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Review Paper

Sizing Standalone PV Systems: A Review of Optimization Techniques and Methodologies

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Abstract:- *This paper presents a comprehensive review of various optimization techniques and methodologies used in sizing standalone photovoltaic (PV) systems, which are crucial for areas without grid connectivity. Standalone PV systems, independent of the electricity grid, are essential for remote and rural electrification. Accurate sizing of these systems is vital for ensuring reliability and cost-effectiveness, avoiding energy waste, and ensuring sufficient power supply. The introduction highlights the importance of solar photovoltaic technology and the criticality of sizing in standalone PV systems. The paper then delves into the components of PV systems, their functions, load analysis, and the importance of optimizing system sizing for reliability and efficiency. The findings emphasize the need for precision in sizing methodologies and explore different approaches, including intuitive, numerical, and analytical methods. The conclusion underscores the significance of these techniques in enhancing the efficiency and sustainability of standalone PV systems, suggesting further research in the field to adapt to emerging technologies and environmental conditions.*

Keywords: *Standalone Photovoltaic Systems, Optimization Techniques, Sizing Methodologies, Renewable Energy Efficiency, Off-grid Electrification*

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1. Introduction

One of the more promising renewable energy sources is solar photovoltaic technology, which is quickly taking the lead in terms of usage. The key feature of this technology that draws in the most consumers is that it is easy to install anywhere, flexible enough to have built-in wide-range capacity, pollution-free, has a low environmental effect, and is long-term economically stable. [1]. The physical location of Malaysia, which falls between 1°N and 7°N and 100°E and 119°E, close to the equator, allows for around 6 hours of sunlight each day [2]. To maximize the potential of solar energy for Malaysia's power consumption, these conditions are both ideal and realistic. The government and the corporate sectors are just two of the many sectors in Malaysia that collaborate to promote PV systems.

In stark contrast, fossil fuels, such as coal, oil, and gas, paint a bleaker picture. These non-renewable resources necessitate hundreds of millions of years to form, and their utilization for energy generation carries significant environmental and climate consequences. The combustion of fossil fuels releases harmful greenhouse gases, most notably carbon dioxide, into the atmosphere, contributing to global warming and climate change. Additionally, the finite nature of these resources underscores the urgency of transitioning to more sustainable and inexhaustible energy alternatives. Malaysia's shift towards solar energy represents not only a bright idea but also a vital step in safeguarding the environment and securing a cleaner, more sustainable future.

The sizing of a standalone Photovoltaic (PV) system is a critical step in the design and deployment of such systems. Sizing involves determining the appropriate components, configurations, and capacity to ensure the system effectively meets the energy requirements of a specific application, whether it's powering a remote cabin, providing electricity to a rural community, or supporting critical infrastructure in rural areas. The performance of a standalone PV system is intricately linked to the interplay of crucial factors, namely solar radiation, the dimensions of the PV array, and the storage capacity [2] [3]. Achieving the correct sizing is of paramount significance, as it serves as a linchpin for the reliability and effectiveness of these autonomous energy systems. Sizing methods are diverse, classified into intuitive, numerical, and analytical categories [2]. While intuitive methods offer simplicity and quick estimations based on practical experience, numerical methods delve deeper, leveraging data analysis and simulations to provide more accurate results, accounting for variations in energy 2 production and consumption [2]. Analytical methods, on the other hand, aim to optimize the system by considering technical, economic, and environmental criteria, offering a comprehensive approach to sizing that balances performance, cost-effectiveness, and sustainability [2]. In the pursuit of a dependable standalone PV system, the judicious selection of the appropriate sizing method is pivotal in ensuring the system's capacity to meet energy needs efficiently and effectively.

