Design, Dynamic Modeling and Analysis of an On-Grid Photovoltaic System for a House in Lahore, Pakistan

Written by

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Abstract

This thesis investigates the design, analysis, and implementation of a grid-tied solar system for a residential property in Lahore, Pakistan. The objective is to tackle regional energy deficits and improve power availability by employing solar photovoltaic (PV) technology. The study encompassed the creation and execution of a solar power system that fulfils the energy requirements of a standard residential dwelling in Lahore. This encompassed the choice of crucial elements such as photovoltaic modules, power inverters, and necessary equipment for seamless integration with the power grid. Ensuring compatibility with the preexisting power grid, which is frequently affected by power outages and load shedding. An examination of performance, utilizing tools such as the System Advisor Model (SAM) and HOMER Pro, demonstrated that the system connected to the power grid has the ability to greatly decrease dependence on traditional electricity sources. Additionally, there is the possibility of excess energy being returned to the grid through net metering. A novel feature of this study is the creation of a data logging system using Arduino technology, which is seamlessly integrated with Microsoft Excel to enable real-time monitoring of the system's performance. This system collected essential measurements such as energy generation, voltage, and current levels, facilitating proactive maintenance and optimization of the system. The cost-effectiveness of the data logging system highlights its potential for wider implementation in residential solar installations. Although the study showed promising results, it had some limitations. These limitations include the fact that it only focused on one residential installation, the need for longer-term performance data, and the possibility of environmental variability that was not fully considered in the simulations.

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List of Nomenclature

A. Acronyms and Abbreviations:

AC	Alternating Current
ADC	Analog to Digital Converter
AM	Ante Meridiem
APP	Application
AVR	Advanced Virtual RISC
CSV	Comma Separated File
DC	Direct Current
DWP	Diesel Water Pumping System
GDP	Gross Domestic Product
GPIO	General Purpose Input/Output
GPRS	General Packet Radio Services
GPS	Global Positioning System
GSM	Global System for Mobile Communications
GW	Gigawatt
I2C	Inter-Integrated Circuit
IC	Integrated Circuit
IDE	Integrated Development Environment
LDR	Light Dependant Resistor
MATLAB	Matrix Laboratory

MIT	Massachusetts Institute of Technology
MPPT	Maximum Power Point Tracking
MQTT	Message Queuing Telemetry Transport
MW	Megawatt
NPC	Net Present Cost
OLED	Organic Light-Emitting Diode
PM	Post Meridiem
PV	Photovoltaic
PVWP	Photovoltaic Water Pump
RISC	Reduced Instruction Set Computer
SCADA	Supervisory Control and Data Acquisition
SD	Secure Digital
SIM	Subscriber Identity Module
SMS	Short Messaging Service
SPDT	Single Pole, Double Throw
SPI	Serial Peripheral Interface
SPP	Solar-Powered Pumps
TDH	Total Dynamic Head
TTL	Time To Live
UART	Universal Asynchronous Receiver/Transmitter
USB	Universal Serial Bus

B. Symbols and Variables:

ρ: Density of water

g: Gravitational acceleration (m/s^2)

h: Dynamic head (m)

Q: Water flow (m^3/hour)

η: Motor efficiency

P_h: Hydraulic power of the water pump (Watts)

P_m: Motor Power (Watts)

P: Required Power (kW)

HP: Horsepower

Chapter 1

Introduction and Literature Review

1.1 Introduction

Solar energy, as a renewable resource, has gained considerable attention due to its potential to provide sustainable and clean electricity. With the ever-increasing concerns regarding global warming and the depletion of fossil fuels, the adoption of solar photovoltaic (PV) systems has become more prevalent. Figure 1.1 illustrates a PV system and its submodules. In many regions, including Pakistan, solar energy is seen as a viable alternative to conventional energy sources, which are associated with pollution and carbon emissions.

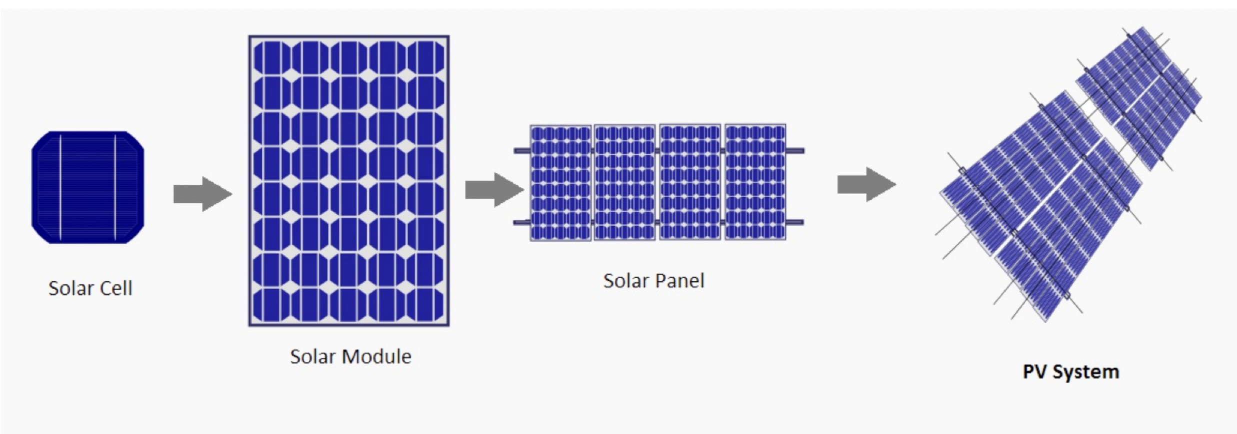

Figure 1.1 PV system constructed from PV module

This chapter aims to provide a comprehensive introduction to solar energy systems, specifically focusing on grid-tied solar systems. The concept of grid-tied systems has revolutionized the integration of renewable energy into existing power infrastructures, allowing for a more flexible and efficient energy network. We will examine the basic components of solar PV systems and discuss the principles underlying grid-tied solar systems. Additionally, this chapter will explore the existing literature on both stand-alone and grid-tied solar PV systems, highlighting the advancements and challenges within the field.

1.2 Solar System

A solar system comprises various components designed to convert sunlight into electricity. The most common type of solar system is the photovoltaic (PV) system, which uses solar panels to generate direct current (DC) electricity from sunlight. Solar panels are typically composed of photovoltaic cells made of semiconductor materials, most commonly silicon.

These cells, when exposed to sunlight, create an electric field that facilitates the movement of electrons, generating DC electricity. This DC electricity can be used to power electrical devices or stored in batteries for later use. However, to connect with the electrical grid or use standard household appliances, this DC electricity must be converted to alternating current (AC), which requires additional components.

1.3 Working Principle of Solar System

The fundamental working principle of a solar system is the photovoltaic effect, where solar cells convert sunlight into electricity. When sunlight strikes a solar cell, it excites electrons in the semiconductor material, causing them to flow and generate an electric current. This current is then harnessed to power devices or feed into a larger electrical network.

In a typical solar system, the solar panels are connected to an inverter, which transforms the DC electricity generated by the solar panels into AC electricity. The AC electricity can then be used to power household appliances or sent to the electrical grid. The efficiency of this process depends on factors such as the quality of the solar panels, the efficiency of the inverter, and the level of sunlight exposure.

A grid-tied solar system, also known as a grid-connected system, is designed to work in conjunction with the electrical grid. Unlike stand-alone systems, which rely solely on solar power or backup batteries, grid-tied systems can draw electricity from the grid when solar power is insufficient and feed excess electricity back into the grid when solar power production is high.

In a grid-tied system, the solar panels generate DC electricity, which is converted to AC electricity through an inverter. This AC electricity can then be used to power the home or business. If the solar system generates more electricity than needed, the excess power is sent to the grid, allowing the user to receive credits or compensation through a process called net metering.

Grid-tied systems offer several advantages over stand-alone systems. They typically require fewer batteries, reducing costs and maintenance, and they allow for greater flexibility in energy usage. However, they also rely on a stable grid connection, making them susceptible to power outages in the broader electrical network.

1.4 Literature Review

The literature on solar energy systems is extensive, with a focus on both stand-alone and grid-tied systems. Researchers and engineers have made significant advancements in improving the efficiency and reliability of solar PV systems, as well as developing innovative grid-integration techniques. In this section, we will review the existing literature on stand-alone PV systems and grid-tied solar systems. We will discuss the key findings, current trends, and ongoing challenges in these areas. By exploring the latest research, we aim to provide a comprehensive overview of the state of solar energy systems and identify opportunities for further development and innovation.

Pakistan has considerable solar energy potential due to its geographical location and high levels of solar irradiance. However, the adoption of solar technology has been limited by infrastructure, policy, and other challenges. Hashmi et al. [1] examine solar power usage in southern Pakistan, highlighting the significant potential for solar energy production. The authors suggest that the successful adoption of solar power depends on building robust infrastructure and implementing policies that support renewable energy integration. Mehmood et al. [2] focus on solar PV systems, conducting a comprehensive techno-economic and environmental analysis to explore ways to achieve energy sustainability. They emphasize that solar energy can play a significant role in reducing dependency on non-renewable sources, while Hashmi et al. [3] suggest that using solar reflectors can increase the efficiency of solar panels. Awais et al. [4] assess the impact of installing solar PV systems in Pakistan, identifying significant benefits for environmental and economic development. Their study shows that solar energy is the best renewable energy option for the country based on price, lifespan, and maintenance costs.

Manoo et al. [5] compare on-grid and off-grid hybrid energy systems in remote areas, concluding that grid-connected systems are more cost-effective. The analysis from Rehman et al. [6] indicates that net metering regulations play a crucial role in residential solar installations, suggesting the need for consistent and supportive policies. Further research by Zahid et al. [7] explores a hybrid solar-biomass on-grid system for industrial applications, demonstrating that hybrid systems can reduce costs and emissions while offering flexible energy solutions. The role of net metering and its impact on grid stability is explored by Tahir et al. [8], pointing out that successful net metering requires effective grid management to prevent instability. Khalid et al. [9] focus on the socio-technical aspects of solar power adoption in remote off-grid communities, underlining the importance of inclusive energy systems. Additionally, Bhutto et al. [10] discuss the broader issues and challenges for solar energy in Pakistan, emphasizing the need for more comprehensive approaches to promote solar adoption.

Single-phase grid-connected photovoltaic (PV) systems have been widely studied due to their growing adoption in residential and commercial applications. The following studies delve into various aspects of modeling, simulation, and control strategies for these systems. Tina and Celsa [11] developed a MATLAB/Simulink model for a grid-connected single-phase inverter, providing a valuable tool for simulating and analyzing the behavior of such systems. Their model offers insights into the dynamic response and stability of inverters when integrated with the grid. Gulzar et al. [12] introduced an innovative control strategy for a grid-connected hybrid PV/wind/fuel-cell system, aiming to minimize converter use while ensuring stable grid integration. This approach enhances efficiency and reduces system complexity, contributing to more robust hybrid energy systems. Automatic voltage regulation (AVR) is critical for maintaining grid stability in PV systems. Xie et al. [13] utilized a Lyapunov-based sliding mode controller to achieve AVR with a finite-time approach, providing a robust solution for voltage control in grid-connected PV systems. Zeb et al. [14] employed a Fuzzy-PI controller to regulate DC-link voltage in single-phase grid-tied PV systems, demonstrating that fuzzy logic can effectively manage voltage variations and maintain system stability. This approach reduces oscillations and improves control precision.

Stand-alone PV systems also require careful design and analysis. Iqbal and Iqbal [15] examined a stand-alone PV system for a rural house in Pakistan, highlighting the importance of system design for off-grid applications. Their work demonstrates the feasibility of using solar energy to power remote locations. To achieve optimal grid integration, maximum power point tracking (MPPT) is essential. Ali et al. [16] designed and simulated a power electronic controller for grid-connected PV arrays with MPPT, illustrating the importance of efficient power tracking in enhancing system performance. For hybrid systems, Habib et al. [17] conducted design optimization and applied model predictive control for a stand-alone hybrid renewable energy system in Pakistan. Their work explores the benefits of combining different renewable sources to meet residential energy needs.

In terms of MATLAB/Simulink-based modelling, Ropp and Gonzalez [18] developed a single-phase grid-connected PV system model, offering a detailed framework for analysing system dynamics. Kumar and Padma [19] presented a MATLAB/Simulink-based model for a residential grid-connected solar PV system, further contributing to the field's understanding of system behaviour and performance. Mohammed Benaissa et al. [20] also explored modelling and simulation of grid-connected PV systems, providing insights into the control strategies required for effective grid integration. Their work contributes to the growing body of research aimed at optimizing PV system performance.

Data acquisition and monitoring systems play a crucial role in the efficient operation and maintenance of solar photovoltaic (PV) power plants. They allow for real-time data collection, system analysis, and early detection of issues. Several studies have explored various approaches to design and develop such systems. Hakim et al. [21] developed a low-cost data acquisition system for monitoring solar PV power plants. Their system focused on capturing key parameters like current, voltage, and temperature to assess solar panel performance. By using low-cost components, they aimed to make monitoring accessible for a broader range of solar power applications. Shompa and Hoque [22] implemented an IoT-based solar power monitoring and data logging system. Their approach utilized Arduino technology and cloud-based data storage to enable real-time monitoring and analysis. The system provided data on temperature, humidity, voltage, and current, allowing technicians to detect and address issues more efficiently. Effendi et al. [23] designed a data logger for a PV analyser based on Arduino. This system was capable of measuring and recording the output parameters of PV systems, such as current, voltage, and power. The data logger was portable, allowing for on-site analysis and quick diagnosis of PV system performance.

Rehman [24] focused on an ultra-low-power data logger for stand-alone PV energy systems. By using an ESP32-S2 microcontroller, the system was designed to operate in deep-sleep mode to conserve energy. The data logger could collect data on voltage, current, and light, providing a detailed record of PV system performance. Pachauri et al. [25] developed a data acquisition system (DAS) for solar PV array characterization under partial shading conditions. This system utilized Arduino-based sensors to collect real-time data on voltage and current. The DAS was designed to be economical while minimizing the testing period for PV system characterization. Franklin et al. [26] presented a cost-effective data acquisition system for evaluating the performance of solar photovoltaic thermal (PVT) systems. They used microcontrollers to measure PV panel surface temperature, inlet and outlet air temperatures, and PV current and voltage. This system allowed for experimental analysis and comparison with reference PV systems. Sesa and Mahmuddin [27] designed a real-time monitoring system for off-grid PV systems. The system was equipped with a data logger and SD card storage, allowing for automatic data recording. It also included a software component for analysis and visualization of data, providing a comprehensive monitoring solution.

It is evident from these studies that solar energy holds immense potential, especially in regions with high solar irradiance, such as Pakistan. However, the adoption of solar energy systems, whether grid-tied or off-grid, brings with it a unique set of challenges and opportunities.

From the analysis of grid-tied and off-grid systems, we can draw several conclusions. The work by Tina and Celsa [11] and Gulzar et al. [12] highlights the importance of control strategies and inverters in ensuring stability and efficiency in grid-tied systems. Studies like those by Zeb et al. [14] and Xie et al. [13] illustrate how advanced control methods can address voltage regulation and system performance issues. Meanwhile, Iqbal and Iqbal [15] demonstrate the feasibility of stand-alone systems in rural settings, emphasizing the need for robust design and energy management.

The critical role of data acquisition and monitoring is underscored by studies from Hakim et al. [21], Shompa and Hoque [22], and Effendi et al. [23], among others. These studies show that reliable data collection and real-time monitoring are essential for the efficient operation of solar PV systems, enabling early detection of issues and ensuring system longevity. The innovations in low-cost and IoT-based monitoring systems make it easier to maintain and optimize solar energy systems.

Despite these advancements, the problem statement remains clear: Lahore, Pakistan, continues to face power shortages and load shedding due to a strained power grid. The challenge lies in designing a grid-tied solar system that addresses these issues while ensuring optimal performance and grid integration. Additionally, the need for a reliable data logging system is crucial for monitoring system performance and identifying any problems early on.

1.5 Problem statement

Lahore, Pakistan, is a rapidly growing city with a significant demand for electricity. The local power grid is subject to frequent outages and load shedding, which leads to disruptions in daily life and business operations. Given Pakistan's abundant sunlight, solar photovoltaic (PV) systems have emerged as a viable solution to supplement the traditional power grid and enhance energy reliability. However, installing solar systems can be complex due to varying energy needs, grid integration challenges, and the need for efficient energy management. The problem, therefore, is twofold. First, it involves the optimal design and analysis of an on-grid solar system for a residential setting in Lahore, ensuring sufficient energy generation and efficient grid integration. Second, it requires a reliable data logging system for monitoring the performance of the solar system to track its effectiveness and identify any issues. This thesis addresses these issues through detailed analysis, simulation, and real-world testing.

1.6 Research Objectives

This thesis aims to design and analyze an on-grid solar system for a house in Lahore, Pakistan, to address the problem of power shortages and load shedding. The specific objectives of this research are as follows:

1. Design and Analyze a Solar System for a Residential Setting in Lahore, Pakistan.
2. Model and Simulate a Grid-Tied Three-Phase PV System.
3. Develop and Test a Data Logging System for Performance Monitoring.

1.7 Thesis Overview

Chapter 1: Introduction and literature review

This chapter introduces the topic, discusses the working principles of solar systems and grid-tied solar systems, and provides a literature review of the existing research. It also outlines the problem statement, research objectives, and an overview of the thesis structure.

Chapter 2: Design and Analysis of an On-Grid Solar System for a House in Lahore, Pakistan

This chapter focuses on the design and analysis of a solar system for a residential setting. It includes a description of the site, details of the installed solar PV system, and performance analysis using the System Advisor Model (SAM) and other simulation tools.

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Chapter 3: ***Modeling and Simulation of Grid-Tied Three-Phase PV System in Lahore, Pakistan***

This chapter explores the modelling and simulation of a grid-tied three-phase PV system. It describes the methodology, system components, and results of the simulations, providing insights into the system's behaviour under various conditions.

Chapter 4: Development and Evaluation of an Arduino-Based Data Logging System Integrated with Microsoft Excel for Monitoring On-Grid Photovoltaic Systems

This chapter details the development of a data logging system for monitoring the solar system's performance. It covers hardware and software design, experimental setup, and results from the data logging system.

Chapter 5: Conclusions and recommendations

This chapter summarizes the findings of the thesis, discusses the implications of the research, and suggests potential directions for future work in the field of solar energy and grid integration.

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Chapter 2

Design And Analysis of An On-Grid Solar System for A House In Lahore, Pakistan

Preface

A version of this chapter has been accepted in the Jordon Journal of Electrical Engineering (JJEE) Reviews, March 2024. I am the primary author, and I carried out most of the research work performed the literature reviews, carried out the system design, implementations, and analysis of the results. I also prepared the first draft of the manuscript. The Co-authors, Dr. M. Tariq Iqbal supervised the research, provided the research guide, reviewed, and corrected the manuscript, and contributed research ideas to the actualization of the manuscript.

2.1 Introduction

Pakistan's geographical location, characterized by abundant sunlight throughout the year, presents a unique opportunity to harness solar energy, transforming it into a sustainable and cost-effective solution for households across the country [1], [2]. With the ever-increasing demand for electricity coupled with the challenges of energy security and affordability, solar energy emerges as a beacon of hope, offering a viable alternative to traditional fossil fuel-based power generation [3], [4]. By embracing solar power, Pakistani households can generate electricity, reducing their reliance on the often unreliable grid and mitigating the impact of frequent power outages [5].

The adoption of rooftop solar photovoltaic (PV) systems in Pakistan has gained significant traction, particularly following the introduction of a green metering system by utility companies [6]–[8]. This approach allows homeowners to generate clean and uninterrupted electricity and sell excess generated energy back to the grid, eliminating the need for battery storage. This mutually beneficial arrangement reduces household electricity bills and contributes to a more sustainable and resilient energy infrastructure [9]–[11].

Several studies have explored the viability and long-term impact on environmental, economic, and social aspects of PV systems in Pakistan. For instance, the study [12] explores optimal component planning for a grid-connected microgrid in Pakistan. The objective is to reduce the cost of energy, increase the renewable share, cut greenhouse gas emissions, enhance power supply reliability, and make electricity generation sustainable. Results show a 92.47% reduction in the cost of energy for residential applications and a 48.52% reduction for commercial applications.

This study [13] assesses the socio-technical aspects of implementing solar power in Tharparkar, Pakistan, focusing on equitable energy access. It discusses the potential for solar power to replace current energy sources at lower costs and improve gender-related energy access. The analysis emphasizes long-term planning for the lowest prices, emissions reduction, and equitable outcomes. This study [14] evaluates a solar-biomass on-grid hybrid system for the Hattar Industrial Estate in Pakistan. The study aims to provide cost-effective and uninterrupted power supply by considering available resources. The optimal system combines solar PV and biogas generation, reducing energy costs, achieving a payback period of 4.6 years, and significantly cutting carbon emissions. This paper [15] examines the barriers and potential for solar energy development in Pakistan. It highlights the need for cleaner energy sources and identifies solar energy as a promising option. The study proposes policy recommendations to overcome barriers and promote solar energy use. This research [16] evaluates the techno-economic effectiveness of grid-connected and standalone integrated hybrid energy systems for remote electricity supply. The study considers factors like net present cost, cost of energy, and payback time, concluding that grid-connected hybrid systems are best for reliable energy supply in remote areas. This work [17] proposes a hybrid energy model for fulfilling Pakistan's educational institute's power requirements. It considers various stand-alone and grid-connected energy systems and shows that PV, wind, and fuel cells are cost-effective for energy production and storage. This study [18] conducts a life cycle assessment of multi-Si PV systems in Pakistan. It evaluates environmental impacts and energy payback time, concluding that these systems have an EPBT of 2.5 to 3.5 years, making them a viable option for energy production. This research [19] employs the Unified Theory of Acceptance and Use of Technology 2 (UTAUT2) to understand the acceptance of solar technology in Pakistan's southern region. Environmental beliefs, social influence, and price value influence consumers' intention to use solar technology. This study [20] evaluates a 150.7 kW grid-connected PV system in a public university in Pakistan. It analyses energy generation, performance ratios, and annual energy yields, concluding that the system is efficient and has a performance ratio of 79.64%. This study [21] focuses on integrating solar photovoltaic (PV) energy into the residential sector. It uses a decision tree and design parameters optimization to assess sustainability and electrification requirements. The research quantifies synergies and trade-offs between design parameters, evaluates the impact of solar PV systems on energy sustainability, and analyses the competitiveness of various solar PV integrated energy systems. The findings suggest that combining solar PV systems with grid power has a greater impact, while combining them with battery energy storage systems is more competitive, providing valuable insights for encouraging renewable solar integration. This paper [22] investigates the challenges hindering the adoption of distributed solar photovoltaics (PV) in Pakistan. It finds resistance from incumbent actors due to misaligned institutional logics, focusing on difficulties in acquiring finance and insufficient incentives for distribution companies to facilitate distributed generation. This misalignment leads to user preferences for fossil-fuel backup energy systems, under-facilitation of distributed generation, restricted lending behaviour, and limited coordination between system actors. The findings have generalizable implications for regions facing similar challenges. This study [23] explores the economic viability and feasibility of installing photovoltaic (PV) solar energy systems in Pakistan, specifically in Faisalabad. It highlights Pakistan's favourable solar radiation characteristics and assesses the cost-benefit analysis of installing PV systems in households. The research shows that the true financial cost of a PV module decreases significantly when energy cost savings are considered in generating conventional electricity, emphasizing the potential for solar energy in Pakistan. This work [24] focuses on the risk assessment and mitigation strategies for large-scale solar PV systems in Pakistan. It collects data on complaints related to PV systems from reputable companies and presents insights into potential risks and their severity. The study also provides risk mitigation strategies to address these complaints, aiming to reduce risks associated with large-scale solar PV installations in developing countries.

The paper is structured as follows: Section 2 presents the methodology; section 3 presents and discusses the results obtained from the simulation software and section 4 concludes the study.

2.2 Site Data and System Analysis

In this section, we present site details and the software used to simulate the PV setup on a house in Lahore, Pakistan.

2.2.1 Site Description

The site selected for this research is a house in Lahore. Lahore is considered the second densely populated city and most populated division of Pakistan with a total population of around 22 million [25]. The exact location of this site is long 31.5481, Lat 74.3916 and google map in Figure 2.1 shows the image of solar panels installed on the roof of this house. House is in Askari X housing society, Lahore and the total rooftop area of this house is 1680 ft2. This house is made of bricks with a flat rooftop.

Figure 2.1 Site Location on Google Maps (Latitude: 31.5481, Longitude: 74.3916).

Structure of the house, size of the house, number of family members living in a house and their lifestyle play a very important role in the energy demand of a household. Seven family members are living in this house including three kids and four adults. Fig. 2 shows monthly energy consumption of the house before the installation of the Solar PV system. This data is collected through old utility bills. High energy consumption in summer months is mainly due to the use of window type air conditioner.

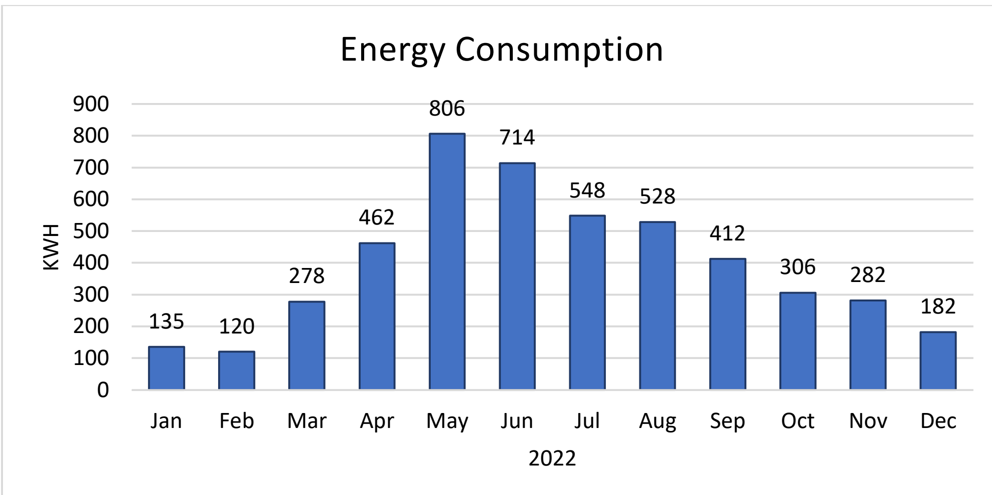


Figure 2.2 Electric Energy Consumption of the House in 2022.

