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Sizing and Siting of Large-Scale Batteries in Transmission Grids to Optimize the Use of Renewables

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Abstract—Power systems are a recent field of application of Complex Network research, which allows to perform large scale studies and evaluations. Based on this theory, a power grid is modeled as a weighted graph with several kinds of nodes and edges, and further analysis can help in investigating the behaviour of the grid under critical conditions. Among the crucial aspects of a power network, those concerning flow limits and power flow distribution are gaining relevance due to the increasing introduction of large scale renewable energy generation facilities. Storage systems are a key element in having a more sustainable but still reliable grid. This paper focuses on a new research challenge regarding the siting of the storage on the transmission grid and its appropriate sizing. The problem is tackled by considering realistic configurations based on the IEEE-RTS-96 bus and data coming from the Italian transmission operator, and evaluating novel economic and Complex Network based metrics on these configurations. Power flows are modeled in a linear way and the representative optimization problem is expressed as a linear programming problem. The results show the potential benefits of storage in transmission lines and indicate that the siting has a minor role in the optimal operation of the system.

Index Terms—Power systems, storage, DC power flow, Complex power grid, Renewable energy sources, Energy curtailment, RTS-96, Flow-based centrality

I. INTRODUCTION

Given their complexity and importance to modern economies, it is not surprising that power systems have received growing attention in the fields of network science and complex system analysis, especially with the aim to investigate the behaviour of power grid in case of unexpected failure and of targeted attacks [1]–[4]. However, a pure topological approach might not catch most of the crucial aspects of a power network, such those concerning flow limits and power flow distribution through the grid [5], [6].

These features have become increasingly relevant as a result of fostering the use of renewable energy sources (RES). In fact, the uncontrollable nature of renewable sources generation poses new challenges to the network in terms of operational conditions: power flows do not follow any more the traditional paths from major centres of production to consumption ones,

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since most of RES plants are linked to the distribution grid or far away from consumption sites, e.g. off-shore wind farms. Therefore, the transmission network has to be ready to accommodate bi-directional flows and be flexible. The expansion and planning of power systems is, however, a long-lasting and expensive process, that often has to face the strongest public opposition against new overhead lines [7], [8]. Storage technologies can be the key elements in the realization of an electrical system that is secure and reliable as the traditional one [9], [10], providing the (*smart*) flexibility required to increase the share of renewable to meet and exceed the goals of policy makers [11]–[13].

In this work, the power systems is modeled as a weighted graph, taking into account flow limits, lines' reactance and voltage angles, and four kinds of nodes are characterised according to the element they represent. The following research question is addressed: *what is the optimal size and location of storage systems to increase the stability of the system, while reducing the operation costs?* According to [14] and [15], batteries and underground CAES are the most attractive technologies for transmission and distribution grid support and load shifting. However, underground CAES require geographical considerations that are out of the scope of this work, while electrochemical batteries are more flexible [16], not only for mobility applications [17]. Therefore, the present work considers only large-scale batteries as storage technology.

To answer the above-mentioned research question several configurations of sizing and siting of batteries are considered, using the high-voltage IEEE RTS-96 as test system, the Italian power system for modeling the energy demand, and a range of capacities and locations for wind and solar energy production. The configurations are seen as a graph on which power flows according to a linear model over subsequent time intervals. Flow and Complex Network based metrics are used to model the physics of the system towards measures of economic optimality and system resilience. In particular, a novel application of betweennes is proposed. The analysis of the configurations shows that batteries are beneficial in storing energy in excess that otherwise would be curtailed; the siting of the storage has a limited influence on the optimality of the configuration. In addition, the batteries are beneficial in limiting the use of conventional power production plants during high demand periods by using stored energy. The last aspect is important from an economic perspective showing a case for a large scale adoption of batteries on the transmission

network. In the present work, an investigation on how proper sizing (and to a smaller extent siting) of storage can enable a smarter use of the transmission grid allowing the flexibility required by an higher stake of renewables is presented. Policy and regulatory consideration are outside of the scope of the present research.

The paper is organized as follows. Section II provides an overview of the state of the art on the main ingredients of the present study: modeling the power systems as a graph, on the one hand, and the inclusion of storage in the electrical grid, on the other hand. Section III provides some fundamentals of power flows in HV-power systems and network theory, while Section IV defines the model used in this work. Sections V and VI provide respectively the main features of the sizing and siting policies and the characteristics of the minimization problem to be solved. The details of the test case and the results are explained in Section VII. Concluding remarks and lines for future research are presented in Section VIII.

II. STATE OF THE ART

A systemic approach is taken and the transmission lines are modeled as a graph on which power flows. The time horizon covers a whole day, discretized in 15-minutes time intervals, and power flows are linearised. Batteries are the storage mean and are considered as nodes of the network [18]. The present work thus relates to the state of the art in network/graph models of power systems, on the one hand, and on storage systems for power transmission, on the other hand. As, to the best of authors' knowledge, little work has been done on their combination, the state of the art in the two fields is reviewed separately, next.