The pursuit of enhancing the efficiency and performance of photovoltaic systems has spurred significant research interest, driven by the need to optimize maximum power and energy production across various climatic conditions [2]. The incident solar energy on a solar panel is a multifaceted function influenced by a myriad of factors, including local radiation levels, geographic coordinates, the earth position relative to the sun, panel orientation and tilt, and ground reflection properties [4] [5]. Beyond assessing the amount of solar irradiance reaching the panel surface, the critical challenge lies in extracting the utmost energy to efficiently supply residential areas or the grid while minimizing costs and ensuring reliability [6]. Achieving a superior output at a reduced cost is the goal. Addressing issues related to inaccurate assumptions in PV system parameters and inadequate load power assessments, which can lead to excessive material and installation expenses, highlights the challenges and limitations of standalone PV system size optimization techniques. In this context, a novel sizing model is proposed to optimize the PV generator's capacity for remote power supply, incorporating pumped storage to overcome these challenges and pave the way for more cost-effective and reliable energy solutions [2].

This paper presents a comprehensive review of the diverse optimization techniques and methodologies employed in sizing standalone photovoltaic systems. It aims to provide a detailed understanding of the various approaches and their implications, offering valuable insights for practitioners and researchers in the field of renewable energy.

2. Sizing of Standalone Photovoltaic System

2.1 System Components and Their Functions.

The researchers in [7] have stated that conventional photovoltaic systems (PV) technologies comprise crystalline, silicon-based solar cells, such as the widely used monocrystalline and polycrystalline types that have demonstrated dependability and efficiency. In addition, thin-film solar cells that meet installation requirements, such as amorphous silicon, cadmium telluride (CdTe), and copper indium gallium selenide (CIGS), provide flexibility and cost advantages.

According to the researchers [8], however, state-of-the-art research in PV efficiency in recent years has concentrated on novel materials, intricate cell designs, and precise engineering techniques to achieve record-breaking conversion efficiencies. Tandem solar cells, multi-junction designs, and inventive light control strategies are being researched to maximize solar energy extraction and revolutionize the solar energy industry.

According to the researchers [9], perovskite materials' superior light absorption, charge-carrier mobilities, and use lives lead to high device efficiencies and potentially low costs, which could contribute to photovoltaics (PV) becoming a dominant source of electricity in the future.

PV modules can directly convert sunlight into electricity, according to researchers in [10], but they are unable to store the electricity they generate. Grid-connected photovoltaic systems can directly feed electricity into the grids. As a result, in standalone PV systems, energy storage components like batteries can be used to store the electricity produced by the PV modules throughout the day.

Researchers, [11] discovered that, under standard test conditions (STC), the performance of solar modules and arrays is typically rated based on their maximum DC power output. The module operating temperature of 250°C, the incident solar irradiance level of 1000 W/m2, and the air mass 1.5 spectral distribution are the standard test conditions. Under these conditions, actual performance is typically 85–90% of the STC rating because this is not always how PV modules and arrays operate in the field.

Researchers in [12] discover the inverter with integrated charge controller is the component that changes the direct current (DC) electricity generated by the photovoltaic (PV) modules into alternating current (AC) electricity suitable for powering electrical appliances. Additionally, the integrated charge controller manages the batteries' charging to ensure optimal performance and longevity.

Together, these parts create a comprehensive independent photovoltaic system that can supply a steady and consistent electrical supply, especially for uses like community health centers in Mali. To maximize the standalone PV system's performance, dependability, and affordability, these components must be integrated and sized correctly.

2.2 Load Analysis and Assessment

According to the study conducted in [13] energy consumption in a rural community was systematically divided into three categories: domestic loads, which included necessities like fans, lights, TVs, radios, and different household appliances; community loads, which included the power needs of community organizations like panchayat offices, schools, post offices, and hospitals; and commercial loads, which included electricity consumption in shops, flour mills, and other commercial enterprises. Additionally, industrial loads which are associated with activities at enterprises such as sawmills and paddy hullers—were recognized as a separate category.

Additionally, the researcher in [13] also claimed that the electrification plan for residential loads in isolated rural settlements was painstakingly designed to meet a variety of energy needs. This method considered the unique load profiles linked to residential power use, taking into consideration variables like the number of working days and the local atmospheric conditions. Based on these variables, electrification plans were customized with the goal of optimizing energy distribution and guaranteeing the effective and dependable supply of electricity to satisfy the distinct requirements of every sector in the rural community. By allocating the electrical equipment's running time based on user demand, this load profile is maximized. The load profile of the consumer influences how big a PV system and batteries are needed.

