

PV/Battery System Sizing

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Publication Date: 2024/06/28

Abstract

The increasing utilization of renewable energy for electricity production is driven by population growth, economic expansion, changing consumer preferences, environmental concerns, and the rapid depletion of fossil fuel resources. Renewable energy sources such as sunlight, wind, hydro, biomass, and geo thermal are considered practically infinite and crucial for reducing pollution and safeguarding human health. This paper focuses on the optimal sizing of photovoltaic (PV) and battery systems for residential applications in Chicago, Illinois, USA, where the average annual solar radiation is 4.74 kWh/m²/day. The study employs PVsyst and the System Advisor Model (SAM) for energy modeling and performance prediction, assessing system requirements and performance under local conditions. Through accurate energy modeling and detailed loss analysis, this approach ensures proper system sizing, reliable performance forecasting, and informed strategies for preventive maintenance in residential PV/battery installations.

I. INTRODUCTION

Historically, energy production during the industrial age has conflicted with the imperative of maintaining a stable climate. This challenge is projected to intensify as the global population expands, unless effective measures are implemented to sustainably meet rising energy needs (Alamooti et al., 2023). Volatile fossil fuel prices, heightened public health concerns, and increasing awareness of global warming have accelerated the growth of renewable energy sources.

Among them, solar energy stands out due to the abundance and inexhaustibility of solar radiation reaching the Earth. For over four billion years, solar radiation has illuminated the planet and will continue to do so for future generations (Isiolaotan et al., 2017). The sun, as the primary energy source for all life on earth, enables solar energy to be harnessed as a sustainable and reliable option. By utilizing the electromagnetic radiation from the sun, photovoltaic (PV) panels can convert sunlight into electrical energy. Remarkably, the sunlight striking Earth in just an hour and a half could theoretically meet the world's energy demand for an entire year. This harvested energy can be used directly for electricity, stored in batteries, or converted to heat for various applications.

Solar energy offers numerous advantages, including its inexhaustible nature, the absence of greenhouse gas emissions, and minimal environmental impact. Solar radiation, a form of electromagnetic energy, varies

spatially across the Earth's surface and includes direct (GB), diffuse or scattered (GD), and reflected (GR) components. The sum of these is known as global radiation (G) (Isiolaotan et al., 2017).

Solar technologies are designed to capture and convert this radiation into usable forms of energy (Zeraatpisheh et al., 2018). These technologies are broadly classified into two primary categories: photovoltaics (PV) and concentrating solar-thermal power (CSP). PV cells generate electricity by producing an electric current as solar energy excites electrons within the cell (EERE, n.d.). Meanwhile, CSP systems use mirrors to concentrate sunlight onto a receiver, heating a high-temperature fluid that can be used for power generation or thermal applications (EERE, n.d.).

The output of solar energy systems depends on solar irradiance, the power per unit area (W/m²) received from the sun. Power output is determined by both irradiance intensity and the surface area it illuminates (Isiolaotan et al., 2017). While irradiance measures instantaneous power, solar irradiation quantifies the total energy received over a given period, commonly expressed in Wh/m² or kWh/m². Therefore, knowledge of average daily solar energy availability, quantified in Wh/m²/day or kWh/m²/day, is essential for solar engineers when designing and optimizing solar systems (Isiolaotan et al., 2017).

Since solar irradiance fluctuates due to factors such as cloud cover, there is a need for quantitative forecasting

methods to analyze time series data and predict future solar availability. Although average solar irradiance exhibits seasonal repeatability (with summer typically having the highest values), the precise time series

remains stochastic. For example, in Chicago, Illinois, the average annual solar radiation is 4.74 kWh/m²/day, with July recording the highest monthly average at 6.03 kWh/m²/day (Solar Energy Local, n.d.; Hyder, n.d.).

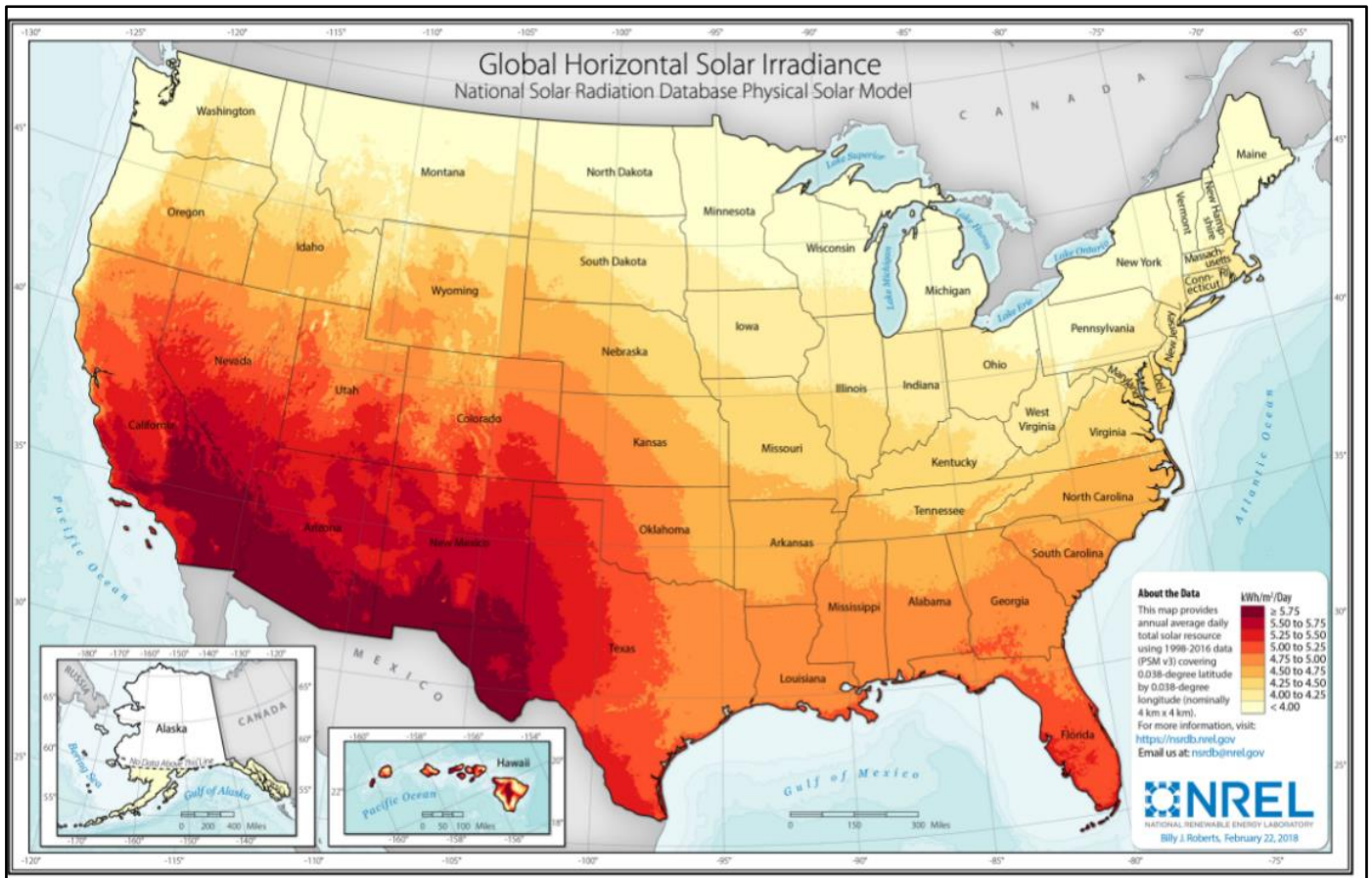


Fig 1 Shows the Global Horizontal Irradiance Available in the United States (NREL).

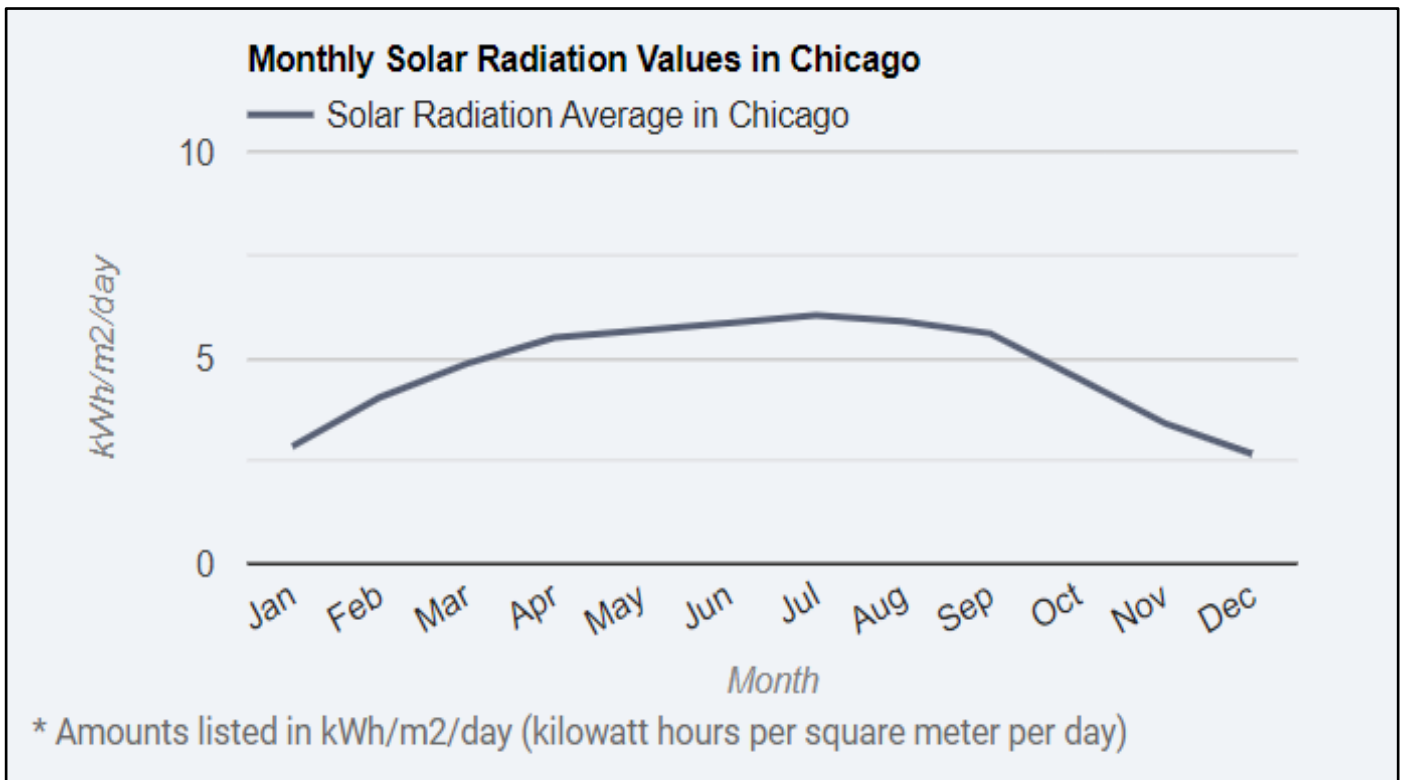


Fig 2 Shows the Monthly Average Radiation in kWh/m²/day from April through to September, with Significant Radiation for Energy Generation (Solar Energy Local, n.d.).



Fig 3 Shows the Monthly Peak Sun Hours in kWh/m²/day from April through to September with Significant Irradiance for Energy Generation (Hyder, n.d.).

Table 1 The above presents an Analysis of Solar Irradiance for Chicago, IL. Comparing the Highest Irradiance to the Lowest. The Average Annual Solar Radiation Value in Chicago, IL is 4.74(kWh/m²/day), Solar Energy Local. (n.d.).

