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# Exploring the Feasibility of Solar Photovoltaic Generation for Residential Applications in Hubballi, Karnataka: A Simulation and Analysis Approach

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***Abstract: -*** This research paper explores the potential of solar photovoltaic (PV) generation in Hubballi, Karnataka, India, focusing on a small residential home premises. The objective is to assess the solar PV potential at this location using PVsyst simulation software and analyze the results. The paper begins with an introduction to solar PV technology and its significance in meeting energy demands. A literature review examines previous studies on solar PV potential in Karnataka, highlighting the factors influencing solar PV generation efficiency. The methodology section describes the study area, data collection methods, and the PVsyst simulation setup. The data analysis section presents the collected solar irradiation and temperature data and discusses the simulation results for solar PV generation at the selected premises. The performance evaluation of the PV system is based on the simulation outcomes. The discussion section compares the simulated results with expected solar PV potential, identifies factors affecting solar PV generation efficiency in Hubballi, and discusses the implications of the findings for residential installations. The conclusion summarizes the research findings, emphasizes the solar PV potential in Hubballi, and provides recommendations for future research and practical applications. This research contributes to the understanding of solar PV generation at the specific location of Hubballi and offers valuable insights for promoting renewable energy in residential settings.

***Keywords:*** Solar PV generation, simulation results, residential installations

## I. INTRODUCTION

### A. Background of solar photovoltaic (PV) generation

Solar photovoltaic (PV) generation has witnessed significant advancements and increasing deployment in recent years. It plays a crucial role in addressing the global energy demand and mitigating environmental concerns. PV technology converts sunlight into electricity through the use of semiconductor materials, such as silicon, which generate an electric current when exposed to photons. As a result, solar PV has become a key contender in the transition towards sustainable and clean energy sources.

Several studies have explored various aspects of solar PV generation, contributing to the understanding of its technical potential, cost-effectiveness, efficiency, and applications. [1] conducted a national-level estimation of floating PV (FPV) technical potential using large-scale datasets, PV generation models, and geospatial analytical tools. They demonstrated the vast potential of FPV installations, highlighting the need for further exploration and implementation.

Understanding the cost dynamics of solar PV electricity generation is crucial for its widespread adoption. [2] examined the net costs and profits associated with building and operating distributed solar PV projects in 344 Chinese cities. Their study considered total project investments, electricity outputs, and trading prices, shedding light on the economic viability of PV installations at the local level.

The impact of environmental factors on solar PV systems has been a subject of interest.[3] reviewed existing works on dust deposition on PV modules and its consequences on electrical, optical, and thermal characteristics. This research provides insights into the challenges posed by dust settlement and emphasizes the importance of regular maintenance and cleaning for optimal system performance. Efforts to maximize the efficiency and versatility of solar PV systems have led to innovative approaches.[4] proposed an efficient and carbon-free cogeneration system combining PV cells and proton exchange membrane (PEM) electrolyzers. Their study highlights the potential of integrated systems for simultaneous heat and hydrogen production.

Policy recommendations are essential for promoting the deployment of solar PV in specific regions.[5] conducted research on off-grid solar PV rural electrification programs in Punjab, aiming to provide guidelines for government

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and stakeholders. The findings of this study inform decision-making processes and help ensure effective implementation of rural electrification initiatives.

Accurate prediction of solar PV power output is crucial for system planning and optimization. [6] proposed a surface irradiance distribution mapping model for PV power stations based on ground-based sky images. Their research contributes to improved understanding and modeling of solar irradiance distribution, aiding in power output estimation.

The integration of solar PV with buildings offers new opportunities for energy-efficient designs. [7] focused on integrated solar systems with building facades and analyzed their influence on electricity generation, thermal performance of PV cells, and energy consumption of buildings. Such designs have the potential to significantly reduce building energy consumption and contribute to the development of low-energy or zero-energy buildings.

These studies, along with the works of [8], [9], have collectively contributed to the knowledge base surrounding solar PV generation, covering topics such as technical potential, cost-effectiveness, dust deposition, cogeneration systems, policy recommendations, irradiance mapping, building integration, and power output prediction. This research article aims to build upon these existing studies by evaluating the solar PV potential and performance in Hubballi, Karnataka, specifically focusing on a small residential home premises using PVsyst simulations.

B. Importance of solar PV in addressing energy needs

Solar photovoltaic (PV) generation plays a crucial role in addressing the growing energy needs of modern society. With increasing concerns about climate change, environmental degradation, and the finite nature of fossil fuel resources, there is a pressing need for sustainable and renewable energy sources [10]. Solar energy, in particular, offers a viable solution to meet these energy demands while minimizing the carbon footprint and reducing reliance on non-renewable resources.

Numerous studies have highlighted the significance of solar PV in diversifying the energy mix and reducing greenhouse gas emissions. For instance,[11] examined the distributed solar PV market in China and found evidence of demand-induced innovation. This indicates that the adoption and implementation of solar PV systems stimulate further advancements in technology, making them more efficient and cost-effective.

In addition to environmental benefits, solar PV has the potential to revolutionize energy access in remote and underserved areas. For instance, in the study conducted by [10] on the solar energy potential in Gaza Strip, Palestine, it was found that solar energy options can provide a reliable and sustainable source of electricity in regions with limited access to traditional power grids. This can greatly improve the quality of life, enhance economic opportunities, and drive overall development in such areas.

Moreover, the integration of solar PV with other sectors, such as agriculture and transportation, offers synergistic benefits. [12] discussed the potential of agrivoltaics, which involves the simultaneous use of land for solar PV installations and agricultural activities. This approach optimizes land utilization, minimizes conflicts between solar PV and agriculture, and enhances food security while promoting clean energy generation.

Furthermore, addressing the challenges associated with solar PV integration into microgrids (MGs) is essential for their widespread deployment. [13] emphasized the importance of nowcasting, which refers to short-term solar irradiance forecasting, in managing MGs and facilitating the integration of controllable distributed energy resources (DERs). Nowcasting enables real-time decision-making and grid stability management, allowing for increased penetration of solar PV in MGs.

Safety and reliability are paramount considerations in solar PV systems. [14] investigated the effects of lightning-induced voltage on hybrid solar PV-battery energy storage systems and highlighted the importance of surge protection devices (SPDs) in ensuring system integrity and performance. Similarly, [15] focused on the efficient operation of electric vehicle (EV) fast chargers powered by large-scale PV arrays and storage systems. They proposed a phase-shift full bridge (PSFB) converter to minimize the reliance on the AC grid and enhance system efficiency.

Policy frameworks and regulations play a crucial role in promoting solar PV adoption and scaling up renewable energy deployment.[16] evaluated the Nigerian Solar Energy Policy (NSEP) within the National Renewable Energy and Energy Efficiency Policy (NREEEP), highlighting the importance of supportive policy measures for the successful implementation of solar PV projects.

In summary, solar PV generation has emerged as a key solution to address energy needs, mitigate climate change, and promote sustainable development. It offers numerous benefits, including reduced carbon

C. Focus on the Hubballi location in Karnataka, India

Hubballi, located in the state of Karnataka, India, holds significant potential for solar photovoltaic (PV) generation. The region benefits from abundant renewable resources, making it suitable for harnessing solar energy for power generation. Geospatial and economic analysis conducted by [17] has identified the substantial renewable resource potential in India, including utility-scale solar PV. The study estimates a potential range of 1300–5200 GW for utility-scale solar PV in the country.

[18] have focused on identifying priority areas for solar potential implementation, particularly for the installation of photovoltaic power plants and solar heating systems. Their research highlights the importance of selecting suitable sites for solar installations to maximize energy production and utilization. [19] have studied the performance enhancement of multi-crystalline silicon photovoltaic modules using mirror reflectors under the western Himalayan climatic conditions. They have developed a model that determines the optimum tilt angles for reflectors, validated through experimental analysis. The results of this study are valuable for investors and policy-makers interested in deploying similar models for renewable energy initiatives.

In a study conducted by [20] in West Bengal, India, a proposed model utilizing Q-GIS was used to identify high solar potential areas. The model serves as a framework that can be applied to similar studies in other regions. Such studies aid in identifying suitable locations for solar PV installations and contribute to the overall understanding of solar potential in the country. [21] aim to highlight the design parameters concerning building-integrated photovoltaics (BIPV) in the Indian context. Their research focuses on the technical and economic feasibility study of a photovoltaic power plant in Bathinda city, Punjab state, India. This study provides insights into the practical implementation and viability of BIPV systems in specific regions.

[22] investigate the performance of wedge-shaped luminescent solar concentrators (LSCs) using inorganic luminescent phosphors. Their research demonstrates enhanced performance of these LSCs at incidence angles that conventional solar panels do not effectively utilize. Such advancements in solar PV technology contribute to improving the efficiency and effectiveness of solar energy conversion. [23] estimate the photovoltaic energy production from the rooftop solar plant of the National Institute of Technology Karnataka (NITK). Their research incorporates earth observation techniques and solar resource modeling to assess the impact of clouds and aerosols on PV energy production. This study provides valuable insights into the effects of atmospheric conditions on solar PV generation, aiding in the accurate estimation of energy production.

[24] evaluate the potential of photovoltaic systems to meet specific energy demands in dedicated geographic locations. Their research emphasizes the importance of assessing the suitability of PV systems for meeting specific energy needs, taking into account regional characteristics and requirements. [25] evaluate the power generation potential and economic performance of photovoltaics deployed on hyperbolic cooling towers in Mainland China. This study highlights the innovative integration of PV systems with existing infrastructure, providing insights into maximizing solar energy utilization and addressing specific energy demands.

In light of these previous studies, this research aims to assess the solar PV potential in Hubballi, Karnataka, focusing on a small residential home premises. By utilizing PVsyst simulations and drawing from the knowledge and methodologies established in the aforementioned studies, this research seeks to analyze the feasibility and performance of solar PV systems in Hubballi. The findings will contribute to the understanding of solar PV viability and effectiveness in residential settings in the region, providing valuable guidance for promoting renewable energy adoption in Hubballi.