As the researcher in [14] implemented, the electrical load is primarily composed of smaller demands, making it a good candidate for solar photovoltaic system coverage. This renewable energy source is especially useful for producing power during the day, in line with the solar energy availability patterns of the day. Due to the site's favorable qualities and electrical load, solar power may be effectively harnessed to supply the area's daytime energy needs in a sustainable manner. The remote area household is simple and does not require large quantities of electrical energy used for lighting and electrical appliances. The average energy consumption of electrical appliances of a typical residential home is assumed 626 kWh/month, i.e. 20 kWh/day The [15] researcher discovers that the basic, low-energy needs of the rural region household for lighting and electrical appliances allow for reduced energy use. An average residential home's electrical appliance usage is estimated to be 626 kWh per month, or 20 kWh per day.

The authors of [16] described an off-grid solar power system and examined how load management affected the cost and size of the system's component parts. Four distinct load needs are examined in this instance: completely coordinated load (irrigation), partially coordinated load (industrial and residential), and non-coordinated load (street lighting). For comparative analysis, all instances under consideration have a fixed total daily load need of 39 kWh. The optimization outcomes will be tracked in terms of the cost and size of PV system components.

2.3 PV Module Sizing

According to the researchers in [17], standalone PV systems dependability depends on their appropriate size. Sizing methods fall into three categories: analytical, numerical, and intuitive. The first set of algorithms is very likely to provide incorrect results, making them very erroneous and unreliable because they just use instinctive knowledge and do not use reasoning processes. The second is more accurate, but algorithms need a huge time series of solar radiation for proper modelling.

The goal of this research [18] is to maximize the output power of the PV modules and minimize the life cycle cost of the system. The third group of approaches uses equations to characterize the size of the PV system as a function of dependability. This approach produces a more dependable outcome by providing a comprehensive explanation of the solar geometry and analyzing the solar irradiance from the source to the surface of the tilted panels.

As per [17], the researchers have discovered a solar panel or solar array should be oriented so that it faces directly towards the sun and is perpendicular to the line connecting the panel installation location to the sun to maximize energy capture, as most solar energy travels in a straight line. The solar panel must then be facing the terrestrial equator, which is either facing north in the southern hemisphere or south in the northern, to receive the maximum amount of solar energy during the day.

The researchers in [4] [5] thought the optimization of optimum power and energy output under various climatic conditions has attracted a lot of study interest, nonetheless, because of the low conversion efficiency displayed by solar systems. The local radiation, latitude, longitude, earth's position in relation to the sun, the orientation and tilt of the exposed solar panel surface, the characteristics of ground reflection, and other variables all play a complex role in determining the amount of solar energy incident on a solar panel at any one time.

To properly size, optimize, and increase the reliability of the system, we concentrate on characterizing the effective load utilized throughout the installation of PV systems. This paper also studies the impact of unpredictable fluctuations in load demand on the status of charge. [3]

2.4 Battery Sizing and Storage Considerations

To improve system dependability in standalone renewable systems, battery storage integration as a backup system is crucial, according to researchers in [16]. The generated power meets the hourly load needs throughout each hour of system operation, with any excess output being stored in the battery storage units.

The researchers in [3] established the idea of daily battery condition for improved dependability using minimum excess energy, minimum cost limitations, and minimum likelihood of power supply failure in their analysis of PV systems. However, as the load profile is a time-varying and probabilistic parameter, additional control should be applied to its respect and random variation. The current study presents the concept of autonomy test and system sensitivity in addition to optimal load evaluation, adequate power generation, and consumption. The sensitivity of the power supply to the initial state of charge and random load variation was investigated to verify the adaptability and dependability of the system. Here, we investigate the best tilt angles to maximize energy collection at a minimal cost by considering the time of year and their mechanical applicability to the panel network.

According to the researcher [17], solar PV arrays can be set up as either grid-tied or stand-alone systems. To store extra electrical energy, a battery storage device is required, regardless of the connection type. A battery ensures that extra energy is stored in a standalone system, particularly when the power provided by the PV system is less than what is required by a connected load.