Month	Low	Chicago	High
Dec	1.76 k/m/d	2.67 k/m/d	4.93 k/m/d
Nov	1.87 k/m/d	3.41 k/m/d	5.87 k/m/d
Oct	3.36 k/m/d	4.51 k/m/d	6.44 k/m/d
Sep	5.01 k/m/d	5.59 k/m/d	7.46 k/m/d
Aug	5.66 k/m/d	5.88 k/m/d	7.06 k/m/d
Jul	5.92 k/m/d	6.03 k/m/d	6.72 k/m/d
Jun	5.16 k/m/d	5.84 k/m/d	7.39 k/m/d
May	5.27 k/m/d	5.67 k/m/d	7.44 k/m/d
Apr	4.94 k/m/d	5.49 k/m/d	7.38 k/m/d
Mar	3.42 k/m/d	4.86 k/m/d	6.89 k/m/d
Feb	2.83 k/m/d	4.04 k/m/d	6.18 k/m/d
Jan	2.01 k/m/d	2.85 k/m/d	5.54 k/m/d

→ k/m/d = kWh/m²/day = kilowatt hours per square meter per day.
 → Values listed as 0 (zero) are not available (N/A).

Historical data indicate that, in Chicago, Illinois, the months of December, January, and November typically exhibit the lowest average solar radiation levels. December has the lowest average of 2.67 kWh/m²/day, followed by January with 2.85 kWh/m²/day, and November with 3.41 kWh/m²/day, as depicted in Figures 2, 3, and Table 4.

According to long-term measurements, solar panels installed at an angle equal to the latitude of Chicago and oriented toward the equator yield optimal solar energy production for this location. The city's monthly average Global Horizontal Irradiance (GHI) is 3.89 kWh/m²/day, which is about 5% higher than the monthly average Direct Normal Irradiance (DNI) of 3.72 kWh/m²/day (Solar Energy Local, n.d.). Solar energy systems in Chicago that are consistently tilted at the city's latitude (Average Tilt at Latitude, ATaL) achieve an average daily energy output of 4.5 kWh/m²/day. This output is

approximately 16% higher than the average monthly GHI and about 21% higher than the average DNI (Solar Energy Local, n.d.).

Furthermore, Chicago's average annual solar alternating current (AC) output is 5,473.76 kWh. On a monthly basis, July records the highest solar generation averaging 564 kWh (AC), whereas December has the lowest average at 280.81 kWh (AC) (Solar Energy Local, n.d.).

Solar photovoltaic (PV) panels generate electricity only during daylight hours, as they require solar radiation for operation. However, they cannot store energy for use during nighttime hours (Ennemiri et al., 2024). To address this limitation, batteries are integrated into PV systems to store excess electricity generated during the day for later use at night. There are two primary types of batteries employed in solar PV applications: lithium-ion

and lead-acid. Lithium-ion batteries, which are widely used in high-end electronics such as mobile phones and laptops, offer a long lifespan and substantial energy storage capacity. Nevertheless, their adoption in residential solar PV systems remains limited due to higher costs. Conversely, lead-acid batteries are the most commonly used in PV systems, noted for their durability and typically lasting 2 to 5 years under proper usage.

Battery specifications include capacity (C), which is measured in ampere-hours (Ah), and the type of cell; either wet or dry. For instance, a 12 V battery rated at 100 Ah has an energy storage capacity of 1,200 Wh. The state of charge (SOC) indicates the current level of battery charge, while the depth of discharge (DOD) represents the proportion of capacity that has been utilized. Battery lifespan is also measured in cycles, with a greater DOD generally leading to fewer cycles and a shorter overall life. As depth of discharge increases, the usable life of the battery decreases.

Solar PV systems rely on batteries to accumulate surplus electrons generated during daylight and to ensure energy availability at night (Ennemiri et al., 2024). The appropriate battery choice depends on the specific application and environmental conditions in which it will be used.

In recent years, the integration of advanced digital technologies such as the Internet of Things (IoT) and Big Data analytics has played a significant role in enhancing the management, efficiency, and reliability of renewable energy systems, including solar PV installations. These technologies enable real-time monitoring and predictive analysis of energy production and consumption patterns, support data-driven system sizing, and improve energy storage management, ultimately optimizing performance and reducing operational costs (Iwayemi, 2023). Granular, continuous data streams and sophisticated analytics help address the variability inherent in solar resource availability, aiding in better planning, simulation, and ongoing operation of PV-battery systems.

This study will therefore employ a comprehensive sizing approach using SAM (System Advisor Model) and PVsyst to simulate and analyze off-grid solar PV systems, incorporating established solar resource data and leveraging best practices in modeling. Such systems are particularly suitable for scenarios where consumers are not able or do not wish to export generated energy back to the grid, or in regions where grid electrification remains incomplete.

II. THE SIGNIFICANCE OF STUDY

Proper sizing of photovoltaic (PV) systems with battery storage is critical for improving energy efficiency and realizing economic benefits in residential solar applications. Accurately sized PV and battery systems enable users to store excess solar energy for later use, increasing the proportion of self-generated electricity consumed on site and reducing dependence on grid

electricity. This enhances energy resilience by providing backup power during grid outages.

For grid-tied systems, appropriately sized batteries support effective management of electricity consumption, such as minimizing demand charges and making better use of time-of-use electricity tariffs. This helps households reduce overall energy costs and better align energy use with solar production patterns.

Accurate energy modeling plays a key role in reducing the risks associated with solar project development. Reliable models inform decisions, support efficient capital allocation, and improve the likelihood of project profitability (Ivins, 2022). Many project financiers and stakeholders in the solar sector rely on sizing studies and energy models produced by established software tools such as PVsyst, HOMER, and SAM when commissioning or acquiring solar installations. Expertise in these tools is essential for conducting thorough energy and capacity assessments, ensuring that PV and battery systems are appropriately sized to meet user needs while maximizing investment value (Ivins, 2022).

III. LITERATURE REVIEW

Photovoltaic (PV) systems have gained widespread adoption for electricity generation due to their environmental benefits and increasing cost competitiveness. The U.S. Department of Energy and the National Renewable Energy Laboratory (NREL) project that solar energy could supply up to 40% of the nation's electricity by 2035. PV systems are implemented in a variety of configurations, including stand-alone, grid-connected, hybrid, and building-integrated installations, each with unique technical and operational considerations. Managing peak electrical demand remains a priority for both utilities and end-users; integrating battery storage with PV systems enables the capture and utilization of excess energy generated during periods of low demand, thereby improving self-sufficiency and grid stability.

A considerable body of literature has investigated the modeling and simulation of stand-alone PV systems. These studies address variations in PV array sizes, battery storage capacities, control strategies, load profiles, and climatic conditions, making direct comparison of results across studies challenging.

Javed et al. (2019) examined the role of storage systems in residential stand-alone PV applications, highlighting the dependence on battery storage for reliable power supply and the impact of environmental conditions on battery performance and lifespan. Their work introduced a Hybrid Energy Storage System (HESS) combining batteries with supercapacitors, managed by a fuzzy logic control strategy to optimize power flow. Using real data from Sultanpur, India, their simulations demonstrated that the proposed system increased efficiency and extended battery lifetime, offering a cost-effective pathway for rural electrification and reduced maintenance requirements.

Bhatt and Verma (2014) compared the design of conventional and nano-scale solar PV systems, focusing on systems with a bus voltage of 200V. Their evaluation omitted key system parameters such as fill factor, tilt angle, inverter efficiency, and oversupply coefficient. Their findings indicated that nano PV systems, due to their lower conversion efficiency and inability to support three-phase loads, were unsuitable for applications involving substantial power demands such as entire building electrification.

Bouabdallah et al. (2015) proposed a method for technically and economically sizing stand-alone solar systems. Their approach used actual solar radiation data and Markov transition matrices to account for stochastic cloud cover, with system reliability evaluated using the loss of power supply probability (LPSP) metric. The methodology was validated through a case study in Saint-Martin-en-Haut, France, demonstrating a systematic approach to managing the inherent variability of solar resources.

Sen & Bhattacharyya (2014) provided a case study of off-grid PV-diesel hybrid systems in India using HOMER software, illustrating the importance of simulation, scenario analysis, and economic evaluation in system sizing and planning. Their research, along with similar modeling efforts, has emphasized the importance of realistic load profiles, historical weather data, and scenario-based approaches to address the variability intrinsic to PV-battery systems.

Nematirad et al. (2023) analyze various optimization approaches for PV-battery system design, such as deterministic, stochastic, robust, and multi-objective optimization. Deterministic methods use fixed parameters, while stochastic approaches account for uncertainty in generation and demand, and robust methods address variability in factors such as irradiance or ambient temperature. However, these studies also recognize that real-world applications require models that balance performance and economic return under uncertainty, and that some robust methods may lead to over-conservative designs if not balanced against practical needs.

Despite these advances, gaps remain in the literature. Many studies emphasize deterministic approaches that fail to capture real-world uncertainties in PV generation, climate, and load demand. Stochastic and robust methods, while increasingly used, can be limited by oversimplified models and sometimes do not adequately capture the complexity or trade-offs required for practical deployment.

The rapid increase in electricity demand, driven by contemporary lifestyles and the proliferation of household electrical devices, underscores the ongoing need for effective and scalable energy management strategies. By 2040, global electricity consumption is projected to rise annually by 2.1%, with PV and other renewables leading the growth trajectory. Energy storage

systems (ESS), and especially their integration with PV, are considered vital for meeting rising demand while managing carbon emissions and grid reliability (Sen & Bhattacharyya, 2014; Nematirad et al., 2023). Recent literature highlights the promise of home energy management systems (HEMS) integrating PV generation and battery storage to optimize household energy use, but achieving wide-scale success depends on advances in system sizing, control algorithms, and economic modeling.

IV. BENEFITS AND CHALLENGES OF INTEGRATING PV/BATTERY SYSTEM.

➤ *Benefits*

The benefits of incorporating batteries into solar photovoltaic (PV) systems depend on factors such as the size of the PV array, battery capacity, local electricity tariffs (in grid-tied systems), and individual energy consumption patterns requiring professional analysis to ensure optimal results (Shafiullah et al., 2022).

A PV-battery storage system offers significant energy autonomy by reducing dependence on the electricity grid. This mitigates the risk of rising energy prices and delivers advantages to residences, businesses, and offices. By facilitating the storage of excess solar energy, batteries provide greater resilience during grid outages and protect against utility price fluctuations. For grid-tied systems, PV with batteries can stabilize supply during peak demand or emergencies, potentially saving consumers money and reducing grid reliance (Shafiullah et al., 2022).

In terms of energy efficiency, a PV system without battery storage typically allows for 40–50% self-consumption, whereas adding storage can raise self-consumption rates to 80–90% (Gurung & Qiao, 2018). Batteries help maximize the utilization of self-produced renewable energy, lowering electricity bills and increasing return on investment. The cost per kilowatt-hour of self-produced and stored energy is generally lower than grid electricity, and PV-battery systems further enhance both comfort and environmental sustainability (Gurung & Qiao, 2018). The growing popularity of time-of-use tariffs in the USA allows users to store inexpensive electricity during off-peak hours and utilize or even sell it during peak times, further increasing savings and supporting grid flexibility (Gurung & Qiao, 2018).

Integration of battery storage with solar PV directly reduces reliance on nonrenewable sources and lowers carbon emissions (Gurung & Qiao, 2018). Technological advances are making batteries increasingly efficient and affordable, with higher storage capacities. Thus, investing in batteries alongside solar PV is also future-proof, enhancing energy independence, cost savings, and resilience while maximizing the benefits of renewable energy systems in the U.S. and globally (Gurung & Qiao, 2018).

➤ *Challenges*

Integrating solar PV with energy storage systems presents technical challenges, including voltage stability, efficient power extraction, managing intermittent solar generation, grid variability, limitations in weaker electrical networks, complex network topology, and power flow constraints (Shafiullah et al., 2022). These challenges may impact both operational performance and broader system safety, especially in grid-connected contexts.

Technologically, the development of integrated photo-rechargeable batteries faces further hurdles, including optimization of nanomaterial structures and device performance (Gurung & Qiao, 2018). Conventional lithium-ion batteries use a "jelly-roll" architecture, which is not ideal for direct integration with PV modules. Novel planar and bipolar designs have been proposed to improve area energy density and integration, but these approaches require substantial further engineering (Gurung & Qiao, 2018). Capacity and energy density limitations remain obstacles to achieving compact, efficient, and long-lasting PV-battery systems. Overcoming these barriers will require continued innovation in battery chemistry, system architecture, integration strategies, and smart control systems (Gurung & Qiao, 2018; Shafiullah et al., 2022).