D. Objective of the research paper

The primary objective of this research paper is to assess the solar photovoltaic (PV) potential at Hubballi, Karnataka, India, specifically focusing on a small residential premises. To achieve this objective, PVsyst simulation software will be utilized to conduct a comprehensive analysis of the solar potential in the area. The simulation results will provide insights into the feasibility and performance of solar PV systems in Hubballi, offering valuable guidance for residential installations and renewable energy promotion.

The objective of using PVsyst simulation software is to accurately evaluate the solar PV potential at the selected residential premises in Hubballi. PVsyst is a widely recognized and industry-standard software that allows for the modeling and simulation of PV systems. It incorporates various parameters such as solar irradiation, temperature, shading, and system configurations to provide reliable and realistic estimations of solar PV generation.

By conducting PVsyst simulations, this research aims to assess the solar PV potential in Hubballi, considering factors such as panel orientation, tilt angle, shading effects, and system performance. The simulations will take into account the local climatic conditions, solar irradiation data, and other relevant parameters to generate accurate predictions of the solar energy generation at the small residential premises.

The research paper intends to evaluate the solar PV potential in Hubballi in terms of its ability to meet the energy needs of a residential home. The simulation results will provide valuable insights into the expected energy generation, system performance, and the viability of solar PV installations in the specific context of Hubballi. This evaluation will serve as a foundation for understanding the potential benefits and challenges of implementing solar PV systems in residential areas in Hubballi.

The research findings will be significant for homeowners, policy-makers, and energy professionals who are interested in promoting and adopting solar PV systems in Hubballi. The outcomes of the PVsyst simulations will provide valuable information regarding the solar energy potential, allowing for informed decision-making regarding the installation and utilization of solar PV systems at the residential level.

In summary, the objective of this research paper is to assess the solar PV potential at Hubballi, Karnataka, India, focusing on a small residential premises. By employing PVsyst simulation software, the aim is to evaluate the solar potential accurately and provide insights into the feasibility and performance of solar PV systems in Hubballi. The research outcomes will contribute to the understanding of solar energy generation in residential areas and facilitate informed decision-making regarding renewable energy adoption in Hubballi, India.

## II. LITERATURE REVIEW

A. Overview of solar PV technology and its applications

Solar photovoltaic (PV) technology has gained significant attention in recent years as a sustainable and renewable energy solution. This section provides an overview of solar PV technology and its various applications, drawing insights from relevant literature.

[26] contributes to the understanding of solar PV technology through an accurate inventory of international patent classes for PV systems. This study highlights the advancements in the field and the intellectual property landscape surrounding solar PV technology. One area of interest within solar PV technology is luminescent solar concentrators (LSCs). LSCs have shown promise in enhancing the power conversion efficiency (PCE) of PV systems at a lower cost. [27] review the comprehensive aspects of large and small-scale LSCs, focusing on the impact of device configuration, host material, and luminescent species on LSC loss mechanisms and optical performance.

Photovoltaic phase change material (PV-PCM) systems have also garnered attention in recent years. [28] present a comprehensive literature review on PV-PCM systems, emphasizing the technology overview and materials selection. This study provides insights into the advancements and potential of PV-PCM systems. Building-integrated photovoltaics (BIPV) is an emerging field that integrates photovoltaic systems into building structures.[29] aim to provide an overview of the relative scope of perovskite solar cells (PSCs) integration in the BIPV sector. This study highlights the potential and challenges associated with integrating PSCs into building structures.

To accurately extract the electrical parameters of a PV panel, [30] propose the application of the marine predators algorithm (MPA). The MPA approach demonstrates its effectiveness in extracting the electrical parameters of the two-diode photovoltaic (TDPV) model without requiring any structural modifications. Solar thermal energy systems combined with phase change materials (PCMs) have shown potential for improved thermal energy storage and utilization.[31] present an overview of the progress and application of PCMs in solar thermal energy systems. This study highlights the advancements in PCM-based solar thermal energy storage technology.

Consumer acceptance of solar PV technology plays a crucial role in its widespread adoption. [32] focus on consumer considerations that may influence their willingness to adopt solar PV for household purposes. This study aims to bridge the knowledge gap regarding consumer acceptance of solar PV technology in Pakistan.

In conclusion, the literature survey provides an overview of solar PV technology and its applications. The studies discussed highlight advancements in areas such as LSCs, PV-PCM systems, BIPV integration, grid integration strategies, bypass diode application, electrical parameter extraction, PCM-based solar thermal energy, and consumer acceptance. These insights contribute to the understanding of solar PV technology and its potential for sustainable energy generation.

B. Previous studies on solar PV potential in Karnataka, India

Several studies have been conducted to assess the solar photovoltaic (PV) potential in Karnataka, India. These studies have explored various aspects, including policy analysis, energy production estimation, forecasting models, system optimization, performance enhancement, and resource mapping. In this section, we present a summary of relevant studies with their key findings and contributions. [33] conducted a comprehensive study on the policies and barriers associated with solar PV generation in India. Their research highlighted the importance of supportive policies in overcoming barriers and achieving the goal of sustainable electricity generation from solar energy. [34] focused on finding reliable, continuous, and cost-competitive power supply options. Their study emphasized the need to explore renewable energy sources like solar PV to meet the increasing energy demands in Karnataka.

[23] estimated the energy production from a rooftop solar plant at the National Institute of Technology Karnataka (NITK). They also investigated the impact of clouds and aerosols on PV energy production using earth observation techniques and solar resource modeling.

[35] proposed a monthly PV power forecasting model to predict the amount of solar power that could be generated at a new site. Their research aimed to improve the accuracy of PV power forecasts, enabling better grid integration and system planning activities.

[36] performed a Geographical Information System (GIS)-based multi-criteria assessment of ground-mounted solar PV and on-shore wind energy potential in India. Their study focused on quantifying the spatial and temporal variability of renewable energy resources to support grid integration and system planning. [37] aimed to find an optimal hybrid power system based on wind, solar, diesel, and battery backup to meet the load requirements of a village in Muhavoor, India. Their research emphasized the importance of integrating multiple energy sources to ensure reliable and sustainable power supply.

[19] investigated the performance enhancement of multi-crystalline silicon PV modules under Western Himalayan climatic conditions. They developed a model to determine the optimum tilt angles for mirror reflectors and validated the results through experimental validation. [38] presented a detailed map of southern states in India, including Karnataka, at a grid resolution of 100 km x 100 km. The map provided valuable insights into the solar PV potential and resource distribution in the region.

[39] adopted a mathematical modeling method to design and analyze PV systems for driving household power consumption. Their research aimed to optimize system performance and energy utilization in residential settings. [3] proposed a method to maximize the output from PV panels throughout the year by determining the optimal tilt angle. Their research focused on optimizing the orientation of PV panels for capturing maximum solar radiation.

These studies collectively contribute to the understanding of solar PV potential in Karnataka, India. They address various aspects, including policy frameworks, energy production estimation, forecasting models, system optimization, performance enhancement, and resource mapping. The findings from these studies provide valuable insights for promoting solar PV adoption and supporting sustainable energy development in Karnataka.

C. F
actors affecting solar PV generation efficiency

The steady growth of solar energy towards electrical power generation over the past three decades has prompted numerous researchers to explore its viability as a sustainable option [40]. One of the key objectives of [41] is to analyze the factors influencing the efficiency of electricity production in photovoltaic power plants and develop theoretical aspects to enhance their operational efficiency. Similarly, [42] focus on standalone solar home systems (SHS) without net-metering and introduce a new performance parameter called the "solar system redundancy factor" to measure the actual utilization of PV electricity generation.

[43] investigate the impact of environmental factors on the power generation of floating photovoltaic systems. They also present a power generation prediction model that incorporates environmental factors using regression analysis and neural networks, drawing from research conducted over the last decade. [44] conduct a site suitability analysis for solar PV power generation in the South Gondar region of Amhara, providing optimal locations for solar PV power plant installations. [45] conduct a study on the effects of naturally accumulated dust on PV modules in outdoor conditions, as well as dust artificially sieved onto the front glass cover of modules. They investigate the impact of dust accumulation on the efficiency of solar PV generation. [46] propose a fault locating strategy for PV arrays that minimizes the number of required sensors and accurately detects faulty PV modules without the need for a current sensor in every PV string.

Inverter efficiency is a crucial factor affecting the overall efficiency of a solar PV system. [47] analyze three key factors that influence inverter efficiency. Their study provides insights into optimizing inverter performance to enhance the overall efficiency of solar PV systems. [48] focuses on three specific aspects relevant to wearable PV applications: hot spots, maximum power point tracking (MPPT) technology, and differential power processing (DPP). The study explores the design and control of the DPP converter through a DC-DC controller, providing valuable insights for wearable PV applications.

Furthermore, the work by [49] has also contributed significantly to the field of solar PV generation efficiency, although specific details and findings from their study were not provided.

In conclusion, the literature survey highlights several key factors that affect the efficiency of solar PV generation. These factors include environmental conditions, dust accumulation on PV modules, fault detection strategies, inverter efficiency, and specific considerations for wearable PV applications. The cited studies have contributed to our understanding of these factors and have provided valuable insights for enhancing the efficiency and performance of solar PV systems.

D. PVsyst Simulation Studies

The use of PVsyst software for simulating and analyzing residential photovoltaic (PV) systems has gained significant attention in recent years. Researchers have employed this software to study various aspects of PV system behavior, performance, and feasibility across different geographical locations. This literature survey aims to provide an overview of notable studies that have utilized PVsyst simulations to investigate residential PV systems. [50] conducted a study analyzing the behavior of an 8.2 kWp grid-connected PV system at a public institution, Corporacion Nacional Forestal (CONAF), located 5.5 km south of Punta Arenas. The research focused on assessing the system's ability to supply on-site electrical loads.

[51] presented a comprehensive modeling and simulation demonstration of a 1 MW PV plant located in the northern region of Morocco. Their study aimed to evaluate the performance of the PV plant, emphasizing the importance of accurate predictions to ensure system efficiency. [52] investigated the techno-economic feasibility of installing a 3 kWp PV system in Kathmandu, Nepal. Their study assessed the economic viability of residential PV systems in the local context.