Table 2-1 shows major electric appliances installed in this house and their load. Temperature rises to 45°C during summers in Pakistan, so air conditioning units are used to maintain indoor temperature. Historical energy trend of the house shows that average monthly energy consumption of this house is around 400 kWh with peak consumption in summer. Total in Table 1 shows that the full load of this house is around 5.1 kW. All the appliances in this house are rated at 220 VAC. Air conditioners are used only for a few hours a day.

Table 2-1 Installed Electric Load in House.

Sr. No	**Appliances**	**Load (Watt)**	**Qty**	**Total Load (Watt)**
1	Ceiling fan	60	7	420 W

2	LED light	10	16	160 W
3	Refrigerator	400	1	400 W
4	LED TV	350	1	350 W
5	Air Conditioner	1250	2	2,500 W
6	Microwave	1200	1	1,200 W
7	Laptop	100	1	100 W
8	Modem	20	1	20 W
	Total			**5,150 W**

2.2.2 Details of Installed Solar PV System

Local utility supply company in Lahore is offering net metering options to the residential users to promote the domestic clients to install rooftop solar PV units. The selected house is equipped with a grid-tied Solar PV unit which supplies electric power to the house and feeds extra energy back to the grid during daytime. Inverter and Solar PV panels are two major parts of a Grid-tied system. This Solar PV unit is equipped with an 8.2 kW hybrid inverter and 14 solar panels of 545 watts each. The following are some details of installed components.

2.2.2.1 Solar Panel

A total of 14 Monocrystalline solar panels manufactured by JA Solar are being used in this project. The model number of the solar panel is JAM72S30, and the total rated power of each solar panel is 545 watts. JA Solar used half-cut configuration of the modules which offers advantages of higher power output, better temperature-dependent performance, reduced shading effect on the energy generation, lower risk of hot spot, as well as enhanced tolerance for mechanical loading. The company offers 12 years of product warranty and 25 years of linear power output warranty with 0.55% annual degradation over 25 years as illustrated in Figure 2.3.

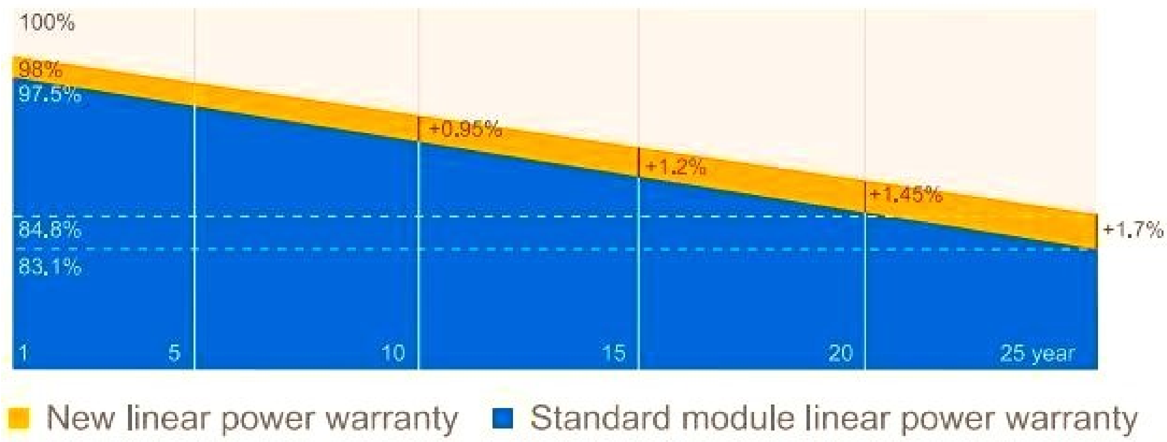


Figure 2.3 Projected efficiency of Solar Panel for 25 years [3].

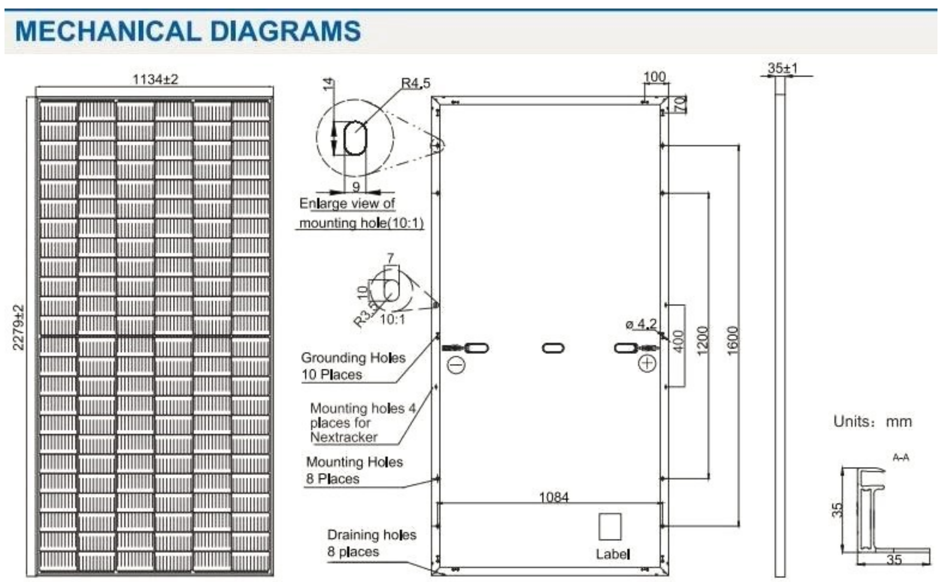


Figure 2.4 Physical dimensions of Solar Panel

This solar panel has 2,279 mm Length and 1134 mm width with a net weight of 28.6 kg each as shown in Figure 2.4. 14 solar panels and their mounting frames will put 700 kg load on the roof of the house, which will not be any problem with roof structure type of this house. 14 panels will produce total 7630W as per following formula:

$$Power\ of\ single\ Panel\ =\ 545\ W$$
$$Total\ Solar\ Panels\ =\ 14$$
$$Total\ DC\ Capacity\ of\ System\ =\ 545 \times\ 14\ =\ 7{,}630\ W$$

Table 2-2 Electrical Specification of Solar Panel

Type	Rating
Maximum Power (Pmax)	545 W
Open Circuit Voltage (Voc)	49.75 VDC
Maximum Power Voltage (Vmp)	41.80 VDC
Short Circuit Current (Isc)	13.93 A
Maximum Power Current (Imp)	13.04 A
Module Efficiency	21.10%
Power Tolerance	0 – 5W
Temperature Coefficient of Isc (α_Isc)	-0.045% °C
Temperature Coefficient of Voc (β_Isc)	-0.275% °C
Temperature Coefficient of Pmax (γ_Isc)	-0.350% °C

Table 2-2 shows electrical parameters of the solar panel. This panel is rated for 1500V DC maximum system voltage and operating temperature range is -40C to 85C. The maximum series fuse rating of this solar panel is 25A [3].

2.2.2.2Inverter

Crown Nova PV-12000 8.2 kW pure sine wave hybrid inverter is used in this system. This inverter is rated for 230 VAC and 50Hz systems as per the local demand of the utility supply company. The maximum efficiency of this inverter is 93% and users can synchronize up to 6 units in parallel. Nova 8.2 kw comes with two solar MPPT with maximum PV input current capacity of 27A each. MPPT voltage range is 90Vdc to 450VDC.

Table 2-3 Technical Specifications of inverter.

Type	Rating
Rated Output Power	8200VA/8200W
Rated Voltage	230 VAC
Frequency range	50Hz/60Hz Auto sense

Surge Power	16000VA
Peak Efficiency	93%
Maximum PV Array	12000W (6000W X 2)
MPPT Range	90 - 450 VDC
Maximum PV Array Voc	500 VDC
Maximum Solar Charging Current	150A
Operating Temperature	10 °C – 50 °C

This inverter offers three different operating modes. This can be used as a stand-alone inverter by adding battery backup and removing utility supply, grid-tied by only connecting solar panels and utility and hybrid inverter by connecting battery backup and utility supply at the same time. Inverter also offers dual output for smart load management, which means one of the outputs can be programmed as noncritical load to turn off a certain level of battery backup during nighttime. Table 2-3 shows major technical specifications of the inverter as an online datasheet [4].

2.2.2.3 System Layout

The inverter used in this system has 2 MPPT charge controllers and 2 strings of 7 panels are arranged to connect to each charge controller. Both strings have their own isolation switches and circuit breakers in the PV combiner box as shown in Figure 2.5.

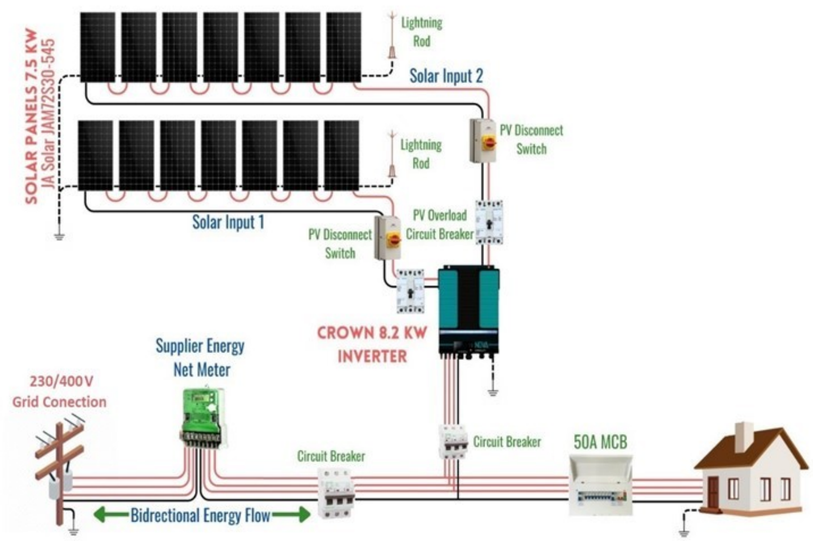


Figure 2.5 System Layout

Table 2-4 shows the rating of each string in this solar PV system. The voltage of a string is 7 times the voltage of a single panel due to series connection.

Table 2-4 Technical Specifications of PV setup

Parameter	Rating
Open Circuit Voltage (Voc) [V]	348.25 VDC
Maximum Power Voltage(Vmp)	292.6 VDC
Short Circuit Current (Isc)	13.93 A
Maximum Power Current (Imp)	13.04 A

House is running totally on solar energy during daytime and extra energy is sold to the grid. House consumes electric energy from the grid during nighttime and cloudy days. Solar inverter is logging the total energy delivered by a solar PV unit. This house is equipped with a green energy meter and sells extra energy back to the grid. PV Inverter counts the electric units fed to and from the grid and the utility company charges the client for net electric units. Solar PV system installed at this house is generating more than the consumption of the house and the user is always getting credit from the electric supply company. System was installed in August 2022, but net metering of the grid was approved in December 2022.

Solar PV inverter counted energy production by this PV system and shows 9,173 kWh from Sep-2022 to Aug-2023. Figure 2.6 shows monthly production logs of PV inverter. The result shows that the Solar PV system produces maximum output during the summer season. This result also proves that solar PV systems are the best solution as per the energy consumption trend of Pakistani homeowners. Residential consumers use more energy during summer for cooling and Solar PV systems will also be producing extra energy due to prolonged summer daylight.

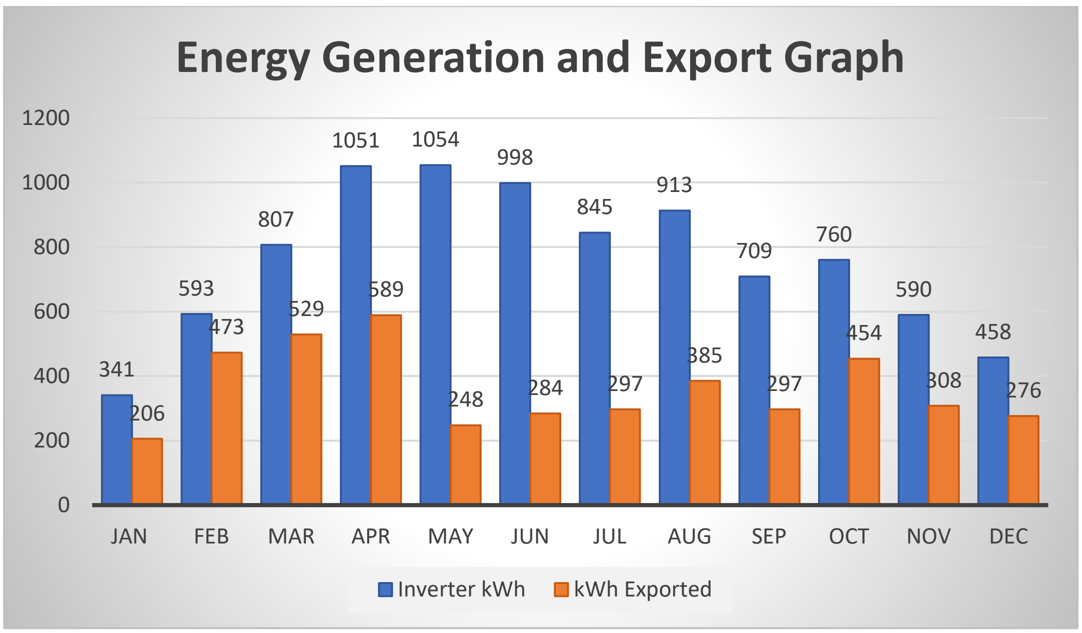


Figure 2.6 Monthly Energy Production Log of Inverter

2.2.3 Performance Analysis in System Advisor Model (SAM)

System Advisor Model is software that is used for performance and financial analysis of any Solar PV system. This software collects online weather data and performs a simulation on the designed system. Simulation results of SAM can provide the estimation of return on investment by projecting system's out for the next 25 years. Sam can model many types of solar energy systems including rooftop PV systems, battery storage systems, concentrating solar power systems for electric power generation and solar water heating systems. SAM requires all system details before running the simulation. Analysis and results are presented in the next section.

2.2.3.1 Financial Analysis of selected system in ROpt

The REopt is a platform used by NREL researchers for the optimization of energy systems for buildings, institutions, communities, micro grids, and more. REopt provides techno-economic analysis of selected systems. REopt proposes the ideal combination of renewable energy, grid generation, and energy storage technologies to meet cost savings, resilience, emissions reductions, and energy efficiency goals. REopt is a web tool that helps to evaluate the economic viability of distributed PV, wind, battery backup storage, combined heat, and power (CHP), and thermal energy storage. This tool can also identify system sizes and dispatch strategies to reduce energy costs. Users can also estimate the capability of a system to sustain critical load during a grid outage. REopt offers system selection at the beginning of every simulation design. User must select the proper site, Energy goals, and technology to get the desired results. Figure 2.7 shows an overview of these selections.

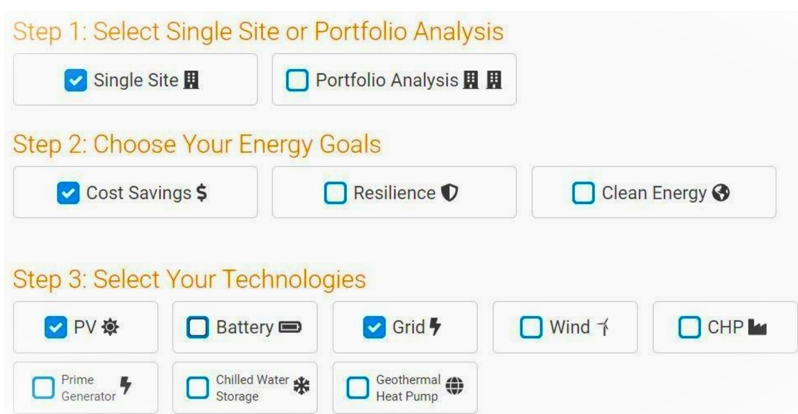


Figure 2.7 REopt Simulation Category Selection

Site selection offers a choice between a single site and portfolio analysis. Users can analyse more than one site by selecting Portfolio analysis. Single site selection will provide financial analysis of one site. Users can select between cost saving, resilience, and clean energy as their energy goals. As this software is used for financial analysis of selected systems, only cost saving is selected as energy goals of this simulation. Step 3 for data input is technology selection. The selected system is a grid-tied PV system so only PV and grid are selected for step 3.

REopt requires data for site location, local electric rates, load profile, system costing, electric grid emission factor and PV sizing limits. REopt will be able to get solar irradiance and electricity charges by local grid after the location selection of proper site. Solar irradiance data helps to determine annual energy yield of solar PV systems. REopt can determine the minimum size of the system by load profile. REopt will make sure to run load defined in load profile 100% on renewable energy if selected by the user. Analysis and results are presented in the next section.

2.2.3.2 System Modeling in HOMER Pro

HOMER Pro is a software tool developed by HOMER Energy that is widely used for energy system analysis, optimization, and planning. This versatile software is particularly valuable for professionals and researchers in the fields of renewable energy integration, microgrid design, and the overall sustainability of energy systems. HOMER Pro is equipped with a user-friendly interface and a range of powerful features, making it an essential resource for designing and evaluating energy solutions. Users can model and simulate various energy systems, from small-scale residential setups to complex industrial microgrids. These models can account for factors like energy sources, load profiles, costs, and environmental considerations.

One of the key strengths of HOMER Pro is its ability to perform optimization, helping users find the most cost-effective and environmentally friendly solutions for their energy needs. It can suggest combinations of energy sources, storage options, and grid interconnections to achieve desired objectives, whether they involve cost reduction, reduced environmental impact, or ensuring power reliability. In summary, HOMER Pro plays a vital role in the energy industry by enabling professionals and researchers to design and analyze energy systems that are not only economically efficient but also sustainable and environmentally friendly. It provides a comprehensive platform for making informed decisions in the complex and evolving landscape of energy system design and management.

Homer pro has access to an online solar irradiance database and uses it to simulate efficient results for selected projects. Homer Pro calculates annual energy production of the designed system by using online solar GHI and temperature database. Selected grid-tied solar PV system is designed in Homer Pro after selection of location. Figure 2.8 shows the designed system structure in Homer pro. This diagram shows 7.63 kW solar panels connected to a DC busbar and 8.2 kW PV inverter connecting the system to household and power grid. Household load is also designed as per annual energy consumption data of the house collected through electric bills.

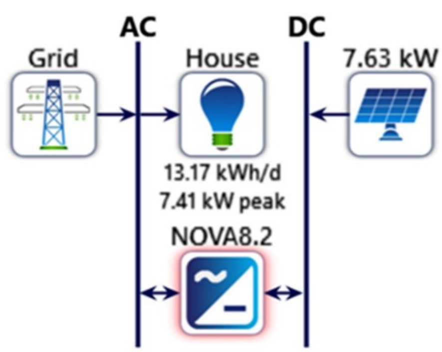


Figure 2.8 System Structure in Homer Pro

2.3 Results and Discussion

2.3.1 Simulation Results by SAM

SAM needs basic parameters to simulate projected energy and ROI of the desired system. SAM requires the location parameters to extract online solar irradiance data. Weather data was downloaded for selected location and added in the weather library of the software. SAM has many brands in solar panels and inverter libraries, but users can also define a new product if parts are not available in the list.

Figure 2.9 shows monthly global irradiance of the site. This data is being downloaded from the online Solar Resource Library by providing the exact location of the site. As per this data, May and June are the best energy yield months for solar PV systems installed at selected location. Most of the time, solar irradiance data is calculated through weather records of the previous year. Solar Irradiance data indicates that winter is not a good season for solar power systems at selected locations. It does not affect the efficacy of the system because load trend shows that energy consumption is also low during these months. Data in this graph indicates kWh/m2/day for selected site. As described in Table 2.2, maximum efficiency of selected solar panels is 21.1 % and only 21.1 % of this available solar resource will be converted to electrical energy by using these panels.

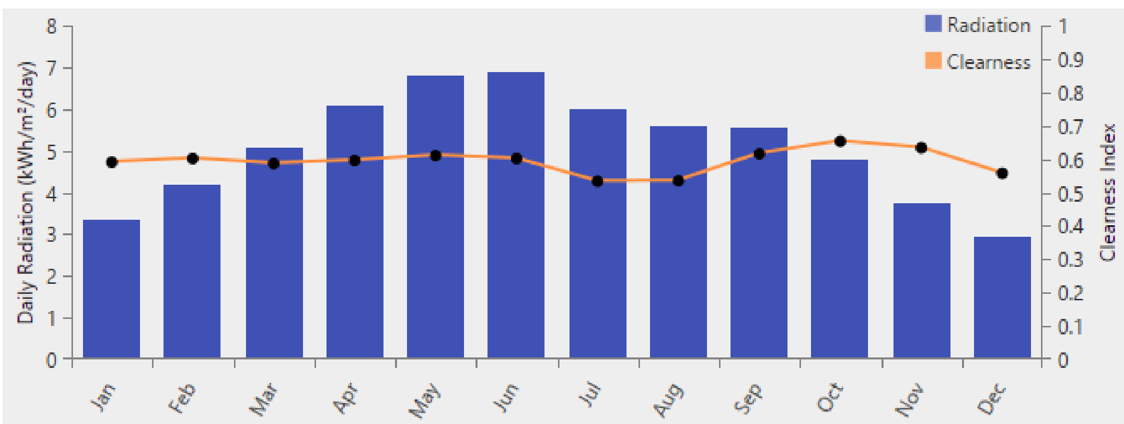


Figure 2.9 Monthly Global Irradiance of Site

The second most important parameter to calculate annual energy output of a solar PV system is the temperature graph of the selected location. Figure 2.10 shows the dry bulb temperature of the selected location for one year. This graph shows that temperature reaches up to 46 °C during summer season, which is way higher than standard test condition (STC) temperature. This rise in temperature will affect the energy output from solar panels. Installed solar panels will lose energy with respect to temperature coefficients of solar panels described in table 2.2.

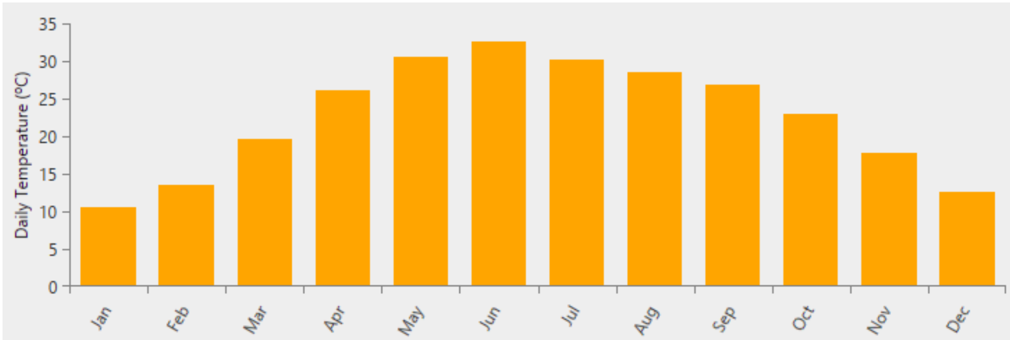


Figure 2.10 Dry Bulb Temperature of Site

Solar Irradiance reaches to peak during April and May, but temperature still shows it below 35 °C. This indicates that solar PV system installed at this site will experience comparatively less temperature losses during these months of summer. Figure 2.11 shows monthly energy production of installed solar PV system. This data correlates with the GHI graph downloaded in SAM. Result also shows that May is at top in terms of energy production. Energy production in June is quite low as compared to May because June is a very hot month in Lahore and the rise of temperature directly affects the performance of Solar PV systems.

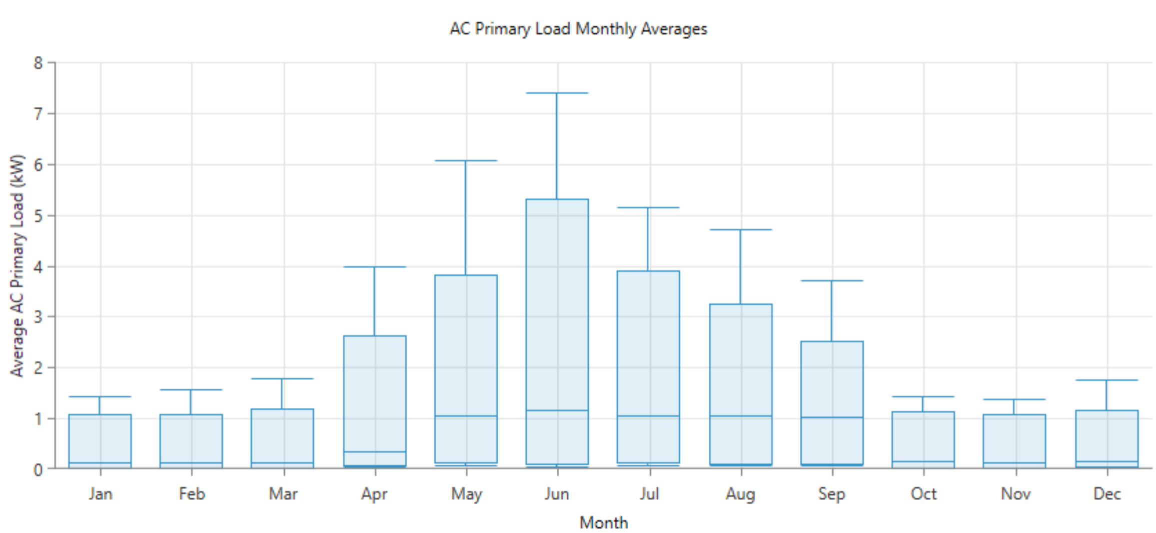


Figure 2.11 Monthly AC Energy in a year

This result shows that the energy production capacity of this system is way more than the electric energy consumption of the house. Figure 2.12 shows the heat graph of annual AC energy production by the system. This results in performance losses of inverter and solar panels. The top axis of this graph represents the number of days in the year and the left axis is the total hours of the day.

