Coordination of Regulated and Merchant Energy Storage Investments

Kristina Pandžić, *Student Member, IEEE*, Hrvoje Pandžić, *Member, IEEE*, Igor Kuzle, *Senior Member, IEEE*

***Abstract*—Distributed transmission–scale energy storage is becoming economically feasible due to the growing share of renewable generation and cost reduction of specific storage technologies, primarily batteries. Under these circumstances, independent merchants may start investing in storage facilities. On the other hand, system operators, besides investing in transmission lines, may, under certain conditions, invest in storage units as well.**

This paper formulates a trilevel model where the upper–level problem optimizes system operator's transmission line and energy storage investments, middle–level problem determines merchant energy storage investment decisions, while the lower–level problem simulates market clearing process for representative days. After replacing the lower–level problem with its primal–dual equivalent conditions, the middle– and lower–level problems are merged into a mixed integer problem with equilibrium constraints. The resulting bilevel structure is iteratively solved using a cutting plane algorithm.

The proposed formulation is first applied to a six–bus system to present the mechanics of the model and then to the IEEE RTS–96 test system. The results show that even at the low cost of energy storage, the SO still prefers line investments, while merchant investments are driven by the volatility of LMPs. Both the SO and merchant investments increase the social welfare, although this increase is mostly driven by the SO investments.

***Index Terms*—electricity market, energy storage, transmission expansion.**

I. Notation

1) Indices and sets:

- i Index of generating units, from 1 to I.
- k Index of representative days, from 1 to K.
- l Index of transmission lines, from 1 to L, where expansion candidate lines belong to set $\tilde{L}$, $\tilde{L} \subseteq L$.
- n Index of buses, from 1 to N.
- t Index of operating intervals, from 1 to T.
- w Index of wind farms, from 1 to W.

2) Binary variables:

- $u_{n,j}$ Merchant storage expansion decision at bus n.
- v_l SO expansion decision on line l.

3) Continuous primal variables:

- $ch_{k,t,n}$ Charging power of SO storage at bus n during interval t on day k, MW.
- $d_{k,t,n}$ Cleared load at bus n during interval t on day k, MW.
- $dis_{k,t,n}$ Discharging power of SO storage at bus n during interval t on day k, MW.
- $e_n^{\max}$ Energy rating of merchant storage at bus n, MWh.
- e_n^{SOmax} Energy rating of SO storage at bus n, MWh.
- $f_{k,t,l}$ Power flow through line l during interval t on day k, MW.
- $g_{k,t,i}$ Power output of generating unit i during interval t on day k, MW.
- $p_{k,t,n}^{\mathrm{c}}$ Charging of merchant storage at bus n during interval t on day k, MW.
- $p_{k,t,n}^{\mathrm{d}}$ Discharging of merchant storage at bus n during interval t on day k, MW.
- $p_n^{\max}$ Power rating of merchant storage at bus n, MW.
- p_n^{SOmax} Power rating of SO storage at bus n, MW.
- $s_{k,t,n}$ State of charge of merchant storage at bus n during interval t on day k, MWh.
- $s_{k,t,n}^{\mathrm{SO}}$ State of charge of SO storage at bus n during interval t on day k, MWh.
- $ws_{k,t,w}$ Wind spillage of wind farm w during interval t on day k, MW.
- $\theta_{k,t,n}$ Voltage angle at bus n during interval t on day k, rad.

4) Continuous dual variables:

- $\alpha_{k,t,i}^{\min}, \alpha_{k,t,i}^{\max}$ Generator production limits dual variables.
- $\beta_{k,t,i}^{\mathrm{RD}}, \beta_{k,t,i}^{\mathrm{RU}}$ Generator ramp limits dual variables.
- $\delta_{k,t,n}^{\min}, \delta_{k,t,n}^{\max}$ Demand bid limits dual variables.
- $\gamma_{k,t,w}^{\min}, \gamma_{k,t,w}^{\max}$ Wind production limits dual variables.
- $\epsilon_{k,t,n}$ State of charge equation dual variable.
- $\phi_{k,t,n}^{\mathrm{cmin}}, \phi_{k,t,n}^{\mathrm{cmax}}$ Storage charging bids limits dual variables.
- $\phi_{k,t,n}^{\mathrm{dmin}}, \phi_{k,t,n}^{\mathrm{dmax}}$ Storage discharging offers limits dual variables.
- $\phi_{k,t,n}^{\mathrm{smin}}, \phi_{k,t,n}^{\mathrm{smax}}$ Storage state of charge limits dual variables.
- $\epsilon_{k,t,n}^{\mathrm{SO}}$ SO's storage state of charge equation dual variable.
- $\phi_{k,t,n}^{\mathrm{SOcmax}}$ SO's storage charging limit dual variable.
- $\phi_{k,t,n}^{\mathrm{SOdmax}}$ SO's storage discharging limit dual variable.
- $\phi_{k,t,n}^{\mathrm{SOsmax}}$ SO Storage state of charge limits dual variables.
- $\mu_{k,t,l}$ Line flow equation dual variable.
- $\mu_{k,t,l}^{\min}, \mu_{k,t,l}^{\max}$ Line capacity limits dual variables.
- $\lambda_{k,t,n}$ Power balance equation dual variable.

5) Parameters:

- C_l Annualized capital cost of expansion for line l, \$.
- C_n^{b}, C_n^{o} Bidding and offering price of merchant storage at bus n, \$/MWh.
- C_n^{d} Bidding price of load at bus n, \$/MWh.
- C^{e} Annualized energy capital cost of merchant storage, \$/MWh.
- C_i^{g} Energy price offered by generator i, \$/MWh.
- C^{p} Annualized power capital cost of merchant storage, \$/MW.
- C^{SOe} Annualized energy capital cost of SO storage, \$/MWh.
- C^{SOp} Annualized power capital cost of SO storage, \$/MW.
- $D_{k,t,n}^{\max}$ Demand at bus n during interval t on day k, MW.
- $F_l^{\max}$ Flow limit of transmission line l, MW.
- $\Delta F_l^{\max}$ Expansion capacity of transmission line l, MW.

$G_i^{\max}$ Capacity of generator i, MW.
$\overline{IC}^{\text{st}}$ Overall merchant storage investment budget, \$.
$\overline{IC}^{\text{SO}}$ Overall SO storage and line investment budget, \$.
$N^{\tilde{L}}$ Maximum number of new lines.
RD_i Ramp down limit of generator i, MW.
RU_i Ramp up limit of generator i, MWh.
ΔS Storage investment energy increment, MWh.
$U_n^{\max}$ Maximum number of storage increments per bus.
$WG_{k,t,w}^{\text{f}}$ Wind forecast at bus n during interval t on day k, MW.
X_l, ΔX_l Reactance of line l and its expansion adjustment.
$\Delta\tau$ Duration of the operating interval, h.
η^{ch} Storage charging efficiency.
η^{dis} Storage discharging efficiency.
κ Minimum annual profit of merchant–owned storage.
π_k Frequency of representative day k, between 1 and 365.
χ Energy–to–power ratio of storage, h.

II. Introduction

A. Motivation

Energy storage has become one of the pivotal technologies that enables higher integration of non-controllable renewable energy sources. Although energy storage is at an early stage of adoption, its integration is growing spurred by various policies and mandates. However, there is an ongoing debate on the issue of storage ownership and market implications. As elaborated in [1], the 500 MW Lake Elsinore Advanced Pumping Station (LEAPS) plant in Southern California was denied ratebase because of the regulator's (Federal Energy Regulatory Committee) rationing that the system operator's (California ISO) dispatching of LEAPS plant would affect market prices. In other words, LEAPS plant should recover all of its investment cost providing market–remunerated services only.

On the other hand, Italian Transmission System Operator TERNA installed 35 MW of storage in Campania region to deal with congestion caused by wind farms in southern Italy [2]. Italian Regulatory Authority for Electricity Gas and Water allowed this installation as it reduces wind curtailment and thus ensures safety and cost–effective management of the Italian transmission grid.

