Impacts of Centralized Energy Storage Systems on Transmission Grid Operation: A Portuguese Case Study

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***Abstract*— A large quantity of variable renewable energy sources (RESs), most notably wind and solar, is now connected to the Portuguese network system, which makes it somehow unique. Yet, in the coming years, the network is expected to accommodate more of these and other technologies of "clean" power productions. The deployment and efficient utilization of various flexibility options are certainly required in a system experiencing such levels of dynamic changes so as to ensure a standard level of service provision in terms of security, stability and reliability. Among these is a battery energy storage system (BESS), which is emerging as one of the viable and effective options of increasing the much-needed flexibility in power systems. This work aims to assess the impact of BESS deployments on the operational performance of the Portuguese transmission grid, mainly in terms operational flexibility and variable RES power support. In particular, the potential benefits of strategically placed BESSs are investigated using a stochastic optimization framework. Numerical results show that integrating BESSs leads to a more efficient use of renewable power by considerably minimizing curtailments, and a 10% reduction in system-wide cost. Energy losses are moderately increased as a result of BESS deployments. But this is offset by the savings in operation and emission costs.**

***Index Terms*—Battery energy storage systems, transmission grid operation, renewable energy sources, stochastic MILP.**

I. Nomenclature

A. Sets/Indices

es/Ω^{bess}	Index/set of energy storage
g/Ω^{g}	Index/set of generators
h/Ω^{h}	Index/set of hours
$i,j/\Omega^{i}$	Index/set of buses
s/Ω^{s}	Index/set of scenarios
l/Ω^{l}	Index/set of transmission lines

B. Parameters

$E^{min}_{es,n,s,h}, E^{max}_{es,n,s,h}$	Energy storage limits (MWh)
ER_g	Emission rate (tCO_2e/MWh)
G_l, B_l, S^{max}_l	Conductance, susceptance and flow limit of line l, respectively ($\Omega^{-1}, \Omega^{-1}, MVA$)
OC_g	Cost of unit energy production by generator g, ($€/MWh$)
$p^{min}_{g,i}, p^{max}_{g,i}$	Power generation limits (MW)
$p^{ch,max}_{es,i}, p^{dch,,max}_{es,i}$	Charging/discharging limits (MW)
$PD^{i}_{s,h}$	Demand at node i (MW)
R_l, X_l	Resistance and reactance of line l (Ω, Ω)
$\eta^{ch}_{es}, \eta^{dch}_{es}$	Charging/discharging efficiency
λ^{CO_2}	Cost of emissions (tCO_2e)
λ^{es}	Variable cost of storage system ($€/MWh$)
μ_{es}	Scaling factor (%)
$v^{p}_{s,h}$	Unserved power penalty ($€/MWh$)
ρ_s	Probability of scenario s

C. Variables

$E_{es,i,s,h}$	Reservoir level of BESS (MWh)
$I^{ch}_{es,i,s,h}, I^{dch}_{es,i,s,h}$	Charging/discharging binary variables
$P_{g,i,s,h}$	Generated power (MW)
$P^{ch}_{es,i,s,h}, P^{dch}_{es,i,s,h}$	Charged/discharged power (MW)
$P^{NS}_{i,s,h}$	Unserved power (MW)
$P_{l,s,h}$	Power flow through a line l (MW)
$PL_{l,s,h}$	Power losses in each line (MW)
$\theta_{l,s,h}$	Voltage angles across the nodes of line l

D. Functions

TEC	Expected cost of energy (€)
$TENSC$	Expected cost for unserved energy (€)
$TEmiC$	Expected cost of emissions (€)

II. Introduction

A. Motivation, Aims, and Background

Battery energy storage systems (BESSs) are proving to be viable solutions to a number of problems associated with management and control of power grids that feature an increasing level of variable power generations. The added flexibility brought to such systems by optimal deployment of BESSs promotes the growth of renewable energy share. As it is known, the production of energy from the prominent renewable sources (such as wind and solar) is characterized by high variability and uncertainty i.e. their availabilities are

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dependent on weather conditions [1], [2]. However, energy storage systems can help to lessen the intermittency of energy production from such technologies [3], [4]. The performance of storage systems depends on the technical their respective technical characteristics such as storage capacity, discharge rate, efficiency cycle, lifetime, energy and power density and cost [4], [5].