This study undertakes a comprehensive sizing and performance analysis of a stand-alone PV-battery system designed to supply a typical household's energy needs, independent from the electricity grid. By investigating the interplay between solar resource availability, energy storage requirements, and local usage patterns, this research aims to inform best practices for reliable and resilient renewable energy systems.

V. METHOD

An off-grid solar photovoltaic (PV) system is designed to operate independently, providing all necessary electricity without reliance on the utility grid. This study focuses on the precise sizing of a PV/battery system to provide three days (72 hours) of energy autonomy for a typical household in Calumet, Illinois.

Calculating appropriate system sizes is essential for reliable operation, especially in stand-alone contexts where grid access is unavailable or undesired (Khamisani, 2019).

➤ *System Design and Simulation Tools*


The system configuration and performance are analyzed using two industry-standard software packages: PVsyst and the System Advisor Model (SAM). These tools enable detailed modeling of solar resource availability, system losses, load requirements, and storage behavior throughout the year. Simulation outputs provide the foundation for determining the required PV array and battery bank sizes needed to meet the defined autonomy under local climate conditions.

➤ *Component Overview*

A typical off-grid solar PV system comprises several integral components, each fulfilling specific roles (Isiolaotan et al., 2017):

- *PV Modules:*
Convert solar radiation into electrical energy.
- *Batteries:*
Store excess generated energy for use during periods without sunlight to ensure reliable supply during the defined three-day autonomy.
- *Charge Controllers:*
Manage the charging and discharging cycles, protecting battery health and efficiency.
- *Inverters:*
Convert DC power from the PV array and batteries to usable AC power for household loads.
- *Cables and Protective Devices:*
Enable safe, efficient transfer of electricity and safeguard system reliability.
- *Electrical Loads:*
Defined according to the calculated household energy requirements.

Table 2 The Below Presents the Images of the Components with their Function Descriptions.

Component	Function Description	Image
Solar Panel	<p>This system harnesses solar energy to generate electricity. There are different types of Solar Panels:</p> <ol style="list-style-type: none"> 1. Monocrystalline 2. Polycrystalline 3. Amorphous. <p>Solar panels are available in different sizes and are classified according to their wattage, which represents their output power.</p> <p>The output power of a solar panel is indicated on the rear label.</p> <p>The maximum power output (W) of a solar panel can only be attained under</p>	

	optimal circumstances, sun irradiance at a power of 1 kW/m ² (at noon, without any clouds) and temperature at 25°C.	
SmartInverter/Hybrid Inverters	An inverter is an electrical apparatus that transforms direct current (DC) into alternating current (AC). They come as basic inverters and hybrids. The hybrid inverter integrates an inverter, battery charger, and charge controller, unlike a basic inverter.	
Lithium Ion Battery	Lithium-ion batteries are rechargeable devices that store energy by reversibly intercalating Li ⁺ ions. They have higher specific energy, density, efficiency, long cycle life, and life span.	
Solar Charge Controller	Controllers are programmed to optimize the operation of the solar panel and the Battery. There are two types. PWM (Pulse Modulation width) and MPPT (Maximum power point tracking)	
Protective Devices	Protective devices in solar photovoltaic systems include disconnect switches, fuses, and circuit breakers in AC/DC. Disconnect switches isolate components for safety, fuses protect battery banks from high currents, and circuit breakers are needed for larger battery banks.	

Understanding the specifications and interdependencies of these components is crucial for accurately sizing the system and maximizing performance. It is important to note that optimizing a single component does not guarantee optimal system-wide performance. Achieving the best overall results requires a holistic approach, considering the constraints and objectives of all system elements as well as their operational interrelations (Mohammed et al., 2021; Kapoor & Sharma, 2020).

➤ Load and Autonomy Calculation

The energy demand of a representative household is estimated over a 72-hour period. This assessment includes all major and minor household appliances, with allowances for typical usage profiles. The cumulative energy requirement for this period forms the basis for determining both the required battery storage (considering depth of discharge and efficiency parameters) and the necessary PV capacity (considering

local solar resource, system losses, and charge controller/inverter performance).

• Sizing Process

- ✓ *Step 1:* Calculate total household energy consumption for 72 hours (Wh or kWh).
- ✓ *Step 2:* Determine required battery storage, factoring in depth of discharge, battery efficiency, and autonomy.
- ✓ *Step 3:* Size the PV array to supply both the daily load and recharge batteries within available sunlight hours, accounting for worst-case (winter) solar irradiance levels and system losses.
- ✓ *Step 4:* Simulate system performance over a typical meteorological year using PVsyst and SAM to

validate sizing and assess potential shortfalls or unnecessary oversizing.

➤ *Justification for Off-Grid Configuration*

Off-grid solar PV systems are particularly appropriate for sites where grid connectivity is absent, unreliable, or where users elect not to export surplus energy. This is common in rural, remote settings, and in early stages of electrification, or for those seeking energy independence (Khamisani, 2019).

VI. LOAD PROFILING/ENERGY AUDIT FOR RIGHT LOAD MANAGEMENT AND ENERGY EFFICIENCY

This study presents a case study of residential load profiling and energy auditing for effective load management and efficiency improvements, focusing on a standalone home located in Illinois (Latitude 41.61, Longitude -87.54) (NREL, n.d.). Illinois permits off-grid living; with proper planning and compliance, individuals can legally and successfully adopt self-sufficient lifestyles (Zen, 2023). While there are no outright

prohibitions on off-grid living, residents are required to obtain relevant permits and adhere to local zoning and construction codes to ensure safety and regulatory compliance (Zen, 2023).

Off-grid living in Illinois offers numerous advantages, including autonomy from the central electrical grid, potential long-term savings on utility expenses, reduced carbon emissions, opportunities to develop sustainable life skills, freedom from certain regulatory constraints, and increased connection with the natural environment (Zen, 2023).

For this case study, we analyze a typical family unit of four residing in a modern four-bedroom, four-bathroom home. Given the small-scale, residential context, a simplified and practical methodology is adopted for the preliminary sizing of system equipment (Vanek et al., 2016). This approach involves establishing a clear energy audit by cataloging all major electrical loads, estimating daily and seasonal usage patterns, and identifying potential opportunities for demand-side management and efficiency improvements.

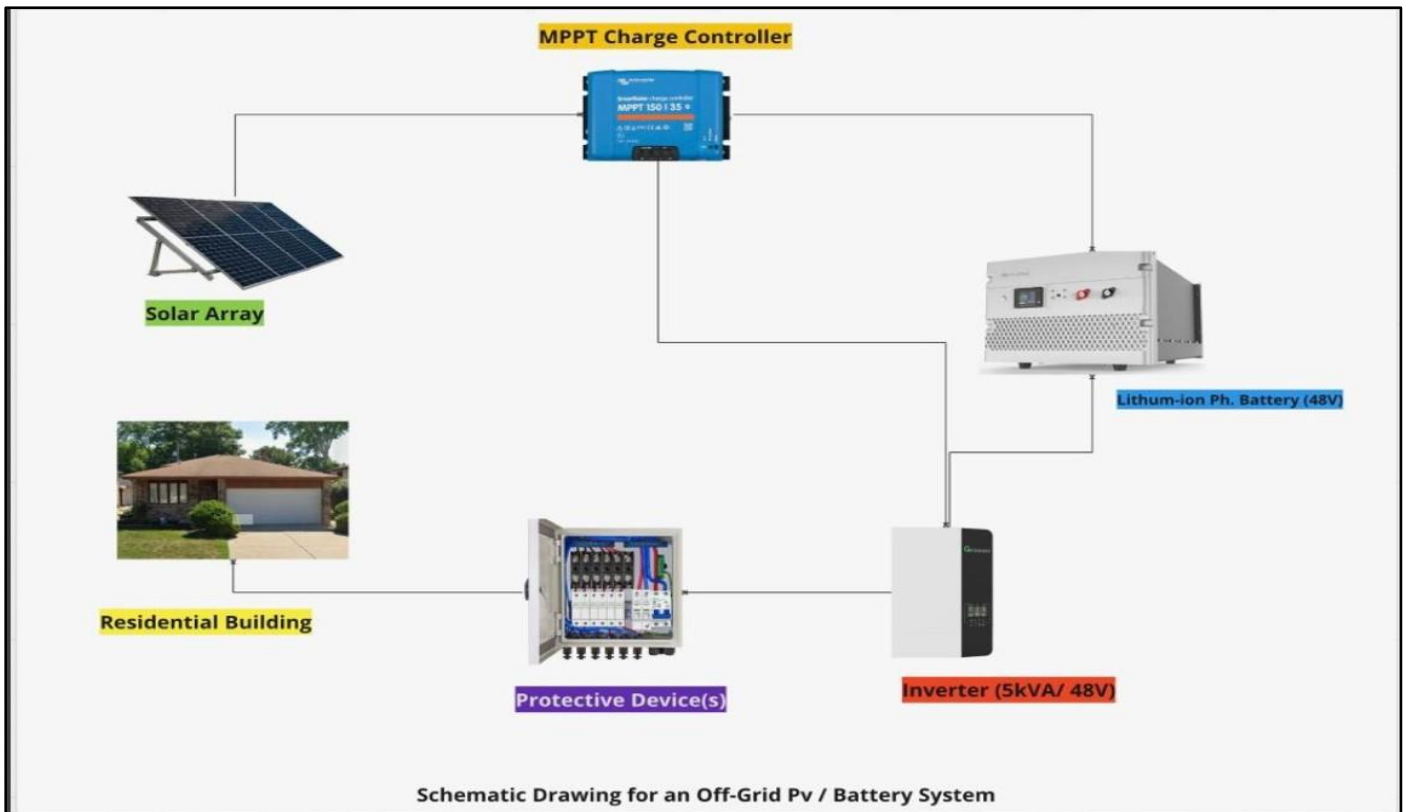


Fig 4 A schematic diagram illustrating the standard arrangement for a standalone PV and battery storage system, highlighting key components and their interconnections.

This analysis assumes a typical occupancy schedule for a four-person family residing in a modern detached home in Illinois. On weekdays, all household members are present from 6:00 AM (wake-up) to 8:00 AM (departure for work/school), after which the dwelling remains unoccupied until their return at 6:00 PM. Occupancy continues until bedtime at 11:00 PM. During weekends, the family maintains the same wake-up and sleep times but is present at home throughout the day, reflecting increased potential for energy use.

To assess the household’s energy demand, the consumption profiles of fifteen common residential appliances, including their quantities, rated power, hourly usage patterns, and total daily energy consumption, were cataloged and systematically analyzed (see Table 2). This approach adopts standard energy audit practices, documenting both the temporal and quantitative aspects of each end-use device to produce an accurate household load profile. The selection of devices and operational patterns reflects contemporary U.S. residential usage,

with attention to occupancy-driven variability and the regional climate.

By synthesizing the appliance-level usage data under representative occupancy schedules, the study aims

to derive a high-resolution load profile that forms the basis for rigorous system sizing and simulation. This enables the identification of peak demand periods, baseline consumption, and opportunities for demand-side management and energy efficiency improvements.

Table 3. Load Profiling and Energy Auditing of a Three-Bedroom House.