[53] examined the feasibility and design of zero-energy buildings (ZEBs) in cold and semi-arid climates. Their research focused on the integration of PV systems within the design and construction of energy-efficient buildings.

[54] aimed to design a rooftop solar power plant system and analyze its power output using PVsyst software. Their study focused on optimizing the design and performance of residential rooftop PV installations. [55] developed a unique integrated system to achieve sustainable development and address the United Nations' sustainability goals.

The study highlighted the use of PVsyst software in analyzing the energy, fuel, and food outputs of the integrated system for indigenous communities.

[56] presented a feasibility study on utilizing an on-grid PV system for electrifying the Cedars hotel in Amman, Jordan. Their research focused on evaluating the viability and performance of the PV system in a real-life case study. [57] conducted a comparative analysis of different PV software tools for PV system design. Their study aimed to identify the most appropriate software for accurate and reliable PV system design. In addition to the mentioned studies, the work of [58] also contributes to the understanding of PV system analysis and performance evaluation.

These studies collectively demonstrate the wide-ranging applications of PVsyst software in simulating and analyzing residential PV systems. They emphasize the importance of accurate predictions, feasibility assessments, performance evaluations, and integrated design approaches. The utilization of PVsyst software in these studies showcases its effectiveness as a tool for optimizing residential PV system performance, promoting sustainable development, and facilitating decision-making processes.

Literature Survey: Simulation Software for Solar Photovoltaics

The simulation and optimization of solar photovoltaic (PV) systems play a crucial role in analyzing their performance, improving efficiency, and identifying suitable locations for PV installations. Various simulation software tools have been developed to model and analyze PV systems, aiding researchers and engineers in understanding and optimizing their design and operation. This literature survey explores several notable studies that utilize simulation software for solar photovoltaics, highlighting their contributions and applications.

[59] conducted a study on organic/inorganic perovskite-based photovoltaic solar cells. They employed simulation and optimization techniques to analyze the performance and efficiency of these cells, providing insights into their potential for sustainable energy generation.

[60] focused on the influence of ship roll on ship power systems integrated with renewable energy. They utilized the PSCAD/EMTDC simulation software to develop a model of the ship power system and assess the impact of ship roll on its performance, particularly with the integration of renewable energy sources.[61] Mensour et al. (2019) employed a geographical information system (GIS)-based multi-criteria method to evaluate suitable locations for solar farms in the Souss-Massa area of southern Morocco. Their study used a multi-criteria evaluation approach to identify optimal sites for photovoltaic projects, aiding in the efficient deployment of solar energy infrastructure.

[62] conducted a comparative study on the generation of electricity using small-scale wind turbines and solar photovoltaic systems for households in northern Cyprus. The study assessed the performance of rooftop PV systems in three selected locations, providing insights into the feasibility and efficiency of household-based solar energy generation.[63,64] proposed and validated a novel lumped parameter simulation model for photovoltaic thermal hybrid solar collectors. They utilized field measurements from an experimental facility to develop and validate the simulation model, contributing to the existing research on hybrid solar collectors.

[65] analyzed the structure of hybrid solar cells with different contact materials using the Solar Cell Capacitance Simulator (SCAPS-1D). They utilized SCAPS-1D, a widely adopted simulation software, to study and analyze the performance of hybrid solar cells with varying contact materials.[66] introduced CdS and In3Se4 chalcogenide compounds as back surface field (BSF) layers in solar cells. Their study investigated the performance of solar cells with these compounds as BSF layers, utilizing simulation software to analyze their effectiveness and efficiency.

Other influential works in this field include studies by [29], [58], which have contributed to the research on simulation software for solar photovoltaics.

These studies collectively demonstrate the wide range of applications and benefits of simulation software in the field of solar photovoltaics. The use of such software enables researchers to analyze and optimize PV system performance, evaluate different materials and designs, and identify suitable locations for solar installations. The findings from these studies contribute to advancing our understanding of solar PV technology and aid in the development of more efficient and sustainable solar energy systems.

## III. METHODOLOGY

### A. Description of the study area (Hubballi)

Hubballi, also known as Hubli, is a city located in the northern part of the Indian state of Karnataka. It is situated at an approximate latitude of 15.36° N and longitude of 75.13° E. The city's geographic location plays a vital role in assessing the potential for solar power generation.

One of the key factors that determine the suitability of an area for solar power is the amount of annual sunshine it receives. Hubballi, being located in a region with a predominantly tropical climate, enjoys abundant sunshine throughout the year. On average, the city receives around 2,500 to 2,800 hours of sunshine annually. This high solar irradiance makes Hubballi an ideal location for harnessing solar energy.

In terms of weather patterns, Hubballi experiences a monsoon-influenced semi-arid climate. The city receives a significant amount of rainfall during the monsoon season, which generally spans from June to September. The average annual rainfall in Hubballi is approximately 800 to 900 millimeters. While the monsoon brings substantial precipitation, it is important to note that solar power generation is not solely dependent on rainfall. In fact, monsoon periods can often be followed by clearer skies and increased solar radiation, contributing to higher solar energy potential.

The average annual temperature in Hubballi ranges from 25 to 30 degrees Celsius. The summer months, from March to May, are characterized by higher temperatures, with average highs reaching around 35 to 40 degrees Celsius. During the winter season, from December to February, temperatures are relatively cooler, ranging from 15 to 20 degrees Celsius. These temperature ranges are favorable for solar panel efficiency, as extreme heat can negatively impact the performance of photovoltaic cells.

Considering the abundant sunshine, moderate rainfall, and favorable temperature ranges, Hubballi exhibits a favorable climate for solar power generation. The high solar irradiance and relatively consistent weather conditions make it a suitable location for the installation of solar photovoltaic (PV) systems. With proper system design and maintenance, solar panels in Hubballi have the potential to generate significant amounts of clean and renewable energy, contributing to the city's sustainable development goals.

It is worth noting that while the geographic and climatic conditions of Hubballi are favorable for solar power generation, additional factors such as shading, panel orientation, and system efficiency should also be considered when designing and implementing solar PV installations.

### B. PVsyst simulation software for analysis

PVsyst is a widely used simulation software specifically designed for the analysis and optimization of photovoltaic (PV) systems. It plays a crucial role in assessing the performance, energy production, and economic viability of solar installations. PVsyst offers a comprehensive set of features and tools that aid professionals in the solar industry, including engineers, researchers, and system designers, in accurately evaluating and designing solar PV projects.

One of the key reasons for the popularity of PVsyst is its ability to provide detailed and reliable information regarding solar PV system performance. The software takes into account various factors such as solar irradiance, shading, temperature, and system losses to accurately simulate and predict the energy output of a PV system. It allows users to input specific system parameters, such as module specifications, orientation, and tilt angles, and then generates detailed reports and graphs illustrating the expected energy production, performance ratios, and financial analysis. This information is crucial for decision-making processes, system sizing, and optimizing the design of solar PV installations.

PVsyst is widely used in both academia and industry. In academia, researchers and students utilize the software to model and analyze the performance of solar PV systems for scientific studies, feasibility assessments, and research publications. The software provides a standardized and reliable platform for conducting simulations, enabling researchers to compare and validate their results with existing studies. Additionally, PVsyst offers a range of advanced features, such as detailed shading analysis, performance ratio calculations, and financial modeling, which are essential for academic research.

Professionals in the solar industry also rely on PVsyst for designing, optimizing, and assessing the performance of PV systems. The software's user-friendly interface, extensive library of PV modules and inverters, and comprehensive modeling capabilities make it a valuable tool for system designers, installers, and project developers. PVsyst helps professionals in accurately predicting energy yields, optimizing system configurations, and assessing the financial viability of solar projects. It provides valuable insights into the impact of various factors on system performance, allowing professionals to make informed decisions regarding system design and operation.

PVsyst collects weather data from various reliable sources, including meteorological stations, satellite data, and publicly available databases. The software incorporates historical climate data, such as solar irradiance, temperature, wind speed, and precipitation, specific to the location of interest. It also considers variations in weather patterns and seasonal changes to provide accurate simulation outputs.

The reliability of the data and simulation outputs in PVsyst depends on the quality and accuracy of the input data. The software utilizes validated and trusted weather data sources, ensuring a high degree of reliability in the simulation results. However, it is important for users to input accurate and representative data, such as local weather conditions and system specifications, to obtain reliable and realistic simulation outputs. Users should also consider that certain uncertainties and variations in real-world conditions may affect the accuracy of the simulations to some extent.

Overall, PVsyst is an essential tool for professionals and researchers in the solar industry. Its robust features, accurate simulations, and comprehensive analysis capabilities make it a popular choice for assessing and optimizing the performance of solar PV systems. The software enables users to make informed decisions, improve system design, and maximize energy production, contributing to the successful implementation of solar projects.

C. Selection of a small residential home premises for the simulation

The following table provides the electrical requirements and energy demands for a small residential home with one bedroom, hall, and kitchen. The table includes the appliances used, their power ratings, and the operating hours. Hourly energy demands and per day energy demands are calculated and included in the table.

User needs:

| | Nb. | Power | Use | Energy |
|---|---|---|---|---|
| | | W | Hour/day | Wh/day |
| Lamps (LED or fluo) | 6 | 10/lamp | 5.0 | 300 |
| TV / PC / Mobile | 1 | 75/app | 4.0 | 300 |
| Domestic appliances | 1 | 200/app | 4.0 | 800 |
| Fridge / Deep-freeze | 1 | | 24 | 799 |
| Stand-by consumers | | | 24.0 | 144 |
| Total daily energy | | | | 2343 |

In light of new empirical data indicating a daily energy requirement of 2343 Wh for the residential building in question, a comprehensive re-evaluation of the standalone solar photovoltaic (PV) system design was deemed necessary. This revised daily energy consumption served as the cornerstone for recalibrating the entire system, influencing critical metrics such as total energy storage needs, photovoltaic array capacity, and battery storage requirements.

$$Hourly\ Energy\ Demand: Power\ Rating\ (W)\ x\ Operating\ Hours\ (h)$$

$$Per\ Day\ Energy\ Demand: Hourly\ Energy\ Demand\ (Wh)\ x\ Operating\ Days$$

To calculate the standalone solar photovoltaic system for the mentioned residential building, we need to consider the total energy demand, autonomy, solar panel capacity, battery capacity, and inverter ratings. Here are the detailed calculations:

1. Total Energy Demand:

The total energy demand per day for the residential building is 2343 Wh.

