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Transmission Planning with Battery-based Energy Storage Transportation for Power Systems with High Penetration of Renewable Energy

Giorgia Pulazza, *Graduate Student Member, IEEE*, Ning Zhang, *Senior Member, IEEE*, Chongqing Kang, *Fellow, IEEE* and Carlo Alberto Nucci, *Fellow, IEEE*

Abstract— Battery-based Energy Storage Transportation (BEST) is the transportation of modular battery storage systems via train cars or trucks representing an innovative solution for a) enhancing Variable Renewable Energy (VRE) utilization and load shifting, and b) providing a potential alternative for managing transmission congestions. This paper focuses on point b) and proposes a long-term transmission-planning model coordinated with both stationary and mobile storage units. The planning-problem objective function minimizes the total system cost, i.e. the sum of i) the investment cost of candidate transmission lines, stationary and mobile storage systems, and ii) the operation cost, including conventional generating units fuel consumption, load shedding penalty and BEST transportation costs. An alternative approach for BEST vehicle scheduling problem is implemented. The contribution lies in the accomplishment of the spatial-temporal scheduling of the mobile storage units by including the Number-of-nonzero mathematical function in the optimization model set of constraints instead of using additional binary variables as generally accomplished. The identification of either storage systems optimal location, or both optimal location and size of storage systems is also allowed. BEST usefulness is analyzed and discussed for a test-system emulating a real system in China-Northwestern-grid with high VRE penetration divided in five regional areas, of which the most promising one for BEST implementation is identified.

Index Terms—Battery-based energy storage transportation, renewable energy, stationary storage, transmission planning

NOMENCLATURE

Indices

i	Index for thermal generators.
i_b	Index for nodes.
i_{bes}	Index for BES systems.
i_{best}	Index for BEST systems.
j	Index for operation conditions.
t	Index for time periods.
l	Index for transmission lines.
w	Index for wind farms.
pv	Index for photovoltaic generators.
Sets	
Ω_L	Sets of all lines.
Ω_{LC}	Sets of candidate lines.
Ω_{LE}	Sets of existing lines.
Ω_{OP}	Sets of operating conditions.
Ω_I	Sets of thermal units.
Ω_{bes}	Sets of BES systems.
Ω_{best}	Sets of BEST systems.
$\Omega_{i_b}^{L_1}$	Sets of lines whose sending end node is i_b .
$\Omega_{i_b}^{L_2}$	Sets of lines whose receiving end node is i_b .

$\Omega_{i_b}^I$	Sets of thermal units located at node i_b .
$\Omega_{i_b}^W$	Sets of wind farms located at node i_b .
$\Omega_{i_b}^{pv}$	Sets of photovoltaic systems located at node i_b .
$\Omega_{i_b}^{bes}$	Sets of BES systems located at node i_b .
$\Omega_{i_b}^{best}$	Sets of BEST systems located at node i_b .
Constants	
τ	Duration of one time period [h].
d_j	Duration of operating condition j , i.e. number of days included in each operating condition j [-].
n_{oc}	Number of operating conditions.
C_i^{gen}	Generation cost of thermal unit i .
C^{shed}	Load shedding operation cost.
K_{dist}^{best}	BEST transportation cost for each unit distance travelled.
C_l^{Line}	Annualized investment cost of line l .
$C_{bes}^{Storage}$	Annualized investment cost of BES system i_{bes} .
C_{best}^{Best}	Annualized investment cost of BEST system i_{best} .
S_0^{best}	Energy content of BEST system i_{best} at time $t=0$.
$\eta_{ch}^{best}, \eta_{dis}^{best}$	Charge and discharge efficiency of BEST system i_{best} .
T	Number of time periods.
M	A large enough constant.
$S_{min}^{best}, S_{max}^{best}$	Minimum and maximum energy content of BEST system i_{best} .
$P_{min,ch}^{best}, P_{max,ch}^{best}$	Minimum and maximum charging power of BEST system i_{best} .
$P_{min,dis}^{best}, P_{max,dis}^{best}$	Minimum and maximum discharging power of BEST system i_{best} .
S_0^{bes}	Energy content of BES system i_{bes} at time $t=0$.
$\eta_{ch}^{bes}, \eta_{dis}^{bes}$	Charge and discharge efficiency of BES system i_{bes} .
$S_{min}^{bes}, S_{max}^{bes}$	Minimum and maximum energy content of BES system i_{bes} .
$P_{min,ch}^{bes}, P_{max,ch}^{bes}$	Minimum and maximum charging power of BES system i_{bes} .
$P_{min,dis}^{bes}, P_{max,dis}^{bes}$	Minimum and maximum discharging power of BES system i_{bes} .
x_l	Reactance of line l .
F_l^{max}	Capacity of line l .
$P_{pv,j,t}^f$	Forecasted power output of pv unit at time t in operating condition j .
$P_{w,j,t}^f$	Forecasted power output of wind farm w at time t in operating condition j .
$R_{j,t}$	Spinning reserve requirement at time t in operating condition j .
$L_{i_b,j,t}$	Load demand at node i_b at time t in operating condition j .
L_{param}^{shed}	Load shedding parameter. It is equal to 1 when allowed and 0 otherwise.
n_{dist}^0	Distance between adjacent buses.

Variables

X_l	Binary variables that equals 1 if line l is built and 0 otherwise.
$Y_{i_{bes}}$	Variables that indicate whether to settle the BES system i_{bes} .
$V_{i_{best}}$	Variables that indicate whether to settle the BEST system i_{best} .
$P_{i,j,t}^{gen}$	Power output of thermal unit i at time t in operating condition j .
$L_{i_b,j,t}^{shed}$	Load shedding power at node i_b at time t in operating condition j .
n_{trip}^{best}	Trips number of the BEST system i_{best} .
$n_{dis,j}^{best}$	'Bus distance' between operating conditions j and $j+1$ of BEST system i_{best} .
n_j^{best}	Bus position of BEST system i_{best} in operating condition j .
$n_{0,j}^{best}$	Variable that indicates whether the BEST system i_{best} is operative in operating condition j .
$P_{i_{best},i_b,j,t}^{best, ch}$	Charging power of BEST system i_{best} at node i_b , at time t in operating condition j .
$P_{i_{best},i_b,j,t}^{best, dis}$	Discharging power of BEST system i_{best} at node i_b , at time t in operating condition j .
$r_{i_{best},j,t}^{best}$	Reserve content of the BEST system i_{best} at time t in operating condition j .
$P_{i_{bes},j,t}^{bes, ch}$	Charging power of the BES system i_{bes} at time t in operating condition j .
$P_{i_{bes},j,t}^{bes, dis}$	Discharging power of BES system i_{bes} at time t in operating condition j .
$r_{i_{bes},j,t}^{bes}$	Reserve content of BES system i_{bes} at time t in operating condition j .
$P_{w,j,t}^{wind}$	Power output of wind farm w at time t in operating condition j .
$P_{pv,j,t}^{solar}$	Power output of solar generator pv at time t in operating condition j .
$F_{l,j,t}$	Power flow of line l at time t in operating condition j .
$\theta_{i,j,t}$	Voltage angle of node i at time t in operating condition j .

I. INTRODUCTION

A. Motivation And Approach

Variable Renewable Energy (VRE) is becoming relevant in power system across the world as it supplies an increasing percentage of the demand. The total cumulative wind power installations are expected to reach about 840 GW by the end of 2022 [1] and the total solar power capacity is estimated to reach 1.1 TW in 2022 [2]. In China, both the wind power capacity and solar power capacity reached 200 GW by the end of 2019 [3].