A. Complex network models for power systems

Modeling power systems as a complex graph and looking at its statistics from a global perspective has been mostly the object of research assessing the reliability of the network, in particular to identify critical points [19], [20]. Rosas-Casals *et al.* present an analysis of the topological structure and tolerance to failures and attacks of the Union for the Co-ordination of Transmission of Electricity (UCTE) power grid, by introducing a simple model that ignores physical characteristics of the grid, such as the impedance and capacity of lines [1]. Chassin and Posse propose a method for estimating system loss of load probability only based on the topological structure of the network and they test it on the North American eastern and western electric grids [2]. The authors of [21] show that the Italian transmission grid is rather robust to most failures, but very vulnerable when the failures occur on the nodes with the highest betweenness, a measure of the importance of a node with respect to minimal paths of the graph. These and many other studies use pure topological metrics, neglecting the physics governing a power system. To fill these gaps, Bompard *et al.* combine a topological model with the DC load flow model and propose new metrics to provide an assessment of the system vulnerability, bringing into the model the concept of line flow limit [22], [23]. The strength of these graph based approaches is to provide a global

view of the system and identify emerging properties not necessarily designed in the system. On the negative side, important physical characteristics may be overlooked, especially when ignoring the dynamics and flows on the network and just considering the static topological picture.

B. Sizing and siting of storage systems

Studies regarding the storage sizing problem typically aim at find the optimal capacity at a fixed location, usually close to a wind farm or a large load. Chakraborty *et al.* approach the problem by proposing a methodology for determining the sizing of energy storage system in order to reduce the total operational costs of two electric power systems with different number of thermal units and associated costs [24]. In [25] and [26], batteries are combined with a wind farm, and the capacity is determined to reduce the difference between the expected and the actual production, and to keep the injected power at a constant level, respectively. A novel perspective is presented by Makarov *et al.*, where, using discrete Fourier transform to decompose the required balancing power into different periodic components, the optimal sizing of storage systems is determined in the time horizons over which they are most effective, according to their technologies [27]. The storage siting problem is often connected with the previous one. Dvijotham *et al.* develop a heuristic algorithm, which places storage at all buses with an unlimited power and energy capacities and then solves an optimization problem to restrict the number of devices, based on their activity at each node [28]. In [29], assuming a vertically integrated utility, Pandžić *et al.* consider both the economic and technical aspects of the problem. By minimizing the sum of the generation costs and the daily investment cost in storage over a whole year, they identify the best storage locations based on the benefits that distributed storage units can perform by lessening congestions, and finally their optimal size is determined averaging over a year the daily maxima of stored energy and injected or extracted power. Ghofrani *et al.* prove that distributed storage is to be preferred to a centralized one in order to better use the transmission capacity and more efficiently integrate the wind power in terms of profits [30].

III. POWER SYSTEM AS A NETWORK

To perform an analysis of the siting and sizing of storage, one needs a sufficiently realistic model of the transmission grid. This is done by resorting to a DC load flow model and a weighted graph based representation of the system.

A. Linearized power systems model

Power transmission systems operate in AC regime, where the *complex power* $\overline{S}_i$ that flows through a node i is defined as follows:

$$\overline{S}_i = P_i + jQ_i \tag{1}$$

where P and Q are called *real* and *reactive* power, respectively. Since all quantities involved in a AC system have a sinusoidal waveform, solving a full AC power flow model

means solving a system of non linear equations for each node i:

$$\begin{cases} P_i = \sum_{j=1}^{N} |Y_{ij}V_iV_j| \cos(\theta_i - \theta_j - \gamma_{ij}) & \text{(2a)} \\ Q_i = \sum_{j=1}^{N} |Y_{ij}V_iV_j| \sin(\theta_i - \theta_j - \gamma_{ij}) & \text{(2b)} \end{cases}$$

where V_i and V_j are the voltage amplitudes at node i and j, while θ_i, θ_j and γ_{ij} are the phases of voltages and line impedance, respectively. However, in a well meshed grid, as it is the case for transmission grids and the IEEE-RTS 96 bus [31], some assumptions can be done to reduce the problem to a set of linear equations known as *DC power flow*:

- all voltages magnitude can be considered constant and, as a consequence, normalized to 1 per unit;
- if resistances are at least an order order of magnitude smaller than reactances, that is, the difference between reactances' and impedances' modules is very small, lines are assumed lossless, and only the reactances x in per unit are considered;
- differences between voltage angles are small;
- all admittances are inductive; and
- reactive power flows are ignored, as the power factor is very close to 1.

In this way, the active power flowing between nodes *i* and *j* is given by:

$$f_{ij} = \frac{\theta_i - \theta_j}{x_{ij}} \tag{3}$$

The DC power flow is a useful approximation of the sinusoidal AC power flow equations and is frequently adopted, especially at the transmission level (e.g. [22], [28], [29], [32]–[34]). For further illustration, the reader is referred to [35].

B. Fundamentals of network theory

A *Network* is a collection of objects that are pairwise related. The objects are referred to as vertices or nodes and the relationships are referred to as edges [36]. A *Power grid graph* is a pair (V, E) such that each element $v_i \in V$ is either a substation, transformer, or consuming unit of a physical power grid. There is an edge $e_{i,j} = (v_i, v_j)$ with $e_{i,j} \in E$ between two nodes if the elements represented by v_i and v_j are physically connected, by a power line. One can associate a weight to the edge representing a physical property (e.g. resistance, reactance). A *Weighted Power Grid graph* is a Power Grid Graph graph $G_w(V, E)$ with an additional function $w : E \to \mathbb{R}$ associating a real number to an edge representing a physical property of the physical cable represented by the edge [37]. The physical property can be the reactance of the line, taken in per unit (pu).

