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Strengthening renewable energies: The crucial role of photovoltaics as backup power

Fortaleciendo las energías renovables: El papel crucial de la energía fotovoltaica como respaldo

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Abstract

Renewable energies emerge as one of the great tools in the fight against imminent climate change. Their variable nature gives rise to the need for backup energy systems. And in that context, photovoltaic energy presents itself as an effective option. Currently, there are simulation studies to evaluate solar energy performance and proposals for storage improvements. However, many of these findings are scattered or disconnected, and the possibility of using photovoltaic energy as a backup solution is often not considered. In this research, a literature review was conducted to synthesize relevant information and create a comprehensive vision on the topic. It was found that by having a hybrid system, it is possible to cover up to 50% of the demand, and when combined with backup storage and a prediction system, this increases significantly. Therefore, this work offers a holistic vision that considers the technical, environmental, and economic factors that enable the use of photovoltaic cells as a backup solution.

Photovoltaics, Renewable energies, Energy backup systems

Resumen

Las energías renovables se alzan como una de las grandes herramientas en la lucha contra el cambio climático inminente. Su naturaleza variable hace que surja la necesidad de contar con sistemas de respaldo energético. Y, en ese contexto, la energía fotovoltaica se presenta como una opción efectiva. En la actualidad existen estudios de simulaciones para evaluar el desempeño de la energía solar, y propuestas de mejoras en almacenamiento. Sin embargo, muchos de estos hallazgos se encuentran dispersos o inconexos y, además, no se suele considerar la posibilidad de usar la energía fotovoltaica como una forma de respaldo. En esta investigación se realizó una revisión de literatura científica para sintetizar la información relevante y crear una visión integral sobre el tema. Se encontró que al tener un sistema hibrido es posible cubrir hasta el 50% de la demanda, y combinado con un almacenamiento de respaldo y un sistema de predicción esto incrementa notablemente. Con ello, este trabajo ofrece una visión holística que considera cuales son los factores técnicos, ambientales, y económicos que permiten el uso de las celdas fotovoltaicas como una forma de respaldo.

Fotovoltaica, Energías renovables, Sistemas de respaldo energético

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Introduction

For many years, scientists like John Tyndall and Svante Arrhenius have warned that changes in the composition of the atmosphere could have a significant impact on the planet's temperature. What were once possibilities have now become a disturbing reality, as evidenced by records showing that 2016 and 2020 have been the hottest years on record to date (NASA, n.d).

In the battle against the disaster of climate change, the harnessing of renewable energies emerges as one of our most valuable resources to reduce greenhouse gas emissions and avoid the use of fossil fuels. However, the nature of renewable energies is fluctuating and intermittent due to climate conditions, geography, and other factors beyond human control. This is one of today’s greatest challenges, hindering the complete transition to renewable energies. Such intermittency makes it absolutely necessary to develop backup systems that provide us with a reliable and constant energy flow. In this context, the use of photovoltaic panels as backup energy systems holds incredible potential.

The objective of this paper is to evaluate the effectiveness and feasibility of using photovoltaic panels as a backup for renewable energy systems. It aims to assess the advantages, limitations, and successful implementations of this approach, considering technical considerations, integration challenges, economic viability, and environmental impacts. By investigating the role of photovoltaic panels as backup, this study contributes to the understanding of sustainable energy solutions and offers valuable insights for energy planners and policymakers.

Overview of photovoltaic energy

The photovoltaic effect is the generation of electric voltage between two electrodes attached to a solid or liquid system caused by shining a light on the system (Hayat et al., 2018).

Photovoltaic cells are capable of harnessing this phenomenon because they are made out of semiconductor material, that can absorb photons which create free electrons that then flow through an external circuit.

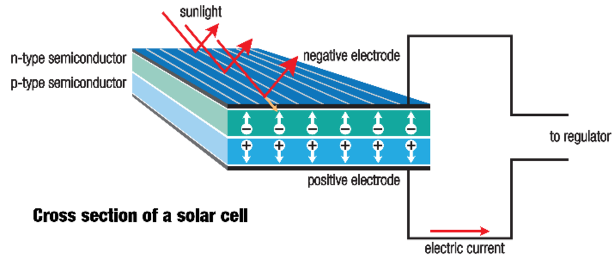

Figure 1 How solar panels work
Source: Visual Capitalist. (2019). [Animated infographic]. Visual Capitalist. https://www.visualcapitalist.com/animation-how-solar-panels-work/

As shown in Figure 1, photovoltaic cells are composed of different layers: The outer crystal, an n-type semiconductor at the top, and a p-type semiconductor at the bottom. Together they create a PN junction.