Due to the high penetration of non-dispatchable power generation units, such as VRE ones, power system operation and planning has facing several challenges to ensure reliability, flexibility and security of supply. Two of the major problems related to primary energy source conversion are: 1) how to match Renewable Energy Resources (RESs), affected by strong variability, with load demand; and 2) how to build enough transmission to deliver VRE from generation bases, usually in remote locations to load centers [4]. Moreover, in transmission grids under high share of VRE, the intermittent and variable nature of green energy resources leads to a significant increase in the transmission capacity needed to ensure the security of supply. As a result, transmission line utilization rate is decreasing. In this regard, the key role of Energy Storage Systems (ESSs) needs to be fully

This work was supported by the European union funded project called IRES-8. G. Pulazza and C. A. Nucci are with the Department of Electrical, Electronic and Information Engineering, University of Bologna, Bologna 40136, Italy (e-mail: giorgia.pulazza3@unibo.it; carloalberto.nucci@unibo.it)

N. Zhang and C. Kang are with the State Key Laboratory of Power Systems, Department of Electrical Engineering, Tsinghua University, Beijing 100084, China (e-mail: ningzhang@tsinghua.edu.cn; cqkang@tsinghua.edu.cn).

exploited in order to face the above-mentioned challenges related to power system transition. ESSs provide resiliency against VRE curtailment and are able to mitigate the intermittency of renewable energy by storing energy during period of high renewable production and releasing energy during period of low renewable production. Despite other kinds of grid ESSs, Battery Energy Storage System (BES) can provide many benefits such as fast response time, low maintenance and, being rather compact in size, can be used in mobile applications. Furthermore, when dealing with transmission networks, BESs not only allow the shift of peak load flow induced by either load or renewable energy, hence postponing or reducing the investment of transmission lines, but they also increase the support on frequency and voltage enabling higher transmission capability.

In light of the above, this paper proposes an optimal coordinated storage and transmission planning under high share of renewable energy, in which Battery-based Energy Storage Transportation (BEST) are included. BEST is the transportation of modular BESs modules via train cars or trucks. Through such an innovative solution the potentiality of BESs in terms of load shifting and VRE utilization can be further exploited. This is particularly attractive for huge countries like China where VRE curtailment is still a major challenge.

BEST application provides a reasonable but rather expensive alternative for managing the transmission congestion. However, BES technology is increasingly developing, and its price is expected to continuously drop while due to the decrease of transmission line utilization rate, new transmission facility may not be an economically feasible option for power system operation [5]. Moreover, in case of natural disaster, mobile storage units enhance the power system resilience by providing energy quickly to emergency areas.

B. Literature Review

In the technical literature, quite few works regard the use of mobile energy storage systems in the power grid. In [4] Sun et al. established a spatiotemporal network to optimize locational and hourly charging/discharging schedule of BEST. The authors, in [6], established a security constraint unit commitment (SCUC) model for investigating the benefit of BEST to relieve transmission congestion. In [7], a post-disaster joint restoration scheme considering transportable energy storage system (TESS) was proposed to study the effect of transportability of TESS for a more reliable distribution system. In [8], an efficient SCUC with integrated BEST model was presented and solved using Benders Decomposition approach. A stochastic programming model was proposed in [5] to optimize the schedules of power system with battery transportation under high share of wind energy, taking into account both load and wind energy forecasting uncertainties.

Lu & Li proposed a long-term planning with BEST in power system considering the investment cost of power generation, transmission line and BESs [9]. The obtained results showed that, the proposed mixed integer linear programming model could not solve large problems. In [10] a new approach, called Battery Transportation and Logistics was proposed to investigate the transportation and logistics (T&L) model for delivering green energy to end users. A multi-stage transport and logistic optimization approach where the batteries are charged in the renewable power plants and transported back and forth by railways between the renewable power plants and cities, was proposed in [11]. In [12], a sizing and allocation algorithm of mobile energy storage system (MESS) was proposed, which showed that the MESS could maintain the power quality while achieving the profit for the distribution system operator. In [13], authors presented a

day-ahead energy management system for a truck-mounted mobile energy storage system that aims at minimizing the total energy procurement cost in a distribution system. Finally, the benefit of mobile storage systems of enhancing the distribution system resiliency was investigated in [7], [14], [15] and [16].

In that respect, we note that in literature there is still a lack concerning BEST integration in the transmission grid. On the one hand, several papers investigate BEST optimal operations and locations [4], [6], [8], and on the other hand, very few works consider mobile storage systems in the expansion planning problem [9], [17], and this is accomplished using a different mathematical formulation from the one proposed in this paper.

C. Contributions and Paper Organization

This paper addresses the long-term planning problem providing the best combination of transmission lines and storage units to achieve minimum cost in the considered power system. This planning model includes both stationary and mobile storage systems as candidate units and provides the optimal BEST site, size and scheduling for each operating condition considered.

The main contributions of this paper are:

- the accomplishment of a long-term planning model with mobile storage units suitable for transmission system under high share of variable renewable energy. To the best of our knowledge, there is little evidence of previous research addressing the problems of transmission planning with BEST, which is a much more complex problem compared with operation model investigated in some of the papers above referred to e.g. [4], [6]. We have indeed conceived our model to be suitable for significantly large portions of power networks with large penetration of renewables. The relevant mathematical formulation, described in Section III, makes use of continuous variables, which allow for the evaluation of both the optimal size and location of stationary and transportable storage systems;
- an alternative mathematical approach implementation for the relevant vehicle scheduling problem suitable for transmission grids, which avoids the need of several complex constraints involving a large number of binary variables that may cause numerical problems in the optimization. This is accomplished by the use of Number-of-nonzero (NZ) operator and an extremely limited number of constraints.

The rest of the paper is organized as follows. In Section II the main features of the proposed planning model are described. The formulation of this model is provided in Section III. Section IV provides several case studies, including an illustrative example based on a real regional grid with high RE penetration in China, and a case study based on a 190-bus test system to show the tractability of the proposed method to larger networks. Finally, conclusions are provided in Section V.

II. PROBLEM DESCRIPTION AND ASSUMPTIONS

As earlier mentioned, the planning model presented in this paper solves a coordinated expansion problem involving transmission lines, stationary storage systems and BEST.

In this paper, the proposed planning model is static as it only considers the investment decisions for a single year planning horizon (single-stage planning); the investment of transmission lines and storage systems is indeed annualized, the total investment cost being amortized equally within the investment payback period, considering the discount rate, and therefore the operation cost and investment cost are comparable. Long-term uncertainties

of load growth and available production capacity are disregarded in a first approximation, while short-term uncertainties are addressed by means of several operating conditions, each including 24-hour profiles of correlated demand, wind and solar production.

Each operating condition represented by 24-hour load demand, is obtained from the actual power system [18] and the hourly wind and photovoltaic (PV) daily available production based on simulated data. Both wind and PV output data are simulated considering the bus location and statistics of VRE in real power system, by means of Grid Optimization Planning Tool (GOPT) power system analysis software [18]. In each operating condition, BEST can be charged and discharged only in one bus because it seems reasonable not to allow intra-day BEST routes when dealing with transmission networks. Therefore, this paper assumes BEST displacements only between different operating days.

The main assumptions adopted in this model are the following:

- The model is static (single-stage planning). It only considers the investment decisions to supply the demand of a target year.
- DC power flow representation is adopted, and line losses are neglected.
- The generation planning is given as a boundary condition.
- To represent daily storage cycles, demand and VRE production correlations, each operation condition is described by 1 day with hourly resolution.
- A daily energy balance is set for both transportable and stationary storage units.
- BEST operation cost is calculated considering that the distance between consecutive buses has a fixed value. In other words, it is assumed that the distance between e.g. buses 9 and 10 is equal to the distance between buses 10 and 11, so that the distance between 9 and 11 is double than that between 9 and 10 or 10 and 11.
- No BEST intra-daily routes are allowed. This paper proposes BEST displacements only between different operating conditions, i.e. operating days.
- Dynamic planning and long-term uncertainties are beyond the scope of this paper.
- VRE uncertainty in spinning reserve requirement is represented through a Gaussian Distribution.

Note that uncertainties related to VRE power generation can be addressed by considering that they include two layers:

- 1) The diversity of output profile of wind/solar power in different days.
- 2) The forecast uncertainty in the daily dispatch.

Our model considers the first kind of uncertainty using scenario-based model, which can also reflect the operation of BEST. We do not consider the second uncertainty using stochastic or robust models; instead, we consider it using the reserve capacity constraints through Gaussian Distributions. Indeed, as shown in [19], the uncertainty of wind power can be captured by introducing reserve capacity constraints through the Gaussian copula. In [19] it is shown that such an approach achieves similar results compared with the stochastic unit commitment.