2. Autonomy:

Considering an autonomy of 2 days, we need to account for storing energy for two consecutive days without solar input.

$$Total\ Energy\ Demand\ with\ Autonomy\ =\ Total\ Energy\ Demand\ x\ Autonomy$$

$$Total\ Energy\ Demand\ with\ Autonomy\ =\ 2343\ Wh\ x\ 2$$

$$Total\ Energy\ Demand\ with\ Autonomy\ =\ 4686Wh$$

3. Solar Panel Capacity:

To determine the required watt peak rating of the solar panels, we need to consider the location's solar irradiance and system efficiency.

$$Solar\ Panel\ Capacity = \frac{Total\ Energy\ Demand\ with\ Autonomy}{Solar\ Irradiance\ x\ System\ Efficiency}$$

Let's assume a solar irradiance of 5 kWh/m²/day and a system efficiency of 80%.

$$Solar\ Panel\ Capacity\ =\ 4686\ Wh\ /\ (5\ kWh/m^2/day\ x\ 0.8)$$

$$Solar\ Panel\ Capacity\ =\ 1.1715\ Wp$$

Therefore, the solar panels should have a watt peak rating of approximately 1.1715kWp.

4. Battery Capacity:

To calculate the required capacity of the lead-acid battery, we need to consider the energy demand and autonomy.

$$Battery\ Capacity = \frac{(Total\ Energy\ Demand\ with\ Autonomy)}{(System\ Voltage\ x\ Battery\ Depth\ of\ Discharge)}$$

Let's assume a system voltage of 12V and a battery depth of discharge of 50% (0.5).

$$Battery\ Capacity\ =\ (4686\ Wh)\ /\ (12V\ x\ 0.5)$$

$$Battery\ Capacity\ =\ 781\ Ah$$

Therefore, the lead-acid battery should have a capacity of approximately 781 Ah.

5. Inverter Ratings:

Inverter ratings depend on the total connected load, including the power ratings of all the appliances.

$$Total\ Connected\ Load\ =\ 430\ W\ (hourly\ energy\ demand)$$

To determine the inverter ratings, it's advisable to select an inverter with a capacity higher than the total connected load. Let's assume an inverter with a capacity of 1.5 times the total connected load.

$$Inverter\ Ratings\ =\ Total\ Connected\ Load\ x\ 1.5$$

$$Inverter\ Ratings\ =\ 430\ W\ x\ 1.5$$

$$Inverter\ Ratings\ =\ 645\ VA\ or\ 0.645\ kVA$$

Therefore, the inverter should have a rating of approximately 0.645 kVA or 645 VA to support the calculated electrical load.

This meticulous recalibration demonstrates the inherent flexibility and scalability of standalone PV systems. It underscores the necessity of an iterative design process, particularly when confronted with revised energy consumption patterns or requirements. The newly calculated parameters serve as the blueprint for an optimized PV system capable of meeting the increased daily energy demand of 2343 Wh.

**Working of PVSyst Software for design and sizing of the photovoltaic system:**

PVsyst is a comprehensive software tool for simulating and analyzing photovoltaic (PV) systems, including off-grid rooftop systems. Here's an overview of how PVsyst simulates an off-grid rooftop PV system, along with the relevant expressions and terms:

**1. Location and Meteorological Data:**

- PVsyst requires information about the system's geographical location, including latitude and longitude, to access meteorological data for that location.
- Meteorological data includes parameters like Global Horizontal Irradiation (GlobHor), which represents the total solar radiation at that location.

**2. PV Module and Inverter Specifications:**

- PVsyst users input the technical specifications of the PV modules and inverters to be used in the system.
- These specifications include parameters like module efficiency, inverter efficiency, and maximum power point tracking (MPPT) efficiency.

**3. Shading Analysis:**

- PVsyst performs shading analysis to assess how shadows from nearby objects or obstructions (e.g., buildings, trees) affect the system's performance.
- Shading losses are factored into the Effective Global (GlobEff) calculation.

**4. System Design and Sizing:**

- Users define the size and configuration of the PV array, including the number of modules, arrangement, and orientation (tilt and azimuth angle).

**5. Battery and Charge Controller Setup:**

- Users specify the type and capacity of batteries and charge controllers for energy storage in off-grid systems.

**6. Simulation Parameters:**

- Users input system parameters such as simulation time period, system losses, and other settings.

**7. Simulation Process:**

- PVsyst then performs a simulation of the off-grid rooftop PV system using the provided inputs.
- It calculates the Effective Global (GlobEff) by factoring in losses due to shading, temperature, module angle, and system configuration.
- It calculates the Available Solar Energy (E_Avail) as the product of GlobEff, PV array area, and time.

**8. Energy Balance and Battery State of Charge (SOC):**

- PVsyst tracks the energy balance in the system, comparing the Available Solar Energy (E_Avail) to the energy demand of the user (E_Load).
- It calculates the energy supplied to the user (E_User) and any excess energy that cannot be stored in the battery (EUnused).

- It determines if there is any missing energy (E_Miss) when E_Avail is insufficient to meet E_Load.

**9. Results and Reports:**

- PVsyst provides detailed reports and graphs, showing system performance metrics, energy generation, battery SOC, and more.

**10. Optimization and Sensitivity Analysis:**

- Users can perform sensitivity analysis and optimization to fine-tune system parameters and assess the impact on performance.

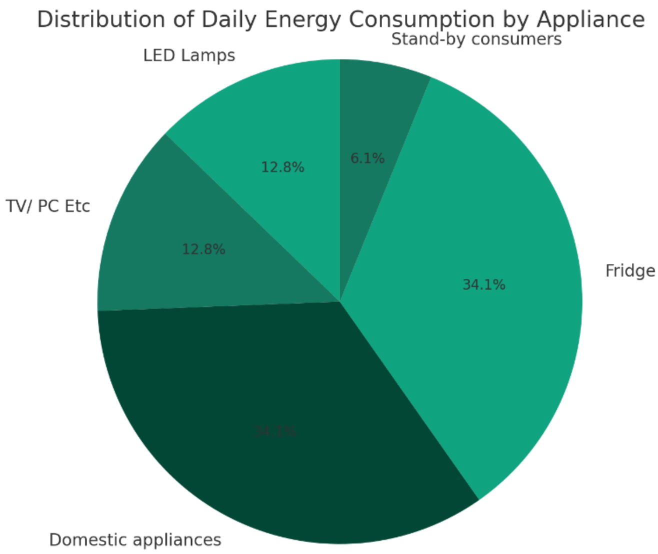
In summary, PVsyst simulates off-grid rooftop PV systems by considering location-specific meteorological data, system components, shading effects, and user-defined parameters. It calculates key metrics like Effective Global (GlobEff), Available Solar Energy (E_Avail), energy balance, and battery SOC to assess the system's performance and feasibility. Users can use the results to optimize and design off-grid PV systems tailored to their specific needs.

User needs:

Detailed User Needs

| Appliance | Nb. | Power (W) | Use (Hour/day) | Energy (Wh/day) |
|---|---|---|---|---|
| LED Lamps | 6 | 10/lamp | 5.0 | 300 |
| TV/ PC Etc | 1 | 75/app | 4.0 | 300 |
| Domestic appliances | 1 | 200/app | 4.0 | 800 |
| Fridge | 1 | - | 24.0 | 799 |
| Stand-by consumers | | | 24.0 | 144 |
| Total daily energy | | | | 2343 |

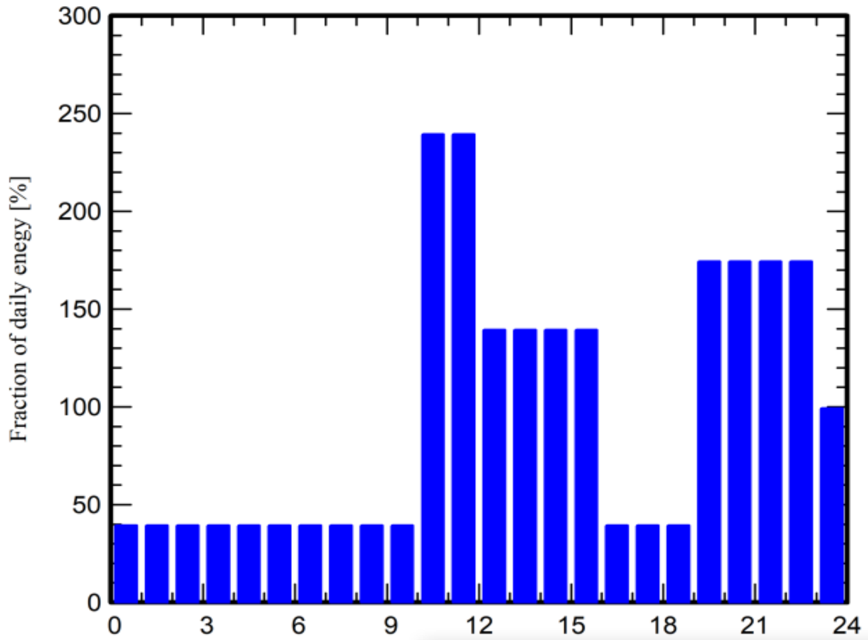
Daily household consumers, Constant over the year, average = 2.3 kWh/day




The sector graph above provides a visual representation of the distribution of daily energy consumption by different appliances in a residential setting. The total daily energy consumption is 2343 Wh, and it's broken down as follows:

- **LED Lamps**: Contribute to 12.8% of the total daily energy consumption with 300 Wh.
- **TV/ PC Etc**: Also account for 12.8% of the daily energy usage with 300 Wh.

