JREE: Vol. 10, No. 1, (Winter 2023) 34-42

Journal of Renewable Energy and Environment

Journal Homepage: www.jree.ir

Materials and Energy Research Center

MERC

Technical Note

Potential for Battery Energy Storage System in Zimbabwe

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PAPER INFO

Paper history:
Received: 24 August 2021
Revised in revised form: 28 December 2021
Scientific Accepted: 08 January 2022
Published: 20 August 2022

Keywords:
Battery Energy Storage System,
Solar Photovoltaic,
BESS Investments,
Levelized Cost of Energy Storage,
Lithium-Iron Phosphate,
Zimbabwe

ABSTRACT

This study aims to assess the potential of coupling solar PV power plants with Battery Energy Storage System (BESS) to curtail load-shedding and provide a stable and reliable baseload power generation in Zimbabwe. Data from geographical surveys, power plant proposals, and investment information from related sources were reviewed and applied accordingly. Areas considered to be of good potential to employ the use of BESS were identified considering such factors as feasibility of PV plants, proximity to transmission lines, the size of a town or neighborhood, and energy demands for BESS Return On Investment (ROI) calculations. Previous studies have proven that 10 % of the suitable land for PV systems has the capability to generate thirty times the current power demand of the nation operating even with the least efficiency. In recent years, coupling renewable energy sources with a suitable energy storage system yielded improved performances, giving consumers a reliable, stable, and predictable grid. BESS technologies on the utility scale have improved in recent years, giving more options with improved safety, and decreasing the purchase costs, too.

https://doi.org/10.30501/jree.2022.294957.1230

1. INTRODUCTION

Zimbabwe is currently experiencing power outages that have a drastic impact on the nation's development, economy, education, and health systems. There have been no significant investments in power generation besides the growth of the country's population and migration to urban centres (urbanization) that have increased the power demands. Electricity accessibility and rural electrification are below standard due to the high demand of electricity in urban centers which are prioritized first though load shedding continues. Initially, hydropower and coal-fired power plants generating respectively at a ratio of 38 % to 62 % were able to sufficiently meet the energy demands in the country before the major factors came into consideration [1]. Currently, Zimbabwe's power supply companies cannot generate enough energy to meet the national demands or pay for adequate power imports from South Africa or Mozambique due to the growing number of energy consumers. The national electricity demand as of May 2021 was estimated between 1800 MW and 2200 MW depending on season, yet the generated power from the Kariba hydropower and all the thermal power plants in the country only amounts to 1200 MW [2]. After a hiatus, the Zimbabwean government introduced new renewable energy policies with the aim of eradicating power outages in the country, and the Infrastructure Development Bank of Zimbabwe issued proposals to seek partners develop small-scale PV plants as alternatives to improve the country's grid and reduce the load-shedding crisis.

Due to the decent amount of unhindered solar radiation of approximately 6.5 kWh/m^2 DNI daily available in Zimbabwe, there are high possibilities of solar PV panels producing more electrical energy than required during the day [3]. Like any other country, high energy consumption periods (peak-loads) are experienced during morning and evening hours when there is little to no sunlight. The proposed small-scale PV plants are capable of improving the grid but will not be able to meet the energy demands of the country; therefore, the introduction of Energy Storage Systems (ESSs) should be considered. Energy storage is essential in PV systems to overcome the intermittency of the energy generated by the system which could be caused due to daily, monthly, or seasonal solar irradiance fluctuations. Other countries can offer several ESS alternatives for PV plants like Pumped Storage Hydropower (PSH) or grid-storage, but for a country like Zimbabwe, grid storage is impractical since the grid is already failing to meet the demands. Also, PSH entails construction of large water reservoirs and alteration of topographies, which result in high capital expenditures (CAPEX) as well as a long duration of time until the constructions are finished. Other ESSs are not technically and economically favorable considering Zimbabwe's current economic situation. Considering these factors and the advances in Battery Energy Storage System (BESS) technology in the past years, BESS utility has the capability to increase the stability and resiliency of the grid,

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URL: https://www.jree.ir/article_155040.html

Please cite this article as: Njovana, A.G., Yu, W.Y., Shen, Q., Li, J., Zhu, Y. and Liu, Y.S., "Potential for battery energy storage system in Zimbabwe", ***Journal of Renewable Energy and Environment (JREE)***, Vol. 10, No. 1, (2023), 34-42. (https://doi.org/10.30501/jree.2022.294957.1230).

thus meeting consumers' energy demands and possibly offering a Lower Levelized Cost of Electricity (LCOE).

This study addresses the following BESS application objectives:

- How much electricity does Zimbabwe need?
- Identification of the functions of a BESS;
- Discussion and selection of the ideal BESS technology for Zimbabwe's situation;
- Selection of a suitable location and method of coupling BESS with the PV system;
- Assessment of the economic and technical barriers hindering the employment of BESS technology;
- BESS sizing and economic analysis including Capital Expenditure (CAPEX) and Operation Expenditure (OPEX);
- Advising policy-makers and potential investors on the potential for BESS in Zimbabwe.

