MULTIFUNCTIONAL BATTERY ENERGY STORAGE SYSTEMS IN ISOLATED NETWORKS WITH WIND GENERATION

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ABSTRACT

In recent years, the increased levels of Renewable Energy Sources' (RES) integration, particularly Wind Generation, in electrical islanded power systems has been driven by economic and environmental goals. However, the intermittent character and the grid operational constraints may impose limits to the wind power output. Battery Energy Storage Systems (BESS) may contribute to adequately accommodate renewable sources while enhancing its value in islanded systems.

This study presents a methodology that assesses the technical and economic impact of a multifunctional BESS, performing backup reserve, renewables intermittency response and energy time-shift, in an islanded distribution network with very high wind penetration levels. Results demonstrate that BESS technical and economic contributions justify its deployment in isolated systems with a combined production based on diesel and wind generators.

INTRODUCTION

In electrical islanded systems, diesel generating units are the most common power production systems, presenting high fuel costs and CO_2 emissions. The integration of RES may reduce fuel usage and offset the need of reinforcing the installed capacity of the isolated system contributing to the reduction of the Operational Expenditure (OPEX) and Capital Expenditure (CAPEX) [1]. Particularly, wind generation has been given increased attention as islands are often characterized by relevant wind potential [2]. Nonetheless, accommodating large shares of RES invokes several demanding challenges due to their intermittent and limited predictability characteristics.

Battery Energy Storage Systems (BESS) represent a technological solution to accommodate renewables, providing higher operational flexibility, security and reliability [3]. Electrical islanded systems present a clear opportunity for the integration of BESS. Its benefits and costs are better straightforwardly assessed and quantified than in interconnected systems where the lack of regulation and several split benefits bring uncertainty and difficulties in establishing a business case for BESS. However, due to its current deployment costs, a combination of services is identified as a crucial point to reach profitability [4, 5].

The objective of this work is to assess the optimal operating strategies of a multifunctional BESS, identifying and quantifying its technical and economic impact in an isolated distribution network with increasing penetration levels of wind generation. Backup reserve, RES intermittency response and RES energy time-shift are the BESS applications focused in this work. Moreover, the developed methodology allows a detailed evaluation of the system operation in terms of fuel consumption reduction, diesel generators' operating hours' reduction, wind generation curtailment as well as the impact on the BESS cycle life.

ELECTRICAL ISLANDED SYSTEMS

In recent years, the integration of RES and particularly wind generation has posed challenges to the planning and operation of islanded power systems. Traditionally, load characteristics such as its valley, peak, seasonality, and pattern are the main factors when defining the operation strategy of an islanded system. Therefore, sufficient diesel generators to maintain the N-1 criteria, i.e. to ensure reserve requirements that allow the system to meet total demand if an online generator is tripped, are always kept running. Additional generators need to be connected to meet peak demand. Renewables' challenges are related with the present difficulties in properly accommodating increasing shares of such variable sources as conventional generators have to adjust to the short-term and long-term variations of both wind generation and demand.

Operational Challenges with Wind Generation

Technical constraints of diesel generation units are further stressed by the presence of wind generation. Such features have been studied in the literature [2, 6] and have been recognized as major limiting factors to the adequate addition of renewables in electrical islanded systems. These limitations are related with minimum loading levels (technical) of diesel generators and with their often limited ramp response. Due to the increased wear and thermal conditions, diesel generators cannot be operated under a certain threshold of rated power. This technical minimum varies according to factors such as fuel type, age and engine condition and typically presents values between 20-50% of rated power in diesel-fired units [2]. The need to fulfil reserve requirements leads to lower operating points of the diesel generators as the system's load has to be allocated to more generators. Consequently, the penetration of wind generation aggravates this effect as it reduces the load fed by diesel generators and thus their operating point. Nonetheless, reserve requirements to guarantee security criteria are not lowered by variable wind power. This means that, on one hand, wind generation has to be curtailed frequently due to this operational limit and, on the other hand, wind penetration further deteriorates the efficiency of the generators due to a lower operating point. This is justified by the typical consumption curve of a diesel generator (in Liters per kWh), presented in Figure 1.

