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An Optimal Methodology for Sizing and Selection of Battery Energy Storage System in Standalone Solar PV Systems

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Abstract: This paper presents a two-step cost-based method of optimally sizing and selecting BESS in standalone solar PV system applications considering predicted solar radiation data and economic performance (BESS cost analysis). The methodology is basically divided into two distinct parts; the first part is the sizing process and the second part is the selection process. In the first part, several BESS sizes suitable for a particular standalone PV system are determined using energy deficit and supply interruption outcomes of a PV system simulation with predicted hourly solar radiation series, hourly load demand and battery storage capacity as simulation parameters. In the second step, the economic performance of the determined BESS sizes is evaluated through a cost analysis process where two financial metrics; net present value (NPV) and payback period (PBP), are utilized. This step is necessary in order to ascertain the investment risks and benefits of the BESS sizes. To test its adequacy, the methodology was applied to two case studies; a residential load and a commercial load, and the results obtained for both case studies suggests that combining BESS sizing using predicted solar radiation data and BESS selection considering economic performance is an adequate process of incorporating BESS in standalone PV system applications.

Keywords: BESS sizing; Economic performance; Financial metrics; Isolated PV system; Net present value; Payback period; Solar radiation; Synthetic series.

1. INTRODUCTION

Solar energy is of, if not the most available renewable energy resource on the planet and the world has in the past few decades, been witnessing an exponential increase in solar PV deployment for residential and commercial building applications mostly due to concerns of environmental pollution, fragile fuel market and operational complexity and hazards associated with fossil fuel generation (Dulout et al., 2017; Abubakar, Gemignani and Meschini Almeida, 2019). Solar PV systems are suitable for various application are hardly restricted by the availability of solar resource and manufacturing material, geography or transmission distance (Wang *et al.*, 2015). The exponential deployment of the technology can also be attributed to technology advancements, the consequence of which is the decrease in PV systems' installation and component costs, and to its ability to be used in isolated system applications especially where connection to public grid is difficult or practically impossible.

Standalone PV systems pose a number of power supply concerns as intermittency of solar resource and isolation of the system presents difficulties to maintain constant power supply. The generation output of these solar resource is for the most part random (Zhou *et al.*, 2016) with unpredictable variation (Dulout *et al.*, 2017) which can adversely affect electric systems, causing power issues in the system and resulting in damages, power unreliability and low power quality. These types of systems are usually equipped with fossil fueled generators as backup which are expensive to run and harmful to the environment due to GHG emissions.

The use of battery energy storage system (BESS) is a possible solution to avoiding fossil fuel-dependent backups, mitigating the power issues in the system as well as ensuring constant supply. BESS sizing otherwise known as battery bank sizing is a crucial process in PV system applications. It is important to ensure that loads are being supplied in the absence of solar PV generation. Having the right battery size in a PV system is important to handle the load coming from the PV panel and to serve as a reliable backup to the system without having to discharge the battery to an unhealthy level (Alternative Energy, 2020). Unnecessarily oversizing BESS leads to unnecessary expenses to the system while also making the system more complex which leads to high maintenance costs (Wholesale solar, 2020). The basic idea of BESS sizing is to select a battery that is compatible with the PV system while also meeting the load requirements without the risk of power outage or damage to the system.

