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REVIEW ARTICLE

Battery Energy Storage System for Building Integrated Photovoltaic Applications

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ABSTRACT

Human pursuits' daily energy needs are consistent; however, renewable energy sources are intermittent in nature. Thus, an energy storage system is required to bridge the generation-demand gap. Electrical energy storage (EES) is a system that converts electrical energy into a form that can be easily stored in various devices and converted back into electrical energy as needed. The battery energy storage system (BESS) is one of the most well-known and promising EES technologies for storing renewable energy. Today, various BESS types are in use; some are established technology, while others are still in R&D. The selection of BESS capacity for building integrated photovoltaic (BIPV) systems necessitates a trade-off between critical criteria, including power vs. energy, design voltage, and operating temperature. This research analyzed various BESS technologies and presented optimal capacity selection and design criteria. Hence, the best BESS design approach takes into account climatic data, PV panel specifications, and budget constraints. While BESS technology varies depending on project requirements and other considerations, lithium-ion batteries are the most commonly used due to their high energy density, efficiency, and extended cycle life. For cost-sensitive BIPV systems, lead-acid batteries are preferred due to their low capital cost, technological maturity, and relatively good cycle efficiency. Thus, the correct quantity of batteries in a BESS bank is determined by energy storage goals, BESS type and size, and service load. Finally, the paper concluded with recommendations for best practices for BESS design, appropriate operation, and maintenance conditions for Nigeria's prevalent BESS technology for BIPV applications.

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INTRODUCTION

Electricity systems unavoidably require a continuous, balanced, dependable, and high-quality supply (maintaining steady voltage and frequency) without any interruptions and the potential to harm electrical gadgets. At certain periods, there are always significant fluctuations in the electricity demand. As a result, there may be periods when energy production exceeds demand and vice versa. Similarly, renewable energy sources are intermittent in nature, while daily energy requirements for human activities are constant. Thus, an energy storage system is needed to close the gap between supply and demand. The Electrical Energy Storage (EES) system involves converting electrical energy into a form that allows it to be stored in various devices and retrieved back to electrical form when needed (AL Shaqsi et al., 2020). The term "battery energy storage system" (BESS) refers to an electrochemical device that stores electrical energy as chemical energy. Today's BESS technologies come in a variety of sizes and chemical compositions. When setting up a photovoltaic (PV) system, factoring in the energy storage requirements is crucial.

Choosing the right battery for each PV system type can be challenging as reliable information is scarce. Overall, electrochemical energy storage has many advantages, including friendly environmental operation, high round-trip efficiency, scalability of power and energy suitable for different grid purposes, cycle-long life, and low maintenance (Abumeteir & Vural, 2016). Hence, several questions must be considered when selecting batteries for different BIPV systems applications. Such as, what type of BESS technology is most suitable for BIPV for a particular temporal horizon? Which criteria are to be considered in terms of BESS design? How to determine the BESS capacity for a specific application? Consequently, the present study seeks to explore various

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types of electrochemical devices reported in different literature, thereby providing answers to these questions while citing a specific scenario.

REVIEW OF BESS TECHNOLOGIES

There are varieties of BESS technology in use today; some are matured technology, while others are still in their research and development. BESS selection for BIPV application entails a trade-off between certain operation conditions of the battery while considering the site climatic factor. Finding the most crucial battery parameters and weighing them against others helps one to choose the best battery for their application. The important details of a few well-known technologies, as well as their benefits and drawbacks as described in various literatures, are explained briefly in the following paragraphs.

Lead-acid battery

The most well-established battery technology, with a track record in a wide range of applications, is lead-acid batteries (Zakeri & Syri, 2015). It consisted of stacked cells with sponge lead (Pb) as the negative electrode and lead dioxide (PbO_2) as the positive electrode submerged in an electrolyte constituted of a diluted sulfuric acid (H_2SO_4) solution. Lead-acid batteries are primarily manufactured using the flooded and valve-regulated methods. Fast response times, comparatively high cycle efficiencies (63 to 90%) (Luo et al., 2015), low daily self-discharge rates (0.1%) (Díaz-González et al., 2012), and low capital costs (120 to 291 $/kWh) (Mongird et al., 2019) are benefits of lead-acid batteries. Lead-acid batteries have traditionally been used for applications such as spinning reserves, UPSs, and power quality (Chen et al., 2009). However, their applications in energy management are limited by their limited cycle life (500 to 2500 cycles, depending on DoD), low energy density (30 to 50 Wh/kg), and thermal management due to poor operation at low temperatures.