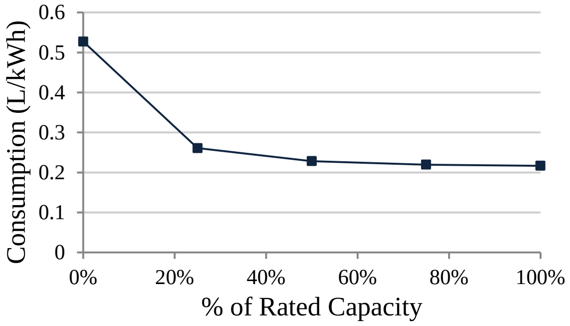

Figure 1 – Typical diesel generator consumption curve

In electrical islanded systems, diesel generators have to compensate very rapidly sudden power deficits or surpluses. However, conventional units often present limited ramp response (e.g. 15% of rated capacity per minute) to power fluctuations [2]. Therefore, the variable and intermittent character of wind generation poses an additional challenge for conventional units and may lead to severe frequency excursions. Such frequency deviations rely on the magnitude and speed of wind power output fluctuations counterbalanced by the diesel generators ramp rate capability. In an extreme case, wind speed surpassing the cut out speed of wind turbines may lead to the loss of a wind park and, subsequently, severe generation and demand unbalance may occur resulting in under-frequency protection tripping and thus load curtailment. Additionally, continuous variations on diesel generators production, which mean constant changes in the throttle motion of the units, often deteriorates their fuel specific consumption i.e. their operational efficiency. This problem may also increase maintenance needs and reduce their useful life [2].

The aforementioned technical constraints of conventional thermal units restraint the flexibility of an electrically isolated system and difficult the use of the available wind potential and the pursuit for higher levels of wind penetration. Furthermore, curtailed wind power not only negatively affects the economics behind wind integration itself but also counteracts the OPEX and CO_2 reductions that it could potentially provide. Figure 2 presents a conceptual view of the actual and potential effects of wind generation on the fuel consumption of an electrical islanded system.

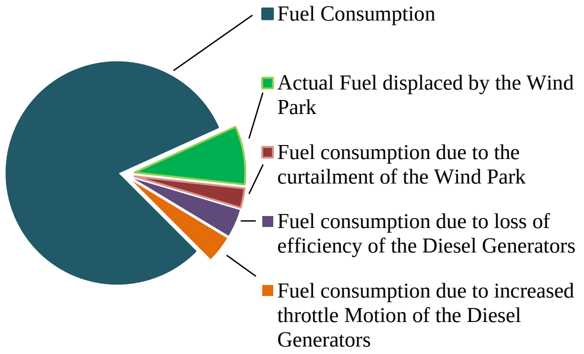

Figure 2 – Impacts of wind generation on fuel consumption.

MULTIFUNCTIONAL BATTERY ENERGY STORAGE SYSTEMS

Electrical islanded systems provide unique technical, economic and regulatory conditions for BESS integration due to their usual vertically integrated system [4]. Although Pumped Hydro Storage (PHS) has been traditionally the most procured and investigated storage technology for islanded power systems, its physical site requirements along with changes in BESS economics have granted them with increased importance, adequate for smart grid roles.

BESS have emerged as a relevant solution to cope with the operational challenges posed by wind generation, however, its high investment costs still stand as a barrier to its deployment. Consequently, an aggregation of functionalities is fundamental to attain high performance and reach profitability [7]. Most important, however, is the operating strategy followed in the presence of a multifunctional BESS which determines the system performance and ensures the fulfilment of its potential benefits.