A *Path P* between two nodes is a sub-graph of the form:

$$V(P) = \{v_0, v_1, \ldots, v_l\},$$
$$E(P) = \{(v_0, v_1), (v_1, v_2), \ldots, (v_{l-1}, v_l)\}$$

such that $V(P) \subseteq V$ and $E(P) \subseteq E$. The vertices v_0 and v_l are the *end-vertices* or *end-points* of P and $l = |E(P)|$ is

the *length* of P, that is the number of edges that the path P contains [38]. According to this, given a graph G, the *Shortest path* from v_i to v_j has the least number of edges among all paths for which v_i and v_j are the end-vertexes.

The *betweenness* $C_b(e)$ of an edge $e \in E$ is

$$C_b(e) = \sum_{v_i, v_j} \sigma_{v_i, v_j}(e) / \sigma_{v_i, v_j} \tag{4}$$

where σ_{v_i, v_j} is the total number of shortest paths from node v_i to node v_j and $\sigma_{v_i, v_j}(e)$ is the number of those paths that pass through edge e. The concept of betweenness is useful to describe the importance of an edge (or a node) with respect to minimal paths. Vertices and edges that occur on many shortest paths between any given pair of vertices have higher betweenness than those that do not; that is, they have relatively higher importance within the graph [39]. The measures of betweenness, however, are based on the assumption that information flows only along the shortest paths, while in a power network it is not always the case. According to power flow equation (3), power flows along all available lines between two nodes, depending on the ratio of phase angles difference to reactance, therefore other more precise measures have to be used.

Let f_{max} be the maximum flow from the node v_i to the node v_j during a single time step and let f_e be the portion of maximum flow passing through the edge $e \in E$ of the network. The *Flow-based centrality index* $C_f(e)$ is defined as [40]:

$$C_f(e) = \sum_{v_i} \sum_{v_j} f_e \tag{5}$$

and, by dividing it by the total flow between all pairs of node, the above equation is normalized and expressed in percentage:

$$\widehat{C_f}(e) = \sum_{v_i} \sum_{v_j} \left[f_e / f_{max} \right] \cdot 100 \tag{6}$$

The *Utilization index* is defined to assess what percentage of the edge capacity is used. Let f_e be the flow passing through the edge e and let c_e be its capacity, the *Utilization index* $U(e)$ is defined as:

$$U(e) = \left[f_e / c_e \right] \cdot 100 \tag{7}$$

It is expressed as a percentage of the edge capacity. The edges are ranked according to the portion of flow that they carry or to how much they are exploited by resorting to Equations (6) or (7), respectively.

IV. THE MODEL AND ITS TOPOLOGICAL REPRESENTATION

In this paper, a modified version of the IEEE Reliability Test System 1996 is used as a test case, where some renewable plants are added for a total capacity varying from 0% to 74% of winter total global load demands, lines' capacities are reduced to their 75% and some electrochemical storage systems are introduced. Parameters such as phase angle and reactance are included to achieve accurate results from the DC load flow, and the nodes are distinguished in four sets by assigning different properties. The most exploited lines are ranked by defining an Utilization index, in order to determine

what percentage of the line's capacity is used, and a multi-period Centrality analysis is provided, based on the index proposed in [40]. A set of batteries is added, whose size is determined according to the capacity of the connected lines. Different locations are chosen, by following three policies, in order to investigate their possible effects on the grid in terms of reduction of curtailment and relief of overloads and congestions.

The grid is topologically represented as a graph, and its main components are distinguished among four kinds of nodes and two types of edges. Generation plants $s_i \in S$ with $S \subset V$, that is the sources set. This set is partitioned in two disjoint subsets *renewable R* and *conventional P*; we consider only "non-programmable" sources in R, i.e., wind and photovoltaic. Two subsets of S are defined, such that $R \cup P = S$ and $R \cap P = 0$. They inject power to be transmitted through the edges to the distribution substations. Each plant s has upper $P_{s,max}$ and lower $P_{s,min}$ power generation limits which cannot be violated, depending on the technology. For renewable plants, the lower limit is assumed equal to zero, the upper one is the installed capacity $P_{r,max}$, but the actual production is restricted by the power potentially available, $P_{r,av}$. Moreover, a marginal cost coefficient c_p or c_r (euro/MWh) is assigned to each plant according to its technology [41].

The load buses are sinks, $t_i \in T$ with $T \subset V$. They have only incoming flows and their power demand has always to be satisfied. The power l_t requested by the node t can be valued through its assumed load in percentage $l_{t,\%}$ of the global system demand.

The storage nodes $b_i \in B$ with $B \subset V$ represent energy storage systems. Such nodes are allowed to act as generators or loads thus having both incoming and outgoing flows. In the first case, they behave as a device that charges, in the second one a device that discharges. Their main characteristics are:

- an upper limit of the state of charge $SoC_{b,max}$ expressed in term of (MWh), that is the energy capacity;
- a lower limit of the state of charge $SoC_{b,min}$ in (MWh), that is:

$$SoC_{b,min} = (100\% - DoD_b) \cdot SoC_{b,max} = p_\% \cdot SoC_{b,max} \tag{8}$$

  where DoD_b is the depth of discharge;
- an upper limit of the rate of charge and discharge $ch_{b,max}$ in (MW), that is the power capacity;
- an energy/rated power ratio $K_b = SoC_{b,max}/ch_{b,max}$ in hours, that is the duration that the battery can operate while delivering its rated output; and
- a charge and discharge efficiency, η_{ch} and η_{dis} respectively;

