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Optimizing Renewable Energy Use: Direct Current Load Management in Residential Photovoltaic Systems

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Abstract

This work conducts a thorough analysis and a practical experiment on the DC load management capability of household photovoltaic systems. This study was set up to investigate the capability of DC load management to improve energy efficiency and self-sufficiency within residential contexts that are equipped with a photovoltaic system. A simulated model of a domestic photovoltaic system was prepared to present the patterns of solar energy generation, household energy consumption, and resulting energy balance over a time span of 24 hours. Different load management approaches were addressed, such as load shifting or using smart controllers that improve system performance. In general, it was concluded that the application of efficient DC load control can provide a reasonable energy surplus and reduce electrical grid consumption, hence increasing the sustainability of a domestic energy system. This report describes concepts for better DC load control and provides paths for further research, with emphasis on the implications of future smart home technology. (This refers to an hourly simulation representing one full daily operating cycle of the proposed PV system.)

Keywords: Photovoltaic solar power system, AC, Load management, Energy efficiency, Smart controllers

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تحسين استخدام الطاقة المتجددة: إدارة أحمال التيار المستمر في أنظمة الطاقة الشمسية الكهروضوئية السكنية

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الملخص:

يتناول هذا البحث تحليلًا معمقًا مدعومًا بتجربة محاكاة لقدرة أنظمة الطاقة الشمسية الكهروضوئية المنزلية على إدارة أحمال التيار المستمر، وذلك بهدف تقييم مدى إسهام هذه الإدارة في تحسين كفاءة استخدام الطاقة وتعزيز مستوى الاكتفاء الذاتي في المباني السكنية المجهزة بهذه الأنظمة. تم تطوير نموذج محاكاة لنظام طاقة شمسية كهروضوئية منزلي لتمثيل أنماط توليد الطاقة الشمسية، واستهلاك الأحمال المنزلية، وتوازن الطاقة على مدار دورة تشغيل يومية تمتد لـ 24 ساعة. كما جرت دراسة ومقارنة عدد من استراتيجيات إدارة الأحمال، من بينها تحويل الأحمال واستخدام وحدات تحكم ذكية، بغرض تحسين الأداء الكلي للنظام.

أظهرت نتائج الدراسة أن تطبيق أساليب فعّالة للتحكم في أحمال التيار المستمر يساهم في تحقيق فائض طاقي ملحوظ وتقليل الاعتماد على شبكة الكهرباء العامة، مما يعزز استدامة أنظمة الطاقة المنزلية. ويستعرض هذا البحث كذلك مفاهيم متقدمة لتحسين التحكم في أحمال التيار المستمر، ويقترح اتجاهات بحثية مستقبلية مع التركيز على دور تقنيات المنازل الذكية في تطوير كفاءة واستدامة أنظمة الطاقة الشمسية الكهروضوئية.

الكلمات المفتاحية: نظام الطاقة الشمسية الكهروضوئية، تيار متردد، إدارة الأحمال، طاقة فعالة، وحدات التحكم الذكية.

1. Introduction

The onset of renewable energy technologies has ushered in a new epoch of power generation based on sustainability, and photovoltaic systems are at the forefront of this environmentally aware campaign. The use of photovoltaic systems, which directly convert sunshine into power, is gaining momentum globally in an effort to reduce reliance on fossil fuels and thus help combat the results of climate change. An essential component in the furtherance of the DC load that it carries is what properly administers the performance and efficiency of any Photovoltaic systems. Management challenges in DC loads of Photovoltaic systems are reviewed in this paper, hence the importance, challenges that come with DC load management, and various innovative ways to enhance the reliability and longevity of the systems were addressed. [1]

Photovoltaic systems are basically direct current DC electricity producers, but can either be used directly to feed a DC load or changed to AC to power conventional AC loads. The proper distribution of DC loads is of vital concern as their usage takes an important role in maximizing the use of electricity derived from solar sources, reducing energy losses, and increasing system efficiency. In regions where sunlight is plentiful, photovoltaic systems can generate substantial amounts of electricity. It is, therefore, often necessary that attention should be given to efficient load management strategies to ensure such power is put to optimum use [2]

The incorporation of DC loads in photovoltaic systems presents a number of new challenges and opportunities. Firstly, electricity could be used directly from solar sources, thereby eliminating the need for energy conversion and the consequent inefficiencies. However, the intermittent profile of solar power output and variation in load demand create the need to implement sophisticated management approaches in order to maintain stability and reliability within the system [2]. Secondly, the intermittent nature of solar energy and variability in DC load demand necessitate intelligent load coordination.

The focus of this paper is on DC load management in photovoltaic systems, where the critical contribution of DC load management to the improvement in the performance of the overall system performance is discussed in detail along with increasing sustainability. The work focuses on the importance of efficient DC load management in the context of solar energy use, which is depicted here. Problems in different management systems, along

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with real-world analysis, may help to illustrate how effective DC load management can transform and revolutionize the harnessing and utilization of solar energy. Since the world is considering sustainably viable alternatives to fossil fuels, there has been an increasing quest to optimize systems that apply photovoltaic conversion using advanced load.