When the sun hits the p-type semiconductor it excites the extra electrons and releases them from their atoms, which are then attracted to the n-layer. This creates a charge difference that generates an electric field, which accelerates the electron and generates a charge that is picked up by the metal contacts, which then flows through the network (Parida, Iniyan, & Goic, 2011).

When multiple photovoltaic cells are used together, we obtain solar panels, a technological marvel that allows us to harness the power of the sun to energize our day-to-day lives. According to Hayat et al. (2018), the sun can generate 4.6 x 10^{20} J in one hour. Which is equivalent to all the energy used by humanity for one year. In other words, the sun has an unparalleled capacity to supply all the energy needs of human beings. The question is the capacity of the solar cells to absorb the energy adequately.

Advantages and limitations of photovoltaic energy

Photovoltaic cells have a variety of intrinsic characteristics that make them stand out as an excellent and highly useful option. According to Hayat et al. (2018), the following are the most prominent features:

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- They are a modular technology, meaning they can be installed on various surfaces to adapt to different needs, spaces, and even economic capacities. In other words, they can be effectively used in residential areas, rural locations, industrial facilities, and even space vehicles like NASA's Martian rovers.

- Unlike other energy generation systems, PV cells do not produce any pollution. They can be used without fear of harming human and animal health or contributing to environmental damage.

- When solar energy is generated locally, it eliminates the cost of transmission and energy losses that occur in transformers and distribution lines.

- Photovoltaic panels require minimal maintenance and can last for many years without issues.

- They have the capacity to provide electrical independence for individuals and their communities, which is especially valuable in areas with unreliable access to electricity.

- Photovoltaic systems can be connected to distribution grids to increase their overall efficiency.

However, despite the numerous advantages of PV technology, it is not without limitations. According to Toledo, Oliveira Filho, and Diniz (2010), the following limitations should be considered:

- Not all received solar energy is converted into electricity. In fact, the efficiency of commercial panels typically ranges between 15% and 25%. This means that only a fraction of the incident solar energy is converted into usable electricity.

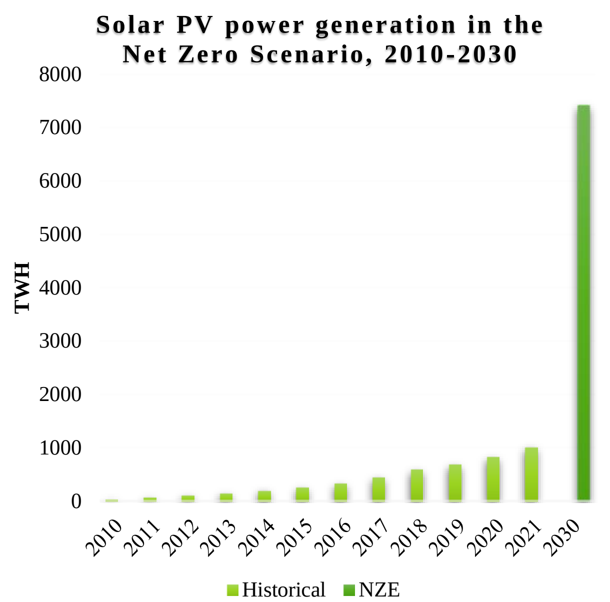
- Power generation is restricted by environmental conditions.

- Photovoltaic generation alone, due to its intermittent nature, usually does not have a significant impact on balancing energy demand during peak hours when integrated into distribution grids (Weitemeyer, Kleinhans, Vogt, & Agert, 2015).

- Although solar panels provide long-term cost savings, the initial investment required can deter some individuals.

Global trends in photovoltaic utilization

Photovoltaic solar generation reached a record increase of 179 TWh (a 22% growth) in 2021, surpassing 1,000 TWh. It is the second renewable technology with the highest absolute growth in generation in 2021, following wind power. Photovoltaic solar energy accounted for 3.6% of global electricity generation (International Energy Agency, 2021).



