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Review

Exploring Optimal Charging Strategies for Off-Grid Solar Photovoltaic Systems: A Comparative Study on Battery Storage Techniques

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Abstract: This paper presents a comparative analysis of different battery charging strategies for off-grid solar PV systems. The strategies evaluated include constant voltage charging, constant current charging, PWM charging, and hybrid charging. The performance of each strategy is evaluated based on factors such as battery capacity, cycle life, DOD, and charging efficiency, as well as the impact of environmental conditions such as temperature and sunlight. The results show that each charging strategy has its advantages and limitations, and the optimal approach will depend on the specific requirements and limitations of the off-grid solar PV system. This study provides valuable insights into the performance and effectiveness of different battery charging strategies, which can be used to inform the design and operation of off-grid solar PV systems. This paper concludes that the choice of charging strategy depends on the specific requirements and limitations of the off-grid solar PV system and that a careful analysis of the factors that affect performance is necessary to identify the most appropriate approach. The main needs for off-grid solar photovoltaic systems include efficient energy storage, reliable battery charging strategies, environmental adaptability, cost-effectiveness, and user-friendly operation, while the primary limitations affecting these systems encompass intermittent energy supply, battery degradation, environmental variability, initial investment costs, fluctuations in energy demand, and maintenance challenges, emphasizing the importance of careful strategy selection and system design to address these factors. It also provides valuable insights for designing and optimizing off-grid solar PV systems, which can help to improve the efficiency, reliability, and cost-effectiveness of these systems.

Keywords: Li-ion battery; cathode materials; batteries; energy storage; renewable energy

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1. Introduction

The use of off-grid solar photovoltaic (PV) systems has increased due to the global shift towards renewable energy. These systems offer a dependable and sustainable source of electricity to remote areas that lack grid connectivity [1,2]. To ensure their success, off-grid solar PV systems require an efficient energy storage system, usually in the form of a battery. The battery storage system's performance is influenced by several factors, including the battery charging strategy [3,4], which has a significant impact on the overall off-grid solar PV system performance. Various battery charging strategies are employed in off-grid solar PV systems, each with its own advantages and disadvantages. This study compares different battery charging strategies for off-grid solar PV systems, focusing on their effects on system performance and battery life. Off-grid solar PV systems are increasingly popular in remote areas where grid connectivity is unreliable or nonexistent [5]. These systems use batteries to store excess solar energy generated during the day, which is used to power devices and appliances at night or during overcast weather conditions. The battery storage system plays a critical role in the performance and reliability of off-grid solar PV systems, ensuring a consistent and reliable supply of electricity [6].

Effective battery charging strategies are essential to ensure optimal battery performance and longevity in off-grid solar PV systems. There are several battery charging strategies available, such as constant voltage, constant current, pulse charging, and float charging. Each strategy has its advantages and disadvantages and can impact battery performance, system efficiency, and overall system cost [7,8].

Off-grid solar PV systems are self-contained renewable energy systems that generate electricity using solar panels and store excess energy in batteries for later use [9,10]. Unlike grid-tied solar PV systems, off-grid systems are not connected to the utility grid and are often used in remote areas where grid electricity is not available or is unreliable [11,12]. Off-grid solar PV systems consist of several components, including solar panels, batteries, charge controllers, inverters, and sometimes backup generators. Solar panels generate DC electricity from sunlight, which is then converted into usable AC electricity via the inverter. The batteries store excess energy generated via solar panels for later use when there is no sunlight available. The charge controller regulates the flow of energy between the solar panels and batteries to prevent overcharging or undercharging [13]. Off-grid solar PV systems can be designed to meet different energy needs, from powering a small cabin or RV to providing electricity to an entire village. The size and capacity of the system depend on several factors, including energy demand, location, available sunlight, and budget [14]. Off-grid solar PV systems offer several benefits, including lower energy costs, independence from the grid, and reduced environmental impact [15]. However, they also require careful planning, design, and maintenance to ensure reliable and efficient performance. The optimization of battery charging strategies is crucial for improving the performance and efficiency of off-grid solar PV systems [16,17].

This paper aims to conduct a thorough comparative analysis of different battery charging strategies for off-grid solar PV systems, assess their performance based on factors like battery capacity, cycle life, DOD, and charging efficiency, identify the strengths and limitations of each strategy, and offer insights that can inform the design and optimization of off-grid solar PV systems, ultimately contributing to improved system efficiency, reliability, and cost-effectiveness.

2. Materials and Methods

Battery storage is a critical component of off-grid solar PV systems because it allows for the storage of excess energy generated via the solar panels for later use when there is no sunlight available. In other words, it enables energy to be stored for use during night-time or on cloudy days [18]. Battery storage allows off-grid solar PV systems to be more reliable and efficient by providing a stable source of power even when solar panels are not generating electricity. Without battery storage, off-grid solar PV systems would only be able to provide electricity during the day, which may not meet the energy demand of the user [19,20]. Moreover, battery storage can help reduce the size and cost of off-grid solar PV systems by reducing the need for larger solar panels or backup generators. This is because batteries can store excess energy during peak sunlight hours and release it when energy demand is high, reducing the need for additional energy-generating components [21]. Battery storage also enables off-grid solar PV systems to be more sustainable and environmentally friendly by reducing the dependence on fossil fuels for backup power [4]. This is particularly important in remote areas where grid electricity is not available, and reliance on diesel generators can be expensive and environmentally damaging [22].

There are several battery charging strategies used in off-grid solar PV systems, and each strategy has a different impact on the system's performance. Some of the commonly used battery charging strategies include [22,23]:

(1) Constant voltage charging: This strategy involves charging the battery at a constant voltage level until the battery is fully charged. This strategy is simple and cost-effective, but it can lead to overcharging and reduce battery life.

(2) Pulse charging: This strategy involves charging the battery with short bursts of high current followed by a period of rest. This strategy can improve battery life by preventing sulfating, but it may also increase the risk of overcharging.
(3) Float charging: This strategy involves maintaining a constant voltage level to keep the battery fully charged. This strategy is ideal for batteries that are not frequently used, but it may not be suitable for batteries that are subjected to heavy use.
(4) Smart charging: This strategy involves using advanced algorithms to monitor the battery's state of charge and adjust the charging voltage and current accordingly. This strategy can optimize battery charging and improve battery life, but it can be more complex and expensive.

The choice of battery charging strategy depends on several factors, including the battery type, temperature, and state of charge. The wrong choice of strategy can lead to poor system performance, reduced battery life, and increased maintenance costs.

The circuit in Figure 1 consists of a solar panel, a diode, a resistor, and a battery. The solar panel converts sunlight into electricity, which is then passed through the diode. The diode prevents the current from flowing back into the solar panel. The resistor limits the current that flows into the battery.