The time horizon considered is 24 hours and each time step is 15 minutes, thus resulting in 96 time slots per day. At the end of each time period j, the state of charge of the storage b, $SoC_{b,j}$, is a function of its initial state $SoC_{b,in}$ and of the incoming or outgoing flow during the period Δj, $ch_{b,j}$ and $dis_{b,j}$ respectively.

$$SoC_{b,j} = SoC_{b,in} + ch_{b,j} \cdot \Delta j - dis_{b,j} \cdot \Delta j \tag{9}$$

where, the relationship between the flows seen by the storage itself (i.e., internal flow), $ch_{b,j}$ and $dis_{b,j}$, and the one seen by the grid (i.e., external), $f(b,n)_j$, is governed by the following equations:

$$ch_{b,j} = f(b,n)_j \cdot \eta_{ch} \tag{10}$$

$$dis_{b,j} = \frac{f(b,n)_j}{\eta_{dis}} \tag{11}$$

Moreover, the state of charge has to be included between the upper and lower limits:

$$SoC_{b,min} \leq SoC_{b,j} \leq SoC_{b,max} \tag{12}$$

Lastly, a set of inner nodes is defined as $n_i \in N$ with $N = V \setminus (S \cup T \cup B)$ and it includes all busbars.

The edges are distinguished in *real* and *virtual*. The *real* edges represent physical transmission lines. They have a weight equal to the line reactance in pu and their capacity is set equal the one of the line. Several components can be linked to the same inner node, by means of one or more switch connector in series with a circuit breaker. This group of elements is represented by a virtual edge, that connects a source node (or a sink or a storage) to an inner one; a conventional weight of 10^{-4} is given. The introduction of virtual edges allows, indeed, to characterize every single node of the graph in an univocal way. The capacity of these edges is chosen great enough to drain out the upper power generation limit of the plant or to satisfy the power demand from the load.

The angle phase θ is a parameter assigned to all nodes in order to run a DC power flow, considering a base power P_b of 100 MW.

V. SIZING AND SITING OF BATTERIES

Given a power grid represented as a graph and an optimality measure, solving the *sizing and siting problem* consists in selecting a size and location on the network for storage such that the optimality measure scores best.

A. Sizing

The size of each storage added to the grid is determined by the capacity of the line it is connected to. It is assumed that the energy capacity of the battery to be set is sufficient to store energy for one hour at the maximum flow allowed on the selected line. Further, all storage systems are energy intensive applications, mainly oriented towards the shifting of energy flows over time. Therefore, a typical energy/rated power ratio values similar to those of NaS batteries is adopted (i.e., usually with values between 6 and 8) [42]. Moreover, the model assumes that a line (u,v) has a capacity of $c(u,v)$ (MW) and the added storage has an energy capacity equal to $c(u,v)$ (MWh) and a power capacity equal to $c(u,v)/K$ (MW). As many devices as the lines whose capacities are saturated by a wind farm are added.

B. Siting

For each line, all utilization indexes can be ordered in descending order to obtain an *overload duration curve* that shows for how long the exploitation in percentage of a line is above a given level. In this way, an utilization index-based analysis helps to identify the most critical lines of the network during the day and classify them in a ranking to chose the best location for the storage systems.

Given a configuration of installed renewable plants, the quarters of an hour in which a line is loaded up to the 100% of its capacity on all days are counted; then, the average is calculated over all configurations. Four representative days are taken into consideration, that is, one per season. Thus the maximum value that this parameter may obtain is 384, considering 96 time steps per day as explained above. The ranking is compiled according to this average.

The lines can be distinguished between those linked to a wind farm and those that are not. The storage systems are located by following three different policies:

- choosing a fixed number of buses connected to the most overloaded lines only among the ones linked to a wind farm;
- choosing a fixed number of buses connected to the most overloaded lines among all the grid, in the order of the ranking; and
- choosing a fixed number of buses connected to the most overloaded lines in a random way.

The exploitation of batteries is considered as the optimality function to identify their best location. The time steps in which $SoC_{b,j} > SoC_{b,min}$ are counted, and the average over four days of the maximum energy stored and the average of the maximum power injected in or extracted from the battery is calculated.

VI. MINIMIZATION OF DAILY PRODUCTION COSTS

To determine optimal size and site, the production costs over a determined time horizon are minimized, reducing the renewable power curtailment by means of electrochemical storage systems. A 24-hours horizon and a 15-minutes resolution are taken into account. The state of the grid at the end of a time step j represents the initial state of the next one, i.e., $j + 1$.

When the available renewable production is too high to fulfill the constraint of balance or transmission capacity, then only a limited part of this is injected into the grid, while the one in excess is cut off. The amount of curtailed energy (MWh) from renewable energy sources (RES) can be valued as follows:

$$curtailment = 0.25 \sum_{j=0}^{95} \sum_{r \in R} (P_{r,j,av} - P_{r,j}) \qquad (13)$$

where $P_{r,j,av}$ is the RES power potentially available at time step j. With the aim of minimizing the curtailment of wind or solar production, this solution is penalized with a high cost *curt_cost*.