Management techniques are one of the most crucial fields of research and development in terms of paving the way towards a more resilient and clean energy future.

2. Background

The integration of renewable energy resources into the global energy mix is an important step in sustainable development and climate change mitigation. Photovoltaic systems have been one of the major approaches toward the conversion of solar energy to electrical energy directly, which is clean and abundant in supply. Enhanced performance and efficiency of photovoltaic systems are increasingly important as their acceptance is on the rise. Particularly, there has been an increased interest in the control of DC loads. [3]

The PV systems can generate DC electricity that can be directly used for feeding DC loads, or it can be converted to AC and feed typical AC loads. Optimization of the energy-conversion process is of great importance because all the losses during the conversion stage can affect significantly the overall efficiency of the system. Because DC can utilize the power directly available from the solar sources, effective DC load management is the key. This practice reduces all the possible losses that can result from the conversion process furthering overall efficiency. The configuration of a typical stand-alone solar PV system is illustrated in Figure 1.

In historical perspective, a majority of the electrical loads were designed for single-phase AC power both in residential and commercial facilities. This is because AC power infrastructures are widely adopted around the world. However, DC loads are gaining popularity in energy systems due to growing adoptions of photovoltaic systems and other DC-powered appliances such as LED lighting, electric vehicles, and electronic devices. [4]

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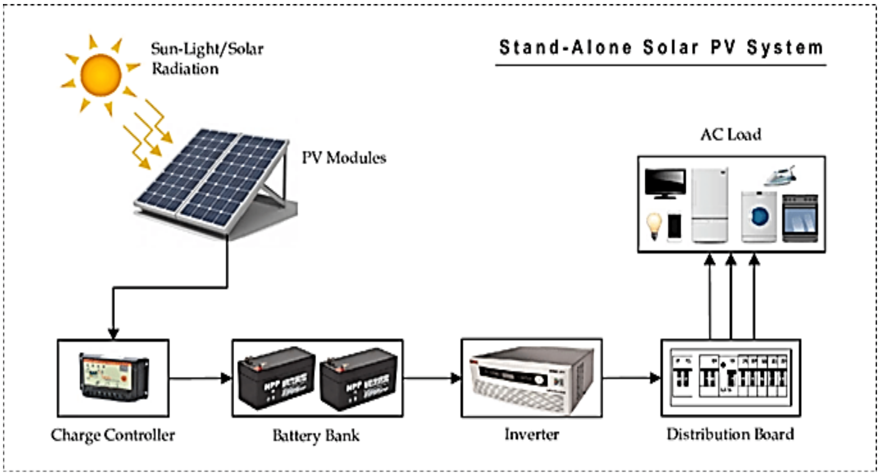

Figure 1. Stand- alone solar PV system

Opportunities and challenges in the effective management of DC loads on a PV system vary widely. The fact that it optimizes solar-generated electricity, minimizing energy storage and grid reliance, carries on one side, while the other side of this presents various complexities towards an appropriate energy supply owing to the sporadic nature of solar power and changes in load demand. [5]
It therefore lays the background that will result in the detailed review of DC load management in photovoltaic systems, with emphasis on its importance, challenges, and some creative approaches used in order to maximize the system efficiency and further the energy sustainability and resilience goals in general.

2.1. Advancements in PV Technology

Photovoltaic technology has gone through many improvements in past decades due to continuous research, novelty, and pressing demand for green energy solutions. Due to these improvements, the photovoltaic systems are much more efficient, affordable, and functional, turning solar energy
into an alternative for many people from all over the world [6].
Probably one of the most significant steps forward in PV technology has been the development of new materials and cell shapes. Silicon-based solar cells remain the most prevalent, but new technologies such as thin-film, perovskite, and organic photovoltaic cells are gaining ground since they could have lower manufacturing costs and

more uses. These new materials have now made it possible to add solar cells to the most impossible objects: windows, buildings, and even clothes [7].

Besides the use of new materials, solar cells have become much more efficient. Scientists and engineers have been in a position to devise methods of reducing energy losses resulting from resistance, recombination, and reflection, thus coming up with solar cells able to convert more sunlight into power. Concentrated solar power systems have also come a long way with the use of mirrors or lenses to focus sunshine on a small area. This makes solar energy even more useful [8].

Improvement in ancillary components, such as inverters, batteries, and charge controllers, has also contributed to overall development in PV systems. Moreover, with the integration of smart grid integration and energy management systems, solar-generated electricity had become smartly utilized and distributed, further enhancing reliability and stability in solar power.

2.2 Role of DC Electricity in PV Systems

Among the applications of photovoltaic systems, DC electricity has a particular place because it is the first type of energy generated by solar cells. The photovoltaic effect, the meaning of the basic process which takes place in solar cells-means the direct conversion of sunlight into DC electrical energy. This intrinsic characteristic of PV systems underlines the decisive role of DC electricity, influencing the way in which solar energy is captured, processed, and used [9].

One great advantage of PV systems over other renewable sources of energy is that they generate DC electricity and not AC. This makes it a more direct way of energy transfer, particularly in powering DC loads. In modern scenarios of energy use, several devices and systems require DC electricity for their functioning, like LED lighting, electronic devices, and electric vehicles. The ability to directly power these loads with solar-generated DC electricity circumvents the need for energy conversion, reducing losses and enhancing overall system efficiency [10].