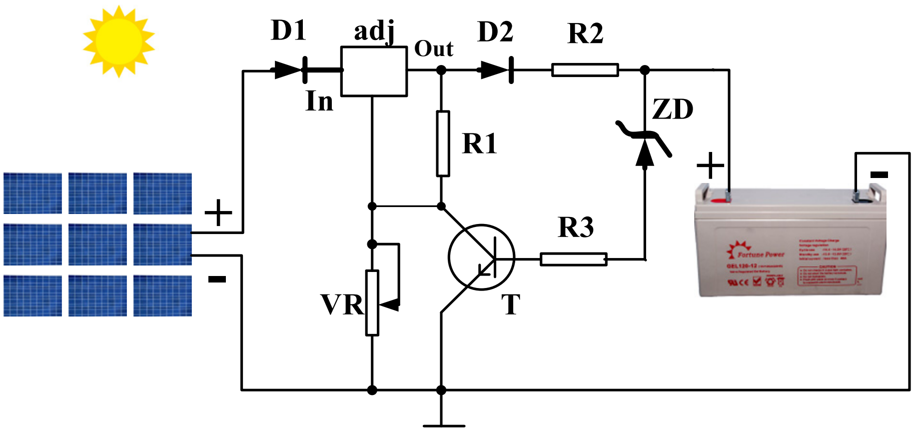

Figure 1. A schematic diagram of the solar battery charging circuit.

The battery is charged when the voltage of the solar panel is greater than the voltage of the battery. The charging current will decrease as the battery gets closer to being fully charged.

This is just a simple circuit, and there are many other ways to charge a battery from solar power. The specific circuit that you use will depend on the type of battery, the solar panel, and the desired charging rate.

3. Type of Battery Used in Solar System

Solar systems typically use deep-cycle batteries to store energy generated from solar panels. These batteries are designed to discharge a large amount of energy over an extended period, which makes them ideal for solar power systems that require a steady stream of energy [1]. Deep-cycle batteries come in several different types, including lead-acid, lithium-ion, and nickel-cadmium [24]. The most used deep-cycle battery for solar systems is the lead-acid battery because it is affordable, reliable, and widely available. However, lithium-ion batteries are becoming increasingly popular due to their higher energy density and longer lifespan [25].

Several types of batteries can be used in a solar system, but the most used are

(1) Lead-acid batteries: These are the most common type of batteries used in solar systems. They are reliable, durable, and have been in use for many years. They are also relatively inexpensive [26].

(2) Lithium-ion batteries: These batteries are becoming increasingly popular due to their high energy density and long lifespan. They are more expensive than lead-acid batteries, but they have a longer lifespan and are more efficient.
(3) Nickel-cadmium batteries: These batteries are known for their durability and ability to withstand extreme temperatures. They are more expensive than lead-acid batteries, but they are a good option for harsh environments [27].
(4) Flow batteries: These batteries use a liquid electrolyte and can store large amounts of energy. They are more expensive than other types of batteries but can be a good option for large-scale storage systems [28].

4. Characteristics of Battery Charging Using Off-Grid

When charging batteries using an off-grid system, several characteristics are important to consider:

(1) Charging voltage: The charging voltage must be carefully controlled to prevent overcharging or undercharging the batteries. Too much voltage can damage the battery, while too little voltage may not fully charge the battery [29].
(2) Charge current: The current supplied to the battery during charging must also be carefully controlled. If the current is too high, the battery can overheat and be damaged. If the current is too low, the battery may not fully charge.
(3) Charging time: The charging time depends on the capacity of the battery and the charging rate. It is important to allow enough time for the battery to fully charge without overcharging it [30].
(4) Temperature: The temperature of the battery and the charging environment can affect the charging process. Batteries should be charged at a moderate temperature, ideally between 20 °C and 25 °C.
(5) Battery type: Different types of batteries have different charging requirements. For example, lead-acid batteries require a different charging method than lithium-ion batteries.
(6) Charging controller: An off-grid charging system should include a charging controller to regulate the charging voltage and current, and to prevent overcharging and undercharging of the batteries [31].
(7) Charging source: The charging source can be solar panels, wind turbines, generators, or a combination of these. The charging source must be able to provide enough power to fully charge the batteries [32,33].

Here are some tables (Tables 1 and 2) summarizing the characteristics of battery charging using an off-grid system:

Table 1. Charging voltage and current characteristics for different battery types [33].

Battery Type	Charging Voltage	Charging Current
Lead-acid	13.8–14.4 V	10–20% of C * [33].
Lithium-ion	4.2 V per cell	0.5–1 C * [17].
Nickel-cadmium	1.5–1.6 V per cell	0.1–0.3 C * [33].

* Note: C refers to the capacity of the battery in ampere-hours (Ah).

Table 2. Charging temperature recommendations for different battery types [33].

Battery Type	Charging Temperature	Recommended Charging Controller
Lead-acid	20–25 °C	PWM or MPPT with float charging [30].
Lithium-ion	10–30 °C	MPPT with constant current [33].
Nickel-cadmium	10–40 °C	Constant current with temperature sensing [33].

Note: Extreme temperatures (too high or too low) can damage the battery and reduce its lifespan.

5. Comparative Studies on Battery Charging Strategies in Off-Grid Solar PV Systems

Off-grid solar PV systems are becoming increasingly popular in areas where there is no access to grid electricity [34]. One of the most important components of these systems is the battery, which stores solar energy for use when the sun is not shining [35]. There are different strategies for charging batteries in off-grid solar PV systems, and this section presents some comparative studies on these strategies.

5.1. Constant Voltage Charging vs. MPPT Charging

A study conducted by researchers in Malaysia compared the performance of lead-acid batteries in off-grid solar PV systems using constant voltage charging and MPPT charging [36]. The results showed that MPPT charging improved the efficiency of the charging process and increased the lifespan of the batteries compared to constant voltage charging [37].

MPPT charging is a more efficient and effective charging strategy for off-grid solar PV systems compared to constant voltage charging as shown in Table 3 [38]. However, it is also more complex and requires additional components, which can increase the cost of the system.

Table 3. Constant voltage charging vs. MPPT charging [37].

Charging Strategy	Charging Temperature	Recommended Charging Controller
Definition	Supplies a fixed voltage to the battery during the charging process.	Adjusts the voltage and current supplied to the battery to maximize the power output of the solar panel [31].
Efficiency	Lower efficiency due to the risk of overcharging or undercharging the battery.	Higher efficiency due to the ability to adjust the voltage and current to match the battery's needs [33].
Charging Time	Longer charging time due to the lower efficiency of the charging process.	Shorter charging time due to the higher efficiency of the charging process [37].
Battery Lifespan	Reduced battery lifespan due to the risk of overcharging or undercharging.	Increased battery lifespan due to the ability to prevent overcharging or undercharging [37].
Complexity	Simple and easy to implement	More complex and requires additional components, such as an MPPT controller [37].
Cost	Lower cost due to the simplicity of the charging strategy	Higher cost due to the additional components required [37].

5.2. Float Charging vs. Cycle Charging

A study conducted in India compared the performance of lead-acid batteries in off-grid solar PV systems using float charging and cycle charging. The results in (Table 4) showed that cycle charging was more effective in maintaining the battery capacity and increasing its lifespan compared to float charging [39].

Table 4. Characteristics of float charging and cycle charging [39].

Characteristics	Charging Temperature	Recommended Charging Controller
Purpose	Maintains battery at full charge	Recharges battery from partial discharge [39].
Voltage	Lower voltage to maintain battery charge	Higher voltage to fully recharge the battery [39].
Charging time	Longer charging time	Shorter charging time [39].
Battery lifespan	Longer lifespan due to lower voltage	Shorter lifespan due to higher voltage [39].
Efficiency	Higher efficiency as it maintains full charge	Lower efficiency as it requires higher voltage to recharge battery [39].
Complexity	Simple and easy to implement	More complex and requires monitoring to prevent overcharging [39].