Sodium-sulfur (NaS) battery

Sodium anode, sulfur cathode, and beta-alumina (Al_2O_3) are electrolytes and separators in a tubular NaS battery. To keep the Na and S in a molten condition and ensure efficient mobility of the Na^+, it operates within a temperature range of 300-350°C (Cho et al., 2015). NaS batteries typically have a life cycle between 2500 and 4500 cycles, an overall efficiency between 75 and 85%, a high discharge duration of up to 7 hours, a lifespan of 15 years, and nearly no daily energy leakage (Luo et al., 2015; Zakeri & Syri, 2015). NaS batteries also have low maintenance requirements, cheap material usage that is 99% recyclable, high power densities (150 to 240 W/kg) and energy densities (150 to 230 Wh/kg) (Chen et al., 2009; Díaz-González et al., 2012; Luo et al., 2015). The main drawback of NaS batteries is their high operating temperature requirement, which results in high yearly running costs (80 $/kW/yr.) and high capital costs in the range of 350 to 1000 $/kWh (Ferreira et al., 2013; Mongird et al., 2019).

Sodium-nickel-chloride ($NaNiCl_2$) battery

In terms of their high-temperature range (270 to 350 degrees Celsius), sodium-nickel-chloride batteries, often called ZEBRA (Zero Emission Battery Research Activity), are comparable to NaS batteries. However, nickel chloride is used in place of sulfur in these batteries. Compared to NaS batteries, $NaNiCl_2$ batteries are significantly smaller and lighter, have quick response times, and are durable to full discharge. Compared to NaS batteries, these batteries have a lower power density of 150 W/kg, a lifespan of 8 to 10 years, and a low energy density of 120 Wh/kg (Ferreira et al., 2013; Zakeri & Syri, 2015).

Nickel-cadmium (NiCd) battery

One of the first electrochemical technologies still in use today is nickel-cadmium battery. Potassium hydroxide (KOH) was used as the electrolytic material, and the anode and cathode electrodes were produced from nickel and cadmium species, respectively (Díaz-González et al., 2012). It comes in two forms: sealed and flooded. It has good technological characteristics, including low maintenance requirements, high energy density (55 to 75 Wh/kg), and a life cycle of 2000 to 2500 cycles, depending on DoD, which can be increased up to 50,000 cycles at 10% DoD (Zakeri & Syri, 2015). NiCd batteries also showed good operational temperature tolerance in the range of (-40 to 50℃) (Luo et al., 2015). Despite this, NiCd batteries face significant challenges because of their parts' toxicity, relatively high cost (1000 $/kWh), and a memory effect where the battery can only be fully charged when it has been entirely discharged (Chen et al., 2009).

Nickel-metal-hydride (NiMH) battery

Since NiMH batteries contain non-toxic ingredients, they have a better energy density than NiCd batteries and pose less environmental risk (Ferreira et al., 2013). It has improved memory, which is noticeably better than NiCd batteries, and has an energy density of 70 to 100 Wh/kg. NiMH batteries outlast Li-ion batteries in terms of cycle life. The sensitivity to deep cycling within a few hundred full cycles and the high self-discharge rate (5 to 20%) of its capacity within a day of being fully charged are two issues with NiMH (Luo et al., 2015).