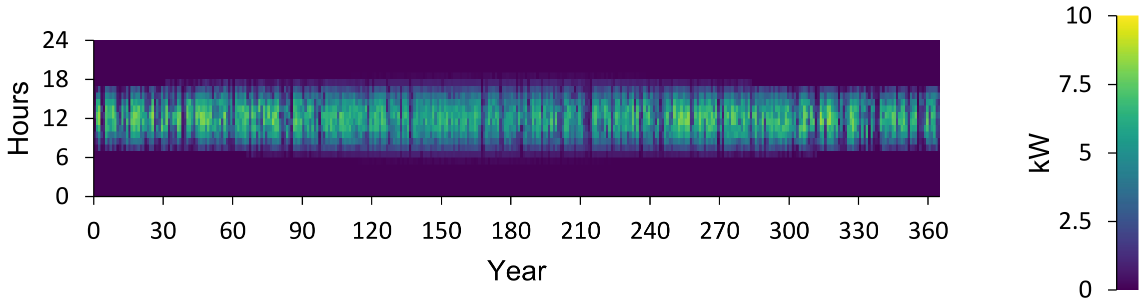


Figure 2.12 Annual AC Energy Production

Figure 2.13 demonstrates all the losses that SAM considered during the simulation. These are shading loss, Soiling loss, DC wire loss, DC mismatch loss, reflection loss, diodes and connection loss, AC wire loss, Dc module deviation from STC, inverter power consumption loss, and AC inverter efficiency loss. Most of the losses reported by the software are DC module deviations from STC. Solar Panels are tested under standard test conditions (STC) which is 25'C and solar panel will not be providing same output at higher temperatures.

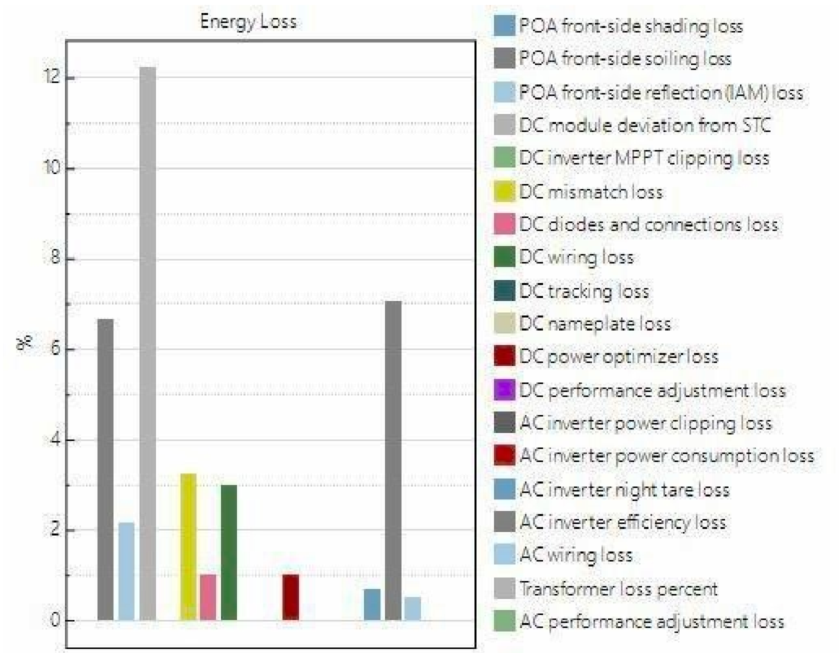


Figure 2.13 Energy Losses of the system

Table 2-5 illustrates the summary of the system over 1 year. The table shows that this system can produce 10,620 kWh annually and the internal rate of return (IRR) calculated for 10 years is 18.41%. Total capital cost for installed system is 4,696 CAD. Local utility supply company is purchasing energy generated from residential solar PV systems at a rate of 18 PKR (0.09 CAD).

Figure 2.14 shows the projected energy of the system for the next 25 years. SAM also factored in annual degradation of solar panels to generate these results. This graph calculates 0.55% annual solar panel efficiency loss for the next 25 years. Results show that this system will still be producing 9,300 kWh after 25 years of operation.

Table 2-5 System Summary Chart

Metric	**Value**
Annual AC Energy in year 1	10,620 kWh
DC Capacity factor in Year 1	15.9 %

Energy Yield in Year 1	1,392 kWh/kW
Performance ratio in year 1	0.73
PPA Price in Year 1	9.00 ¢/kWh
PPA Price escalation	0.50 %/kWh
LLPA Levelized PPA Price Nominal	9.49 ¢/kWh
LLPA Levelized PPA Price Real	7.04 ¢/kWh
LCOE Levelized cost of Energy Nominal	3.78 ¢/kWh
LCOE Levelized cost of Energy Real	2.81 ¢/kWh
NPV Net present value	$ 10,574
IRR Internal rate of return	18.41 %
Year IRR is achieved	10
IRR at end of project	21.95 %
Net capital cost	$ 4,752
Equity	$ 4,752
Size of debt	$0.00
Minimum DSCR	Inf

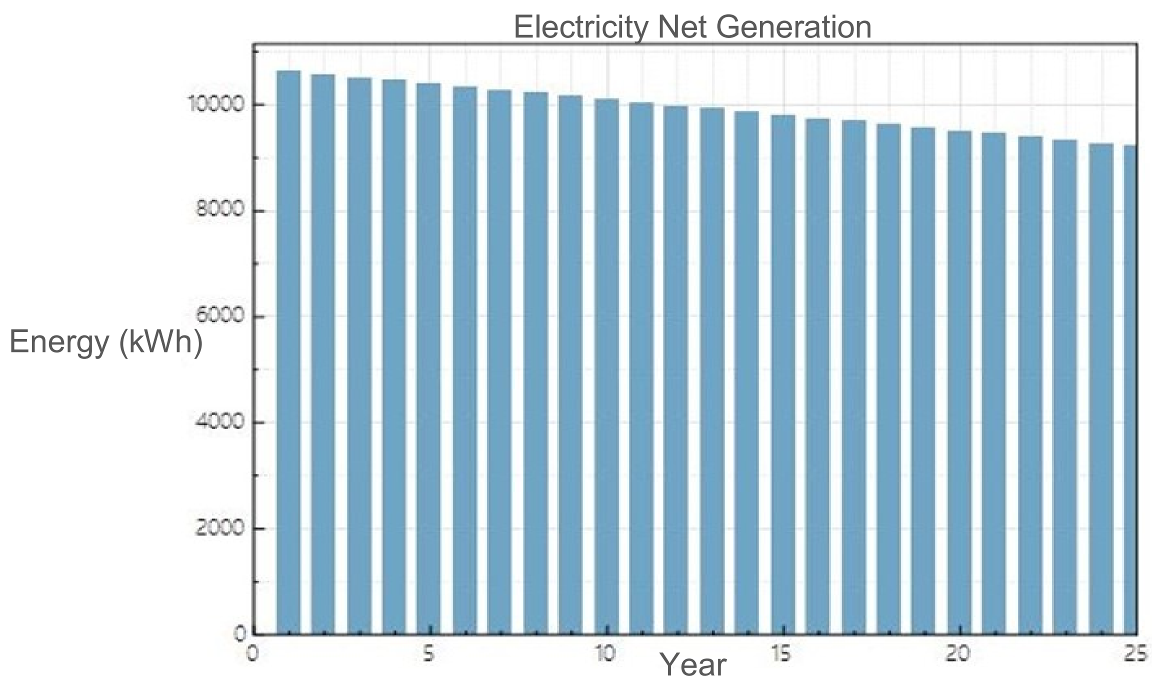


Figure 2.14 Projected Energy of the system for 25 years

2.3.1.1Comparative Analysis of SAM results with Inverter Data

SAM collects online available solar irradiance data for a selected location and simulates expected energy generation for the next 25 years. Solar Irradiance data in SAM for this simulation is downloaded for year of 2017 for selected location. SAM shows results after factoring all losses, but any type of system failure or maintenance downtown will not be calculated by this software. As Solar irradiance data is not from the same year, there is a minor difference between SAM results and inverter data. Data collected from the inverter as shown in Figure 2.15 describes that installed system generated 9,119 kWh energy from Aug-2022 to Aug-2023.

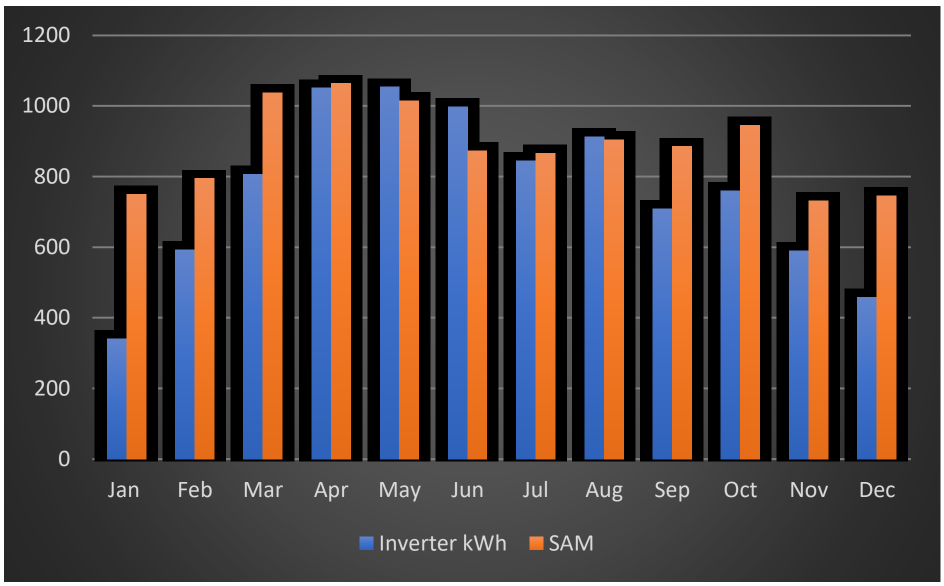


Figure 2.15. Comparison Chart of Inverter Output and SAM Results.

There are some mismatches between energy output for winter months because solar irradiance is not the same every year. SAM results show the annual output of this system should be 10,620 kWh and solar inverter logged 9,119 kWh for 1 year. Error between SAM simulation results and real time data can be calculated by using the following formula:

$$SAM\ Projected\ Annual\ Energy\ =\ 10{,}620\ kWh$$
$$Inverter\ real\ time\ annual\ energy\ =\ 9{,}119\ kWh$$
$$SAM\ Results\ Accuracy\ = \frac{9119}{10620}\ =\ 0.87$$

Calculation shows that SAM results are 87 % close to the real time solar generation data. Realtime output is less than SAM results because the installed system will only generate maximum energy in the presence of grid connection. The load of this site is very low during winter and in case of any grid outage, grid-tied solar PV system will not be able to feedback extra generation to the grid. Pakistan is facing energy shortages, and this leads to around 6-10 hours of power outage in major cities. Energy lost during the power outage of grid can be stored in battery backup system but presently, there is no battery bank installed at this site. SAM results show that the installed system can produce 13% extra energy by adding battery backup to the inverter. Energy lost due to grid outage would have been exported to the grid at a rate of 18 PKR (0.09 CAD) per unit. The following calculation shows annual loss due to absence of battery backup.

$$Annual\ Energy\ Loss\ =\ 10{,}620 - 9{,}119\ =\ 1{,}501\ kWh$$
$$Energy\ Sale\ Rate\ =\ 0.09\ CAD$$
$$Total\ Loss\ per\ year\ =\ 1{,}501 \times\ 0.09\ =\ 135\ CAD$$

The above calculation shows that users of this system can save around 135 CAD annually by adding battery backup to the system and get a power backup during nighttime power outage.

2.3.2 REopt Simulated Results

As the system is already installed and running, minimum and maximum selection in PV sizing parameters is adjusted to get system recommendation near the installed unit. Figure 2.16 shows that REopt recommended a 7kW solar PV unit after providing all basic site parameters. This system size is recommended by REopt to minimize the life cycle cost of energy at selected sites. This system will meet the energy requirements of the local site and feed extra generated energy back to the grid. The size recommended by REopt is near to the PV system size for selected size.

Figure 2.17 shows the designed system's performance for one year. This performance is calculated by REopt after collecting solar irradiance data of site location. REopt provides daily energy yield of the system, and this graph is being zoomed out to show data for the whole year.

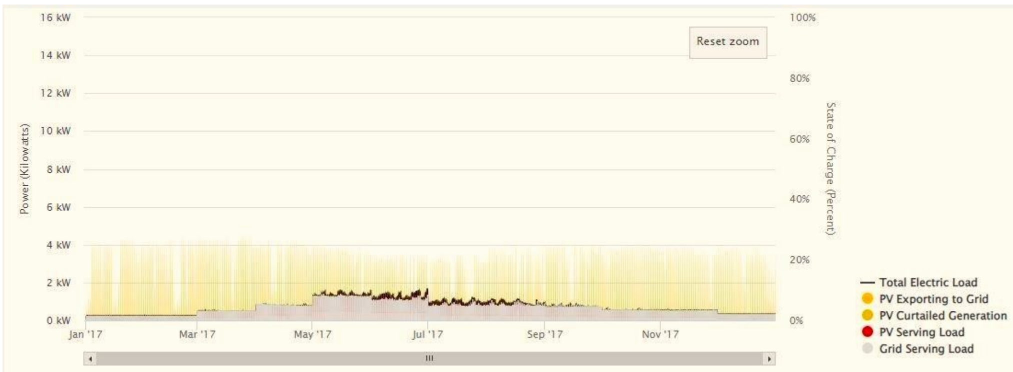


Figure 2.16 System Performance for one Year

The yellow marking in this graph represents energy exported to the grid. PV energy consumed by load is marked red in this graph. RED colour is more visible from May to Sep because the site consumes more energy during these months. Grey colour defines the energy imported from the local grid. This system imports energy from the local grid during nighttime and during cloudy weather. Figure 2.17 is a zoomed view of the previous power analysis graph and shows daily power analysis of the site. This graph clearly indicates the full site load runs on grid supply during nighttime. Most of the energy generated during daytime is exported to the grid as the yellow colour represents in this graph.

Figure 2.17 Daily Power Analysis

Figure 2.18 shows net load duration of the site. This interactive graph shows the reduction in peak load that occurred after the installation of the Solar PV system on this site. Users can also zoom in on the date range and check the system's impact for a particular day. Grey colour represents energy demand before installation of Solar PV system and blue colour represents energy demand after implementation of solar PV solution.

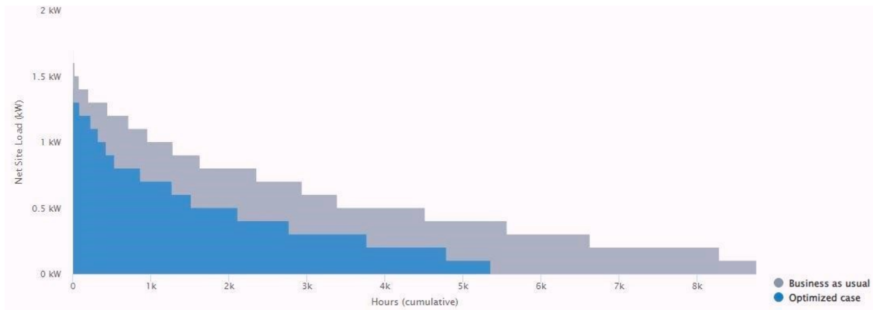


Figure 2.18 Net Load Duration

REopt calculated that a 7kW solar PV system for selected sites will save 21,208 CAD within the next 25 years. This saving is calculated after considering 0.1 CAD per kWh rate of Solar PV reverse feeding at selected site. The self-load of this site is 4,770 CAD per year and this load is fully powered on solar PV units throughout the year. Extra units consumed from the grid at night are returned during daytime. Local electric supply company is currently charging 0.25 CAD per kWh average (including taxes). REopt is charging every imported electric unit at a rate of 0.25 kWh but as per the power purchase agreement of electric supply company, customer will not be charged for any imported energy if the solar PV system is feeding back more than consumption of the site and net units at the end of the month is negative. Table 2-6 shows financial analysis of the system including the comparison of electric energy cost before and after the installation of Solar PV system. This comparison shows that the selected site will import 2,410 kWh annually from the local grid and REopt calculated this as a utility electricity cost. As a result, electric energy consumed from the grid will cost 31,395 CAD within 25 years of operation. This cost also includes the 7,400-capital cost of the project. Results demonstrate that the 7kW system at this site will produce 8,813 kWh annually which is way more than self-consumption of the site.

Table 2-6 Financial Analysis of Site

	Business As Usual	Financial	Difference
System Size			
PV Size	0 kW	7 kW	7 kW
Energy Production and Fuel Use			
Annual Average PV Energy Production	0 kW	8,813 kW	8,813 kW
Average Annual Energy Supplied from Grid	4,770 kW	2,410 kW	-2,2360 kW
Renewable Energy Metrics			
Annual Renewable Electricity (% of electricity consumption)	0%	100%	100%
Year 1 Utility Electricity Cost – Before Tax			
Utility Energy Cost	$1,192	$982	-$210
Utility Demand Cost	$20	$19	-$1
Total Year 1 Utility Cost – Before Tax	$1,213	$1,001	-$211
Life Cycle Cost Breakdown			
Technology Capital Costs + Replacements, After Incentives	N/A	$7,400	$7,400
O&M Costs	$0	$1,850	$1,850
Total Utility Electricity Cost	$38,026	$31,395	-$6,632

2.3.2.1 Analysis of REopt Results

REopt calculated 38,026 CAD cost of electric energy for next 25 years without any solar PV system. This value is calculated after factoring in the 2% annual electric energy price increase for the next 25 years. REopt projected 8,813 kWh annually by a 7kW PV system at this site which is almost the same as calculated in SAM and inverter after factoring it as 7.5kW. The REopt considered 31,395 CAD electric cost for this system for the next 25 years but as per the contract, the electric supply company will not be able to charge any bill to the customer because net units at end of each month would be in negative. As per the local tariff, the energy export rate for this site is 0.1 CAD/kWh and energy import rate for this site is 0.25 CAD/kWh (including all taxes). The following calculation gives an estimated idea of indirect savings for 25 years of life span.

Let's assume self-consumption of the site is denoted by A, electric unit cost by utility company by B, total annual electric cost for self-energy consumption by C, and electric cost for 25 years by D, then:

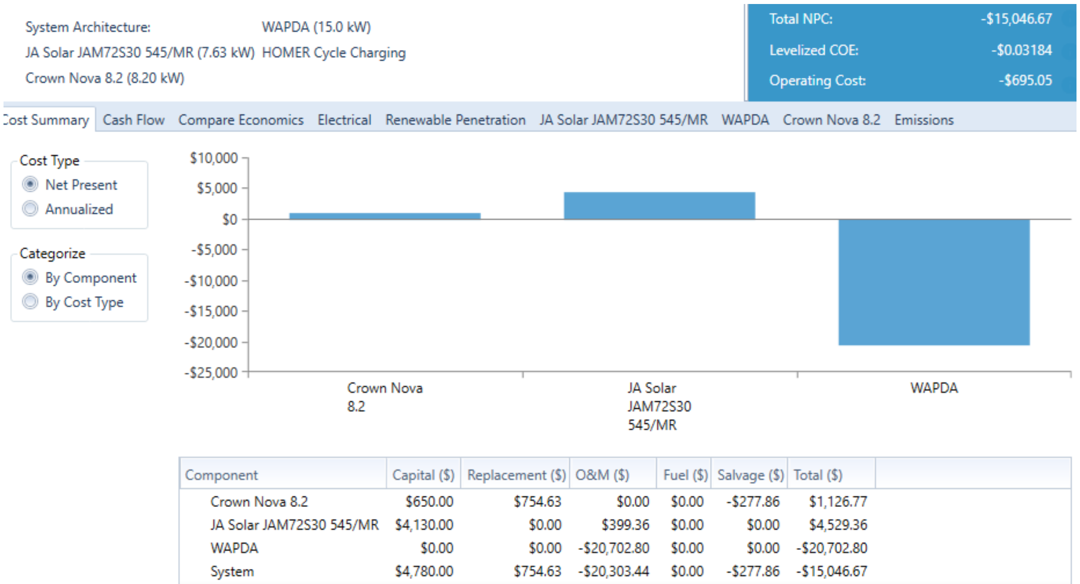
$$A = 4{,}770\ kWh$$
$$B = 0.25\ CAD/kWh$$
$$C = A \times B = 1{,}192\ CAD/Year$$
$$D = 1{,}192 \times 25 = 29{,}875\ CAD$$

Above calculations show that consumers will save 29,875 CAD within 25 years by switching their load to the Solar PV system. Furthermore, annual energy production of the system by E, energy exported to grid by U, local PV energy export rate by R, annual revenue by energy export by L, revenue for 25 years by M, and total savings for 25 years by S. Then, revenue due to reverse feeding to the grid can be calculated as follows.

$$E = 9{,}173\ kWh$$
$$U = E - A = 4{,}403\ kWh$$
$$R = 0.1\ CAD/kWh$$
$$L = U \times R = 440.3\ CAD$$
$$M = L \times 25 = 11{,}007\ CAD$$
$$S = M + D = 40{,}882\ CAD$$

2.3.3 HOMER Pro Results

The calculation done using HOMER Pro shows that user will save around 40,882 CAD within 25 years of operation. 11,007 is the revenue through reverse feeding to the grid and 29,875 CAD would have been the electric bill for this site. All the costing calculations are carried out in Canadian dollar and energy sale rate of 0.09 CAD is used for the simulation. Figure 2.19 shows a projected cost summary of the designed system for the next 25 years. The cost summary of Homer pro shows that designed solar PV system will sale 20,702 CAD value of electric power back to the grid within next 25 years. The total cost of the system used for this calculation is 4,780 CAD which is equal to 970,000 PKR as per local currency of the system location.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Crown Nova 8.2	$650.00	$754.63	$0.00	$0.00	-$277.86	$1,126.77
JA Solar JAM72S30 545/MR	$4,130.00	$0.00	$399.36	$0.00	$0.00	$4,529.36
WAPDA	$0.00	$0.00	-$20,702.80	$0.00	$0.00	-$20,702.80
System	$4,780.00	$754.63	-$20,303.44	$0.00	-$277.86	-$15,046.67

Figure 2.19 Cost Summary of Selected System.

Figure 2.20 shows cash flow of the system for 25 years of time spam. The first year shows an initial investment and the next 14 years show revenue from utility company after selling extra generated energy.

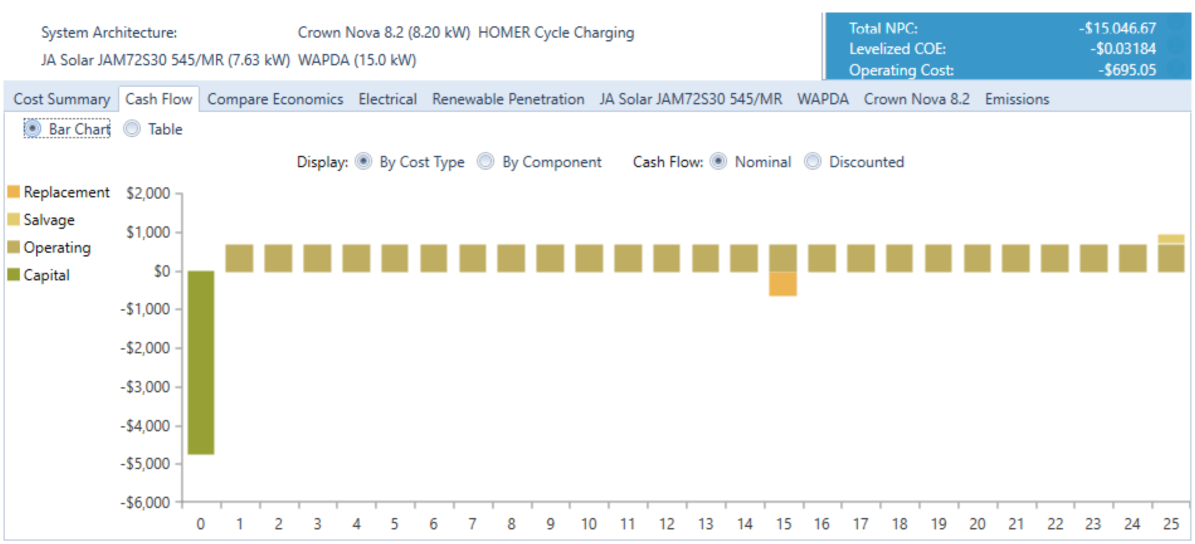


Figure 2.20 Projected Cash Flow for 25 Years.

15th year in this result shows replacement cost for inverter because projected life of PV inverter is approximately 15 years. The internal return rate (IRR) of this system calculated by homer pro is 23.7% with a return on investment (ROI) of 19.6% annually. This sums up a payback time of 4.2 years, which makes it an ideal project from an investment point of view. This Solar PV unit generates a revenue of 711 CAD annually with an initial investment of 4,780 CAD.