Considering these two examples, we conclude that energy storage investment can be made by both the system operator (SO)[1] and a merchant, but with significantly different roles. In case of the SO ownership, energy storage can be operated as any other transmission asset, i.e. transmission line, with the only difference that transmission lines transfer electricity in space, while energy storage transfers electricity in time. However, an SO owned energy storage can only be used for non–market services. On the other hand, a merchant–owned energy storage is an active player in the market seeking to maximize its profit and cannot receive any ratebased payments.

[1]In this paper, the term System Operator refers to a regulated company that plans and operates the transmission network, regardless if it is public– or investor–owned.

B. Literature Review

Energy storage investment problem has been assessed in literature from two standpoints. One is the centralized approach, where the goal of energy storage is to provide higher savings in operating cost than its installation cost. This approach can combine SO's energy storage and transmission line investments. The second one is the merchant–owned approach, where the investor seeks to maximize its profit in electricity markets.

A centralized storage investment model that penalizes wind spillage and unserved load within the uncertainty set is formulated in [3]. This two-stage problem, where the storage placement decisions are made at the first stage and system operation is simulated in the second stage, utilizes the column–and–constraint generation algorithm to iteratively approach the solution. This model determines optimal locations of energy storage in predefined capacity blocks. Another centralized energy storage investment model is presented in [4]. First, optimal energy storage location and size is decided for each day of the year individually. The assumption is that the optimal storage locations are the ones chosen most frequently among 365 days. In the second stage, storage investments are allowed only at the preferred locations and an individual day–by–day optimization is performed to determine optimal size of storage for each day. Based on these results, a near–optimal size of energy storage is chosen, e.g. as an average size over all days. The presented case study indicates that the distribution of wind resources has small effect on the overall investment in energy storage, but affects the location and distribution of storage units. As opposed to [3] and [4], where the authors consider each day of the year, centralized storage investment models presented in [5] and [6] consider representative days. The model in [5] determines optimal location and size of energy storage, within the allowed investment budget, accounting for uncertainty of wind generation. Due to complexity of the model, the authors apply multi–cut Benders decomposition. The results indicate that the investment budget should be carefully selected after comparing the investment decisions and resulting savings in operating costs for different investment budgets. In [6], the authors formulate an energy storage investment model and apply it to a realistic case of Western Electricity Coordinating Council (WECC), consisted of 240 buses and 448 lines. The authors report that energy storage operation in the centralized model does not necessarily guarantee profitability of the energy storage investment.

Optimal storage investment problem in market–based power system is examined in [7]. The upper–level problem makes decisions on optimal siting and sizing of merchant–owned energy storage while minimizing the total cost of system operation and investment. The lower–level problem minimizes economic dispatch and considers transmission constraints. The upper–level contains merchant–owned storage minimum profit constraint that forbids investment unless the investor can retrieve satisfactory level of profit. This paper confirms that installation of energy storage yields lower levels of wind spillage and that energy storage may affect locational marginal prices. Sizing of energy storage in market environment is addressed in [8]. The upper–level problem determines optimal storage size and market bids, while the lower–level problem simulates market clearing. The model considers uncertainty related to the future load levels and to the generator strategic behavior. Since this model is stochastic, the authors employ Benders decomposition to efficiently solve the problem. The paper concludes that the energy storage investment is highly dependent on the number and quality of scenarios. A model for assessing the impact of demand response providers on energy storage investment decisions is formulated in [9]. In order to consider the interaction between the demand response providers, who bid in the market through an aggregator, and the merchant investor in energy storage, the model is formulated as an equilibrium problem with equilibrium constraints. The results indicate that in case of a strategic operation, the demand response aggregator and the investor in energy storage can affect each others profitability.

While papers [3]–[9] consider only storage expansion, there are papers that co–optimize transmission and storage expansion planning. A centralized co–planning of transmission lines and energy storage investments is proposed in [10]. This year–by–year planning method considers stochastic wind and demand scenarios and energy storage degradation. The authors emphasize the importance of energy storage in preserving the desired levels of reserve in the system. Joint transmission and energy storage expansion model that considers transmission switching is presented in [11]. The proposed min–max–min structure finds a robust expansion plan feasible for any realization of uncertainty within the given uncertainty set. The model is solved using a decomposition algorithm based on column–and–constraint generation method. The authors report that transmission switching can significantly reduce investment costs. Regarding the computational efficiency, primal cutting planes reach the convergence quicker than dual cutting planes. Finally, the authors emphasize the importance of a proper choice of *big M* values used in the model, as their high values may cause intractability of the subproblem. A model for co–planning of transmission line expansion and merchant investments in energy storage is presented in [12]. The proposed trilevel model is also solved using the column–and–constraint generation method. The results of a realistic case based on WECC system indicate that optimal level of merchant–owned storage is around 3% of the peak hourly renewable output. A top–level assessment of contribution of energy storage in the future power system of Great Britain is presented in [13]. The objective function of the presented model contains system operating costs and annuitized investment cost of generation, storage, transmission and distribution reinforcements. One of the important findings of the presented case study is that interconnections and flexible generation compete less directly with energy storage than demand response, whose presence significantly diminishes the value of storage.

A unified two–stage energy storage, transmission and generation expansion model is proposed in [14]. The first stage considers investment costs, while the second stage considers operational cost, including penalties for not complying with the Renewable Portfolio Standards, based on the probability of each scenario. The authors conclude that the highest value of energy storage is in deferring investments in transmission and generation facilities. Also, the value of energy storage grows with the required levels of renewable generation in the system.

In [15], the authors propose a method for co–planning of transmission and energy storage facilities when connecting large–scale wind farms to the existing network. This locational model returns the structure of the network with determined transmission lines, but undetermined storage capacity. Energy storage size is determined by a closed–form upper bound. The results indicate that, in most cases, even energy storage with small capacity can significantly reduce total system operating costs.

A mixed–integer linear program that integrates transmission expansion planning, generation investment and market operation is formulated in [16]. An equilibrium problem subject to equilibrium constraints is formulated to simulate competitive investors and all possible pure Nash equilibria on generation investment problem are computed. The generator investment decisions are made based on expected market clearing results and these decisions are used by an anticipative transmission planner to make transmission line investment decisions.

C. Contributions

Similarly to [10]–[12], this paper considers coordinated transmission and storage investments. The main difference is that we consider these investments from the point of view of the SO anticipating merchant decisions. This anticipatory transmission planning paradigm is somewhat similar to [16]. However, in [16] the authors focus on competition between generation companies, as opposed to merchant energy storage in this paper. Furthermore, model in [16] considers continuous transmission line capacity investments, whereas model presented in this paper is more realistic and considers lumpy investments in transmission lines. On the other hand, unlike the model from [12], which takes the merchant investor perspective, this model puts the SO in perspective of an anticipator of investor decisions, which is in line with the current SO practice, see e.g. [17]. Finally, as opposed to both [12] and [16], in this model both the SO and the merchant may own a storage. Their storage units are operated in a different way while a merchant seeks to maximize its profit, the SO uses storage in the same way it uses transmission lines. This means that the SO's storage is passive and its charging/discharging schedule is the outcome of the optimization process. On the other hand, merchant-owned storage is active and submits bids in the market trying to maximize its profit.

The main contributions of the paper are summarized as follows:

1) Formulation of a trilevel model where the upper level decides on the SO's transmission line and energy storage investments, middle level decides on merchant's energy storage investments, while the lower level simulates market clearing for representative days. The structure of the problem is visualized in Figure 1. The LMPs generated in the market clearing problem are used in the upper level to determine optimal line and storage investments by the SO,

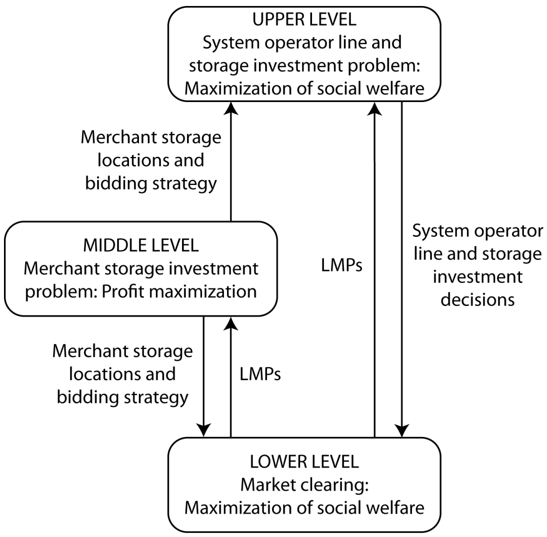

Fig. 1. Problem structure.

and in the middle level to determine optimal merchant storage investment. Merchant investment decisions from the lower–level problem affect the social welfare and thus the SO's investment problem in the upper level. In turn, the SO's investments tend to reduce congestion, which influences the LMPs and thus may impact merchant's revenue and investment decisions.

