to drive miles after miles. Due to lack of charging and grid integration infrastructure, EVs are facing massive challenge to sustainability of future energy infrastructure. Moreover, development costs of such infrastructure are another big issue specially for residential customers (i.e. as most of the EV owners are residential consumers) because of having small numbers of charging infrastructure. Establishment of PV-BESS plant will have a positive impact behind the development of EVs integration and charging infrastructure.

According to optimization analysis (from chapter 4), we can see that, 142 kW PV plant can be able to product 2,28,125 kWh of electrical energy per year where residential load consumption are one fourth (i.e. 59,860 kWh/year) of total energy production and rest of energies are not utilized. In that case, EVs like Tesla S model and Nissan Leaf can be charged up though the BESS to utilize such excess energy. Tesla S model has a BESS capacity of 70 kWh and Nissan Leaf has a BESS capacity of 30 kWh. So, we can see that, excess energy of PV plant can be utilized to charge around 2400 Tesla S model EVs and 5600 Nissan Leaf model EVs in a year. On the other hand, such EVs can be able to operate as portable power station where real time demand is required. From the potentiality point of view, it can be said that, EVs has huge potential to rebuild a sustainable of electricity market to serve unmet energy demand and to increase reserve capacity of energy resources. [69] [70]

5.2 Case-Bangladesh

In this part of the chapter, we will discuss potential application areas of PV-BESS plant in Bangladesh.

5.2.1 Load Shedding Mitigation

Load shedding is a common phenomenon in the developing countries like Bangladesh. It is a controlled process in which the utility company drops off part of the load in order to balance the demand and the generated capacity. Balancing demand and generation through grid interruption process causing an alarming situation among the residential and organizational consumers. According to world bank statistics (2003), people of Bangladesh faces 840 hours of power outage scenario per year on average. Moreover, load shedding needs to initiate while actual generation does not match predicted demand. Implication of PV-BESS plant will play massive role as distributed generator to mitigate load shedding in the long run. [71] [72]
According to optimization results in Bangladesh case (from chapter 4), we can see that, 686 kW PV plant can able to produce 11,52,430 kWh/year where only one fifth (i.e. 2,82,667 kWh/year) is utilized by the five residential buildings-based consumers. So, excess electricity can be able to supply through distribution transformers and by stored energy from large number of BESS to the near localities during the blackouts. As a result, grid stability will increase and less chances of load shedding.

5.2.2 Energy sharing through Net Metering

Currently, net metering is a hot topic in Bangladesh because of having ample potential of renewable energy resources like solar PV. Moreover, installing millions of solar home system (SHS) for rural electrification in recent years is the biggest motivator behind establishing such energy integration process to increase grid durability and resiliency. Moreover, promoting distributed generation based on renewables by the government is another big reason behind the fast track establishment of such energy management mechanism. Net metering helps to adjust electricity bill of the prosumers based on the calculations of net energy exports and imports. This mechanism helps prosumers to earn energy incentives by sharing their excess PV energy through locally connected meter which stores data about the exports and imports of electricity. Since, electricity tariff for residential customer is based on per unit (i.e. kWh) consumption based so consuming less grid power will help to reduce electricity bill and sharing more electricity than their consumption will help them to earn price-based incentive in a large scale. [73] [74]
Considering generation of optimized PV plant of Bangladesh (from chapter 4), we can see that, 686 kW plant have a huge amount of excess electricity which can be easily shared to grid to earn a price based incentives for the residential prosumer of PV-BESS

plant all year round. Sharing excess electricity of 8,69,760 kWh (i.e. deducted value from yearly consumption of 2,82,667 kWh) at a tariff rate of 0.04 €/kWh (i.e. considering. half price of maximum tariff rate for the residents of Dhaka city which is 0.08 €/kWh) will help them to earn around € 34,790 per year from their 686-kW plant. As a result, establishment of PV-BESS plant is quite profitable if such kind of energy selling agreement and policy can be made by the Government.