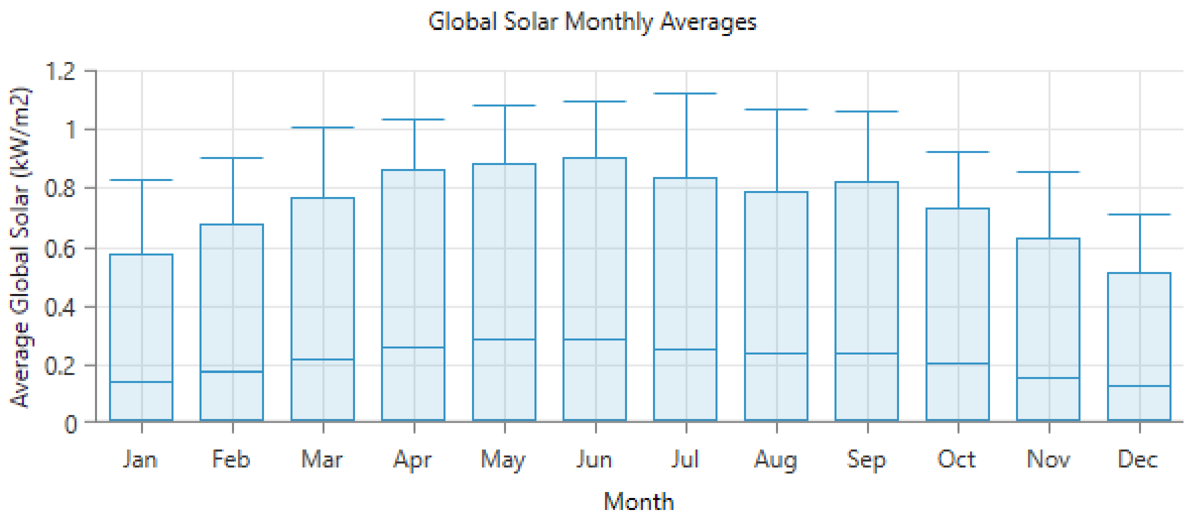


Figure 2.21 Global Solar Monthly Average

Global solar monthly average is shown in Figure 2.21, which is an important parameter for the calculation of annual energy production of selected system. The average solar irradiance value cannot exceed the defined solar constant value of 1,367 W/m2 which is defined as the amount of solar light reaching to earth surface. Solar irradiance data shows that selected locations are enriched with natural solar light throughout the year. Figure 2.22 shows the annual energy graph of the system. Orange color indicates the energy imported from grid and green generation of solar PV unit.

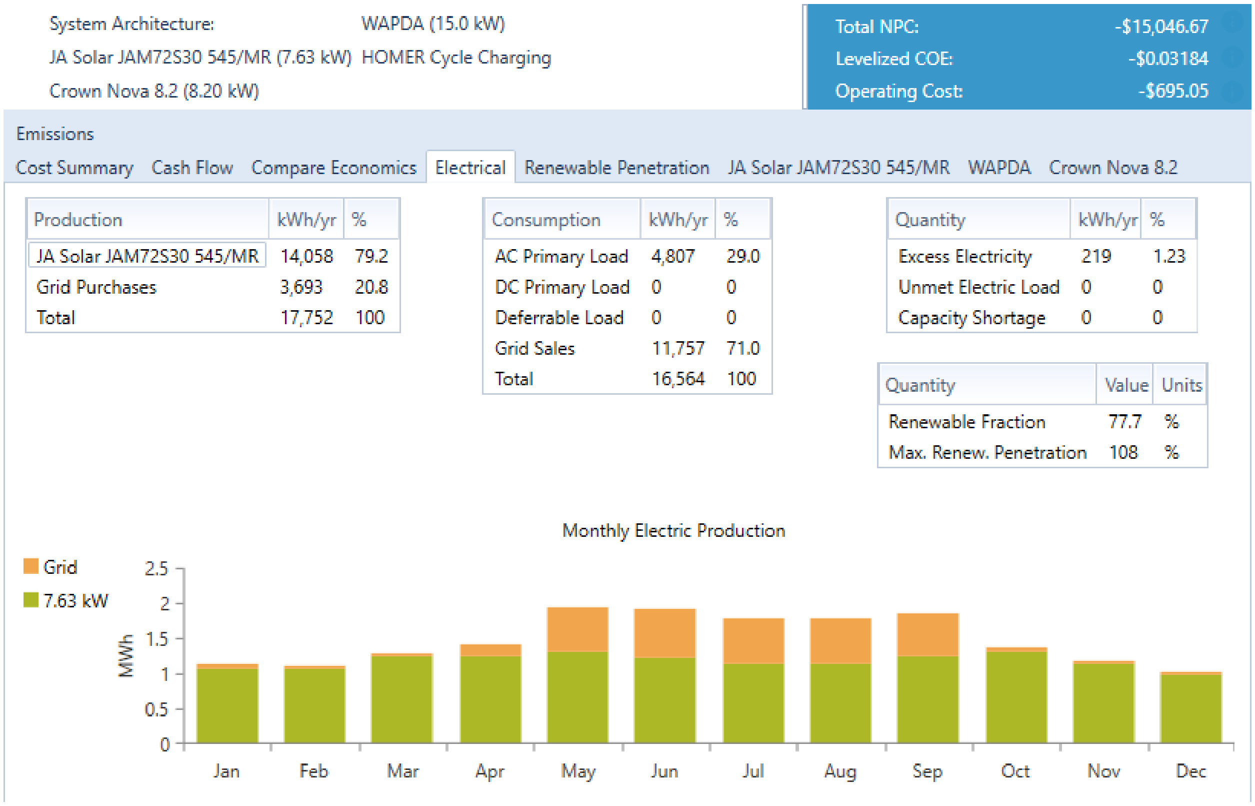


Figure 2.22 Monthly Electric Production

These results show that Solar PV system will generate 14,058 kWh annually which is way more that annual production results of SAM. Self-consumption of the house is 4,807 kWh annually which projects the true power consumption of the house. Figure 2.23 shows energy purchase from grid and energy sold to grid throughout the year. Energy purchased from grid is more intense in summer because power consumption of the house is more during summer nights. Energy sold to the grid is intense in winter due to the same reason. House consumes less energy during winter and sales more to the grid.

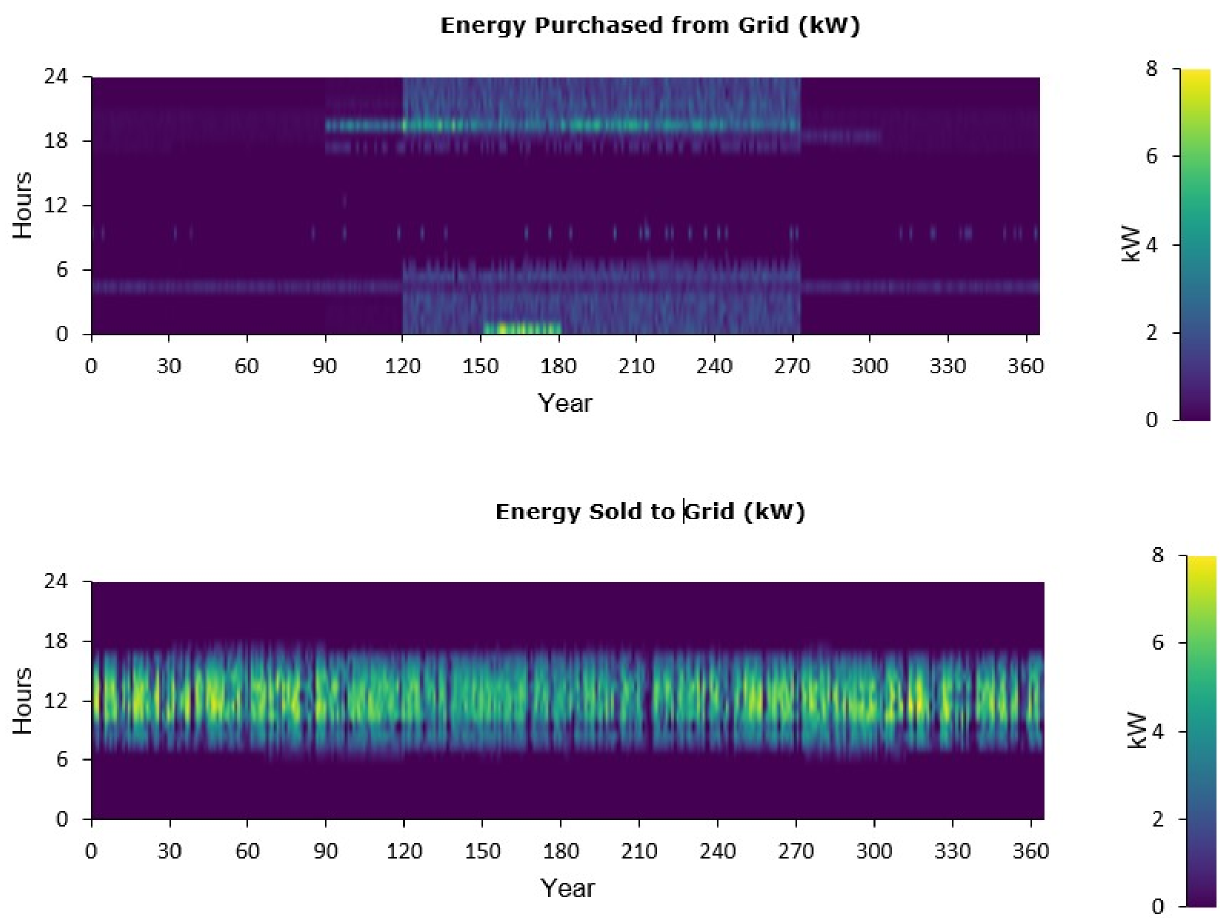


Figure 2.23 Power Grid Import and Export graphs

Figure 2.24 shows PV annual power output results of homer simulation. Total operational hours of this system are 4,385 hours/year with a capacity factor of 21 %. This sums up 14,058 kWh annually with a mean output of 38.5 kWh/day. PV penetration of this system in 292% with respect to self-load trend of the site. All these results make solar PV energy unit a reliable energy source for selected location.

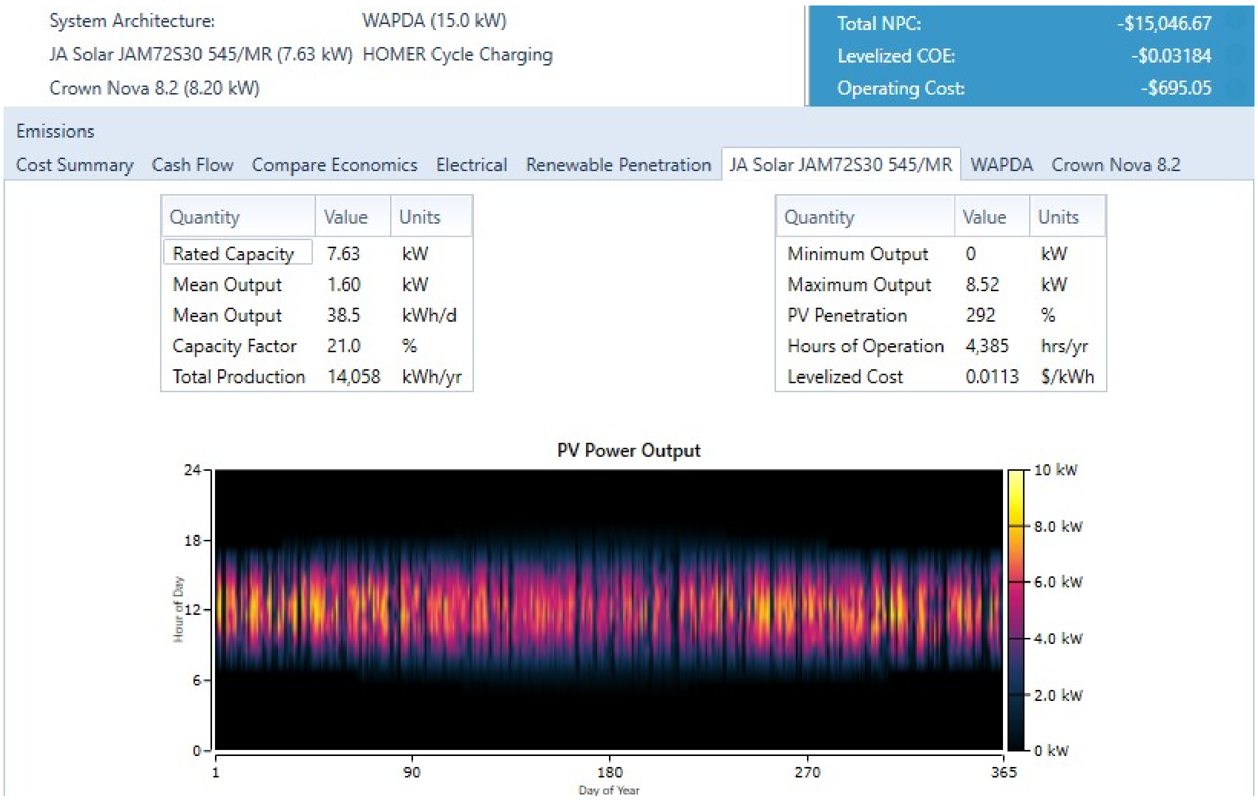


Figure 2.24 Monthly Electric Production

2.3.4 Comparison of the analysis done by the three software's

The decision to utilize multiple software tools, including Homer Pro, SAM, and REopt, in our study was driven by the need for a comprehensive and multifaceted analysis of the proposed solar PV system with battery backup. Each software brings unique capabilities to the table, allowing us to address different aspects of system design, performance assessment, and economic analysis. Homer Pro, renowned for its versatility, offers a robust platform for simulating hybrid renewable energy systems, facilitating rapid prototyping and scenario analysis. SAM, developed by the National Renewable Energy Laboratory (NREL), specializes in solar energy system modeling, providing detailed insights into energy production and financial viability. Lastly, REopt, also developed by NREL, focuses on optimizing renewable energy systems with energy storage, enabling us to identify cost-effective system configurations and operational strategies.

The inclusion of Homer Pro, SAM, and REopt in our study enhances the reliability and comprehensiveness of our analysis by leveraging the unique strengths of each software tool. By employing a multi-tool approach, we mitigate the risk of software-specific biases or limitations, ensuring robustness and consistency in our findings. Moreover, the use of multiple software platforms enables us to validate results across different simulation environments, enhancing the credibility and trustworthiness of our study outcomes. This approach also provides stakeholders with a more holistic understanding of the proposed solar PV system's performance, resilience, and economic feasibility.

Homer Pro: The annual production predicted by Homer simulation is 14,058 kWh for the 7.63 kW grid-tied solar PV system. This indicates the highest annual energy production among the three software tools used in the study. Homer Pro is known for its robust simulation capabilities and comprehensive modelling of hybrid renewable energy systems. Its ability to accurately predict energy production aligns with the observed high output in this case.

SAM (System Advisor Model): SAM results show an annual production of 10,620 kWh per year for the same system. While this is lower than the output projected by Homer Pro, SAM is widely recognized for its accurate modelling of solar photovoltaic systems and financial analysis tools. Despite a slightly lower energy production estimate compared to Homer Pro, SAM still provides valuable insights into system performance and economic viability.

REopt: The REopt analysis for the 7-kW system calculated an annual production of 8,813 kWh per year. REopt specializes in optimization algorithms for renewable energy and storage systems, aiming to identify optimal system configurations based on user-defined objectives. While the energy production estimate from REopt is lower than both Homer Pro and SAM, it offers unique optimization capabilities that contribute to a more thorough analysis of system design and operation.

2.4 Conclusions

The annual energy production estimates vary among the software tools, with Homer Pro predicting the highest output at 14,058 kWh per year, followed by SAM at 10,620 kWh per year, and REopt at 8,813 kWh per year. These variations highlight the importance of considering different simulation and optimization approaches to obtain a comprehensive understanding of system performance. SAM's energy production estimate aligns closely with the observed data from the PV inverter, indicating its ability to accurately model solar photovoltaic systems and factor in various losses. This underscores SAM's reliability in predicting energy production and assessing the financial viability of the system. Despite yielding a lower energy production estimate compared to Homer Pro and SAM, REopt offers valuable optimization capabilities for identifying optimal system configurations. By leveraging REopt's optimization algorithms, further enhancements in system design and performance can be achieved, contributing to long-term operational efficiency and cost-effectiveness. The discrepancies in energy production estimates emphasize the importance of thorough system modeling and analysis to ensure accurate sizing and performance evaluation. Integrating battery backup solutions, as suggested by the study, proves to be a viable approach for addressing grid outage issues and enhancing energy resilience. The proposed solar PV system with battery backup demonstrates promising economic returns, with a projected capital cost recovery within 5 years and significant cost savings of 40,882 CAD over the next 25 years of operation. These findings underscore the financial attractiveness of investing in `renewable energy solutions with energy storage capabilities.

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Chapter 3

Modeling and Simulation of Grid-Tied Three-Phase PV System in Lahore, Pakistan

Preface

A version of this chapter has been published in the European Journal of Electrical Engineering and Computer Science (EJECE), February 2024. I am the primary author, and I carried out most of the research work performed the literature reviews, carried out the system design, implementations, and analysis of the results. I also prepared the first draft of the manuscript. The Co-author Dr. M. Tariq Iqbal supervised the research, provided the research guide, reviewed, and corrected the manuscript, and contributed research ideas to the actualization of the manuscript.

3.1 Introduction

The use of renewable resources is a crucial step towards sustainable development in the rapidly changing energy landscape [1]. Grid-tied solar inverters, which are essential for integrating renewable energy into urban power infrastructures [2], play a significant role in cities like Lahore. The city's escalating energy demands make the role of grid-tied solar inverters increasingly important. To understand the current state of solar energy adoption in Lahore, it is crucial to examine the city's energy consumption patterns, existing infrastructure, and climatic conditions that determine the feasibility and practicality of solar photovoltaic systems. The city's geographical location and climate have a significant impact on the efficiency of solar installations. Lahore's predominantly arid climate provides an ideal setting for solar energy harnessing, with copious amounts of intense sunlight available throughout the year. Nevertheless, the complexities of temperature variations, dust levels, and other local factors necessitate a customized approach to designing grid-tied systems in this context. The utilization of grid-tied solar inverters presents a significant opportunity to transform the energy landscape. By flawlessly integrating solar power into the existing electrical grid, these systems offer a practical solution for Lahore, paving the way for environmentally friendly and sustainable energy management. Our examination of Lahore's context extends beyond mere academic inquiry, as it represents a deliberate attempt to emphasize the practical applications of grid-tied systems in real-world urban situations. By addressing peak load demands and reducing dependence on conventional power sources, the influence of these systems goes beyond theoretical boundaries, making them essential contributors to Lahore's energy security and stability.

3.2 Literature Review

Several studies have explored the modelling of grid tied solar system in various software. For instance, Benaissa et al. [3] conducted a thorough examination of a solar photovoltaic (PV) system that is connected to the utility grid using MATLAB/Simulink. This system features a DC-DC boost converter and a DC/AC inverter (VSC) that facilitate the transfer of electrical power to the grid. The model consists of two 100 kW solar arrays, a boost converter, and a three-level grid-side inverter. The authors have included several notable features, such as an accurate PV cell model that considers external temperature and solar radiation, as well as a maximum power point tracking (MPPT) algorithm. The simulation results demonstrate the influence of changes in solar radiation on the power output and showcase the effective control performance of the grid-connected PV system. Similarly, Kumar and Padma [4] conducted a study on the mathematical modeling and simulation of a residential grid-connected solar photovoltaic (PV) system using a 170W Mitsubishi solar module. They utilized a one-diode equivalent circuit to analyze the current-voltage (I-V), power-voltage (P-V), and power-current (P-I) characteristics of the system. The simulation incorporated a Perturb and Observe Maximum Power Point Tracking (MPPT) algorithm and a single-phase grid-tied inverter, which were implemented using MATLAB/Simulink. The objective of their research was to improve understanding of the dynamic behavior and performance characteristics of the system. In their study, Raut and Bhattrai [5] performed a performance analysis on a grid-connected solar PV system. They mathematically modeled a 1 kWp grid-connected system and calculated the power profile using historical environmental data. The researchers identified potential operational issues in grid-connected PV systems and suggested various strategies to address these challenges. Furthermore, the paper assessed the overall performance of the system under different scenarios. Tina and Celsa [6] presented a thorough description of a single-phase grid-connected system in their paper. The model encompasses an inverter, unipolar SPWM, inverter control strategy, Phase Locked Loop, and filter. The implemented inverter control strategy allows for the regulation of active and reactive power flow separately, enabling voltage regulation at the point of common coupling (PCC). The model is rigorously tested both numerically and experimentally, showcasing its effectiveness in regulating power flow and voltage stability. In their paper [7], Molina and Espejo provided a thorough analysis of the performance and dynamic behaviour of grid-connected photovoltaic (PV) energy conversion systems. They introduced PVSET 1.0, a versatile and precise simulation and evaluation tool for PV systems developed using MATLAB/Simulink. This tool enables the assessment of the effect of PV generation on electricity grids, offering valuable information on the behaviour of grid-connected PV systems under different operating scenarios. AbdelHady [8] designed a MATLAB/Simulink model of a solar PV system connected to a micro grid. The model was based on a 91 kW PV system located at the National Water Research Centre in Egypt. The study's objective was to assess the system's performance in relation to both the local low voltage grid and the national high voltage grid, and to compare economic savings under various scenarios, providing valuable insight into the economic feasibility of micro grid-connected solar PV systems.

Iqbal et al. [9] investigated the modelling of a conventional rural house in Pakistan using BEopt to identify the hourly load profile. They subsequently designed a standalone photovoltaic (PV) system using HOMER Pro, which included a 5.8 kW PV array and eight batteries, as well as a 1.4 kW inverter. The simulation results in MATLAB-Simulink demonstrated the system's ability to power lighting and appliance loads in a rural setting, highlighting the versatility of such systems for various regions around the world. The study by Xie et al. [10] examines the difficulties of managing voltage in grid-connected photovoltaic systems. The researchers propose a non-linear controller design that utilizes Lyapunov-based finite-time control to regulate reactive power and DC link voltage. This innovative approach outperforms conventional proportional-integral controllers, particularly in situations involving disturbances such as alterations in solar insolation levels and bus faults. The simulation results confirm the superiority of the proposed algorithm in maintaining system stability and robustness. Gulzar et al. [11] have developed an innovative converter less control strategy for a hybrid grid-connected system that integrates PV, wind, fuel cell, and battery energy storage. This system eliminates the need for a PV converter, resulting in increased cost efficiency. The design features controllers for grid-connected hybrid systems, which optimize the power flow from renewable sources to the grid. The simulation results in MATLAB Simulink demonstrate the efficiency of the proposed hybrid system, highlighting its potential advantages over conventional configurations. Ali et al. [12] explored on the design and simulation of a power electronic controller for a grid-connected photovoltaic array with maximum power point tracking (MPPT). The project involves the use of a DC boost converter in conjunction with an MPPT controller to enhance the extraction of power from the solar array. The study, conducted in MATLAB/Simulink, compares the performance of open-loop and closed-loop systems, demonstrating the effectiveness of the proposed controller in maintaining a stable power output to the grid. Gulzar et al. [13] aims to enhance the control capabilities of a grid-connected photovoltaic (PV) system in rapidly changing atmospheric conditions. By utilizing artificial intelligence optimization, the researchers determine optimal sliding mode controller gains, resulting in improved stability and reduced voltage overshoots. Their proposed finite-time sliding mode maximum power point controller exhibits superior performance, particularly in terms of transient, steady-state, and dynamic responses. Mahmood et al. [14] tackle the obstacles of voltage stability, regulation, and fault exposure in grid-connected Photovoltaic/Fuel Cell Hybrid Energy Systems.

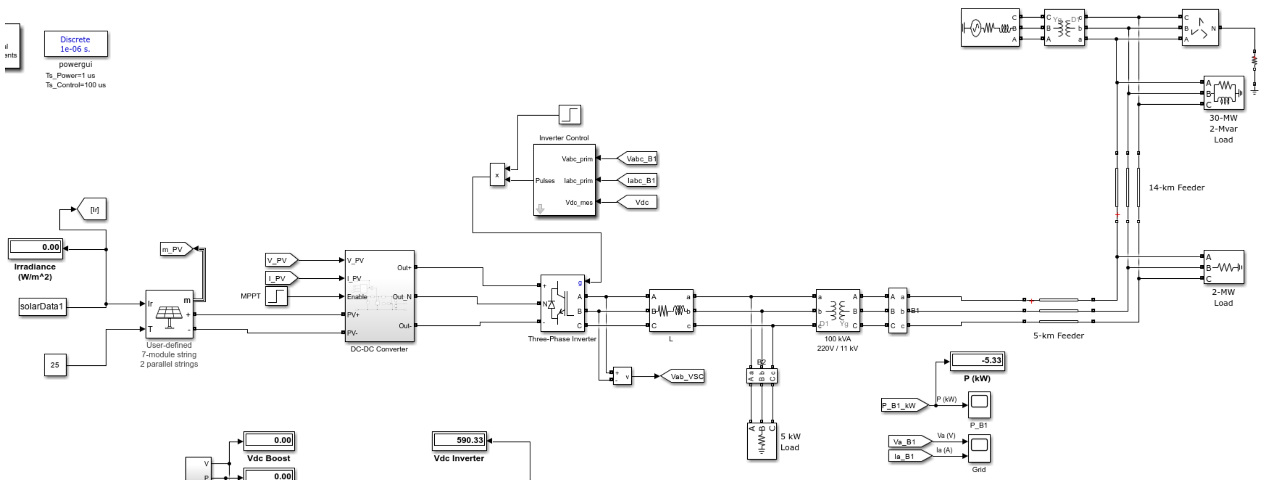

Figure 3.1 Overall structure of the installed system modelled in Simulink

By proposing a multi-input multi-output (MIMO) controller, they aim to monitor, control, and track the maximum power point of both the fuel cell and PV power sources. A simulation conducted in MATLAB/Simulink showcases the efficiency of the developed controllers in maintaining a stable output to the grid while minimizing Total Harmonic Distortion (THD). Zeb et al. [15] have developed a Fuzzy-PI controller to effectively regulate the DC-link voltage in a 3 kW single-phase grid-tied PV system. This research tackles the issues of voltage ripples and fluctuations in input DC voltage, as well as the reduction of DC-link capacitors. The proposed controller, implemented in MATLAB/Simulink, demonstrates fast, robust, and reliable performance, and improves the power quality in grid-tied PV systems. Habib et al. [16] investigates the design optimization and model predictive control for a hybrid renewable energy system that consists of wind, diesel, battery, and converter. This research was applied to a real case study in a remote rural area in Pakistan, and it involves the optimization of component sizes, power management strategies based on battery state of charge, and model predictive control to improve the output voltage profile and reduce total harmonic distortion. The proposed design and control strategy for the hybrid renewable energy system are cost-effective and environmentally friendly, which enhances the reliability and power quality of standalone renewable energy systems.