2) The trilevel formulation is efficiently solved using a decomposition approach based on a cutting plane algorithm. This approach consists of solving the master problem and the subproblem iteratively. In the master problem, the SO optimizes its line and storage investments to maximize social welfare, while fixing the merchants investment decisions. In subproblem, the merchant maximizes its profit considering its storage investment decisions and optimal bidding strategy while the SO's investment decisions are fixed.
3) SO and merchant–owned energy storage are modeled based on the real–world regulatory framework. Charging and discharging variables of an SO's energy storage appear in the power balance constraint, but not in the market–clearing objective function, as it does not act in the market. On the other hand, merchant energy storage charging and discharging variables appear in the market–clearing objective function, as this storage actively participates in the market.

III. Formulation

A. Model Formulation

1) Upper–level problem: In objective function (1) the SO seeks to maximize social welfare throughout the year, consisting of demand bids, merchant storage bids and offers, generator offers, and annualized transmission line and energy storage investment costs. This means that the SO will invest in transmission lines and/or energy storage only if the resulting improvement in social welfare is higher then their annualized investment costs.

$$\underset{\Xi^{\mathrm{UL}}}{\text{Maximize}} \sum_{k=1}^{K}\pi_k\Bigg(\sum_{t=1}^{T}\sum_{n=1}^{N}C_n^{\mathrm{d}}\cdot d_{k,t,n}+\sum_{t=1}^{T}\sum_{n=1}^{N}\left(C_n^{\mathrm{b}}\cdot p_{k,t,n}^{\mathrm{c}}-C_n^{\mathrm{o}}\cdot p_{k,t,n}^{\mathrm{d}}\right) -\sum_{t=1}^{T}\sum_{i=1}^{I}C_i^{\mathrm{g}}\cdot g_{k,t,i}\Bigg)-\sum_{l=1}^{\tilde{L}}C_l\cdot v_l -\sum_{n=1}^{N}\left(C^{\mathrm{SOe}}\cdot e_n^{\mathrm{SOmax}}+C^{\mathrm{SOp}}\cdot p_n^{\mathrm{SOmax}}\right) \tag{1}$$

where $\Xi^{\mathrm{UL}}=\left\{v_l, e_n^{\mathrm{SOmax}}, p_n^{\mathrm{SOmax}}\right\}$.

The objective function (1) is subject to the following constraints:

$$\sum_{l=1}^{\tilde{L}} v_l \le N^{\tilde{\mathrm{L}}} \qquad \forall l\in\tilde{L} \tag{2}$$

$$v_l\in\{0,1\} \qquad \forall l\in\tilde{L} \tag{3}$$

$$v_l=0 \qquad \forall l\notin\tilde{L} \tag{4}$$

$$p_n^{\mathrm{SOmax}}\cdot\chi=e_n^{\mathrm{SOmax}} \qquad \forall n\in N \tag{5}$$

$$\sum_{l=1}^{\tilde{L}}C_l\cdot v_l+\sum_{n=1}^{N}\left(C^{\mathrm{SOe}}\cdot e_n^{\mathrm{SOmax}}+C^{\mathrm{SOp}}\cdot p_n^{\mathrm{SOmax}}\right)\le\overline{IC}^{\mathrm{SO}} \tag{6}$$

Constraint (2) limits the number of new transmission lines, while constraints (3) and (4) allow construction of new lines only within the set of candidate lines. Equation (5) sets the energy–to–power ratio of the storage technology. This constraint is omitted if a specific storage technology allows energy and power capacities to be determined independently, e.g. flow batteries. Constraint (6) limits the annualized SO's transmission line and storage investment budget. Annualized transmission line investment cost, c_l, is calculated based on the actual line investment cost, C_l^{cost}, interest rate m and expected line lifetime h using the following formula:

$$C_l=C_l^{\mathrm{cost}}\cdot\frac{m\cdot(1+m)^h}{(1+m)^h-1} \tag{7}$$

Annualized SO energy storage energy and power investment costs are calculated using expressions equivalent to (7).

2) Middle–level problem: Merchant investor in energy storage aim at maximizing its expected profit with respect to the annualized energy storage investment cost:

$$\underset{\Xi^{\mathrm{ML}}}{\text{Maximize}} \underbrace{\sum_{k=1}^{K}\pi_k\sum_{n=1}^{N}\sum_{t=1}^{T}\left(\lambda_{k,t,n}\cdot p_{k,t,n}^{\mathrm{d}}-\lambda_{k,t,n}\cdot p_{k,t,n}^{\mathrm{c}}\right)}_{Pr} \underbrace{-\sum_{n=1}^{N}\left(C^{\mathrm{e}}\cdot e_n^{\max}+C^{\mathrm{p}}\cdot p_n^{\max}\right)}_{Inv} \tag{8}$$

subject to:

$$Inv \leq \overline{IC}^{\mathrm{st}} \tag{9}$$

$$Pr \geq \kappa \cdot Inv \tag{10}$$

$$p_n^{\max} \cdot \chi = s_n^{\max} \qquad \forall n \in N \tag{11}$$

where $\Xi^{\mathrm{ML}} = \{e_n^{\max}, p_n^{\max}\}$.

In objective function (8) profit, Pr, is the difference between the collected revenue while discharging, $\lambda_{k,t,n} \cdot p^{\mathrm{d}}_{k,t,n}$, and incurred expenses while charging, $\lambda_{k,t,n} \cdot p^{\mathrm{c}}_{k,t,n}$, over the representative days. On the other hand, investment cost, Inv, is the sum of the annualized investment cost related to energy capacity, $C^{\mathrm{e}} \cdot e_n^{\max}$, and power capacity, $C^{\mathrm{p}} \cdot p_n^{\max}$. Overall annualized investment cost is limited by the annualized investment budget in constraint (9). Minimum profit parameter κ is used in (10) to set the minimum profit of investor storage. Objective function (8) will never be negative because in case of an insufficient revenue the model will return no storage investment, resulting in $Pr - Inv = 0$. However, if an independent storage investor requires annual profit of at least 15%, parameter κ should be set to 1.15. Eq. (11) couples energy storage energy and power capacities in the same way as eq. (5) does it for the SO–operated storage. Annualized energy storage investment costs are calculated using an equivalent of (7).

3) Lower–level problem: Lower–level problem simulates market clearing. Thus, its objective function (12) is the maximization of social welfare, which includes generator offers, merchant–owned energy storage discharging offers and charging bids, and demand bids. In the following formulation, dual variables of each constraint are listed after a colon:

$$\underset{\Xi^{\mathrm{LL}}}{\text{Maximize}} \; -\sum_{t=1}^{T}\sum_{i=1}^{I} C_i^{\mathrm{g}} \cdot g_{k,t,i} - \sum_{t=1}^{T}\sum_{n=1}^{N}\left(C_n^{\mathrm{o}} \cdot p^{\mathrm{d}}_{k,t,n} - C_n^{\mathrm{b}} \cdot p^{\mathrm{c}}_{k,t,n}\right) + \sum_{t=1}^{T}\sum_{n=1}^{N} C_n^{\mathrm{d}} \cdot d_{k,t,n} \tag{12}$$

subject to:

$$0 \leq g_{k,t,i} \leq G_i^{\max} \quad : \alpha^{\min}_{k,t,i}, \alpha^{\max}_{k,t,i} \quad \forall k \in K, t \in T, i \in I \tag{13}$$