Hybrid solar PV topologies are shown in Figure 2, where scheme (a) represents the AC-coupled hybrid PV topology, and scheme (b) represents the DC-coupled hybrid PV topology.

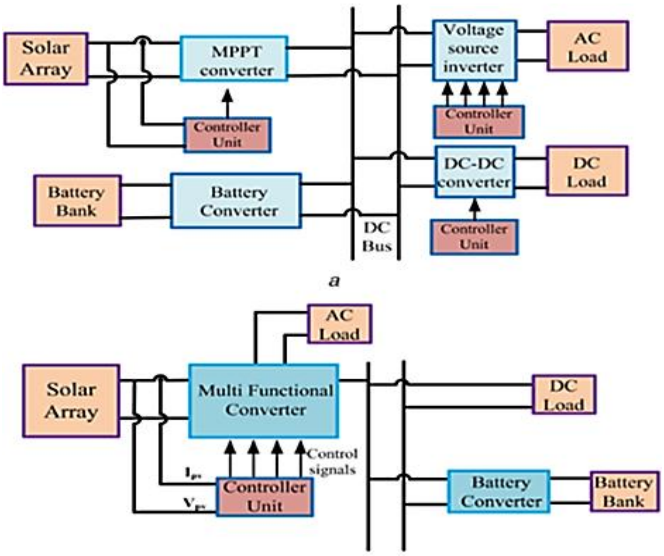

Figure 2. Schemes for hybrid solar PV system topologies

Moreover, the role of DC electricity in PV systems extends to energy storage. Batteries, which are integral components for ensuring a stable and reliable energy supply, store electricity in DC form. The direct compatibility of solar-generated DC electricity with battery storage systems simplifies the energy storage process, further contributing to the efficiency and effectiveness of PV systems.

Even with these benefits, many apps need to change DC electricity to AC electricity because of the widespread use of AC grids and appliances that run on AC power; this is where inverters come in. This change is needed for AC loads to work and for the grid to work, but it uses energy and makes it less useful. Newer inverter technologies are trying to cut down on these losses, but the role of DC power in PV systems is still something that needs to be improved [5].

2.3. Advantages of Using DC Loads in PV Systems

The .incorporation of direct current (DC) loads inside photovoltaic (PV) systems offers numerous benefits, hence augmenting the efficacy and effectiveness of solar energy consumption. One of the primary benefits is the elimination of energy losses associated with the conversion of DC to alternating current.

Conventional PV systems convert the DC output into AC for use by normal appliances and for grid connection. The process of conversion is normally done through inverters, and as it is a conversion process, there is a loss of energy in the process, reducing the overall efficiency of the systems [11].

In the case of DC application directly from the PV system, they are connected directly, which increases direct usage of electrical energy generated through solar energy conversion without the conversion of energy. This direct usage will reduce the energy losses and also the architecture of the system, which will reduce the installation and maintenance costs. Moreover, using DC loads can provide quite substantial efficiency gains in off-grid or remote installations where the conservation of energy is crucial.

Another advantage of using DC loads in PV systems is that they provide increased compatibility with battery storage. With batteries storing electricity in DC form, systems with DC loads are able to draw power directly from the batteries, thereby bypassing the need for energy conversion by an inverter. Where there is a direct connection between the storage and utilization of energy, the effectiveness in the use of stored energy is normally at higher levels, especially at times when the sun does not shine enough or at night [12].

In the end, utilizing DC loads within PV systems has a host of merits on energy efficiency, simplicity of the system, and in providing compatibility for battery storage. These advantages, mentioned above, make it easier to increase solar energy utilization and, therefore, align with the general goals of sustainable and efficient energy use.

2.4. Challenges and Limitations

While there are several benefits for the integration of direct current loads in photovoltaic systems, there are disadvantages associated with it as well. Among the major drawbacks: DC appliances and equipment are costlier and more rarely available compared to their ac counterparts. The major energy infrastructure globally is AC, so AC gadgets are more widely available and more reasonably priced.

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This can make the price difference increase for PV systems to switch over to DC loads, especially for the final customers [13].

Besides increasing the complexity of installation and system design, other disadvantages could be the lack of standards in DC systems that may lead to incompatibilities. In this regard, special solutions might be required since DC systems might differ from AC systems, which have well-set standards and procedures, which can hamper their wider diffusion.

Furthermore, there are efficiency advantages to using DC loads that are greatest in smaller, more localized systems. Because of the inherent nature of DC electricity, larger or long-distance electrical transmission applications suffer from higher energy losses relative to AC transmission. This indicates that great consideration must be taken in the size and layout of a system when integrating DC loads within PV systems [14].

2.5. Importance of DC Load Management

The incorporation of DC load into the PV systems involves thoughtful planning regarding the management of the load in order to enable performance and efficiency. Effective DC load management is supportive in harmonizing the patterns of energy generation and consumption that impact directly upon reliability and sustainability. This section provides an overview of the importance of DC load management and how it affects the operation of the system and energy use [15].