III. MODEL FORMULATION

A. Objective Function

The objective is to minimize the total cost, which is the sum of the annualized investment costs and the operation costs of the system under study:

$$OF = \min C^{Inv} + C^{Oper} \quad (1)$$

where

$$C^{Inv} = \sum_{l \in \Omega_{LC}} C_l^{Line} X_l + \sum_{i_{bes} \in \Omega_{bes}} C_{i_{bes}}^{Storage} Y_{i_{bes}} + \sum_{i_{best} \in \Omega_{best}} C_{i_{best}}^{Best} V_{i_{best}} \quad (2)$$

$$C^{Oper} = \tau \sum_{j \in \Omega_{OP}} d_j \sum_{i \in \Omega_I} C_i^{gen} \sum_{t=1}^T P_{i,j,t}^{gen} + \tau \sum_{j \in \Omega_{OP}} d_j \sum_{t=1}^T \sum_{i_b} L_{i_b,j,t}^{shed} C^{shed} + \quad (3)$$

$$+ \sum_{i_{best} \in \Omega_{best}} n_{dist}^{i_{best}} K_{dist}^{i_{best}} + \sum_{i_{best} \in \Omega_{best}} \frac{C_{i_{best}}^{Best}}{365} (n_0^{i_{best}} + n_{Trip}^{i_{best}})$$

In (1), C^{Inv} denotes the annualized investment cost of transmission lines, BESs and BESTs.

C^{Oper} includes only variable costs and, as shown in (3), it is given by the sum of three components: the fuel consumption of conventional generating units, the load shedding penalty and the BEST operation cost, respectively. BEST operation cost is given by the sum of the last two terms of (3). The third term of (3) represents the total BEST transportation cost, where $n_{dist}^{i_{best}}$ represents the distance to be covered for the transportation of the BEST system i_{best} and $K_{dist}^{i_{best}}$ is the transportation cost for each unit distance travelled. As already mentioned in Section II, in our model the distance covered by BEST, i.e. $n_{dist}^{i_{best}}$ is formulated considering that the distance between consecutive buses has a fixed value, but no limitations exist concerning the BEST mobility paths. The fourth term of (3) represents the cost associated to the operating conditions (i.e. days) where BEST is not providing any contribution to the system, namely $n_0^{i_{best}}$, in addition to one BEST inoperative day for each trip of the device, namely $n_{Trip}^{i_{best}}$. The fixed operation and maintenance costs of transmission lines, BESs and BESTs are usually equal about 1-1.5% of the investment cost. It is therefore included in the coefficient of their investment cost, respectively.

B. BEST model

Constraints (4) enforce the energy limits for the transportable storage systems in each time period and operating condition.

$$V_{i_{best}} S_0^{i_{best}} + \sum_{ib} \sum_{t=1}^{t_n} (\eta_{ch}^{i_{best}} P_{i_{best},i_b,j,t}^{best,ch} - P_{i_{best},i_b,j,t}^{best,dis} / \eta_{dis}^{i_{best}}) \tau \geq V_{i_{best}} S_{min}^{i_{best}}$$

$$V_{i_{best}} S_0^{i_{best}} + \sum_{ib} \sum_{t=1}^{t_n} (\eta_{ch}^{i_{best}} P_{i_{best},i_b,j,t}^{best,ch} - P_{i_{best},i_b,j,t}^{best,dis} / \eta_{dis}^{i_{best}}) \tau \leq V_{i_{best}} S_{max}^{i_{best}} \quad (4)$$

$$\forall i_{best}, j, t_n = 1, 2, \dots, T$$

Constraints (5) enforce the transportable storage energy balance per day.

$$\sum_{ib} \sum_{t=1}^T (\eta_{ch}^{i_{best}} P_{i_{best},i_b,j,t}^{best,ch} - P_{i_{best},i_b,j,t}^{best,dis} / \eta_{dis}^{i_{best}}) \tau = 0 \quad (5)$$

$$\forall i_{best}, j$$

Constraints (6) are the charging and discharging bounds for the transportable storage systems.

$$V_{i_{best}} P_{min,ch}^{i_{best}} \leq P_{i_{best},i_b,j,t}^{best,ch} \leq V_{i_{best}} P_{max,ch}^{i_{best}} \quad (6)$$

$$V_{i_{best}} P_{min,dis}^{i_{best}} \leq P_{i_{best},i_b,j,t}^{best,dis} \leq V_{i_{best}} P_{max,dis}^{i_{best}} \quad \forall i_{best}, i_b, j, t$$

Constraints (7) set the mutual exclusion constraint of the charge and discharge state of the BEST. It enforces the BESTs to be only in one bus of the network in each time period and operating condition.

$$NZ(P_{i_{best},i_b,j,t}^{best,ch}) + NZ(P_{i_{best},i_b,j,t}^{best,dis}) \leq 1 \quad (7)$$

$$\forall i_{best}, j, t \quad NZ = \text{number of non zeros}$$

As we are dealing with a transmission network, we feel it reasonable to enforce BESTs to be in one bus only of the network in each operating condition, that in our case refers to a day.

$$NZ(\sum_{t=1}^{t_n} P_{i_{best},i_b,j,t}^{best,ch} + \sum_{t=1}^{t_n} P_{i_{best},i_b,j,t}^{best,dis} + P_{i_{best},i_b,j,t+1}^{best,ch} + P_{i_{best},i_b,j,t+1}^{best,dis}) \leq 1 \quad (8)$$

$$\forall i_{best}, j, t, t_n = 1, 2, 3, \dots, T-1$$

It should be noted that the application of the number of non-zero function as done in (7) and (8) (which in the equations and in the following has been referred to as NZ function for simplicity) makes it possible to successfully model the transportable storage systems avoiding the use of additional binary variables, which could increase drastically the computational burden, especially for large scale power network. We shall come back on this point more in detail in section III.E.

Constraints (9) enforce the reserve content bounds for the transportable storage systems in each time period and operating condition.

$$0 \leq r_{i_{best},j,t}^{best} \leq P_{max}^{i_{best}} V_{i_{best}} + \sum_{ib=1}^{N_b} (\eta_{ch}^{i_{best}} P_{i_{best},i_b,j,t}^{best,ch} - P_{i_{best},i_b,j,t}^{best,dis} / \eta_{dis}^{i_{best}})$$

$$r_{i_{best},j,t}^{best} \tau \leq SOC_{i_{best},j,t}^{best} - S_{min}^{i_{best}} V_{i_{best}} \quad \forall i_{best}, j, t \quad (9)$$

where

$$SOC_{i_{best},j,t}^{best} = V_{i_{best}} S_0^{i_{best}} + \sum_{ib} \sum_{it=1}^t (\eta_{ch}^{i_{best}} P_{i_{best},i_b,j,it}^{best,ch} - P_{i_{best},i_b,j,it}^{best,dis} / \eta_{dis}^{i_{best}}) \tau \quad (10)$$

Concerning the BEST operation cost, the following equations define $n_{dist}^{i_{best}}$, $n_0^{i_{best}}$ and $n_{Trip}^{i_{best}}$, respectively.

$$n_{dist}^{i_{best}} = n_{dist}^v \sum n_{dist,j}^{i_{best}} \quad \forall i_{best} \quad (11)$$

where

$$\left\{ \begin{array}{cccc} \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots \end{array} \right. \quad \forall i_{best} \quad (12)$$

and

$$n_j^{i_{best}} = \text{find} \sum_{t=1}^T (P_{i_{best},i_b,j,t}^{best,ch} + P_{i_{best},i_b,j,t}^{best,dis}) \quad \forall i_{best}, j \quad (13)$$

$$n_0^{i_{best}} = n_{oc} - \sum_{j=1}^{n_{oc}} n_{0,j}^{i_{best}} \quad \forall i_{best} \quad (14)$$

where

$$n_{0,j}^{i_{best}} \leq NZ(\sum P_{i_{best},i_b,j,t}^{best,ch} + P_{i_{best},i_b,j,t}^{best,dis}) \quad n_{0,j}^{i_{best}} \in [0,1] \quad \forall i_{best}, j \quad (15)$$

$$n_{Trip}^{i_{best}} = NZ(n_{dist,j}^{i_{best}}) \quad \forall i_{best} \quad (16)$$

where:

- n_{dist}^{best} is the distance to be covered for the transportation of the BEST system i_{best} .
- n_{dist}^0 represents the distance between adjacent buses,
- $n_{dist,j}^{best}$ denotes the non-dimensional ‘bus distance’ between operating conditions j and $j+l$ of the BEST system i_{best} ,
- n_j^{best} represents the bus number of the BEST system i_{best} in operating condition j ,
- n_0^{best} is the number of operating conditions where the BEST system i_{best} is not used, and
- $n_{0,j}^{best}$ indicates whether the BEST system i_{best} is operative in operating condition j .