Planning and Operation Framework

A methodology that provides a systematic analysis of the technical and economic impacts of a storage system in electrical islanded systems has been developed. The planning horizon varies according to the battery technology (e.g. depending on the manufacturer, 15 years for some Li-ion batteries and 10 years for some Lead-acid batteries [8]) although estimation on the battery cycle life is performed. The sizing of the storage system is assessed based on the battery technology and its modularity, on power system data such as generation and demand profiles, and on the functionality or combination of functionalities that are included. The operation strategy is established according to the BESS' functionalities and is guaranteed by an integrated optimal management of the storage system's State of Charge (SoC).

In order to adequately model the intermittency nature of wind generation and the system response, the methodology assesses 3 years of operation on a minute basis of the electrical islanded system. In order to surpass limitations of data availability, when applicable, load and wind power time-series may be generated stochastically based on historical data and using the first-degree Markov chain method. The 1-min wind fluctuations are generated as white noise based on wind gusts and wind speed standard deviation measures. While wind power profile considers time-of-day and month, due to the seasonality of electricity demand, load profiles consider time of day, week day and month.

The OPEX of an electrical islanded system is mainly dictated by fuel consumption. Fuel oil is the type of fuel consumed during normal operation of diesel generators. However, gasoil and lubricants also take a significant share of overall fuel consumption. Typically, due to thermal and efficiency concerns, gasoil can be used during starts of diesel generators. Therefore, the developed method assumes that gasoil consumption is proportional to the number of generator's starts. Lubricant is assumed to be proportional to the number of operating hours of the generating units as its consumption is related with generators wear. According to Portuguese data [9], the cost of fuel oil, gasoil and lubricant is assumed to be 0.70 €/L, 0.80€/L and 2.5 €/L, respectively. The economic assessment considering Net Present Value (NPV) and pay-back time is fundamental to evaluate the cost effectiveness of BESS and to demonstrate the relevance of investing in such technologies in electrical islanded systems [8, 10]. These economic features depend on revenue and on cost parameters as well as on financial indices such as discount rate, inflation and fuel costs growth. Revenues of BESS consist on avoided costs regarding fuel consumption. Depending on BESS technology, capital investment and maintenance are the considered cost parameters.

Backup Reserve

BESS performing backup reserve has the purpose of ensuring N-1 security criteria on generation during 100% of the time. The presence of adequately sized BESS means that the N-1 criteria are ensured in the islanded system with fewer generators running. Therefore, in this functionality, BESS must immediately respond in case of a generator failure. The system must start discharging to maintain balance between supply and demand until other two diesel generators are brought online. These two generators are responsible for maintaining N-1 security until BESS is sufficiently charged to allow performing this functionality.

Minimum Size Requirements

There are BESS' minimum size requirements to fulfil the backup reserve functionality. The discharging power of the storage system must cope with the worst case scenario i.e. losing the largest diesel generator of the generation system. The minimum energy requirement for BESS is given by the diesel generators starting curve (Figure 3).

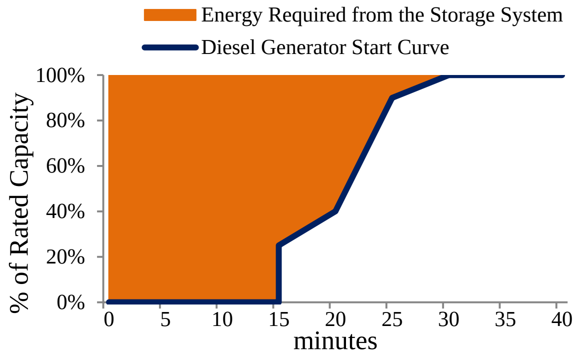

Figure 3 – Typical diesel generator starting curve and BESS energy requirement

Along with the starting curve of the diesel generators, BESS efficiency and energy capacity decay over its useful lifetime must be included when calculating BESS size requirements (Equation 1).