The main reasons for which DC load management is important lie in the intermittency of solar energy. Due to the day-to-day sun-position changes and influenced also by the weather, big fluctuations of generated energy happen. Primary objectives of DC load management strategies include aligning DC load operation to optimal periods of solar generation. The aim of this approach is the optimal consumption of solar-generated electricity, therefore minimizing its storage or reliance on grid supplies.

It results in optimization of the system efficiency by optimizing DC load management. There is a reduced need for converting energy between direct current and alternating current and vice versa, hence minimizing energy loss associated with such conversions. More produced solar energy is tapped into use since DC electricity is

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utilised directly, which enhances the general performance of the PV system [16].

Also, DC load control can prolong the life of energy storage elements like batteries by serving them dependably. Where proper discharge and charge cycle of the batteries takes place, matching solar production with load demand, batteries have less stress on them, which results in an improvement in the long-term performance and longevity of the batteries.

Coupled with the operational benefits, there is also a cost element in managing DC loads. Optimum utilization of energy and the resultant reduction in the dependence on external sources can result in considerable cost benefits to the end-user. This becomes particularly important for off-grid or remote installations where energy self-sufficiency attains far greater significance [17].

DC load control is important in terms of efficiency, reliability, and economic viability; hence, it is a major component of PV system design and operation. A holistic approach that includes the interplay of energy generation, storage, and use is required to ensure PV systems meet their full potential. Efficient DC load control, therefore, is an increasing need with increased utilization of PV systems and integrating DC loads within such systems.

2.6. Strategies for DC Load Management

DC load management in a photovoltaic system optimizes the consumption of energy and system reliability effectively. These can be made through a number of strategies that further enhance the balanced operation of the system. Such strategies are meant to align energy use with the generation of solar energy, enhance efficiency in the systems, and provide a stable energy supply [18].

The most common strategy is load shifting, which simply means planning energy usage during peak solar energy production times. In this way, it aligns energy-intensive operations with peak sunlight times and thus maximizes the amount of electricity generated directly from sunlight for usage in the system while minimizing the need for energy storage or grid supply. It also deals not only with system efficiency but also contributes to saving money for the end-user.

Another important strategy is demand-side management, where the focus lies on operating the system optimally concerning real-time

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energy availability and demand of the DC loads. Smart controllers and energy management systems are quite helpful for this approach since they would monitor energy generation and consumption patterns continuously. In some cases, operation modes can be dynamically changed for DC loads by such systems so that optimal energy utilization is done while maintaining stability [19].

Another important part of DC load management involves incorporating energy-efficient DC loads. By selecting appliances and devices with higher efficiency and lower energy consumption, there will be less demand on the entire PV system. This helps not only to make the ability of the system meet the energy needs more effectively but also to extend the life expectancy of the energy storage components.

In the case of systems with energy storage, there is a need for intelligent management of the accumulator. That means maintaining the optimization of charge-discharge cycles of batteries in sync with the demand of loads and solar production. In fact, the advanced control management system of the batteries extends their life span, enhances reliability in the system, and gives the assurance of continuity in energy supply, particularly during rainy days or on peak demand [20].

2.7. Smart Controllers and Energy Management Systems

The improvement in DC load management in the photovoltaic systems is highly attributed to the advancement in technology. In this regard, the progress in the development and implementation of smart controllers and energy management systems has formed the nova of improved systems. The use of the contemporary tool ensures that it optimizes DC loads operation, hence improving energy efficiency and, therefore, contributing to the overall performance and reliability of photovoltaic systems. [21].

Smart controllers are advanced devices that enable the intelligent operation of DC load systems. This involves monitoring at all instances a set of parameters, including solar energy generation, load demand, and battery status, in order to make instantaneous decisions with the objective of optimizing energy flows. Besides, Smart Controllers optimize energy consumption by dynamic updating of the operating modes of DC-loads according to a set of predefined criteria. In this way, energy consumption is performed in

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correspondence with the periods of high solar production in order to maximize the utilization of electric energy generated from solar resources [21].

Energy management solutions extend this optimization process to one that offers a holistic approach toward effectively controlling all aspects of a photovoltaic system. In addition, this allows the integration of a wide array of sensors, controllers, and communication networks into an interactive adaptive energy ecosystem. Besides managing the operation of inverters, batteries, and other system components, they manage DC loads and assure peak performance of each component involved.

Energy management programs and smart controllers are crucial for improving the efficiency of systems. These directly contribute to better utilization of solar electricity by minimizing the need for energy conversion and by reducing losses. They are also critical to demand-side management, deploying techniques like peak shaving and load shifting to balance the supply and demand of energy [22].

These technological advances further enhance the reliability and longevity of PV systems in addition to operational advantages. Smart controllers and energy management systems extend the life of system components and further reduce maintenance needs, prevent deep draining or overcharging of batteries, ensuring DC loads function within optimum parameters.

Furthermore, the communication capabilities integrated into these systems enable the monitoring and control of the systems from a distance, affording the system operators and end-users real-time insight into system functionality. Besides facilitating easier preventive maintenance and troubleshooting, this connectivity offers opportunities for integrating PV systems into smart grids that will further increase efficiency and dependability even more.