Lithium-ion (Li-ion) battery

Graphitic carbon serves as the anode, while lithium metal oxide ($LiCoO_2$, $LiMO_2$, $LiNiO_2$, etc.) functions as the cathode in lithium-ion batteries. As the electrolytic material, dissolved lithium salts such as $LiPF_6$ and $LiClO_4$ are used in an organic carbonate-forming non-aqueous liquid (Chen et al., 2009; Luo et al., 2015). The high energy density (75 to 200 Wh/kg), a reasonably high round-trip efficiency (0.85 to 0.90), and long cycle life (10,000 cycles) are just a few of the key characteristics of lithium-ion batteries (Díaz-González et al., 2012; Zakeri & Syri, 2015). Other benefits include the battery's low self-discharge rate of less than 8% per month, quick charge and discharge capabilities, and wide working temperature range (20 to 60 degrees Celsius for charge and 40 to 65 degrees Celsius for discharge, respectively) (Cho et al., 2015; Díaz-González et al., 2012). Because of these features, li-ion batteries make a strong choice for applications where response time, portability, and weight are key considerations. According to (Cho et al., 2015; Luo et al., 2015), the primary drawbacks of Li-electrochemistry are its expensive cost, low heat tolerance, and the need for constant monitoring of electrolytic breakdown and DoD. Small appliances primarily employ lithium-ion batteries because of their high energy density, low self-discharge rate, high efficiency, and reliability. Nonetheless, the cost is still higher (260 $/kWh) in terms of medium and large-scale power applications, although they have been deployed more widely, which will probably lower the cost in the near future (Ferreira et al., 2013; Mongird et al., 2019).

BEST PRACTICE IN TERMS OF BESS DESIGN

Battery cycling is a crucial component of a photovoltaic system integrated into a building. This entails charging the battery throughout the day and discharging it at night to power loads. In addition, a cyclical cycle coincides with periods of lower radiation availability. These aspects affect how long a battery lasts and how much maintenance it needs, coupled with other operating variables like ambient temperature, current, and voltage (Energypedia, 2023).

Lead-acid battery is the prevailing technology used in PV systems storage design in Nigeria (Isaac, 2022). However, its optimal operation condition is often not achieved due to some factors overlooked in the system design. According to universal standards for solar home systems, the following operating conditions must be avoided for optimal use of Lead-acid batteries in building integrated PV systems (Energypedia, 2010).

- ✓ Prolong charging at high voltage (increases corrosion and water loss)
- ✓ Discharging at low voltage (promote corrosion process)
- ✓ Extended charging at very low current (triggers sulphation)
- ✓ Excessive discharge (causes sulphation and dentrites)
- ✓ Partial charging for an extended period (produces sulphation)
- ✓ High operating temperature (catalyst for corrosion, sulphation, and dentrites)
- ✓ Electrolytic stratification (sulphation)

These instructions outline the essential steps for safeguarding the battery, such as employing a charge controller, and specify criteria for estimating the right battery size and the solar generator (panels capacity). It is important to remember that some recommendations may be at odds with one another. For instance, the requirement for high voltage to accomplish a full charge can speed up corrosion. Therefore, concessions must be made to take into consideration the environmental parameters (such as the irradiance, surrounding temperature, and available space for the solar panels), PV module's type & capacity, battery costs, taxes and tariffs, local manufacturing if available, and recycling infrastructure in designing effective PV energy storage systems.

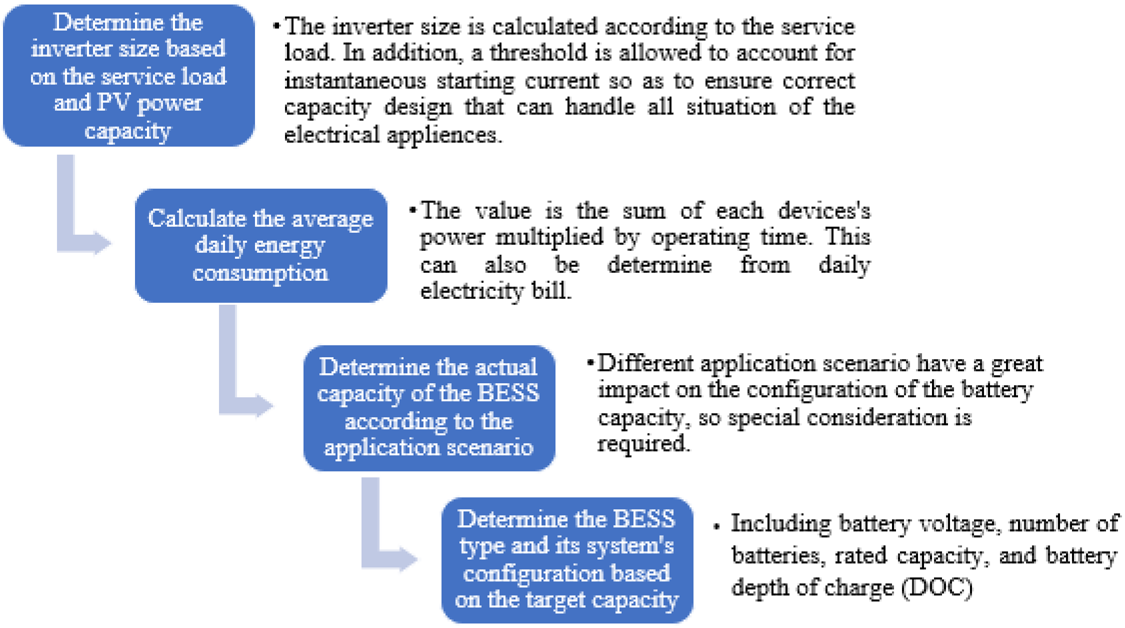
The maximum depth of discharge PD_{MAX}, must be kept to a specific level, usually between 0.3 and 0.6, though it can go as high as 0.8, depending on the battery type, to prevent over-discharging the battery. The power supply to the load must be cut off when this limit is reached. This indicates that the nominal capacity, C_B, which is the maximum charge that might be drawn from the battery without any restrictions, is greater than the real or effective capacity, C_U. Since the effective capacity is equal to the product of C_B and PD_{MAX} as shown below.