$$E_{min} = \frac{A_{start\ curve}}{Efficiency_{discharge}} \times \frac{1}{Energy\ Decay} \times \frac{1}{DoD_{max}} \quad (1)$$

where E_{min} is the minimum BESS energy requirement (kWh); $A_{start\ curve}$ is related with the identified area in Figure 3 (kWh); $Efficiency_{discharge}$ corresponds to the BESS discharging efficiency (%); and $Energy\ Decay$ (%) is the difference between the BESS energy capacity at the beginning of life (BOL) and its energy capacity at the end of life (EOL). The Energy capacity decay depends on the BESS technology and on the calendar and cycle life of the storage system. DoD_{max} is the maximum depth of discharge that the battery system may achieve. This parameter depends on the battery technology and is often established to improve the BESS' cycle life.

Wind Intermittency Response

Frequency excursions (mitigated by the response of diesel units) and higher fuel consumption are two consequences of the intermittent nature of wind generation. BESS, when addressing wind intermittency, is required to fast charge or discharge to reduce the severity of ramp down and ramp up of diesel generators and thus avoid penalization on fuel consumption and wear of the units. The specific fuel consumption is penalized proportionally to the fluctuation magnitude, up to 7.5%.

Minimum Sizing Requirements

The minimum storage system size to perform this functionality is related with the ramp capability of the diesel generators as the storage system must ensure that the fast adjustments by the diesel generators are limited to their ramp capability. When planning DESS integration, a smoother conventional units operation may be aimed in order to further reduce the throttle motion of the conventional units and thus reduce their fuel consumption. Nonetheless, probabilistic constraints (e.g. success rate in responding to wind intermittency of at least 90%) may be implemented as covering all possible events may lead to BESS oversizing both in power and energy capacity. Therefore, the minimum size requirements may be established through the analysis of a relevant sample of wind speed measures.

Wind Energy Time-Shift

Wind power may not be available when it is most needed and usually presents a pattern that does not match electricity demand. BESS may be used to adequate wind availability to load demand, time-shifting wind energy and thus enhancing its technical and economic value. Therefore, the battery system must charge during periods where wind power leads to diesel generators' low operating points, consequently avoiding wind curtailment. Also, BESS's discharging is performed during periods of peak load where generators often present higher operating points.

In this functionality, there are no minimum size requirements criteria as BESS impacts increase with the allocated battery capacity to pursue its objectives. Therefore, including this functionality contributes to an optimized utilisation of the storage capacity and to the maximization of the added value of BESS in electrical islanded systems with wind generation. Nevertheless, the SoC of the battery needs to be optimally managed as the fulfilment of this functionality shall not jeopardize other pursued objectives such as the backup reserve.

CASE STUDY AND RESULTS

The developed methodology is applied to a case study that contemplates the deployment of a Li-ion based BESS in an electrical islanded system. The purpose of this study is to demonstrate how a multifunctional battery system can handle different wind penetration levels, assess and quantify its impact in the system's OPEX, and evaluate the economics of the BESS investment project. The penetration level is defined as the ratio between wind rated installed capacity and the islanded system peak load.

Description of the electrical islanded system

The simulated islanded power system is constituted by four 4 MW diesel generators with peak load of 9 MW and yearly consumption around 50 GWh. Diesel units present a technical minimum of 30% of rated capacity and a ramp limit of 15% of rated capacity per minute i.e. 600 kW/min. Their fuel consumption curve is presented in Figure 1. Based on wind speed measures on a Portuguese island, the capacity factor of wind generation is 43%. This means, for instance, that a wind park with 4 MW (wind penetration level of 44%) could potentially provide sufficient energy to feed 30% of the electricity demand.

Multifunctional BESS sizing

To the backup reserve functionality, the minimum Li-ion BESS size requirements are presented in Table I, based on the generator starting curve presented on Figure 2, a Li-ion battery round-trip efficiency of 90% and an expected energy capacity decay of 25% over a 15 year planning horizon [11, 12].