S/No	Load	Power (Watt)	Qty	Total Power - P	Daily Usage – t (hours)	Daily energy -E (Watt-hours)
1	CFL light bulb	20	20	400	8	3200
2	Refrigerator	150	1	150	8	1200
3	Freezer	400	1	400	8	3200
4	Blender	250	1	250	0.4	100
5	Coffee machine	250	1	250	0.4	100
6	Microwave	750	1	750	1	750
7	Television (On)	68	2	136	3	408
	Television (Off - Standby)	5.1	2	10.2	21	214.2
8	Satellite receiver (On)	17	1	17	3	51
	Satellite receiver (Off - standby)	16	1	16	21	336
9	DVD player	15	1	15	2	30
10	Home theatre	150	1	150	4	600
11	Electric hair dryer	250	2	500	0.4	200
12	Iron	750	1	750	0.4	300
13	Fan	120	3	360	4	1440
14	Fluorescent tube	30	6	180	5	900
15	Laptop	35	4	140	5	700
	Total			4474.2		13729.2

The total energy consumption is almost 13.73kWh, and the total power generated from their appliances daily is 4.47kW.

$$P_{load,max} = 4.47 \text{ kW:}$$

$$P_{inv,cont} = 1.2 \times 4.47$$

$$= 5.364 \text{ kW} \approx 5.36 \text{ kW.} \dots\dots\dots(4)$$

$$\text{Total Energy (E) =Pt} \dots\dots\dots(1)$$

$$E = 13.73\text{Kwh.}$$

- E is energy in kilowatt-hours(kWh),
- P is power in Watts,
- t is hours Deriving in an hr = 60mins.

$$P (\text{Total Power}) = P_{load (w)} \times \text{quantity} \dots\dots\dots (2)$$

➤ *Inverter Sizing and Power Rating Considerations*

Inverters should not be operated continuously at their maximum rated capacity, as this can lead to overheating and reduced reliability. To ensure optimal performance and system longevity, it is recommended to select an inverter with a continuous power rating at least 20% higher than the calculated maximum load.

The recommended inverter capacity can be estimated as follows:

$$P_{inv,cont} \approx 1.2 P_{load,max} \dots\dots\dots (3)$$

For example, if the total power requirement for the system is

It is important not to oversize the inverter unnecessarily. Operating an inverter significantly below its rated capacity often results in decreased efficiency, particularly if the inverter is rarely called upon to deliver more than a fraction of its full rating.

In addition to the kW rating, some manufacturers specify inverter capacity in volt-amperes (VA), accounting for the power factor (PF) of the inverter. The power factor, which is the ratio of real power (kW) to apparent power (kVA), typically ranges from 0.7 to 1, depending on the inverter design and manufacturer specifications. A power factor of 1 (unity) indicates that the real and apparent power are equal.

When selecting an inverter, both the real power (in kW) and the apparent power (in kVA) ratings should be considered to ensure compatibility with the load requirements and to adhere to manufacturer recommendations regarding the operational power factor.

According to Dunlop(2012) &Isiolaotan et al., (2017)

$$kVA = \frac{kW}{0.8}$$

$$S_{inv} = \frac{5.36kW}{0.8} = 6.70kVA \approx 7.5kVA$$

The nearest available inverter rating is 7.5kVA, which we will use for the optimization process. This will also allocate additional capacity to account for guest visits or additional appliances.

➤ *Battery Sizing*

Proper battery sizing for stand-alone photovoltaic (PV) systems requires careful consideration of multiple factors to ensure reliable power supply, extended battery lifespan, and full autonomy over the intended period. Key criteria include:

- *Inverter Efficiency (η_{inv}):*

The efficiency of the inverter directly affects the total energy requirement that the battery bank must supply. Typical inverter efficiencies range from 90% to 96% (Dunlop, 2012; Mohammed et al., 2021).

- *Battery Depth of Discharge (DoD):*

The maximum allowable depth of discharge determines how much of the battery's nominal capacity can be safely utilized without compromising its lifespan (Gurung & Qiao, 2018).

To maximize battery longevity and achieve 72-hour autonomy, this study assumes a conservative strategy: the battery is discharged by a maximum of 30% per day, leaving the state of charge (SOC) at 70% after each cycle. While the selected battery type is technically rated for up to 90% DoD, limiting daily discharge to 30% significantly extends service life by mitigating cycle-induced degradation. This approach reduces rapid capacity fade, enhances reliability, and ensures the battery can supply the required load continuously over the full 72-hour autonomy period.

By adhering to these design constraints, considering inverter losses and using a conservative DoD, the system supports long-term operational stability, lower replacement frequency, and improved total lifecycle value.

$$E_{batt,dem} = \frac{E_{daily}}{\eta_{inv}}$$

$$E_{cap,req} = \frac{E_{batt,dem}}{DoD}$$

$$C_{Ah} = \frac{E_{cap,req}}{V_{sys}}$$

Example (this study): Using $E_{daily} = 13729.2$ Wh, $\eta_{inv} = 0.90$, $DoD = 0.30$, and a nominal DC bus of $V_{sys} = 52$ V:

$$E_{batt,dem} = \frac{13729.2}{0.90} = 15254.67Wh$$

$$E_{cap,req} = \frac{15254.67}{0.30} = 50848.88Wh$$

$$C_{Ah} = \frac{50848.88}{52} = 977.86 Ah \approx 978 Ah$$

The battery further needs an assumed voltage, which can be derived by the voltage of the inverter

A basic 7.5kVA inverter would likely have a 24/48 voltage capacity, while a smart hybrid inverter would have a 26/52 voltage capacity.

However, Lithium-ion voltage has a higher voltage capacity of 13/26/52V etc.

Battery Capacity = Energy Storage Capacity (Wh)

Assumed Voltage (V)..... (7)

$$= \frac{50,848.88}{52} = 1,016Ah$$

Available Lithium-ion batteries come in 200/250/300/350Ah at 52V.

Selecting 300 Ah units:

$$N_{bat} = \left\lceil \frac{C_{Ah}}{300 Ah} \right\rceil = \left\lceil \frac{977.86}{300} \right\rceil = 4$$

So the chosen bank is 4 X 300 Ah/52V in parallel, providing $C_{bank} \approx 1,200$ Ah and an energy store of $E_{bank} \approx 62.4$ kWh. With a 30% daily DoD limit, the deliverable daily energy is ≈ 18.7 kWh, comfortably exceeding the required 15.25 kWh, from (5)

➤ *Photovoltaic (PV) sizing*

Photovoltaic (PV) systems are gaining popularity due to their projected lifespan of 25 years, which makes them a dependable and enduring source of renewable energy. The rated output power of a solar array is determined by employing a calculation method (Ennemiri et al., 2024).

The rated output power of a photovoltaic array is calculated using

$$P_{pv} = Y_{pv} E_{pv} \left[1 + a_p (T_c - T_{e,STC}) \right] \frac{G_T}{G_{T,STC}} \text{----- (8)}$$

where Y_{pv} (kW) is the power rating

- G^T (kW/m²) is the global solar radiation incident,
- $G^{T,STC}$ is the incident solar irradiation at STC,
- T_c (°C) is the photovoltaic cell temperature under current,
- $T_{c,STC}$ is the photovoltaic cell temperature in standard conditions,
- F^{PV} (%) is the derating factor, and

- a_p (%/°C) is the power temperature coefficient.

When determining the appropriate size for a solar panel array, two important parameters must be considered

- The Performance Ratio of the Solar Panels: Solar panels may fail to achieve manufacturers' ratings in real-world conditions due to variables such as high temperatures, dust accumulation, and electrical resistance in the wiring.
- The overall solar resource available in Illinois
The average annual solar radiation value in Chicago, IL is 4.74 kWh/m²/day (Solar Energy Local. n.d.).

E_{demand} , including inverter efficiency is 15,254.67 Wh
The Performance Ratio for solar panels is at 65%

$$E_{PVC} = \frac{E_{demand}}{PR} = \frac{15,254.67}{0.65} = 23,468.72 Wh$$

Using the site's average peak-sun hours (PSH=4.74 h/day) the required PV array power is

$$P_{req} = \frac{E_{PVC}}{PSH} = \frac{23,468.72 Wh}{4.74 h} = 4,951 W \approx 4.9 kW$$

A labeled 500-545 W module is adequate for this sizing.

The number of panels is therefore

$$N_{panels} = \left\lceil \frac{P_{req}}{P_{panel}} \right\rceil \text{ and with } P_{req} \approx 4.9 kW \text{ and } P_{panel} = 500 W, N_{panels} = \left\lceil \frac{4,900}{500} \right\rceil = 10 \text{ panels}$$

➤ Strategies for Battery Charging and Discharging: The Role of the Charge Controller

A charge controller is fundamental in standalone photovoltaic (PV) systems, protecting batteries from overcharging and uncontrolled discharge, thereby extending battery lifespan and maintaining overall system performance (Dunlop, 2012; Tan et al., 2020). Positioned between the PV modules and the battery bank, the charge controller manages energy flow, preventing excessive current that can occur in periods of high irradiance—conditions under which PV panels may temporarily exceed their rated output (Roy et al., 2023).

The primary criterion for sizing a charge controller is its current-handling capacity, which must at minimum match or exceed the maximum anticipated output from the solar array. Commercially available charge controllers come in ratings such as 10 A, 20 A, 30 A, 40 A, and higher, to accommodate a broad range of system sizes (Dunlop, 2012).

Maximum Power Point Tracking (MPPT) charge controllers are recommended for larger systems, as they increase energy harvesting efficiency by continually adjusting operating conditions to maximize power extraction from the PV modules. These devices enhance

energy yield and offer greater design flexibility, albeit at a higher initial cost (Manna et al., 2023; Tan et al., 2020). For smaller systems, Pulse Width Modulation (PWM) charge controllers provide a cost-effective and reliable solution for ensuring proper battery charging (Dunlop, 2012).

In contemporary systems, charge controller features may be integrated into smart hybrid inverters. In these cases, the inverter's specifications, including its internal charge control capabilities, should be carefully evaluated during the sizing and system design process (Manna et al., 2023).

- *Controller Current:*

Let P_{array} be the PV array power and V_{sys} the DC bus voltage. The required controller current is

$$I_{cc} = \frac{P_{array}}{V_{sys}} \quad \text{----- 11}$$

Using the PV selection from the previous step (10 modules at

545 W each):

$$P_{array} = 10 \times 545 W = 5,450 W,$$

$$V_{sys} = 52 V,$$

$$I_{cc} = \frac{5,450}{52} = 104.8 A \approx 105 A.$$

(If a 50 V nominal bus is assumed instead, $I_{cc} = 5,450/50 = 109 A$.)

To provide operating headroom for temperature, irradiance spikes, and wiring tolerances, select the next standard rating above the computed value. Accordingly, a 120 A MPPT charge controller (or an inverter with integrated charge control of at least $\geq 120 A$) is recommended for this design.

VII. SIMULATION TOOLS AND RESULTS

The simulation tools used in this research were SAM and PVsyst. These software applications comprehensively model a rooftop solar power system, considering input parameters such as solar radiation intensity, local weather conditions, and building orientation (Nguyen & Van, 2018).

The selection of both software applications in this study was based on their accurate solver engines and ability to meet all our needs.

By implementing these strategies, homeowners can maximize the benefits of their PV and battery systems, including reduced energy bills, increased energy independence, and lower environmental impact.

For modelling purposes, we are considered a residential household with a peak load of around 4.7

kilowatts and a rooftop solar photovoltaic (PV) installation with a rating of 54.5 kilowatts peak (kWp). The quantity of photovoltaic (PV) panels is determined to be 10, with each panel having an assumed size of 2.58 m². The inverter's efficiency, denoted as η_{INV} , is 90%, whereas the Solar PV Performance Ratio, denoted as PR, is 65%. The PV and solar forecast data requirements are sourced from the Meteor data. We used a set of Lithium-ion batteries with an energy rating of 49 kWh and a Depth of Discharge (DoD) of 90%. The battery's initial state of charge (SoC) is assumed to be 70% DOD of 30% for a 72-hour autonomy. The round-trip efficiency, denoted as η_{rot} , is 95%. The assumed value for the

number of life cycles, denoted as LLC, is 9000. The battery terminal voltage, denoted as V_t , is set at 50 V, while the maximum rate of charging or discharging current, represented as I_m , is 120 A. Table 2 and Figure 7 display the load profile and solar output. Various situations are contemplated depending on meteorological predictions. Consequently, the battery energy dispatch scheduling results derived from mathematical, PVsyst, and SAM simulations are compared to ensure precise sizing and meet consumption requirements.