3.3 Methodology

The platform of MATLAB/SIMULINK is a versatile and powerful tool in the field of system modelling, providing a comprehensive environment for dynamic simulation and modelling. It has been selected for the modelling of the Grid-Tied PV System due to its ability to seamlessly integrate mathematical modelling with simulation, making it particularly well-suited for complex systems such as solar inverters. With this platform, it is possible to construct a holistic model that accurately reflects the real-world dynamics of the chosen system.

3.3.1 Site Description

The site selected for this research is a house in Lahore. Lahore is considered the second densely populated city and most populated division of Pakistan with a total population of around 22 million. The location of this site is long 31.5481, Lat 74.3916. House is located in Askari X housing society, Lahore and the total rooftop area of this house is 1680 ft2. This house is made of bricks with a flat rooftop.

Table 3-1 shows major electric appliances installed in this house and their load. Temperature rises to 45°C during summers in Pakistan, so air conditioning units are used to maintain indoor temperature. Historical energy trend of the house shows that average monthly energy consumption of this house is around 400 kWh with peak consumption in summer. Total in table 1 shows that the full load of this house is around 5.1 kW. All the appliances in this house are rated at 220 VAC. Air conditioners are used only for a few hours a day.

Table 3-1 Appliances and Their Load at Site

Sr. No	Appliances	Load (Watt)	Qty	Total Load (Watt)

1	Ceiling fan	60	7	420 W
2	LED light	10	16	160 W
3	Refrigerator	400	1	400 W
4	LED TV	350	1	350 W
5	Air Conditioner	1250	2	2,500 W
6	Microwave	1200	1	1,200 W
7	Laptop	100	1	100 W
8	Modem	20	1	20 W
	Total			**5,150 W**

3.3.2 Model Description

The focus of our investigation is a comprehensive model of the Grid-Tied PV System. In this section, we shall explore the system's architecture and constituent parts, which have been carefully crafted to accurately capture the interaction between a solar inverter and the grid. The model encompasses the photovoltaic array, power electronics, control mechanisms, and the complex interplay of these elements to provide a detailed representation of real-world operations. Our approach involves breaking down the system into smaller subcomponents, each represented by mathematical equations and algorithms. This modular design enhances the model's adaptability and allows for a detailed examination of each element's influence on the overall performance. Throughout the modelling process, we carefully consider the unique aspects of Lahore's climate, incorporating specific parameters that reflect the city's environmental conditions. Figure 3.1 shows the overall structure of the simulated system modelled in Simulink. The model consists of a PV array block, a DC-DC converter, an MPPT controlled Three-Phase Inverter, and Three-Phase Grid.

3.3.3 PV Array

The PV array is simulated based on the model installed on site. A total of 14 Monocrystalline solar panels manufactured by JA Solar are installed on site. The model number of the solar panel is JAM72S30, and the total rated power of each solar panel is 545 watts. JA Solar used half-cut configuration of the modules which offers advantages of higher power output, better temperature-dependent performance, reduced shading effect on the energy generation, lower risk of hot spot, as well as enhanced tolerance for mechanical loading. The company offers 12 years of product warranty and 25 years of linear power output warranty with 0.55% annual degradation over 25 years. 14 panels produce a total of 7630W. Figure 3.2 illustrates the I-V and P-V curves of the PV array.

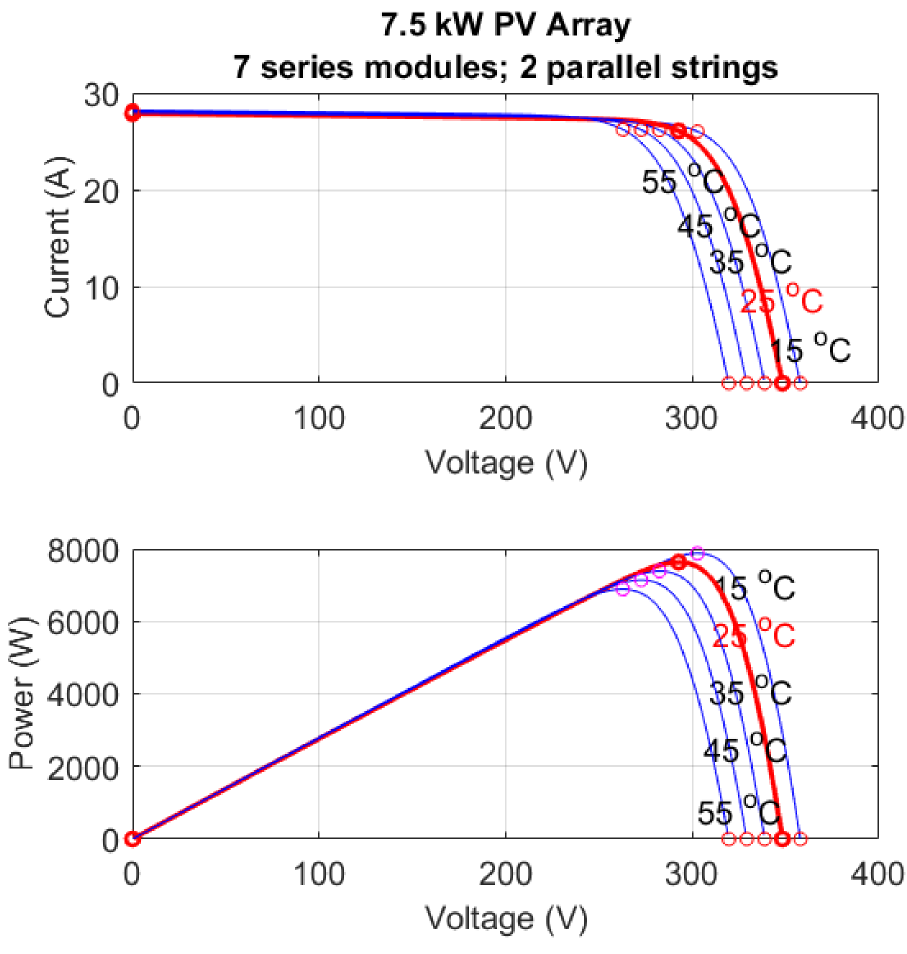

Figure 3.2 I-V and P-V Curves of the PV Array

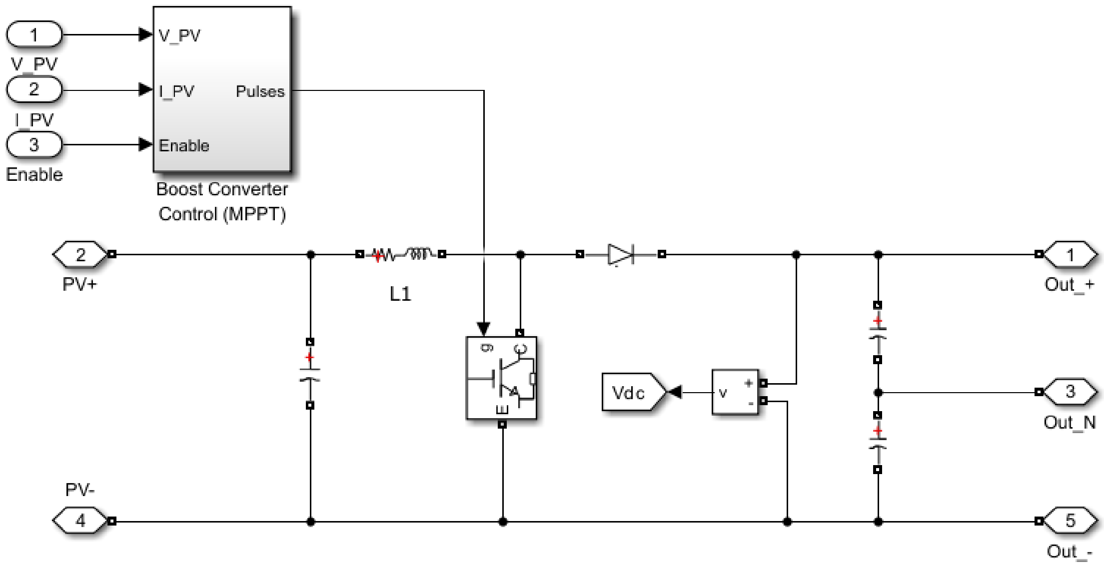

Figure 3.3 DC-DC Converter

3.3.4 DC-DC Converter:

In the simulation framework, the integration of a DC-DC converter within the inverter system is a critical aspect that demands a nuanced approach. Although the actual inverter incorporates an embedded DC-DC converter, for the purposes of simulation in Simulink, a Boost Converter model has been employed to accurately replicate the functionality and dynamics of the real-world system. The Boost Converter serves as a pivotal component in the simulation setup, mirroring the essential role of the embedded DC-DC converter in the physical inverter. This simulation strategy not only facilitates a more granular examination of the converter's behaviour but also allows for a detailed analysis of its impact on the overall system performance.

Figure 3.3 provides a visual representation of the Boost Converter model within the Simulink environment. The schematic encapsulates the intricacies of the Boost Converter, illustrating the flow of DC power from the photovoltaic (PV) panel through the converter to the inverter at an output voltage of 400V. The Boost Converter, in this simulation context, serves as an intermediary stage, optimizing the power transfer from the PV array to the inverter, ensuring compatibility and efficiency in the energy conversion process. This modelling decision aligns with the dual objectives of accuracy and flexibility in the simulation setup. While recognizing the presence of an integrated DC-DC converter in the actual inverter, the use of a Boost Converter model allows for a more detailed examination of its transient response, efficiency characteristics, and the influence on the overall system dynamics.

The implementation of Maximum Power Point Tracking (MPPT) control is a pivotal aspect in optimizing the performance of the DC-DC converter within the overall photovoltaic (PV) system, provides a graphical representation of the MPPT controller specifically designed for the DC-DC converter. In this instance, the MPPT strategy is realized through a combination of Incremental Conductance and Integral Regulator techniques.

The Incremental Conductance method is renowned for its ability to dynamically track and adjust the operating point of the PV system to maximize power output. This technique involves monitoring the instantaneous changes in power and voltage and adjusting the operating point to ensure it corresponds to the maximum power point on the power-voltage characteristic curve of the solar panel. The Incremental Conductance approach is particularly effective in environments with variable irradiance and temperature.

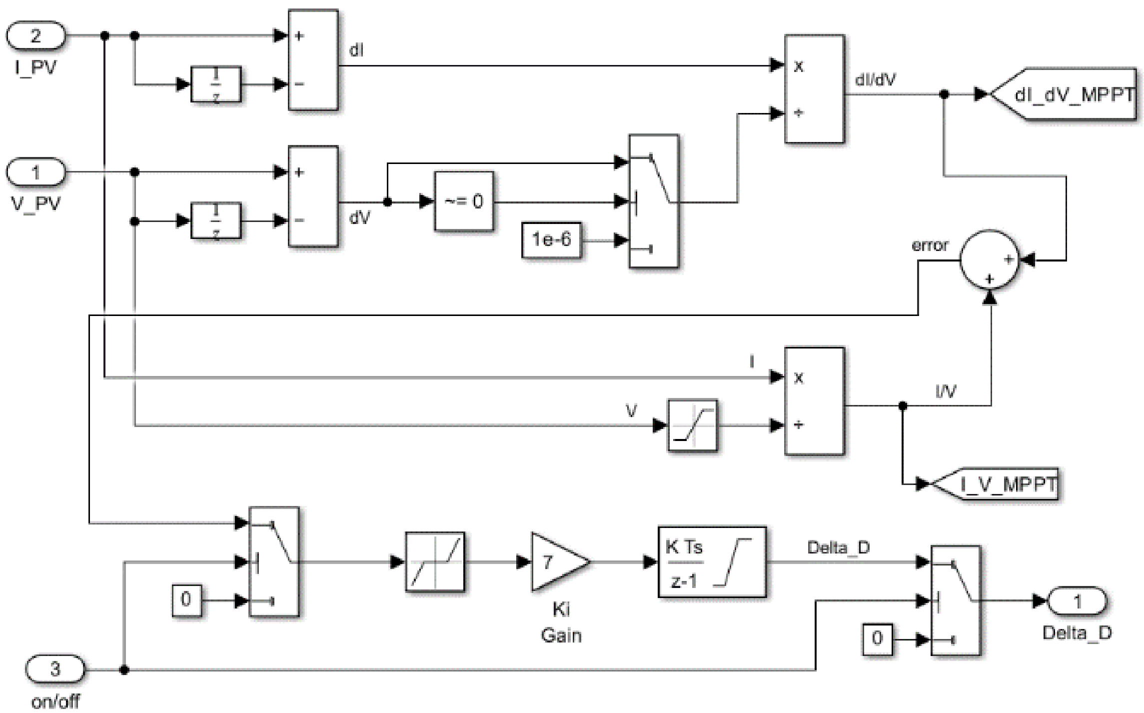

Figure 3.4 MPPT Controller for DC-DC Converter

conditions, as it allows for swift and adaptive adjustments. Incremental Conductance is often based on the ratio of the change in power to the change in voltage. The algorithm seeks to make this ratio equal to the negative of instantaneous conductance. The Incremental Conductance (IC) algorithm equation can be expressed as:

$$IC = \Delta P/\Delta V - G \qquad (1)$$

where:

ΔP is the change in power,

ΔV is the change in voltage,

G is instantaneous conductance.

The goal is to adjust the operating point until $IC = 0$, indicating that the system is operating at the maximum power point.

Along with Incremental Conductance, the Integral Regulator adds a layer of stability and precision to the MPPT control strategy. By incorporating integral control, the regulator minimizes any steady-state errors that may arise during the tracking process. This ensures that the operating point converges to and remains at the optimal point for power extraction over a range of environmental conditions. The Integral Regulator adds a term based on the integral of the error signal. The error is the difference between the actual operating point conductance and the conductance at the maximum power point. The equation for the Integral Regulator can be written as:

$$I_{Reg} = I_{Reg} + k_i \cdot error \qquad (2)$$

Where:

I_{Reg} is the integral term,

k_i is the integral gain,

$error$ is the difference between the actual conductance and the conductance at the maximum power point.

3.3.5 Three-Phase Inverter:

The integration of the DC-DC converter and the subsequent provision of stable DC voltage to the Three-phase Inverter form a crucial link in the photovoltaic (PV) system. The specific inverter utilized in the system, the Crown Nova 8.2 kW pure sine wave hybrid inverter, plays a pivotal role in transforming the DC power from the solar panels into usable AC power for the electrical grid. Table 3-2 provides the specifications of the inverter.

Table 3-2 Specifications of the Inverter

Type	**Rating**
Rated Output Power	8200VA/8200W
Rated Voltage	230 VAC
Frequency range	50Hz/60Hz Auto sense

Surge Power	16000VA
Peak Efficiency	93%
Maximum PV Array	12000W (6000W X 2)
MPPT Range	90-450 VDC
Maximum PV Array Voc	500 VDC
Maximum Solar Charging Current	150A
Operating Temperature	10 °C to 50 °C

The Crown Nova 8.2KW inverter is designed to meet the local demand of the utility supply company, adhering to the standard specifications of 230 VAC and 50 Hz. The pure sine wave output ensures a clean and stable power supply, making it suitable for a variety of applications. The inverter has a maximum efficiency of 93%, indicating its effectiveness in converting the DC power from the PV array to AC power with minimal losses. Additionally, the capability to synchronize up to 7 units in parallel enhances the scalability and adaptability of the system, allowing for increased power output as needed. The inclusion of two solar Maximum Power Point Tracking (MPPT) controllers further optimizes the system's performance. These MPPTs accommodate the variability in solar irradiance and ensure that the inverter operates at the maximum power point of the PV array. The specified MPPT voltage range of 90Vdc to 450VDC provides flexibility in supporting a diverse range of PV panel configurations.

Figure 3.5 illustrates the MPPT controller for Three-Phase Inverter. The MPPT encompasses three essential components: Phase-Locked Loop (PLL), Voltage Regulator, and Current Regulator. Together, these elements facilitate the synchronization of the inverter with the grid when connected. The PLL component plays a pivotal role in synchronizing the inverter's output with the grid frequency. It continuously monitors the grid voltage and adjusts the inverter's output phase to align with the grid. By maintaining a precise phase relationship, the PLL ensures seamless integration of the PV-generated power into the grid. PLL employs the abc_dq0 transformation that is commonly used to convert three-phase quantities from the stationary abc reference frame to the rotating dq0 reference frame. This transformation involves rotating the coordinates to align with the instantaneous phase angle of the AC load.

The transformation for voltage involves rotating the three-phase voltage vector $[V_a, V_b, V_c]^T$ in the abc frame to the dq0 frame, resulting in the vector $\left[V_d, V_q, V_0\right]^T$. The transformation equations are given by:

$$V_d = \frac{2}{3}\left(V_a \cos(\theta) + V_b \cos\left(\theta - \frac{2}{3}\pi\right) + V_c \cos\left(\theta + \frac{2}{3}\pi\right)\right) \quad (3)$$

$$V_q = \frac{2}{3}(V_a \sin(\theta) + V_b \sin(\theta - \frac{2}{3}\pi) + V_c \sin(\theta + \frac{2}{3}\pi)) \quad (4)$$

$$V_0 = \frac{1}{3}(V_a + V_b + V_c) \quad (5)$$

where θ is the instantaneous phase angle.

Similarly, the transformation for current involves rotating the three-phase current vector $[I_a, I_b, I_c]^T$ in the abc frame to the dq0 frame, resulting in the vector $\left[I_d, I_q, I_0\right]^T$. The transformation equations are given by:

$$I_d = \frac{2}{3}(I_a \cos(\theta) + I_b \cos(\theta - \frac{2}{3}\pi) + I_c \cos(\theta + \frac{2}{3}\pi)) \quad (6)$$

$$I_q = \frac{2}{3}(I_a \sin(\theta) + I_b \sin(\theta - \frac{2}{3}\pi) + I_c \sin(\theta + \frac{2}{3}\pi)) \quad (7)$$

$$I_0 = \frac{1}{3}(I_a + I_b + I_c) \quad (8)$$

In these equations, I_d and I_q represent the direct and quadrature components of the current, respectively, in the rotating dq frame.

The Voltage Regulator is responsible for maintaining the output voltage of the inverter within the specified limits. It adjusts the inverter's output voltage to match the grid voltage, ensuring that the power injected into the grid is at the required voltage levels. This component contributes to the stability and reliability of the inverter's interaction with the grid. The Current Regulator focuses on controlling the output current of the inverter. It ensures that the inverter injects the appropriate amount of current into the grid, aligning with the grid's requirements. This regulation is crucial for grid compatibility and prevents undesirable effects such as overcurrent or instability. The collective operation of these three components within the MPPT system enables the inverter to seamlessly synchronize with the grid. The coordinated efforts of the PLL, Voltage Regulator, and Current Regulator ensure that the inverter's output adheres to the grid specifications, including frequency, voltage, and current.

The voltage and current regulators in a Maximum Power Point Tracking (MPPT) system are essential components that control the output of the inverter to optimize the power extracted from the photovoltaic (PV) panels. These regulators adjust the inverter's output voltage and current to ensure that it operates at the maximum power point of the PV array.

The voltage regulator ensures that the inverter output voltage (V_{inv}) aligns with the maximum power point voltage (V_{mpp}) of the PV array. The basic proportional-integral (PI) control equation for the voltage regulator is:

$$V_{ref} = V_{mpp} + K_p \cdot (V_{mpp} - V_{inv}) + K_i \cdot \int (V_{mpp} - V_{inv}) dt \qquad (9)$$

where:

V_{ref} is the reference voltage for the inverter,

K_p is the proportional gain,

K_i is the integral gain,

t is time.

The current regulator adjusts the inverter output current (I_{inv}) to match the maximum power point current (I_{mpp}) of the PV array. The PI control equation for the current regulator is:

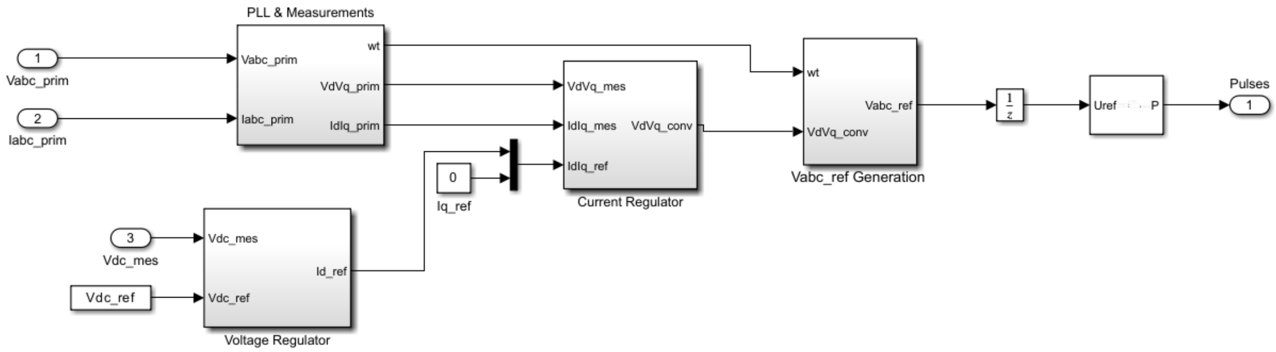

Figure 3.5 MPPT Controller for Three-Phase Inverter

$$I_{ref} = I_{mpp} + K_p \cdot (I_{mpp} - I_{inv}) + K_i \cdot \int (I_{mpp} - I_{inv}) \qquad (10)$$

where:

I_{ref} is the reference current for the inverter,

K_p is the proportional gain,

K_i is the integral gain,

t is time.

These equations represent a basic form of the PI control used in regulators. The gains (K_p and K_i) are tuning parameters that need to be adjusted to achieve stable and efficient control.

The voltage and current regulators work in conjunction to dynamically adjust the inverter's output to maximize power extraction from the PV array under varying environmental conditions.

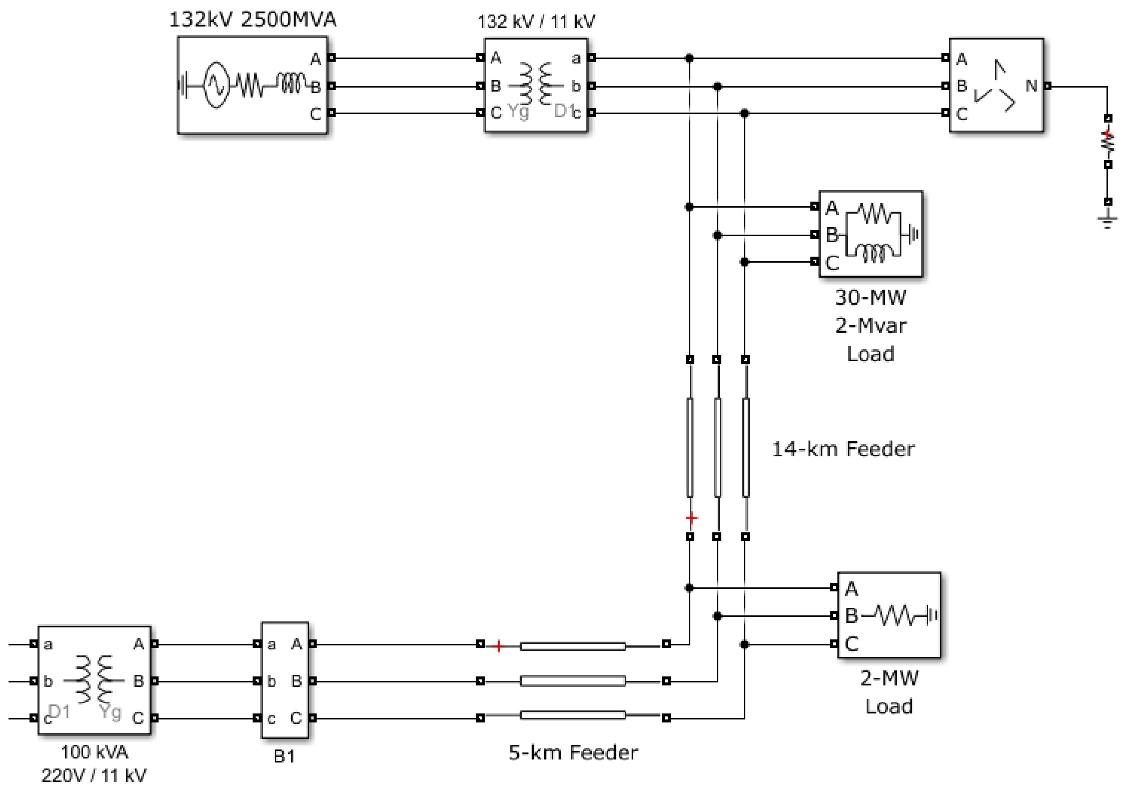

Figure 3.6 Three-Phase Grid modelled in Simulink

3.3.6 Three-Phase Grid Modelling:

The grid model for the three-phase grid-connected PV system in Lahore is accurately constructed to mirror the characteristics of the power distribution network in Pakistan as shown in Figure 3.6. At the heart of this model lies the primary energy source, a three-phase transformer with a substantial voltage rating of 132 kV/11 kV and an impressive power rating of 2500 MVA. This transformer serves as the linchpin of the grid, facilitating the transformation and distribution of electrical power.

The energy transfer across the grid is facilitated by two transmission lines, each designed to transport power from the source to distinct loads within the system. The first transmission line spans a length of 14 km, while the second covers 5 km. To accurately capture the real-world complexities of power transmission, impedance blocks are strategically incorporated into the model. These impedance blocks play a pivotal role in replicating voltage drops and losses that occur during power transmission, ensuring a comprehensive representation of the grid dynamics.