Float charging uses a lower voltage to maintain battery charge, resulting in a longer battery lifespan and higher charging efficiency. Cycle charging, on the other hand, uses a higher voltage to fully recharge batteries from partial discharge, resulting in a shorter battery lifespan and lower charging efficiency [40,41].

While float charging is simpler and easier to implement, cycle charging requires monitoring to prevent overcharging and ensure optimal charging performance. Ultimately, the choice between float charging and cycle charging depends on the specific needs and requirements of the off-grid battery system.

5.3. Battery Temperature Management

A study represented in Table 5 conducted in China compared the performance of lithium-ion batteries in off-grid solar PV systems with and without battery temperature management. The results showed that battery temperature management significantly improved the charging efficiency and increased the lifespan of the batteries [42,43].

Table 5. Battery temperature management [44].

Performance Metrics	Without Battery Temperature Management	Recommended Charging Controller
Battery lifespan	Shorter lifespan due to high operating temperatures	Longer lifespan due to optimal temperature control [44].
Charging efficiency	Lower efficiency due to high operating temperatures	Higher efficiency due to optimal temperature control [44].
Performance degradation	Faster degradation due to high operating temperatures	Slower degradation due to optimal temperature control [44].
Battery capacity	Reduced capacity due to high operating temperatures	Maintained capacity due to optimal temperature control [44].

Implementing battery temperature management in off-grid solar PV systems can improve the performance and lifespan of lithium-ion batteries. Without temperature management, high operating temperatures can lead to a shorter battery lifespan, lower charging efficiency, faster performance degradation, and reduced battery capacity. With optimal temperature control, lithium-ion batteries can operate at their best performance levels, resulting in a longer lifespan, higher charging efficiency, slower performance degradation, and maintained battery capacity [44].

Battery temperature management can be achieved using active cooling and heating systems or passive insulation. While implementing battery temperature management can be more complex and expensive, it is important to consider the potential benefits in terms of battery performance and lifespan when designing and implementing off-grid solar PV systems [45].

Battery capacity and charging rate. A study conducted in Nigeria compared the charging characteristics of lead-acid batteries with different capacities and charging rates in off-grid solar PV systems. The results showed that higher charging rates reduced the charging time but also increased the risk of overcharging and reduced battery lifespan [46].

6. Battery Technology

A study conducted in the United States compared the performance of lead-acid batteries and lithium-ion batteries in off-grid solar PV systems. The results showed that lithium-ion batteries had higher charging efficiency and longer lifespan compared to lead-acid batteries.

In summary, the choice of battery charging strategy in off-grid solar PV systems depends on various factors, such as battery type, capacity, charging rate, and temperature management [2]. Comparative studies have shown that MPPT charging, cycle charging, and battery temperature management can improve the charging efficiency and increase the lifespan of the batteries [47]. Additionally, newer battery technologies represented in Table 6, such as lithium-ion batteries, may offer better performance than traditional lead-acid batteries [48].

Table 6. Battery temperature management [48].

Battery Technology	Without Battery Temperature Management	Recommended Charging Controller
Lead-acid	Low cost, proven technology, wide availability	Shorter lifespan requires regular maintenance, heavy and bulky [42].
Lithium-ion	High energy density, longer lifespan, lighter and smaller	Higher cost requires careful management to prevent overheating, limited availability [48].
Nickel-cadmium	Long lifespan, high cycle life, wide temperature range	Higher cost, contains toxic materials, lower energy density [48].
Flow batteries	Scalable, longer lifespan, high efficiency	Higher cost, less mature technology, more complex [48].
Sodium-ion	Low cost, longer lifespan, high energy density	Less mature technology, limited availability, may require special handling [48].

As shown in Table 6 the choice of battery technology for off-grid systems depends on the specific needs and requirements of the system. Lead-acid batteries are a common choice due to their low cost and wide availability, but they have a shorter lifespan and require regular maintenance [49]. Lithium-ion batteries have a higher energy density and longer lifespan, but they are more expensive and require careful management to prevent overheating [50].

Nickel-cadmium batteries have a long lifespan and high cycle life, but they contain toxic materials and have a lower energy density [51]. Flow batteries are a newer technology with scalability and high-efficiency advantages, but they are more expensive and less mature. Sodium-ion batteries have a low cost and longer lifespan, but they are a less mature technology and may require special handling [52,53].

Ultimately, the choice of battery technology for off-grid systems depends on the specific needs and requirements of the system, including factors such as cost, performance, lifespan, and availability.

6.1. Design Batteries in Off-Grid Solar PV Systems

Designing batteries in off-grid solar PV systems requires careful consideration of several factors, including the energy needs of the system, the capacity and characteristics of the batteries, the charging method, and the system's overall efficiency. Here are some steps to follow when designing batteries in off-grid solar PV systems:

Determine the energy needs: Calculate the amount of energy needed to power the load(s) in the system, considering factors such as the time of day, weather conditions, and seasonal variations [54].

(1) Choose the battery capacity: Select a battery with sufficient capacity to meet the energy needs of the system. Consider factors such as the expected daily energy use, the battery discharge rate, and the desired depth of discharge (DOD).
(2) Select the battery technology: Choose a battery technology that meets the specific requirements of the system, considering factors such as cost, performance, and lifespan [55].
(3) Determine the charging method: Decide on the appropriate charging method for the system, such as constant voltage charging or MPPT charging. Consider the efficiency of the charging method and its impact on the lifespan of the batteries [56].

(4) Choose the charge controller: Select a charge controller that is compatible with the battery technology and charging method, and that can regulate the charging voltage and current to prevent overcharging or undercharging.
(5) Install temperature management: Install temperature management systems to maintain optimal operating temperatures for the batteries and prevent overheating or overcooling.
(6) Monitor the system: Regularly monitor the performance of the battery system to ensure optimal efficiency and lifespan. Measure the battery voltage and current, as well as the state of charge (SOC) and state of health (SOH) of the batteries.

By following these steps, we can design a battery system for off-grid solar PV systems that meets the energy needs of the system, while maximizing efficiency and ensuring optimal battery lifespan [57].

A rechargeable lithium-ion (Li-ion) battery represent in Figure 2 shows the comprises several essential components: a cathode, which is typically made of lithium-based compounds like lithium cobalt oxide; an anode, usually composed of carbon materials such as graphite; an electrolyte, a conductive medium containing a lithium salt; a separator, a thin, porous membrane preventing direct contact between the cathode and anode; current collectors that collect and distribute electrical current; an external enclosure for protection; terminals for external connections; and, in some cases, a pressure relief vent and thermal management system for safety and temperature regulation [58].