$$-RD_i \leq g_{k,t,i} - g_{k,t-1,i} \leq RU_i \quad : \beta^{\mathrm{RD}}_{k,t,i}, \beta^{\mathrm{RU}}_{k,t,i} \quad \forall k \in K, t \in T, i \in I \tag{14}$$

$$0 \leq d_{k,t,n} \leq D^{\max}_{k,t,n} \quad : \delta^{\min}_{k,t,n}, \delta^{\max}_{k,t,n} \quad \forall k \in K, t \in T, n \in N \tag{15}$$

$$0 \leq ws_{k,t,w} \leq WG^{\mathrm{f}}_{k,t,w} \quad : \gamma^{\min}_{k,t,w}, \gamma^{\max}_{k,t,w} \quad \forall k \in K, t \in T, w \in W \tag{16}$$

$$s_{k,t,n} = s_{k,t-1,n} + p^{\mathrm{c}}_{k,t,n} \cdot \eta^{\mathrm{ch}} \cdot \Delta\tau - p^{\mathrm{d}}_{k,t,n}/\eta^{\mathrm{dis}} \cdot \Delta\tau \quad : \epsilon_{k,t,n} \forall k \in K, t \in T, n \in N \tag{17}$$

$$0 \leq p^{\mathrm{c}}_{k,t,n} \leq p_n^{\max} \quad : \phi^{\mathrm{cmin}}_{k,t,n}, \phi^{\mathrm{cmax}}_{k,t,n} \quad \forall k \in K, t \in T, n \in N \tag{18}$$

$$0 \leq p^{\mathrm{d}}_{k,t,n} \leq p_n^{\max} \quad : \phi^{\mathrm{dmin}}_{k,t,n}, \phi^{\mathrm{dmax}}_{k,t,n} \quad \forall k \in K, t \in T, n \in N \tag{19}$$

$$0 \leq s_{k,t,n} \leq s_n^{\max} \quad : \phi^{\mathrm{smin}}_{k,t,n}, \phi^{\mathrm{smax}}_{k,t,n} \quad \forall k \in K, t \in T, n \in N \tag{20}$$

$$s^{\mathrm{SO}}_{k,t,n} = s^{\mathrm{SO}}_{k,t-1,n} + ch_{k,t,n} \cdot \eta^{\mathrm{ch}} \cdot \Delta\tau - dis_{k,t,n}/\eta^{\mathrm{dis}} \cdot \Delta\tau : \epsilon^{\mathrm{SO}}_{k,t,n} \quad \forall k \in K, t \in T, n \in N \tag{21}$$

$$0 \leq ch_{k,t,n} \leq p_n^{\mathrm{SOmax}} \quad : \phi^{\mathrm{SOcmax}}_{k,t,n} \quad \forall k \in K, t \in T, n \in N \tag{22}$$

$$0 \leq dis_{k,t,n} \leq p_n^{\mathrm{SOmax}} \quad : \phi^{\mathrm{SOdmax}}_{k,t,n} \quad \forall k \in K, t \in T, n \in N \tag{23}$$

$$0 \leq s^{\mathrm{SO}}_{k,t,n} \leq e_n^{\mathrm{SOmax}} \quad : \phi^{\mathrm{SOsmax}}_{k,t,n} \quad \forall k \in K, t \in T, n \in N \tag{24}$$

$$f_{k,t,l} \cdot (X_l - v_l \cdot \Delta X_l) = \theta_{k,t,o(l)} - \theta_{k,t,r(l)} \quad : \mu_{k,t,l} \quad \forall k \in K, t \in T, l \in L \tag{25}$$

$$-\overline{F}_l - v_l \cdot \Delta F_l \leq f_{k,t,l} \leq \overline{F}_l - v_l \cdot \Delta F_l \quad : \mu^{\min}_{k,t,l}, \mu^{\max}_{k,t,l} \quad \forall k \in K, t \in T, l \in L \tag{26}$$

$$-\sum_{i \in I|B} g_{k,t,i} + \sum_{l|o(l)=n} f_{k,t,l} - \sum_{l|r(l)=n} f_{k,t,l} - \sum_{w \in W|B}\left(WG^{\mathrm{f}}_{k,t,w} - ws_{k,t,w}\right) + p^{\mathrm{c}}_{k,t,n} - p^{\mathrm{d}}_{k,t,n} + ch_{k,t,n} - dis_{k,t,n} + d_{k,t,n} = 0 \quad : \lambda_{k,t,n} \quad \forall k \in K, t \in T, l \in L \tag{27}$$

where $\Xi^{\mathrm{LL}} = \{\ ch_{k,t,n},\ d_{k,t,n},\ dis_{k,t,n},\ f_{k,t,l},\ g_{k,t,i},\ p^{\mathrm{c}}_{k,t,n},\ p^{\mathrm{d}}_{k,t,n},\ s_{k,t,n},\ s^{\mathrm{SO}}_{k,t,n},\ \theta_{k,t,n},\ ws_{k,t,w}\ \}$.

Single–block generator offers are modeled in constraint (13), while generator ramp up and down limits are imposed in constraint (14). Constraint (15) limits the served demand to the demand requirement, while constraint (16) limits the spillage of renewable generation to the forecasted value. Eq. (17) calculates merchant's storage state of charge, while (18)–(20) limit its charging power, discharging power, and energy capacity. Equivalently, eq. (21) keeps track of the SO's energy storage state of charge, while constraints (22)–(24) limit charging/discharging power and energy state of charge. Eq. (25) calculates power flows, while constraint (26) imposes transmission capacity limits. Both (25) and (26) consider transmission expansion decisions from the upper–level problem using binary variable v_l. Finally, eq. (27) is the power balance constraint. It is important to note that the merchant–owned storage charging and discharging schedule, i.e. values of $p^{\mathrm{c}}_{k,t,n}$ and $p^{\mathrm{d}}_{k,t,n}$, in (27) is decided based on active market participation, while values of the SO–owned storage variables, $ch_{k,t,n}$ and $dis_{k,t,n}$, are a direct outcome of the market–clearing process, the same as the power flows through transmission lines.

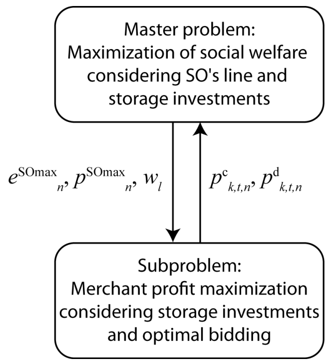

Fig. 2. Interaction between the master problem and the subproblem.

IV. Solution Methodology

Since the mathematical formulation from the previous Section is of a trilevel structure, it cannot be directly solved using commercial solvers. Therefore, we convert the middle–level problem and the lower–level problem into an equivalent mathematical program with equilibrium constraints (MPEC). This is achieved by substituting the convex lower–level problem with an equivalent set of constraints to the middle–level problem. This set consists of the primal and dual lower–level problem constraints and the strong duality equality. The obtained MPEC acts as a lower–level problem to the original upper–level problem. Since this structure still cannot be directly solved, we employ an iterative procedure where the master problem (upper–level problem in our formulation) and the subproblem (MPEC derived from the middle–level and lower–level problems) are iteratively solved. This procedure is shown in Fig. 2. When solving the master problem, merchant storage bidding strategy is included through variables $p^{\text{c}}_{k,t,n}$ and $p^{\text{d}}_{k,t,n}$ new limits whose values are determined in the subproblem. After solving the master problem, the SO's storage investment decisions, s^{SOmax}_n and p^{SOmax}_n, and line investment decisions, v_l, are used in the subproblem, where merchant storage investment and bidding problem is solved. Master problem and subproblem are alternatively solved until the optimal solution is reached. Structure and modeling of the subproblem and the master problem are explained in details in the following subsections.