BESS installation in solar PV system application for standalone or isolated systems is a delicate topic in the renewable energy world. (Rodríguez-Gallegos *et al.*, 2018) proposes an approach of sizing and placement of PV solar panels and battery in isolated systems running on diesel generators as the only source pf electricity. The approach uses a multi-objective optimization method with the objective to minimize levelized cost of electricity, CO_2 emission and total grid voltage deviation. Similarly, in order to minimize annualized system cost, (Giallanza *et al.*, 2018) carried out a high-resolution analysis that allows sizing of hybrid PV-wind turbine- battery banks. (Barzegkar-Ntovom *et al.*, 2020) evaluates the economic viability of a hybrid grid-connected PV-storage system for residential applications under a pure self-consumption scheme where no compensation is provided for injecting excess PV energy into the grid. (Vonsien and Madlener, 2019) presents the economic modeling of the economic efficiency of Li-ion battery storage where the increase in self-consumption of electricity from a solar PV system by means of a home battery storage system is quantified using a hybrid model which is a combination of a self-developed economic model and a technical battery-aging model. (Branco, Castro and Setas Lopes, 2018) assessed the integration of RES considering the installation of BESS into an isolated power grid to provide a portion of the spinning reserve needs and to alleviate the load of thermal generators. (Killer, Farrokhseresht and Paterakis, 2020) provides an overview of how large-scale Li-ion BESS are currently being implemented in Europe, the middle East and Africa (EMEA) region, answering the questions: What are the main use-cases of large-scale Li-ion batteries that are being implemented? What are the key factors that are enabling the deployment of BESS projects in the present market? How can current tendencies be extrapolated to the future outlook of Li-ion BESS implementation? (Mandal, Das and Hoque, 2018) investigates the optimal sizing of standalone hybrid energy system with BESS in rural areas while (Colmenar-Santos *et al.*, 2019) presents an optimal method of designing BESS to integrate into any solar PV power plant with delivery limitations. (Vonsien and Madlener, 2020) analyzes the economic impacts of Li-ion battery storage aging and pooling in private households with PV systems using a techno-economic model. (Najafi Ashtiani *et al.*, 2020) presents a novel framework to optimally size a grid-connected PV/battery system in order to minimize total net present cost using an optimization algorithm based on teaching and learning process. (Rezk, Abdelkareem and Ghenai, 2019) conducted a research of the performance evaluation and optimal design of standalone solar PV-battery system for irrigation in isolated regions. Improvements to the iterative method of electric system cascade analysis (ESCA) was presented in (Singh, Bansal and Singh, 2018) for the purpose of optimizing an isolated PV system with BESS for a residential load. (Zolfaghari, Ghaffarzadeh and Ardakani, 2019)on the other hand, proposed a cost-based method of determining the optimal BESS in a micro-grid application with the objective of calculating optimal BESS size while minimizing the total cost using convex optimization method. (Cai *et al.*, 2020) proposed a framework to optimally size and locate a hybrid system with PV, battery and diesel technology in an off-grid application. The framework uses a GIS module to identify the best location based on technical, economic, reliability, social and environmental criteria. An optimization algorithm is then used to determine the appropriate capacity to meet load requirement via total lifecycle cost minimization.

In this paper, an optimal two-step cost-based method of sizing and selection of BESS in standalone PV system application using predicted solar radiation data and BESS economic performance evaluation (cost analysis) is presented. In the first step of the methodology, Box-Jenkins method is used to process hourly solar radiation data of a location in Brazil to obtain time series models suitable for the prediction and generation of synthetic series. The models are then validated using confident interval and comparison indices methods. One year hourly synthetic series solar radiation data is then generated using the validated time series models. A typical standalone PV system simulation is ran utilizing predicted solar radiation series, hourly load demand and battery storage capacity as simulation parameters. BESS is then sized considering energy deficit and supply interruption outcomes of the simulation. Fig. 1 is a representation of the Box-Jenkins method of obtaining time series models.

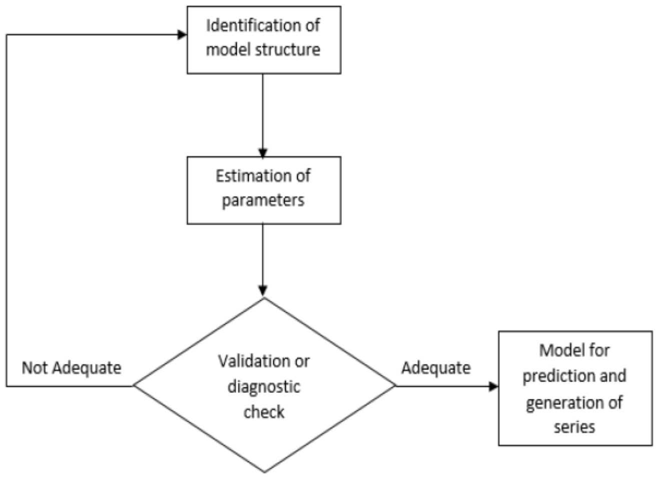

Fig. 1 Flowchart of Box-Jenkins method.

The second step of the methodology utilizes NPV and PBP financial metrics to evaluate the economic performances of the BESS sizes determined in the first part of the methodology.

2. CASE STUDY

For practical application of the methodology proposed in the study, the case study considers two load profiles; a residential consumer located in the city of Abuja in Nigeria (ECN, 2013) and a commercial consumer located in the city of Campinas in Brazil (Martinez-Bolanos *et al.*, 2020). Fig. 2 and Fig. 3 show the load profile characteristics of the residential and commercial consumers respectively.