2.8. Residential PV Systems with DC Load Management

The application of residential photovoltaic systems that employ DC load management demonstrates practical viability and the everyday benefits of solar energy. This report on some case studies illustrates how practical applications of the systems offer an insight into the effects on cost-effectiveness, environmental friendliness, and energy conservation [23].

These PV systems for DC load management are often tailor-made, mainly according to one's specific energy needs. The components involved include solar panels, a battery storage device, a charge controller, an inverter, and a host of DC appliances. A majority of homeowners can integrate the DC load management mechanisms to increase solar-generated electricity that supplies electricity directly to DC appliances. This action negates the need for conversion to alternating current and therefore reduces the energy losses.

A prominent case study pertains to a residential community wherein dwellings are outfitted with photovoltaic (PV) systems that incorporate intelligent energy management systems. These systems facilitate the real-time monitoring of residential energy consumption, battery storage levels, and solar energy production.

Intelligent controllers synchronize the operation of DC appliances, including energy-efficient refrigerators, HVAC systems, and LED lighting, with periods of peak solar generation. By virtue of this synchronization, solar energy supplies the majority of the household's energy requirements, thereby substantially diminishing electricity expenditures and dependence on the electrical grid. The data and experimental results presented in Table 1 demonstrate the effectiveness of smart management systems in synchronizing appliance operation with periods of peak solar power generation [24].

An additional instance is a residential photovoltaic (PV) system that incorporates DC load management and is situated in a remote area without grid connectivity. The system's capacity to effectively oversee and prioritize energy consumption is critical in this particular situation. A reliable battery storage solution is incorporated into the system to store surplus solar energy. The energy is then utilized to feed power to all critical DC loads, such as lighting, communication equipment, and water pumps, during periods of low sunlight or at night.

Besides, the residential PV systems also offer scalability and customization possibilities. House owners can start with simple systems and, over time, gradually progress with the installation of more solar panels or even batteries, according to their financial ability and energy needs. Integration of smart meters with IoT devices has provided further details to the householders regarding

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patterns of energy use, promoting more conscious consumption and enhancing energy savings [25]

Domestic PV systems integrated with DC load control thus demonstrate a promising future in developing household energy systems.

3. System Modelling and Simulation

A simulation model of the proposed residential PV system was developed to evaluate DC load management performance and energy balance during a 24-hour operating cycle.

3.1 Simulation Model Description

A simulation model of the residential photovoltaic system was developed using MATLAB/Simulink environment. The model consists of a PV array, a DC–DC converter with MPPT control, a battery storage system, a smart load management controller, and various residential DC loads. The simulation was conducted over a 24-hour operating cycle to evaluate energy generation, consumption, surplus, and deficit conditions.

3.2 Practical experiment case study

The homes described in this paper are a prototype of how progressive technology can be put to work in building an ecologically friendly, efficient, and independent house tailored according to the needs and goals of the specific owners.

The overall structure of the proposed residential photovoltaic system with DC load management is illustrated in Figure 3.

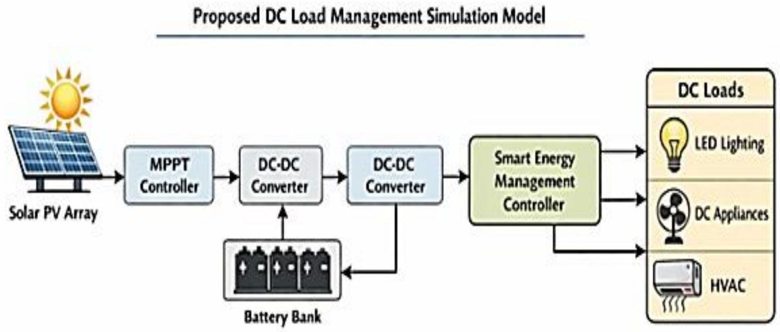

Figure 3. Proposed DC Load Management Simulation Model of the Residential PV System

3.3. Solar Radiation and Temperature Analysis

Table 1 presents the statistical characteristics of solar radiation and ambient temperature as reported in a previous study [24] to describe the climatic conditions of the study area.

Table 1. Statistical summary of solar radiation and ambient temperature [24]

Statistical measures	Solar Irradiance (kW/m^2)	Temperature (c)
Count	24	24
Mean	0.609	20
Std	0.336	3.206
Min	0	15
25%	0.318	17.5
50%	0.681	20
75%	0.901	22.5
77Max	1.2	25

As shown in Table 1, the statistical summary data on daily solar irradiance and temperature. The daily average is 0.609 kW/m^2. The graphs in Figure 4 illustrate the levels of solar irradiance and temperature, showing plotted curves that represent daily variations.