2. ZIMBABWE ENERGY CONSUMPTION AND GENERATION

According to International Energy Agency (IEA) 2019 data, 18 % of the total power used in Zimbabwe was imported from neighboring countries. Total annual imports depend on certain aspects like climate and turbine breakdowns since Zimbabwe's electricity generation derives mainly from hydropower and coal-fired thermal power plants. In 2017, Southern Africa received less rainfall compared to the previous years and experienced high temperatures under which all the factors had a significant impact on hydropower generation. Kariba Dam water levels decreased because of low rainfall and high evaporation rate caused by intense heat. In the year 2000, Zimbabwe had the highest import rate of over 5000 GWh and the rate declined due to the extension of the Kariba South Dam hydropower and high implementation of individual off-grid system. The country has never been able to export electricity as the grid cannot meet the nation's energy demands.

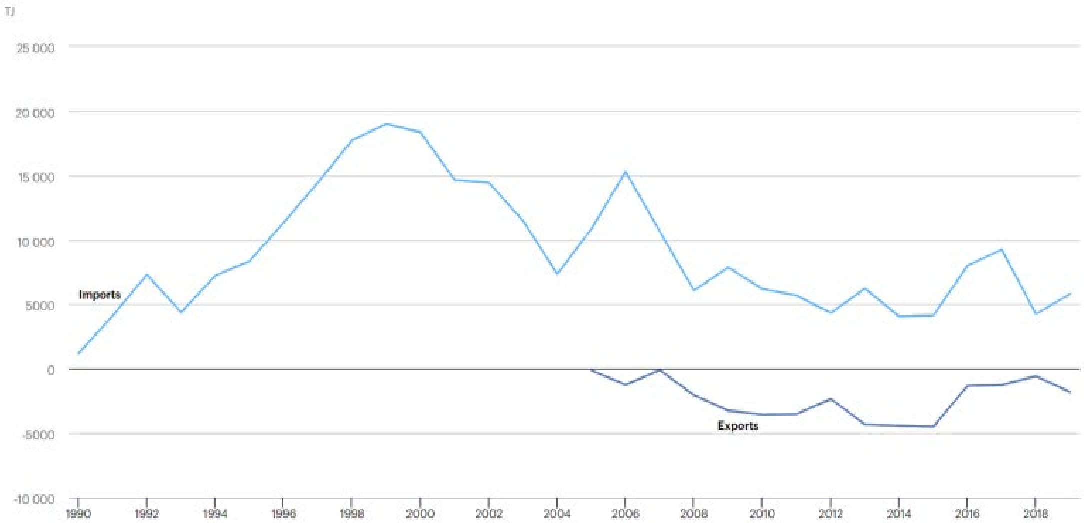

Figure 1. Electricity imports vs. exports, Zimbabwe 1990-2019 [IEA]

The country's population is estimated at 14.8 million and national electricity access stands at 41 %, leaving most of the population without access to electricity. Electricity consumption per capita in 2020 was estimated at 1,320 kWh, (830 kWh less than the required) and the total annual generation at 8,200 GWh (1.3 GWh less). Most of Zimbabwe's electricity is generated through coal thermal power and hydropower plants at a ratio of 58 % to 38 %, respectively. Biofuels and oil currently have a total capacity of less than 5 % combined, although the biofuels sector is experiencing great investments. Zimbabwe receives 3000 hours of sun per year and the most radiated region receives up to 6.5 kWh/m^2; this proves the great potential of solar energy generation through both solar photovoltaic (PV) and solar thermal compared to other renewable sources given they are easily affected by climate change.

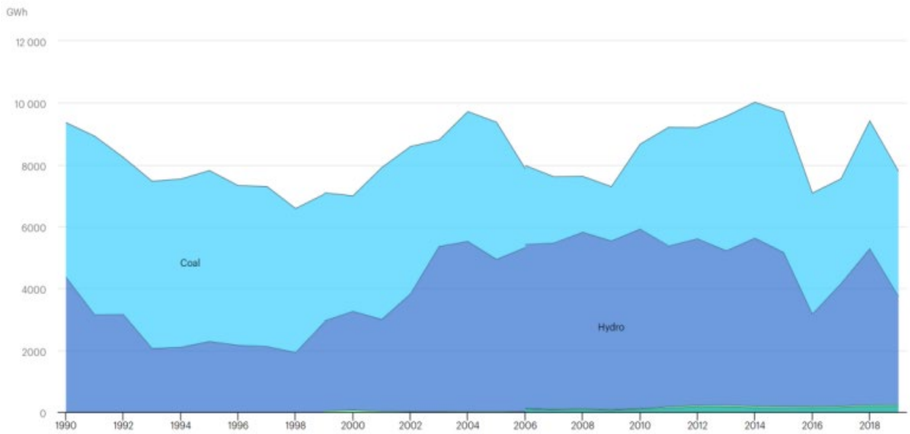

Figure 2. Electricity generation by source, Zimbabwe 1990-2019 [IEA]