Within this grid model, various loads are strategically placed to simulate real-world scenarios. Load 1, a 30 MW and 2 MVAR load, is connected at the terminus of the 14 km feeder, representing a substantial demand on the grid. Load 2, a 2 MW load, is situated at the endpoint of the 5 km feeder, contributing to the overall load distribution. Additionally, Load 3, designed as a 5.1 kW residential load, is introduced to represent household consumption. For the purposes of this study, Load 3 remains fixed at 5.1 kW over a 24-hour period, providing a stable and consistent residential demand profile for analysis.

3.4 Results

The simulation of the model was conducted using MATLAB/Simulink 2023b, and the obtained results affirm the accuracy of the model's representation. The load was intentionally set at 5.1 kW to emulate the actual load conditions at the site under investigation. The simulation encompasses three distinct cases, each shedding light on different aspects of the grid-connected PV system.

3.4.1 Grid Disconnected and constant Irradiance.

In the first case, the scenario involves the grid being disconnected. The PV array, with a capacity of 7.5 kW, is demonstrated to be fully capable of meeting the 5.1 kW load demand. As depicted in Figure 3.7, the PV array consistently generates 7.5 kW of power.

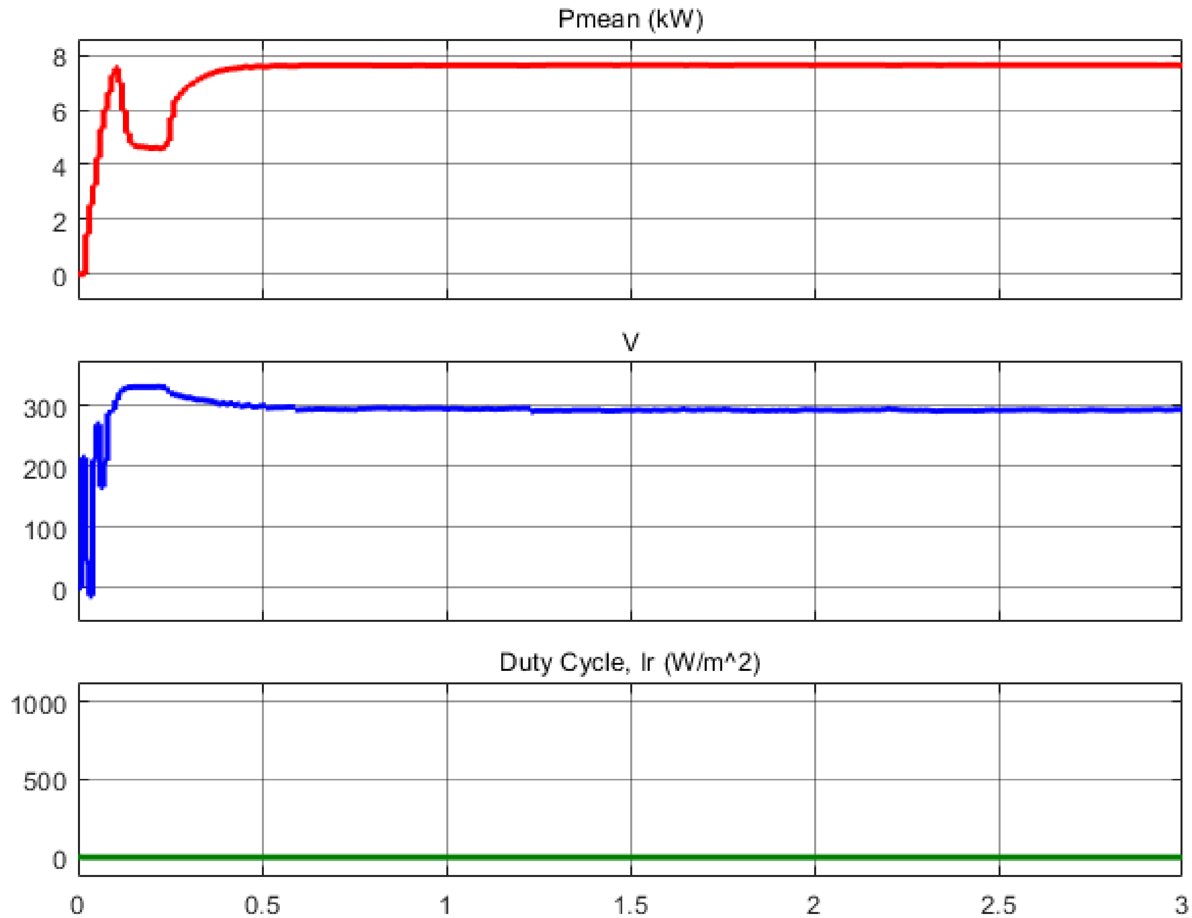

Figure 3.7 PV array providing power to the load. Grid is not connected

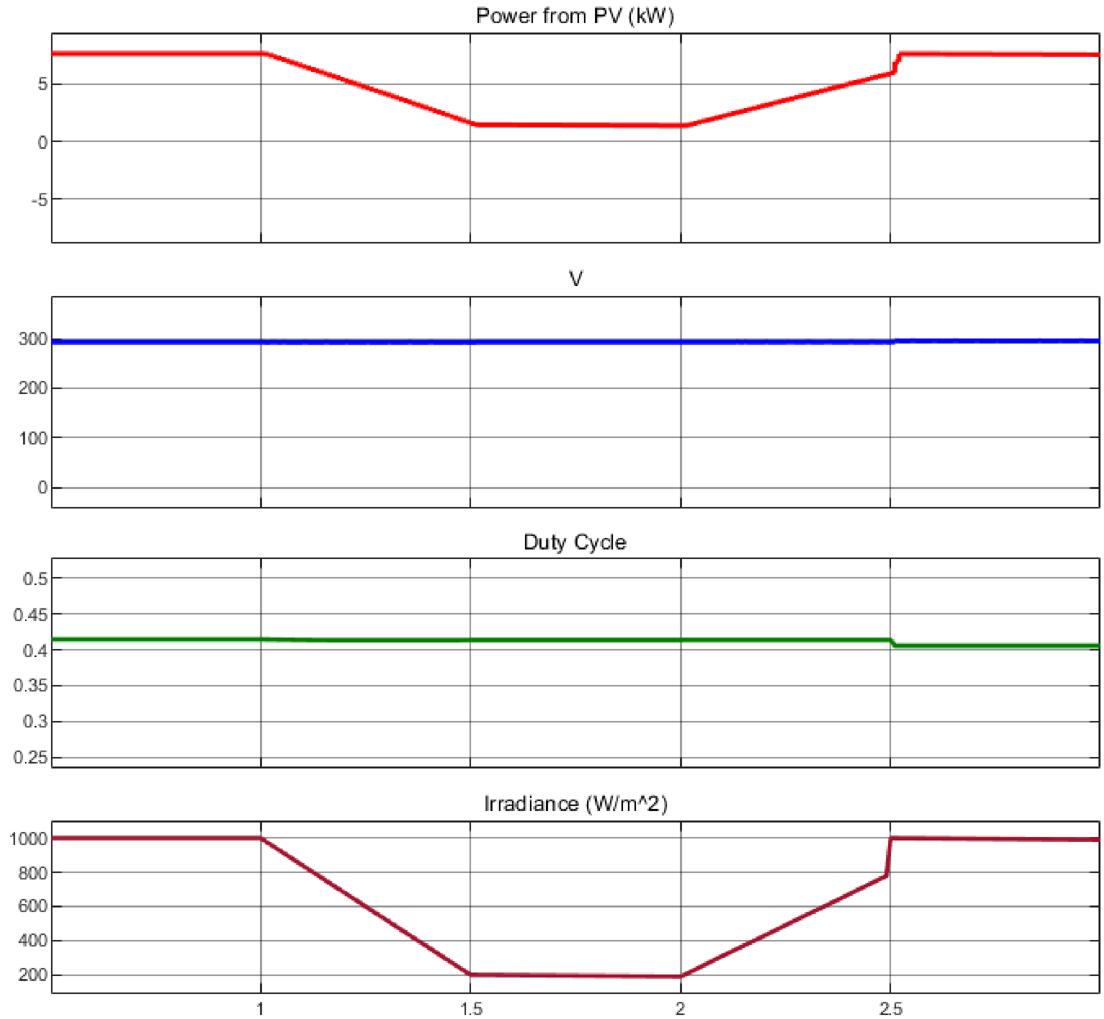

Figure 3.8 Varying Irradiance from 1000 W/m2 to 200 W/m2

The voltage within the system remains stable at 300V, indicating the robustness of the PV array in handling the load independently. This scenario showcases the self-sufficiency of the PV system in generating and supplying power without relying on the external grid. The figure not only illustrates the power generation and voltage stability but also serves as a visual confirmation of the successful simulation in MATLAB/Simulink. The alignment of simulated results with the expected outcomes further validates the accuracy of the model, providing confidence in its representation of real-world conditions.

3.4.2 Grid Connected with varying Irradiance.

In Case 2, the simulation explores the grid-connected scenario with varying irradiance, specifically focusing on the net metering setup installed at the site. In this configuration, the PV array is connected to the grid and continues to supply power to the load. The net metering system allows for the excess power generated by the PV array to be fed back into the grid. Figure 3.8 illustrates the scenario.

Figure 3.9 illustrates the dynamics of power flow within the system. Three distinctive waveforms are presented: the red line represents the power generated by the PV array, the blue line signifies the power consumed by the load, and the green line depicts the power exchanged with the grid. Notably, the grid waveform (green) exhibits a negative trend, indicating that the PV array is contributing excessive power to the grid. This negative value signifies the net export of power from the PV system to the grid, a characteristic feature of net metering systems.

To further investigate the system's behavior under reduced irradiance conditions, the irradiance is intentionally reduced to 200. Therefore, the power generation by the PV array diminishes. In this scenario, the system dynamically compensates for the reduced power generation by acquiring additional power from the grid. Consequently, the grid waveform (green) transitions to a positive value, reflecting the influx of power from the grid to meet the load demand.

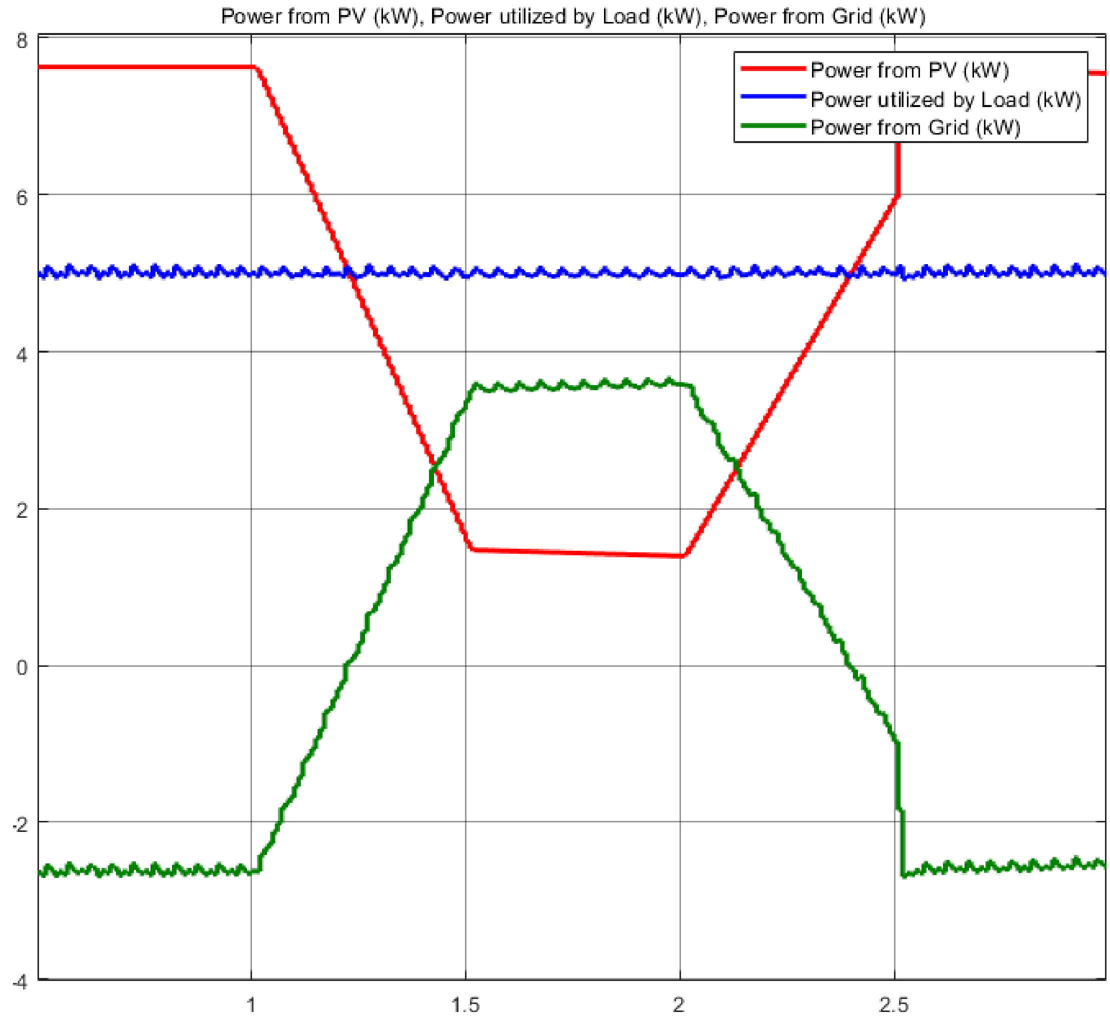

Figure 3.9 Grid Connected with varying Irradiance.

This simulation scenario, characterized by varying irradiance levels, provides valuable insights into the adaptability and performance of the grid-connected PV system. The net metering mechanism allows for a dynamic interplay between power generation, load demand, and grid interaction, showcasing the system's ability to seamlessly balance energy supply and demand under changing environmental conditions. The visualization of these waveforms in the simulation output is instrumental in comprehending the intricacies of the grid-connected PV system in practical scenarios.

3.4.3 Grid Connected with realistic Irradiance and Temperature

In this scenario, the simulation takes a step further by incorporating realistic irradiance values that reflect the day and night schedule of the site. The irradiance values follow a pattern corresponding to the natural variations in sunlight throughout the day, reaching a maximum of 700 W/m². The temperature is kept constant at 25°C to maintain consistency in the simulation conditions. Figure 3.10 illustrates the scenario.

The simulation results, as depicted in Figure 3.11, showcase the accurate modelling of the photovoltaic (PV) system installed at the site under realistic irradiance conditions. The Fig. captures the dynamic response of the PV array to the varying sunlight intensity, providing a comprehensive representation of its performance throughout the day. The realism in the irradiance values allows the simulation to closely mimic the actual behaviour of the PV system in response to changing environmental conditions. The accuracy of the model is evident in the waveform patterns, demonstrating how the power output from the PV array dynamically adjusts in accordance with the available sunlight. This scenario is particularly valuable for assessing the practical viability of the grid-connected PV system under realistic operating conditions. It enables a thorough examination of the system's ability to adapt to the inherent variability in solar irradiance and validates the model's representation against real-world expectations.

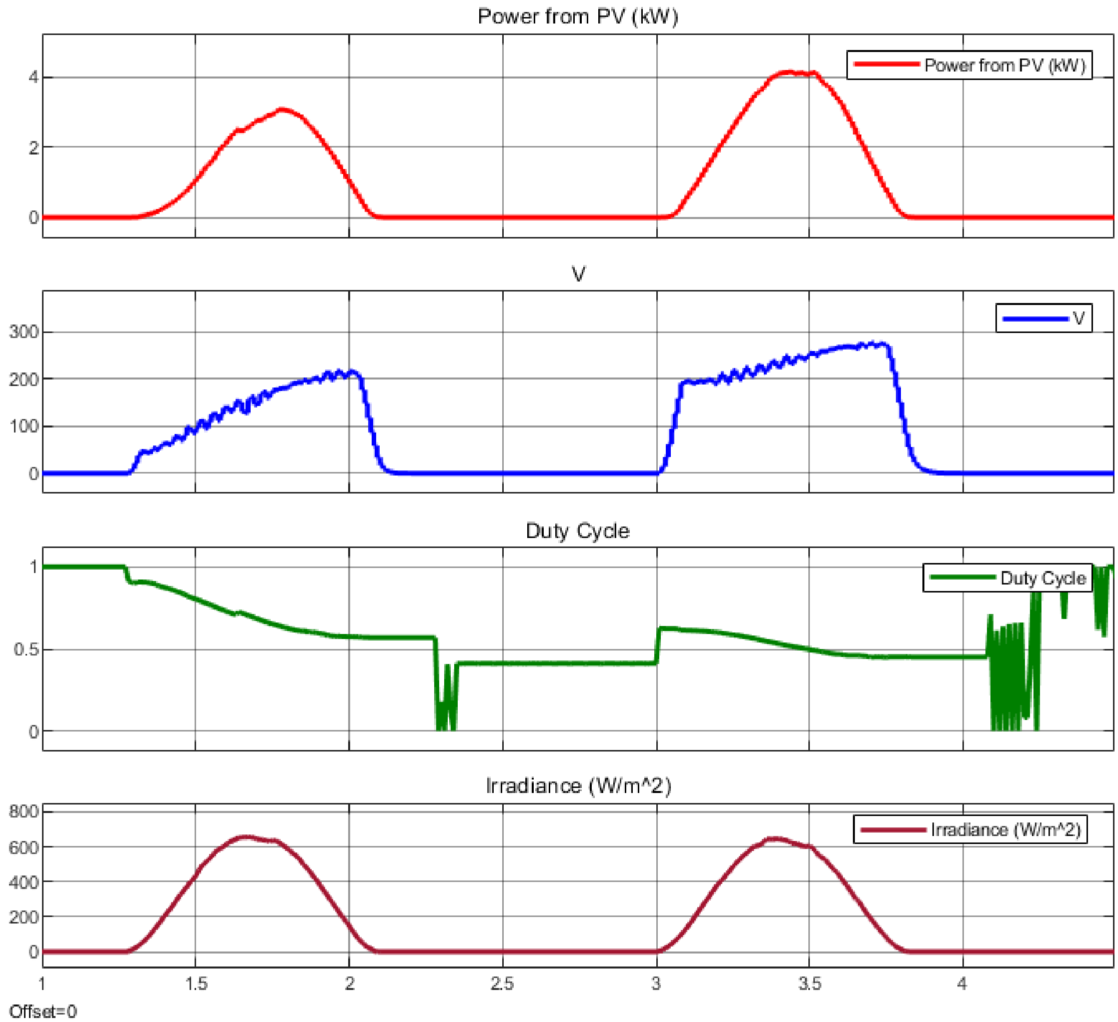

Figure 3.10 Realistic Irradiance to simulate day and night cycle

The fidelity of the simulation outcomes further reinforces the robustness of the MATLAB/Simulink model, providing a reliable platform for studying and optimizing the performance of the grid-connected PV system under diverse and realistic environmental scenarios. The insights gained from this scenario contribute to a more comprehensive understanding of the system's behaviour in actual operational contexts.

3.5 Discussion

The simulation study of the grid-connected three-phase PV system in Lahore, conducted using MATLAB/Simulink, has provided a comprehensive understanding of the system's behaviour under various scenarios. This detailed discussion will delve into key aspects of the simulation results, addressing the system's performance, implications for grid integration, and the broader implications for sustainable energy solutions.

3.5.1 Performance Evaluation

The simulation's first case, where the grid was disconnected, demonstrated the self-sufficiency of the PV array in meeting the 5.1 kW load demand. The stability of the voltage at 300V showcased the PV system's ability to operate autonomously, underscoring its reliability and potential for off-grid applications. The second case explored the net metering scenario with varying irradiance. The dynamic power exchange between the PV system and the grid showcased the adaptability of the system to changing environmental conditions. The negative values in the grid waveform during high irradiance periods indicated successful power export to the grid, emphasizing the potential economic benefits of net metering. In the third case, the incorporation of realistic irradiance patterns provided a nuanced understanding of the system's performance throughout the day. The accuracy of the model in capturing the fluctuating power generation under real-world conditions solidified the simulation's reliability and applicability to practical scenarios.

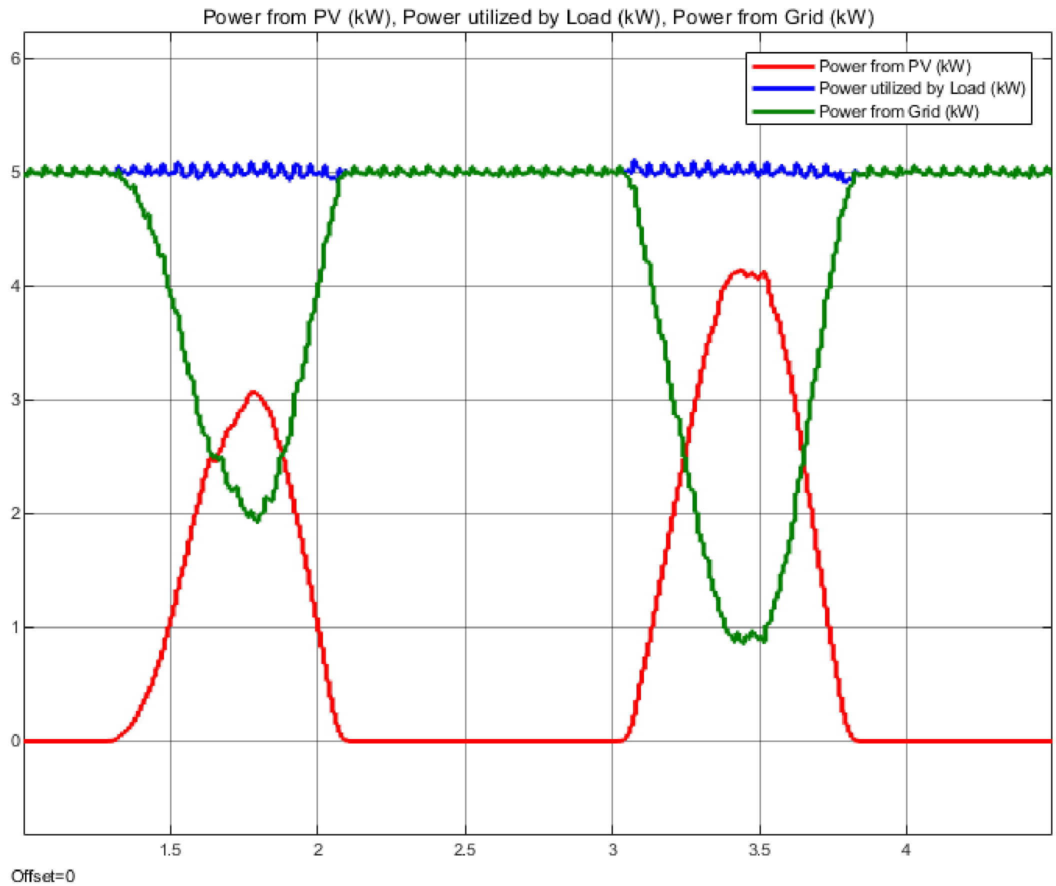

Figure 3.11 Power generation of PV and Grid along with Power utilized by the load during Day and Night scenario.

3.5.2 Grid Integration Implications

The grid-connected scenarios highlighted the dynamic interaction between the PV system and the grid. The excess power export during periods of high irradiance raises important considerations for grid stability. Future analyses should delve into the impact of such scenarios on grid parameters, including voltage and frequency stability. The net metering scenario revealed the economic implications of surplus power generation. While the PV system demonstrated its capacity to contribute excess power to the grid, future research should explore the economic viability of net metering arrangements, considering regulatory frameworks and incentives.

3.5.3 Limitations and Future Directions

While the model has proven its accuracy under simulated conditions, real-world validation with on-site data acquisition remains a crucial next step. Integration with actual PV system data will enhance the model's credibility and provide insights into its real-world applicability. The current simulation assumed constant temperature conditions, and future studies should explore the impact of temperature variations on PV system performance.

3.6 Conclusion

The simulation study of the grid-connected three-phase PV system in Lahore using MATLAB/Simulink has yielded valuable insights into its performance under different scenarios. The accuracy of the model was verified through three distinct cases, showcasing the system's behaviour when operating independently, during net metering with varying irradiance, and with realistic irradiance patterns. In the first case, where the grid was disconnected, the PV array demonstrated self-sufficiency in meeting the 5.1 kW load demand. This scenario underscored the system's capability to operate independently, showcasing its resilience and reliability. In the second case, the grid-connected scenario with varying irradiance and net metering was explored. The model effectively illustrated power dynamics, with the PV array contributing excess power to the grid during periods of high irradiance and acquiring power from the grid under reduced irradiance. This demonstrated the adaptability of the system to varying environmental conditions and the effectiveness of net metering in optimizing energy utilization. The third case incorporated realistic irradiance values, closely mimicking the day and night schedule of the site. The model accurately captured the dynamic response of the PV system under these conditions, providing a realistic representation of its performance throughout the day.

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Chapter 4

Development and Evaluation of an Arduino-Based Data Logging System Integrated with Microsoft Excel for Monitoring On-Grid Photovoltaic Systems

Preface

A version of this chapter has been accepted in the European Journal of Electrical Engineering and Computer Science (EJECE), May 2024. I am the primary author, and I carried out most of the research work performed the literature reviews, carried out the system design, implementations, and analysis of the results. I also prepared the first draft of the manuscript. The Co-author Dr. M. Tariq Iqbal supervised the research, provided the research guide, reviewed, and corrected the manuscript, and contributed research ideas to the actualization of the manuscript.

4.1 Introduction

The widespread adoption of renewable energy sources, particularly photovoltaic (PV) systems, has led to a growing interest in monitoring and optimizing their performance. On-grid PV systems, which are connected to the utility grid, play a significant role in meeting energy demands while reducing carbon emissions and dependency on fossil fuels. However, ensuring the efficient operation of these systems requires continuous monitoring of various parameters such as solar irradiance, temperature, voltage, and current levels.

