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# Benefits of transmission switching and energy storage in power systems with high renewable energy penetration

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## HIGHLIGHTS

- A stochastic programming approach is proposed to model TS and ESS sizing simultaneously.
- The model considers DSM and renewable energy curtailment policies with various limits.
- The effect of TS on total cost, sizes, locations of ESS are discussed.
- We find that TS is noteworthy to analyze for power systems with renewable targets.

## ARTICLE INFO

*Keywords:*
Transmission switching
Renewable energy
Energy storage siting
Energy storage sizing

## ABSTRACT

Increasing the share of renewable energy sources in electricity generation helps address concerns about carbon emissions, global warming and energy security (i.e. dependence on fossil fuels). However, integrating intermittent and variable energy sources into the grid imposes new challenges for power system reliability and stability. To use these clean sources in electricity generation without endangering power systems, utilities can implement various control mechanisms, such as energy storage systems, demand side management, renewable energy curtailment and transmission switching. This paper introduces a two-stage stochastic programming model that co-optimizes transmission switching operations, and transmission and storage investments subject to limitations on load shedding and curtailment amounts. We discuss the effect of transmission switching on the total investment and operational costs, siting and sizing decisions of energy storage systems, and load shedding and renewable energy curtailment in a power system with high renewable penetration. An extensive computational study on the IEEE 24-bus power system with wind and solar as available renewable sources demonstrates that the total cost and total capacity of energy storage systems can be decreased up to 17% and 50%, respectively, when transmission switching is incorporated into the power system.

## 1. Introduction

### 1.1. Motivation

In the last two decades, the electricity industry experienced major changes. Increasing concerns about the environment and energy security reveal the necessity of using clean and sustainable energy resources in electricity generation. To encourage new investments to use more renewable energy sources (RESes), utilities implement policies such as feed-in tariffs, carbon taxes and/or renewable portfolio standards [1], and as a result, a 19% share of RESes in meeting world electricity demand in 2000 increased to 24% in 2016 [2]. Improvements such as this help reduce carbon emissions and dependence on fossil fuels. However, increased penetration of RESes can lead to high variability and uncertainty in electricity generation as these sources are intermittent and dependent on atmospheric conditions and spatial locations. Low predictability and variability of electricity generation from RESes can cause difficulties in sustaining a load-energy balance and/or power frequency in a grid, and thus can impose new challenges around power system reliability and stability. To continue utilizing these clean sources without endangering power system reliability, utilities implement various control mechanisms such as energy storage systems (ESSes), demand-side management (DSM), renewable energy curtailment (REC) and transmission switching (TS).

Energy storage systems are the most effective solutions for integrating RESes into the grid. These systems smooth the intermittency of RESes by storing electrical energy generated at off-peak hours to use at peak hours, and thus more electricity can be generated from RESes

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**Nomenclature**

*Sets*

| | |
|---|---|
| $B$ | set of buses, indexed by $i$, $j$ |
| $C$ ($C_R$) | set of all (renewable) generation units, indexed by $g$ |
| $A$ ($EA$) | set of all (existing) lines, indexed by $a$ |
| $AS_{ij}$ | set of lines between buses $i$ and $j$ |
| $T$ | set of hours of a scenario, indexed by $t$ |
| $S$ | set of scenarios, indexed by $s$ |
| $\Psi^{+}(a)$ ($\Psi^{-}(a)$) | sending-end (receiving-end) bus of line $a$ |

*Parameters*

| | |
|---|---|
| $D_{its}$ | demand of bus $i$ at hour $t$ of scenario $s$ (MW) |
| $\overline{G}_{igts}$, ($\underline{G}_{igts}$) | maximum (minimum) generation limits from unit $g$ in bus $i$ at hour $t$ of scenario $s$ (MW) |
| $R_g^{up}$ ($R_g^{down}$) | ramp-up (ramp-down) rate of unit $g$ |
| $c_g^{om}$ | operation cost of unit $g$ ($/MWh) |
| $\overline{F_a}$ | capacity of line $a$ (MW) |
| $c_a^{line}$ | annualized investment cost of candidate line $a$ ($) |
| $\varphi_a$ | susceptance of line $a$ (p.u.) |
| $\overline{E}$, ($\underline{E}$) | maximum (minimum) energy capacity of energy storage systems (ESS) (MWh) |
| $\overline{P}$, ($\underline{P}$) | maximum (minimum) power rating of ESS (MW) |
| $c^E$ | annualized investment cost of ESS for energy capacity ($/MWh) |
| $c^P$ | annualized investment cost of ESS for power rating ($/MW) |
| $c^d$ | discharging (or ageing) cost of ESS ($/MW) |
| $\eta$ | charging/discharging efficiency of ESS |
| $\alpha$ | energy-power ratio of ESS |
| $E_0$ | initial energy level of ESS |
| $\sigma_s$ | probability of scenario $s$ |
| $NS$ | number of days in the target year |
| $\tau$ | maximum number of switchable lines |
| $p^{ls}$ | ratio of load that can be shed to total load |
| $p^{rec}$ | ratio of renewable generation that can be curtailed to total generation |