The contribution of BESSs in terms of the stability and flexibility of electrical networks has been studied in several aspects. One of the factors to take into consideration before installing energy storage systems is their location in the electrical system [6]. The optimal positioning of BESSs technology not only optimizes their efficient use from the point of view of the reliability, safety and system operation, but also minimizes grid-related investment needs [5]–[7]. However this does not mean that network upgrades are no longer necessary since the integration of energy storage systems may not be sufficient to provide the network with the necessary reliability and flexibility [5]. Hence, a comparison of investment and associated costs of both options becomes very important, since the analysis of the benefits considering both solutions can become advantageous [7], [8].

The integration energy storage systems has been investigated in recent years using different approaches and methods. In [6], an energy storage planning model is described, which determines the location and capacity of an ESS in an electric network system, with the aim of meeting electricity demand at least cost and delay grid-related investment needs. Aguado *et al.* [5] studies the relevance of deploying ESSs in power transmission systems and outlines the main aspects that needs to be taken into account. In [9], a research method is presented to evaluate the impact and interdependencies between the operation of the storage market and participation in re-dispatch measures. Authors in [9] also introduce a methodology for evaluating the benefits of ESSs that are managed by the transmission system operator only. Hu *et al.* in [8] discuss the costs and benefits of deploying ESS, as well as its role in transmission networks. Thus, a new formulation is developed, taking into account the simultaneous addition of new circuits and ESS installations, allowing to determine the location and capacity of the ESSs in order to reduce the investment in transmission lines. The work in [10] emphasizes on the advantages of improved renewable energy exploitation and system flexibility resulting from the coordinated management of wind power generation systems and energy storage systems. Virasjoki *et al.* [3] assess the economic and environmental consequences of energy storage systems through a complementarity model on stylized Western European power system with market power, transmission network representation and uncertainty from renewable energy production. Authors in [11] present an analysis of the operation mode of the energy storage system based on two modes: daily mode and weekly mode modulated in sets. The objective in their work is to analyze and compare the modes presented in terms of operation and cost. In [12], a probabilistic reliability assessment method is proposed to determine the appropriate size of an energy storage system to be installed in wind farms, wind generation capacity and the necessary upgrades to run on the transmission network, in order to connect the wind power source with the system.

To the authors' best knowledge, existing literature on the subject matter is sufficient to understand the viability of deploying BESSs at transmission levels and their impacts on system-wide performance metrics (such as cost, RES energy curtailment, etc.). Majority of the existing studies focus on conventional storage technologies (mainly pumped hydro power). Moreover, earlier analysis are mainly based on case studies carried out on synthetic systems. Hence, the main focus of our work is on the deployment of BESSs on a Portuguese Transmission Network (PTN). Such a real-life case study helps us to simultaneously explore the costs and benefits of BESSs in terms of operational performance of the system as a whole, mainly in terms of operational flexibility and support to the integration of variable renewable generation.

B. *Contributions*

The main contributions of this work are:

- A stochastic optimization framework to evaluate the benefits of deploying BESSs in the Portuguese transmission network;
- Experimental analysis based on numerical results obtained from real-life system.

III. MATHEMATICAL FORMULATION

This section describes the stochastic mixed integer linear programming optimization model employed in this work when carrying out the analysis i.e. the optimal operation of PTN in the presence of large-scale variable renewable power sources accompanied by BESS integrations. The objective function and associated constraints of the resulting optimization model are described below.

A. *Objective Function*

The objective function of the problem dealt with in this work is the minimization of the sum of appropriate cost terms. These costs are related to costs of operation, unserved power and emissions in the system.

$$Minimize\ TC = \alpha * TEC + \beta * TENSC + \gamma * TEmiC \quad (1)$$

where TC denotes the total operation cost in the system, and $\alpha,\ \beta$ and γ are weighting factors which are set equal in the current work for the sake of simplicity.