3. BESS FUNCTIONS

Energy storage systems have the ability of storing energy using thermal, mechanical, chemical, and electrochemical solutions. BESS typically utilizes an electrochemical solution to store electrical energy in a chemical form, which enjoys significant benefits since both electrical and chemical energies share the same common carrier and electron. This makes batteries a commonly used system to store excess electricity from different sources. BESS is able to mitigate the sharp fluctuations of variable renewable energy resources for on-grid systems, provides ancillary services for the system, complements, and extends the operating hours of the system in a reliable and cost-effective manner. Before implementing BESS, there is a need for identifying locations where it is necessary to use storage (based on energy demand statistics) for grid balancing and peak shaving instead of conventional network reinforcement. The following represent a few critical functions that an energy storage system is expected to perform:

Integration into the grid: Just like other renewable sources, solar energy is variable which makes it hard for electricity providers to plug it directly into the electricity grid without a storage medium, thus guaranteeing a constant and smooth supply of electricity to consumers. In most cases, grids balance the supply and demand of electricity and thus benefit the most from dispatchable sources of energy (so far, fossil fuels that could be burned on demand or diesel gensets provide that sort of convenience) [4]. Energy storage makes solar energy and other renewable energy sources more dispatchable (available on-demand grid operators) at any time of the day and hence, more cost-competitive with traditional fuel options. In Zimbabwe, the ageing thermal power plants have resulted in recurring power plant breakdowns leaving consumers in unexpected blackouts. Unsteady diesel imports also affect genset operators. All these prove the best potential for BESS in Zimbabwe.

Peak demand: Responding to peak demands requires the ability to generate power quickly, considering batteries they have an extremely fast response time compared to other ESSs. The energy stored in the batteries is immediately available and can be discharged and used to meet peak demand depending on the battery capacity and storage duration. This helps use the stored renewable power for peak generation to meet consumer demands and avoid grid disruptions or blackouts.

Load/Time shifting: PV modules generate power only during the daytime with the peak at noon hours, which is when electricity demand is also the lowest, while the peak energy demand is often located during evening hours, when the solar irradiation is low or not available. Solar power needs to be “time-shifted” to be available during high demand, and this can be achieved by means of utility-scale energy storage [5]. Thus, BESS allows shifting energy usage by charging batteries with solar energy and discharging them during peak load when electricity is also more expensive.

Figure 3 shows less power demand during the day hours when there is enough sunshine for the PV arrays to generate power; therefore, excess power generated will charge the BESS. During the peak demand, PV arrays will not be generating power; therefore, the BESS discharges and meets the energy demands.

Energy autonomy and emergency backup: For communities living in areas without access to electricity grid, combined renewable energy plus storage systems may be the best option to provide for constant supply of electricity and keep operations running during power outages. This autonomous approach can be realized on both distributed (house/community) and utility (area/region) scales. In such situations, a BESS would be required to have a high energy capacity (amount of stored energy) and a long duration energy storage capacity with a decent rate of charge or discharge (power capacity) to provide a stable and constant power supply.

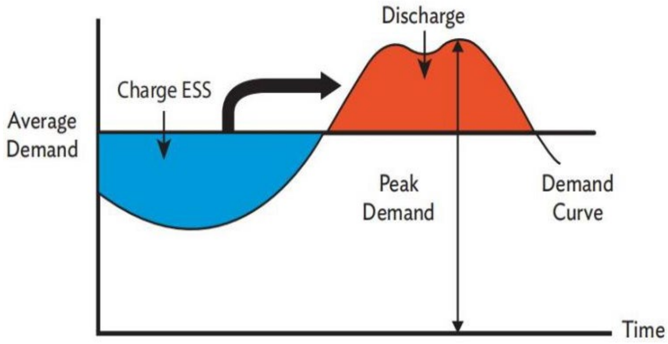

Figure 3. BESS use for load/time shifting [5]

Peak shaving: In a commercial/community setting, the most important application of energy storage is peak shaving. A higher percentage of the utility bills are made up of demand charges that are mostly experienced during early or later hours of the day when there is no availability of sunlight for solar energy generation. Solar arrays alone are not always a sufficient solution to meet these demands as they are affected by time of the day, weather, and season. BESS can guarantee no power disruptions from the grid during peak times. Thus, peak shaving helps the utility meet demand without having to ramp up expensive peaking gensets. In this case, network operators should be required to identify locations where it is necessary to use storage for peak shaving based on energy consumption data instead of conventional network reinforcement.