Note that with this BEST model, we allow the BEST displacement not only between two adjacent buses but any two buses of the area of interest.

C. BES model

Constraints (17) enforce the energy limits for the stationary storage systems in each time period and operating condition.

$$Y_{i_{bes}} S_0^{i_{bes}} + \sum_{t=1}^{t_n} (\eta_{ch}^{i_{bes}} P_{i_{bes},j,t}^{bes,ch} - P_{i_{bes},j,t}^{bes,dis} / \eta_{dis}^{i_{bes}}) \tau \geq Y_{i_{bes}} S_{min}^{i_{bes}}$$

$$Y_{i_{bes}} S_0^{i_{bes}} + \sum_{t=1}^{t_n} (\eta_{ch}^{i_{bes}} P_{i_{bes},j,t}^{bes,ch} - P_{i_{bes},j,t}^{bes,dis} / \eta_{dis}^{i_{bes}}) \tau \leq Y_{i_{bes}} S_{max}^{i_{bes}} \quad (17)$$

$$\forall i_{bes}, j, t_n = 1, 2, \dots, T$$

Constraints (18) enforce the stationary storage energy balance per day.

$$\sum_{t=1}^T (\eta_{ch}^{i_{bes}} P_{i_{bes},j,t}^{bes,ch} - P_{i_{bes},j,t}^{bes,dis} / \eta_{dis}^{i_{bes}}) \tau = 0 \quad (18)$$

$$\forall i_{bes}, j$$

Constraints (19) are the charging and discharging bounds for the stationary storage systems.

$$Y_{i_{bes}} P_{min,ch}^{i_{bes}} \leq P_{i_{bes},j,t}^{bes,ch} \leq Y_{i_{bes}} P_{max,ch}^{i_{bes}} \quad (19)$$

$$Y_{i_{bes}} P_{min,dis}^{i_{bes}} \leq P_{i_{bes},j,t}^{bes,dis} \leq Y_{i_{bes}} P_{max,dis}^{i_{bes}} \quad \forall i_{bes}, j, t$$

Constraints (20) enforce the reserve content bounds for the stationary storage systems in each time period and operating condition.

$$0 \leq r_{i_{bes},j,t}^{bes} \leq P_{max}^{i_{bes}} Y_{i_{bes}} + \eta_{ch}^{i_{bes}} P_{i_{bes},j,t}^{bes,ch} - P_{i_{bes},j,t}^{bes,dis} / \eta_{dis}^{i_{bes}} \quad (20)$$

$$r_{i_{bes},j,t}^{bes} \tau \leq SOC_{i_{bes},j,t}^{bes} - S_{min}^{i_{bes}} Y_{i_{bes}} \quad \forall i_{bes}, j, t$$

where

$$SOC_{i_{bes},j,t}^{bes} = Y_{i_{bes}} S_0^{i_{bes}} + \sum_{it=1}^t (\eta_{ch}^{i_{bes}} P_{i_{bes},j,it}^{bes,ch} - P_{i_{bes},j,it}^{bes,dis} / \eta_{dis}^{i_{bes}}) \tau \quad (21)$$

It is worth noting that BES model differs from the one related to BEST for constraints (7) and (8) and for the operation cost, i.e. equations (11)-(16), which is addressed for the mobile storage system only.

D. TEP and Network constraints

The energy balance at each node of the system is represented in constraint (22).

$$\sum_{i \in \Omega_{ib}^l} P_{i,j,t}^{gen} + \sum_{w \in \Omega_{ib}^w} P_{w,j,t}^{wind} + \sum_{pv \in \Omega_{ib}^{pv}} P_{pv,j,t}^{solar} - \sum_{l \in \Omega_{ib}^l} F_{l,j,t} + \sum_{l \in \Omega_{ib}^l} F_{l,j,t} + \sum_{i_b \in \Omega_{ib}^{best}} (P_{i_{best},i_b,j,t}^{best,dis} - P_{i_{best},i_b,j,t}^{best,ch}) + \sum_{i_{bes} \in \Omega_{ib}^{best}} (P_{i_{bes},j,t}^{dis} - P_{i_{bes},j,t}^{ch}) = L_{i_b,j,t} - L_{i_b,j,t}^{shed} \quad \forall i_b \quad (22)$$

Constraints (23) and (24) include the DC power flow for existing and prospective lines in each time period and operating condition.

$$F_{l,j,t} - (\mathcal{G}_{i_{b1},j,t}^l - \mathcal{G}_{i_{b2},j,t}^l) / x_l = 0 \quad (23)$$

$$\forall l \in \Omega_{LE}, j, t = 1, 2, 3, \dots, T$$

$$-M(1 - X_l) \leq F_{l,j,t} - (\mathcal{G}_{i_{b1},j,t}^l - \mathcal{G}_{i_{b2},j,t}^l) / x_l$$

$$F_{l,j,t} - (\mathcal{G}_{i_{b1},j,t}^l - \mathcal{G}_{i_{b2},j,t}^l) / x_l \leq M(1 - X_l) \quad (24)$$

$$\forall l \in \Omega_{LC}, j, t = 1, 2, 3, \dots, T$$

Constraint (25) enforces the transmission capacity limits for existing and prospective lines, respectively.

$$-F_l^{max} \leq F_{l,j,t} \leq F_l^{max} \quad (25)$$

$$\forall l \in \Omega_{LE}, j, t = 1, 2, 3, \dots, T$$

$$-X_l F_l^{max} \leq F_{l,j,t} \leq X_l F_l^{max}$$

$$\forall l \in \Omega_{LC}, j, t = 1, 2, 3, \dots, T$$

Constraints (26), (27) and (28) refer to the production bounds of thermal units, wind units and solar ones, respectively.

$$P_i^{gen,min} \leq P_{i,j,t}^{gen} \leq P_i^{gen,max} \quad (26)$$

$$\forall i, j, t = 1, 2, \dots, T$$

$$0 \leq P_{w,j,t}^{wind} \leq P_{w,j,t}^f \quad (27)$$

$$\forall w, j, t = 1, 2, \dots, T$$

$$0 \leq P_{pv,j,t}^{solar} \leq P_{pv,j,t}^f \quad (28)$$

$$\forall pv, j, t = 1, 2, \dots, T$$

Constraints (29) enforce the load shedding bound, when allowed.

$$0 \leq L_{i_b,j,t}^{shed} \leq L_{i_b,j,t} L_{param}^{shed} \quad (29)$$

$$\forall i_b, j, t = 1, 2, \dots, T$$

Spinning reserve requirement are satisfied with constraints (30) in each time period and operating condition.

$$\sum_i (P_{i,j,t}^{gen,max} - P_{i,j,t}^{gen}) + \sum_w (P_{w,j,t}^f - P_{w,j,t}^{wind}) + \sum_s (P_{s,j,t}^f - P_{s,j,t}^{solar}) + \sum_{i_{best}} r_{i_{best},j,t}^{best} + \sum_{i_{bes}} r_{i_{bes},j,t}^{bes} \geq R_{j,t} \quad (30)$$

$$\forall j, t$$

It is worth mentioning that a preliminary simplified version of the model above proposed can be found in [20].

E. Problem Solving

Initially, we tackled the optimization problem by expressing the investment cost of stationary and mobile storage units through binary variables. Subsequently, when increasing the complexity of

the mathematical model due to the introduction of spinning reserve, we had to relax these binary variables and turn them into continuous ones, in order to achieve the numerical solutions in a reasonable computational time. It is worth noting that this provides as output also the size of both stationary and transportable storage units and not only their locations.

Further, as earlier mentioned in Section III.B, the methodology we propose presents a novel mathematical approach for the transportable storage systems scheduling, which allows us to avoid the inclusion of additional binary variables, and therefore to decrease the complexity of the problem. To accomplish that, we have made use of the NZ function, which output is the number of nonzero elements of a generic input matrix. The application of NZ function allowed us to add two constraints only, and, to successfully implement the scheduling of each transportable storage systems, which we feel represents a novel contribution to the subject. The reason for using NZ operator is further based on the fact that while in general a non-convex problem cannot be turned into a convex one, it can be transformed into a MILP problem. For our case, the feasible region being non-continuous, we can only model efficiently it through non-convex terms. It is worth noting that, on the other hand, sometimes having more constraints reduces the feasibility region of the problem and may accelerate the calculation speed, but this applies to LP problem, while for MILP problem the discussion is still open and it might be true the opposite, namely that less constraints may help, as it can be inferred from [21] and [22].