In (2), the term TEC models the expected costs by producing power using available technologies: wind, solar, small hydro, hydro and biomass technologies, as well as operating the BESSs. The operation cost of BESSs is a small amount that somehow accounts for the degradation of their continuous use. In our analysis, it is arbitrarily set for the sake of simplicity.

$$\begin{aligned} TEC = & \sum_{s\in\Omega^s}\rho_s \sum_{h\in\Omega^h}\pi_h \sum_{(g,i)\in\Omega^g} OC_g * P_{g,i,h,s} \\ & + \sum_{s\in\Omega^s}\rho_s \sum_{h\in\Omega^h}\pi_h \sum_{(es,i)\in\Omega^{es}} \lambda_{es} * (P^{dch}_{es,i,s,h} + P^{ch}_{es,i,s,h}) \end{aligned} \quad (2)$$

The second term *TENSC* in (1) refers to the cost of energy that is involuntarily curtailed due to technical constraints in the system. This is computed as in (3).

$$TENSC = \sum_{s\in\Omega^s}\rho_s \sum_{h\in\Omega^h}\pi_h \sum_{i\in\Omega^i} \upsilon_{s,h}^P * P_{i,s,h}^{NS} \tag{3}$$

The terms $\upsilon_{s,h}^P$ is defined as a penalty parameter that is correspondent to the involuntary curtailment of active power demand at a particular time. This parameter must be sufficiently high to avoid undesirably large amount of unserved power.

Finally, the last term, $TEmiC$, is responsible for the expected emissions cost in the system. It is as a result of power generation, and is given by (4).

$$TEmiC = \sum_{s\in\Omega^s}\rho_s \sum_{h\in\Omega^h}\pi_h \sum_{(g,i)\in\Omega^g} \lambda^{CO_2} * ER_g * P_{g,i,h,s} \tag{4}$$

B. Constraints

A number of constraints are taken into consideration, all of which must be fulfilled all time to guarantee a safe operation of the transmission network system. The first one is related to the Kirchhoff's current law which states that the sum of all injections at a node should be equal to the sum of all withdrawals at the same node. This constraint is applied to active power flows as in:

$$\begin{aligned}&\sum_{(g,i)\in\Omega^g} P_{g,i,h,s} + \sum_{(es,i)\in\Omega^{es}}\left(P_{es,i,s,h}^{dch} - P_{es,i,s,h}^{ch}\right)\\ &+ \sum_{i\in\Omega^{gpt}}\left(P_{i,s,h}^{HydroPump.} - P_{i,s,h}^{HydroTurb.}\right)\\ &+ P_{i,s,h}^{NS} + \sum_{in,l\in\Omega^l} P_{l,s,h} - \sum_{out,l\in\Omega^l} P_{l,s,h} =\\ &PD_{s,h}^i + \sum_{in,l\in\Omega^l}\frac{1}{2}PL_{l,s,h}\\ &+ \sum_{out,l\in\Omega^l}\frac{1}{2}PL_{l,s,h}\ ;\forall\varsigma\epsilon\Omega^{\varsigma};\ \forall\varsigma\epsilon i;\ l\epsilon i\end{aligned} \tag{5}$$

It can be noted in (5), that the power injected into a node comprises the active power from generators, incoming active power flows associated with lines, the power that can be discharged from BESSs, power that can be generated by pumped hydro power plants. Whereas, withdrawals are the demand at that node, losses which are fictitious loads, the flows that are leaving the node through the lines connected to it, and the amounts of power charged to BESSs and consumed during a pumping mode of operation of pumped hydro power plants.