In general, peak load problems could be reduced, electrical stability improved, and power quality disturbances eliminated. Energy storage offers a flexible and multifunctional role in the grid of electric power supply by ensuring more efficient management of available power for consumers. As supply from PV components varies due to its intermittency, energy must be provided to rapidly restore the frequency to the desired limits [6]. This application is ideal for high-power batteries because they can respond quickly and the energy requirement is low. Energy storage can be applied at the power plant where the RES is in support of the transmission network at various points in the distribution areas.

4. BESS TECHNOLOGY

Electrochemical batteries come in many different forms of technologies: some are more applicable to utility-scale energy storage, while others are only applicable to certain devices or equipment. Applicability to large systems depends on such factors as life span, charge, and discharge (round trip) efficiency, ability to scale up with no ill effects or performance loss, design and operation mode, power densities, and Depth of Discharge (DOD). Utility-scale BESS requires energy storage ranging from a few megawatt-hours (MWh) to hundreds of MWh and the technology must be able to discharge quickly to match the fluctuations of the variable solar resource during the day or respond quickly to an unexpected power cut at any time of the day providing an Uninterruptible Power Supply (UPS) [7]. Considering the factors and the requirements of a BESS, the two technologies that have a greater potential in Zimbabwe are lithium-ion batteries and flow batteries based on their performance, energy density, safety, and applicability. However, flow batteries are subject to significant technical and economic setbacks in comparison to standard solid-state batteries which make it difficult to implement them in Zimbabwe. In recent years, lithium-ion (Li-ion) batteries are commonly used, and they dominate most of the market growth and their costs are decreasing as technology advances and manufacturing efficiency increases which makes them affordable and an ideal technology for Zimbabwe's investment [8].

Li-ion batteries have a growing share in storage capacity additions and are largely driven by the declining cost of Li-ion technology in recent years, which, in turn, is expedited by the ramp-up in production to meet the growing demand of batteries for electric vehicles [9]. The introduction of the cell-to-pack technology in 2019 led to a further decline in costs of Li-ion batteries although it is currently significant in the EV industry. Compared to other batteries, lithium batteries offer more advantages which are more favorable for a large-scale BESS. Lithium batteries are available in different types with different properties; however, for this assessment, lithium-iron phosphate ($LeFePO_4$)/(LFP) batteries are selected amongst lithium batteries. LFP batteries can withstand more charge-discharge cycles of nearly over 5000 cycles at 80 % Depth of Discharge (DOD) compared to batteries like lead-acid batteries [10]. Although LFP batteries have a relatively lower energy density (watt-hours per kilogram "Wh/kg") than other Li-ion batteries, they still offer a high round trip efficiency of up to 95 % and a longer life span of 10-15 years depending on the area of application [11]. LFP batteries are much safer than other Li-ion batteries due to their thermal and chemical stability, making them incombustible in the event of mishandling, short circuiting, high temperatures, or overcharging, which is probable due to high solar irradiance in Zimbabwe although LFP batteries are equipped with a Battery Management System (BMS).

Figure 4. Modularity of LFP batteries [12]

Figure 4 shows the modularity of lithium-batteries including the LFP batteries. The cells are enclosed in modules and mounted on a rack. Each rack has its own BMS which ensures that each cell remains within the safe limits, and it is enclosed together in a container to form a powerpack [12].

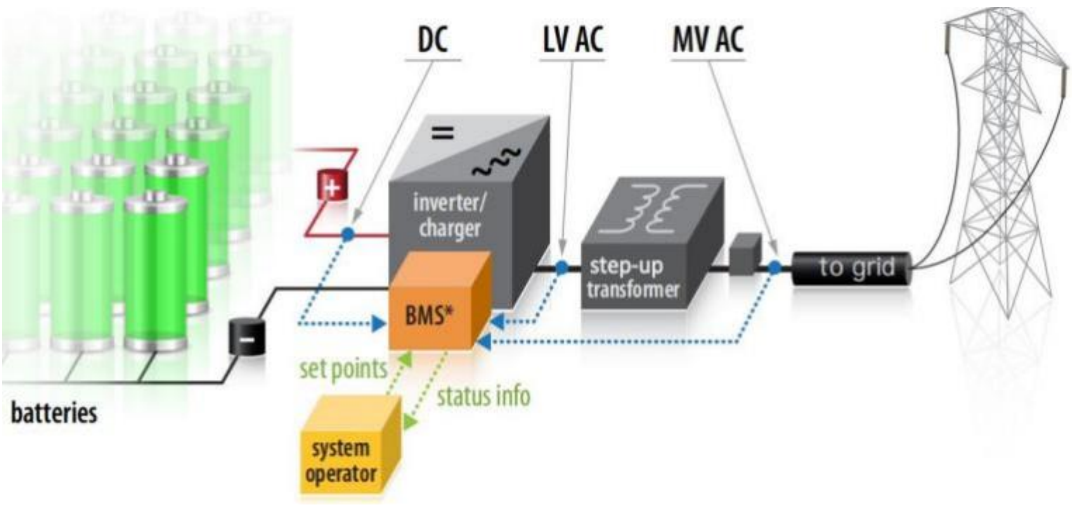

Figure 5. BESS directly connected to the grid [19]