A. Subproblem

In order to obtain an MPEC, the lower–level problem needs to be replaced by its equivalent optimality constraints: primal constraints, dual constraints and duality equality. Dual of the lower–level problem is (corresponding primal variables are listed after a colon in each dual constraint):

$$\begin{aligned}
&\underset{\Xi^{\text{LLD}}}{\text{Minimize}} \\
&\sum_{t=1}^{T}\sum_{i=1}^{I}\left(G_i^{\max}\cdot\alpha_{k,t,i}^{\max}+RD_i\cdot\beta_{k,t,i}^{\text{RD}}+RU_i\cdot\beta_{k,t,i}^{\text{RU}}\right)+ \\
&+\sum_{t=1}^{T}\sum_{n=1}^{N}D_{k,t,n}^{\max}\cdot\delta_{k,t,n}^{\max}+\sum_{t=1}^{T}\sum_{l=1}^{L}F_l^{\max}\cdot\left(\mu_{k,t,l}^{\min}+\mu_{k,t,l}^{\max}\right)- \\
&-\sum_{t=1}^{T}\sum_{w=1}^{W|N}WG_{k,t,w}^{\text{f}}\cdot\lambda_{k,t,n}+\sum_{t=1}^{T}\sum_{w=1}^{W}WG_{k,t,w}^{\text{f}}\cdot\gamma_{k,t,w}^{\max}+ \\
&+\sum_{t=1}^{T}\sum_{n=1}^{N}p_n^{\max}\cdot\phi_{k,t,n}^{\text{cmax}}+p_n^{\max}\cdot\phi_{k,t,n}^{\text{dmax}}+s_n^{\max}\cdot\phi_{k,t,n}^{\text{smax}}+ \\
&+\sum_{t=1}^{T}\sum_{n=1}^{N}p_b^{\text{SOmax}}\cdot\phi_{k,t,n}^{\text{SOcmax}}+p_b^{\text{SOmax}}\cdot\phi_{k,t,n}^{\text{SOdmax}}+ \\
&+\sum_{t=1}^{T}\sum_{n=1}^{N}e_n^{\text{SOmax}}\cdot\phi_{k,t,n}^{\text{SOsmax}}
\end{aligned} \tag{28}$$

subject to:

$$\begin{aligned}
&-\alpha_{k,t,i}^{\min}+\alpha_{k,t,i}^{\max}-\beta_{k,t,i}^{\text{RD}}+\beta_{k,t+1,i}^{\text{RD}}+ \\
&+\beta_{k,t,i}^{\text{RU}}-\beta_{k,t+1,i}^{\text{RU}}+\lambda_{k,t,n|i}=-C_i^{\text{g}} \quad : g_{k,t,i} \\
&\forall k\in K, t<T, i\in I
\end{aligned} \tag{29}$$

$$\begin{aligned}
&-\alpha_{k,t,i}^{\min}+\alpha_{k,t,i}^{\max}-\beta_{k,t,i}^{\text{RD}}+\beta_{k,t,i}^{\text{RU}}+\lambda_{k,t,n|i}= \\
&=-C_i^{\text{g}} \quad : g_{k,t,i} \quad \forall k\in K, t=T, i\in I
\end{aligned} \tag{30}$$

$$\begin{aligned}
&-\lambda_{k,t,n}-\delta_{k,t,n}^{\min}+\delta_{k,t,n}^{\max}=C_b^{\text{d}} \quad : d_{k,t,n} \\
&\forall k\in K, t\in T, n\in N
\end{aligned} \tag{31}$$

$$\begin{aligned}
&(X_l-\omega_l\cdot X_l)\cdot\mu_{k,t,l}-\mu_{k,t,l}^{\min}+\mu_{k,t,l}^{\max}-\lambda_{k,t,n|l}=0 \quad : f_{k,t,l} \\
&\forall k\in K, t\in T, l\in L
\end{aligned} \tag{32}$$

$$\begin{aligned}
&-\lambda_{k,t,n|w}-\gamma_{k,t,w}^{\min}+\gamma_{k,t,w}^{\max}=0 \quad : ws_{k,t,w} \\
&\forall k\in K, t\in T, w\in W
\end{aligned} \tag{33}$$

$$\begin{aligned}
&\epsilon_{k,t,n}-\epsilon_{k,t+1,n}-\phi_{k,t,n}^{\text{smin}}+\phi_{k,t,n}^{\text{smax}}=0 \quad : s_{k,t,n} \\
&\forall k\in K, t<T, n\in N
\end{aligned} \tag{34}$$

$$\begin{aligned}
&\epsilon_{k,t,n}-\phi_{k,t,n}^{\text{smin}}+\phi_{k,t,n}^{\text{smax}}=0 \quad : s_{k,t,n} \\
&\forall k\in K, t=T, n\in N
\end{aligned} \tag{35}$$

$$\begin{aligned}
&-\epsilon_{k,t,n}\cdot\eta^{\text{ch}}-\phi_{k,t,n}^{\text{cmin}}+\phi_{k,t,n}^{\text{cmax}}+\lambda_{k,t,n}=C_n^{\text{b}} \quad : p_{k,t,n}^{\text{c}} \\
&\forall k\in K, t=T, n\in N
\end{aligned} \tag{36}$$

$$\begin{aligned}
&-\epsilon_{k,t,n}/\eta^{\text{dis}}+\phi_{k,t,n}^{\text{dmin}}-\phi_{k,t,n}^{\text{dmax}}+\lambda_{k,t,n}=C_n^{\text{o}} \quad : p_{k,t,n}^{\text{d}} \\
&\forall k\in K, t=T, n\in N
\end{aligned} \tag{37}$$

$$\begin{aligned}
&\epsilon_{k,t,n}^{\text{SO}}-\epsilon_{k,t+1,n}^{\text{SO}}+\phi_{k,t,n}^{\text{SOsmax}}\geq 0 \quad : s_{k,t,n}^{\text{SO}} \\
&\forall k\in K, t<T, n\in N
\end{aligned} \tag{38}$$

$$\begin{aligned}
&\epsilon_{k,t,n}^{\text{SO}}+\phi_{k,t,n}^{\text{SOsmax}}\geq 0 \quad : s_{k,t,n}^{\text{SO}} \\
&\forall k\in K, t=T, n\in N
\end{aligned} \tag{39}$$

$$\begin{aligned}
&-\epsilon_{k,t,n}^{\text{SO}}\cdot\eta^{\text{ch}}+\phi_{k,t,n}^{\text{SOmax}}-\lambda_{k,t,n}\geq 0 \quad : ch_{k,t,n} \\
&\forall k\in K, t\in T, n\in N
\end{aligned} \tag{40}$$

$$\epsilon^{\mathrm{SO}}_{k,t,n}/\eta^{\mathrm{dis}} + \phi^{\mathrm{SOdmax}}_{k,t,n} + \lambda_{k,t,n} \geq 0 \quad : dis_{k,t,n} \qquad \forall k \in K, t \in T, n \in N \tag{41}$$

where $\Xi^{\mathrm{LLD}} = \{\ \alpha^{\min}_{k,t,i},\ \alpha^{\max}_{k,t,i},\ \beta^{\mathrm{RD}}_{k,t,i},\ \beta^{\mathrm{RU}}_{k,t,i},\ \delta^{\min}_{k,t,n},\ \delta^{\max}_{k,t,n},\ \gamma^{\min}_{k,t,w},\ \gamma^{\max}_{k,t,w},\ \epsilon_{k,t,n},\ \phi^{\mathrm{cmin}}_{k,t,n},\ \phi^{\mathrm{cmax}}_{k,t,n},\ \phi^{\mathrm{dmin}}_{k,t,n},\ \phi^{\mathrm{dmax}}_{k,t,n},\ \phi^{\mathrm{smin}}_{k,t,n},\ \phi^{\mathrm{smax}}_{k,t,n},\ \phi^{\mathrm{SOcmax}}_{k,t,n},\ \phi^{\mathrm{SOdmax}}_{k,t,n},\ \phi^{\mathrm{SOsmax}}_{k,t,n},\ \mu_{k,t,l},\ \mu^{\min}_{k,t,l},\ \mu^{\max}_{k,t,l},\ \lambda_{k,t,n}\ \}$.