Another constraint is related to Kirchhoff's voltage law. This governs the power flow in any feeder. This is achieved by modeling the equations of the power flow in a linear approach, considering two approximations. The first approximation is valid in transmission systems, which deals with the bus voltage magnitudes to be close to the nominal value V_{nom}. The second consideration is related with the voltage angle difference θ_k. For practical reasons, this difference is very small, leading to trigonometric approximations $\sin\theta_k \approx \theta_k$ and $\cos\theta_k \approx 1$. With these assumptions, the AC power flow equations can be linearized and the nonlinearities and non-convex functions of voltage magnitude and angles are taken away. This leads to the so-called DC flow model:

$$\left|P_{l,s,h} - S_B b_l \theta_{k,s,h}\right| \le MP_l(1-u_l) \tag{6}$$

Equations (6) includes the state of each line u_l (1 if connected and 0 otherwise). The angle difference $\theta_{k,s,h}$ is defined as $\theta_{l,s,h} = \theta_{i,s,h} - \theta_{j,s,h}$. Here, i and j correspond to the same branch k. The power that flow in each line cannot be higher than its maximum transfer capacity. This constraint is enforced by introducing (7).

$$P_{l,s,h} \le u_l S_l^{max} \tag{7}$$

Active power losses in each line are approximated by quadratic functions as shown in (8). Notice the quadratic flow terms in equations (8), which are easily linearized using a piecewise linearization method [13].

$$PL_{l,s,h} = R_l\, P_{l,s,h}^2 / S_B \tag{8}$$

The next set of constraints is related to BESSs. The power that can be charged to and discharged from the BESS device is limited by the upper and lower bounds as:

$$0 \le P_{es,i,s,h}^{ch} \le I_{es,i,s,h}^{ch} P_{es,i,h}^{ch,max} \tag{9}$$

$$0 \le P_{es,i,s,h}^{dch} \le I_{es,i,s,h}^{dch} P_{es,i}^{ch,max} \tag{10}$$

In reality, it is not possible to charge and discharge BESSs at the same time. This is ensured by using the next constraint.

$$I_{es,i,s,h}^{ch} + I_{es,i,s,h}^{dch} \le 1 \tag{11}$$

The constraint related to the state of BESS is given by the following balance equation:

$$E_{es,i,s,h} = E_{es,i,s,h-1} + \eta_{es}^{ch} P_{es,i,s,h}^{ch} - P_{es,i,s,h}^{dch}/\eta_{es}^{dch} \tag{12}$$

The storage level at any given time should fall between a band formed by the minimum and maximum reservoir capacity.

$$E_{es,i}^{min} \le E_{es,i,s,h} \le E_{es,i}^{max} \tag{13}$$

The initial storage level needs to be set. Likewise, the final storage level at the end of the time period should be the same as the initial storage level. For simplicity reasons, both η_{es}^{dch} and η_{es}^{ch} are often set equal.

$$E_{es,i,s,h0} = \mu_{es} E_{es,i}^{max};\ \ E_{es,i,s,h24} = \mu_{es} E_{es,i}^{max} \tag{14}$$

The active power production limits of conventional generators are considered via:

$$P_{g,i,s}^{min} \le P_{g,i,h,s} \le P_{g,i,s}^{max} \tag{15}$$

In addition, constraints related to the pumped hydro power plants are also included in the model.

IV. NUMERICAL RESULTS AND DISCUSSIONS

A. Data and Assumptions

The Portuguese Transmission Network system, seen in Fig. 1, is used as a case study, and all relevant data associated to this system can be found in [14], [15]. The considered system models three voltage levels 400 kV (see the red lines), 220 kV (see the green lines) and 150 kV (see the blue lines). The network data as well as the location of renewable and non-renewable generation resources can be also found in [15]. Each BESS has as installed capacity of 100 MW/300MWh with both charging and discharging efficiencies assumed to be 90%. The system-wide peak load in the base case is 5384.9 MW. The operational period is assumed to be 672-hours long, representing the four most

Fig 1. Portuguese Transmission Network [14].

representative weeks in a year. This helps one to capture the values of BESSs in a more reasonably accurate manner, rather than using a 24-hour period which is commonly used. The selection process is based on minimizing the error between the year-long net load duration curve and its four-week long approximation.