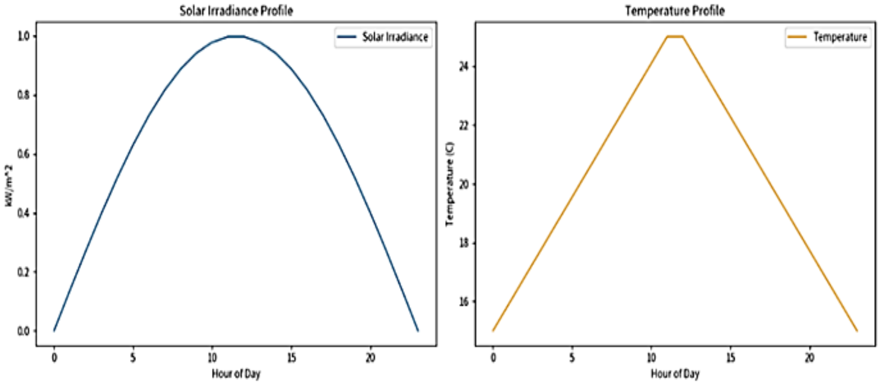

Figure 4. Daily profiles of solar irradiance and ambient temperature

Solar irradiance indicates that there is a reliable value for the PV system to make a proper estimation of the solar energy potentially available. Standard deviation represents the variability expected under the variable position of the sun and always changing atmospheric conditions. The average temperature is 20°C, which is

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considered the optimal range regarding the efficiency of PV systems since performance might be reduced when it gets really hot.
The graph in Figure 4 shows the daily profiles of solar irradiance and temperature: the sinusoidal curve of solar irradiance peaks at noon, which represents the time when maximum solar energy is potentially available. Temperature profile-a usual diurnal pattern of gradual increase in the early afternoon and decrease in the evening. This graph is very important in setting the context in which the potential energy generation of the PV system would fall, as the solar panels are directly impacted by ambient temperature and radiation.

3.4 Energy Generation and Net Energy Analysis

The energy statistics in table 2 show that the PV system generated an average of 3.046 kWh per hour, with a standard deviation indicating variability in generation due to the solar irradiance. The net energy statistics highlight the balance between generation and consumption, with an average net energy of 2.552 kWh per hour, the minimum net energy of -1.2 kWh. The table summarizes the statistics of energy generation and consumption, highlighting the average net energy and the impact of fluctuations in solar irradiance. indicates periods when energy consumption exceeded generation, which is crucial for considering energy storage solutions.

Table 2. Energy generation and consumption statistics

Index	Energy Generated (kWh)	Net Energy (kWh)
Count	24	24
Mean	3.046	2.552
Std	1.679	1.642
Min	0	-1.2
25%	1.831	1.199
50%	3.046	2.552
75%	4.507	3.761
Max	5.4	5.4

The energy consumption graph in figure 5 illustrates the hourly usage of various household DC appliances, including LED lighting, a DC refrigerator, an HVAC system, and electronics. Moreover, it is a graph that shows the overall energy consumption of all appliances and household energy consumption patterns throughout the day, indicating peak usage hours for various household

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appliances. This graph is very important in making sense of the demand side of the energy equation. It will be able to show both the peak and valley points of energy consumption, which can then be used to formulate the energy management strategy, such as load shifting or peak trimming.

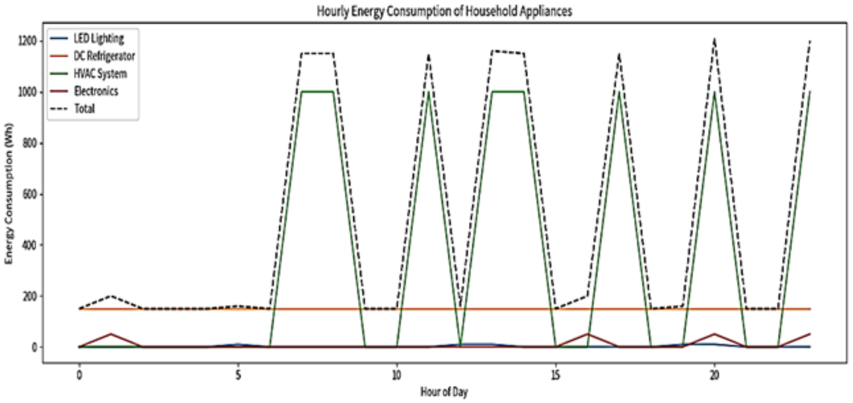

Figure 5. Hourly profile of household energy consumption and daily usage patterns of direct current (DC) appliances

3.5. Hourly Energy Consumption Analysis

Table 3 provides an overview of the aggregated energies over the course of a day. On the whole, the PV system generated 73.097 kWh of energy, while the household consumed approximately 11.85 kWh, which, in turn, translates to a net surplus of 61.247 kWh. The surplus observed has great relevance because it shows the proper dimensioning of the system concerning household demand and allows opportunities either to store or to commercialize the surplus energy.

Table 3: Total energy calculations

Metric	value
Total Energy Generated (kWh)	**73.097**
Total Energy Consumed (kWh)	**11.85**
Total Net Energy (kWh)	**61.247**

Figure 6, illustrates the quantity of energy generated by the PV system and the energy consumed by home appliances in one-hour intervals. Surplus and deficit regions are clearly marked, showing overproduction and scarcity of energy, respectively, within the system. The representation will be important for understanding the performance of the system and the dynamics of the generation and consumption of energy. Also, this can point out the need for energy storage solutions or grid support in times of energy deficit and the energy export in times of excess energy.