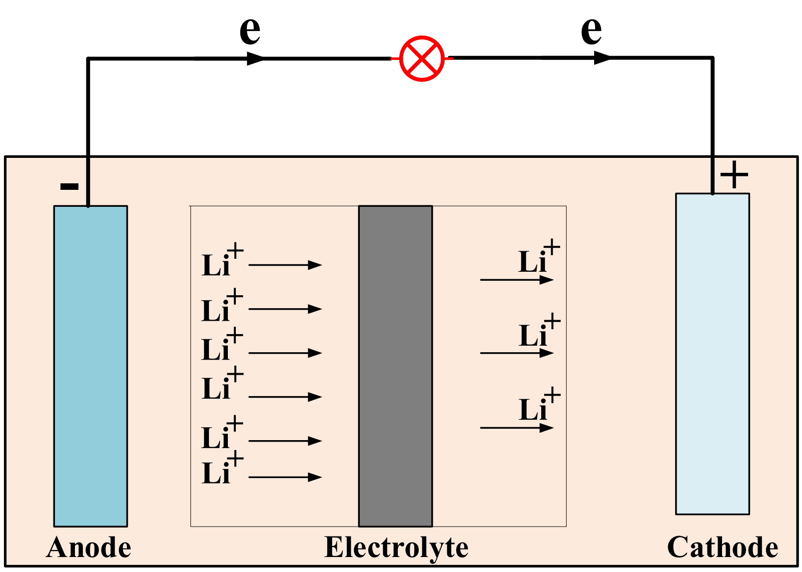

Figure 2. Components of a rechargeable Li-ion battery [58].

6.2. Description of the Testbed and Experimental Setup of Batteries in Off-Grid Solar PV Systems

The testbed and experimental setup for batteries in off-grid solar PV systems typically involves a simulated off-grid environment where batteries are subjected to various loads and charging conditions that replicate the real-world conditions they will experience in the field [58].

The testbed typically includes solar panels, charge controllers, inverters, and various loads, such as lights, appliances, and other electrical devices [59]. The batteries are connected to the charge controller, which regulates the charging and discharging of the batteries based on the energy requirements of the system [60].

The experimental setup may involve testing various types of batteries, including lead-acid, lithium-ion, and other chemistries, to evaluate their performance and durability under different conditions. The batteries may be tested for their capacity, cycle life, DOD, temperature range, and other key parameters [61].

To evaluate the performance of the batteries, data loggers may be used to measure the voltage, current, and temperature of the batteries and other components of the system. The data collected can be used to analyze the performance of the batteries under different loads and charging conditions and to identify any issues or limitations of the batteries [62].

The experimental setup may also involve testing the batteries under different weather conditions, such as varying levels of sunlight, temperature, and humidity. This can help to identify any performance issues that may arise under different environmental conditions and to optimize the operation of the off-grid solar PV system [63].

Overall, the testbed and experimental setup for batteries in off-grid solar PV systems are designed to provide a controlled and realistic environment for testing and evaluating the performance and durability of batteries under real-world conditions. The data collected can be used to optimize the design and operation of off-grid solar PV systems and to inform the selection of batteries for different applications [64].

6.3. Comparative Analysis of Different Battery Charging Strategies

Several different battery charging strategies can be used in off-grid solar PV systems, each with its own advantages and limitations. A comparative analysis of these strategies can help to identify the most appropriate approach for a given application.

(1) Constant Voltage Charging: This strategy involves maintaining a constant voltage across the battery terminals during the charging process. This is a simple and effective approach, but it can result in overcharging if the voltage is set too high [65].
(2) Constant Current Charging: This strategy involves maintaining a constant current in the battery during the charging process. This approach can be more efficient than constant voltage charging, but it can also result in overcharging if the current is set too high.
(3) PWM Charging: Pulse Width Modulation (PWM) charging involves adjusting the pulse width of the charging current to maintain a constant voltage across the battery terminals. This approach can be more efficient than constant voltage charging and is less likely to result in overcharging [66].
(4) MPPT Charging: Maximum Power Point Tracking (MPPT) charging involves adjusting the voltage and current of the charging current to maximize the power output of the solar panels. This approach can be more efficient than other charging strategies, especially in low-light conditions.
(5) Hybrid Charging: Hybrid charging involves combining two or more of the above charging strategies to optimize the charging process. For example, MPPT charging can be combined with PWM charging to provide a more efficient and effective charging strategy [67].

The choice of charging strategy will depend on the specific requirements and limitations of the off-grid solar PV system [68]. Factors such as battery chemistry, capacity, load profile, and environmental conditions will all influence the optimal charging strategy [69]. A comparative analysis of the different strategies can help to identify the most appropriate approach for a given application.

As depicted in Figure 3, upon the initial charging of the battery, there is a rapid surge in voltage. This phenomenon can be likened to raising weight with a rubber band, resulting in a noticeable delay. Eventually, as the battery approaches full charge, its capacity will catch up. It is worth noting that this charging pattern is a common trait shared by all types of batteries. Furthermore, it is important to mention that the rubber-band effect becomes more pronounced with higher charge currents, and factors such as cold temperatures or charging a cell with high internal resistance can amplify this effect.

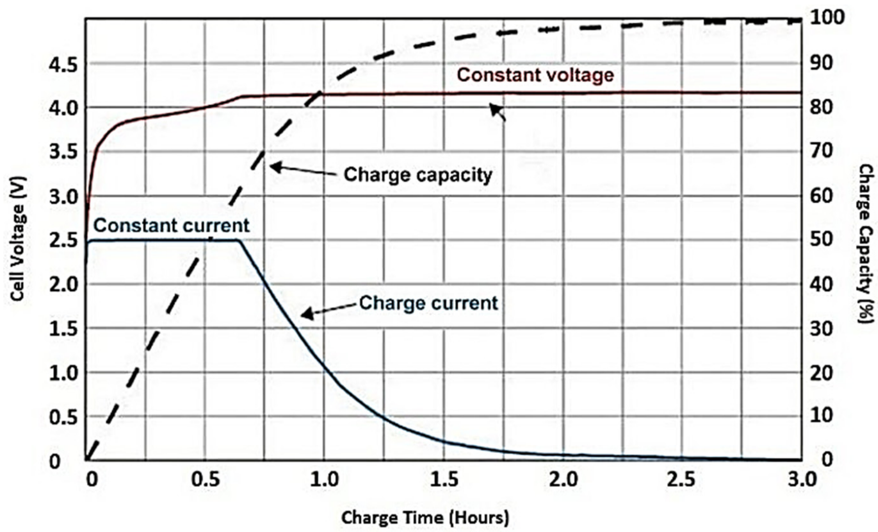

Figure 3. Volts/capacity vs. time during the charging of lithium-ion [70].

6.4. Evaluation of the Impact of Charging Strategies on Battery Life and System Performance

The impact of charging strategies on battery life and system performance can be evaluated based on several factors, including battery capacity, charging efficiency, DOD (depth of discharge), cycle life, and system cost-effectiveness [71].

1. Battery Capacity: Different charging strategies can affect the capacity of the battery, either by reducing the maximum capacity or by reducing the effective capacity due to overcharging or undercharging [29].
2. Charging Efficiency: The efficiency of the charging process can affect the performance and longevity of the battery, as well as the overall system efficiency. Higher charging efficiency can result in a longer battery life and more consistent performance.
3. DOD (Depth of Discharge): The depth of discharge of the battery can affect its cycle life and performance. Charging strategies that reduce the DOD can help to extend the battery life and improve system performance [13].
4. Cycle Life: The cycle life of the battery is a measure of how many charge and discharge cycles it can withstand before losing significant capacity. Charging strategies that reduce the number of cycles or reduce the depth of discharge can help extend the cycle life of the battery.
5. Cost-Effectiveness: The cost-effectiveness of the charging strategy depends on several factors, including the cost of the system components, the energy efficiency, and the lifetime of the battery. Charging strategies that reduce the cost of the system or increase its lifetime can improve its cost-effectiveness [72].