To accomplish the model implementation, we identified Matlab environment with Yalmip interface as the most suitable set that allows us to analyze more complex cases than those dealt with so far in the literature. Within that environment it was possible to use Gurobi as a solver. Gurobi is chosen for the case study because it allows us to adopt easily the proper resolution gap, achieving a suitable trade-off between resolution time and precision.

IV. CASE STUDIES

A. HRP-38 system description

In this section, the proposed High Renewable Penetration (HRP)-38 test system, deeply investigated in [18] and based on a regional power system in China, is presented. The HRP-38 system, shown in Fig. 1, operates at 750 kV according to the reality. Four power generation technologies are considered in the HRP-38 system: thermal units, hydro, photovoltaics (PV) and wind turbines.

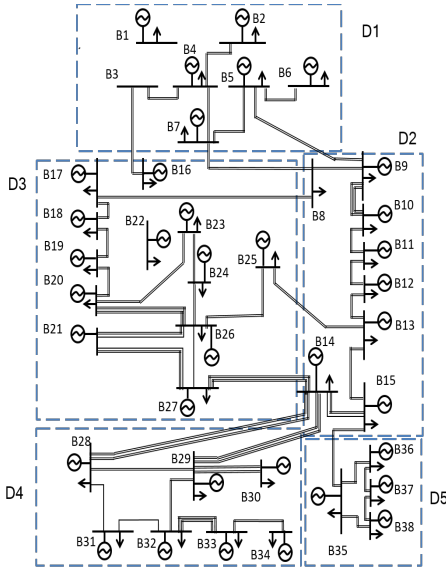
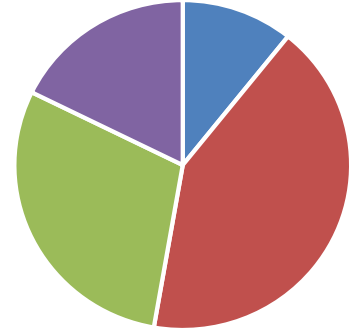


Fig. 1 HRP-38 test system

Both wind and PV output data are simulated considering the bus location and statistics of variable renewable energy in real power system, by means of GOPT power system analysis software [18]. TABLE I includes the data related to each regional area of the proposed HRP-38 test system and Fig. 2 shows its generation mix.

TABLE I
DATA OF HRP-38 TEST SYSTEM

Installed Capacity (MW)	D1	D2	D3	D4	D5	Total
Hydro	18000	12000	31000	6000	0	67000
Thermal	140500	22500	15000	49600	34000	261600
Solar	52800	32100	54600	22200	22200	183900
Wind	48000	36600	6000	9000	10800	110400
Total	259300	103200	106600	86800	67000	622900
Peak Load (MW)	1110000	51000	27000	72000	39000	300000



■ Hydro ■ Thermal ■ Solar ■ Wind

Fig. 2 Generation mix of HRP-38 test system

In order to achieve solutions in a reasonable computational time, the following simplifications are adopted:

- All the lines n_l with a reactance X_l and an investment cost C_l^{line} in the same corridor were grouped considering just 1 line whose reactance and annualized investment cost are, respectively:

$$X_T = \frac{1}{\sum_{l=1}^{n_l} \frac{1}{X_l}}$$

$$C_l^{line} = \sum_{l=1}^{n_l} C_l^{line}$$

- All the $n_{k,i}$ generators of the same type in the same bus i were grouped considering just 1 generator whose generation power is:
- $$P_{T_i} = \sum P_{k_i}$$
- Considering conventional units, the operating costs are the weighted average of the operating costs of all the units which is composed by.

TABLE II and TABLE III include data of BES and BEST candidates, respectively.

TABLE II
CANDIDATE BES DATA FOR THE HRP-38 SYSTEM

$p_{max,dis}^{ibes}$ [MW]	$p_{max,ch}^{ibes}$ [MW]	S_{min}^{ibes} [MWh]	S_{max}^{ibes} [MWh]	η_{ch}^{ibes}	η_{dis}^{ibes}
600	600	120	1200	0.9	0.9

TABLE III
CANDIDATE BEST DATA FOR THE HRP-38 SYSTEM

$P_{\max,dis}^{i,best}$ [MW]	$P_{\max,ch}^{i,best}$ [MW]	$S_{\min}^{i,best}$ [MWh]	$S_{\max}^{i,best}$ [MWh]	$\eta_{ch}^{i,best}$	$\eta_{dis}^{i,best}$
350	350	70	700	0.9	0.9

The investment cost of BES and BEST is the sum of the cost related to the battery storage system power capacity, including all the electronic equipment, and the cost related to the energy capacity of the device. These costs, annualized with a life cycle equal to 15 years and a discount rate (WACC) of 10%, are respectively set equal to 300 kCNY/MW and 55 kCNY/MWh, which is an assumption based on the fact that the cost for Lithium Ferro Phosphate (LFP) storage system [23] will be continuously and significantly dropping as the technology is fast developing and spreading. Also, it is worth noting that we are disregarding possible penalties on renewable energy curtailment that would render the use of BES and BEST even more convenient.

In the following sections, namely Section IV.B and Section IV.C, two study cases are presented and applied to the HRP-38 system: the first one allows for the investigation of stationary and mobile storage systems position, while the second one permits also to identify the optimal size of both BES and BEST.

B. Case I: Allocating position of BES and BEST

The simulations are performed according to the following settings and assumptions:

- Load Shedding is allowed.
- The spinning reserve requirement is neglected.
- BES and BEST decision variables, i.e. Y_{bes} and V_{best} , are set as binary variables. Only storage position is allocated.
- The number of operating conditions, selected to reproduce the most representative days of the year, is set equal to 12, therefore each month is represented by one operating day.
- All the candidate storage systems are Lithium iron Phosphate (LFP) batteries.
- In agreement with (3) the BEST transportation cost is addressed through the value of $K_{dist}^{i,best}$, which is set equal to 760 CNY/km in the case under study.
- The distance between adjacent buses, n_{dist}^0 , is set equal to 100 km.
- The initial storage systems state of charge is set equal to the half of their maximum energy content, i.e. $S_0^{i,best} = 0.5 S_{\max}^{i,best}$ and $S_0^{i,bes} = 0.5 S_{\max}^{i,bes}$.
- Regarding $P_{\min,ch}$ and $P_{\min,dis}$ of both stationary and transportable storage systems, they are set equal to zero.
- In this case study, Gurobi is chosen as a solver, and the resolution gap is set equal to 2%.
- The number of BESs candidate is set equal to 10, therefore there are 2 stationary storage systems candidates for each area of the system.
- The number of BESTs candidate is set equal to 1 due to the complexity of the model implementation, and BEST is restricted in a specific area of the network.

The last assumption means that we have set five different sub-cases, each one restricting BEST within one of the five regional areas only. A benchmark case, which does not have BEST available, is also included.

TABLE IV shows the simulations result for *case I*, which we are dealing with.

The results show that allocating storage systems position, BEST is part of the optimal set of investment for any sub-case analyzed, whatever the area of mobility. As shown in TABLE IV,

BEST installation brings several advantages, such as the decreasing of load shedding of about 30%, the reduction of the total cost of 0.4% and the decrease of wind and solar energy curtailment of 35% and 8%, respectively. Comparing the most convenient BEST, namely the one restricted in area 2, with another sub-case, e.g. BEST restricted in area 4, load shedding is around 40% less and VRE curtailment is about 15% lower.

TABLE IV
CASE I SIMULATIONS RESULTS
(most convenient solutions are denoted with bold fonts)

	BEST in Area 1	BEST in Area 2	BEST in Area 3	BEST in Area 4	BEST in Area 5	No BEST candidate
Total cost [10 ⁹ CNY]	175.4	175.0	175.3	175.3	175.1	175.7
Investment cost [10 ⁹ CNY]	5.1	5.1	4.8	4.6	4.9	4.5
Operation cost [10 ⁹ CNY]	170.3	169.9	170.5	170.7	170.2	171.2
Operation BEST cost [10 ⁶ CNY]	4.6	3.0	5.2	3.0	1.6	-
BESs [-]	4	4	4	3	3	4
BEST [-]	1	1	1	1	1	-
Load Shedding [10 ⁶ MWh]	0.04	0.03	0.04	0.05	0.04	0.04
Wind Curtailment [10 ⁶ MWh]	11.4	7.9	9.8	11.0	11.1	12.2
Solar Curtailment [10 ⁶ MWh]	25.6	29.4	31.9	33.0	31.8	31.9

Fig. 3 shows the operation of both stationary and transportable storage systems in the transmission network under study through the power profile of: a) the total satisfied demand minus the total generation, b) the total BESs discharge power minus the total BESs charge power, and c) BEST discharge power minus BEST charge power.