Accounting for variations in hourly and daily consumption, yearly consumption profiles were simulated from the daily average load curves using regression models similar to those used in the prediction of solar radiation data presented in (Abubakar, Gemignani and Meschini Almeida, 2019).

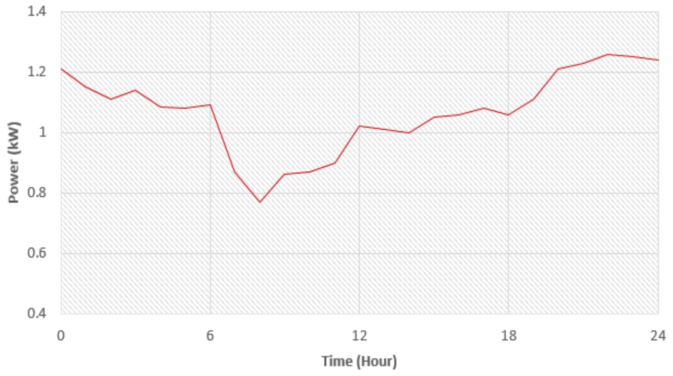

Fig. 2 Residential load profile.

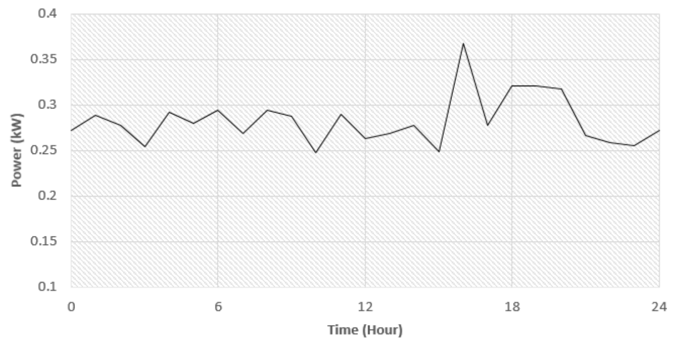

Fig. 3 Commercial load profile.

3. METHODOLOGY

3.1 System Configuration

PV systems of 1.3kWdc and 0.4kWdc nameplate capacities and lithium-ion battery with 80% depth of discharge were considered to serve the residential and commercial consumers respectively. Lithium ion battery chemistry was selected for the systems because of its superiority in energy efficiency, depth of discharge and lifecycle. For the cost evaluation, an analysis period of 15 years (lithium ion battery lifecycle (Mongird *et al.*, 2019)) and interest rate of 7.5% (DiOrio, Dobos and Janzou, 2015) were considered. Interruption cost of 5.36 USD/kWh$_{int}$ and tariff peak/off-peak cost of 0.4/0.14 USD/kWh were obtained from (SINAPSIS, 2016) and (Martinez-Bolanos *et al.*, 2020) respectively. Other financial values used are presented in Table 1.

3.2 BESS Sizing

The study presents an improvement to BESS sizing methodology using synthetic series data in ((Abubakar, Gemignani and Meschini Almeida, 2019). Here, hourly synthetic series data is considered instead of daily synthetic data.

To size the battery system, one year hourly synthetic series solar radiation data is generated and used in simulating PV system in relation to the load demand and storage capacity for each of the case studies. The simulation enables one to determine percentage hourly energy shortage and duration of interruption in the system. The battery size is continuously adjusted until acceptable energy deficit and supply interruptions are obtained. Total energy deficit for each series were calculated by summing up the hourly energy deficit for each series. The hourly energy deficit is the amount of hourly energy demand not supplied. The total supply interruptions for each series were also calculated which is the sum of the hourly interruptions for each series. In this study, it was assumed that there is a possibility of only one supply interruption per hour.

The percentage energy deficit as calculated, is defined as the ratio of total energy deficit in a series to the total demand multiplied by a hundred. The percentage supply interruptions is defined as the ration of the sum of supply interruptions in a series to the total number of hours in the series.