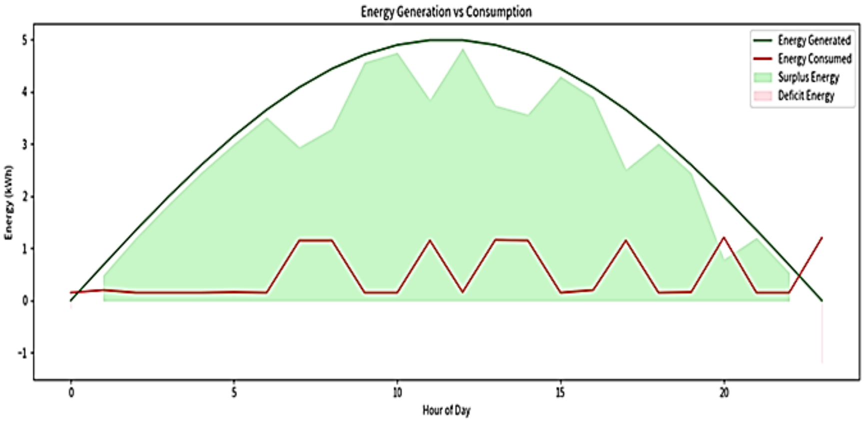

Figure 6. Relationship between energy generation and consumption throughout the day

3.6. Surplus and Deficit Analysis

Table 4 illustrates the number of surplus and deficit hours, clearly demonstrating the achievement of self-sufficiency during most hours of the day, surplus were observed with only 2 hours of energy deficit. This observation suggests that, in fact, for most of the day, the system produced more energy than what was consumed by the household, a reasonable indication of a very significant reduction of reliance on the electrical grid and, therefore, better energy self-sufficiency. The 2 hours of deficit indicate the creation of a plan to cover these energy needs, such as battery storage or supplementation from the grid.

Table 4. The supply, surplus, and deficit energy measures

Metric	value
Hours of Energy Surplus	22
Hours of Energy Deficit	2

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4. Discussion

Figure 6 and Table 4 collectively highlight the relationship between energy generation and consumption; however, the discussion here focuses on the implications of these results rather than restating numerical values. The predominance of surplus energy hours indicates an effective coordination between photovoltaic generation and DC load demand, demonstrating the capability of the proposed system to achieve a high level of energy self-sufficiency. This surplus reflects the potential for either energy storage integration or energy export, enhancing overall system efficiency.

The limited occurrence of deficit periods emphasizes the importance of incorporating appropriate energy storage solutions or grid support to ensure continuity of supply during low generation intervals. From an energy management perspective, these findings confirm that intelligent DC load coordination can significantly reduce grid dependency while maintaining system reliability, which aligns with previously reported findings in the literature [26].

The hourly energy consumption graph of household appliances (Figure 4) revealed that the peak consumption does not coincide with peak generation times, suggesting an opportunity for load shifting strategies. This observation is a practical demonstration of the theoretical concept of load management to enhance system efficiency, a key topic in the paper.

The energy generation versus consumption graph (Figure 6) provided a clear visual representation of the times when the system was self-sufficient and when it required additional energy sources. The surplus energy generated could potentially be stored in batteries or fed back into the grid, aligning with the paper's discussion on the integration of energy storage solutions and grid-tied systems to maximize the utility of generated solar power.

The results validate the research paper's discussion regarding the potential of intelligent controllers and energy management systems. Indicated by the surplus hours, intelligent systems are capable of dynamically managing the energy flow by storing or utilizing excess energy to power other systems, thereby optimizing the overall energy consumption.

The results indicate that a continuous power supply is required; therefore, either a grid-connected system or a robust energy storage

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solution is required to address the two hours of energy deficit. This pragmatic realization bolsters the paper's case for the integration of hybrid systems—which possess the capability to transition between solar, storage, and grid power—in order to ensure a dependable energy provision.

5. Conclusion

The study has done a wide analysis on the topic of DC load control in a house using a PV system. Through a wide literature review and practical experiment, the work has convincingly demonstrated the vast potential of DC load control in making the residential energy system more efficient and sustainable.

The experimental results also show that if a photovoltaic system is adequately engineered, besides a proper load management strategy, the system is capable of offering substantial energy surplus within a day. This surplus energy offers homes the potential to attain a significant level of energy self-sufficiency, hence aiding in mitigating the household's carbon emissions. This also highlighted that energy storage solutions and grid-tied systems are playing a very important role in the efficient handling of the energy deficiency situation, particularly at nighttime or on days with low solar irradiations.

The promising developments in intelligent controllers and energy management systems are reviewed within the paper, which indeed provide encouraging prospects for improving energy efficiency. These controllers provide dynamic load management, possibly able to adapt in real time to the prevailing conditions and hence further optimize the utilization of solar power generated with reduced reliance on external energy sources.

The paper also considers case studies and practical applications that demonstrate successful applications of the DC load management approach. In so doing, these examples provide illustrations, but more importantly, useful insights and recommended approaches that may have wider applicability.