The impact of charging strategies on battery life and system performance depends on the specific requirements and limitations of the off-grid solar PV system [73].

6.5. Cost-Effectiveness of Different Battery Charging Strategies

The cost-effectiveness of different battery charging strategies can vary depending on several factors, including the initial cost of the charging equipment, the operating costs of the system, and the lifetime cost of the batteries. Here are some considerations for evaluating the cost-effectiveness of different charging strategies [1]:

1. Initial Equipment Costs: Different charging strategies require different equipment, which can vary in cost. For example, MPPT charge controllers tend to be more expensive than PWM controllers but may offer better performance in low-light conditions. Constant voltage and constant current charging methods may require less expensive equipment but may also be less efficient or reliable [74].

2. Operating Costs: The operating costs of the system can also vary depending on the charging strategy. For example, MPPT charging may require more energy to operate than PWM charging, which can increase the cost of system operation. Similarly, some charging strategies may require more maintenance or monitoring than others, which can increase the overall operating costs of the system.
3. Lifetime Cost of Batteries: The lifetime cost of batteries is an important consideration in evaluating the cost-effectiveness of different charging strategies. Overcharging or undercharging can reduce the lifespan of batteries, which can increase the cost of replacing them. By optimizing the charging strategy, it may be possible to extend the life of batteries and reduce the overall cost of the system over time.
4. Overall System Efficiency: The overall efficiency of the off-grid solar PV system can also affect its cost-effectiveness. By selecting a charging strategy that maximizes the power output of the solar panels and minimizes energy losses in the charging process, it may be possible to improve the overall efficiency of the system and reduce the overall cost of operation.

In general, the most cost-effective charging strategy will depend on the specific requirements and limitations of the off-grid solar PV system. By carefully evaluating the costs and benefits of different charging strategies, it is possible to identify the most appropriate approach for a given application.

6.6. Limitations of Battery Off-Grid Solar PV Systems

Battery off-grid solar PV systems have many advantages, including providing electricity in remote areas, reducing reliance on grid electricity, and helping to reduce greenhouse gas emissions. However, there are also some limitations to these systems, including:

(1) Limited Energy Storage Capacity: The energy storage capacity of batteries used in off-grid solar PV systems is limited, which means that these systems cannot generate electricity continuously over an extended period. This limitation can be mitigated by adding more batteries to the system, but this can increase the cost and complexity of the system.
(2) Weather-Dependent Energy Generation: Solar PV systems generate electricity only when there is sufficient sunlight, and this can be a challenge in regions with low levels of sunlight or highly variable weather conditions. This limitation can be addressed by combining the solar PV system with other renewable energy sources, such as wind or hydroelectric power [60].
(3) Cost: Off-grid solar PV systems can be more expensive to install than grid-connected solar PV systems due to the need for energy storage batteries, charge controllers, and other components. The cost of batteries has been declining in recent years, but it remains a significant portion of the overall system cost [75].
(4) Maintenance: Off-grid solar PV systems require periodic maintenance, including cleaning the solar panels, checking the batteries, and monitoring the system's performance. The cost and availability of maintenance personnel can be a challenge in remote locations [68].
(5) System Complexity: Off-grid solar PV systems can be complex to design and install, requiring careful consideration of the system components, wiring, and energy storage capacity. Proper installation and maintenance are critical to the system's performance and longevity.

While off-grid solar PV systems have many benefits, they are not suitable for all applications, and their limitations should be carefully considered before implementation [13].

6.7. Zinc-Ion Batteries

Zinc-ion batteries are a type of rechargeable battery that uses zinc ions as the charge carriers. These batteries have gained significant attention in recent years due to their potential for various applications, including energy storage, portable electronics, and electric vehicles. Here are some key features and characteristics of zinc-ion batteries:

1. Chemistry: Zinc-ion batteries typically consist of a zinc anode, a cathode material (often based on transition metal oxides or polyanions), and an electrolyte that allows the movement of zinc ions between the anode and cathode during charge and discharge cycles.
2. Safety: One of the significant advantages of zinc-ion batteries is their safety. Zinc is a relatively stable and non-toxic material, reducing the risk of thermal runaway and fire, which can be a concern with certain other battery chemistries, such as lithium-ion batteries.
3. Cost-Effectiveness: Zinc is abundant and relatively inexpensive, making zinc-ion batteries cost-effective compared to other battery technologies. This affordability can be particularly advantageous for large-scale energy storage applications.
4. High Energy Density: Zinc-ion batteries offer a competitive energy density, allowing them to store substantial energy for a given volume or weight. While they may not match the energy density of lithium-ion batteries, they are still suitable for various applications.
5. Long Cycle Life: With proper electrode materials and design, zinc-ion batteries can achieve a long cycle life, making them suitable for applications where durability and reliability are essential [76].
6. Environmental Friendliness: Zinc-ion batteries are environmentally friendly as zinc is a widely recyclable material. This aligns with the growing emphasis on sustainability and reducing the environmental impact of energy storage technologies.
7. Challenges: Despite their advantages, zinc-ion batteries face some challenges, such as limited cathode material options and issues related to dendrite formation on the zinc anode during cycling. Researchers are actively working to address these challenges to improve the performance and longevity of zinc-ion batteries.
8. Applications: Zinc-ion batteries are being explored for various applications, including grid-scale energy storage, backup power systems, uninterruptible power supplies (UPS), and potentially even in consumer electronics and electric vehicles as the technology matures.
9. Research and Development: Ongoing research and development efforts are focused on enhancing the performance and energy density of zinc-ion batteries and addressing any remaining technical challenges. These efforts may lead to broader adoption of this battery technology in the future.

Zinc-ion batteries offer several advantages, including safety, cost-effectiveness, and environmental friendliness. While they may not yet be as widespread as some other battery types, ongoing research and development are expected to improve their performance and expand their range of applications in the coming years [13,29].

7. Conclusions

A comparative study and overview of battery charging strategies for off-grid solar PV systems provides valuable insights into the most effective and efficient approach for charging batteries in these systems. This study considers the impact of different charging strategies on battery life, system performance, and cost-effectiveness. The overview provides a comprehensive view of the various strategies available for charging batteries in off-grid solar PV systems, including their advantages and limitations.

This study highlights the importance of selecting the most appropriate charging strategy for a given application based on its specific requirements and constraints. The controlled charging approach appears to be the most effective in terms of optimizing battery performance and extending its life, but it may also be more expensive than other strategies. However, the initial cost may be offset with the long-term benefits of improved battery life and system performance.

A comparative study and overview of battery charging strategies can provide valuable guidance for system designers, installers, and users of off-grid solar PV systems. The goal is to provide reliable and sustainable electricity in remote areas while minimizing the environmental impact, maximizing the cost-effectiveness of the system, and exploring valuable insights for designing and optimizing off-grid solar photovoltaic systems. These insights may encompass areas such as performance metrics, advancements in battery technology, load profile alignment, economic feasibility, environmental sustainability, energy accessibility, scalability, maintenance considerations, integration with other renewable sources, user behavior impacts, regulatory implications, and prospects for future research and innovation.