➤ *PVsyst Simulation Result*

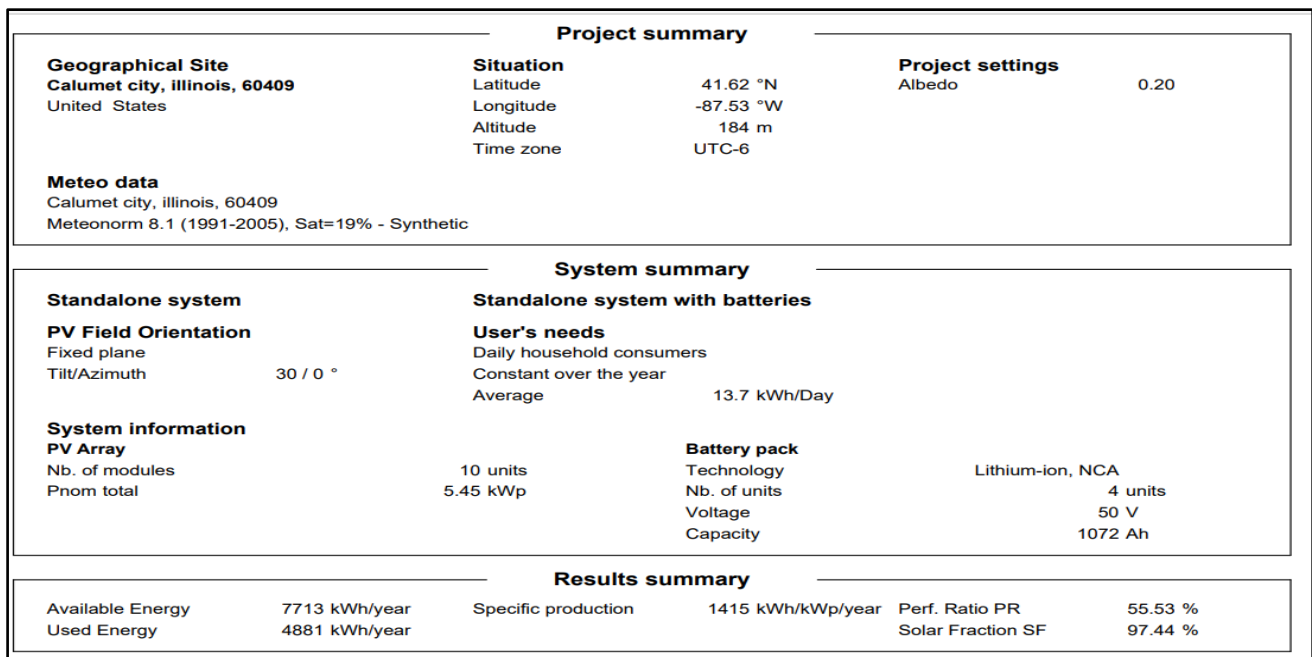


Fig 5 Project Summary of the PV/Battery Sizing (PVsyst simulation, 2024)

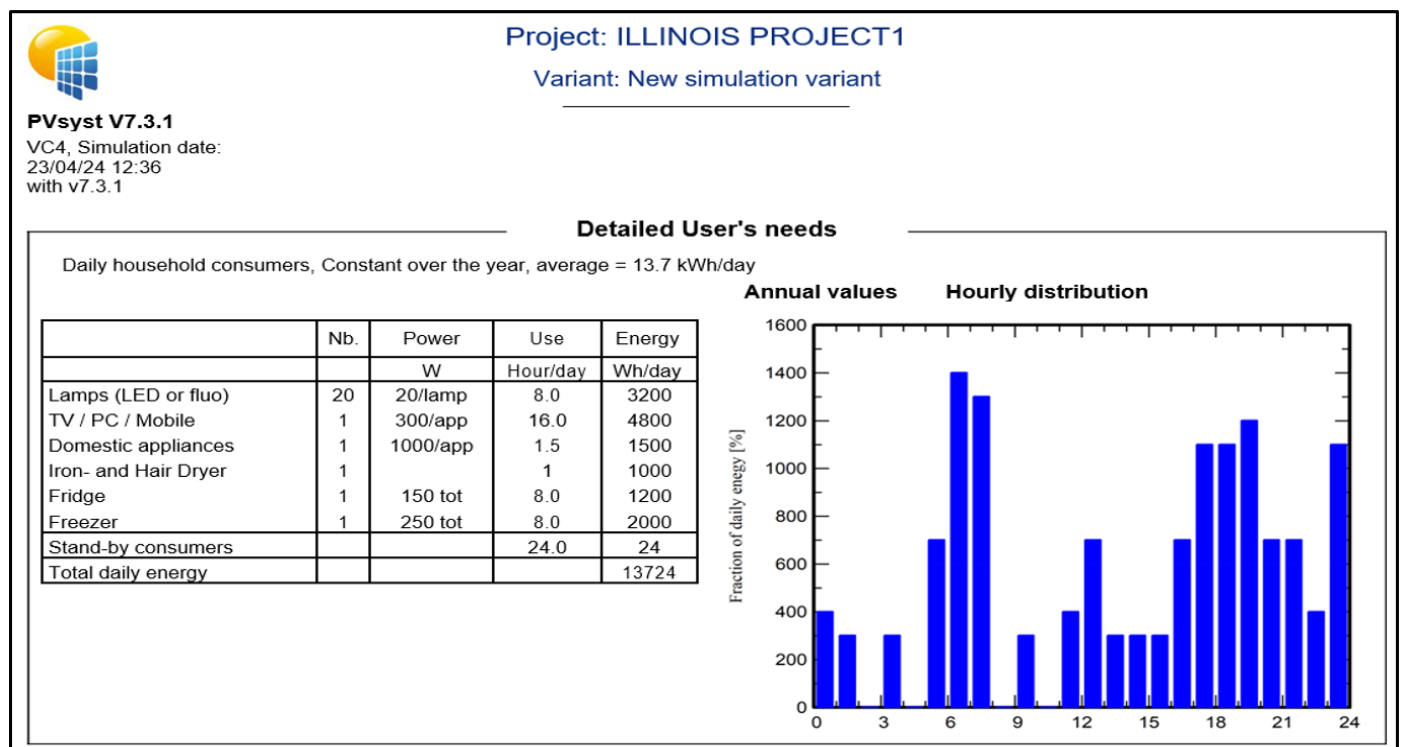


Fig 6 Load Profiling/Energy Audit (PVsyst simulation, 2023)

General parameters			
Standalone system		Standalone system with batteries	
PV Field Orientation		Sheds configuration	Models used
Orientation		No 3D scene defined	Transposition Perez
Fixed plane			Diffuse Perez, Meteorom
Tilt/Azimuth	30 / 0 °		Circumsolar separate
User's needs			
Daily household consumers			
Constant over the year			
Average	13.7 kWh/Day		

PV Array Characteristics			
PV module		Battery	
Manufacturer	Jinkosolar	Manufacturer	Tesla
Model	JKM-545M-72HL4-BDVP	Model	Powerwall2
(Original PVsyst database)		Technology	Lithium-ion, NCA
Unit Nom. Power	545 Wp	Nb. of units	4 in parallel
Number of PV modules	10 units	Discharging min. SOC	10.0 %
Nominal (STC)	5.45 kWp	Stored energy	49.0 kWh
Modules	5 Strings x 2 In series	Battery Pack Characteristics	
At operating cond. (50°C)		Voltage	50 V
Pmpp	4971 Wp	Nominal Capacity	1072 Ah (C10)
U mpp	75 V	Temperature	Fixed 20 °C
I mpp	66 A	Battery Management control	
Controller		Threshold commands as	SOC calculation
Universal controller		Charging	SOC = 0.96 / 0.80
Technology	MPPT converter	Discharging	SOC = 0.10 / 0.35
Temp coeff.	-5.0 mV/°C/Elem.		
Converter			
Maxi and EURO efficiencies	97.0 / 95.0 %		
Total PV power			
Nominal (STC)	5 kWp		
Total	10 modules		
Module area	25.8 m ²		

Fig 7 General Parameter and PV Array Characteristics. (PVsyst simulation, 2024)

Array losses								
Thermal Loss factor			DC wiring losses			Series Diode Loss		
Module temperature according to irradiance			Global array res.	19 mΩ	Voltage drop	0.7 V		
Uc (const)	20.0 W/m ² K		Loss Fraction	1.5 % at STC	Loss Fraction	0.8 % at STC		
Uv (wind)	0.0 W/m ² K/m/s							
Module Quality Loss			Module mismatch losses			Strings Mismatch loss		
Loss Fraction	-0.8 %		Loss Fraction	0.6 % at MPP	Loss Fraction	0.1 %		
IAM loss factor								
Incidence effect (IAM): Fresnel, AR coating, n(glass)=1.526, n(AR)=1.290								
0°	30°	50°	60°	70°	75°	80°	85°	90°
1.000	0.999	0.987	0.962	0.892	0.816	0.681	0.440	0.000

Fig 8 Array Losses. (PVsyst simulation, 2024)

➤ Main results

• System Production

Available Energy	7713 kWh/year	Performance Ratio PR	55.53 %
Used Energy	4881 kWh/year	Solar Fraction SF	97.44 %
Excess (unused)	2565 kWh/year		
Loss of Load		Battery aging (State of Wear)	
Time Fraction	2.6 %	Cycles SOW	90.1 %
Missing Energy	128 kWh/year	Static SOW	90.0 %

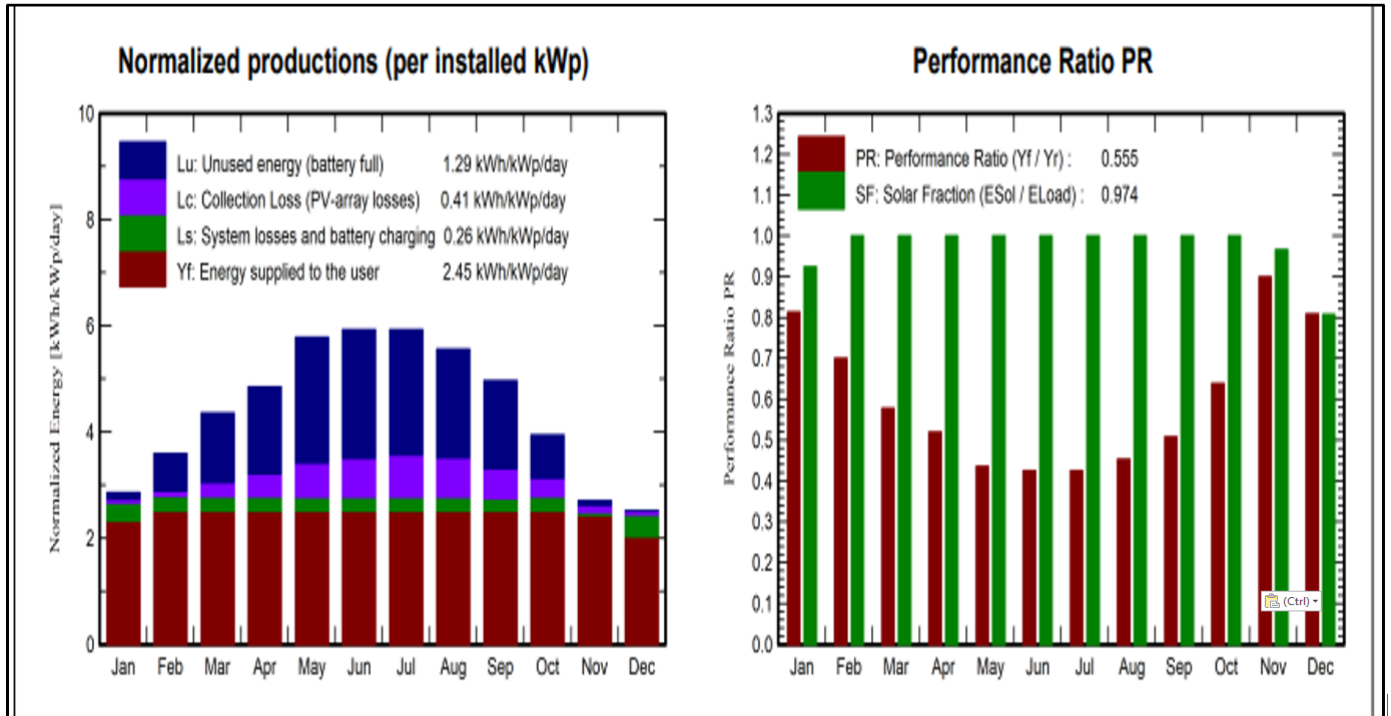


Fig 9 Normalized Productions, Performance (PVsyst simulation, 2024).