6. References

[1] Fthenakis VM, Lynn PA. Electricity from sunlight: photovoltaic-systems integration and sustainability: John Wiley & Sons; 2018.

http://www.doi.org/10.62341/istj-vol38-1-79im

[2] Sukamongkol Y, Chungpaibulpatana S, Ongsakul W. A simulation model for predicting the performance of a solar photovoltaic system with alternating current loads. Renewable energy. 2002;27(2):237-58.
[3] Gielen D, Boshell F, Saygin D, Bazilian MD, Wagner N, Gorini R. The role of renewable energy in the global energy transformation. Energy strategy reviews. 2019;24:38-50.
[4] Aslam A, Ahmed N, Qureshi SA, Assadi M, Ahmed N. Advances in solar PV systems; A comprehensive review of PV performance, influencing factors, and mitigation techniques. Energies. 2022;15(20):7595.
[5] Justo JJ, Mwasilu F, Lee J, Jung J-W. AC-microgrids versus DC-microgrids with distributed energy resources: A review. Renewable and sustainable energy reviews. 2013;24:387-405.
[6] Pandey AK, Tyagi V, Jeyraj A, Selvaraj L, Rahim N, Tyagi S. Recent advances in solar photovoltaic systems for emerging trends and advanced applications. Renewable and Sustainable Energy Reviews. 2016;53:859-84.
[7] Singh BP, Goyal SK, Kumar P. Solar PV cell materials and technologies: Analyzing the recent developments. Materials Today: Proceedings. 2021;43:2843-9.
[8] Tyagi V, Rahim NA, Rahim N, Jeyraj A, Selvaraj L. Progress in solar PV technology: Research and achievement. Renewable and sustainable energy reviews. 2013;20:443-61.
[9] Ramalingam K, Indulkar C. Solar energy and photovoltaic technology. Distributed Generation Systems. 2017:69-147.
[10] Borenstein S. The private and public economics of renewable electricity generation. Journal of Economic Perspectives. 2012;26(1):67-92.
[11] Garbesi K. Catalog of DC appliances and power systems. 2012.
[12] Datta U, Kalam A, Shi J. A review of key functionalities of battery energy storage system in renewable energy integrated power systems. Energy Storage. 2021;3(5):e224.

http://www.doi.org/10.62341/istj-vol38-1-79im

[13] Basit MA, Dilshad S, Badar R, Sami ur Rehman SM. Limitations, challenges, and solution approaches in grid-connected renewable energy systems. International Journal of Energy Research. 2020;44(6):4132-62.

[14] Karlsson P. DC distributed power systems-Analysis, design and control for a renewable energy system. 2002.

[15] Fotopoulou M, Rakopoulos D, Trigkas D, Stergiopoulos F, Blanas O, Voutetakis S. State of the art of low and medium voltage direct current (Dc) microgrids. Energies. 2021;14(18):5595.

[16] Ullah S, Haidar AM, Hoole P, Zen H, Ahfock T. The current state of Distributed Renewable Generation, challenges of interconnection and opportunities for energy conversion based DC microgrids. Journal of Cleaner Production. 2020;273:122777.

[17] Carreiro AM, Jorge HM, Antunes CH. Energy management systems aggregators: A literature survey. Renewable and sustainable energy reviews. 2017;73:1160-72.

[18] Gunasekaran M, Mohamed Ismail H, Chokkalingam B, Mihet-Popa L, Padmanaban S. Energy management strategy for rural communities' DC micro grid power system structure with maximum penetration of renewable energy sources. Applied Sciences. 2018;8(4):585.

[19] Iqbal S, Sarfraz M, Ayyub M, Tariq M, Chakrabortty RK, Ryan MJ, et al. A comprehensive review on residential demand side management strategies in smart grid environment. Sustainability. 2021;13(13):7170.

[20] Li X, Wang S. Energy management and operational control methods for grid battery energy storage systems. CSEE Journal of Power and Energy Systems. 2019;7(5):1026-40.

[21] El-Hawary ME. The smart grid—state-of-the-art and future trends. Electric Power Components and Systems. 2014;42(3-4):239-50.

http://www.doi.org/10.62341/istj-vol38-1-79im

[22] Bayram IS, Ustun TS. A survey on behind the meter energy management systems in smart grid. Renewable and Sustainable Energy Reviews. 2017;72:1208-32.

[23] Aloise-Young PA, Ross EC, Dickmann EM, Cross JE, Zimmerle D, Nobe MC. Overcoming barriers to direct current power: Lessons learned from four commercial building case studies. Energy Efficiency. 2021;14:1-17.

[24] Zhou B, Li W, Chan KW, Cao Y, Kuang Y, Liu X, et al. Smart home energy management systems: Concept, configurations, and scheduling strategies. Renewable and Sustainable Energy Reviews. 2016;61:30-40.

[25] Abu-Bakar H, Williams L, Hallett SH. A review of household water demand management and consumption measurement. Journal of Cleaner Production. 2021;292:125872.

[26] Brunet C, Savadogo O, Baptiste P, Bouchard MA. Shedding some light on photovoltaic solar energy in Africa–A literature review. Renewable and Sustainable Energy Reviews. 2018;96:3.