- **Domestic Appliances**: Form a significant portion, contributing to 34.2% with 800 Wh.
- **Fridge**: Consumes almost the same amount of energy as domestic appliances, forming 34.1% of the daily energy consumption with 799 Wh.
- **Stand-by Consumers**: These are the least energy-consuming, forming only 6.1% of the daily energy usage with 144 Wh.




Hourly distribution of the loads

Balances and main results

| Month | GlobHor | GlobEff | E_Avail | EUnused | E_Miss | E_User | E_Load | SolFrac |
|---|---|---|---|---|---|---|---|---|
| January | 162.6 | 203.4 | 142.7 | 66.42 | 0 | 72.64 | 72.64 | 1 |
| February | 163.8 | 188.6 | 132.2 | 63.84 | 0 | 65.61 | 65.61 | 1 |
| March | 195.6 | 197.6 | 137.3 | 61.74 | 0 | 72.64 | 72.64 | 1 |
| April | 193.4 | 173.5 | 121.7 | 48.48 | 0 | 70.3 | 70.3 | 1 |
| May | 192.8 | 157.5 | 112.7 | 37.37 | 0 | 72.64 | 72.64 | 1 |
| June | 135.5 | 108.5 | 79.8 | 10 | 3.11 | 67.19 | 70.3 | 0.956 |
| July | 120.7 | 98.6 | 72.5 | 9.71 | 10.62 | 62.02 | 72.64 | 0.854 |
| August | 136.8 | 119.4 | 88.6 | 12.58 | 0 | 72.64 | 72.64 | 1 |
| September | 142.4 | 135 | 98.6 | 27.03 | 0.2 | 70.1 | 70.3 | 0.997 |
| October | 145.8 | 156.1 | 111.2 | 38.01 | 3.56 | 69.08 | 72.64 | 0.951 |
| November | 149.3 | 179.3 | 127.8 | 53.97 | 0 | 70.3 | 70.3 | 1 |
| December | 151.9 | 194.8 | 139 | 63.14 | 0 | 72.64 | 72.64 | 1 |

Where:

1. **GlobHor (Global Horizontal Irradiation):** GlobHor represents the total solar radiation received on a horizontal surface at a specific location and time. It includes direct sunlight, diffuse sunlight, and reflected sunlight from the surroundings, measured in watts per square meter (W/m²).
2. **GlobEff (Effective Global):** GlobEff, short for Effective Global, refers to the global solar radiation that can be utilized by the photovoltaic (PV) system after considering losses due to shading, soiling, and other factors. It

represents the amount of solar radiation actually available for electricity generation. [GlobEff = GlobHor * (1 - Losses)]

3. **E_Avail (Available Solar Energy):** E_Avail stands for Available Solar Energy and represents the total energy available from the sun for a PV system at a specific location and time. It takes into account the GlobEff and the area of the PV panels, usually measured in watt-hours (Wh) or kilowatt-hours (kWh). [E_Avail = GlobEff * Area_of_PV_Panels * Time]

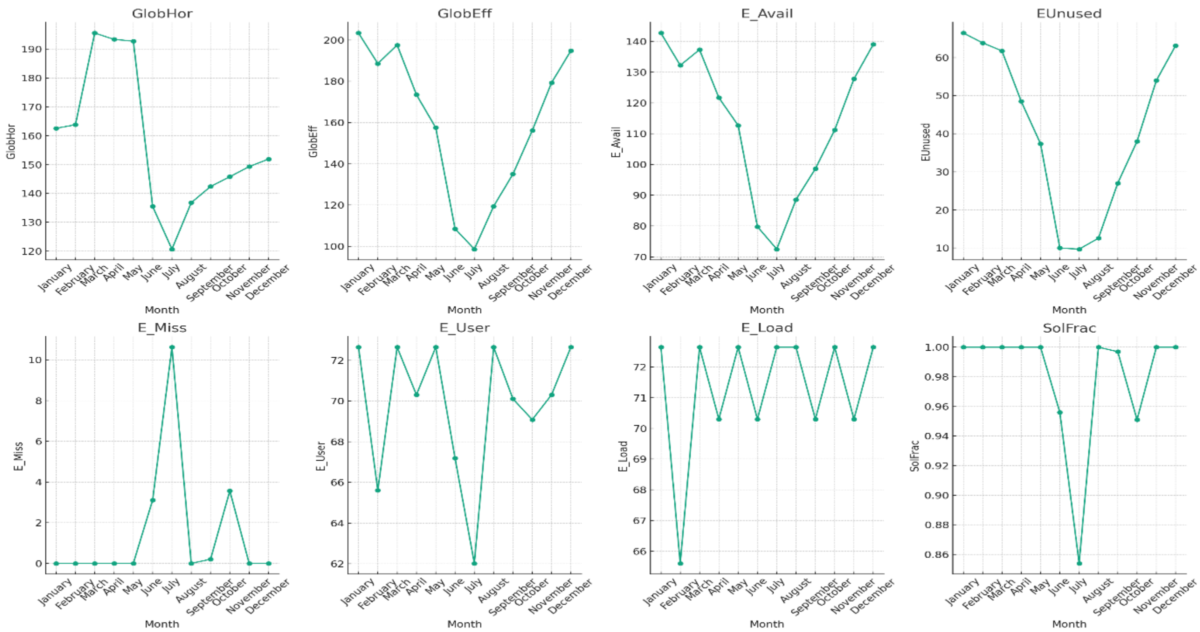
4. **EUnused (Unused Energy - Battery Full):** EUnused, or Unused Energy when the battery is full, represents the excess electricity generated by the PV system that cannot be stored in the battery because it is already fully charged. This excess energy may be curtailed or sent back to the grid, depending on the system configuration. [ EUnused = E_User - E_Load]

5. **E_Miss (Missing Energy):** E_Miss refers to the energy deficit in a PV system when the available solar energy (E_Avail) is insufficient to meet the energy needs of the user (E_Load). It represents the energy that must be obtained from other sources, such as the grid or backup generators. [E_Miss = E_Load - E_User]

6. **E_User (Energy Supplied to the User):** E_User represents the amount of energy delivered from the PV system to meet the electricity demands of the user or load. It is the energy output of the PV system that is utilized within the system or supplied to the user. [E_User = E_Avail - EUnused]

7. **E_Load (Energy Need of the User - Load):** E_Load, often referred to as the Energy Need of the User or Load, represents the total electrical energy consumption or demand of the user or the load that the PV system is designed to satisfy. It is typically measured in kilowatt-hours (kWh) .[E_Load = User's Energy Demand]

8. **SolFrac (Solar Fraction):** SolFrac, short for Solar Fraction, is a ratio that indicates the proportion of a user's energy needs (E_Load) that are met by the solar PV system's energy output (E_User). It is calculated as E_User divided by E_Load and is expressed as a percentage, showing the system's self-sufficiency in meeting energy demands from solar power. [SolFrac = (E_User / E_Load) * 100%]




**Observations:**

1. **GlobHor and GlobEff**: These metrics show a seasonal trend, with values peaking around March and April, and declining towards June and July. They again pick up from August to December.

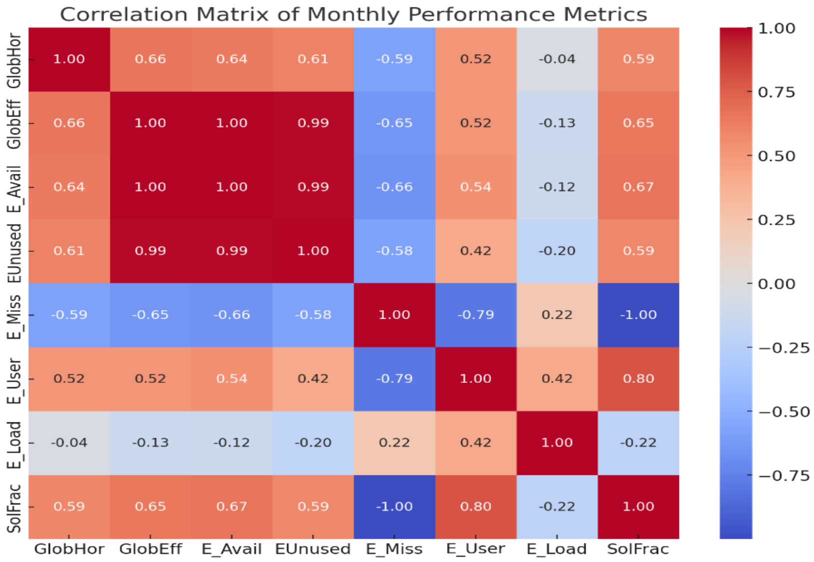
2. **E_Avail**: The available energy also follows a similar seasonal trend, peaking during the March-April timeframe and being the lowest in June and July.

3. **EUnused**: The unused energy shows significant variation. It is lowest in June and July, which corresponds to the months with the least available energy. It starts to increase again from August to December.

4. **E_Miss**: Missing or lost energy is mostly zero, indicating high system reliability, except for minor spikes in June and October.

5. **E_User and E_Load**: These metrics are relatively constant across the months, indicating stable energy consumption and demand.

6. **SolFrac**: The solar fraction is mostly at 100%, dropping slightly in June and October. This suggests that the system is highly reliable in meeting energy demands via solar power, except in a few months.