A BESS is composed of different levels, namely Energy Management System (EMS), battery system, and Power Conversion System (PCS), which need to be considered for both operation and investment [13]. The battery system is composed of containers with several battery packs inter-connected in series and parallel to reach the desired value of current and voltage. The BMS controls the proper operation of each cell to allow the system to work within a desired voltage, current, and temperature so as not to pose any danger for the system itself but ensure viable operation of the batteries. The system also calibrates and equalizes the State of Charge (SoC) of the cells. The BESS is connected to the inverters to convert the power from DC to AC. In each BESS, there is a specific power electronic level, called PCS (Power Conversion System), that is usually grouped in a conversion unit including all the auxiliary services needed for the proper monitoring [14]. Depending on the size of the system, there is a step-up transformer connection from low-voltage to high-voltage to meet the required transmission voltage.

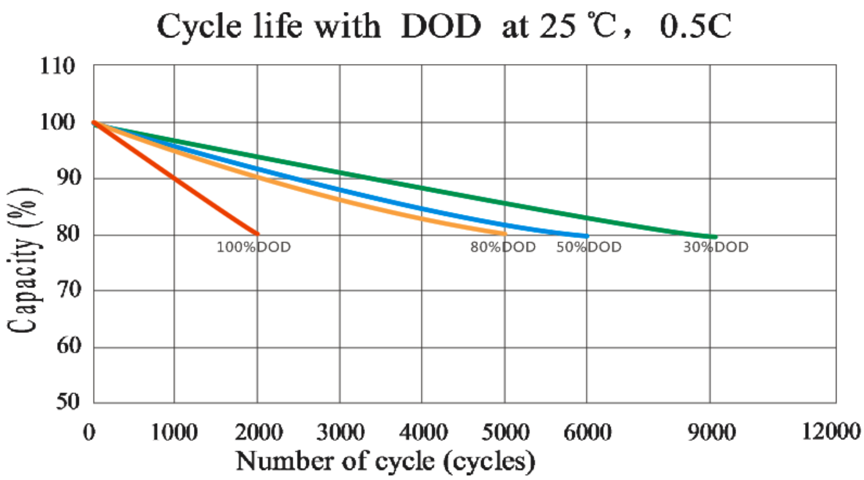

Figure 6. LFP batteries cycles based on DOD [15]

The long service life of LFP batteries makes it possible to use $LiFePO_4$ in utility-scale energy storage applications. Given that the BESS will operate at a constant temperature of around 25 °C at 80 % DOD, 0.5C (charge or discharge rate), this can result in 4500-5000 cycles, which is equivalent to approximately 10-12 years [15]. As shown in Figure 6, LFP battery's lifespan depends on the DOD, operation temperature, the C-rate.

5. BESS COUPLING AND LOCATION

5.1. BESS coupling

Mounting a BESS to a utility PV system requires different methods of coupling, which can be split into two main categories: AC coupling and DC coupling.

AC coupling with the BESS involves coupling using an AC bus. The AC bus is located after the PV array where power is converted to AC using an inverter. With this system method, the power supplied to the grid is maximized by discharging both the battery and PV at maximum power [16]. They offer the ability to be dispatched independently or together. AC coupling is more common when the BESS is deployed in the same area of distribution, i.e., near load/consumers, which is more advantageous for the BESS operator.