Several factors can enhance off-grid solar PV systems, efficiency, reliability, and cost-effectiveness, including advanced storage tech, smart energy management, load balancing, hybrid integration, predictive maintenance, cost-effectiveness measures, eco-friendly practices, user engagement, regulatory support, community solutions, and research opportunities.

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References

1. Chen, W.; Li, G.; Pei, A.; Li, Y.; Liao, L.; Wang, H.; Wan, J.; Liang, Z.; Chen, G.; Zhang, H.; et al. A manganese–hydrogen battery with potential for grid-scale energy storage. *Nat. Energy* **2018**, *3*, 428–435. [CrossRef]
2. Anuphappharadorn, S.; Sukchai, S.; Sirisamphanwong, C.; Ketjoy, N. Comparison the economic analysis of the battery between lithium-ion and lead-acid in PV stand-alone application. *Energy Procedia* **2014**, *56*, 352–358. [CrossRef]
3. Ruetschi, P.; Meli, F.; Desilvestro, J. Nickel-metal hydride batteries. The preferred batteries of the future? *J. Power Sources* **1995**, *57*, 85–91. [CrossRef]
4. Triki, Y.; Triki, A.; Bechouche, A.; Abdeslam, D.O.; Porumb, R. An Efficient Battery-Charging Algorithm with ANN based MPPT Method for Off-Grid PV Systems. In Proceedings of the 2022 IEEE 21st international Ccnference on Sciences and Techniques of Automatic Control and Computer Engineering (STA), Sousse, Tunisia, 19–21 December 2022; pp. 106–111.
5. Lourenssen, K.; Williams, J.; Ahmadpour, F.; Clemmer, R.; Tasnim, S. Vanadium redox flow batteries: A comprehensive review. *J. Energy Storage* **2019**, *25*, 100844. [CrossRef]
6. Hueso, K.B.; Armand, M.; Rojo, T. High temperature sodium batteries: Status, challenges and future trends. *Energy Environ. Sci.* **2013**, *6*, 734–749. [CrossRef]
7. Butler, P.C.; Eidler, P.A.; Grimes, P.G.; Klassen, S.E.; Miles, R.C. Zinc/Bromine Batteries. In *Advanced Battery Systems*; Handbook of Batteries, sandia.gov; 2000; pp. 37.01–37.16.
8. Letcher Trevor, M.; Law, R.; Reay, D. Vanadium Redox Flow Batteries. In *Storing Energy: With Special Reference to Renewable Energy Sources*; Elsevier: Amsterdam, The Netherlands, 2016.
9. Feng, F.; Geng, M.; Northwood, D.O. Electrochemical behaviour of intermetallic-based metal hydrides used in Ni/metal hydride (MH) batteries: A review. *Int. J. Hydrogen Energy* **2001**, *26*, 725–734. [CrossRef]
10. Tong, S.J.; Same, A.; Kootstra, M.A.; Park, J.W. Off-grid photovoltaic vehicle charge using second life lithium batteries: An experimental and numerical investigation. *Appl. Energy* **2013**, *104*, 740–750. [CrossRef]
11. Young, K.H.; Yasuoka, S. Capacity degradation mechanisms in nickel/metal hydride batteries. *Batteries* **2016**, *2*, 3. [CrossRef]
12. Skundin, A.M.; Kulova, T.L.; Yaroslavtsev, A.B. Sodium-Ion Batteries (a Review). *Russ. J. Electrochem.* **2018**, *54*, 113–152. [CrossRef]
13. Xu, L.; Meng, T.; Zheng, X.; Li, T.; Brozena, A.H.; Mao, Y.; Zhang, Q.; Clifford, B.C.; Rao, J.; Hu, L. Nanocellulose-Carboxymethylcellulose Electrolyte for Stable, High-Rate Zinc-Ion Batteries. *Adv. Funct. Mater.* **2023**, *33*, 2302098. [CrossRef]
14. Jossen, A.; Garche, J.; Sauer, D.U. Operation conditions of batteries in PV applications. *Solar Energy* **2004**, *76*, 759–769. [CrossRef]
15. Rodríguez-Gallegos, C.D.; Gandhi, O.; Bieri, M.; Reindl, T.; Panda, S.K. A diesel replacement strategy for off-grid systems based on progressive introduction of PV and batteries: An Indonesian case study. *Appl Energy* **2018**, *229*, 1218–1232. [CrossRef]
16. May, G.J.; Davidson, A.; Monahov, B. Lead batteries for utility energy storage: A review. *J. Energy Storage* **2018**, *15*, 145–157. [CrossRef]
17. Zhou, G.; Li, F.; Cheng, H.M. Progress in flexible lithium batteries and future prospects. *Energy Environ. Sci.* **2014**, *7*, 1307–1338. [CrossRef]
18. Salameh, Z.; Casacca, M.; Lynch, W. A Mathematical Model for Lead-Acid Batteries. *IEEE Trans. Energy Convers.* **1992**, *7*, 93–98. [CrossRef]
19. Manimekalai, P.; Harikumar, R.; Raghavan, S. An overview of batteries for photovoltaic (PV) systems. *Int. J. Comput. Appl.* **2013**, *82*, 28–32. [CrossRef]
20. Van Zyl, A. Review of the zebra battery system development. *Solid State Ion.* **1996**, *86–88*, 883–889. [CrossRef]