Table I – Backup reserve minimum size requirements

Minimum discharge Power	Energy Capacity EOL	Energy Capacity BOL
4,000 kW	1,423 kWh	1,897 kWh

The minimum size requirements, presented in Table II, to maintain power fluctuations in diesel generators output in range of their ramp limit are calculated to achieve an effectiveness of 90% i.e. the battery is able to adequate handle the generators technical limit in 90% of the events where fluctuations would be higher than the ramp response limit. The results presented in Table II reveal that, for example, a Li-ion battery of 1.1 MW for charging, 1.2 MW for discharging with an energy capacity of 400 kWh would be adequate to maintain power fluctuations within the ramp capability of the diesel generators in the presence of a 4 MW wind park.

Table II – Power (in percentage of wind rated capacity) and energy requirements for wind intermittency response

Minimum charge Power	Minimum discharge Power	Discharge duration EOL	Discharge duration BOL
27%	29%	15 minutes	20 minutes

A 4 MW/4MWh Li-ion battery is deployed in this case as it is sufficient to cope with the minimum size requirements of the included functionalities at any considered wind penetration level (0-100%). According to the wind penetration level, the remaining storage capacity is allocated to perform the wind energy time-shift functionality. The considered unit cost of the system is 1250 €/kWh and an yearly maintenance cost of 3% of battery CAPEX [8]. The capital cost, inflation and fuel cost growth are considered to be 8%, 2% and 2%, respectively [8].

Synopsis of the results

Our simulation shows that the electrical islanded system presents high fuel costs without wind generation and without BESS (Figure 4). Without BESS, wind penetration levels up to 50% are translated into significant OPEX reductions. With higher wind levels, a saturation of the capability of the islanded system to properly accommodate further levels of wind generation is achieved as the OPEX curve becomes flat. This means that the absorption of additional wind energy does not compensate the consequent higher levels of wind curtailment and lower operational efficiency of diesel generators. The higher the wind penetration level is, the more technical and economic benefits BESS is able to provide. Indeed, with BESS, wind power curtailment is significantly reduced and only occurs with higher wind penetration levels (more than 25% of wind penetration).

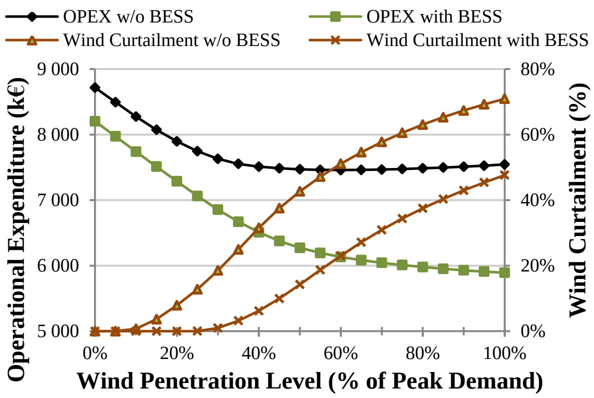

Figure 4 – Contribution of BESS to an adequate accommodation of wind generation

Figure 5 reveals that from a wind penetration level of 30%, the contribution of BESS to OPEX reduction may economically justify its deployment in electrical islanded systems based on diesel generators. Although these results strongly depend on the scenario conditions previously defined, the developed methodology is able to technically and economically demonstrate the benefits of a multifunctional BESS.

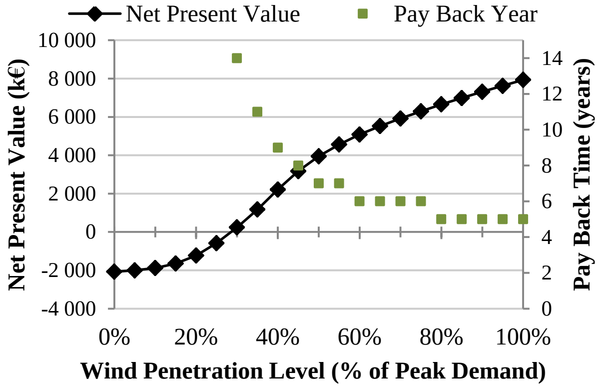

Figure 5 – Economic performance of BESS with increasing levels of wind generation

The reduced operating hours along with a smoother operation of the diesel generators extend their useful life. However, results exclude this potential investment cost deferral provided by multifunctional BESS which could enhance its technical and economic impact.