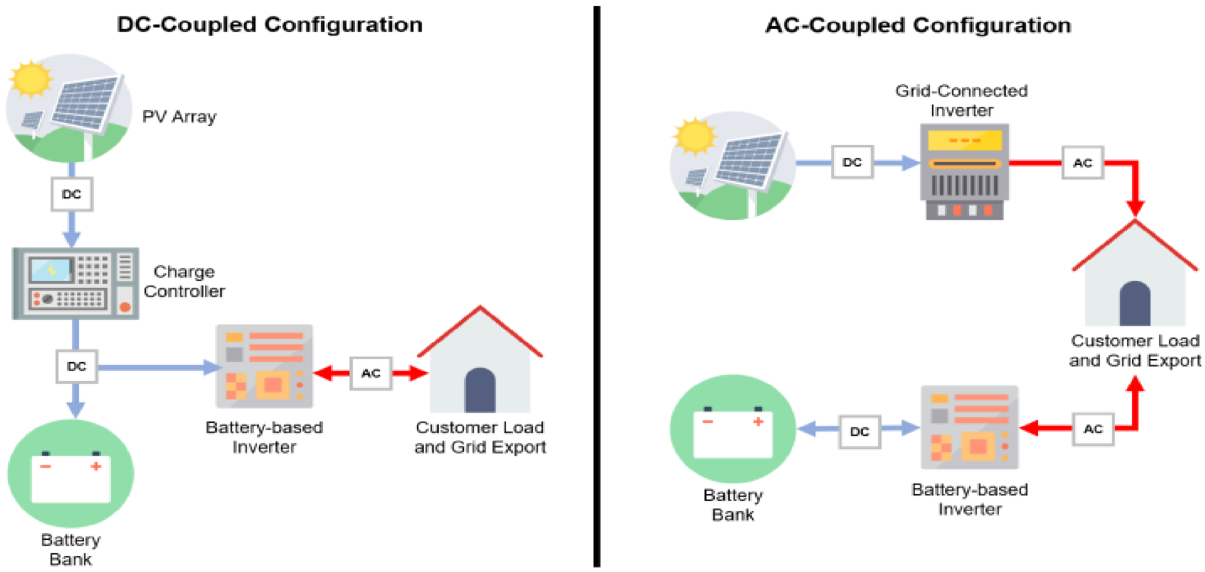

Figure 7. BESS AC and DC coupling [16]

An alternative approach involving coupling energy storage to PV arrays with a DC-to-DC converter can help maximize production and profits for existing and new utility-scale installations. DC-Coupled utility-scale solar plus storage leads to higher round-trip efficiencies and lower cost of integration with existing PV arrays and at the same time, opens new revenue streams not possible with traditional AC-coupled storage [16]. DC coupled BESS, on the other hand, can be co-located with the PV plant as it requires a direct connection using a DC bus, which may have a few limitations.

5.2. BESS location

BESS coupling is dependent on the deployment location of the BESS itself. There are three main ways a utility-scale BESS can be deployed: within the area of distribution that is near load centers; co-located with Renewable Energy Source (RES) (in this case PV plant), or in the transmission network. There are important implications in the siting of the BESS based on the services the system can best provide, and the most appropriate location for the BESS also depends on its intended purpose. Technically, a BESS can provide a broad range of services in any locations; therefore, an important analysis of the costs, safety, and benefits of multiple locations is required to determine the optimal siting to meet system needs [17].

5.3. Area of distribution near load centers

After costs and dispatchability analysis for the ideal BESS location, energy storage systems located within the distribution area where the consumers/energy demand is or co-located with the RES offer a stable grid depending on the BESS operation parameters. BESSs that are in the distribution network have the capability to provide all the services offered by a transmission-network sited storage, in addition to several services related to congestion and power quality issues [18]. It may be difficult to site other energy storage system technologies near load/consumers to provide peaking capacity due to concerns about safety, emissions, or land use. However, BESS and typically LFP batteries can be co-located near load with fewer siting challenges than others due to their high tolerance to different working conditions and the safety they offer. Since the BESS is deployed near the load site, electrical losses in transmission and distribution can be greatly reduced while capacity and energy value are increased; therefore, generated electricity can efficiently reach the intended consumers with minor loss. Distribution-level BESS systems can also provide local power quality services and support improved resilience during extreme weather events [19]. This siting can work effectively for both power providers that operate the BESS and the RES and for private BESS operators as it offers profitable arbitrage opportunities by charging the battery storage during off-peak hours when electricity is cheap and discharging during expensive peak hours. Investments in transmission and distribution are also deferred, leading to reduced CAPEX.

Taking Zimbabwe's residential system into consideration, suburbs are put into three main categories: low-density suburbs, medium-density suburbs, and high-density suburbs. In this case, the ideal suburbs to deploy a load site BESS will be in high density suburbs as they are highly populated areas; therefore, there are more consumers than other suburbs and furthermore, these are the suburbs that experience the highest power cuts during peak demands when the grid is unable to meet all the demands. The siting challenges are very limited and the BESS itself is scalable; as a result, a BESS deployed in high-density suburbs has a greater chance of high Return On Investment (ROI). Medium-density suburbs, on the other hand, may be an ideal location for small-sized BESS as well since the suburbs are less populated and have a great percentage of the population invested in individual on-grid PV systems with energy storage systems connected Behind-The-Meter (BTM). Low-density suburbs are the least populated suburbs that experience nearly no power interruptions and have a great percentage of the population with individual off-grid PV systems.

To summarize, the BESS located in high-density suburbs can be charged during off-peak hours when there is excess electricity generation. The BESS will be connected to the grid which will be transmitting PV power from the PV plant. Below is an example of a BESS located far from the RES, but close to the load center.

Figure 8. BESS located near load center

5.4. Co-located with Renewable Energy Source (RES)

In most cases, RES plants are located far from load centers as their location depends on the availability of adequate supply of natural resource like wind or solar. Solar PV plants require vast open land that is not prone to any sunlight hindrance, which is mostly available far from the urban centers where the electricity demand is located. For the generated energy to reach the demand/consumer area, significant transmission capacity is required. Considering the variability of Variable Renewable Energy (VRE) resources, the transmission capacity used to deliver the power may be underutilized for large periods of the year resulting in low ROI due to increased transmission value. A BESS can reduce the transmission capacity needed to integrate these resources and increase the utilization of the remaining capacity by using storage to charge excess generation during periods of high resource availability and discharge during periods of low resource availability [20]. In this case, it is cost effective to co-locate RES plant and the BESS in an area where there is an existing transmission capacity.