21. Merei, G.; Magnor, D.; Leuthold, M.; Sauer, D.U. Optimization of an off-grid hybrid power supply system based on battery aging models for different battery technologies. In Proceedings of the 2014 IEEE 36th International Telecommunications Energy Conference (INTELEC), Vancouver, BC, Canada, 28 September–2 October 2014; pp. 1–6.
22. Koshtyal, Y.; Olkhovskii, D.; Rumyantsev, A.; Maximov, M. Applications and Advantages of Atomic Layer Deposition for Lithium-Ion Batteries Cathodes. *Batteries* **2022**, *8*, 184. [CrossRef]
23. Gundlapalli, R.; Kumar, S.; Jayanti, S. Stack Design Considerations for Vanadium Redox Flow Battery. *INAE Lett.* **2018**, *3*, 149–157. [CrossRef]
24. Chatzinikolaou, E.; Rogers, D.J. A Comparison of Grid-Connected Battery Energy Storage System Designs. *IEEE Trans. Power Electron.* **2017**, *32*, 6913–6923. [CrossRef]
25. Trovo, A.; Picano, F.; Guarnieri, M. Maximizing Vanadium Redox Flow Battery Efficiency: Strategies of Flow Rate Control. In Proceedings of the 2019 IEEE 28th International Symposium on Industrial Electronics (ISIE), Vancouver, BC, Canada, 12–14 June 2019.
26. Ghenai, C.; Salameh, T.; Merabet, A.; Hamid, A.K. Modeling and optimization of hybrid solar-diesel-battery power system. In Proceedings of the 2017 7th International Conference on Modeling, Simulation, and Applied Optimization (ICMSAO), Sharjah, United Arab Emirates, 4–6 April 2017; pp. 1–5.
27. Zhang, Y.; Wang, J.; Berizzi, A.; Cao, X. Life cycle planning of battery energy storage system in off-grid wind–solar–diesel microgrid. *IET Gener. Transm. Distrib.* **2018**, *12*, 4451–4461. [CrossRef]
28. Hlal, M.I.; Ramachandaramurthy, V.K.; Sarhan, A.; Pouryekta, A.; Subramaniam, U. Optimum battery depth of discharge for off-grid solar PV/battery system. *J. Energy Storage* **2019**, *26*, 100999. [CrossRef]
29. Wu, M.; Zhang, Y.; Xu, L.; Yang, C.; Hong, M.; Cui, M.; Clifford, B.C.; He, S.; Jing, S.; Yao, Y.; et al. A sustainable chitosan-zinc electrolyte for high-rate zinc-metal batteries. *Matter* **2022**, *5*, 3402–3416. [CrossRef]
30. Chtita, S.; Derouich, A.; El Ghzizal, A.; Motahhir, S. An improved control strategy for charging solar batteries in off-grid photovoltaic systems. *Solar Energy* **2021**, *220*, 927–941. [CrossRef]
31. Alnejaili, T.; Labdai, S.; Chrifi-Alaoui, L. Predictive management algorithm for controlling pv-battery off-grid energy system. *Sensors* **2021**, *21*, 6427. [CrossRef] [PubMed]
32. Bilansky, J.; Lacko, M.; Pastor, M.; Marcinek, A.; Durovsky, F. Improved Digital Twin of Li-Ion Battery Based on Generic MATLAB Model. *Energies* **2023**, *16*, 1194. [CrossRef]
33. Jung, W.; Jeong, J.; Kim, J.; Chang, D. Optimization of hybrid off-grid system consisting of renewables and Li-ion batteries. *J. Power Sources* **2020**, *451*, 227754. [CrossRef]
34. Chong, L.W.; Wong, Y.W.; Rajkumar, R.K.; Isa, D. An optimal control strategy for standalone PV system with Battery-Supercapacitor Hybrid Energy Storage System. *J. Power Sources* **2016**, *331*, 553–565. [CrossRef]
35. Li, T.; Yuan, X.-Z.; Zhang, L.; Song, D.; Shi, K.; Bock, C. Degradation mechanisms and mitigation strategies of nickel-rich NMC-based lithium-ion batteries. *Electrochem. Energy Rev.* **2020**, *3*, 43–80. [CrossRef]
36. Ciupageanu, D.-A.; Lazaroiu, G.; Barelli, L. Model predictive control application for a battery energy storage system in a wind power plant. In Proceedings of the 18th International Multidisciplinary Scientific GeoConference SGEM2018, Albena, Bulgary, 2–8 July 2018; pp. 469–475.
37. Guezgouz, M.; Jurasz, J.; Bekkouche, B.; Ma, T.; Javed, M.S.; Kies, A. Optimal hybrid pumped hydro-battery storage scheme for off-grid renewable energy systems. *Energy Convers. Manag.* **2019**, *199*, 112046. [CrossRef]
38. Merei, G.; Berger, C.; Sauer, D.U. Optimization of an off-grid hybrid PV–Wind–Diesel system with different battery technologies using genetic algorithm. *Solar Energy* **2013**, *97*, 460–473. [CrossRef]
39. Rashed, G.I.; Shyirambere, G.; Gasore, G.; Yuanzhang, S.; Shafik, M.B. Applicability study of battery charging stations in off-grid for rural electrification–the case of Rwanda. In Proceedings of the 2019 International Conference on Power Generation Systems and Renewable Energy Technologies (PGSRET), Istanbul, Turkey, 26–27 August 2019; pp. 1–6.
40. Mohamed, M.A.; Mohamed, F.A. Design and Simulate an Off-Grid PV System with a Battery Bank for EV Charging. *Univers. J. Electr. Electron. Eng.* **2020**, *7*, 273–288. [CrossRef]
41. Zhou, H.; Zhang, H.; Zhao, P.; Yi, B. A comparative study of carbon felt and activated carbon based electrodes for sodium polysulfide/bromine redox flow battery. *Electrochim. Acta* **2006**, *51*, 6304–6312. [CrossRef]
42. Yuan, S.; Wu, H.; Ma, X.; Yin, C. Stability analysis for Li-ion battery model parameters and state of charge estimation by measurement uncertainty consideration. *Energies* **2015**, *8*, 7729–7751. [CrossRef]
43. Bordin, C.; Anuta, H.O.; Crossland, A.; Gutierrez, I.L.; Dent, C.J.; Vigo, D. A linear programming approach for battery degradation analysis and optimization in offgrid power systems with solar energy integration. *Renew. Energy* **2017**, *101*, 417–430. [CrossRef]
44. Fodhil, F.; Hamidat, A.; Nadjemi, O. Potential, optimization and sensitivity analysis of photovoltaic-diesel-battery hybrid energy system for rural electrification in Algeria. *Energy* **2019**, *169*, 613–624. [CrossRef]
45. Cervantes, I.; Hernandez-Nochebuena, M.; Cano-Castillo, U.; Araujo-Vargas, I. A graphical approach to optimal power management for uncertain OFF-Grid PV-FC-electrolyzer-battery hybrid systems. *Int. J. Hydrogen Energy* **2018**, *43*, 19336–19351. [CrossRef]
46. Babatunde, O.M.; Munda, J.L.; Hamam, Y. Off-grid hybrid photovoltaic–micro wind turbine renewable energy system with hydrogen and battery storage: Effects of sun tracking technologies. *Energy Convers. Manag.* **2022**, *255*, 115335. [CrossRef]
47. Bhattacharjee, A.; Saha, H. Design and experimental validation of a generalised electrical equivalent model of Vanadium Redox Flow Battery for interfacing with renewable energy sources. *J. Energy Storage* **2017**, *13*, 220–232. [CrossRef]