Table 1. System cost

Variable	Cost
Module cost	0.71 $/Wdc (DiOrio, Dobos and Janzou, 2015)
Inverter cost	0.21 $/Wdc (DiOrio, Dobos and Janzou, 2015)
Battery cost	850 $/kWh (Martinez-Bolanos *et al.*, 2020)
Balance of system	0.57 $/Wdc (DiOrio, Dobos and Janzou, 2015)
Labour	0.15 $/Wdc (DiOrio, Dobos and Janzou, 2015)
Margin and Overhead	0.75 $/Wdc(DiOrio, Dobos and Janzou, 2015)
Permit	0.06 $/Wdc (DiOrio, Dobos and Janzou, 2015)
O&M	20 $/kW-yr (DiOrio, Dobos and Janzou, 2015)

3.3 Cost Analysis

BESS economic performance is evaluated in this study using two financial metrics; Net present value (NPV) and payback period (PBP).

Fig. 4 represents cash flow over the lifecycle of the battery. It is a way to evaluate the financial implications (cost and benefit) of investing in BESS at the same time accounting for the current value of money. The total cost equivalent of the energy supplied (energy benefit) is the total arithmetic sum of individual years' present values of the cost equivalent of energy supplied for that year. The present value (PV) is the current value of a future sum of money or cash flow given a specific interest rate and is mathematically represented in (1). Cost equivalent is the monetary value of the expected energy supplied per year. Total investment on the other hand is the total cash outflow which is the sum of initial investment, and the present value of the sum of O&M cost and cost equivalent of yearly expected energy deficit. Investment cost is the cost of installing the BESS while O&M cost is yearly maintenance of the BESS and equivalent cost of energy deficit is the monetary value of energy deficit or cost of interruption. The arithmetic difference between the total cost equivalent of expected energy supplied and total cost of investment determines the lifecycle cost of the system otherwise known as the net present value (NPV). The higher the NPV, the better the investment i.e. the greater the total cost equivalent of expected energy benefit over the total investment cost, the better.

$$PV = \frac{FV}{(1+i)^t} \tag{1}$$

Where *PV* is present value, *FV* is future value, *i* is interest rate and *t* is number of time periods.

3.3.1 Net Present Value

The net present value (NPV) is a way to evaluate the lifecycle costs and benefits of BESS in PV systems while accounting for the time value of money. Lifecycle costs of BESS include BESS installation costs, O&M costs and cost of load demand not supplied by the system (energy deficit). Lifecycle benefit of BESS on the other hand is the cost equivalent of the energy supplied to the load by the system. A positive NPV signifies that the investment is predicted to yield greater returns or benefits than the summation of initial and future expenditures associated with the system and the higher the NPV, the better the benefit. A negative NPV however signifies that the benefits to be enjoyed from the investment is predicted to be less than the initial and future expenditures associated with the system. NPV is a useful financial metric to utilize when evaluating the economic performance of BESS in PV systems as it accounts for all expenditures including O&M and energy deficit or interruption costs over the lifecycle of the BESS. Equation (2) represents the mathematical expression of NPV.

$$NPV = \sum_{t=0}^{n} \frac{R_t}{(1+i)^t} \tag{2}$$

Where *Rt* in the net cash flow during a single period, *i* is the interest rate and *t* is the number of time periods.