Graphic 1 Solar PV power generation in the Net Zero Scenario, 2010-2030
Source: IEA. (2022). Solar PV power generation in the Net Zero Scenario, 2010-2030. IEA, Paris. Retrieved from https://www.iea.org/data-and-statistics/charts/solar-pv-power-generation-in-the-net-zero-scenario-2010-2030

The trend shows a constant increase in the use of energy generated through photovoltaic cells. And it's not surprising, as the nearly limitless energy of the sun is always within our reach; we just need to create the means to harness it

This, combined with growing concerns that the overuse of fossil fuels and other polluting forms of energy generation will lead to irreversible damage to the environment, along with the increasing energy demand, has led many countries around the world to embark on incredible photovoltaics megaprojects.

According to the Solar Energy Industries Association (2023), in the United States alone, there are currently over 96 GWdc of major solar projects in operation. Furthermore, their database records more than 740 major energy storage projects representing over 10,580 MWh of capacity, and approximately 99 GWdc of large-scale solar projects either under construction or in development.

Similar megaprojects can be found in other parts of the world as well. For example, the Longyangxia Dam Solar Park in China, one of the largest solar parks in the world, covers an area of 27 km2 and produces 850 MW of energy. India boasts the Cochin International Airport, which operates entirely on photovoltaic energy and even feeds excess energy back into the electrical grid. Another notable example is the Benban Solar Park in Egypt, with a capacity of 1650 megawatts and covering an area of 36 km2 (Popular Mechanics, 2023).

Need for backup in renewable energy systems

Renewable energies are a key component in building a brighter future. However, their intermittent nature presents a formidable challenge that necessitates the search for efficient solutions and alternatives.

Intermittent nature of renewable energy sources

Intermittency is arguably the biggest challenge of renewable energies. Even with the intention of transitioning fully to renewable energies, the threat arises when climatic or geographic conditions impact energy production. This has the potential to damage the reputation of renewable energies, labeling them as unreliable, insecure, or insufficient. Such assumptions, to some extent, are grounded. In the past, countries like Germany have experienced situations where 1.1 million solar energy systems generated little electricity during winter, leading to the need for fossil fuel backup energy systems and the importation of gas (Gowrisankaran, Reynolds, & Samano, 2016).

Challenges and the need for backup solutions

The generation of electricity through renewable energy sources brings forth a series of challenges. There is a possibility of not being able to meet the energy demand by relying solely on a single form of renewable energy, especially during peak hours or in high-consumption areas. This can be further exacerbated by intermittencies.

The same variability inherent in renewable energy systems can destabilize electrical grids, causing voltage and frequency fluctuations that hinder proper system operation and create a constant reliance on imports or backup systems that require the use of polluting substances (Gowrisankaran, Reynolds, & Samano, 2016).

It is evident, therefore, that backup systems become almost a necessity in the face of intermittency and serve as a response to the shortcomings of renewable energies. Typically, backup systems store energy produced by more stable sources such as coal, oil, or nuclear power. However, there is also the possibility of exploring the use of other renewable energy sources to power these systems, thus creating a hybrid system that ensures greater security and stability.

Photovoltaic panels as backup for other renewable energy

Among renewable energies, harnessing the power of the sun through photovoltaic panels is an intriguing option, opening the possibility of creating a hybrid energy system.

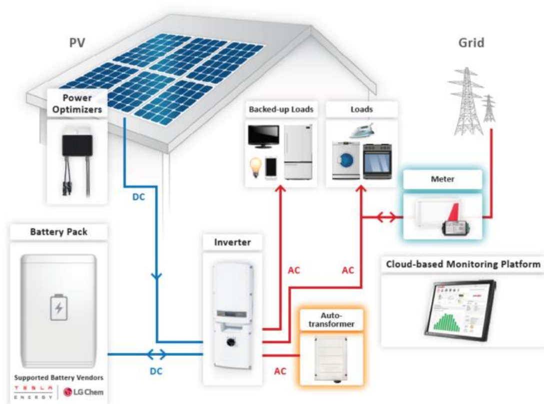


Figure 2 A backup solar system
Source: Artisan Electric. (n.d.). Solar power as backup power storage. The next breakthrough in solar. Artisan Electric. https://artisanelectricinc.com/solar-as-backup-power/

Figure 2 shows a solar backup system that has a connection to the electrical grid as its primary source of energy, and it can be used in a residential setting. The energy generated by the photovoltaic panels is stored in batteries for later use in case of intermittency. Another interesting alternative would be, in a larger context involving electrical grid operators, to store the excess energy and integrate it into the electrical grid when any type of intermittency occurs.

Evaluation of effectiveness and feasibility

In order to determine the feasibility of implementing photovoltaic panels to create a backup system, it is necessary to explore not only the technical or theoretical aspects but also the positive or negative consequences that their use would have on human societies and the planet that hosts them.