*Decision variables*

| | |
|---|---|
| $L_a$ | 1 if candidate line $a$ is built, 0 o.w. |
| $Y_i$ | 1 if ESS is built at bus $i$, 0 o.w. |
| $Y_i^E$ | energy capacity of ESS at bus $i$ |
| $Y_i^P$ | power rating of ESS at bus $i$ |
| $P_{its}^c$ | charging rate of ESS at bus $i$ at hour $t$ of scenario $s$ |
| $P_{its}^d$ | discharging rate of ESS at bus $i$ at hour $t$ of scenario $s$ |
| $X_{its}$ | status of ESS at bus $i$ at hour $t$ of scenario $s$, 1 is for charging/0 is for discharging |
| $E_{its}$ | state of charge of ESS at bus $i$ at hour $t$ of scenario $s$ |
| $G_{igts}$ | power generation of unit $g$ in bus $i$ at hour t of scenario $s$ |
| $DS_{its}$ | load shedding amount at bus $i$ at hour $t$ of scenario $s$ |
| $f_{ats}$ | power flow on line $a$ at hour $t$ of scenario $s$ |
| $Z_{ats}$ | 1 if line $a$ is closed at hour $t$ of scenario $s$, 0 if it is open |
| $\theta_{its}$ | voltage angle of bus $i$ at hour $t$ of scenario $s$ |

and a substantial decrease in greenhouse gas emissions can be achieved.

Demand-side management is another control mechanism that helps utilities reduce demand at peak hours (referred to as load shedding (LS) in this paper) or reshape load profiles [3]. Efficient DSM can also reduce the need for peaking power plants and/or under-utilized electrical infrastructures, which can have high investment and operational costs. However, reducing demand at peak hours intentionally affects quality of life. Therefore, a penalty cost (*value of loss load*) is generally considered to compensate for the impact of cutting electricity [4].

Renewable energy curtailment is also used to handle RES variability. With an increase in RES penetration, a significant amount of renewable energy could be curtailed due to technical and operational reasons to maintain system voltage and frequency levels or to satisfy minimum generation requirements from thermal sources [5]. However, by lowering RES supply, the benefits of using clean sources and revenues from renewable generators are reduced. Thus, to promote new investments in sustainable energy, in some markets, revenue losses from renewable energy generators are sometimes compensated for in some contracts/policies [6,7].

Transmission switching is another control mechanism that adds flexibility to the grid. Transmission congestion, which is another reason for low RES shares in electricity generation, can be prevented by changing the status of transmission lines [8]. Thus, by applying TS operations (switching some lines out of service), RES penetration can be easily increased. Reducing congestion on transmission lines may also improve the efficiency of other components (e.g. generation units) or other control mechanisms, such as ESS, LS and REC. Making optimal siting and sizing decisions for ESS by considering TS operations can decrease the total investment cost of ESS. In addition, efficient DSM policies can be applied with the integration of TS, and thus LS, which is due to transmission congestion, can be minimized. Last but not least, as REC can be a significant waste, especially for countries that have renewable energy targets (such as Australia, Turkey, Brazil and Ireland [9,10]), TS can be a more efficient and cheaper solution compared to building new lines or more expensive ESSes. Therefore, considering TS in power system strategic and/or operational planning leads to higher social welfare by decreasing overall costs, enhancing quality of life and utilizing cleaner sources in electricity generation.

### 1.2. Literature review

Energy storage systems are effective solutions to the need for cleaner energy sources in electricity generation [4]. The value of ESSes has been increasingly discussed in the literature from different perspectives. Most studies focus on system operation and determine the ESS' state of charge (SOC) for each time period [11]. In these studies, given the locations and sizes of the storage units, the aim is to maximize profit by bidding/selling operations in energy markets. However, these studies ignore the effect of ESS locations and sizes (e.g. [12]). To address this deficiency, other studies consider ESS locations and operations simultaneously for multi-stage [13], robust [14] and long-term [15] planning problems. There are also a few studies that optimize only ESS sizes under demand and generation uncertainties [16].

To fully reveal the benefits of ESSes, their siting and sizing decisions should be considered simultaneously during the planning stage; however, few papers focus on this co-optimization. Pandžić et al. [11] propose a three-stage heuristic algorithm to solve the co-optimized problem. Wogrin and Gayme [17] analyze ESS sizes for different technology types, such as pumped storage hydro, compressed-air energy storage, lithium ion batteries and fly-wheel energy storage, and conclude that the ESS sizes and locations are affected by technology type. Fernáandez-Blanco et al. [18] examine the effect of REC penalty costs and the capital costs of storage units on optimal ESS locations and sizes. Go et al. [19] assess the value of co-optimizing ESS, generation and transmission expansion planning on the IEEE 24-bus power system. They consider renewable portfolio standards and require a minimum generation from renewable sources. Xiong and Singh [20] limit the budget of ESS investments and discuss the effect of budget on ESS locations. Qiu et al. [21] focus on long-term planning and minimize total system cost considering battery lifetime and degradation.