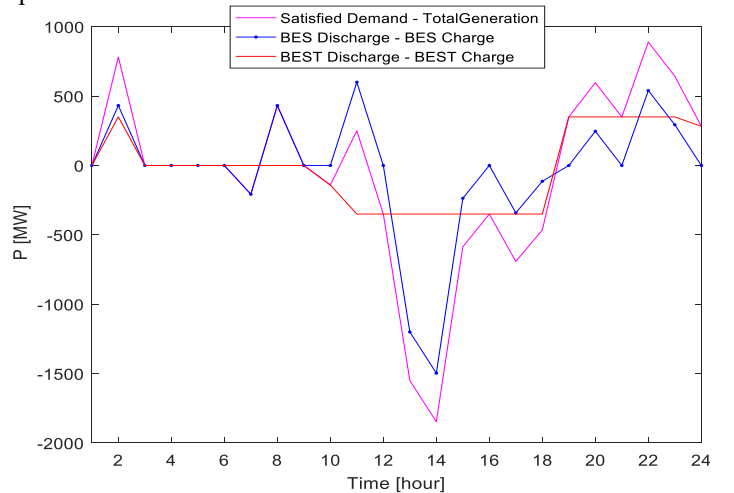


Fig. 3 Case I power profile of: a) demand satisfied - total generation, b) total BESs discharge power - total BESs charge power, and c) BEST discharge power - BEST charge power, in one operating condition..

Fig. 4 and Fig. 6 show the BEST usefulness among the two above-mentioned areas of the HRP-38 system in terms of renewable power curtailment and load shedding, through the trend of the renewable curtailment power profile and the load shedding profile respectively. Fig. 5 illustrates the renewable curtailment of each operating condition, which in our case study corresponds to the representative day of each month. Regarding the correlation between load shedding and operating conditions, the uncovered load is concentrated in the last operating condition only, which reflects the trend of the last month of the year.

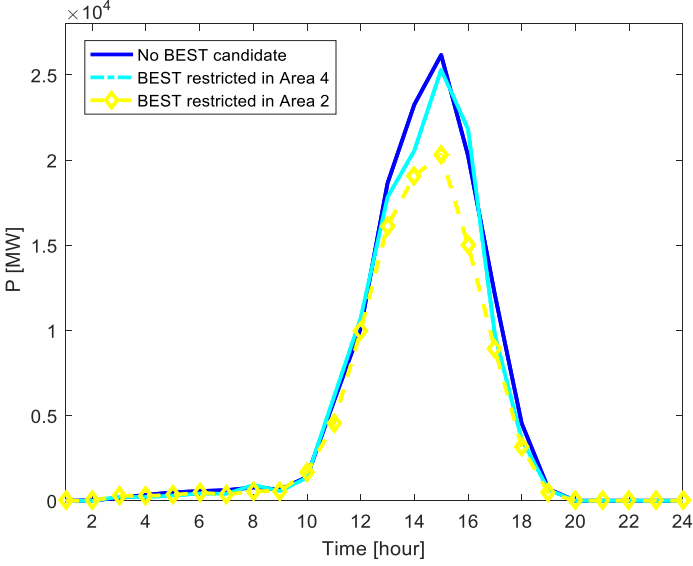


Fig. 4 Case I renewable curtailment comparison

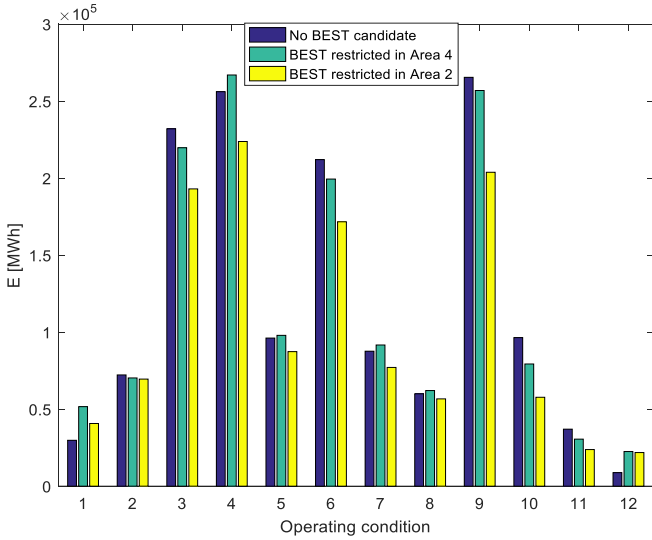


Fig. 5 Case I renewable curtailment in each operating condition

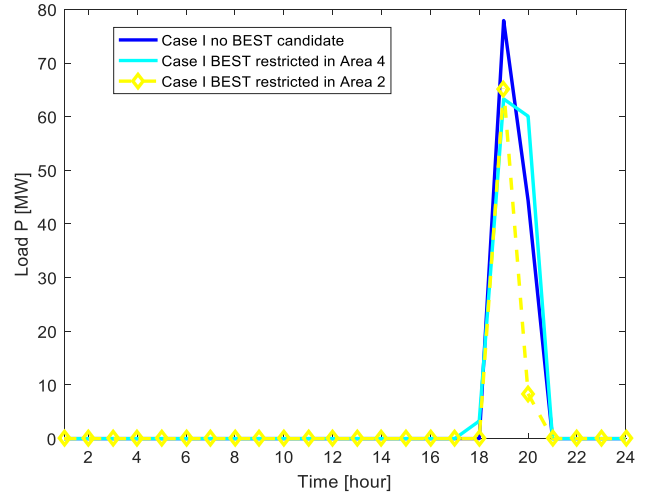


Fig. 6 Case I load shedding comparison

Fig. 7 shows the location of the BEST device in each operating condition and for each area of mobility of the power system under study.

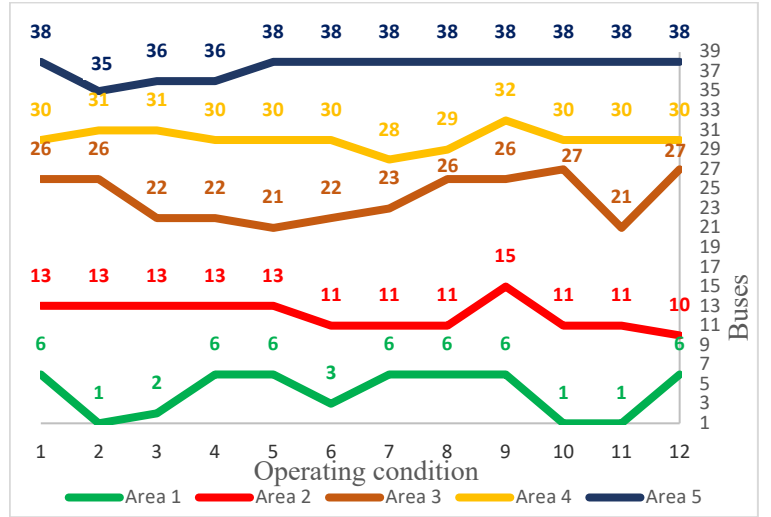


Fig. 7 Case I: BEST position in each operating condition

C. Case II: Allocating position and size of BES and BEST

Dealing with BES and BEST position and size allocation, some further settings and assumptions are considered, in addition to those relevant to Case I:

- The spinning reserve requirement is allocated.
- BES and BEST decision variables, i.e. $Y_{i_{bes}}$ and $V_{i_{best}}$, are set as continuous functions, so that also storage systems size can be determined.
- In agreement with (3) the BEST transportation cost is addressed through the value of $K_{dist}^{i_{best}}$, which is set equal to 45 CNY/km in the case under study.
- For this case, the value of $C_{i_{best}}^{i_{best}}$ in (3) is fixed and it is assumed to be equal to 2.1 MCNY.