In [18], the researcher established a total of eighteen configurations for solar arrays and batteries using components that are readily available on the market. The systems' costs and performances were then assessed for the requested load requirement. For those restricted configurations, the ideal solar array and battery size is determined by striking the right balance between the LPSP and the system cost. Real-world applications rarely employ the combination of two differing capacity batteries in one system.

The researchers in [18] also mentioned that they investigated the impact of tilt angle on the sizes of the SPV system for the given load demand and that, when the tilt angle was changed according to the seasons, the best size for the solar array and battery was found, which made the solar array installation more difficult.

As stated in [19], the researchers discovered that batteries are yet another crucial component of the PV stand-alone system. Because of the variations in the energy provided by the PV generator, the battery is required in such a system.

As per [20], the researchers explained The PV system supplies the load or consumer directly while it is sunny, and any extra power generated is kept in the battery. The battery will supply the consumer's electrical needs throughout the night or other times when there is less sun exposure. Just as with a PV generator, the battery will be chosen from the manufacturer's catalogue based on the specifications of the whole setup.

3. Optimization Techniques for PV Systems

Five broad categories can be used to group prior SAPV scaling approaches: analytical, numerical, intuitive, artificial intelligence (AI), and hybrid methods, according to the study [21]. Simple empirical equations are employed to find the SAPV component sizes, according to the researcher in [22], who used intuitive techniques of reasoning. Experience of the designer is a major factor in these techniques. Average solar radiation measurements are employed in these procedures instead of considering the variable nature of solar radiation. Although these procedures are straightforward, their inherent inaccuracy can result in either overly complex and expensive systems or insufficiently complex and unreliable systems. These methodologies also do not allow for the quantification of system availability.

According to the researcher's analysis of [23], there is a large body of literature on PV system sizing methodologies that may be divided into three categories: analytical, numerical, and intuitive methods. Using the provided load demand, the intuitive approaches entail calculating the PV array and battery storage capabilities in a straightforward manner. As a result, neither the randomness of solar radiation nor the interactions between the system's component parts are considered.

As such, [24] mentioned that the drawback of these approaches is that they may oversize or undersize PV systems, leading to excessive energy production costs or inadequate reliability. The least monthly average, average annual, or monthly solar radiation is used as an input into the calculations of the intuitive sizing methods, which is a common feature.

According to the researcher in [23], a simplified computation of the system's size was made without considering the random nature of solar radiation or creating any relationships between the many subsystems. These techniques can be based on average annual or monthly solar energy or on the lowest monthly solar average.

According to the researchers, [25] a major factor in improving PV system design and dependability is the mathematical model. It is important to note that there are sporadic variations in the weather and sun radiation. Thus, to select the right amount of PV panels and lower the system's overall cost, a precise PV system model is required. To enhance its efficacy, nevertheless, a correct PV model is essential. Researchers are very interested in parameter identification approaches because of the precision of PV systems.

Based on the information provided by [26] it is clear that an accurate PV model must be created to achieve maximum performance. Because PV systems are inherently very accurate, researchers are quite interested in investigating different ways to parameter detection.

4. Conclusion

Based on the review that has been made, to maximize energy efficiency by concentrating on the crucial elements of sizing and improving standalone solar systems. By means of a methodical examination and deliberation of diverse factors including solar radiation, load specifications, and storage capability, our objective was to devise a system that not only satisfies energy requirements but also guarantees dependability and sustainability. Along the way, state-of-the-art parts, and creative methods for improving system performance were integrated into a thorough analysis of the most recent developments in solar technology. There is a need to maximize the total efficiency of the standalone photovoltaic system by utilizing sophisticated algorithms and optimization techniques to create an ideal balance between energy output, consumption, and storage. This review has systematically explored various optimization techniques for sizing standalone photovoltaic systems. Future research should focus on further improving these methodologies, particularly in adapting to emerging technologies and changing environmental conditions. This advancement is crucial for enhancing the efficiency and sustainability of standalone PV systems in diverse applications.

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