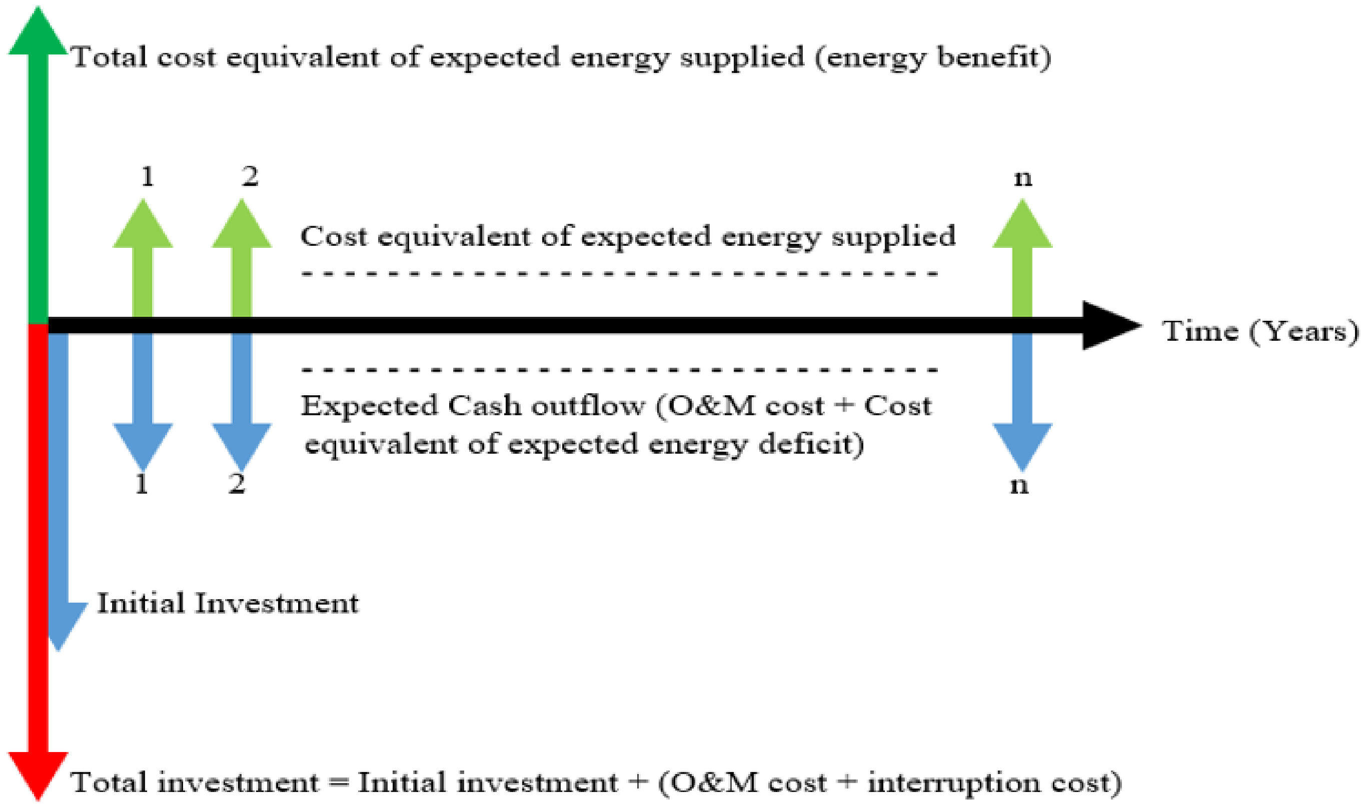

Fig. 4 Cash flow diagram.

3.3.2 Payback Period

Payback period (PBP) represents the number of periods required for the flow of benefits to exceed capital invested. (PBP) quantifies the number of years it takes for the benefits in years two and later of the project to equal or exceed the initial cost. PBP is the financial metric with the ability to quickly communicate tangible value of a project. A system with low PBP is regarded as a profitable one as subsequent years of the system results in benefits for the system owner. However, a system with high PBP or a system that cannot be paid back over its lifecycle period is regarded as a poor investment because at the end of the systems' lifetime, more money will have been spent than the benefit enjoyed. In calculating the PBP, care must be taken to consider all expenditures in later years. The mathematical expression of PBP is presented in (3).

$$PBP = \frac{Initial\ Investment}{Net\ cash\ flow\ per\ period} \tag{3}$$

3. RESULTS AND DISCUSSION

Table 2 and Table 3 present BESS sizing results obtained for the residential and commercial loads respectively. Each BESS with its resulting percentage energy deficit and supply interruption computed considering the total yearly demand and the number of hours in a year. What this means is that, if any of the BESS sizes is installed in the PV system, the system will experience the resulting energy deficit and supply interruption over the course of the whole year. Fig. 5 and Fig. 6 are the graphical representation of the obtained results for the residential and commercial consumers respectively.

Table 2. Residential consumer simulation result

Storage size (kWh)	Percentage Interruption (%)	Percentage Deficit (%)
19.2	0.0	0.0
16	0.4	0.2
14.9	1.9	1.0
14.7	2.5	1.3
14.5	3.0	1.7
14.2	3.6	2.1
14	4.3	2.6
13.8	5.4	3.3

Table 3. Commercial consumer simulation result

Storage size (kWh)	Percentage Interruption (%)	Percentage Deficit (%)
6.5	0.0	0.0
4.5	0.3	0.1
4.3	0.8	0.3
4.1	2.1	0.8
4.0	3.6	1.4
3.9	5.1	2.4
3.8	6.8	3.6
3.7	8.7	5.0

Fig. 7 and Fig. 8 represent the cost analysis results (NPV and PBP) for the residential and commercial consumers respectively. A positive NPV signifies that the investment is predicted to greater returns or benefits and the higher the NPV, the better the benefit. Following this logic, it can be observed in Fig. 7 that the best BESS size for the residential consumer is the 16kWh lithium-ion battery. Notice the curve starts falling afterwards which signifies that investing beyond the 16kWh size will not yield more returns. All BESS sizes with positive NPV are predicted to yield great benefits therefore, depending on budget, one can decide to choose between BESS size 14.6kWh to 16kWh with minimal risk of energy shortage.