Performance assessment

The material from which the photovoltaic cell is constructed will significantly influence the amount of energy that can be extracted from sunlight. Multi-junction solar cells have the highest efficiency rate, reaching about 34.1% (Hayat et al., 2018). This efficiency rate is comparable to that of fossil fuel power plants, demonstrating a solid capacity to generate sufficient energy for human activities.

System design, capacity planning, and grid compatibility

Although the energy conversion rates between modern photovoltaic panels and fossil fuel processing plants may be similar, it does not mean that the same amount of energy is being produced. Therefore, in order for electricity grids to be powered 100% by renewable energy, a combination of different sources is necessary. In this case, solar energy can be used to supply the grid and store backup energy. Research suggests that for proper integration into the electricity grids, the optimal mix of wind and solar power generation is important to balance power fluctuations. It is possible to meet up to 50% of the demand without the need for storage (Weitemeyer, Kleinhans, Vogt, & Agert, 2015).

The number of panels and batteries required should also be considered, especially considering the possibility of intermittency. Khoury, Mbayed, Salloum, and Monmasson (2015) proposed a PV-battery backup system as an alternative to diesel-based systems used in Uganda. It was found that the most cost-effective solution for environments with a 52% cutoff time was a configuration of 14 photovoltaic panels and 20 batteries.

In a hybrid system where solar energy contributes to the grid and serves as backup energy, the use of photovoltaic panels is advantageous when short-cycle storage is utilized. Furthermore, in combination with wind and hydroelectric power, a higher proportion of solar and wind energy reduces the amount of reserve energy needed to ensure hourly supply (Tapetado, Victoria, Greiner, & Usaola, 2021).

Photovoltaic systems can be integrated into buildings or exist in the form of solar farms. In the latter case, it is important to consider the placement of the system to determine its feasibility. The use of a Geographic Information System (GIS) provides valuable data such as temperature, solar radiation levels, and wind speed. Locations with high solar radiation levels are ideal, as well as those that allow easy connection to transmission lines to minimize costs. Therefore, the viability of integrating photovoltaic cells as a backup to the electrical grid heavily depends on the country's geography (Yu et al., 2021).

When photovoltaic energy is used as a backup, we are designing a Hybrid Renewable Energy System (HRES), which typically consists of a combination of photovoltaic panels, wind turbines, battery systems, and diesel generators (That will be excluded from the equation to achieve full renewable energy generation). These systems are optimized using artificial intelligence methods, iterative methods, and software tools such as HOMER and PSO. In this way, the efficiency and cost implications of the HRES can be effectively managed, with the effect amplified by including Battery Energy Storage Systems (BESS) for managing energy balance (León Gómez, De León Aldaco, & Aguayo Alquicira, 2023).

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It can be concluded that using a hybrid photovoltaic backup system has a huge potential for managing the balance between demand and generation of energy and reducing greenhouse gas emissions (Werulkar & Kulkarni, 2015).

Storage and Energy Management

One of the central elements of the photovoltaic backup system is undoubtedly the Battery Energy Storage Systems (BESS). Photovoltaic and wind energy are relatively easy to integrate into these systems. The most common types of batteries include lead-acid, alkaline (nickel), silver, and lithium batteries (Ogunniyi & Pienaar, 2017).

Another interesting method is to use a hydrogen-based storage system, consisting of three components: an electrolyzer, a hydrogen tank, and a fuel cell. The electrolyzer produces hydrogen through electricity, which is then stored in the tank. Energy is generated through a chemical reaction between hydrogen and oxygen when the hydrogen is directed into the fuel cell. The main advantage of this system is its ability to store energy in the long term without significant losses. By combining batteries with hydrogen storage, taking advantage of their efficiency and durability respectively, a hybrid system is obtained that can achieve a high self-sufficiency ratio (SSR), which can help reduce the load on the electrical grids, especially during peak hours (Zhang et al., 2016)

In recent times, neural networks have emerged as a tool to address the intermittency of renewable energies. They can be implemented to predict the generation capacity of a photovoltaic plant up to 4 hours in advance. With this information, it is possible to plan the appropriate distribution of energy based on demand and availability. Additionally, by being able to identify energy excesses produced during periods of high solar radiation, it opens the possibility of planning and scheduling the storage and release of energy to the grid when needed (Xu et al., 2021).