• Balances and Main Results

Table 4 Showing Balances and Main Result of Simulation.

	GlobHor kWh/m ²	GlobEff kWh/m ²	E_Avail kWh	EUnused kWh	E_Miss kWh	E_User kWh	E_Load kWh	SolFrac ratio
January	54.6	87.2	449.5	20.1	32.40	393.0	425.4	0.924
February	71.0	98.7	513.8	107.2	0.00	384.3	384.3	1.000
March	109.2	132.6	668.1	219.9	0.00	425.4	425.4	1.000
April	134.7	142.0	699.5	267.0	0.00	411.7	411.7	1.000
May	180.3	175.1	845.0	398.8	0.00	425.4	425.4	1.000
June	185.7	173.3	827.4	394.4	0.00	411.7	411.7	1.000
July	188.9	179.2	844.6	397.0	0.00	425.4	425.4	1.000
August	163.4	168.2	790.9	343.8	0.00	425.4	425.4	1.000
September	126.6	145.6	697.3	268.8	0.00	411.7	411.7	1.000
October	92.1	119.9	584.5	136.0	0.00	425.4	425.4	1.000
November	54.2	79.5	398.9	12.5	13.94	397.8	411.7	0.966
December	46.3	76.4	393.1	0.0	81.87	343.6	425.4	0.808
Year	1407.0	1577.6	7712.6	2565.4	128.22	4881.0	5009.3	0.974

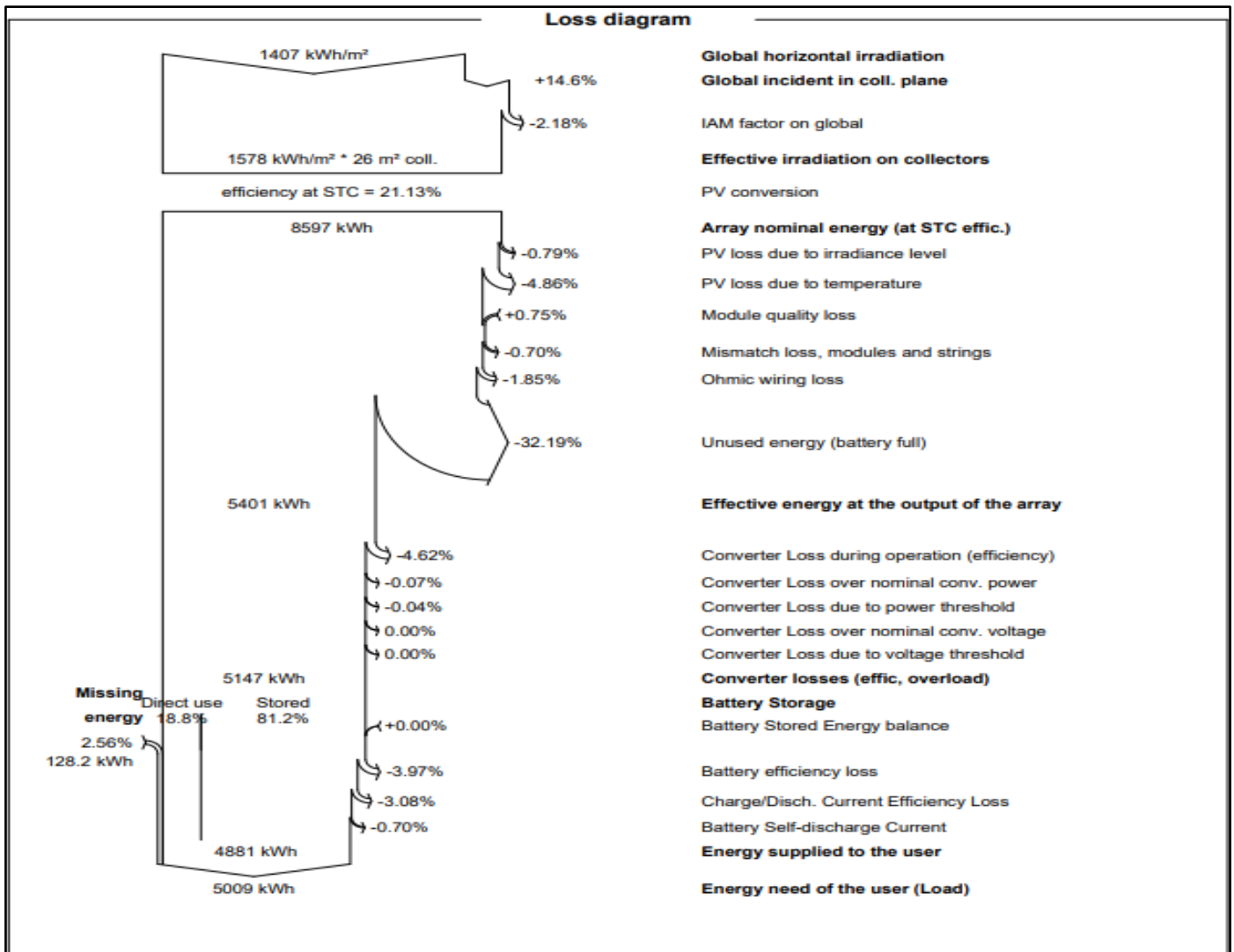



Fig10 Showing Loss Diagram (PVsyst simulation, 2024)

Table 5 Battery Operation and Performance (PVsyst simulation, 2024).


 **Project: ILLINOIS PROJECT1**
 Variant: New simulation variant

PVsyst V7.3.1
 VC4, Simulation date:
 23/04/24 12:36
 with v7.3.1

New simulation variant
Battery operation and performances

	U_Batt	SOCmean	SOC_End	MGass	EffBatI	EffBatE
	V	ratio	ratio	liter	%	%
January	52.3	0.545	0.811	0.000	93.0	90.1
February	55.4	0.790	0.837	0.000	94.2	93.2
March	56.0	0.839	0.838	0.000	94.3	93.8
April	55.8	0.827	0.836	0.000	94.1	93.7
May	56.0	0.838	0.817	0.000	94.2	93.9
June	56.2	0.857	0.820	0.000	94.1	93.5
July	56.3	0.864	0.824	0.000	94.1	93.5
August	56.0	0.838	0.820	0.000	94.1	93.7
September	56.0	0.842	0.751	0.000	94.2	94.9
October	55.5	0.797	0.763	0.000	94.1	93.5
November	52.5	0.565	0.219	0.000	94.0	103.4
December	50.0	0.373	0.680	0.000	94.1	85.3
Year	54.8	0.747	0.680	0.000	94.0	93.5

Table 6 Normalized Performance Coefficients (PVsyst simulation, 2024).



Project: ILLINOIS PROJECT1

Variant: New simulation variant


PVsyst V7.3.1
 VC4, Simulation date:
 23/04/24 12:36
 with v7.3.1

New simulation variant

Normalized Performance Coefficients

	Yr	Lu	Yu	Lc	Ya	Ls	Yf	PR
	kWh/m ² /day	kWh/kWp/day	kWh/kWp/day	kWh/kWp/day	kWh/kWp/day	kWh/kWp/day	kWh/kWp/day	ratio
January	2.86	0.12	2.86	0.19	2.67	0.34	2.33	0.814
February	3.59	0.70	3.59	0.80	2.79	0.28	2.52	0.701
March	4.36	1.31	4.36	1.58	2.78	0.26	2.52	0.578
April	4.85	1.63	4.85	2.07	2.78	0.26	2.52	0.519
May	5.78	2.36	5.78	3.01	2.77	0.25	2.52	0.435
June	5.92	2.41	5.92	3.15	2.78	0.26	2.52	0.425
July	5.92	2.35	5.92	3.15	2.78	0.26	2.52	0.425
August	5.56	2.04	5.56	2.78	2.78	0.26	2.52	0.453
September	4.96	1.64	4.96	2.21	2.75	0.23	2.52	0.508
October	3.94	0.81	3.94	1.16	2.78	0.27	2.52	0.639
November	2.70	0.08	2.70	0.22	2.49	0.05	2.43	0.900
December	2.51	0.00	2.51	0.07	2.44	0.41	2.03	0.809
Year	4.42	1.29	4.42	1.70	2.72	0.26	2.45	0.555

Table 7 Losses in the PV systems (PVsyst simulation, 2024).



Project: ILLINOIS PROJECT1

Variant: New simulation variant

PVsyst V7.3.1
 VC4, Simulation date:
 23/04/24 12:36
 with v7.3.1

New simulation variant

Losses in the PV system

	ModQual	MisLoss	OhmLoss	EArMPP	EArUfix	EUnused	EArray
	kWh	kWh	kWh	kWh	kWh	kWh	kWh
January	-3.588	3.374	7.77	470.8	470.8	20.1	450.7
February	-4.065	3.823	8.82	533.5	533.5	107.2	426.3
March	-5.278	4.963	12.68	691.4	691.4	219.9	470.1
April	-5.513	5.184	13.64	721.8	721.9	267.0	454.7
May	-6.635	6.239	17.59	867.5	867.5	398.8	468.4
June	-6.485	6.098	16.92	848.2	848.2	394.4	453.7
July	-6.623	6.228	17.60	865.8	865.9	397.0	468.9
August	-6.224	5.853	16.67	813.6	813.6	343.8	469.8
September	-5.489	5.162	14.23	718.0	718.0	268.8	449.2
October	-4.630	4.353	11.29	606.3	606.3	136.0	470.3
November	-3.191	3.000	6.68	419.0	419.0	12.5	406.4
December	-3.139	2.952	6.32	412.4	412.4	0.0	412.4
Year	-60.861	57.230	150.21	7968.2	7968.4	2565.4	5401.0

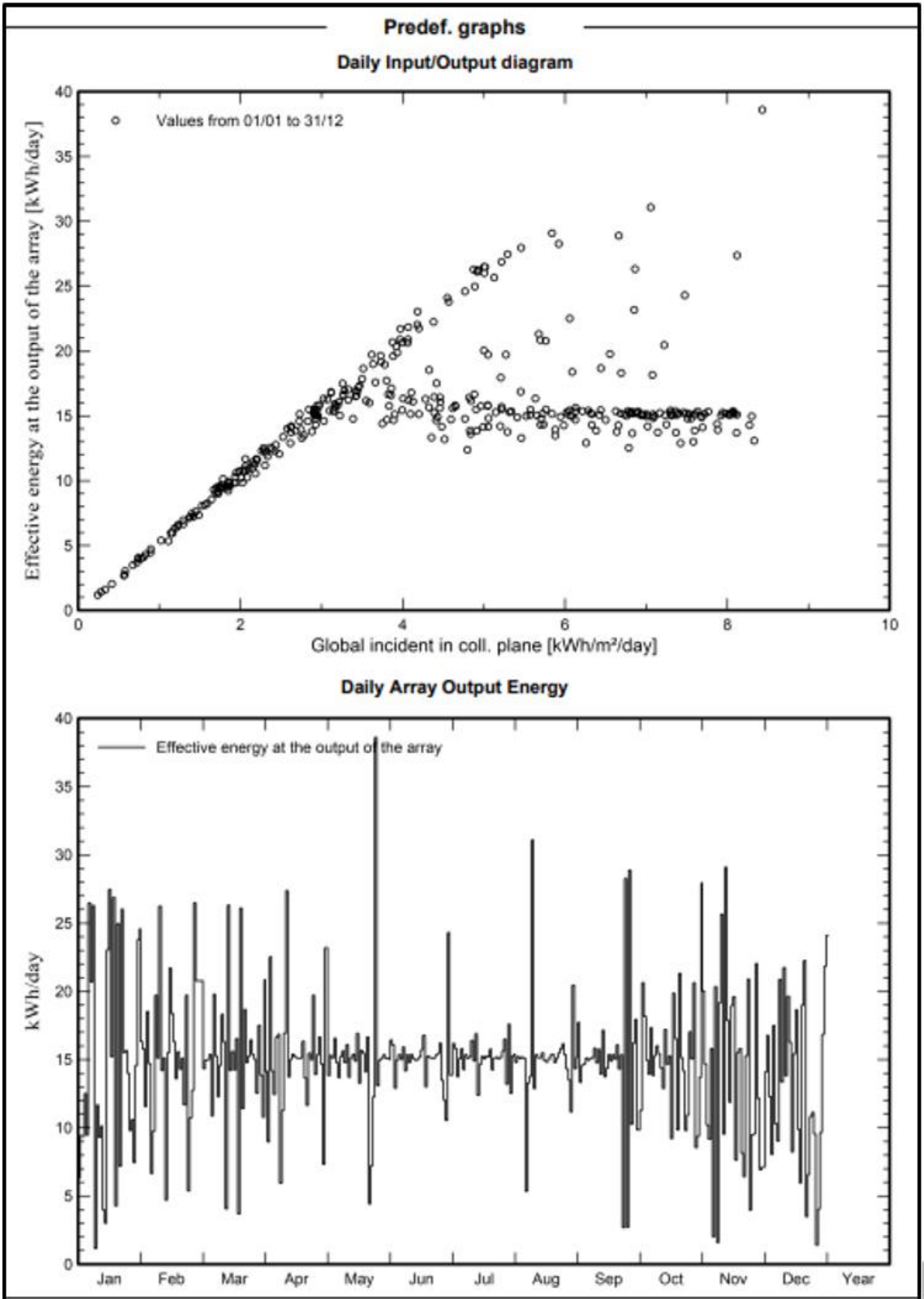


Fig 11 Losses in the PV systems Source: PVsyst stimulation, (2024).