A. Objective function

The daily system cost to be minimised is defined as follows:

$$min \sum_{j=0}^{95} \left[\sum_{p \in P} c_p \cdot P_{p,j} + \sum_{r \in R} c_r \cdot P_{r,j} \right.$$
$$\left. + curt\_cost \cdot \sum_{r \in R} (P_{r,j,av} - P_{r,j}) \right] \qquad (14)$$

where c_p and c_r are the marginal cost coefficients [41]. The following linear constraints must be fulfilled:

- Upper and lower power generation limits $\forall p \in P$

$$P_{p,min} \leq P_{p,j} \leq P_{p,max} \qquad (15)$$

- Upper and lower power generation limits for RES plants $\forall r \in R$

$$0 \leq P_{r,j} \leq P_{r,j,av} \leq P_{r,max} \qquad (16)$$

- Transmission line capacity $\forall (u,v) \in E$

$$-c(u,v) \leq f(u,v)_j \leq c(u,v) \qquad (17)$$

where $f(u,v)_j$ is the flow from node u to node v at time step j.

- Fulfillment of power demand $\forall t \in T$

$$\sum_{v \in \Gamma(t)} f(v,t)_j = l_{t,j} \qquad (18)$$

where $\Gamma(t)$ is the set of all vertices linked to node t through an edge.

- Flow conservation $\forall n \in N$

$$\sum_{(u,n) \in E} f(u,n)_j = \sum_{(n,z) \in E} f(n,z)_j \qquad (19)$$

- Balance between supply and demand

$$\sum_{p \in P} P_{p,j} + \sum_{r \in R} P_{r,j} + \sum_{b \in B} f(b,n)_j = \sum_{t \in T} l_{t,j} \qquad (20)$$

- Power and energy flows $\forall b \in B$ if $f(b,n) > 0$

$$[f(b,n)_j / \eta_{dis}] \leq min \Big(\{ch_{b,max}\},$$
$$\{[SoC_{b,j-1} - SoC_{b,min}]/\Delta j\} \Big) \qquad (21)$$

- Power and energy flows $\forall b \in B$ if $f(b,n) < 0$

$$|f(b,n)_j| \eta_{ch} \leq min \Big(\{ch_{b,max}\},$$
$$\{[SoC_{b,max} - SoC_{b,j-1}]/\Delta j\} \Big) \qquad (22)$$

- State of charge $\forall b \in B$

$$p_\% \cdot ch_{b,max} \cdot K \leq SoC_{b,j} \leq ch_{b,max} \cdot K \qquad (23)$$

- Phase angle constraints:

$$\frac{-\pi}{2} \leq \theta_{v,j} \leq \frac{\pi}{2} \quad \forall v \in V \setminus s : \text{slack node} \qquad (24)$$

$$\theta_{s,j} = 0 \quad s : \text{slack node} \qquad (25)$$

This constraint is required to solve the system of N equations and N unknown bus voltage angles $P_i = \sum_{j \in \Gamma(i)} f_{ij} = \sum_{j \in \Gamma(i)} (\theta_i - \theta_j)/x_{ij}$ obtained from DC load flow, as briefly explained in Section III-A.

VII. TEST CASE AND RESULTS

The model is applied on a slightly modified version of the IEEE Reliability Test System 1996 (RTS-96) [31], [43], while load profile data are coming from the Italian grid. Flows are computed on the test case by running a DC load flow and the optimal configuration is sought.

A. Test case

Starting from the IEEE Reliability Test System 1996 (RTS-96), renewable plants are added for a total capacity ranging from 0% to 74% of winter global load demands, in 7 steps. The new suppliers are placed on the network according the following two policies:

- cutting the 3, 6, 12 or 15 longer transmission lines, that is 1, 2, 4 or 5 per area, and adding a new internal node, a wind generation node and a virtual edge;
- adding a new photovoltaic (PV) solar generation node and a virtual edge to 9 or 12 load buses, that is 3 or 4 per area.

Moreover, a minimal output power for each kind of generation plants is set by considering technical limits of different components, e.g. boiler and prime mover, and the capacities of the edges are reduced to their 75%, since having a system operated in an *N-1* security state [44] is not a goal of this work, which focuses on the network behaviour under critical conditions.

Renewable power injections are assumed to be known as a deterministic input, that means having perfect forecasts. Changes due to forecast errors, while important in real-time operation, are less significant in the long-period horizon, that is, indeed, the context of the sizing and siting problem tackled by this work. Renewable production profiles are estimated using historical wind and solar-PV generation data of two farms located in central Italy, whereas all load data are taken from [45], where the national load demand of the third Wednesday of each month of 2012 are recorded. Since the total installed production capacity in the RTS-96 amounts to 10,2 GW, which is considerably lower than the Italian value, all data have been adjusted. Four days, one per season, are considered in order to analyse different production-demand scenarios. For the detailed data, please refer to [46].

B. Implementation

To evaluate the configurations, the model and the objective function in Equation (14) have been translated into a software program. It takes as input a file with the grid description and renewable production profiles. The software is developed in Java SE 7 and GNU Math Prog [47] in order to find the optimal solution for what is essentially a linear programming problem. The solution is found by means of the simplex method, which guarantees the results optimality if the problem converges. For details about the implementation the reader can refer to [48]. For these simulations, the configuration of the computer hardware used it: CPU Intel®Core™i5-2430M, 2.40 GHz, with 8 Gb of RAM running Ubuntu 14.04 LTS 64 bit. The software guarantees the optimal solution with good