The most interesting idea would be to have a system that can connect to the power grid or function as an isolated system. A proposal by Velasco de la Fuente et al. (2013) addresses energy management through a multi-loop control scheme.

In grid-connected mode, the system uses an inverter to adjust the current it delivers to the grid based on the existing voltage. In isolated mode, the system changes its configuration and uses inverters to adjust the voltage and share the power required by local loads. It also includes an energy storage system composed of batteries and a converter that optimizes the utilization of solar energy. The system uses an algorithm to extract the necessary energy to charge the batteries from both solar energy and the grid when connected. Additionally, the voltage in the system is controlled by a converter and an inverter, thus providing a backup system powered by solar photovoltaic energy (Velasco de la Fuente et al., 2013).

Currently, energy storage and control systems make it possible to use photovoltaic energy as a backup. With accurate demand prediction, energy storage systems can be designed to cover any type of intermittency or additional demand that may arise. In Japan, for example, approximately 40TW would be needed to cover the extra electricity consumed during the summer (Esteban, Zhang, & Utama, 2012).

Economic and feasibility analysis

In a residential context, the investment cost for a solar system with 200 Wp solar panels, solar charge controller, auto controller, additional sub-meters for energy monitoring, inverter, and battery are Rs. 25,000. The price of solar panels has been decreasing year by year due to demand and technological advancements, making it an increasingly affordable option. Photovoltaic modules have reduced their price by 47% in the last ten years (Cladco, 2022).

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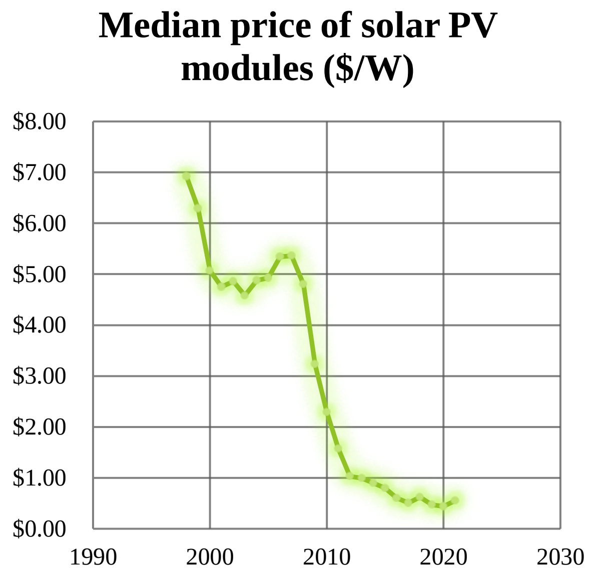

Graphic 2 Solar Panel Prices Over Time
Source: Cladco. (2022, November 16). Solar Panel Prices Over Time. Cladco. Retrieved from: https://www.cladco.co.uk/blog/post/solar-panel-prices-over-time#:~:text=The%20installed%20price%20of%20residential%20solar%20panel%20systems%20dropped%20by,dropped%20by%20a%20massive%2092%25.

Graphic 2 shows the downward trend of photovoltaic module prices since 1998. This is an advantage when developing larger projects that aim to integrate energy into the electricity grid.

According to Khoury, Mbayed, Salloum, & Monmasson (2015), considering capital costs, replacement costs, and maintenance costs, the total system expenditure over a 20-year period is €50,936. The system's payback period is around 10 years and 6 months, with a positive value of €7,830 harvested during that time. This means that the system reduces the electricity cost over time, avoiding the use of fossil fuel-based backups, which tend to have unstable prices.

Photovoltaic systems are economically feasible, as they have been found to have a lower life cycle cost compared to traditional power generation systems, such as diesel or petrol generators (Parida, Iniyan, & Goic, 2011). It can be observed that in the long run, this system presents notable economic benefits but has a relatively large entry barrier as it requires installing an entire system at once

Environmental Impacts

The impact of photovoltaic panels, in broad terms, is positive. Their use reduces the burning of fossil fuels and completely eliminates the emission of greenhouse gases (Parida, Iniyan, & Goic, 2011). However, the absence of such gas emissions does not mean that they do not generate any kind of environmental impact. Large-scale projects like solar farms require extensive land, estimated at 3.5 to 10 acres per megawatt. This can cause damage to habitats or pose an obstacle to land use for agriculture. On the other hand, the manufacturing of photovoltaic cells involves handling hazardous materials both in their preparation and assembly. This necessitates extremely careful handling by workers to avoid exposure to harm and proper management of waste. Materials such as silicon, hydrochloric acid, nitric acid, or arsenic can be involved (Union of Concerned Scientists, 2022). In general, the negative impacts are minimal and overshadowed by the environmental benefits they provide.