The large hydro power plants with pumping capacities are located at Aguieira, Alqueva, Alto Rabagão, Frades, Torrão and Vilarinho das Furnas. In the system, a total of 13 BESSs are optimally placed at the following nodes: Castelo Branco, DiVOR, Falagueira, Gardunha, Estoi, Estremoz, Tunes, Carregado, Sacavém and Ferro. These nodes are either nearby areas with high renewable power generation or high demand centers. The installed capacity of wind power is assumed to increase by 10% over the coming 15 years. And, three demand growth scenarios 5%, 10% and 15% are considered for the target year, each with equal probability of realization.

Three sources of uncertainty are accounted for in our analysis (demand, solar and wind power generation). Uncertainties in each of these uncertain parameters are captured by considering three scenarios, each representing an hourly profile. This is following the work in [13]. The data for the scenarios are based on realistic observations, which are taken from [14].

B. *Discussion of Numerical Results*

To support the required analysis, five cases are considered. These, denoted as Case A – Case E, are each distinguished as follows. Case A considers the base case system where there is no deployed BESSs and that all conventional power plants are not flexible enough to cope with the variable nature of renewables. In this setup, as it is customary in many power systems, conventional power plants cannot operate below a preset minimum value. Case B is the same as the first case with regards to conventional power generation fleet but differs in that BESSs are deployed into the system in Case B. Case C assumes no BESSs in the system, but all conventional power generation plants are equipped with a game-changing mechanism that makes them sufficiently flexible. In this work, two case studies were considered to perform the analysis. The remaining cases consider the presence of BESSs and flexible conventional power generation fleet in the system. The only difference is that Case D, like in the first three cases, assumes a maximum system non-synchronous penetration (SNSP) limit of 80% is imposed; whereas, the last case (i.e. Case E) does not have such a limit. Note that an SNSP is defined as the ratio of variable power generation plus imports to the sum of demand and exports at a given time (in our case, this is computed on an hourly basis). A no SNSP limit is equivalent to saying that this limit is set to 100%. In the case of conventional power plants, the terms "flexible" and "inflexible" should be understood as in the following context. A conventional generator is said to be "flexible" if it can be operated below its minimum power limit; otherwise, it is attributed as "inflexible". Each case is summarily described as follows:

- Case A: No BESS deployed in the system, "inflexible" convention power generation fleet, and 80% SNSP limit imposed;
- Case B: BESSs deployed in the system, "inflexible" conventional power generation fleet, and 80% SNSP limit imposed;
- Case C: No BESS deployed in the system, "flexible" conventional power generation fleet, and 80% SNSP limit imposed;
- Case D: BESSs deployed in the system, "flexible" conventional power generation fleet, and 80% SNSP limit imposed;
- Case E: BESSs deployed in the system, "flexible" conventional power generation fleet, and no SNSP limit imposed;

From the economic aspect, Table I compares the expected system-wide cost terms and energy losses for the different cases. The results in this table clearly show the benefits of deploying BESSs in terms of reducing costs in the system, especially if accompanied with flexible conventional power generation fleet (see Cases D and E). In other words, BESSs are best utilized when the conventional power generation regime is sufficiently flexible. Comparing the cost terms corresponding to Cases A and C, we can observe that having a more flexible conventional power generation fleet leads to a 6.5% reduction in overall costs. Such a reduction in costs is mainly due to more efficient utilization of wind and solar power in Case C than in Case A either by supplying it directly to demand or storing it for a later use. Similar reductions in costs in Cases B, D and E are 3%, 9% and 9.4% respectively. Clearly, the biggest reductions happen when BESSs are deployed in a system with partially or fully flexible power generation fleet (see Cases D and E). Increasing the SNSP limit from 80% to 100% as in Case E does not seem to have significant impact cost-wise, but we acknowledge that this may be case dependent.