CONCLUSIONS

The present study was based on simulated use cases. The analysis considered common assets used in islanded grids, together with their standard operational criteria. Real load and wind historical data were used and modelled so that realistic scenarios could be assessed. A clear wind generation capacity factor was considered.

Multifunctional BESS enhances the value of wind generation in islanded grids, enabling their integration with higher use shares, suitable for other RES.

The study has also shown that BESS is economically and technically feasible, enhancing grid security and reliability by enabling N-1 criteria for diesel generation, which in turn operate more efficiently with a higher loading profile, thus saving fuel, reducing the number of effective generators, as well as their starts and operating hours, leading to an extension of their useful life.

Current automation and management solutions are adequate for BESS easy integration and deployment in the Smart Grid, thus suitable for flexible operation.

REFERENCES

[1] P. Dokopoulos, A. Saramourtsis, and A. Bakirtzis, "Prediction and evaluation of the performance of wind-diesel energy systems," *Energy Conversion, IEEE Transactions on*, vol. 11, pp. 385-393, 1996.

[2] S. A. Papathanassiou and N. G. Boulaxis, "Power limitations and energy yield evaluation for wind farms operating in island systems," *Renewable Energy*, vol. 31, pp. 457-479, 2006.

[3] I. Miranda, N. Silva, and H. Leite, "Technical and economic assessment for optimal sizing of distributed storage," in *Innovative Smart Grid Technologies (ISGT Europe), 2012 3rd IEEE PES International Conference and Exhibition on*, 2012, pp. 1-6.

[4] S. Ruester, X. He, L. Vasconcelos, and J.-M. Glachant, "Electricity storage: How to facilitate its deployment and operation in the EU," *Think Final Report, European University Institute*, 2012.

[5] G. Delille and B. François, "A review of some technical and economic features of energy storage technologies for distribution system integration," *Ecological engineering and environment protection*, pp. 40-49, 2008.

[6] C. A. Hernandez-Aramburo, T. C. Green, and N. Mugniot, "Fuel consumption minimization of a microgrid," *Industry Applications, IEEE Transactions on*, vol. 41, pp. 673-681, 2005.

[7] H. L. Ferreira, G. Fulli, W. L. Kling, and J. P. Lopes, "Storage devices impact on electricity distribution," in *Proc. 2011 Int. Conf. Electr. Distrib*, 2011.

[8] A. A. Akhil, G. Huff, A. B. Currier, B. C. Kaun, D. M. Rastler, S. B. Chen, A. L. Cotter, D. T. Bradshaw, and W. D. Gauntlett, "DOE/EPRI 2013 Electricity Storage Handbook in Collaboration with NRECA," ed: Albuquerque, NM: Sandia National Laboratories, 2013.

[9] ERSE, "Proveitos permitidos das empresas reguladas do setor elétrico em 2014," Portuguese Energy Regulator - Revenues of regulated activities,2013.

[10] I. Miranda, N. Silva, and H. Leite, "Distribution storage system optimal sizing and techno-economic robustness," in *Energy Conference and Exhibition (ENERGYCON), 2012 IEEE International*, 2012, pp. 483-488.

[11] S. Eckroad and I. Gyuk, "EPRI-DOE Handbook of Energy Storage for Transmission & Distribution Applications," 2003.

[12] S. M. Schoenung, "Energy storage systems cost update : a study for the DOE Energy Storage Systems Program," SANDIA, 2011.