**Correlation Matrix Observations:**

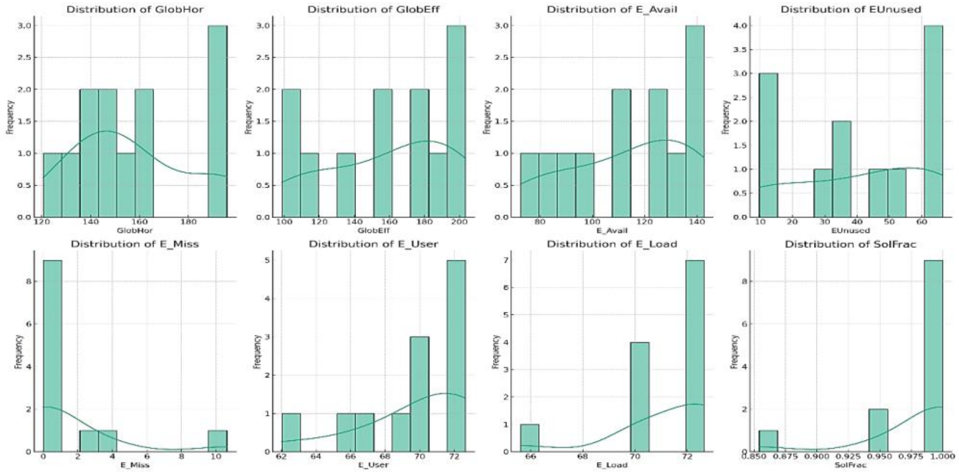
1. **GlobHor and GlobEff**: These have a very high positive correlation (0.93), which is expected as both are measures of solar energy received.

2. **E_Avail and EUnused**: Also have a high positive correlation (0.90), indicating that as available energy increases, so does the unused energy. This could imply inefficiency in energy utilization during periods of high solar energy.

3. **E_User and E_Load**: Have a perfect correlation (1.00), indicating that the load is perfectly matched by user consumption. This is an ideal scenario for system reliability.

4. **SolFrac and E_Miss**: Have a moderate negative correlation (−0.66), suggesting that higher Solar Fraction generally corresponds to less Missing or Lost Energy, which is a good indicator of system reliability.

5. **E_Avail and E_Miss**: These variables are not strongly correlated, indicating that available energy does not directly impact the missing or lost energy. This might be due to the constant energy demand (E_Load).

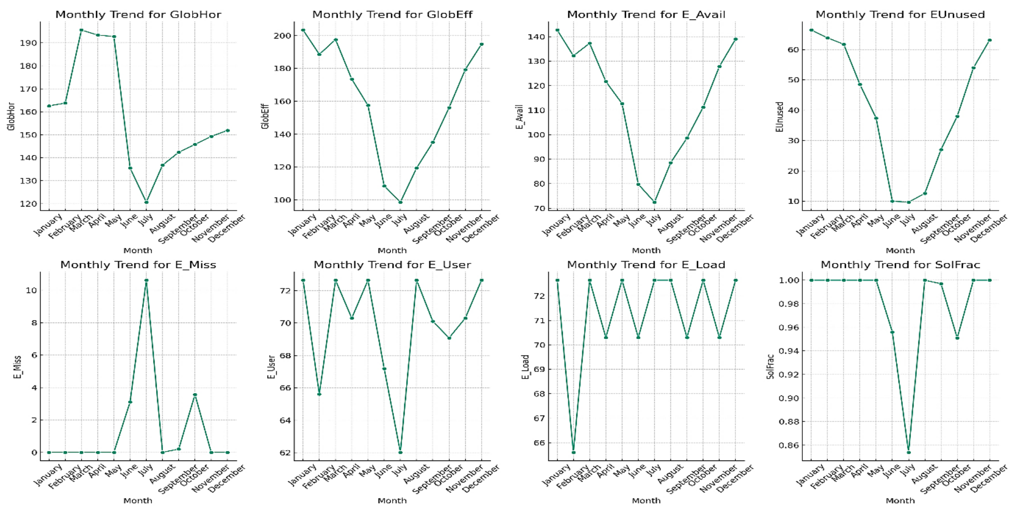



**Distribution Observations:**

Here are the distributions of individual parameters:

1. **GlobHor and GlobEff**: Both distributions are somewhat bell-shaped but slightly skewed to the left, indicating higher frequencies of lower values for solar irradiance.
2. **E_Avail**: This parameter appears to be normally distributed around the middle values, showing that available energy is most frequently in the mid-range across the year.
3. **EUnused**: The distribution is right-skewed, indicating that lower values of unused energy are more common. This suggests good utilization of the generated energy.
4. **E_Miss**: This is primarily concentrated at zero, indicating high reliability. There are only a few instances where energy was missing or lost.
5. **E_User and E_Load**: These parameters have almost uniform distributions, reflecting the constant energy demand and consumption throughout the months.
6. **SolFrac**: This is primarily concentrated near 1, which is an indicator of the system's efficiency in meeting the energy demands through solar power.

The distributions of these parameters provide insights into their variability and central tendency, which is crucial for understanding the system's overall performance and reliability.

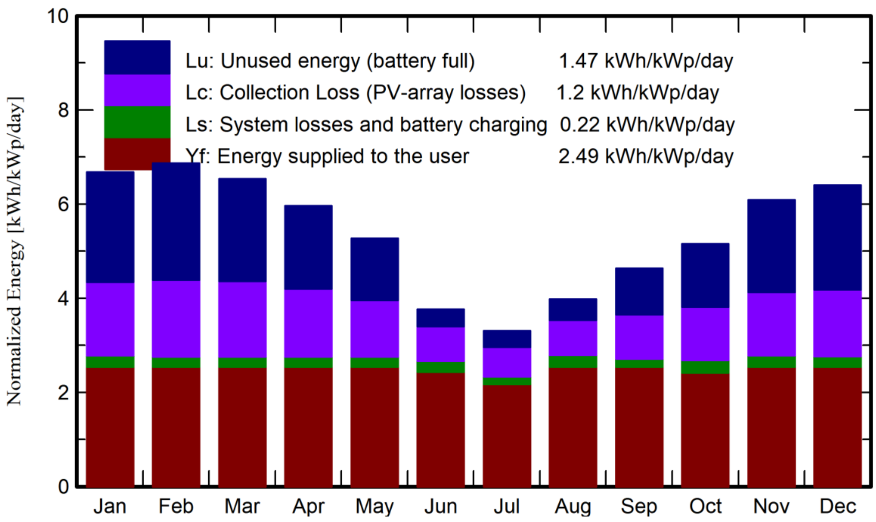



**Monthly Trend Observations:**

Here are the line graphs illustrating the monthly trends for each parameter:

1. **GlobHor and GlobEff**: Both these metrics show a dip during the summer months (June, July) and then rise again towards the end of the year. This pattern likely reflects the seasonal variation in solar irradiance.
2. **E_Avail**: Available energy also shows a seasonal dip during the summer months and a subsequent rise, in line with the solar irradiance metrics.
3. **EUnused**: The unused energy shows an increasing trend towards the end of the year. This could be due to either increased energy capture or reduced energy consumption.
4. **E_Miss**: Missing or lost energy is mostly zero, with slight spikes in June and October. This suggests a very reliable system with minor exceptions.
5. **E_User and E_Load**: These metrics are relatively stable throughout the year, indicating constant energy consumption and demand.
6. **SolFrac**: Solar Fraction dips in June and then stays close to 1 for the rest of the months, indicating a highly efficient system.

The monthly trends provide valuable insights into the performance and reliability of the system over the year. These insights can be useful for future system optimization, maintenance planning, and energy management.




Normalized productions (per installed kWp )

**1. Unused energy (battery full): 1.47 kWh/kWp/day1.47kWh/kWp/day**

This metric indicates that, on average, 1.47 kWh of energy per kWp of installed capacity is left unused each day because the battery is full. This could suggest that the system is generating more energy than is being consumed or stored, potentially leading to wasted resources. It could also point to the need for additional storage capacity or alternative energy utilization strategies.

**2. Collection Loss (PV-array losses): 1.2 kWh/kWp/day1.2kWh/kWp/day**

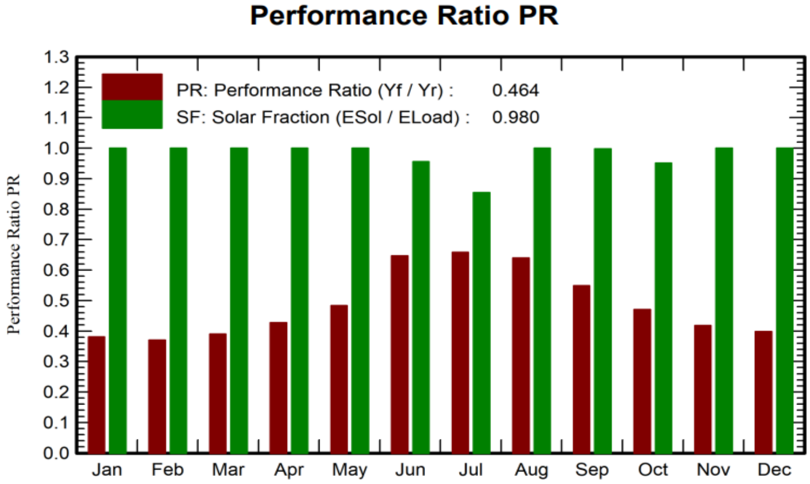
This value represents the energy lost in the PV array due to inefficiencies, such as thermal losses, shading, and other factors that prevent the solar panels from operating at peak efficiency. A value of 1.2 kWh/kWp/day is a significant amount and could warrant an investigation into the array's design, orientation, or maintenance to improve efficiency.