TABLE V summarizes the simulations results of the same sub-cases of TABLE IV but refers to the case where both size and position of storage systems are allocated.

TABLE V does not include the load shedding quantity because allocating storage systems size and position, load shedding is equal to zero in all scenarios investigated.

Comparing TABLE IV and TABLE V, one can infer that in case II the total storage systems installed capacity is larger and concentrated in fewer nodes than for the previous study case. Such

a result causes the total cost reduction and the load shedding equal to zero because it allows to set the most convenient size of each device in each bus of the network.

In *case II*, the suitable areas for BEST are different from the ones of *case I*; this is due to the fact that in *case II*, it is allowed to choose the most convenient size of the storage systems in each bus of the network, and therefore for some areas, like area 1, 3 and 5, BESs is more convenient. Nevertheless as shown in TABLE IV and TABLE V, the most convenient BEST is the one restricted in area 2 for both the cases investigated.

TABLE V
CASE II SIMULATIONS RESULTS
(the most convenient solution is denoted with bold fonts)

	BEST in Area 1	BEST in Area 2	BEST in Area 3	BEST in Area 4	BEST in Area 5	No BEST candidate
Total cost [10 ⁹ CNY]	174.5	174.1	174.4	174.5	175.5	174.4
Investment cost [10 ⁹ CNY]	4.5	5.0	4.8	4.9	5.6	4.9
Operation cost [10 ⁹ CNY]	170.0	169.1	169.5	169.6	169.9	169.5
Operation BEST cost [10 ⁶ CNY]	-	0.4	-	0.06	-	-
BESs [-]	4 (6.2 GWh)	2 (5.0 GWh)	2 (6.0 GWh)	2 (4.7 GWh)	2 (7.0 GWh)	4 (6.2 GWh)
BEST [-]	-	1 (1.2 GWh)	-	1 (2.2 GWh)	-	-
Wind Curtailment [10 ⁶ MWh]	10.8	11.9	12.4	11.6	12.0	12.3
Solar Curtailment [10 ⁶ MWh]	30.9	31.3	28.4	30.3	31.4	30.4

Fig. 8 shows the operation of both stationary and transportable storage systems in the transmission network under study through the power profile of: a) the total satisfied demand minus the total generation, b) the total BESs discharge power minus the total BESs charge power, and c) BEST discharge power minus BEST charge power. Comparing such trends with those of Fig. 3, it can be inferred that in *case II* storage systems have a more relevant impact in the system under study.

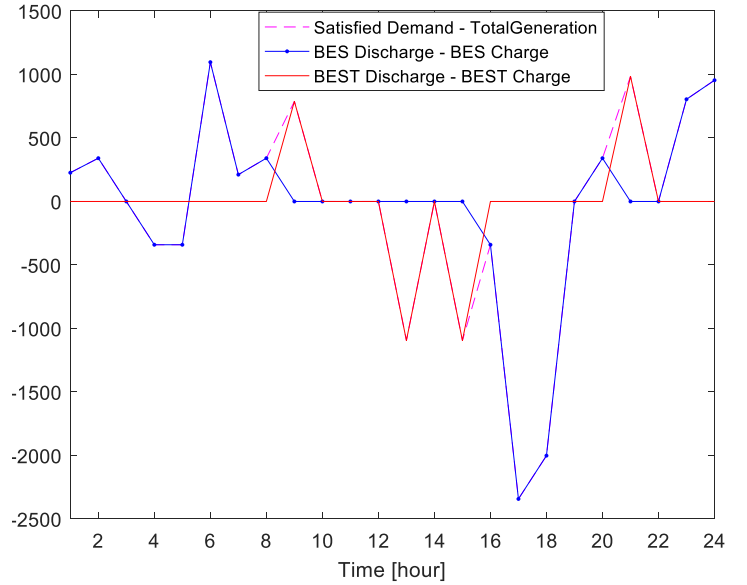


Fig. 8 Case II power profile of: a) demand satisfied - total generation, b) total BESs discharge power - total BESs charge power, and c) BEST discharge power - BEST charge power, in one operating condition.

Fig. 9 and Fig. 10 show the total VRE curtailment of BEST restricted in area 2 and area 4, compared with the benchmark scenario. BEST investment causes the decrease of VRE energy curtailment with respect to the benchmark scenario in few sub-cases only. Indeed, in this study case the size of storage systems is a variable in the optimization problem and compared to *case I* the benchmark scenario provides a reduction of both the total cost and the VRE curtailment. However, the transportable storage system may not bring a considerable further reduction of the VRE curtailment, because in this study it is not economically penalized.

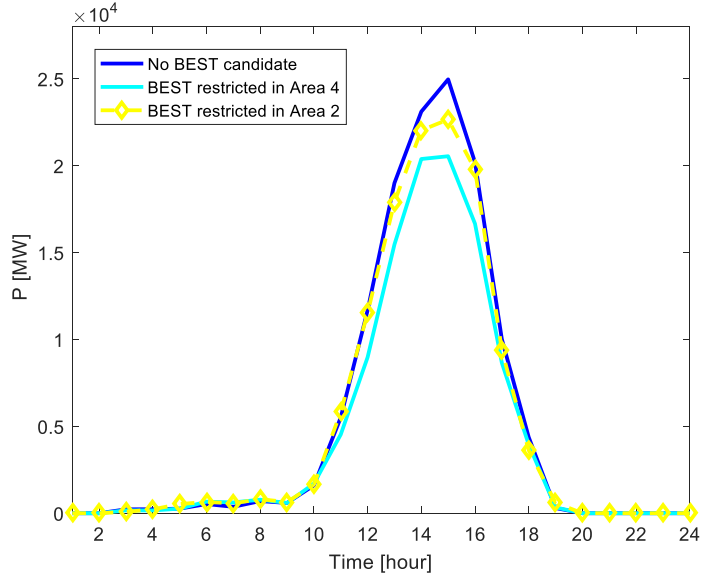


Fig. 9 Case II variable renewable curtailment comparison

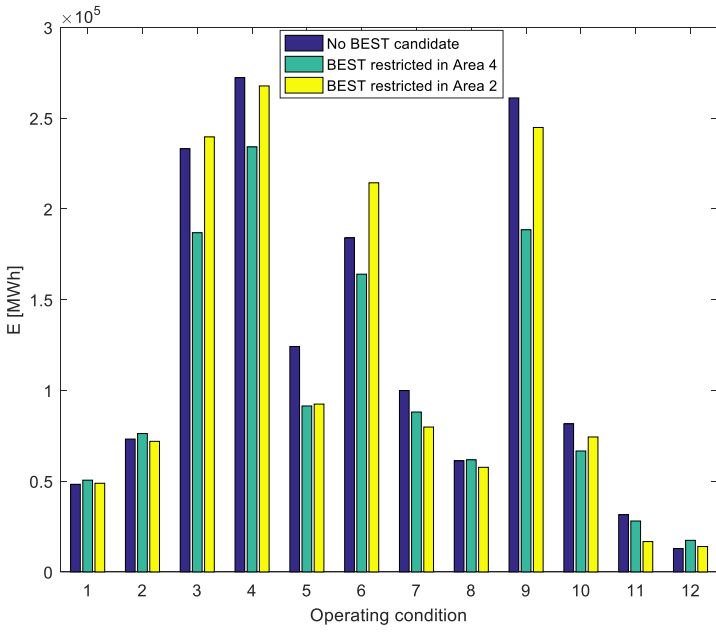


Fig. 10 Case II renewable curtailment in each operating condition

BEST position in each operating condition is shown in Fig. 11 for both the areas of interest, namely Area 2 and Area 4. When BEST is allowed to move among buses of the most convenient area of the network, i.e. Area 2, it changes its position almost every operating day and that reflects the transportable storage usefulness in that area.