The MPEC obtained by merging the middle– and lower–level problems consists of objective function (8) subject to the middle–level problem constraints (9)–(11), primal lower–level problem constraints (13)–(27), dual lower–level problem constraints (29)–(41), and strong duality equality (12)=(28). This MPEC contains the following non–linearities:

1) terms $\lambda_{k,t,n} \cdot p^{\mathrm{d}}_{k,t,n}$ and $\lambda_{k,t,n} \cdot p^{\mathrm{c}}_{k,t,n}$ in the objective function (8),
2) term $(p^{\max}_n \cdot \phi^{\mathrm{cmax}}_{k,t,n} + p^{\max}_n \cdot \phi^{\mathrm{dmax}}_{k,t,n} + s^{\max}_n \cdot \phi^{\mathrm{smax}}_{k,t,n})$ on the right–hand–side of the lower–level problem strong duality equality (28).

After expressing $\lambda_{k,t,n}$ from (36) and (37), we can express storage profit (7) as:

$$\begin{aligned}&\epsilon_{k,t,n}\left(p^{\mathrm{d}}_{k,t,n}/\eta^{\mathrm{dis}} - p^{\mathrm{c}}_{k,t,n}\cdot\eta^{\mathrm{ch}}\right) - \phi^{\mathrm{dmin}}_{k,t,n}\cdot p^{\mathrm{d}}_{k,t,n} + \\ &+\phi^{\mathrm{dmax}}_{k,t,n}\cdot p^{\mathrm{d}}_{k,t,n} - \phi^{\mathrm{cmin}}_{k,t,n}\cdot p^{\mathrm{c}}_{k,t,n} + \phi^{\mathrm{cmax}}_{k,t,n}\cdot p^{\mathrm{c}}_{k,t,n} + \\ &+C^{\mathrm{o}}_n\cdot p^{\mathrm{d}}_{k,t,n} - C^{\mathrm{b}}_n\cdot p^{\mathrm{c}}_{k,t,n}\end{aligned} \tag{42}$$

Complementarity slackness constraint (18) can be expressed as $\phi^{\mathrm{cmin}}_{k,t,n} \cdot p^{\mathrm{c}}_{k,t,n} = 0$ and $\phi^{\mathrm{cmax}}_{k,t,n} \cdot \left(p^{\max}_n - p^{\mathrm{c}}_{k,t,n}\right) = 0 \rightarrow \phi^{\mathrm{cmax}}_{k,t,n} \cdot p^{\mathrm{c}}_{k,t,n} = \phi^{\mathrm{cmax}}_{k,t,n} \cdot p^{\max}_n$. Similarly, complementarity slackness constraint (19) yields $\phi^{\mathrm{dmin}}_{k,t,n} \cdot p^{\mathrm{d}}_{k,t,n} = 0$ and $\phi^{\mathrm{dmax}}_{k,t,n} \cdot \left(p^{\max}_n - p^{\mathrm{d}}_{k,t,n}\right) = 0 \rightarrow \phi^{\mathrm{dmax}}_{k,t,n} \cdot p^{\mathrm{d}}_{k,t,n} = \phi^{\mathrm{dmax}}_{k,t,n} \cdot p^{\max}_n$. To linearize the first term in (42) we rewrite it using (17):

$$\epsilon_{k,t,n}\left(p^{d}_{k,t,n}/\eta^{\mathrm{dis}} - p^{\mathrm{c}}_{k,t,n}\cdot\eta^{\mathrm{ch}}\right) = \epsilon_{k,t,n}\left(s_{k,t-1,n} - s_{k,t,n}\right) \tag{43}$$

Rearranging the order of multiplication results in:

$$\begin{aligned}&\epsilon_{k,t,n}\left(s_{k,t-1,n} - s_{k,t,n}\right) = \\ &= \sum_{t=1}^{T-1} s_{k,t,n}\left(\epsilon_{k,t+1,n} - \epsilon_{k,t,n}\right) - s_{k,t,n}\cdot\epsilon_{k,t,n}\end{aligned} \tag{44}$$

Now, using (34) and (35), we can rewrite (44) as:

$$\begin{aligned}&\sum_{t=1}^{T-1} s_{k,t,n}\left(\epsilon_{k,t+1,n} - \epsilon_{k,t,n}\right) - s_{k,t,n}\cdot\epsilon_{k,t,n} = \\ &\qquad = s_{k,t,n}\left(\phi^{\mathrm{smax}}_{k,t,n} - \phi^{\mathrm{smin}}_{k,t,n}\right)\end{aligned} \tag{45}$$

Again, complementarity slackness associated with constraint (20) can be written as $\phi^{\mathrm{smin}}_{k,t,n} \cdot s_{k,t,n} = 0$ and $\phi^{\mathrm{smax}}_{k,t,n} \cdot (s^{\max}_n - s_{k,t,n}) = 0 \rightarrow \phi^{\mathrm{smax}}_{k,t,n} \cdot s_{k,t,n} = \phi^{\mathrm{smax}}_{k,t,n} \cdot s^{\max}_n$.

The resulting storage profit part, Pr, of objective function (8) is:

$$C^{\mathrm{o}}_n p^{\mathrm{d}}_{k,t,n} - C^{\mathrm{b}}_n \cdot p^{\mathrm{c}}_{k,t,n} + \phi^{\mathrm{smax}}_{k,t,n} s^{\max}_n + \phi^{\mathrm{dmax}}_{k,t,n} p^{\max}_n + \phi^{\mathrm{cmax}}_{k,t,n} p^{\max}_n \tag{46}$$

The last three non–linear terms in (46) are identical to the non–linear terms appearing on the right–hand–side of the strong duality equality (28).

To linearize the multiplication of two continuous variables, we define variable $s^{\max}_n$ as a sum of a finite number of storage increments of a predefined size, i.e., we introduce storage capacity increment ΔS, binary variable $u_{n,j}$ and parameter $u^{\max}_n$ that controls the maximum number of increments per bus.

$$s^{\max}_n = \sum_{j=1}^{J} \Delta S \cdot u_{n,j} \tag{47}$$

$$\sum_{j=1}^{J} u_{n,j} \leq U^{\max}_n \tag{48}$$

Now, to linearize the multiplication of a binary and a continuous variable, we use the big M reformulation, resulting in the following constraints:

$$\Delta S \cdot \phi^{\mathrm{smax}}_{k,t,n,j} - (1 - u_{n,j}) \cdot M \leq US_{k,t,n,j} \leq M \cdot u_{n,j} \tag{49}$$

$$US_{k,t,n,j} \leq \Delta S \cdot \phi^{\mathrm{smax}}_{k,t,n,j} \tag{50}$$

$$\Delta S \cdot \chi^{-1} \cdot \phi^{\mathrm{dmax}}_{k,t,n} - (1 - u_{n,j}) \cdot M \leq UD_{k,t,n,j} \leq M \cdot u_{n,j} \tag{51}$$

$$UD_{k,t,n,j} \leq \Delta S \cdot \chi^{-1} \cdot \phi^{\mathrm{dmax}}_{k,t,n} \tag{52}$$

$$\Delta S \cdot \chi^{-1} \cdot \phi^{\mathrm{cmax}}_{k,t,n} - (1 - u_{n,j}) \cdot M \leq UC_{k,t,n,j} \leq M \cdot u_{n,j} \tag{53}$$

$$UC_{k,t,n,j} \leq \Delta S \cdot \chi^{-1} \cdot \phi^{\mathrm{cmax}}_{k,t,n} \tag{54}$$

where $US_{k,t,n,j} = \phi^{\mathrm{smax}}_{k,t,n,j} \cdot u_{n,j} \cdot \Delta S$, $UD_{k,t,n,j} = \phi^{\mathrm{dmax}}_{k,t,n,j} \cdot u_{n,j} \cdot \Delta S$, $UC_{k,t,n,j} = \phi^{\mathrm{cmax}}_{k,t,n,j} \cdot u_{n,j} \cdot \Delta S$

The final objective function:

$$\begin{aligned}&\sum_{k=1}^{K} \pi_k \left[\sum_{t=1}^{T}\sum_{n=1}^{N} \left(C^{\mathrm{o}}_n \cdot p^{\mathrm{d}}_{k,t,n} - C^{\mathrm{b}}_n \cdot p^{\mathrm{c}}_{k,t,n}\ + \right.\right. \\ &\left.\left. + \sum_{j=1}^{J} US_{k,t,n,j} + UD_{k,t,n,j} + UC_{k,t,n,j}\ \right)\right] - \\ &- \sum_{n=1}^{N} \left(C^{\mathrm{e}} \cdot e^{\max}_n + C^{\mathrm{p}} \cdot p^{\max}_n\right)\end{aligned} \tag{55}$$

is subject to the constraints: (9)–(11), (13)–(27), (29)–(41), linearized strong duality equality (12) = (28) and (47)–(54).