$$C_U = C_B \times PD_{MAX}$$

With a battery whose effective capacity is between one-fourths (in locations where protracted cloudy weather is improbable) to three-quarters (in regions where cloudy weather is predicted) of nominal capacity, it is frequently possible to strike a compromise between cost and dependability. This guarantees that the daily cycle, PD_D, and depth of discharge stays within the range of 1 to 2 and 0.3 to 0.8, respectively. The type of battery selected will have the biggest impact on the needed capacity. Lead acid batteries require daily full charging and are sensitive, while lithium batteries can safely remain at a partial charge. Lead acid batteries typically utilize only 50% of their capacity due to lower efficiency, whereas lithium batteries are more efficient, experiencing less wasted power during charge/discharge and allowing for a deeper discharge depth, enabling full utilization of battery capacity. Generally, a high-quality battery can have smaller nominal capacities for the same purpose as lower-quality batteries because they are less resistant to deep cycling than lower-quality batteries.

BESS CAPACITY SELECTION AND DESIGN PROCEDURE

A solar PV energy storage system's battery capacity must be accurately and precisely calculated, which can be challenging. Other considerations that must be considered in addition to the load needs include the battery's capacity for charging and discharging, the inverter's maximum power, the length of time the load will be powered, the battery's maximum state of charge, the installation location's peculiarities, etc. The required battery capacity for the system can be precisely determined by carefully analyzing each of these elements, as depicted in Figure 1.



- The inverter size is calculated according to the service load. In addition, a threshold is allowed to account for instantaneous starting current so as to ensure correct capacity design that can handle all situation of the electrical appliences.
- The value is the sum of each devices's power multiplied by operating time. This can also be determine from daily electricity bill.
- Different application scenario have a great impact on the configuration of the battery capacity, so special consideration is required.
- Including battery voltage, number of batteries, rated capacity, and battery depth of charge (DOC)

Figure 1: Basic logical decision sequence for BESS capacity selection in building integrated PV system. Adapted from (SAUR Energy, 2022)

Understanding the household's energy usage pattern and loads is crucial before installing a solar energy storage system. Ensuring that the chosen battery capacity and inverter power can meet the household's energy needs requires calculating all equipment's average and instantaneous power consumption. To determine the required inverter size, it can be helpful to tally up the wattages of all the home's equipment, from microwaves and refrigerators to PCs. The result of this computation will specify the required inverter size. For instance, consider the following list of household appliances and their corresponding wattage for a two-bedroom bungalow, as shown in Table 1. To determine the main bus rating capacity, each corresponding load capacity is multiplied by a factor of 1.25 to account for ohmic losses in the conducting cables.

Furthermore, the US Energy Information Administration (EIA) reported an inverter loading ratio of $1.13\ to\ 1.30$ for an individual system (EIA, 2018). Hence, an inverter of $4\ KVA$ is sufficient for the stipulated loads, considering a 1.13 loading ratio and power factor of 0.8, assuming all the loads are applied concurrently. However, in the case of selected load applications the rated capacity may be lower than this for a well organized and oriented users.