In this case, the BESS is deployed in the same location as that of the PV system. The PV system will generate power and transmit it to the BESS via DC-DC coupling. The BESS will charge and transmit power to the grid. Figure 9 below shows a BESS co-located with the PV plant.

Figure 9. BESS co-located with PV plant

6. BESS DEPLOYMENT BARRIERS

In the meantime, there are no commercial or pilot BESS that has been designed and operated on a utility scale in Zimbabwe. Generally, there is little development or investments in storing excess energy produced in the country. The main barriers of the deployment of energy storage can be grouped into three different categories: technical barriers, regulatory barriers, and economic barriers.

6.1. Technical barriers

Large-scale electrochemical energy storages are still emerging technologies that are experiencing rapid changes and advancements regularly and, in some cases, show more investment risks for investors than conventional generator investments. These risks include the technical aspects of BESS, which can be less understood by stakeholders but comprehensible for the engineering team as they are changing faster than other technologies in recent years. Zimbabwe has always been relying on biofuels, hydroelectricity, and thermal power; therefore, investments in thermal energy storage and mechanical energy storage such as pumped storage hydro-electric for the newly opened PV plants are more favorable since the storage systems operation and maintenance procedures are just the same as the current running power plants; however, their response times are slower than the fast-ramping capabilities of BESS. Furthermore, the import of key repairs like turbines and generators may be impacted by the acute foreign currency shortages that constantly recur. Although the battery technology itself requires to be imported, the long lifespan offered specifically by LFP batteries makes it possible for the BESS operator to rely on importations and it also allows the investors to catch up with the new battery technologies available at given times. The gaps in data and analysis capabilities and lack of adequate tools can deter investments and possibly stop battery storage from being considered for services that can be provided by better well-known conventional generators [21-22]. Technical know-how of the battery cells, chemical properties, reactions, and operation parameters may be required before implementing them on a large scale.

6.2. Regulatory barriers

Storage could also be technically able to provide essential grid services, if no regulations or guidelines explicitly state that storage must provide certain services or meet certain requirements. Without a guarantee that services provided by a BESS project can be compensated, storage operators and financing institutions might be unwilling to make the necessary capital investments as they will view it a risk. Among other requirements, the rules must be flexible enough to ensure access to the market for storage systems operators, taking into consideration their unique operating and technical characteristics. Restrictions or lack of clarity around the way how storage can be used across generation, transmission, and distribution roles can lead to investors investing in too big or too small BESS and deploy them in wrong locations. Zimbabwe Energy Regulation Authority (ZERA) has encouraged small-scale Independent Power Providers (IPP) to sell excess generated electricity to Zimbabwe Electricity

Supply Authority (ZESA); however, there are terms on how much power can one sell to ZESA. The amount of power an IPP can sell to ZESA is unlimited; however, there is a set minimum amount of power an IPP can negotiate to sell to ZESA which has been the biggest limitation for IPPs as they are incapable of investing in large-scale systems. Furthermore, to guarantee ZESA with a stable power supply as an IPP, it requires the implementation of BESS in which a lot of IPP cannot afford to invest currently.

The range of various services ESS can often provide cuts across multiple markets and compensation sources. In some jurisdictions, providing services across different compensation sources is restricted by certain regulations [23-24].

6.3. Economic barriers

Although BESS has the capability to provide the same services as those of a conventional grid, it is impossible for an IPP to implement a BESS independently as power distribution requires to be regulated by the power distribution authorities; thus, consumers may be required to apply for the shift from local grid and connect them to BESS. Furthermore, the presence of batteries in the market could distort the pricing formation which could affect storage systems and conventional generators. The one-tariff regime implemented in Zimbabwe could work effectively with thermal or hydro power; however, if a BESS is coupled with a PV system, tariffs may be expected to vary for baseload and peak demand as this will allow a decent ROI and give investors interests to increase the storage capacity and replace batteries after their lifespan. Battery systems can provide certain services much faster and more accurately than conventional resources, which may not be reflected in compensation for the service [25-26]. Similarly, BESS is uniquely suited to produce up or down regulation, given their larger operating range over which to supply regulating reserves (due to their lack of a minimum stable level and capability to supply up and down regulation that may be over their nameplate capacity based on whether they are charging or discharging) [27-28].

To summarize all the barriers, the unavailability of practical references to gain accurate data and knowledge of BESS application benefits has an impact on the investment and deployment of the system. There are currently no policy measures and institutional structures that guide investments in energy storage in Zimbabwe since these will be new and experimental projects. Since utility-scale energy storage is still considered a new technology, there is a possibility of lack of technological know-how and skills based on large-scale BESS in the country. While other barriers require government and policy intervention, other issues such as lack of know-how can be tackled by intensive trainings and with reference to other operational projects around the world, some of which have been operational for several years.