Comparison with other backup solutions

Indicator	Photovoltaics Backup	Diesel Backup	Gas Backup
Cost-effectiveness	Moderate to High (Initial cost)	Moderate (Fuel costs)	High (Infrastructure setup)
Environmental Impact	Low (Clean energy generation)	High (Emissions)	Low (Clean energy generation)
Reliability and Resilience	Moderate to High (Depends on system quality and geographical conditions)	High (Depends on fuel supply)	High (Depends on gas supply)
Scalability and Modularity	High (Expandable system capacity)	Low (Fixed capacity)	Moderate to High (Scalable infrastructure)
Independence from Fuel Supply	High (No reliance on external fuel)	Low (Dependent on fuel availability)	Low (Dependent on gas availability)
Longevity and Durability	High (25-30 years lifespan)	High (Long lifespan)	Moderate to High (Long lifespan)
Grid Support and Energy Exchange	High (Bi-directional energy flow)	Low (One-way energy flow)	Low (One-way energy flow)

Table 1 Comparison of different backup solutions

Methodology

This review article employed a systematic approach to gather and analyze relevant literature on the effectiveness and feasibility of using photovoltaic systems as backup energy in renewable energy systems, aiming to synthesize existing knowledge on the topic. The objective was to assess the current state of research and identify key findings, trends, and gaps in the literature related to the use of photovoltaic systems as backup energy.

The review was guided by the following research questions:

a) What are the advantages and limitations of using photovoltaic systems as backup energy in renewable energy systems?

b) What factors influence the effectiveness and feasibility of using photovoltaic systems as backup energy?

c) What are the best practices and successful case studies of integrating photovoltaic systems as backup energy in renewable energy systems?

An exhaustive search was conducted in multiple electronic databases, including IEEE Xplore, ScienceDirect, and Google Scholar. Search terms such as "photovoltaic systems," "backup energy," "renewable energy," "energy storage systems," and related keywords were used. The search was limited to articles published from 2010 onwards.

Articles were included in the review if they provided information on the use of photovoltaic systems as backup energy, discussed their advantages and limitations, and presented simulations or empirical evidence. Only peer-reviewed articles were considered to ensure the quality and reliability of the sources.

Relevant information, including key findings, methodologies, and conclusions, was extracted from the selected articles. The data were organized and synthesized through thematic analysis, focusing on common themes, trends, and patterns in the literature. The data analysis process involved comparing and contrasting different perspectives and identifying recurring themes.

To ensure the reliability and credibility of the included articles, a quality assessment was conducted. The articles were evaluated based on their methodology, research design, and the authors' expertise. Only articles meeting a minimum quality threshold were included in the final analysis.

Additionally, international reports, statistical data, and relevant news on the global utilization of photovoltaic energy were analyzed. These reports provided updated information on installed capacity, sector growth, government policies, and other key aspects.

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Conclusion

The objective of this research was to determine the feasibility of using photovoltaic panels as a form of backup energy generation and to discover the most important factors to consider. Through a review of scientific literature, it was found that the use of photovoltaic systems as a backup for renewable energy demonstrates the potential to be a key factor in driving towards a 100% renewable future, as proposed by (Esteban, Zhang, & Utama, 2012). This paper makes a valuable contribution by collecting and synthesizing innovative proposals on photovoltaic energy, storage and backup systems, and energy control systems using machine learning models. This will be useful for organizations and individuals responsible for developing energy strategies and policies, seeking to effectively promote clean energy by considering the information presented here to verify the feasibility of implementation in their environment.

While the findings compiled in this paper are rigorous and provide useful information, some of them are based on simulations. Therefore, when translating them into reality, certain parameters such as prices or the efficiency of photovoltaic cell conversion could be uncertain and vary significantly depending on the geographical location. Additionally, although the focus is on using photovoltaic technology to mitigate the intermittency of other renewable energies, many of the reviewed research and simulations were conducted on relatively small-scale systems such as residential or village setups. Therefore, it is suggested that future research conducts studies and investigations regarding the integration of these photovoltaic backup systems in areas with different conditions in terms of intermittency, demand, and availability of renewable energy, as well as in larger-scale systems connected to the electrical grids.

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