The motivation for this research stems from the need for cost-effective and accessible monitoring solutions for on-grid PV setups. While commercial monitoring systems are available, they often come with high costs and limited flexibility in terms of customization and data analysis. Hence, there is a demand for open-source and DIY solutions that leverage affordable hardware platforms such as Arduino for data acquisition and logging.

The objective of this study is to design, implement, and evaluate an Arduino-based data logging system for monitoring an on-grid PV setup. The system integrates a range of sensors to collect data on environmental conditions, solar irradiance, voltage, and current levels. The collected data is logged to a Microsoft Excel spreadsheet in real-time, enabling comprehensive analysis of the PV system's performance over time.

By developing a cost-effective and accessible monitoring solution, this research aims to empower PV system owners, researchers, and practitioners with the tools to optimize energy generation, identify performance issues, and make informed decisions regarding system maintenance and upgrades. Furthermore, the open-source nature of the proposed system encourages collaboration, innovation, and knowledge sharing within the renewable energy community.

In the subsequent sections of this paper, we will delve into the hardware design, software implementation, experimental setup, results, analysis, and discussion, providing a comprehensive overview of the Arduino-based data logging system for on-grid PV monitoring.

4.2 Literature Review

Monitoring the performance of photovoltaic (PV) systems is essential for maximizing energy generation, ensuring reliability, and optimizing return on investment. A review of existing literature reveals several approaches and technologies used for PV monitoring, ranging from commercial monitoring systems to DIY solutions based on open-source platforms like Arduino.

Hakim et al. [17] proposed a low-cost data acquisition system for monitoring solar PV power plants. Their study emphasizes the importance of protecting solar panels from moisture and damage to maintain efficiency. Commercial solar panels typically achieve around 15% efficiency, with rare exceptions exceeding 20%. The use of solar panels contributes to clean energy generation, mitigating the effects of climate change. Shompa & Hoque [18] developed an IoT-based solar power monitoring and data logger system. This system utilizes four sensors to measure temperature, humidity, voltage, and current, storing data in EEP ROM memory and uploading it to the Thingspeak cloud server for analysis. Real-time monitoring allows technicians to identify issues with battery charging promptly. Effendi et al. [19] designed a data logger for PV analysis, integrating current and voltage sensors to measure parameters affecting PV efficiency. The device stores parameter data, enabling automatic data collection over time. Results show a maximum output of 20,016W, indicating the suitability of the data logger for measuring PV performance in various conditions.

Rehman & Iqbal [20] presented an ultra-low powered data logger for off-grid PV systems. Utilizing deep-sleep mode and ESP32-S2 microcontroller, the logger records major system parameters, offering both manual and automatic monitoring modes. Real-time data can be accessed via a local web portal, demonstrating energy consumption of 7.33mWh in deep-sleep mode. Pachauri et al. [21] proposed a data acquisition system for PV characterization under partial shading conditions. Analog sensors integrated with Arduino quantify and store real-time performance data, enabling analysis of parameters such as voltage and power at the global maximum power point (GMPP). Results show improved fill factor and minimize power loss under partial shading. Franklin et al. [22] developed a cost-effective data acquisition system to evaluate the performance of solar PVT systems. Using ATMEL microcontrollers, the system measured parameters such as PV panel surface temperature, inlet and outlet air temperatures, current, and voltage. Results demonstrate acceptable system performance over a three-week testing period.

Sesa & Mahmuddin [23] designed a real-time monitoring system for off-grid PV systems, comprising hardware and software subsystems. An electronic data logger system records data on an SD card, while software developed in Visual Basic facilitates real-time monitoring and data recording. The system enables automatic monitoring of PV results and data analysis. Ramaprabha et al. [24] introduced a low-cost PV panel characterization kit based on Arduino UNO and Excel. The kit monitors PV characteristics and load connected via maximum power point tracker, enabling real-time measurement of voltage, current, and power. Simulation and hardware validation demonstrate the kit's effectiveness. Ali & Mohamad [25] developed a portable wireless data acquisition system for PV solar systems with real-time clock functionality. The system, based on Arduino microcontrollers and NRF24L01 wireless transceivers, aggregates data presented in Excel using the PLX-DAQ data acquisition Excel Macro. Results confirm successful data transmission and monitoring. Djafer & Abdelouarith [26] created a real-time acquisition system for solar panels using Arduino Uno, sensors, and SD card storage. The system tracks voltage, current, and temperature changes, with data accessible for monitoring and analysis via Excel. Real-time monitoring enables prompt identification of system performance issues. Chidolue & Iqbal [27] introduced a monitoring and data logging system for solar-powered oil well pumping. The system, based on Arduino boards and low-cost sensors, monitors battery bank voltage, PV current, AC converter output, and oil well control. Data presented in Excel using PLX-DAQ enables real-time monitoring and analysis.

These studies collectively underscore the importance of reliable data acquisition and monitoring systems for optimizing the performance and efficiency of solar PV systems. While existing research has made significant strides in this area, there remains a need for further advancements in cost-effectiveness, scalability, and integration with emerging technologies to address evolving challenges in solar energy monitoring and management. Despite the growing interest in Arduino-based PV monitoring, none in literature used MS Excel and Arduino for data logging and testing a PV system. This can be done since these tools are commonly available.

The present research aims to address this gap by designing, implementing, and evaluating an Arduino-based data logging system for monitoring an on-grid PV setup, with a specific focus on MS Excel data logging using the MS Data Streamer add-in. By conducting thorough experiments and analysis, this study seeks to assess the effectiveness, limitations, and potential applications of Excel-based data logging in the context of PV system monitoring and management.

4.3 Methodology

The overall block diagram is illustrated in Fig. 1. The block diagram illustrates the proposed data logging setup for a PV system using Arduino and Microsoft Excel. A PV array is connected to the inverter. The AC load is connected to the 220V grid as well as to the inverter. The inverter converts the DC electricity from the PV array into AC electricity compatible with household appliances or the power grid. The currents and voltage are measured using current and voltage sensors connected between the PV array and the inverter as well as load and grid. These sensors measure the electrical parameters of the PV system. An Arduino is the main part of the data logging system. It can read analog signals from the voltage and current sensors. The Arduino is connected with two other sensors that measure the temperature and humidity and solar irradiance. Furthermore, the Arduino is connected to a Windows Computer via USB cable. The computer contains MS Excel that acts as the data storage and analysis platform. The Arduino program transmits the collected voltage and current data (and calculated values like power, irradiance, temperature, etc.) to Excel at regular intervals.

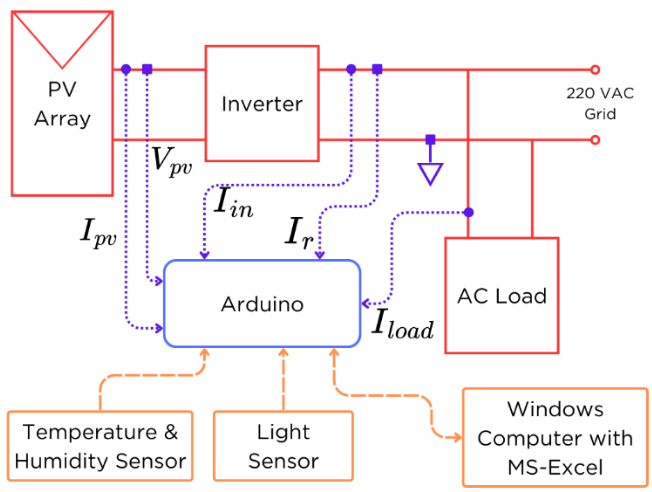


Figure 4.1 Block diagram of the proposed methodology.

4.3.1 Hardware Design

The hardware design of the data logging system for monitoring an on-grid photovoltaic (PV) setup encompasses the selection and integration of various components to facilitate real-time data acquisition and logging. The key components include Arduino Uno microcontroller, sensors for measuring environmental parameters and PV system performance metrics, and necessary interfacing modules.

4.3.2 Arduino Uno Microcontroller:

The Arduino Uno serves as the central processing unit for the data logging system, responsible for interfacing with sensors, collecting data, and communicating with external devices such as Microsoft Excel for data logging. The Arduino Uno offers an accessible and versatile platform with ample digital and analog input/output pins, making it suitable for integrating multiple sensors and peripherals. Arduino can be connected to several sensors to measure and control the process.

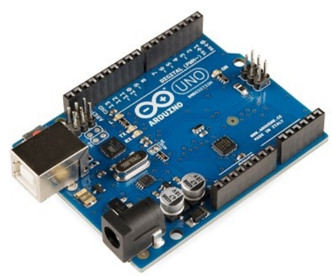


Figure 4.2 Arduino UNO utilized in this study.

4.3.3 Sensors:

Several types of sensors are integrated into the data logging system to monitor environmental conditions and PV system performance metrics. These sensors include:

4.3.3.1 Light Dependent Resistor (LDR) module:

Measures solar irradiance levels to assess the intensity of sunlight falling on the PV panels.

Figure 4.3 LDR Module

4.3.3.2 Temperature and Humidity Sensor (DHT22):

Provides data on ambient temperature and humidity, which influence the efficiency and operation of PV panels.

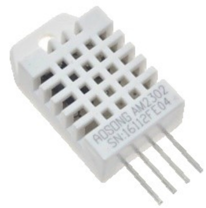


Figure 4.4 Temperature and humidity sensor (DHT22)

4.3.3.3 DC Voltage Sensor:

Measures the voltage output of the PV panels to assess their performance and ensure optimal operation.

Figure 4.5 DC Voltage Sensor

4.3.3.4 Current Sensors (HW-872A/B/C modules):

Monitor the current flowing through the PV system to evaluate power generation and detect anomalies such as overloading or underperformance.

Figure 4.6 Current Sensor

4.3.3.5 Real-Time Clock (RTC) Module:

Provides accurate timekeeping functionality for timestamping data logs and synchronizing data acquisition processes.

Figure 4.7 Real Time Clock Module for timestamping.

4.3.4 Circuit Design:

The hardware connections are established according to the pin configurations of the Arduino Uno and the respective sensors. Analog sensors such as the LDR module, DC voltage sensor, and current sensors are connected to the analog input pins (A0-A5) of the Arduino Uno. Digital sensors like the DHT22 temperature and humidity sensor are connected to the digital pins (2 and above) of the Arduino Uno.

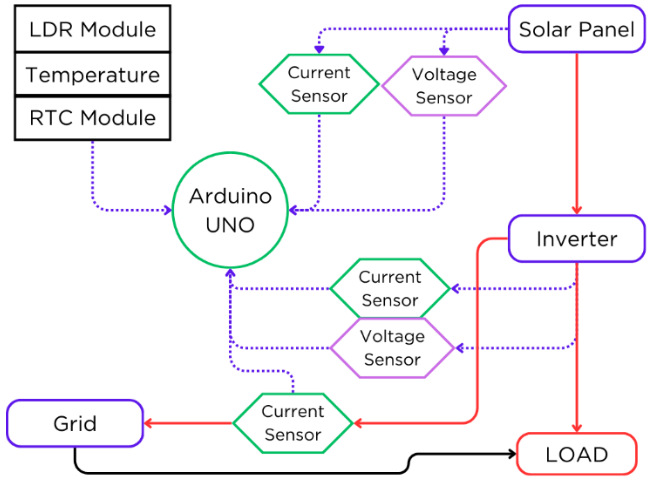


Figure 4.8 Overall block diagram of the proposed study. Here, the red and black lines illustrate the power flow while blue dotted lines shows the connection of sensors with Arduino.

4.3.5 Software Implementation

The software implementation of the data logging system for monitoring an on-grid photovoltaic (PV) setup involves programming the Arduino Uno microcontroller to interface with sensors, collect data, and communicate with Microsoft Excel for real-time data logging. Additionally, the MS Data Streamer add-in for Excel is configured to receive and log data transmitted by the Arduino Uno.

4.3.5.1 Arduino Programming:

The Arduino programming environment (IDE) is utilized to develop the firmware for the Arduino Uno microcontroller. The firmware includes code to initialize sensors, read sensor data, format data packets, and establish serial communication with Microsoft Excel via USB.

4.3.5.2 Sensor Integration:

Each sensor is interfaced with the Arduino Uno using appropriate libraries and communication protocols. For analog sensors such as the LDR module, DC voltage sensor, and current sensors, analogRead() function is used to read sensor values from the corresponding analog input pins. Digital sensors like the DHT22 temperature and humidity sensor require specific libraries for communication and data retrieval.

4.3.5.3 Serial Communication:

Serial communication is established between the Arduino Uno and Microsoft Excel using the USB connection. The Arduino Uno acts as a serial device, transmitting data packets containing sensor readings and timestamps to Excel. The Serial.print() function is used to send formatted data strings over the serial port.

4.3.5.4 Microsoft Excel Configuration:

In Microsoft Excel, the MS Data Streamer add-in is installed and configured to receive data from the Arduino Uno. The Data Streamer tab is activated, and the appropriate data format (e.g., CSV) is selected for parsing incoming data packets. The serial port corresponding to the Arduino Uno is specified in the Data Streamer settings.

4.3.5.5D ata Logging and Visualization:

As data packets are received from the Arduino Uno, the MS Data Streamer add-in automatically logs the data to designated cells in the Excel spreadsheet. Real-time visualization of sensor data is facilitated using Excel's charting and graphing capabilities, allowing users to monitor PV system performance metrics such as solar irradiance, temperature, voltage, and current levels.

4.4 Experimental Setup

The experimental setup for evaluating the Arduino-based data logging system for monitoring an on-grid photovoltaic (PV) setup involves configuring the hardware components, establishing connections, and conducting real-world measurements under controlled conditions. Experimental setup is shown in Fig. 10.

4.4.1 Hardware Configuration:

The hardware components including the Arduino Uno microcontroller, sensors, and interfacing modules are assembled according to the circuit design specifications. The sensors are positioned near the PV panels and environmental conditions to ensure accurate data acquisition.

Figure 4.9 A 30-watt solar panel is placed outside the room on the rooftop.

4.4.2 Sensor Calibration:

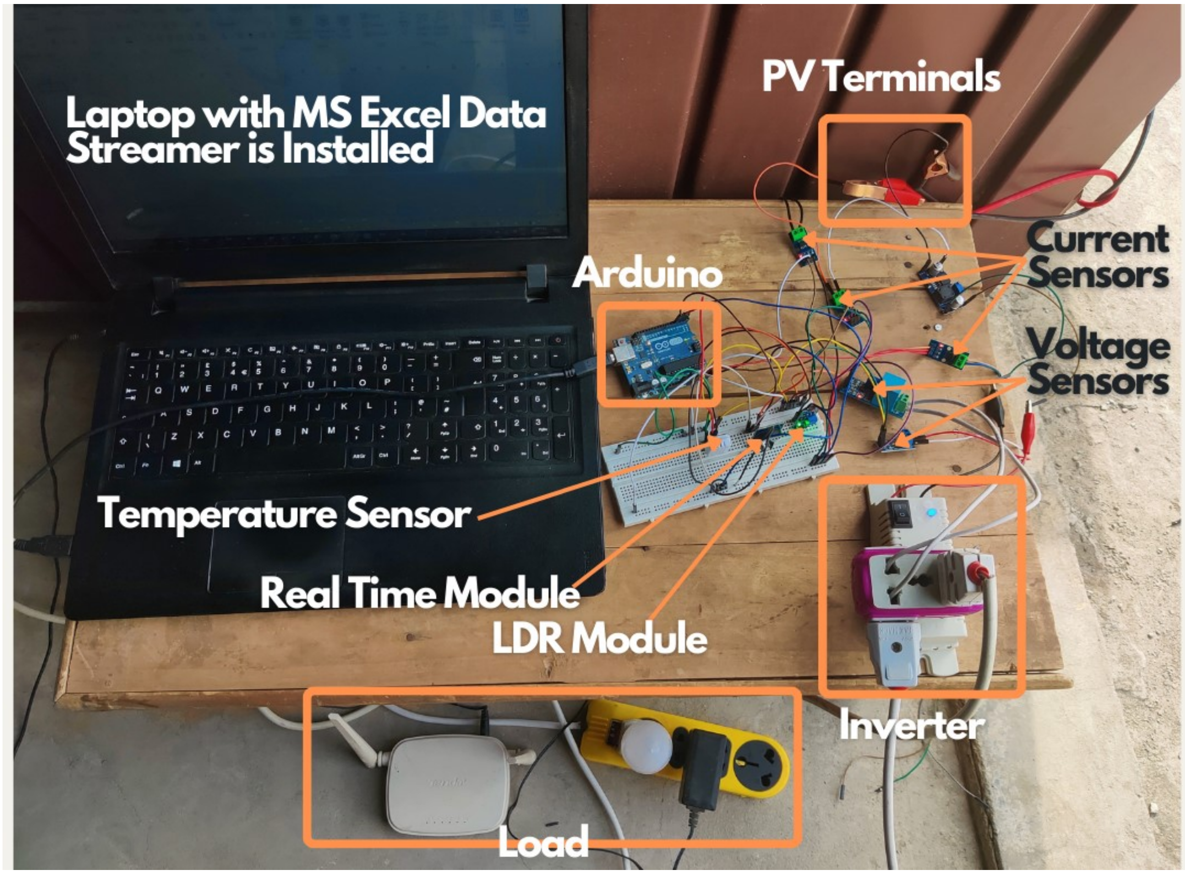


Figure 4.10 Experimental Setup

Prior to data collection, the sensors are calibrated to ensure accuracy and consistency in measurements. Calibration procedures involve adjusting sensor parameters, compensating for environmental factors, and validating sensor readings against known reference values.

4.4.3 Software Setup:

The firmware for the Arduino Uno is uploaded, and the serial communication settings are configured to establish communication with Microsoft Excel via USB. The MS Data Streamer add-in is activated in Excel, and the appropriate data format (i.e., CSV) is selected for parsing incoming data packets.

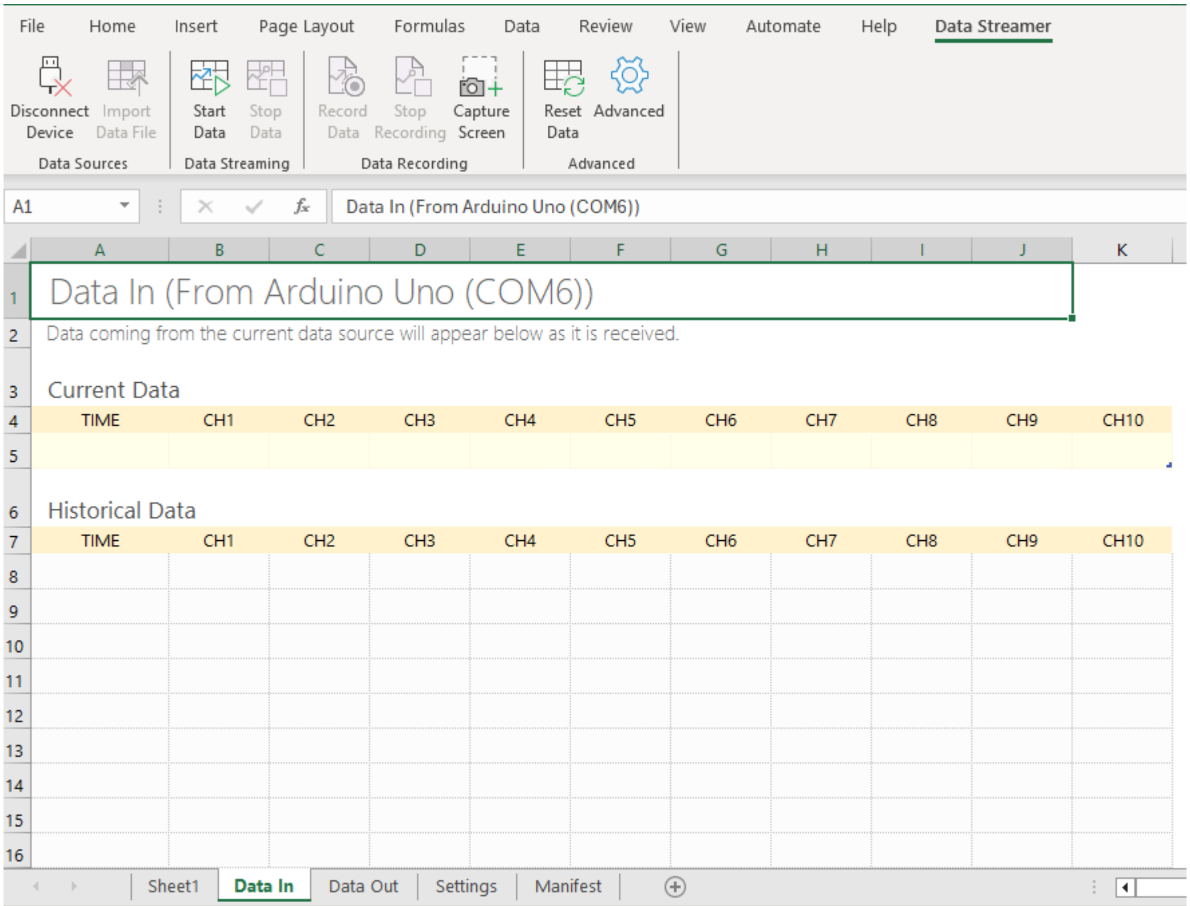


Figure 4.11 MS Excel Data Streamer Interface

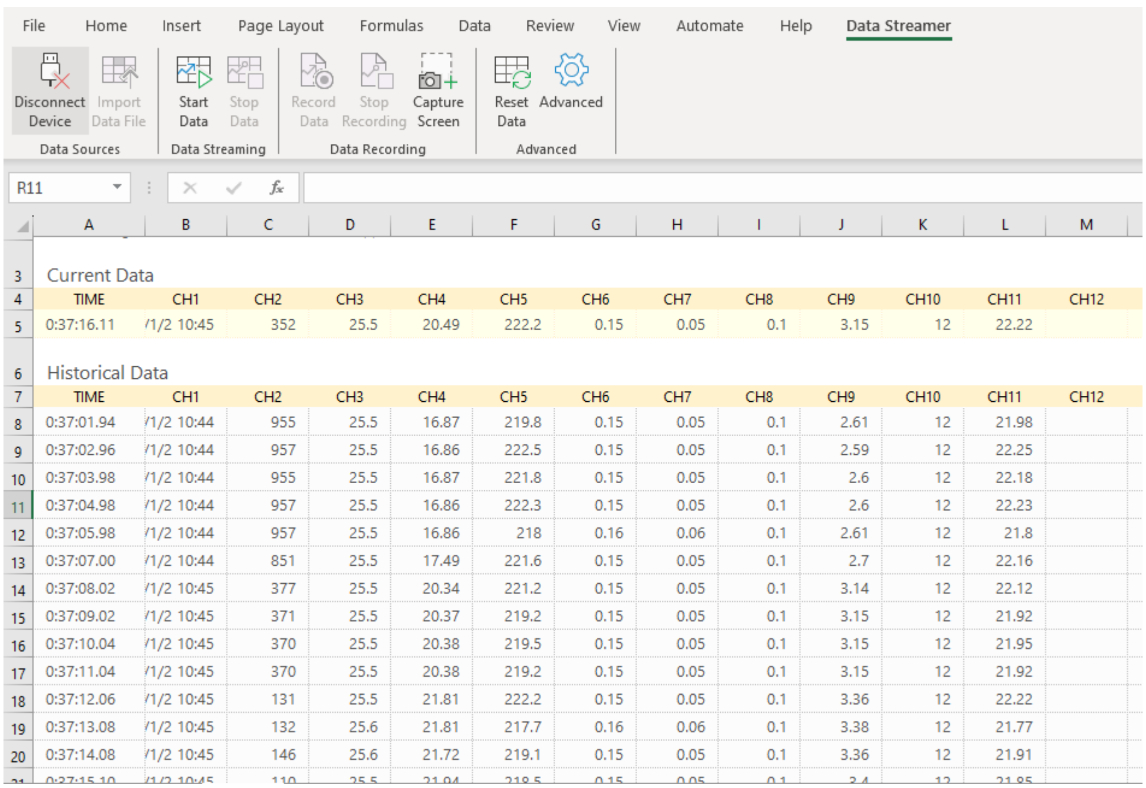
4.4.4 Data Collection Procedure:

Data collection is initiated, and the Arduino-based data logging system begins acquiring sensor readings in real-time. The system logs data to designated cells in the Excel spreadsheet, allowing for simultaneous visualization and analysis of multiple parameters.

During data collection, environmental conditions such as solar irradiance, ambient temperature, and humidity are monitored to provide context for PV system performance. Weather conditions, time of day, and seasonal variations are documented to assess their impact on data quality and system operation. Data is collected at regular intervals of every 10 minutes to track diurnal patterns, transient events, and long-term trends in energy generation and environmental conditions. The data was collected for over 3 weeks.

4.5 Results

The results obtained from the experimental setup provide valuable insights into the performance and effectiveness of the Arduino-based data logging system for monitoring an on-grid photovoltaic (PV) setup. The analysis of the collected data enables us to assess the system's capability to accurately measure and log various parameters, detect anomalies, and provide actionable insights for optimizing PV system performance as illustrated in Table 4-1.



TIME	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8	CH9	CH10	CH11	CH12
0:37:16.11	/1/2 10:45	352	25.5	20.49	222.2	0.15	0.05	0.1	3.15	12	22.22	

TIME	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8	CH9	CH10	CH11	CH12
0:37:01.94	/1/2 10:44	955	25.5	16.87	219.8	0.15	0.05	0.1	2.61	12	21.98	
0:37:02.96	/1/2 10:44	957	25.5	16.86	222.5	0.15	0.05	0.1	2.59	12	22.25	
0:37:03.98	/1/2 10:44	955	25.5	16.87	221.8	0.15	0.05	0.1	2.6	12	22.18	
0:37:04.98	/1/2 10:44	957	25.5	16.86	222.3	0.15	0.05	0.1	2.6	12	22.23	
0:37:05.98	/1/2 10:44	957	25.5	16.86	218	0.16	0.06	0.1	2.61	12	21.8	
0:37:07.00	/1/2 10:44	851	25.5	17.49	221.6	0.15	0.05	0.1	2.7	12	22.16	
0:37:08.02	/1/2 10:45	377	25.5	20.34	221.2	0.15	0.05	0.1	3.14	12	22.12	
0:37:09.02	/1/2 10:45	371	25.5	20.37	219.2	0.15	0.05	0.1	3.15	12	21.92	
0:37:10.04	/1/2 10:45	370	25.5	20.38	219.5	0.15	0.05	0.1	3.15	12	21.95	
0:37:11.04	/1/2 10:45	370	25.5	20.38	219.2	0.15	0.05	0.1	3.15	12	21.92	
0:37:12.06	/1/2 10:45	131	25.5	21.81	222.2	0.15	0.05	0.1	3.36	12	22.22	
0:37:13.08	/1/2 10:45	132	25.6	21.81	217.7	0.16	0.06	0.1	3.38	12	21.77	
0:37:14.08	/1/2 10:45	146	25.6	21.72	219.1	0.15	0.05	0.1	3.36	12	21.91	

Figure 4.12 Realtime data logging in MS Excel, here 11 channels were used to log all the parameters.