7. BESS TECHNO-ECONOMIC ANALYSIS

There are two major costs in the investment of a BESS: the capital expenditure (CAPEX) and the operation expenditure (OPEX). The CAPEX of a BESS is made of a onetime investment that is required to bring the whole BESS into an operating state and it can be separated into direct (Cdirect) and indirect (Cindirect) costs. Here, the Cdirect costs of the BESS are related to the total cost of battery modules or battery packs (Cbatteries), the balance of plant (CBOP) including BMS, the total cost of Power Conditioning System (PCS) (CPCS) required when converting the generated DC power into AC power and the installation costs (Cinstallation) of all the BESS equipment. The BOP costs are the civil work costs only. Given that the BESS is coupled on the DC side, the cost of the PCS is not taken as it is integrated with the RES (PV) PCS. The indirect costs are the engineering costs (Cengineering) associated with the contractors, the tax costs (CTAX) including municipal fees to be paid if the system is deployed in a residential area near consumers, and the project installation or process contingency costs (Ccontingency). BESS CAPEX calculations are done through the equations below:

$$CAPEX_{BESS} = C_{direct} + C_{indirect}$$

$$C_{direct} = C_{batteries} + C_{PCS} + C_{BOP} + C_{installation}$$

$$C_{indirect} = C_{engineering} + C_{TAX} + C_{contingency}$$

Operation expenditure (OPEX) of a BESS has fixed costs and variable costs that can be presented as labor and engineering costs (C_{labor}) associated with the system operation, the O&M costs which mainly consist of operation and maintenance of the PCS, and replacement ($C_{O\&M}$). Since equipment wear with operation, there are decommissioning and disposal costs ($C_{disposal}$) to be incurred.

$$OPEX_{BESS} = C_{labor} + C_{O\&M} + C_{disposal}$$

After several years of use (4-12 years), the BESS will need to be replaced due to the underperformance of the system or the fact that the battery modules may have reached their operational lifespan; this replacement can be equal to C_{direct} or less since the cost of batteries is decreasing yearly.

8. CONCLUSIONS

Zimbabwe has a great potential for high solar PV production and since the grid is failing to meet the nation's energy demands, BESS has a greater potential for stabilizing the grid. However, considering Zimbabwe's situation where electricity tariffs and distribution are mostly governed by Zimbabwe Energy Regulatory Authority (ZERA), arbitrage where in other countries a private BESS operator charges the BESS during off-peak hours when electricity is cheap and discharges during expensive peak hours might be infeasible since ZERA and Zimbabwe Electricity Supply Authority (ZESA) passed a one-tariff regime whether it is off-peak hours or peak hours and an additional 6 % that goes towards the Rural Electrification Agency (REA). On the other hand, power absorbed and delivered by a BESS may also require to be regulated by ZERA with the aim of preventing irregular tariffs. Given that a BESS operator or ZESA itself has coupled the grid with a BESS, it is possible that the 6 % REA levy can be removed with the guarantee of putting fault and contingency into consideration to ensure safety and stability of the grid in return. According to Zimbabwe National Statistics Agency (ZimStat) data, Zimbabwe's electrical energy imports reached 192 %, which is equal to US$192.3 million in 2020; however, due to the Covid-19 pandemic, energy demands decreased, and the grid started to stabilize. The reduced business hours in 2021 lowered the energy demand, which is proof that the application of BESSs to serve both commercial and communal grids can help stabilize the grid.

Since Independent Power Providers (IPPs) in Zimbabwe have been efficiently producing energy for their consumption, there is a high potential for having efficient IPP managed BESSs only if ZESA/ZERA gives incentives to private BESS operators. Investors may be compensated in several ways and may experience a decent return on investment (ROI) within a short period of time depending on the location, targeted consumers, and size of the energy storage system. Instead of a flat tariff system, ZESA uses a stepped tariff system where every individual is entitled to a certain amount of discounted kWh with the aim of making electricity affordable for everyone, especially the less fortunate, although these kWh capacities are not enough to last long. After the discounted power is used up, the more power used by a consumer, the more expensive it becomes. In this case, if a BESS is privately operated, ZESA can pay the predetermined price and recover through retail electricity rates plus an additional REA levy paid by consumers. BESSs have a high possibility for curtailing energy problems in Zimbabwe and provide a better stable and reliable grid for the consumers and might also lower the LCOE in the future since battery costs continue to decline and Zimbabwe is considered to have the largest lithium deposits in Africa as of 2021 that are yet to be exploited.

9. ACKNOWLEDGEMENT

This work is supported by the National Natural Science Foundation of China (No. 51971128), Program of Shanghai Academic/Technology Research Leader (No. 20XD1401800), Science and Technology Commission of Shanghai Municipality (No. 19020501000).

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