5.2.3 Community Energy Management System

Community energy management system (CEMS) might have the biggest prospect and potential for sustainable energy management in residential users' context. It presents completely new concept of energy management standardization mechanism which bring possibilities, predictability, reliability and dynamics ability in a certain community of electricity consumers and prosumers. CEMS creates bridge between electricity consumers and prosumers through mutual energy sharing agreement during demand is ON.
Limitation of CEMS is the distance among consumers and prosumers. PV-BESS can be able to operate through CEMS mechanism within a short distant area. Demand based on CEMS varies from community to community. For example; buildings located in community 1 has a PV-BESS plant of 100 kW which can play a prosumer and buildings located in community 2 and 3 are playing as consumers. Community 2 seeks demand during blackouts where community 3 seeks demand during peak hour period. PV-BESS plant of community 1 should be able to operate based on the needs of demand seekers. Like DSM, CEMS can play monitor, control and operation for demand side by using computers, software and IEDs. Figure 5.3 shows block diagram representation of CEMS concept.

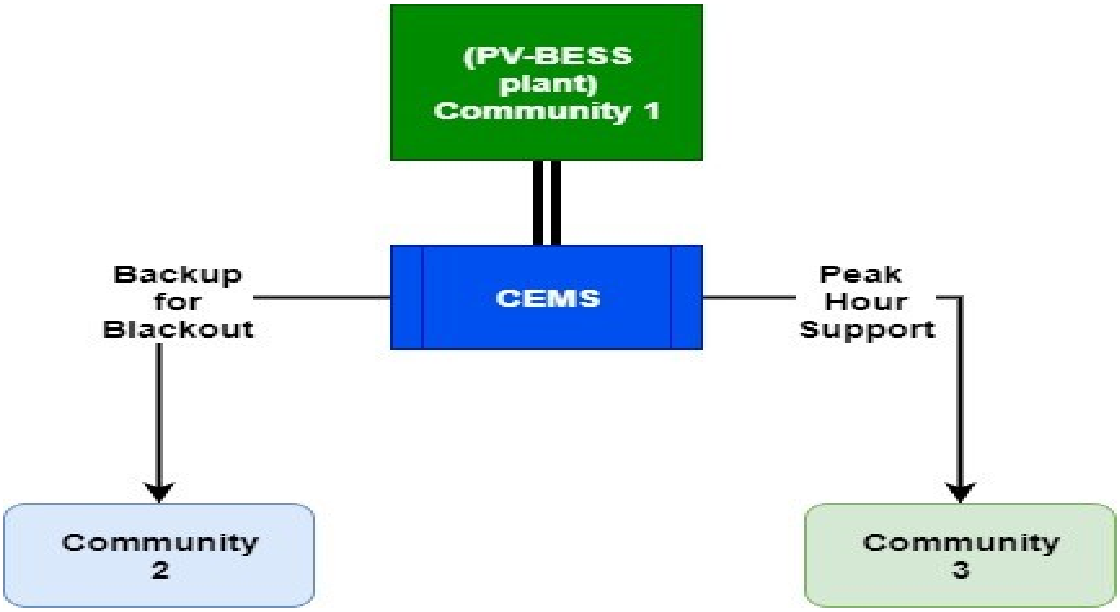


Figure 5.3: Overview of PV-BESS based CEMS architecture for Communities

6. CONCLUSION

Research and studies in PV-BESS technology will enable potential outcome from diversifying renewable energy generation technologies as distribution generators to advanced and optimized grid infrastructure. Moreover, it will enable the opportunity to develop futuristic autonomous building infrastructure in terms of power generation, distribution and consumption with the help of dynamic and advanced energy storage technologies to ensure proper energy management at residential user level and will reduce the pressure on public grid power. Additionally, it will bring reliability and optimal dependency on non- fossil fuel-based energy resources. Thus, generation will be increased by renewable PV technology for large scale customer level of electricity users (i.e. residential consumers). As a result, it will accelerate the development of smart grid systems in residential user context with the help of distributed PV-BESS generation technology with the help of modern communication infrastructures and protocols. Since future of energy is largely dependent on the sustainability of renewable sources so implementation of PV-BESS model will become a necessity for organizational and residential electricity consumer community in near future. Besides, massive implementation of this kind of system will change the behavior of electricity market and forecasting will be much more predictive and energy sharing by grid power will bring reliability during it' operation. As a result, peak hour load demand will be minimized, and it will help to bring stability and faultless operation of electric grid. Finally, we can conclude that, PV-BESS have a great future where rise in grid purchase prices and net imports of national grid is an issue. Initialization of PV-BESS plant will create the opportunity for distributed generator markets for its enormous support for increasing grid capacity.

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