TABLE I – COMPARISON OF SYSTEM-WIDE COST TERMS AND ENERGY LOSSES ON AN ANNUAL BASIS

	Cases				
	A	**B**	**C**	**D**	**E**
Expected cost of O&M (M€) *	734	715	695	679	676
Expected cost of PNS (M€) *	0	0	0	0	0
Expected cost of emissions (M€) *	237	226	212	204	204
Expected total cost (M€) *	971	941	908	883	880
Expected energy losses (TWh/year)	0.63	+1.3%	+6.3%	+7.4%	+8.4%

*** *Net present values per annum*

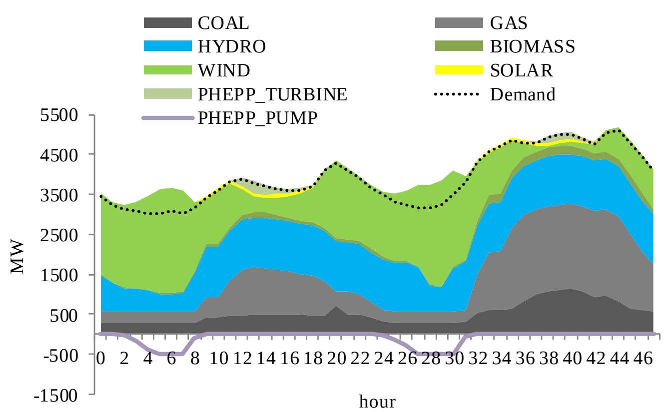

Fig. 2. A two-day long sample power production mix profile in Case A

From a technical perspective, Table I also shows another interesting dimension for comparing the cases – energy losses. Generally, energy losses show an increasing trend as one goes from Case A to Case E. Taking the losses in Case A (i.e. 0.63 TWh) as reference, expected energy losses in Case B are 1.3% higher. The figures are 6.3%, 7.4% and 8.4% in the remaining successive cases. Such an increasing trend could be explained as follows. Deploying BESSs and/or having improving the operability of existing conventional power generation regimes adds extra flexibility to the system, leading to higher utilization levels of variable energy resources that are mostly located far away from major demand centers. This increases flows in lines, and hence losses in the system. Such an increase in losses is however offset by savings in operation and emission costs.

Sample profiles of the energy mix for each case are shown in Figs. 2—6. The results in these figures also reinforce the statements above. Having BESSs in the system for example leads to a better management of excess variable renewable power (wind in particular) by storing it periods of high generation and low demand (see in Fig. 3). This is then partly released during periods of high demand and low RES power productions. Overall, the expected amount of wind power curtailment is slashed by almost 50% in C compared to that of Case A (see Fig. 7).