48. Thirunavukkarasu, M.; Sawle, Y. A comparative study of the optimal sizing and management of off-grid solar/wind/diesel and battery energy systems for remote areas. *Front. Energy Res.* **2021**, *9*, 752043. [CrossRef]
49. Astaneh, M.; Roshandel, R.; Dufo-López, R.; Bernal-Agustín, J.L. A novel framework for optimization of size and control strategy of lithium-ion battery based off-grid renewable energy systems. *Energy Convers. Manag.* **2018**, *175*, 99–111. [CrossRef]
50. Overington, S.; Rajakaruna, S. Application of Battery State of Charge Swing Control for Overall Performance Improvement in Diesel-Solar Hybrid Off-Grid Power Systems. In Proceedings of the 2021 31st Australasian Universities Power Engineering Conference (AUPEC), Perth, Australia, 26–30 September 2021; pp. 1–9.
51. Häring, T.; Rosin, A.; Biechl, H. Using common household thermal storages to support the PV-and battery system in nearly zero energy buildings in off-grid mode. *Sustain. Energy Technol. Assess.* **2019**, *35*, 12–24. [CrossRef]
52. Crossland, A.F.; Anuta, O.H.; Wade, N.S. A socio-technical approach to increasing the battery lifetime of off-grid photovoltaic systems applied to a case study in Rwanda. *Renew. Energy* **2015**, *83*, 30–40. [CrossRef]
53. Madziga, M.; Rahil, A.; Mansoor, R. Comparison between three off-grid hybrid systems (solar photovoltaic, diesel generator and battery storage system) for electrification for Gwakwani village, South Africa. *Environments* **2018**, *5*, 57. [CrossRef]
54. Jurasz, J.; Ceran, B.; Orłowska, A. Component degradation in small-scale off-grid PV-battery systems operation in terms of reliability, environmental impact and economic performance. *Sustain. Energy Technol. Assess.* **2020**, *38*, 100647. [CrossRef]
55. Ghoddami, H.; Delghavi, M.B.; Yazdani, A. An integrated wind-photovoltaic-battery system with reduced power-electronic interface and fast control for grid-tied and off-grid applications. *Renew. Energy* **2012**, *45*, 128–137. [CrossRef]
56. Ganjei, N.; Zishan, F.; Alayi, R.; Samadi, H.; Jahangiri, M.; Kumar, R.; Mohammadian, A. Designing and sensitivity analysis of an off-grid hybrid wind-solar power plant with diesel generator and battery backup for the rural area in Iran. *J. Eng.* **2022**, *2022*, 4966761. [CrossRef]
57. Poullikkas, A. A comparative overview of large-scale battery systems for electricity storage. *Renew. Sustain. Energy Rev.* **2013**, *27*, 778–788. [CrossRef]
58. Yang, Y.; Tang, Y.; Fang, G.; Shan, L.; Guo, J.; Zhang, W.; Wang, C.; Wang, L.; Zhou, J.; Liang, S. Li^+ intercalated $V_2O_5{\cdot}nH_2O$ with enlarged layer spacing and fast ion diffusion as an aqueous zinc-ion battery cathode. *Energy Environ. Sci.* **2018**, *11*, 3157–3162. [CrossRef]
59. Arnot, D.J.; Lim, M.B.; Bell, N.S.; Schorr, N.B.; Hill, R.C.; Meyer, A.; Cheng, Y.T.; Lambert, T.N. High depth-of-discharge zinc rechargeability enabled by a self-assembled polymeric coating. *Adv. Energy Mater.* **2021**, *11*, 2101594. [CrossRef]
60. Lee, B.; Yoon, C.S.; Lee, H.R.; Chung, K.Y.; Cho, B.W.; Oh, S.H. Electrochemically-induced reversible transition from the tunneled to layered polymorphs of manganese dioxide. *Sci. Rep.* **2014**, *4*, 6066. [CrossRef] [PubMed]
61. Vartiainen, E.; Masson, G.; Breyer, C.; Moser, D.; Medina, E.R. Impact of weighted average cost of capital, capital expenditure, and other parameters on future utility-scale PV levelised cost of electricity. *Prog. Photovolt. Res. Appl.* **2020**, *28*, 439–453. [CrossRef]
62. Huang, J.; Wang, Z.; Hou, M.; Dong, X.; Liu, Y.; Wang, Y.; Xia, Y. Polyaniline-intercalated manganese dioxide nanolayers as a high-performance cathode material for an aqueous zinc-ion battery. *Nat. Commun.* **2018**, *9*, 2906. [CrossRef] [PubMed]
63. Wan, F.; Zhang, L.; Dai, X.; Wang, X.; Niu, Z.; Chen, J. Aqueous rechargeable zinc/sodium vanadate batteries with enhanced performance from simultaneous insertion of dual carriers. *Nat. Commun.* **2018**, *9*, 1656. [CrossRef]
64. Qin, H.; Yang, Z.; Chen, L.; Chen, X.; Wang, L. A high-rate aqueous rechargeable zinc ion battery based on the VS_4@rGO nanocomposite. *J. Mater. Chem. A Mater.* **2018**, *6*, 23757–23765. [CrossRef]
65. Wang, L.; Zhengm, J. Recent advances in cathode materials of rechargeable aqueous zincion batteries. *Mater. Today Adv.* **2020**, *7*, 100078. [CrossRef]
66. Peng, Z.; Wei, Q.; Tan, S.; He, P.; Luo, W.; An, Q.; Mai, L. Novel layered iron vanadate cathode for high-capacity aqueous rechargeable zinc batteries. *Chem. Commun.* **2018**, *54*, 4041–4044. [CrossRef] [PubMed]
67. Tang, F.; Zhou, W.; Chen, M.; Chen, J.; Xu, J. Flexible free-standing paper electrodes based on reduced graphene oxide/δ-$NaxV_2O_5{\cdot}nH_2O$ nanocomposite for high-performance aqueous zinc-ion batteries. *Electrochim. Acta* **2019**, *328*, 135137. [CrossRef]
68. Yuan, G.; Huang, T.; Kou, Y.; Ji, Z.; Zhao, Y. Self-assembly of free-standing $LiMn_2O_4$-graphene flexible film for high-performance rechargeable hybrid aqueous battery. *Materials* **2018**, *11*, 1056. [CrossRef]
69. He, P.; Yan, M.; Zhang, G.; Sun, R.; Chen, L.; An, Q.; Mai, L. Layered VS_2 nanosheet-based aqueous Zn ion battery cathode. *Adv. Energy Mater.* **2017**, *7*, 1601920. [CrossRef]
70. What Is the Charger Voltage Graph While Charging Lithium Battery with CC/CV Approach?—Electrical EngineeringStackExchange. Available online: https://electronics.stackexchange.com/questions/473253/what-is-the-charger-voltage-graph-while-charging-lithium-battery-with-cc-cv-appr (accessed on 2 September 2023).
71. Ding, J.; Du, Z.; Gu, L.; Li, B.; Wang, L.; Wang, S.; Gong, Y.; Yang, S. Ultrafast Zn^{2+} intercalation and deintercalation in vanadium dioxide. *Adv. Mater.* **2018**, *30*, 1800762. [CrossRef] [PubMed]
72. Hossain, T.; Adams, M.; Walker, T.R. Role of sustainability in global seaports. *Ocean Coast Manag.* **2021**, *202*, 105435. [CrossRef]
73. Lin, Y.; Eto, J.H.; Johnson, B.B.; Flicker, J.D.; Lasseter, R.H.; Villegas Pico, H.N.; Seo, G.S.; Pierre, B.J.; Ellis, A. *Research Roadmap on Grid-Forming Inverters*; National Renewable Energy Lab. (NREL): Golden, CO, USA, 2020.
74. Lazaroiu, G.; Ciupageanu, D. Multi-criteria decision making in sustainable renewable energy systems. In Proceedings of the 19th International Multidisciplinary Scientific Geoconference SGEM2019, Vienna, Austria, 9–12 December 2019; Volume 19, pp. 569–576.

75. Kundu, D.; Oberholzer, P.; Glaros, C.; Bouzid, A.; Tervoort, E.; Pasquarello, A.; Niederberger, M. Organic cathode for aqueous Zn-ion batteries: Taming a unique phase evolution toward stable electrochemical cycling. *Chem. Mater.* **2018**, *30*, 3874–3881. [CrossRef]
76. Weyers, C.; Bocklisch, T. Simulation-based investigation of energy management concepts for fuel cell–battery–hybrid energy storage systems in mobile applications. *Energy Procedia* **2018**, *155*, 295–308. [CrossRef]