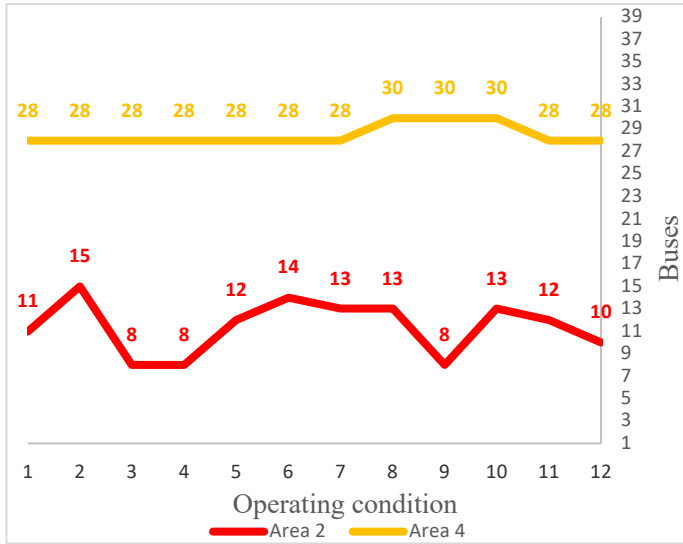


Fig. 11 Case II: BEST position in each operating condition

D. Scalability of the Proposed Model

In this section the proposed model is applied to a 190-bus test system to analyse its scalability to a larger system with larger renewable energy penetration. As shown in Fig. 12 the proposed system is given by the interconnection of five HRP-38 systems. The generation and network settings in each area are the same with the settings in Section IV.A; the 190-bus system consists of 295 generators and 369 lines (275 existing lines plus 94 candidate ones).

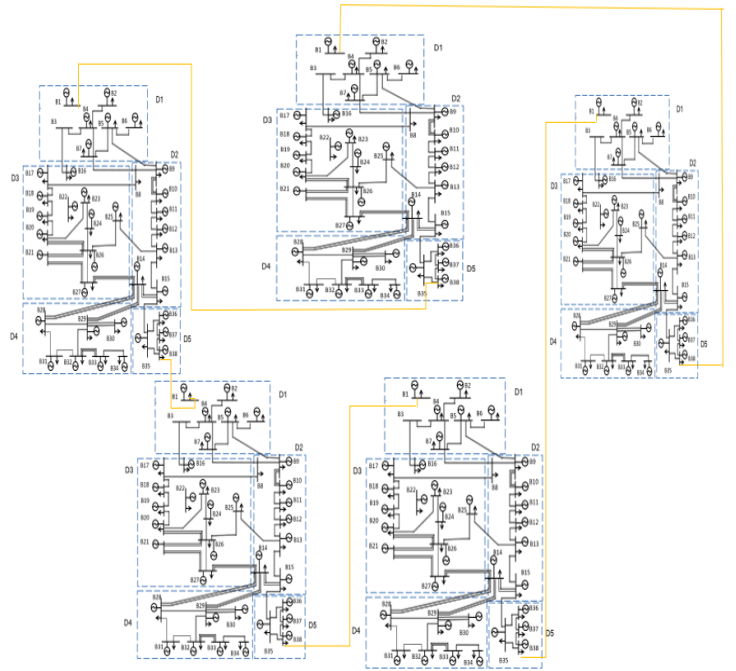


Fig. 12 190-bus test system

Study cases of Section IV.B and Section IV.C, namely Case I and Case II, are analyzed in the proposed 190-bus test system. Relevant results are provided in TABLE VI and refer to the case where BEST is restricted in a specific area of the network, i.e. area 2 of the “first” HRP-38 system.

TABLE VI
190-BUS SYSTEM SIMULATIONS RESULTS

	Case I	Case II
Total cost [10 ⁹ CNY]	966.2	940.5
Investment cost [10 ⁹ CNY]	11.2	20.4
Operation cost [10 ⁹ CNY]	955.0	920.1
Operation BEST cost [10 ⁶ CNY]	4.1	0.2
BESs [-]	5	5 (47.8 GWh)
BEST [-]	1	1 (7.7 GWh)
Wind Curtailment [10 ⁶ MWh]	90.7	90.1
Solar Curtailment [10 ⁶ MWh]	187.0	190.3

The obtained results show that even for the larger network the most convenient solution is reached when allowing the identification of both optimal size and position of the storage devices.

V. CONCLUSIONS

This paper has addressed the long-term transmission planning problem including stationary and transportable battery energy system (BES and BEST, respectively), adopting a novel mathematical approach for the BEST vehicle scheduling problem, which can be suitable for extended portions of large-scale power systems. In particular, the number of non-zero function is included in the optimization model set of constraints, avoiding the use of additional binary variables, as generally accomplished for addressing vehicle scheduling, which would considerably increase the computational burden.

Depending on the variables indicating whether to settle the stationary or transportable battery system, binary or continuous, the model allows us to identify either the storage systems optimal location or both optimal location and size of storage systems.

For our analysis we have used a large portion of network with high renewable penetration, which reproduces the real China system of the Northwestern grid, and that includes five regions and that can be described by an HRP-38 bus network. Finally, in order to show the scalability of the proposed planning model to larger networks, a 190-bus system has been considered.

The model application to the above systems allows us to infer that:

1) BEST system is a suitable alternative to manage transmission congestion in power networks with high penetration of renewable energy.

2) BEST application allows the reduction of renewable energy curtailment almost in all cases and its contribution will be reasonably even more relevant when renewable energy curtailment penalties would be applied. It is worth noting that for one of the examined cases, *case I*, the adoption of BEST results not only in a lower operation cost (1.3 10⁹ CNY), but also in a reduced wind and PV curtailment of 35% and 8% respectively.

3) When technically feasible, both position and size of storage systems should be allocated in the coordinated planning problem.

The proposed approach is more convenient with respect to the case where storage system size has a fixed value, and it allows load shedding to be equal to zero.

The developed methodology can find useful applications also in problems where BEST is investigated as a promising tool for facing emergency situations, and for enhancing power grid resiliency. Moreover, the application of the above-mentioned NZ function can bring interesting benefits also to other optimization problems involving a consistent number of binary variables.

ACKNOWLEDGMENT

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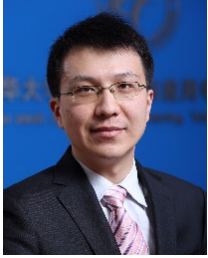
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Giorgia Pulazza (S'19) received the B.Sc. degree in energy engineering from the University of Bologna, Italy, in 2015, and the M.Sc. degree in energy engineering from Politecnico di Torino, Italy, in 2018. She is currently working toward the Ph.D. degree in electrical engineering with the University of Bologna, Italy. Her research interests include renewable energy, storage system, power system planning and operation, and local energy communities.



Ning Zhang (S'10–M'12–SM'18) received the B.S. and Ph.D. degrees from the Electrical Engineering Department, Tsinghua University, China, in 2007 and 2012, respectively, where he is now an Associate Professor. His research interests include multiple energy system integration, renewable energy, and power system planning and operation.



Chongqing Kang (M'01–SM'07–F'17) received the Ph.D. degree from Tsinghua University, Beijing, China, in 1997. He is currently a Professor with Tsinghua University. His research interests include low-carbon electricity, power system planning, renewable energy, power markets, and power system load forecasting.



Carlo Alberto Nucci (M'91–SM'02–F'07) graduated with honors in electrical engineering from the University of Bologna, Bologna, Italy, in 1982. He is a Full Professor and Head of the Power Systems Laboratory of the Department of Electrical, Electronic and Information Engineering “Guglielmo Marconi”, University of Bologna. He is an author or coauthor of over 370 scientific papers published in peer-reviewed journals or in proceedings of international conferences. Prof. Nucci is a Fellow of the IEEE and of the International Council on Large Electric Systems (CIGRE), of which he is also an Honorary member, and has received some best paper/technical international awards, including the CIGRE Technical Committee Award and the ICLP Golde Award. From January 2006 to September 2012, he served as Chairman of the CIGRE Study Committee C4 System Technical Performance. He has served as IEEE PES Region 8 Rep in 2009 and 2010. Since January 2010, he serves as Editor-in-Chief of the *Electric Power Systems Research* journal (Elsevier). He has served as the President of the Italian Group of the University Professors of Electrical Power Systems (GUSEE) from 2012 to 2015. He is presently serving as Italian Representative in the Horizon Europe Mission Board Sub-group “Climate-neutral and Smart cities”, and as a member of the Technical Scientific Committee of the Regional Energy Plan of Emilia Romagna Region, Italy. Prof. Nucci is Doctor *Honoris Causa* of the University *Politehnica* of Bucharest and a member of the Academy of Science of the Institute of Bologna. He is also serving as vice-chair of the International Conference on Lightning Protection, ICLP.