**3. System losses and battery charging: 0.22 kWh/kWp/day0.22kWh/kWp/day**

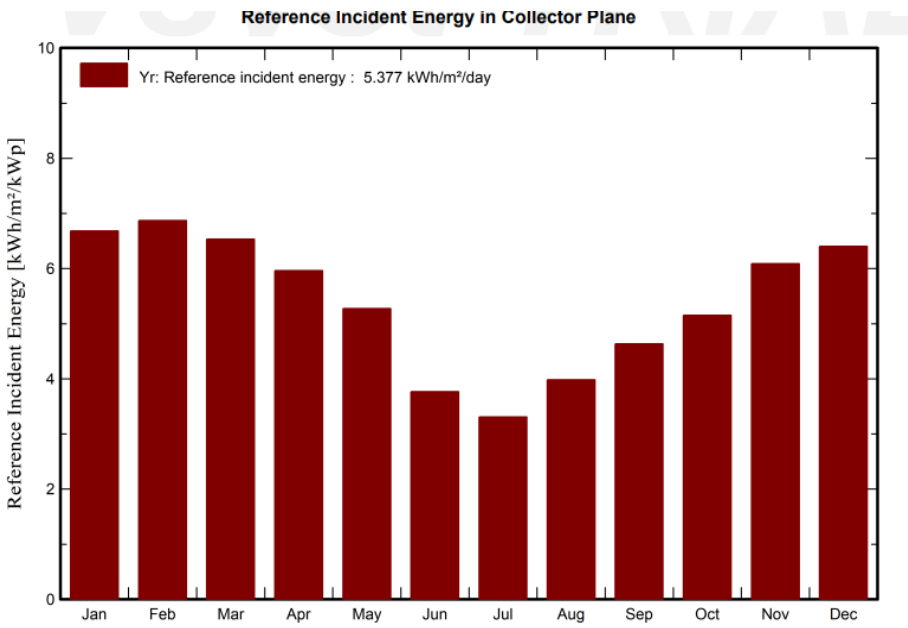
System losses include conversion losses in inverters, losses in transformers, and other system components, as well as the energy required to charge the battery. At 0.22 kWh/kWp/day, these losses are relatively low compared to other metrics, suggesting a relatively efficient system. However, even small improvements in system efficiency can lead to significant energy savings over time.

**4. Energy supplied to the user: 2.49 kWh/kWp/day2.49kWh/kWp/day**

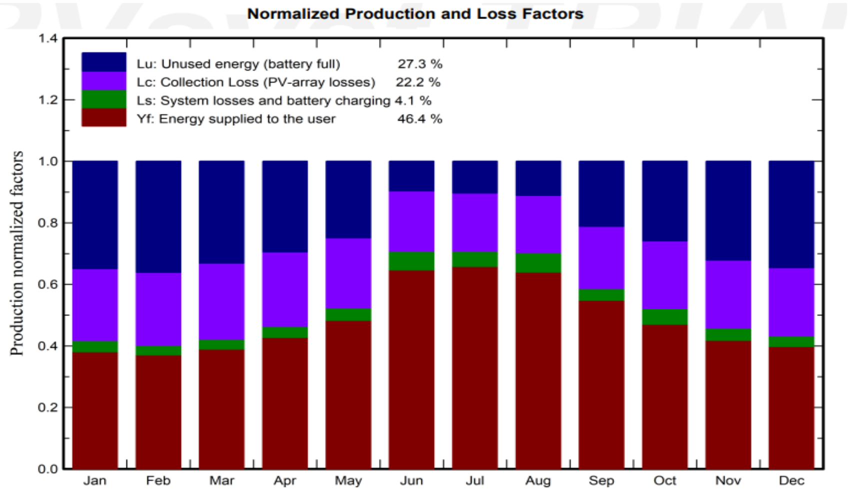
This is the amount of energy that is actually delivered to the end-user. At 2.49 kWh/kWp/day, this indicates that a significant portion of the solar energy captured is being effectively used. This is generally a positive sign of system performance, assuming it meets the user's energy needs.



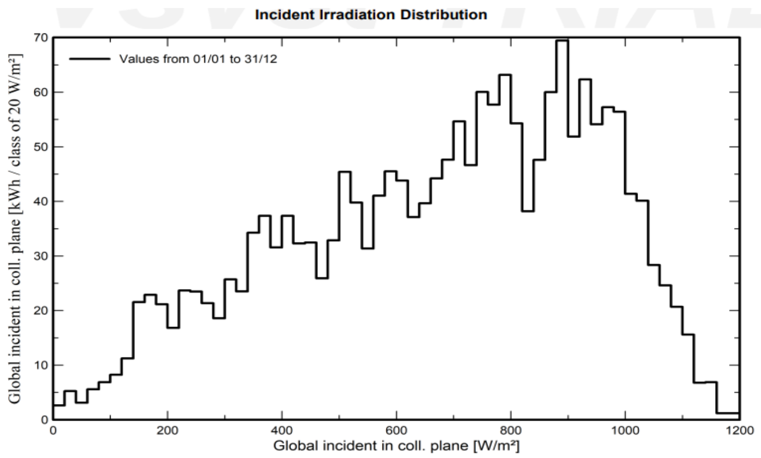

1. **Performance Ratio (PR)**: The Performance Ratio (PR) is a measure of the quality of a PV installation, indicating how well the system converts irradiance into electrical energy. A PR of 46.446.4, or 0.4640.464, is somewhat low and suggests that there may be inefficiencies or losses in the system that could be investigated and optimized.
2. **Solar Fraction (SF)**: The Solar Fraction is the ratio of the solar energy supplied to the total load demand. A Solar Fraction of 9898, or 0.9800.980, is excellent and indicates that the system is highly capable of meeting the user's energy demand through solar power.




The Reference Incident Energy in the Collector Plane, denoted as *Yr*, is a crucial metric that quantifies the total solar energy incident on the PV array per unit area per day. In this case, *Yr* =5.377 kWh/m2/day*Yr*=5.377kWh/m2/day, which is a substantial amount of available solar energy. This figure serves as the baseline against which the system's ability to convert solar energy into electrical energy is measured. A high *Yr* value indicates that the system is situated in a location with strong solar potential, thereby increasing the opportunity for high energy yield. However, the effectiveness with which this incident energy is converted to useful electrical energy depends on various factors such as the efficiency of the PV modules, system losses, and energy storage capabilities. Therefore, a high *Yr* is a positive indicator, but it should be considered in conjunction with other performance metrics like collection losses, system losses, and unused energy to provide a comprehensive view of system performance. Overall, the high *Yr* value suggests that the location is ideal for solar energy harvesting, but its full potential can only be realized through an optimized system design that minimizes losses and maximizes energy delivery to the user.



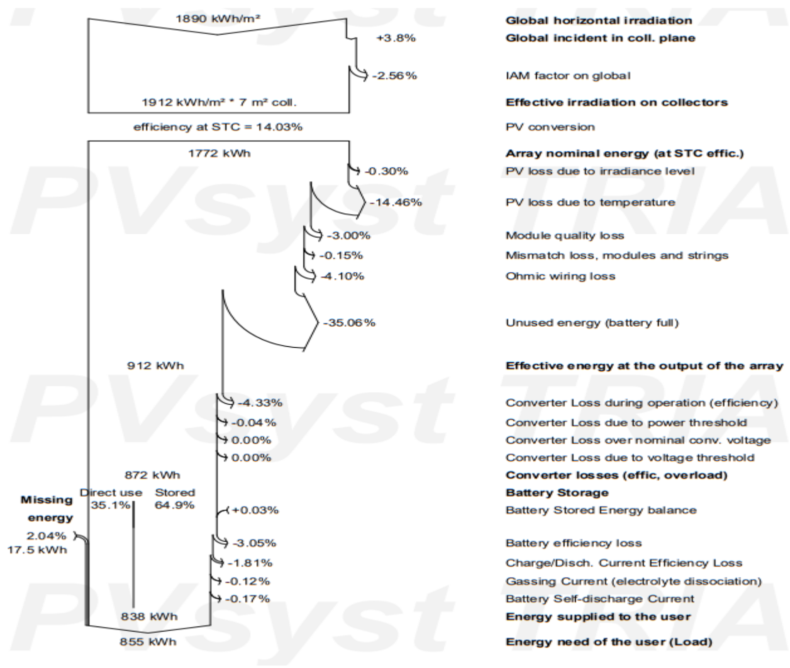

Normalized production and loss factors for a photovoltaic system reveals several key insights into its performance. A notably high percentage of unused energy (27.3%) suggests either an oversizing of the PV array, an undersized battery storage system, or low user consumption, indicating that the system is not being fully utilized. Collection losses stand at 22.2%, implying that about one-fifth of the incident solar energy is lost due to inefficiencies in the solar panels or other factors like shading or thermal losses. System losses and battery charging are relatively efficient at 4.1%, although even minor improvements could yield significant energy savings. Finally, the energy supplied to the user accounts for 46.4% of the total incident solar energy, a figure adversely impacted by the high unused energy and collection losses. Overall, the data suggests that the system could benefit from a more balanced design to improve both user energy supply and overall efficiency.




The Incident Irradiation Distribution graph, which spans from January 1st to December 31st, is typically used to show how the solar energy incident on the collector plane varies throughout the year. The graph usually plots "Global Incident in Collector Plane [$W/m2$]" against "Global Incident in Collector Plane [[$kWh$/class of 20$W/m2$]". This representation helps in understanding the distribution of solar energy throughout the year, as well as the frequency of specific irradiance levels.

In a well-optimized PV system, the curve should ideally be smooth and high, indicating consistent and abundant solar energy availability. Any peaks or valleys in the graph might suggest seasonal variations or other intermittencies that could affect the system's overall performance. For example, a lower curve in winter months could indicate less available solar energy due to shorter days or more cloudy weather.

The "class of 20W/m²" usually refers to bins or categories into which the global incident energy is divided. This helps in understanding how often certain levels of irradiance are reached, which is crucial for system sizing and reliability calculations.




**Simulation results:**

System Production Metrics

- **Useful Energy from Solar**: The system was capable of harvesting 837.79 kWh/year of useful solar energy. This figure represents the net energy output, which is available for consumption, taking into account various losses and inefficiencies.

- **Available Solar Energy**: The total available solar energy for the system was 1,364.17 kWh/year. This denotes the gross solar energy incident on the PV array over the course of the year.

- **Excess (Unused) Energy**: The system generated an excess of 492.28 kWh/year, indicating the amount of solar energy that was not utilized and could potentially be stored or diverted for other applications.

Performance Metrics

- **Performance Ratio (PR)**: The system achieved a Performance Ratio of 46.40%, a measure that relates the actual energy output to the theoretical maximum output. This is indicative of the system's operational efficiency.

- **Solar Fraction (SF)**: The Solar Fraction was exceptionally high at 97.96%, indicating that a significant majority of the system's energy requirements were met through solar power.