TABLE I
RANKING OF THE LINES REACHING THEIR MAXIMUM CAPACITY BEFORE STORAGE INTEGRATION

Ranking	Line	Time steps	Renewable
1	132-133	98	
2	117-178	77	✓
3	95-177	68	✓
4	96-180	67	✓
5	141-179	46	✓
6	156-157	39	
7	108-109	35	
8	152-173	34	✓
9	153-176	20	✓
10	165-170	17	✓
10	128-172	17	✓
11	154-156	16	
12	146-150	15	
13	130-132	12	
14	117-118	11	
15	143-179	9	✓
15	158-169	9	✓
16	98-102	7	
17	118-122	6	
18	129-175	5	✓
19	113-170	3	✓
20	119-140	2	
21	93-177	1	✓
21	99-100	1	
Av. dur.		26	

Ranking of the edges according to the average number of time steps in which the edge reaches its flow limit. A ✓sign indicates which lines are linked to renewable farms.

performance in term of run-time and use of memory, around 82 s and 20 Mb respectively [46]. They both increase linearly with the number of nodes, that means the software could be used for investigating the behaviour of real grid with much more nodes, such as a part of the European HV network, by simply enhancing the hardware's computational capabilities.

C. Results

One of the goals is to identifying the most stressed lines, in order to see where storage can be of relieve to the system. Table I provides a ranking of the edges according to the average number of time steps in which the edge reaches its capacity limit, that is $U(e)_j = 100$. Line 132-133 is congested for 98 out of 384 quarters of hour, about 25% of the times, meaning that it represents a bottleneck of the grid. A ✓sign indicates which lines are linked to renewable farms, in fact wind plants. PV solar plants are added, indeed, by the biggest loads and of a size such that their output is often not even enough for satisfy the local demand. Therefore, these plants do not cause lines congestions.

Table II summarizes the characteristics of the storage added to the grid, by following the sizing policy explained in Section V-B. For both kind of devices, the DoD and the charge/discharge efficiency are estimated to be equal to 80% and 87%, respectively [49]. The energy/rated power ratios are 6.89 h and 6.69 h. Ten batteries are added by following three siting policies, referred to as "Wind", "Ranking" and "Random" as described in Section V-B. The total power and energy capacities are 412 MW and 2774 MWh, respectively.
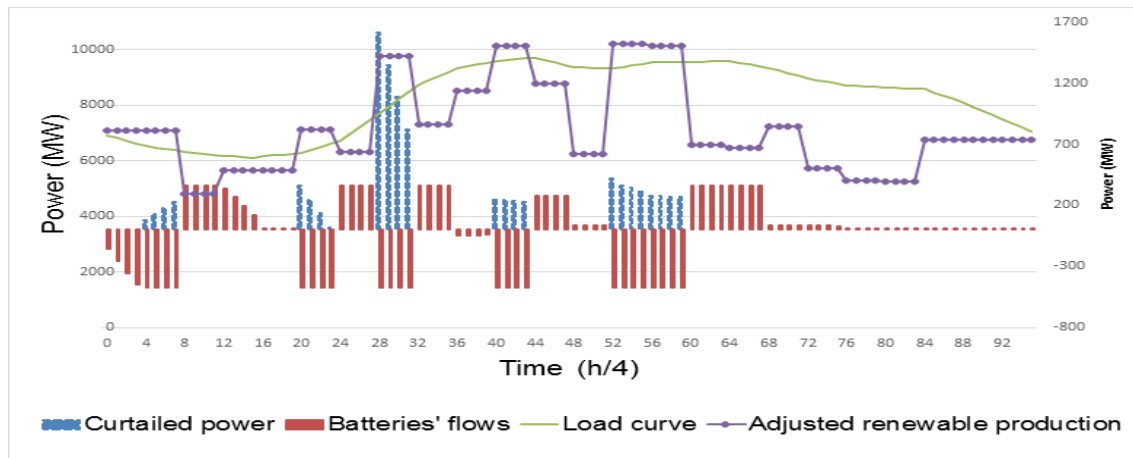
Fig. 1. Shifting of energy flows over time: batteries optimal operation. The "Adjusted renewable production" includes the minimum technical output of conventional generators, which cannot be reduced. One can see that the batteries charge (negative values of batteries' flows) when the load is lower than the available production, while they discharge (positive values) as soon as the load decrease. In this way, renewable energy is shifted over time and conventional generation is limited.
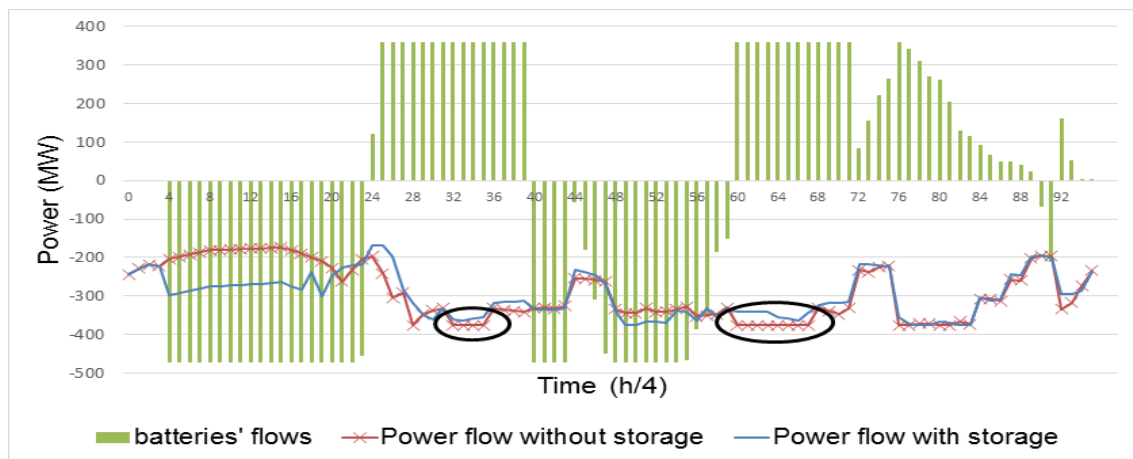

Fig. 2. Transmission congestion: comparison between chronological power flows without and with storage on the most stressed line in Summer, with 66% of RES penetration and storage located according to "Wind" policy. The number of time step in which the line reaches its flow limit (±375 MW) is significantly reduced.