B. Master Problem

The master problem consists of the upper–level problem (1)–(6) and market clearing constraints of the lower–level problem (13)–(27). However, merchant storage charging and discharging quanitites in (18) and (19) are no longer limited to maximum capacity but to merchant storage actions derived from the previous iteration of the subproblem.

The only non–linearity in the master problem $f_{k,t,l} \cdot \omega_l$ in eq. (25) is easily linearized using the big M reformulation:

$$FL_{e,t,l} = f_{e,t,l} \cdot \omega_l \tag{56}$$

$$-M \leq FL_{e,t,l} \leq M \tag{57}$$

$$-M \cdot \omega_l \leq FL_{e,t,l} \leq M \cdot \omega_l \tag{58}$$

$$\Delta x_l \cdot f_{e,t,l} - (1 - \omega_l) \cdot M \leq FL_{e,t,l} \tag{59}$$

$$\Delta x_l \cdot f_{e,t,l} + (1 - \omega_l) \cdot M \geq FL_{e,t,l} \tag{60}$$

TABLE I. ILLUSTRATIVE TEST CASE GENERATOR DATA

Generator	$G_i^{\max}$	C_i^{g}	Generator	$G_i^{\max}$	C_i^{g}
G1	100	12	G3	50	50
G2	75	20	G4	50	100

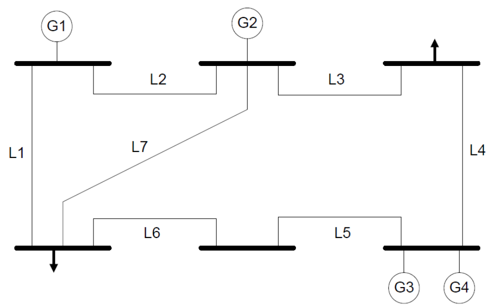

Fig. 3. Illustrative test case.

V. CASE STUDY

We considered two case studies in this paper – a six bus illustrative example and the IEEE RTS-96 test system.

A. A Six-Bus Illustrative Example

This section presents the results obtained on a six-bus system from [19] to demonstrate the mechanics of the proposed method. Technical characteristics of conventional generators are given in Table I. The capacity of transmission lines is 50 MW, except for line 7 whose capacity is 25 MW. The system is shown in Fig. 3. We consider the target year represented by a single representative day. The load is distributed equally among buses 3 and 4 and it bids at $450/MWh. The hourly system load data are provided in [19]. Storage investment is considered at $20/kWh and $500/kW with 20 years lifetime. Line is priced at $60.000 per mile with 40 years lifetime. Interest rate is 10%.

Table II shows iterations to the final solution of the illustrative test case. The baseline social welfare, i.e. when no investments are made by the SO or the merchant, for the target year is $682.090.000. After running the master problem in the first iteration, the welfare is increased to $731.250.000 as a result of the SO's investment in lines L3 and L7, as well as in 80 MWh of storage at bus 4. Considering these SO's investment decision, subproblem results in 40 MWh of merchant storage at bus 4 and 30 MWh at bus 6, which further increases the welfare to $744.888.24. In the second iteration, the SO keeps the investment in lines L3 and L7, but reduces storage investments to 4 MWh at bus 3 and 10 MWh at bus 4. In the subproblem, the merchant invests now in a 20 MWh storage at bus 5 and increases its investment in storage at bus 6 to 60 MWh. In the third iteration, the SO voids any storage investments and invests in lines L3 and L7. Consequently, merchant invests in an 80 MWh storage at bus 4. Finally, the master problem solution in the fourth iteration results in the same SO investment decisions as in the previous iteration and yields the highest possible social welfare.

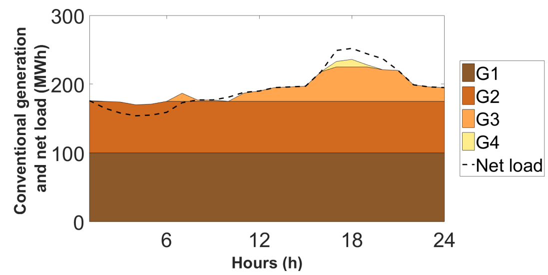

Fig. 4. Conventional generation and net load.

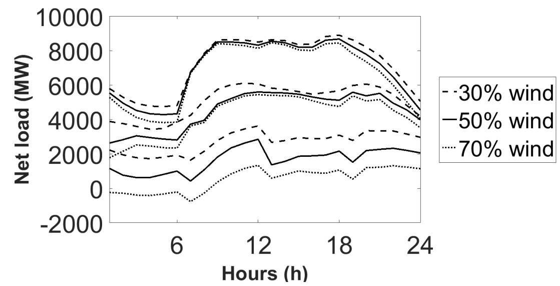

Fig. 5. Net load during three representative days for 30%, 50% and 70% wind energy penetration levels.

Fig. 4 shows output of conventional generators in the system. Generators G1 and G2 cover the base load, while generators G3 and G4 operate during the peak hours. Merchant energy storage system charges at the beginning of the day taking advantage of the lower LMPs and discharges in the afternoon, reducing the load peak.

B. IEEE RTS–96 system

This case study uses IEEE RTS–96 system data available at [20]. The system consists of 73 buses, 96 generators and 19 wind farms. Due to high transmission capacity, all the double lines are replaced by single ones and all line capacities are reduced to 70% of the original values. We consider three levels of wind energy penetration: 30%, 50% and 70%. The entire year is characterized using three representative days obtained using the forward–selection algortihm [21]. Fig. 5 shows the net load for three representative days for each wind penetration level.

TABLE II. ITERATIONS TO THE SOLUTION OF THE ILLUSTRATIVE EXAMPLE

Iteration	Welfare UL	SO lines	SO storage	Welfare LL	Merchant storage
1	$731.250.000	L3, L7	80 MWh (n4)	$744.888.224	40 MWh (n4) and 30 MWh (n6)
2	$744.990.000	L3, L7	4 MWh (n3), 10 MWh (n4)	$743.960.314	20 MWh (n5) and 60 MWh (n6)
3	$743.880.000	L3, L7	–	$745.647.310	80 MWh (n4)
4	$745.647.310	L3, L7	–		

TABLE III. SO AND MERCHANT INVESTMENTS FOR IEEE RTS–96 CASE STUDY FOR DIFFERENT WIND ENERGY PENETRATION LEVELS AND ENERGY STORAGE COSTS

Storage cost	Low			Medium			High		
Wind level	30%	50%	70%	30%	50%	70%	30%	50%	70%
SO investment	L25, L63, L101	L25, L63, L101	L25, L39, L63, L101	L25, L63, L101	L25, L63, L101	L25, L39, L63, L101	L25, L63, L101	L25, L63, L101	L25, L39, L63, L101
Merchant investment, MWh (bus)	140 (n103), 60 (n223)	200 (n223), 120 (n107), 40 (n322)	200 (n103), 200 (n223), 60 (n123), 40 (n318), 40 (n212), 20 (n322)	40 (n103)	80 (n223), 20 (n107)	160 (n103), 140 (n223), 20 (n212), 20 (n318)	–	–	–
Social welfare, m$ (%)	20.659 (2,6%)	20.968 (2,3%)	21.189 (2,3%)	20.577 (2,2%)	20.948 (2,0%)	21.107 (1,9%)	20.539 (2,0%)	20.864 (1,8%)	21.051 (1.6%)
SO investment – no lines	200 (n321), 120 (n124), 100 (n115)	180 (n321), 120 (n124), 100 (n115)	180 (n321), 130 (n115), 30 (n221)	–	–	–	–	–	–
Merchant investment – no lines, MWh (bus)	160 (n115), 140 (n124), 140 (n103), 60 (n223)	200 (n223), 160 (n115), 140 (n124), 60 (n322)	200 (n103), 200 (n123), 160 (n223), 80 (n322), 40 (n318)	100 (n115), 60 (n124)	80 (n223), 40 (n115), 40 (n124)	140 (n103), 130 (n123), 80 (n223), 20 (n322)	–	–	–
Social welfare – no lines, m$ (%)	20.436 (1,5%)	20.743 (1,2%)	20.982 (1,3%)	20.376 (1,2%)	20.682 (0,9%)	20.920 (1,0%)	20.134	20.497	20.713