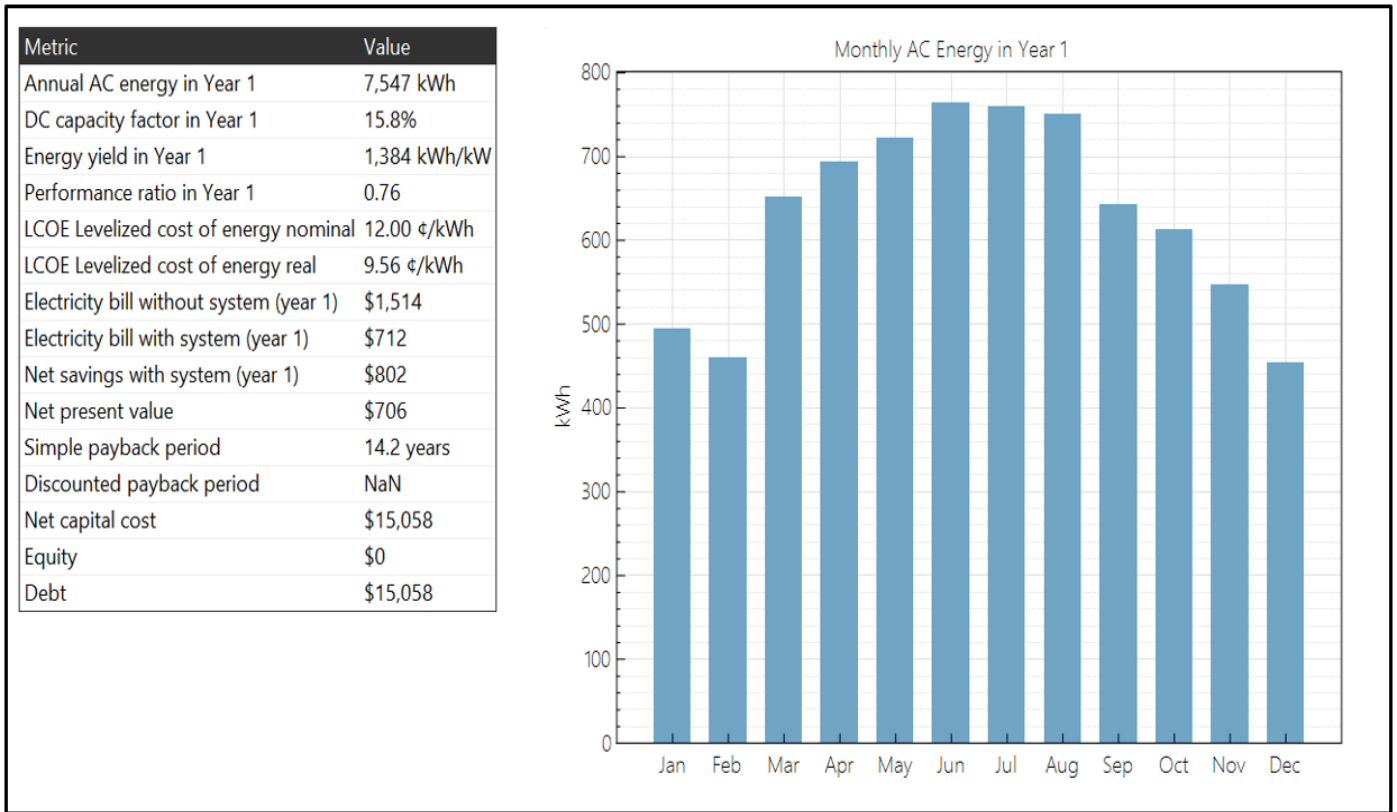


Fig 12 Data Metric and Monthly AC energy generated (SAM, (2024)).

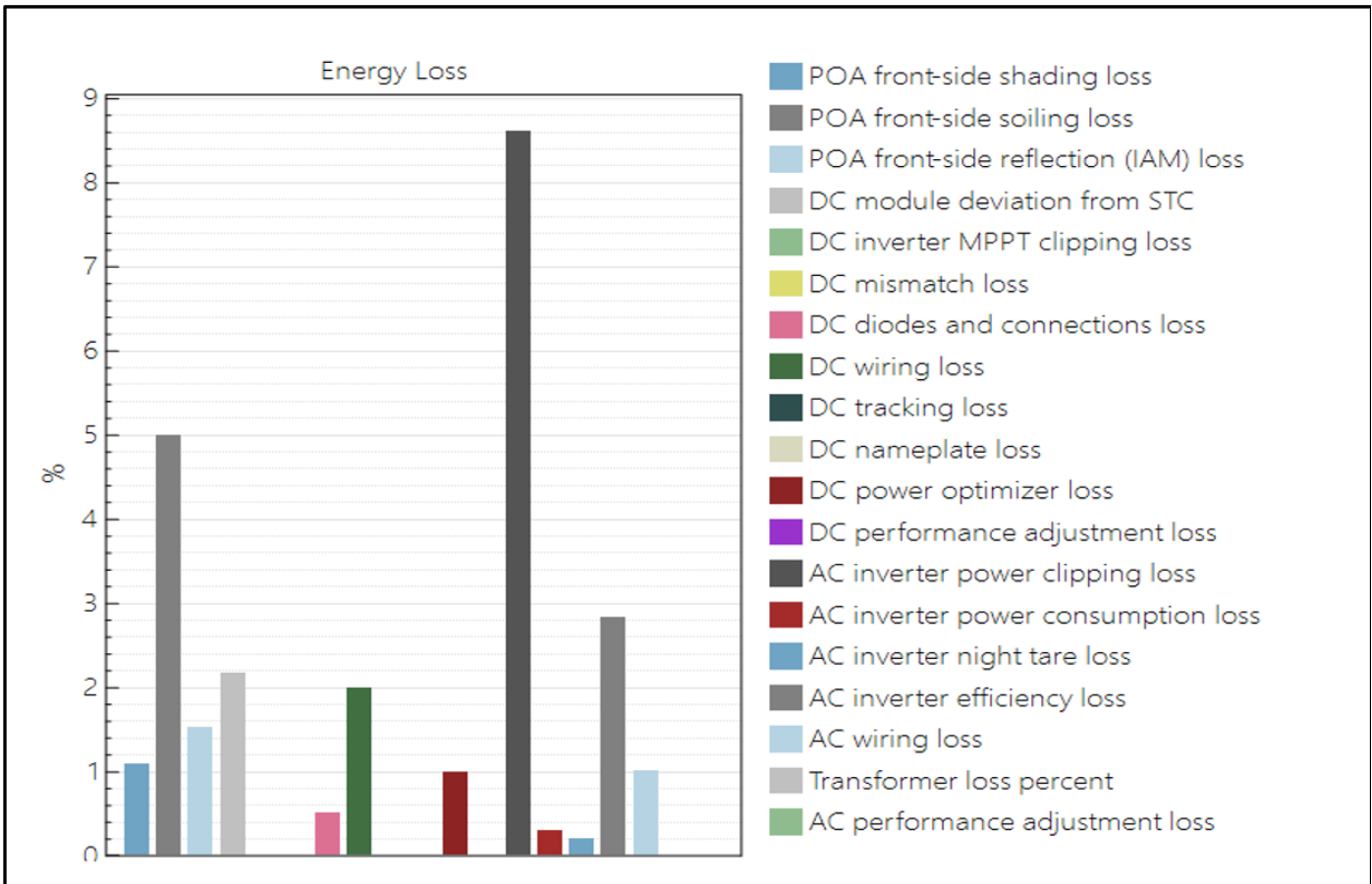


Fig 13 Energy Losses (SAM, (2024)).

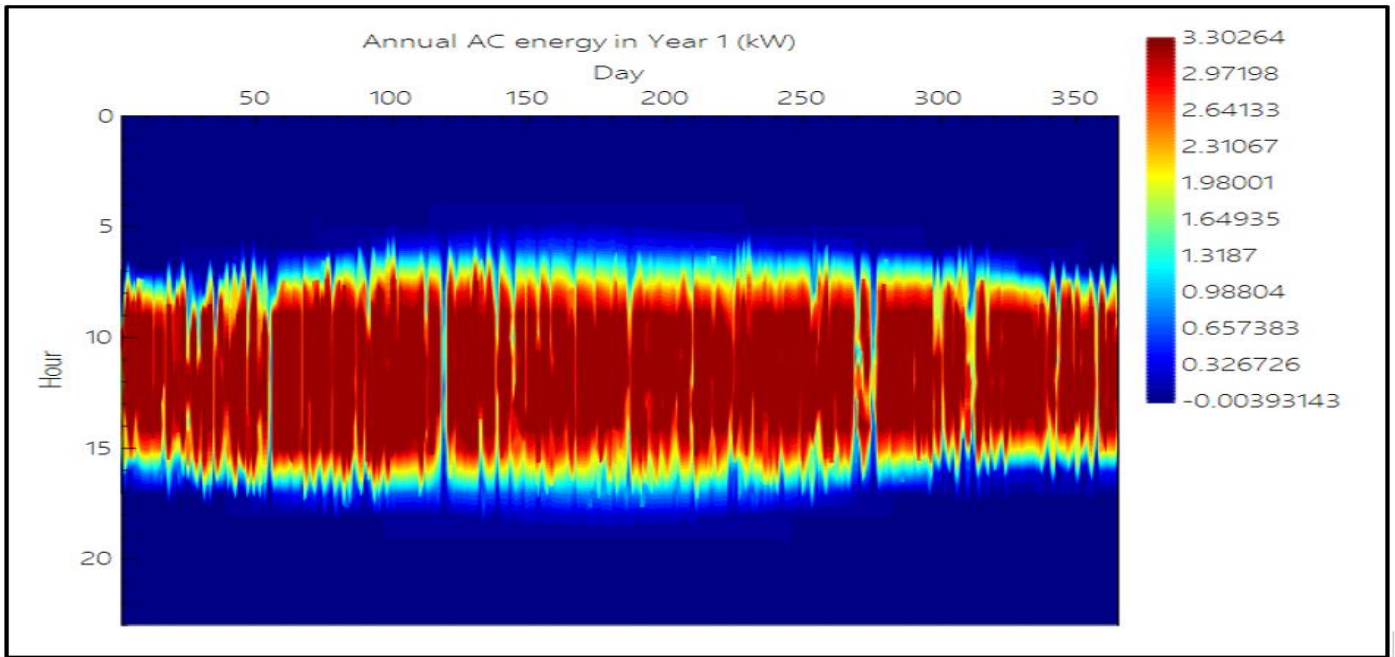


Fig 14 Annual AC Energy in year 1 (SAM, 2024).