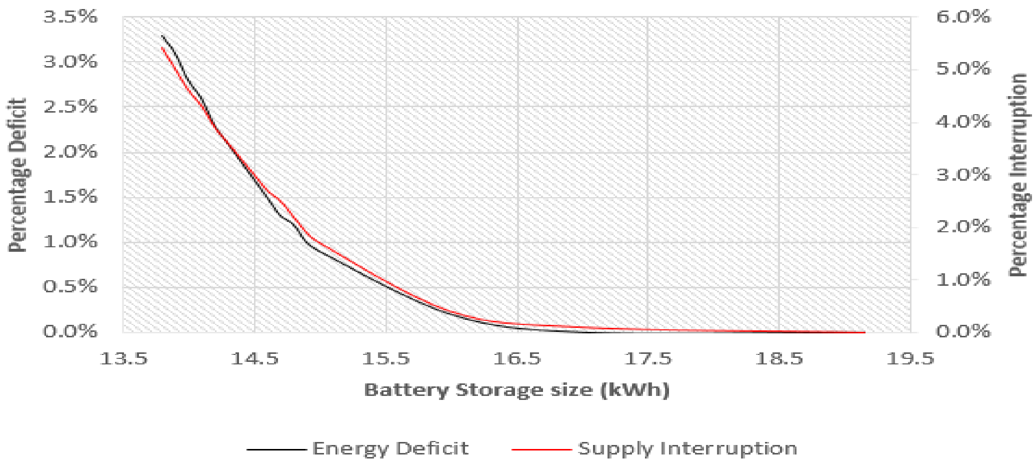

Fig. 5 Energy deficit and supply interruption graphs for the residential consumer.

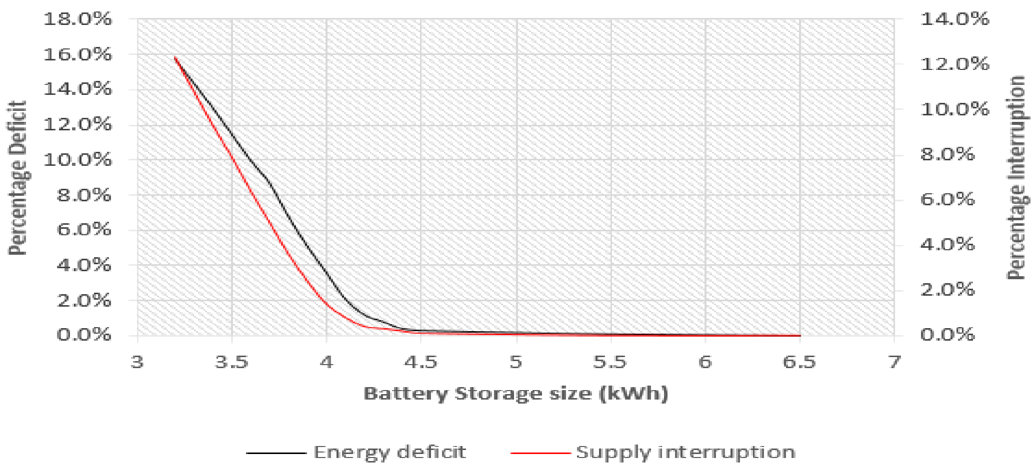

Fig. 6 Energy deficit and supply interruption graphs for the commercial consumer

For the commercial consumer, it can be seen from Fig. 8 that the 4.3kWh lithium-ion battery has the best NPV and PBP values signifying that it is the best battery to be invested in the system. However, depending on one's budget, BESS sizes between 4kWh and 4.3kWh are all considered good investments with different returns and payback periods, and with considerably lower risks of energy shortage.