Table 1: Daily average energy consumption for a typical two-bedroom bungalow

No.	Load	Rated Capacity (W)		Quantity	Total Capacity (W)	Usage Time (h)	Daily Energy Demand (Wh)
		Sink Point	**Main Bus**				
1	Lighting	5	6.25	10	62.5	6	375
2	T.V Set	150	187.5	1	187.5	6	1,125
3	Cooling Fan	30	37.5	3	112.5	16	1,800
4	Refrigerator	300	375	1	375.0	12	4,500
5	Cell Phone/PC	15	18.75	5	93.8	3	281
6	Submersible Pump	500	625	1	625.0	1	625
7	Microwave Oven	1200	1500	1	1500.0	0.25	375
	Total				2,956		9,081

To determine the BESS capacity, typical daily energy use, and BESS autonomy (which is the number of hours required to support the load, usually determined by the application scenario such as self-consumption, peak-valley electricity price balance, backup power, and pure off-grid application) are taking into consideration. The following relationship can be used to calculate the required BESS capacity.

$$C_{BESS} = \frac{P_{Load}\Delta t_{atn}}{PD_{MAX}V_{BESS}\eta_{inv}}$$

$$where\ P_{Load}\ is\ the\ total\ load\ capacity\ in\ watts$$

$$\Delta t_{atn}\ is\ the\ BESS\ operation\ time\ autonomy\ in\ hours$$

$$PD_{MAX}\ is\ the\ maximum\ depth\ of\ discharge$$

$$V_{BESS}\ is\ the\ BESS\ norminal\ voltage\ in\ volt$$

$$\eta_{inv}\ is\ the\ inverter\ efficiency\ factor\ in\ range\ of\ 0.9\ to\ 0.95$$

For instance, considering the daily energy demand in Table 1, with a self-consumption scenario and BESS autonomy of 6 hours daily. The required number of BESS amounts to $12\ units$ of lead-acid batteries of $220\ Ah, 12V$ nominal capacity. Whereas, half of the required number for a lithium-ion battery will be sufficient.

CONCLUSION

In conclusion, the choice of battery type and capacity depends on the system's economic benefits as well as its ability to supply sufficient power. Considering the varying requirements of specific application settings when choosing battery capacity is crucial. Thus, determining what type of BESS technology is most suitable for building integrated photovoltaic (BIPV) applications for a particular temporal horizon may vary based on several factors, and the optimal choice can depend on specific project requirements. However, lithium-ion batteries are widely used for various applications, including building integration. They are known for their high energy density, efficiency, and relatively long cycle life. In addition, they are lightweight, scalable, and compact in size. Their major downside is their poor heat tolerance. But for cost-sensitive BIPV projects, lead-acid batteries may be a better choice for their low capital cost, technological maturity, and relatively high cycle efficiency. While the criteria for optimal BESS design consider the meteorological parameters, technical specifications of the chosen PV panels, and budget requirements.

Moreover, defining the correct number of batteries required for a BESS bank depends largely on the target goal of the energy storage system, the size and type of the BESS, and the size of the service load. It is, therefore, essential to thoroughly study the application settings, which should consider factors like the battery's capacity for charging and discharging, the inverter's maximum power, the duration of the load's power consumption, and the battery's actual maximum discharge capacity. Selecting appropriate, compatible equipment is essential to getting the best performance from any solar battery energy storage system.

FURTHER RESEARCH

While this study has shed light on Battery Energy Storage Systems for Building Integrated Photovoltaic Applications, several avenues for future research can be explored to deepen our understanding and address existing gaps.

One promising direction for further exploration is how can the economic benefits and power supply capabilities of different battery types and capacities be compared systematically? This aspect was beyond the scope of our current study but represents a crucial dimension that requires in-depth investigation. Another area that warrants attention is establishing a comprehensive performance comparison framework that guides the choice of BESS technology in various scenarios, where conflicting findings have surfaced, suggesting additional research to resolve these inconsistencies.

Furthermore, incorporating user experience and feedback into future studies could enhance the accuracy and reliability of results. Considering the potential impact of interdisciplinary collaboration, researchers are encouraged to explore partnerships with experts in behavioral psychology to bring diverse perspectives to the study of BESS for BIPV application.

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