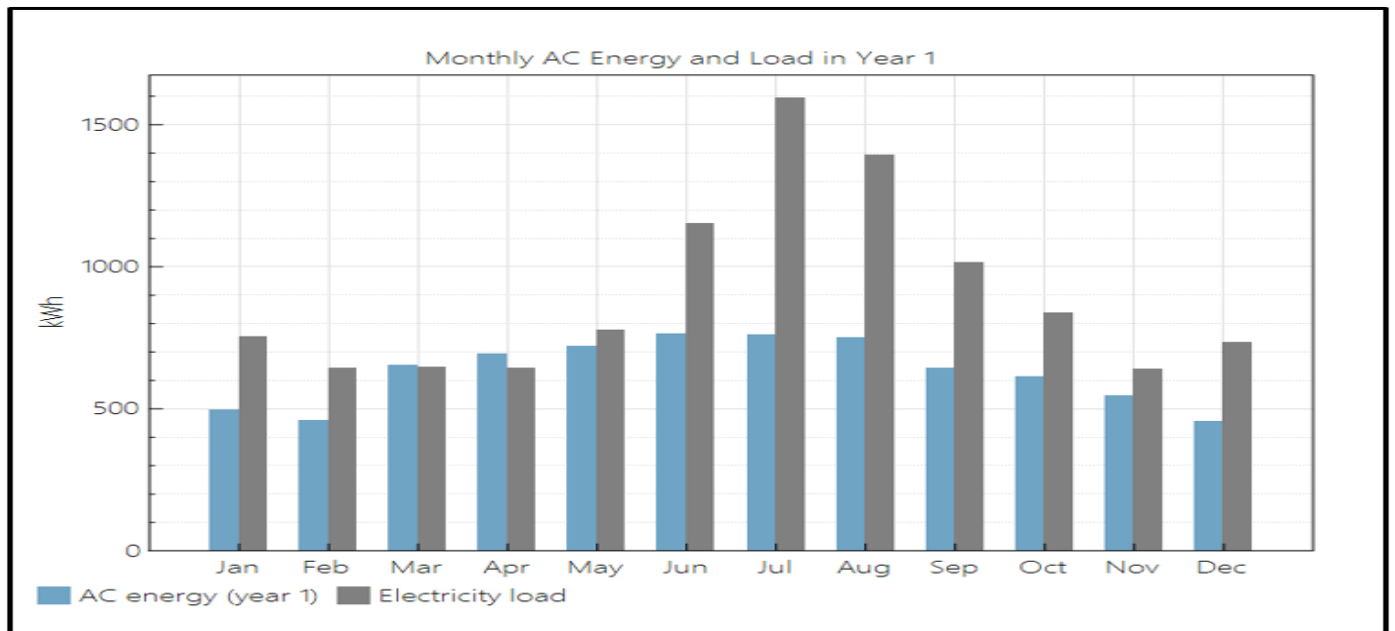


Fig 15 Monthly AC Energy and Load (SAM, 2024).

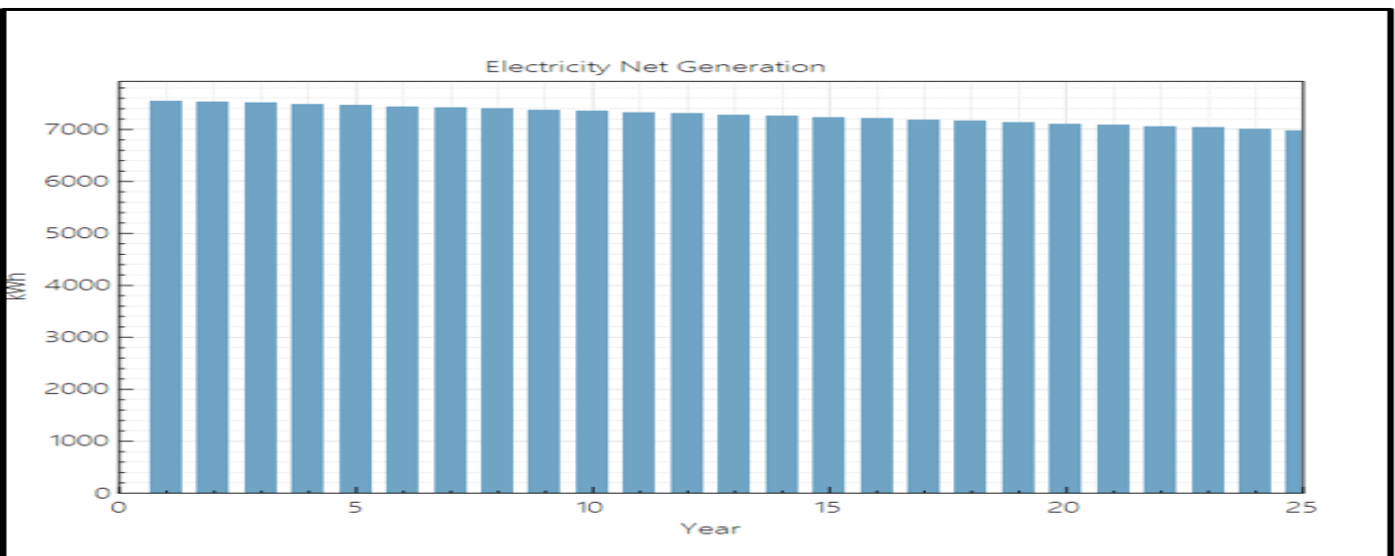


Fig 16 Electricity Net Generation (SAM, 2024).

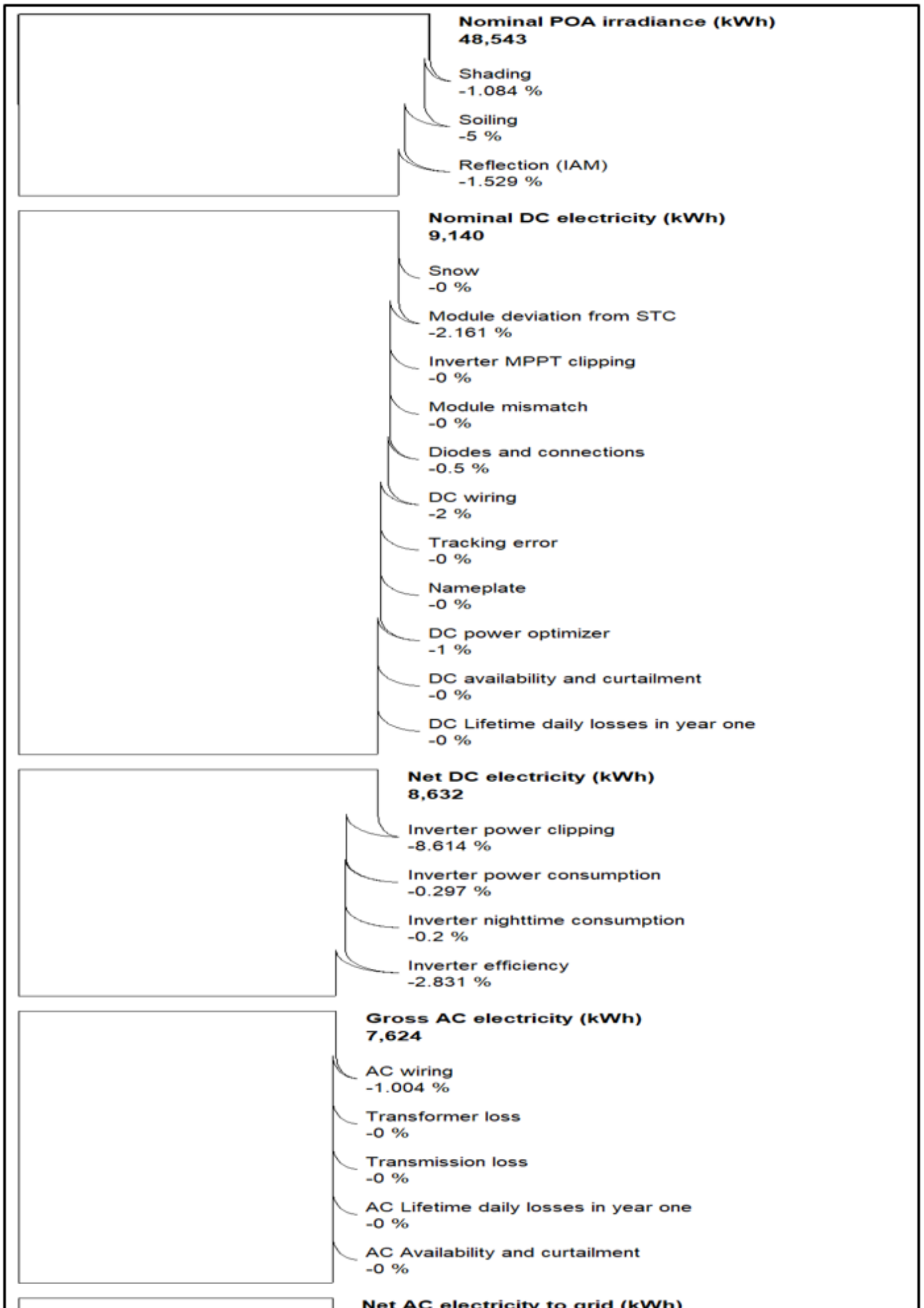


Fig 17 Showing Loss Diagram (SAM, 2024).

VIII. RECOMMENDATIONS

Proper design and management of residential PV/battery systems can deliver significant benefits to energy consumers in Illinois by reducing electricity bills and providing backup power during outages. Based on the results of this study and supporting literature, several important recommendations emerge:

➤ *Guidelines for Enhanced Design and Sizing*

- Employ advanced software tools, such as PVsyst, MATLAB/Simulink, and the System Advisor Model (SAM) with automated dispatch controls, for robust, site-specific simulation and precise sizing of PV panels and battery storage. This approach supports accurate system design, preventive maintenance, and thorough scenario analysis (Hasan & Serra Altinoluk, 2023; Aboagye et al., 2022).
- Carefully consider and balance key design trade-offs, including system cost, battery chemistry and cycle life, system efficiency, safety (and appropriate certifications), and integration with residential settings.

IX. EFFECTS ON RESIDENTIAL CONSUMERS

Accurate sizing and matching of PV and battery systems to actual household load profiles increases financial value by enabling surplus solar energy to be used during times of high electricity rates or grid outages (Aboagye et al., 2022). Battery storage also increases solar energy self-consumption and ensures reliable backup power. Using smart dispatch aligned with time-of-use rates and demand control can further improve savings.

X. FUTURE WORK

Further research should focus on advanced control strategies and energy management methods that increase the service value and flexibility of battery storage. Future studies may also explore household-scale "virtual power plants" and new approaches for aggregating distributed energy resources, as well as improved modeling methods to handle uncertainties in solar availability, load variability, and market factors over the lifetime of the system.

XI. CONCLUSION

This study demonstrates the use of established modeling tools, SAM and PVsyst, for the accurate design, sizing, and feasibility assessment of standalone residential PV/battery systems.

SAM provides advanced capabilities for modeling PV systems with storage, including technical and economic studies and support for different operating

scenarios such as time-of-use energy management and demand charge reduction (Ivin, 2022).

PVsyst is widely used for detailed analysis and financial assessment of both small and large PV systems, including configurations with batteries. It allows for in-depth investigation of irradiance losses, array performance, system efficiency, and degradation over time (Ivin, 2022). Both programs offer probabilistic analysis (e.g., P50 and P90 yield estimates) that increase confidence in solar performance projections (NREL, 2023).

In summary, advanced simulation tools like SAM and PVsyst support adoption of renewable energy by improving the financial feasibility, reliability, and integration of residential solar in both grid-connected and off-grid settings. Proper sizing and periodic system review maximize renewable energy generation and minimize downtime. This study presents a comprehensive approach to the design and sizing of PV/battery systems for robust off-grid performance.

FUNDING

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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