TABLE II
STORAGE SYSTEMS' CHARACTERISTICS

Line's capacity MW	$SoC_{b,max}$ MWh	$ch_{b,max}$ MW	$SoC_{b,min}$ MWh	$SoC_{b,0}$ MWh	#
131	131	19	27	27	4
375	375	56	75	75	6

Summary of batteries' characteristics: flow limit of the line the battery is linked to (MW); energy capacity (MWh); power capacity (MW); energy/power ratio (h); SoC min (MWh); SoC at time step 0 (MWh); number of storage added to the grid.

TABLE III
CURTAILED ENERGY BEFORE THE INTRODUCTION OF BATTERIES

	Winter MWh	Spring MWh	Summer MWh	Autumn MWh	Total MWh	PV-solar MWh
10%	0	0	0	550	550	-
20%	184	0	0	2 755	2 939	-
30%	2 591	753	0	7 784	11 128	-
40%	4 422	1 258	81	11 107	16 867	66
50%	8 250	2 458	1 448	18 208	30 363	418
66%	17 003	4 135	5 241	26 029	52 408	579
74%	26 635	5 425	9 001	32 773	73 834	668

Curtailed energy before the introduction of storage: penetration of RES sources expressed as percentage of winter-peak demand; curtailed energy for each day; total curtailment over 4 days; curtailed energy from PV-solar farms.

Wind and solar productions are intermittent and volatile, so that the grid is not always able to totally absorb them due to transmission and operating constrains. Table III reports the curtailed energy for each supply-demand scenario and the sum over four days, before the introduction of batteries.

The curtailment affects mainly the wind farms. In the configuration, solar farms are involved for 40% of renewable installed capacity, and for less than 2% of total curtailed energy, since they often do not inject power into the rest of the grid.

With low levels of renewable penetration, batteries would be scarcely used. Therefore, the possible effects of these devices are investigated with the renewable installed capacity equal to 40% and 66% of the winter global load demands.

An example of batteries optimal operation to minimize the daily production costs is shown in Figure 1. The adjusted renewable production includes the minimum technical output of conventional generators. Batteries' flows are positive during discharging and negative during charging (right y axis). As one can see, the devices are charged when the available production is higher than load demand and discharge as soon as possible to limit the supply from conventional plants.

TABLE IV
CURTAILED ENERGY AFTER THE INTRODUCTION OF BATTERIES BY FOLLOWING THREE POLICIES

	No batteries	Random	Ranking	Wind
40%				
Total (MWh)	16 867.4	12 252.5	12 252.5	12 252.5
Reduction %		-27.36	-27.36	-27.36
66%				
Total (MWh)	52 408	40 945.5	40 966	41 003.1
Reduction %		-21.87	-21.83	-21.76

Curtailed energy after the introduction of storage, when RES penetration is 40% and 66% of winter-peak load. Total curtailed energy following three siting policies and reduction as percentage of curtailment when no storage are installed.

Different locations do not affect significantly the reduction in energy curtailment, that amounts to -27.36% and -21.87%, as evident from Table IV. The small differences in the second scenario are attributed to local transmission congestions that does not allow the charge of a battery, resulting in a non-optimal operation. Moreover, Table V reports the batteries exploitation, as explained in Section V-B. Without affecting the validity of the overall considerations, only the Wind siting policy is reported in Table V. The batteries utilization increases considerably with the percentage of RES installed in terms of time steps and stored energy. However, the energy capacity is rarely fully exploited, that results in a maximum SoC_{av} of 74.7% and 70.7% for the two types of devices.

TABLE V
SUMMARY TABLE ABOUT BATTERIES' EXPLOITATION WHEN "WIND" POLICY IS APPLIED FOR SITING

Type	40%			66%		
	h/4	**SoC$_{av}$**	**ch$_{av}$**	**h/4**	**SoC$_{av}$**	**ch$_{av}$**
		MWh	%	MW		MWh	%	MW
131/19	107	71.5	54.5	16.7	245	97.8	74.7	19.0
375/56	81	203.6	54.3	51.5	233	265.3	70.8	56.0

Batteries exploitation when "Wind" policy is applied for siting: type of battery (MWh, MW); number of time step in which $SoC > SoC_{min}$; average over four days of the maximum energy stored (MWh) and as percentage of energy capacity; average over four days of the maximum power injected in or extracted from the battery (MW).