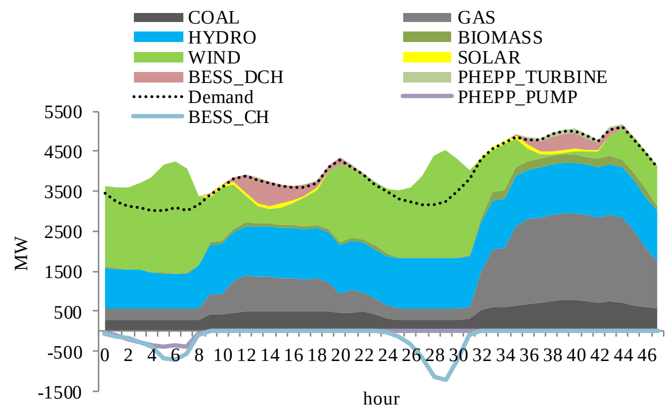

Fig. 3. A two-day long sample power production mix profile in Case B

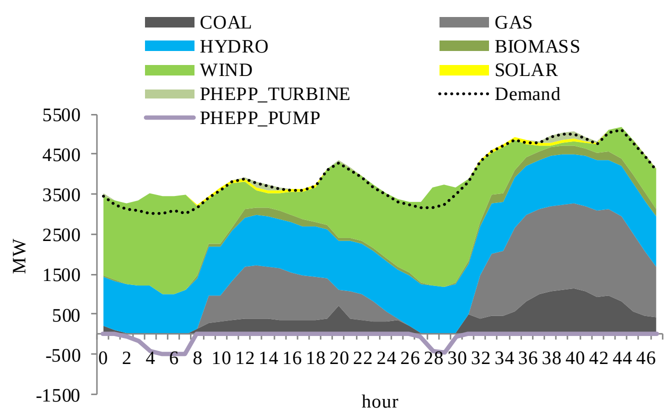

Fig. 4. A two-day long sample power production mix profile in Case C

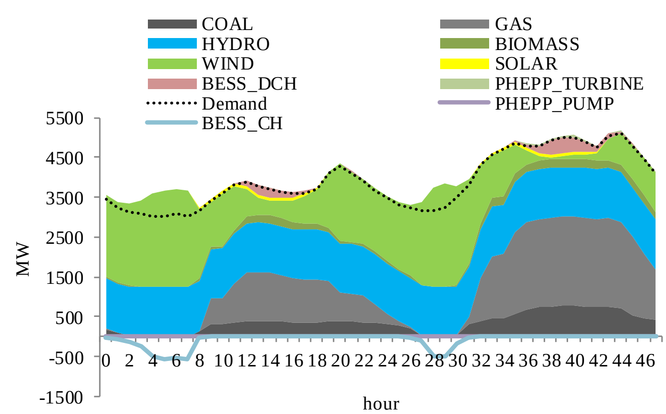

Fig. 5. A two-day long sample power production mix profile in Case D

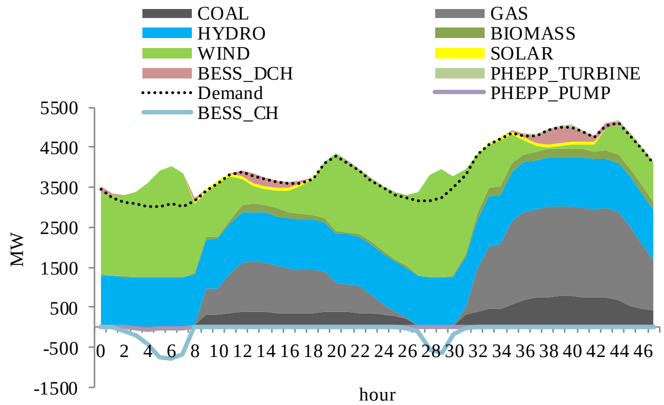

Fig. 6. A two-day long sample power production mix profile in Case E

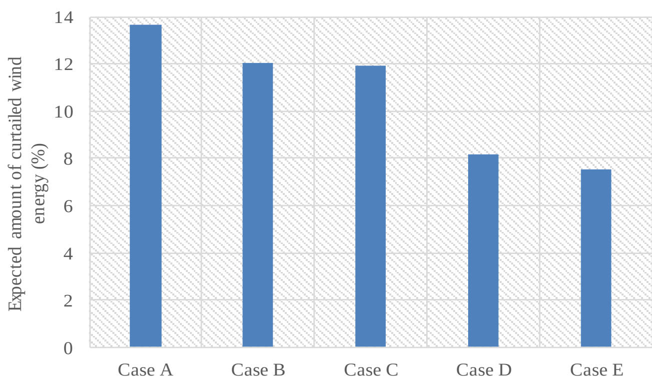

Fig. 7. Impacts on the level of curtailed wind energy

V. Conclusions

This paper analyzes the economic and technical contributions of BESSs in terms of flexibility in the operation of the Portuguese Transmission Network (PTN), taking into account the intermittent nature of renewable generation sources. To perform this analysis, we have used a MILP stochastic model based on least cost optimization subject to a set of technical and economic constraints. The analysis is based on numerical results obtained from simulations carried out on the PTN, where centralized BESSs are optimally allocated. The main objective of this work has been to assess the impact of BESSs on the operational performance of the Portuguese grid. According to the numerical results, the integration of BESSs into the system leads to a more efficient use of existing renewable resources since they are connected directly to areas with large renewable generation, in most cases. The introduction of BESSs into the system leads to as high as 10% reduction in total system cost. Significant reductions in expected wind power curtailments are also observed. Energy losses may moderately increase as a result of BESS deployments but this is offset by the savings operation and emission costs. In general, the results show that the integration of BESSs into the Portuguese transmission network may be more beneficial than being thought, as this increases the flexibility of the network system as whole, an interesting aspect for better management of the intermittency of renewables and their more efficient use in the system.

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