4.5.1 Sensor Data Analysis:

The sensor data collected by the data logging system is analysed to evaluate the performance of individual sensors and their correlation with PV system performance metrics. Key parameters such as solar irradiance, temperature, humidity, voltage, and current levels are examined for diurnal patterns, seasonal variations, and transient events.

Table 4-1 Data Collected From Current and Voltage Sensors with Timestamping

Time	I	T	V(PV)	I(PV)	V(AC)	I(Inv)	I(Grid)	P(DC)	P(Inv)	P(Grid)
10:00	337.9	12.1	9.54	0.726	215	0.032	0.022	7.48	6.73	4.90
10:10	329.4	12.2	9.31	0.732	214	0.032	0.022	7.36	6.62	4.99
10:20	335.6	12.6	9.50	0.756	210	0.034	0.020	7.90	7.27	4.47
10:30	362.4	13.1	10.2	0.786	226	0.036	0.018	8.97	8.25	4.12
10:40	404.2	13.8	11.5	0.828	214	0.045	0.009	10.2	9.26	2.19
10:50	404	14.3	11.5	0.858	226	0.044	0.010	10.8	9.90	2.36
11:00	401.4	15.2	11.5	0.912	221	0.048	0.007	11.3	10.06	1.54
11:10	418.8	15.3	12.0	0.918	222	0.050	0.004	12.2	11.14	1.06
11:20	431.5	15.4	12.3	0.924	220	0.052	0.002	12.4	11.10	0.55
11:30	440.2	15.5	12.6	0.93	212	0.055	0.00	12.6	11.30	-0.20
11:40	440.1	16.1	12.6	0.966	218	0.056	0.00	13.4	12.25	-0.35
11:50	465.2	16.4	13.4	0.984	225	0.059	0.00	14.5	13.21	-0.90
12:00	479.1	16.4	13.8	0.984	215	0.063	0.00	14.9	13.45	-1.91
12:10	498.2	16.3	14.3	0.978	224	0.063	0.00	15.5	13.87	-1.79

4.5.2 PV System Performance Metrics:

PV system performance metrics such as energy generation, efficiency, and reliability are derived from the collected sensor data. Analysis of voltage and current levels enables calculation of power output, power efficiency, and capacity factor, providing insights into the overall performance of the PV system under different environmental conditions.

4.5.3 Data Visualization:

Data visualization techniques such as charts, graphs, and histograms are employed to visualize sensor data and PV system performance metrics in Microsoft Excel. Real-time plotting of sensor data enables users to monitor trends, identify patterns, and make informed decisions regarding system maintenance and optimization.

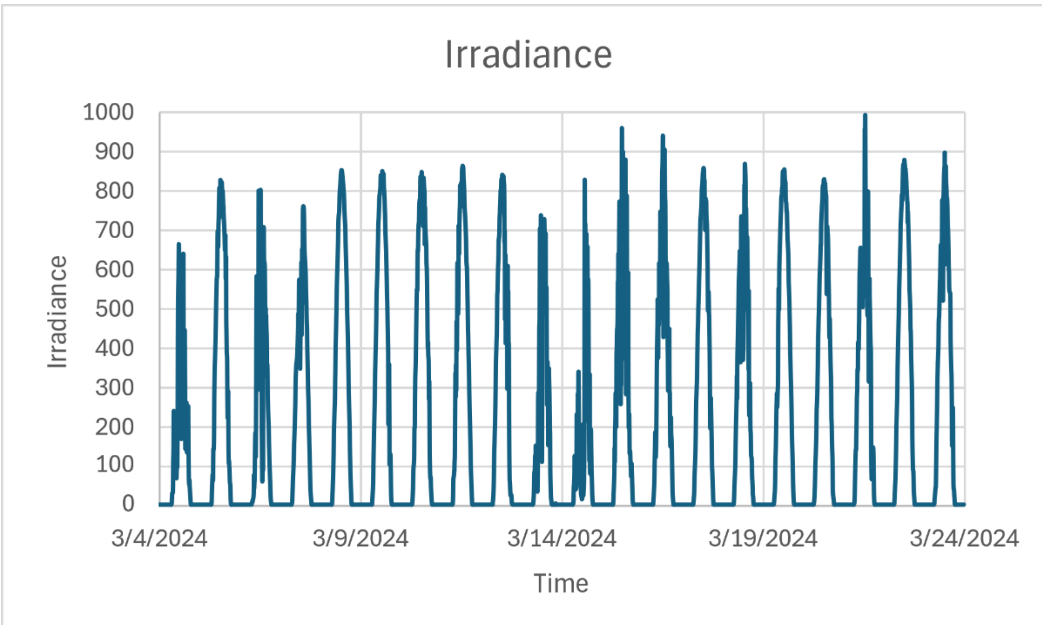


Figure 4.13 Irradiance logged during the experimental setup.

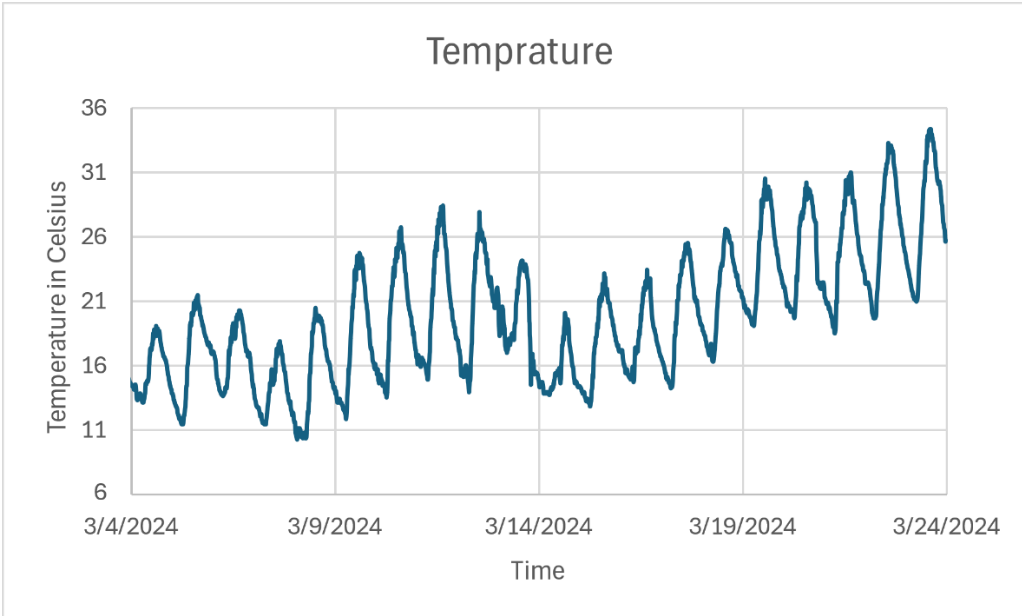


Figure 4.14 Temperature measured during the experimental setup recordings.

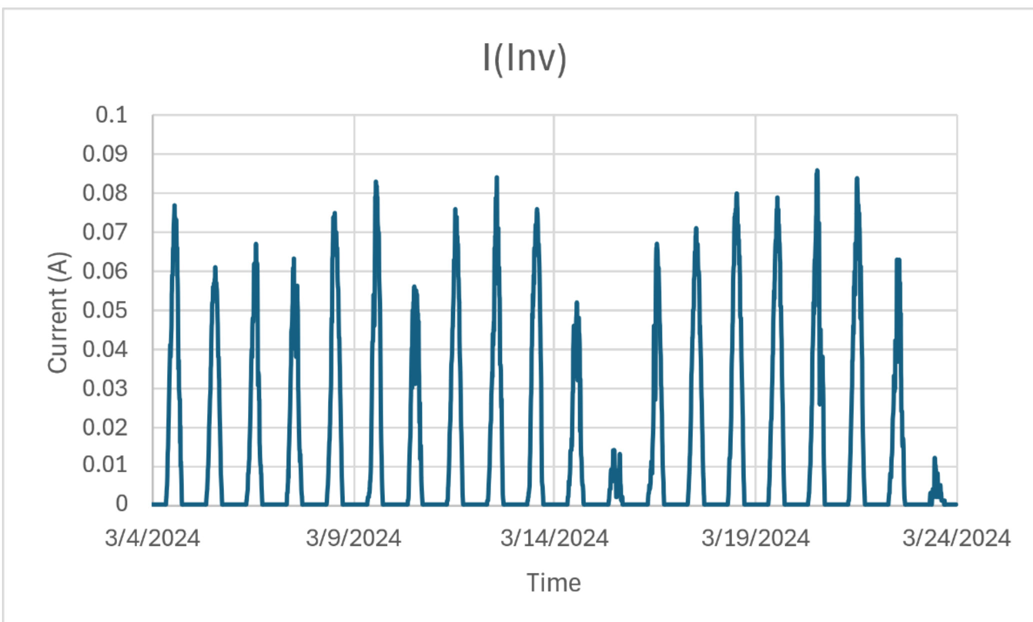


Figure 4.15 Inverter current measured using curent sensor.

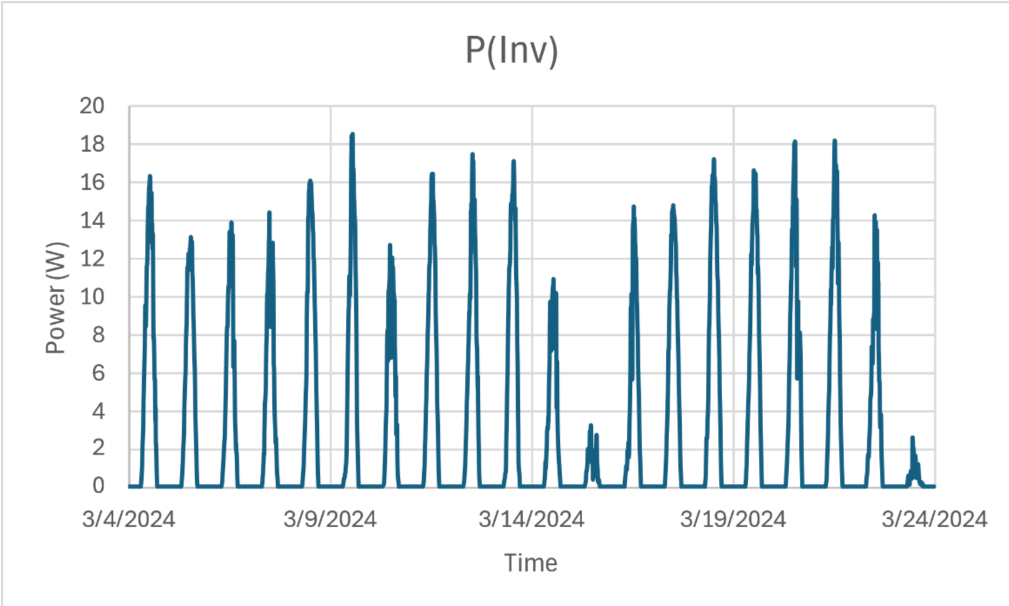


Figure 4.16 Output power calculated using Inverter voltage and inverter current.

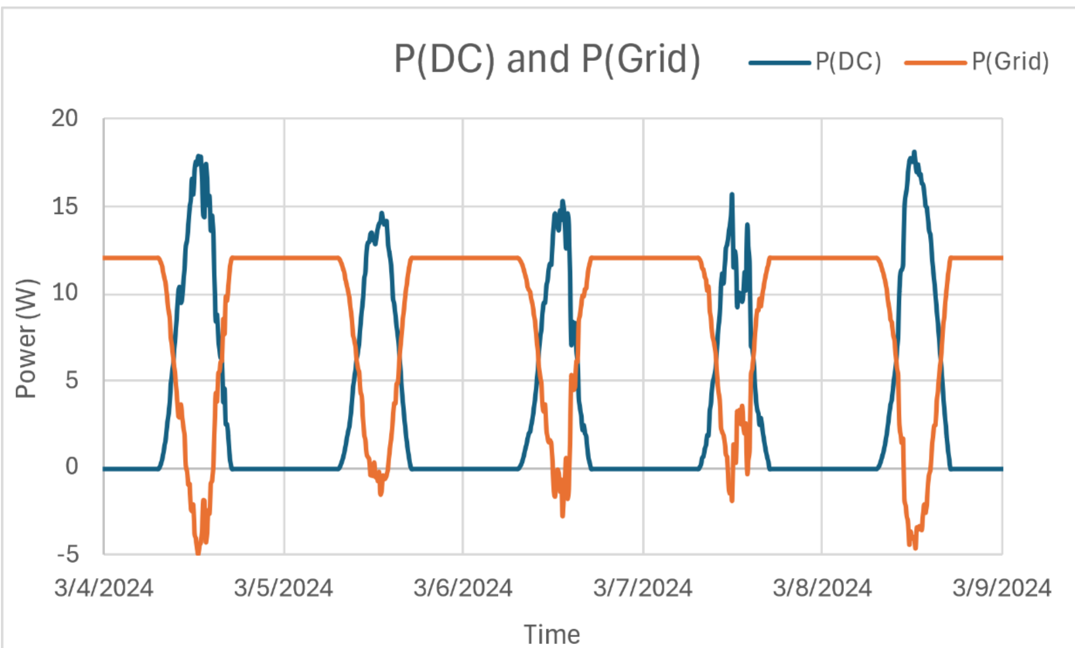


Figure 4.17 Power provided by PV and grid during day and night sessions for first 5 days.

4.6 Discussion

The findings from the experimental setup reveal the effectiveness of the Arduino-based data logging system in monitoring on-grid PV setups. The system demonstrates accurate measurement and logging of various parameters, enabling real-time analysis and visualization of

PV system performance metrics. The strengths of the Arduino-based data logging system lie in its versatility, ease of use, and compatibility with Microsoft Excel for data logging and analysis. However, limitations such as sensor accuracy, calibration requirements, and potential data transmission issues may impact the system's reliability and robustness in long-term monitoring applications.

The findings from this research have implications for PV system owners, researchers, and practitioners involved in renewable energy monitoring and management. The Arduino-based data logging system offers a cost-effective and accessible solution for real-time monitoring of PV system performance, enabling informed decision-making and optimization strategies. Future research endeavors may focus on addressing the limitations of the Arduino-based data logging system, such as reducing power losses in Arduino and sensors, using low power computer.

4.7 Conclusion

The research presented in this paper aimed to design, implement, and evaluate an Arduino-based data logging system for monitoring an on-grid photovoltaic (PV) setup. Through a combination of hardware design, software implementation, and experimental validation, the effectiveness and feasibility of the proposed system were assessed in real-world conditions. The findings from the experimental setup demonstrated the capability of the Arduino-based data logging system to accurately measure and log various parameters critical to PV system performance, including solar irradiance, temperature, voltage, and current levels. The integration of Microsoft Excel with the MS Data Streamer add-in facilitated real-time data logging and visualization, enabling users to monitor trends, detect anomalies, and make informed decisions regarding system optimization and maintenance. While the Arduino-based data logging system offers several advantages such as affordability, versatility, and accessibility, it is not without limitations. Challenges related to sensor accuracy, calibration, and data transmission may impact the system's reliability and robustness in long-term monitoring applications. Further research and development efforts are warranted to address these limitations and enhance the system's performance and scalability.

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Chapter 5

Conclusions & Future Work

This thesis explored the design, analysis, and implementation of a grid-tied solar system for a residential house in Lahore, Pakistan, with a specific focus on addressing local power shortages and load shedding. Our research aimed to enhance energy reliability and sustainability through the adoption of solar photovoltaic (PV) technology and innovative data monitoring systems.

5.1 Key Findings

The research presented in this thesis highlights the critical aspects of grid-tied solar systems and their role in enhancing energy reliability for residential applications in Lahore, Pakistan. The key findings of this research are broken down into three major areas: design and implementation, performance analysis, and data monitoring.

5.1.1 Design and Implementation of Grid-Tied Solar Systems

The primary objective of this study was to design a grid-tied solar system that meets the energy needs of a typical residential household in Lahore. The design process involved selecting appropriate components, including solar panels, inverters, and other hardware essential for connecting to the grid. By integrating these components, the system could harness solar energy efficiently and reduce reliance on conventional electricity sources. A significant aspect of the design was ensuring compatibility with the existing power grid, which can be unstable due to frequent outages and load shedding. The successful design of this grid-tied system demonstrates that solar energy can play a vital role in providing a reliable and sustainable power source, even in regions with challenging grid conditions. The tailored design accounted for the specific energy demands of the residential setting, ensuring that the system could meet the expected electricity consumption. This included considerations for peak energy usage times and the potential to supply excess energy back to the grid through net metering, contributing to overall energy sustainability.

5.1.2 Performance Analysis and Simulations

To validate the design, comprehensive performance analysis and simulations were conducted using System Advisor Model (SAM) and HOMER Pro. These tools allowed for detailed simulations of the system's behavior under varying conditions, including different levels of solar irradiance, ambient temperatures, and grid stability scenarios. The performance analysis revealed that the grid-tied solar system could generate a substantial portion of the household's energy requirements, reducing dependence on the grid and lowering electricity costs. In some cases, the system produced surplus energy, enabling net metering, where excess electricity is fed back into the grid, potentially earning credits for the household. The simulations also provided insights into the system's resilience to fluctuations in solar irradiance and grid disturbances. This analysis was crucial for understanding how the system would perform over time and under various environmental conditions, supporting its robustness and reliability.

5.1.3 Development of Data Logging Systems

The research introduced a data logging system designed to monitor the performance of the grid-tied solar system in real-time. This system played a crucial role in capturing key performance metrics, such as energy production, voltage, and current levels, which are essential for system maintenance and optimization. The data logging system was cost-effective, making it accessible for broader adoption in residential solar installations. Its ability to collect real-time data allowed for early detection of issues, such as system malfunctions or inefficiencies, enabling preventive maintenance and reducing downtime. Furthermore, the data logging system contributed to a better understanding of the long-term behavior of grid-tied solar systems. The data collected over time provided a valuable resource for analyzing trends, identifying potential degradation in system components, and informing future improvements in design and maintenance practices.

5.2 Limitations

Despite the positive outcomes, the research faced certain limitations:

- **Scope and Scale:** The study was limited to a single residential installation, which may not capture the full range of complexities associated with larger-scale grid-tied solar systems or other types of installations, such as commercial or industrial setups. This research was conducted with the constraints of available resources and aimed to provide an in-depth analysis of a specific residential PV system. While this approach offers detailed insights into the system's performance, it inherently limits the applicability of the results to a broader context. To enhance the generalizability of the findings, future research should aim to conduct broader testing across multiple sites. This could include installations in different types of residential buildings, commercial setups, and various geographic locations with distinct environmental conditions. Such an expanded scope would allow for a more comprehensive evaluation and better understanding of the PV system performance under diverse conditions, ultimately leading to more universally applicable insights.
- **Environmental Variability:** The simulations and analyses were based on typical weather patterns in Lahore. Extreme weather events, seasonal variations, or climate change impacts could affect system performance in ways not fully explored in this study. The simulations and experimental setups presented in this thesis were designed

to closely replicate real-world conditions; however, they may not fully account for the full range of environmental variability encountered in practical installations. Factors such as dust accumulation, shading from nearby objects, and changes in weather conditions (e.g., cloud cover, temperature fluctuations) can significantly impact the performance of PV systems. Future research should incorporate comprehensive environmental modeling into simulations to better predict real-world performance. This could involve the use of advanced computational models that simulate the impact of these environmental factors on PV output. Additionally, experimental setups should be expanded to include various scenarios that mimic these conditions, allowing for a more thorough evaluation of system performance under diverse and challenging environments.

- **Long-Term Performance Data:** Although the data logging system provided real-time monitoring, a longer-term study is needed to understand the system's durability, reliability, and overall impact on energy costs and grid stability.
- **Sensor Accuracy and Calibration:** As highlighted in the thesis, these are critical factors that significantly affect the reliability and robustness of the data logging system. Accurate and well-calibrated sensors are essential for capturing precise data, which forms the basis for effective monitoring and analysis. However, achieving and maintaining high sensor accuracy over long-term deployments can be challenging due to factors such as sensor drift, environmental influences, and installation variations. The current work provides a foundation by identifying these issues and proposing initial solutions, such as regular calibration and the use of reference sensors. Future research should focus on developing advanced calibration techniques, potentially

incorporating automated calibration systems that can adapt to changing conditions in real-time. Additionally, the exploration of higher precision sensors could further enhance data reliability, ensuring that the monitoring system delivers consistent and accurate performance over extended periods.

5.3 Future Work

Building on the conclusions of this thesis, the following areas are suggested for future research:

- **Expansion to Diverse Installations:** Future studies could expand to include a variety of residential, commercial, and industrial solar installations in different regions. This would offer a broader perspective on the effectiveness of grid-tied solar systems across diverse environments and energy demands. This expansion is critical to understand how the PV monitoring system performs in different environments, which can vary significantly in terms of climate, sunlight exposure, and environmental factors. By testing the system in diverse geographic locations, researchers can gather a broader dataset that reflects a wide range of conditions. This approach will help identify any location-specific issues and allow for the optimization of the system for different settings. Additionally, such validation will increase the robustness and applicability of the research findings, providing valuable insights that can be generalized to a wider range of installations and informing best practices for PV system monitoring across various regions.
- **Advanced Control Strategies:** Further research into advanced control mechanisms, such as adaptive control, machine learning-based approaches, and fuzzy logic controllers, could enhance the stability and efficiency of grid-tied solar systems. These

advanced methods may offer improved responses to fluctuating grid conditions and variable solar irradiance.

- **Integration of Hybrid Systems:** Exploring the integration of solar energy with other renewable sources, such as wind or biomass, could lead to more resilient hybrid systems. This approach would not only provide a more continuous energy supply but also increase system flexibility and reduce dependency on a single energy source.
- **Comprehensive Monitoring and Data Analysis:** A longer-term study focusing on comprehensive data monitoring could yield valuable insights into system performance, degradation over time, and maintenance needs. This could also help identify patterns or trends that inform future system designs and improve efficiency. Investing in higher precision sensors and developing robust calibration techniques will enhance the accuracy and reliability of the data logging system. Higher precision sensors can provide more accurate measurements, which are essential for detailed analysis and monitoring of PV systems. However, these sensors also require careful calibration to maintain their accuracy over time. Robust calibration techniques, possibly involving automated and periodic calibration processes, can ensure that sensors remain accurate despite potential environmental and operational changes. This could involve the use of reference sensors or calibration standards that the system can regularly compare against to adjust for any deviations. Implementing these improvements will significantly enhance the overall performance of the monitoring system, providing more reliable data for analysis and decision-making.
- **Economic and Environmental Impact Studies:** Future research could delve into the economic benefits of grid-tied solar systems, including cost savings, return on

investment, and energy payback periods. Additionally, environmental impact studies could assess the reduction in carbon emissions and other environmental benefits of adopting solar energy.

- **Robust Data Transmission Protocols:** Future research should focus on implementing such protocols and incorporating redundancy to ensure data integrity and reliability, which are critical for long-term monitoring. Robust data transmission protocols can include secure encryption methods to protect data, error-checking algorithms to detect and correct transmission errors, and redundant communication pathways to ensure data is not lost if one pathway fails. Incorporating these features will enhance the reliability of the monitoring system, ensuring that accurate and complete data is transmitted and received consistently over long periods, which is essential for effective PV system monitoring and analysis.
- **Data Transmission:** In the current thesis, the issue of data transmission has been acknowledged, but a deeper exploration of potential solutions and mitigation strategies is warranted. Reliable data transmission is crucial for the integrity and continuity of monitoring systems, especially in long-term applications. Future research should focus on implementing robust data transmission protocols that can handle various challenges such as signal interference, network instability, and data loss. Incorporating redundancy in the data transmission process can also enhance reliability. For example, using multiple communication pathways or backup systems can ensure that data is consistently transmitted and received, even if one pathway fails. Furthermore, the development and integration of error-checking algorithms can help detect and correct

any anomalies in the transmitted data, thereby maintaining its accuracy and reliability over extended periods.

This thesis demonstrated that grid-tied solar systems offer a viable solution to address power shortages and enhance energy sustainability in Lahore, Pakistan. By integrating effective design, robust data monitoring, and comprehensive performance analysis, this research provides a foundation for future work aimed at advancing renewable energy adoption and creating a more sustainable energy infrastructure. The insights gained from this study could guide policymakers, engineers, and stakeholders in implementing solar energy solutions across various contexts, contributing to a cleaner and more reliable energy future.

Articles in Refereed Publications

- Akhtar, M.U., Iqbal, M.T. (2024). *Design and Analysis of an On-Grid Solar System for a House in Lahore, Pakistan*. Jordon Journal of Electrical Engineering (JJEE). The paper is reviewed, accepted by the Journal, and in press to be published soon.

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- Akhtar, M.U., Iqbal, M.T. (2024). *Development and Evaluation of an Arduino-Based Data Logging System Integrated with Microsoft Excel for Monitoring On-Grid Photovoltaic Systems.* European Journal of Electrical Engineering and Computer Science (EJECE). The paper is reviewed, accepted by the Journal, and published in Volume-8, Issue-3, June.2024.