Considering lines congestions, the storage introduction causes a re-dispatch of power flows, that changes with different siting policies [50], but the average overload duration among all lines remains almost the same. With a further examination, one can see examples of transmission congestions resolution. A daily chronological power flow of the most stressed line is shown in Figure 2, before and after the introduction of storage. This power line (edge in the model) is located in a strategical position between an area with an excess of conventional production and one with many loads. One can

see that without batteries, the line is overload in several time steps (i.e., 32-35, 60-67, and 76-83). After the introduction of storage systems, thanks to their discharge (positive values), the congestions are avoided in 32-35 and 60-67, when the flow is significantly reduced, by using previously stored energy. However, the batteries keep discharging and, therefore, once the line has to face another contingency (76-83), not all of them can discharge at their maximum power capacity, limiting the positive effects. Overall, in this case, the overload is reduced from 20 time steps to 4, that is a reduction of 80%.
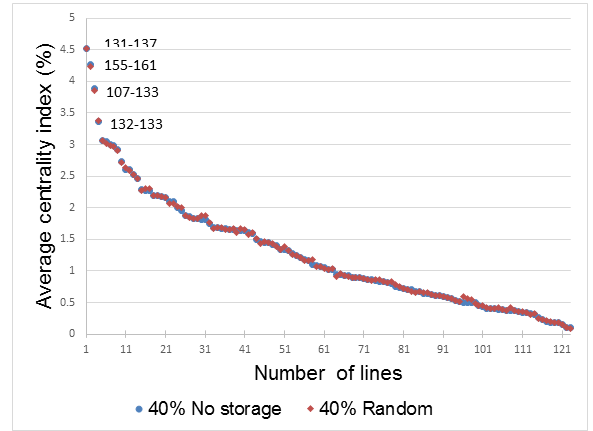

Fig. 3. Centrality index trend: from no storage to introduction of batteries. This index, which is flow-based but does not take into account lines' flow limits, is influenced by neither the sizing nor the siting of storage.

Finally, the Centrality index defined in Equation (6) is applied on the multi-stage time horizon, by using a weighted mean approach with total load demands as weights, to perform a Centrality analysis. The total flow on the grid is far greater than the flow on a line, therefore, the flow-based centrality index is not significantly affected by the introduction of storage, whatever siting policy is followed, as expected. The RES production influences the centrality index instead: for lines carrying mainly energy from conventional plants, this parameter tends to decrease as the renewable capacity increases, vice-versa it decreases for the edges linked to wind farms [46]. A comparison of overall trend of average centrality index between a scenario with 40% of RES, before and after introduction of batteries, is shown in Figure 3. There are four edges with a high value, that is this small portions of lines carries a significant part of the global flow (around 16%), followed by an almost linear trend. These edges transmit the production of plants with small marginal costs, e.g. nuclear and hydroelectric ones, from the upper to the lower part of each area, there are more expensive plants and more loads. This result shows how good and optimized is the IEEE RTS-96 model, although real networks might not have such a smooth behaviour and show key bottlenecks [51].

VIII. CONCLUDING REMARKS

The need to increase the amount of renewable sources in high voltage networks is changing their traditional operational conditions. Growing amount of rapid and unpredictable power has to be dispatched, while the balance and reliability of the

system have to be guaranteed. Such trend poses the necessity to take into account not only the topological aspects of the network, but also physical properties and laws governing power flows.

In the present paper, large scale storage systems are introduced in a transmission network with high RES penetration, and their appropriate size and location are sought in order to foresee a smart power grid. By considering configuration with the introduction of storage devices into transmission grids,the problem is mathematically formulated as the minimization of the production costs over a 24-hours-horizon. Taking four different supply-demand scenarios and RES power capacities, ten batteries, and a modified version of IEEE-RTS 96, three siting policies (i.e., random, ranking, wind) are followed. Representing the network as a weighted graph, by including the physical characteristics of its main components, is helpful in having a valid model of a realistic infrastructure, without needing a very precise level of details. Moreover, the present method applies metrics based on real flows, instead of on static topological considerations (e.g. shortest paths on graphs) on a multi-period scenario and it shows good scalability, that means larger network samples could be analysed.

The introduction of batteries allows the grid to store energy when the renewable availability is excessive, and use them to limit the supply from conventional plants at a later time, during high demand periods. Even if detailed economic considerations are out of the scope of this work, it shows how proper sizing (and to a smaller extent siting) of batteries can be a key step towards a more flexible and smarter use of transmission grids, as it is required by the increasing exploitation of renewables.

The analysis evidences that, on the one hand, the different policies of siting have no significant influence on the average overload duration of the lines, on the other hand, the introduction of storage appears to considerably reduce the congestion of critical corridors. Somewhat unexpectedly, the proposed method shows that placing a storage close to a wind farm does not automatically imply that the major contributions in terms of relief of congestions are gained on the lines linked to the renewable nodes itself. Instead, the major positive effects are achieved on critical junctions, even if no storage are located to their end-nodes. This result is important both from a technical and economical point of view. The action of the storage can help while a permanent mitigation measure, such as generation re-distribution or start-up of a fast unit, takes effect or, in the best case, can lower the flow on the line for a time frame long enough to overcome the contingency. The mentioned mitigation measures are, indeed, expensive, since they would usually involve generators with fast ramp rates, such as gas or oil-fired facilities.

The centrality analysis shows that this index is not significantly affected by neither the sizing nor the siting of storage. This result underlines an approach which does not take into account flow limits might be weak when investigating crucial aspects of power systems concerning congestion and power flows distribution.

Based on the present work, further research is on-going to understand to what extent the advantages of introducing

batteries can be enhanced. Different siting policies are under consideration, together with an economic evaluation of the benefits when considering market-related requirements.

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