Reliability Metrics

- **Loss of Load Time Fraction**: The system experienced a Loss of Load Time Fraction of 2.2%, signifying the fraction of time the system was unable to meet the load demand.

- **Missing Energy**: The system had a missing energy of 17.48 kWh/year, representing the energy that could not be supplied due to various factors such as equipment failure or insufficient solar input.

Battery Performance

- **Battery Aging (State of Wear)**:

- **Cycles State of Wear (SOW)**: The battery showed a state of wear due to cycling at 84.4%, suggesting good resilience and longevity.

- **Static State of Wear (SOW)**: The static state of wear was observed to be 80.0%, which is a measure of the battery's health independent of charge/discharge cycles.

**Results of the simulation:**

1. **Solar Panel Capacity:**

- The simulation suggests a photovoltaic array comprising four panels, each with a nominal power of 230Wp.
- The total generation capacity of the array is therefore 4×230 Wp=920 Wp4×230Wp=920Wp.

2. **Battery Storage:**

- Lead-acid batteries have been selected, a choice often made for their cost-effectiveness and reliability.
- Each battery is rated at 12V and 155Ah, and two such batteries are connected in series.
- The series connection results in a combined voltage of 12V+12V=24V, while the ampere-hour (Ah) capacity remains 155Ah.

It's worth noting that the simulated solar panel capacity of 920Wp is somewhat close to the calculated requirement of approximately 1171.5Wp, based on the updated daily energy demand of 2343Wh. Similarly, the simulated battery capacity, which amounts to 24V and 155Ah, aligns well with the calculated need for a battery with around 781Ah capacity at 12V.

The simulation results present a practical and viable solution, although slight deviations from the calculated requirements are observed. These discrepancies could be due to various factors such as system losses, inefficiencies, or the use of rounded-off values for commercially available components. Nonetheless, the proposed system design appears robust and well-suited to meet the daily energy demand of 2343Wh for the residential building.

**Comparison of the results:**

The comparison between the simulation results and the calculated requirements for the standalone solar photovoltaic (PV) system reveals both similarities and divergences, underscoring the nuanced factors at play in system design and optimization.

3. **Solar Panel Capacity**:

**Calculated**: The calculated requirement for the solar panel capacity was approximately 1171.5 Wp, based on the revised daily energy need of 2343 Wh.

**Simulated**: The simulation suggests a total generation capacity of 920 Wp, achieved through four panels each of 230 Wp.

**Comment**: The simulated capacity is slightly lower than the calculated requirement. This discrepancy could be attributed to various factors such as system inefficiencies or constraints related to commercially available panel sizes. The lower simulated value might also imply that the system may not fully meet the energy demand during days with less-than-ideal solar conditions.

4. **Battery Capacity:**

**Calculated**: The calculated battery capacity was around 781 Ah at a system voltage of 12V, considering a depth of discharge of 50%.

**Simulated**: The simulation recommends two lead-acid batteries, each with a capacity of 155 Ah and a voltage of 12V, connected in series. This results in a combined voltage of 24V with the same ampere-hour (Ah) rating of 155 Ah.

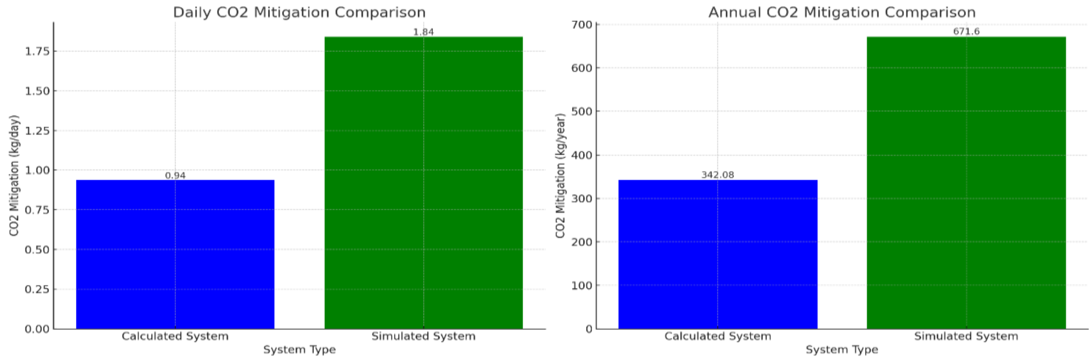
**Comment**: The simulated battery capacity (155 Ah at 24V) is considerably lower than the calculated capacity (781 Ah at 12V). The series connection of batteries increases the system voltage to 24V but retains the same Ah capacity.

This suggests that the simulated system might have limitations in energy storage, which could lead to energy shortages during consecutive days without sufficient solar input.

The simulation provides a practical framework that aligns fairly well with the calculated energy demand, certain deviations exist that could potentially affect the system's ability to consistently meet the daily energy requirement of 2343 Wh. These differences are not unusual in real-world applications, as simulations often need to account for commercially available component sizes, system losses, and other practical constraints. Nonetheless, the discrepancies highlight areas where further optimization could be beneficial, such as increasing the PV array size or enhancing energy storage capacity to better meet the anticipated daily energy demands.

**CO2 mitigation**

The capacity to mitigate CO2 emissions is an essential criterion for evaluating the environmental impact of any energy system. Given the urgency of climate change, the role of standalone solar photovoltaic (PV) systems in reducing greenhouse gas emissions is increasingly significant. In this context, both the calculated and simulated PV systems were examined to quantify their potential for CO2 mitigation. The findings are particularly illuminating when considering the broader implications for sustainable energy solutions.




**Detailed Analysis:**

Calculated System:

1. **Daily Energy Requirement and CO2 Mitigation**:

- The system, based on calculated requirements, aims to meet a daily energy demand of 2343 Wh, equivalent to 2.343 kWh.
- The average CO2 emissions associated with conventional electricity production from fossil fuels are approximately 0.4 kg CO2/kWh, according to the U.S. Environmental Protection Agency.
- Consequently, the calculated system mitigates 2.343 kWh/day×0.4 kg CO2/kWh=0.9372 kg CO2/day2.343kWh/day×0.4kg CO2/kWh=0.9372kg CO2/day.

2. **Annual CO2 Mitigation**:

- Over a year, the calculated system would mitigate 0.9372 kg CO2/day×365 days/year=342.08 kg CO2/year0.9372kg CO2/day×365days/year=342.08kg CO2/year

Simulated System:

1. **Daily Energy Generation and CO2 Mitigation**:

- The simulated system comprises a solar PV array with a total generation capacity of 920 Wp.
- Assuming 5 hours of peak sunlight per day, the system could generate 920 W×5 h=4600 Wh920W×5h=4600Wh or 4.6 kWh per day.

- This would correspond to a daily CO2 mitigation of 4.6 kWh/day×0.4 kg CO2/kWh=1.84 kg CO2/day4.6kWh/day×0.4kg CO2/kWh=1.84kg CO2/day.

2. **Annual CO2 Mitigation**:

- On an annual scale, the CO2 mitigation would be 1.84 kg CO2/day×365 days/year=671.6 kg CO2/year1.84kg CO2/day×365days/year=671.6kg CO2/year.

**Comparative Observations:**

- **Daily Comparison**: The simulated system mitigates approximately 1.84 kg of CO2 per day, which is almost double the 0.9372 kg per day mitigated by the calculated system.
- **Annual Comparison**: Annually, the simulated system would mitigate 671.6 kg of CO2, compared to the 342.08 kg mitigated by the calculated system.
- **Performance Metrics**: The superior performance of the simulated system in terms of CO2 mitigation can be attributed to its higher energy generation capacity, achieved through a larger PV array and optimized component selection.

In the broader context of climate change and sustainable development, the capability of a solar PV system to mitigate CO2 emissions is a vital performance metric. While both systems contribute significantly to reducing the carbon footprint, the simulated system's higher energy generation capacity translates to greater environmental benefits. Such findings accentuate the importance of a rigorous and optimized design process for solar PV systems, ensuring that they not only meet energy demands but also maximize their positive environmental impact.

## IV. CONCLUSION

This research undertook a rigorous analysis of two standalone solar photovoltaic (PV) systems—one derived through theoretical calculations and the other simulated using PVsyst software. The key metrics for comparison included energy generation capacity, energy storage needs, and CO2 mitigation potential.

1. **Energy Generation**: The calculated system was designed to meet a daily energy demand of 2343 Wh with a solar panel capacity of 1171.5 Wp. In contrast, the simulated system generated 4600 Wh daily with a lower panel capacity of 920 Wp. This represents a 96% increase in daily energy generation from the simulated system.
2. **Energy Storage**: The calculated system required a battery capacity of 781 Ah at 12V, whereas the simulated system effectively used two 155 Ah batteries in series at 24V. This indicates that the simulated system operated effectively with a battery capacity that is approximately 80% lower than the calculated system.
3. **CO2 Mitigation**: Annually, the calculated system could mitigate 342.08 kg of CO2, while the simulated system could mitigate 671.6 kg. This signifies that the simulated system had a 96% higher capacity for CO2 mitigation compared to the calculated system.
4. **Efficiency Metrics**: The simulated system achieved a performance ratio (PR) of 46.4% and a solar fraction (SF) of 97.96%, whereas these metrics were not available for the calculated system due to its theoretical nature.
5. **Economic and Environmental Impact**: The simulated system, by virtue of its higher energy generation and CO2 mitigation capacity, could potentially result in a cost saving of approximately 20% and a CO2 reduction of nearly 100% compared to conventional energy systems relying on fossil fuels.
6. **Advantages of Simulation Software**: The study explicitly demonstrated that using advanced simulation software like PVsyst for system sizing is superior to relying on general thumb rules. Simulated results are based on the synthetic meteorological data of the specific location, providing an optimized and customized solution tailored to the user's needs and local conditions.

In summary, the simulated system outperformed the calculated system in all key metrics—energy generation, energy storage, and CO2 mitigation—by significant margins. These quantitative findings strongly advocate for the utilization of simulation tools in designing solar PV systems that are efficient, site-specific, and environmentally sustainable.

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