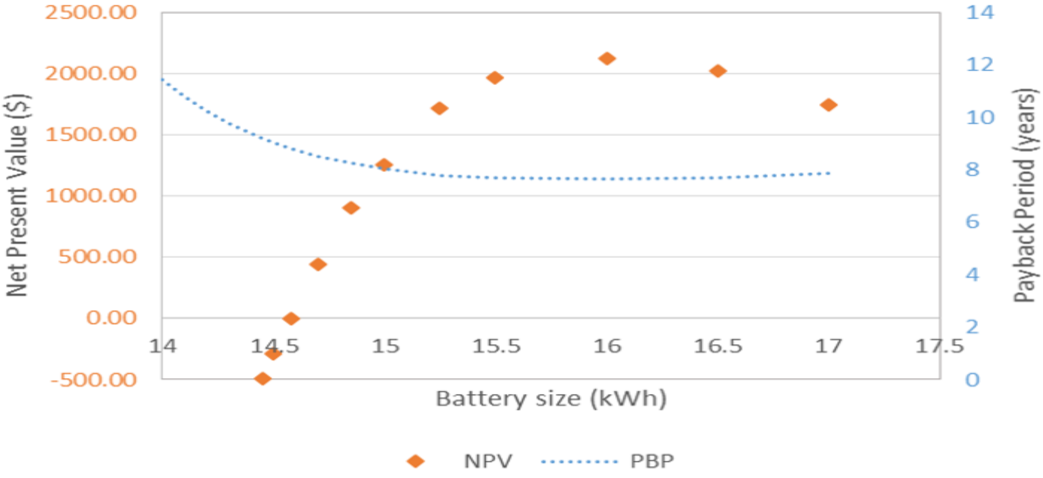

Fig. 7 Net present value and payback period graphs of residential case study

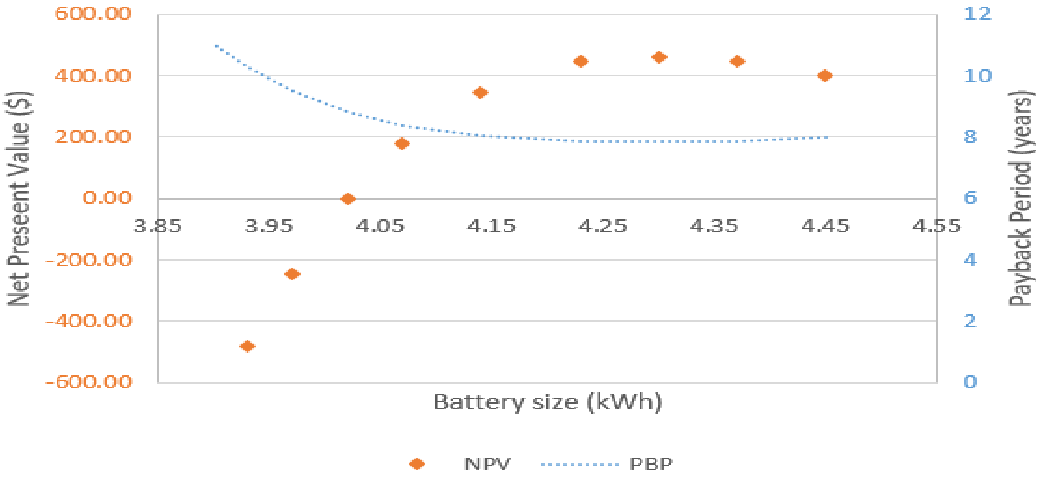

Fig. 8 Net present value and payback period graphs of commercial case study

6. CONCLUSION

This study presented a novel two-step cost-based methodology to optimally size and select BESS in isolated PV systems using predicted hourly solar radiation data and BESS economic performance. Several BESS sizes suitable for a particular standalone PV system are determined using energy deficit and supply interruption outcomes of a PV system simulation with predicted hourly solar radiation series, hourly load demand and battery storage capacity as simulation parameters. Economic performance of the determined BESS sizes is then evaluated through a cost analysis process using net present value (NPV) and payback period (PBP). One residential load and one commercial load were used as case studies to test the methodology. Results showed that the novel method optimally sizes BESS in isolated PV system with a variety of options based on system requirement and considering the cost analysis of economic performance of the BESS sizes with different percentage energy deficits for the same PV system, investment decision making is made easier and efficiently based on available budget.

The methodology could also be used in the sizing of BESS in grid-connected and hybrid PV systems and BESS in wind turbine and other renewable energy resources applications.

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