The results for different wind levels (30%, 50% and 70%) and battery costs (high – \$100/kWh, \$150/kW, medium – \$50/kWh, \$100/kW and low – \$20/kWh, \$50/kW) are presented in Table IV. Its upper part shows the SO and merchant decisions when the SO can invest in both lines and batteries. The SO invests in lines 25, 63 and 101, all of which are highly congested due to the transfer of wind generation from the north to the large loads in the south. Additionally, in the case of 70% wind penetration level, the increase in social welfare compensates for investment in line 39 as well. The SO does not invest in energy storage, even in scenarios with low investment cost. The SO line investments result in 1,6%-2% increase in social welfare, depending on the wind penetration level, while merchant investments increase social welfare by 0,2%-0,7%. Merchant investments in energy storage increase with wind penetration level. Generally, the most attractive locations for merchant storage are buses n103 and n223.

Lower part (last three lines) of Table III shows the results of the case when the SO can only invest in energy storage, which might reflect real–life problems with obtaining line corridors. The SO invests in batteries at locations close to the most congested lines that are reinforced in the case when the SO can invest in lines. Combined with merchant investments, the social welfare increases by 1,2%-1,5%, which indicates that line investments are more suitable means of increasing the social welfare. Merchant invests more in energy storage than the SO because active market participation enables better return of investment than passive storage operation. Additionally, merchant storage investments increase the social welfare, thus diminishing the value of the SO's storage investments.

C. Sensitivity of Results on Minimum Merchant Profit

In order to analyze the impact of minimum merchant profit constraint (11) on the results, we perform additional simulations for different values of κ. In the results shown in Table III the value of κ was set to 1. For values below 1, constraint (11) is inactive because the merchant objective function (8) will take value zero at worst, reflecting the no investments decision. Results from Table IV show sensitivity analysis for different values of κ in case of medium storage costs. For 5% required profitability, some investments for 50% and 70% wind penetration levels are reduced as compared to κ=1.0 because they cannot generate sufficient revenue. For instance, in case of 70% wind penetration, capacity of energy storage at bus 223 is reduced, while installation at bus 318 is voided. Merchant storage investments further reduce as the required profitability increases. At 20% required profitability, no merchant storage investments are made. Social welfare values reduce with the increased profitability requirements, thus resulting in the same investment decisions as for high energy storage investment cost. The SO investments remain the same for all values of κ, i.e. the SO invests solely in transmission lines.

Sensitivity analysis for different values of parameter κ for medium storage cost, but when the SO is unable to invest in transmission lines, is shown in Table V. Again, merchant investments reduce as the required investment profitability increases and for κ=1.2 merchant storage is not installed. However, SO storage is not installed either because the improvement in social welfare is insufficient to cover the storage installation costs.

VI. Conclusions

This paper presents a methodology for coordinated transmission expansion, including both transmission lines and energy storage; and merchant storage expansion. The results from the presented case study yield the following conclusions:

1) Even at low cost of energy storage, the SO will prefer transmission line investment since those assets are more lasting (longer lifetime) than energy storage.
2) Merchant energy storage investments are made in parts of the network with volatile LMPs and where the SO cannot increase the social welfare sufficiently to justify its investments.

TABLE IV. SENSITIVITY ANALYSIS FOR DIFFERENT VALUES OF κ FOR MEDIUM STORAGE COST

Minimum Merchant Profit		Wind Penetration Level		
		30%	50%	70%
κ=1.05	SO investment	L25, L63, L101	L25, L63, L101	L25, L39, L63, L101
	Merchant investment, MWh (bus)	40 (n103)	80 (n223)	160 (n103), 100 (n223), 20 (n212)
	Social welfare, m$ (%)	20.577 (2,2%)	20.916 (2,0%)	21.101 (1,9%)
κ=1.10	SO investment	L25, L63, L101	L25, L63, L101	L25, L39, L63, L101
	Merchant investment, MWh (bus)	20 (n103)	60 (n223)	120 (n103), 60 (n223)
	Social welfare, m$ (%)	20.556 (2,1%)	20.886 (1,9%)	21.085 (1,8%)
κ=1.15	SO investment	L25, L63, L101	L25, L63, L101	L25, L39, L63, L101
	Merchant investment, MWh (bus)	20 (n103)	20 (n223)	60 (n103), 20 (n223)
	Social welfare, m$ (%)	20.556 (2,1%)	20.868 (1,8%)	21.065 (1,7%)
κ=1.20	SO investment	L25, L63, L101	L25, L63, L101	L25, L39, L63, L101
	Merchant investment, MWh (bus)	-	-	-
	Social welfare, m$ (%)	20.539 (2,0%)	20.864 (1,8%)	21.051 (1,6%)

TABLE V. SENSITIVITY ANALYSIS FOR DIFFERENT VALUES OF κ FOR MEDIUM STORAGE COST WHEN THE SO IS NOT ALLOWED TO INVEST IN TRANSMISSION LINES

Minimum Merchant Profit		Wind Penetration Level		
		30%	50%	70%
κ=1.05	SO investment	-	-	-
	Merchant investment, MWh (bus)	40 (n115), 20 (n124)	80 (n223), 40 (n115), 20 (n124)	140 (n103), 70 (n123), 70 (n223), 20 (n322)
	Social welfare, m$ (%)	20.335 (1.0%)	20.680 (0.9%)	20.920 (1.0%)
κ=1.10	SO investment	-	-	-
	Merchant investment, MWh (bus)	40 (n115), 20 (n124)	50 (n223), 10 (n115)	30 (n321), 80 (n103), 30 (n123), 20 (n322)
	Social welfare, m$ (%)	20.315 (0,9%)	20.661 (0,8%)	20.879 (0,8%)
κ=1.15	SO investment	-	-	-
	Merchant investment, MWh (bus)	30 (n115)	30 (n223), 10 (n124)	30 (n321), 40 (n103), 20 (n123), 20 (n322)
	Social welfare, m$ (%)	20.235 (0,5%)	20.600 (0,5%)	20.858 (0,7%)
κ=1.20	SO investment	-	-	-
	Merchant investment, MWh (bus)	-	-	-
	Social welfare, m$ (%)	20.134 (0,0%)	20.497 (0,0%)	20.713 (0,0%)

3) Both the SO and merchant investments increase the social welfare. However, this increase is mainly driven by the SO's investments in transmission lines.
4) Merchant storage investments increase social welfare, thus diminishing the value of the SO's regulated storage. In case where the SO is allowed only to invest in energy storage, merchant investments will prevail as merchant–owned storage both is operated in for profit manner and also increases social welfare.
5) Merchant storage investments depend on the required minimum profit, which is in the presented case study limited to 15%.

The future work will be expanded to include the reserves market, where merchant–owned energy storage is expected to gain additional revenues. On the other hand, the SO–owned energy storage should not be allowed to provide reserves, since this is a market service. In this case, there is no competition between the SO– and merchant–operated energy storage.

ACKNOWLEDGEMENT

This work was supported by the Croatian Science Foundation under project FENISG (grant no. 7766) and Croatian Transmission System Operator HOPS and Croatian Science Foundation under project SIREN (grant no. I-2583-2015).

REFERENCES

[1] R. Sioshansi, "Using Storage-Capacity Rights to Overcome the Cost-Recovery Hurdle for Energy Storage," *IEEE Trans. Power Syst.*, early access.
[2] Terna storage overview. [Online]. Available at: www.terna.it/engb/azienda/chisiamo/ternastorage.aspx
[3] R. A. Jabr, I. Dafi, and B. C. Pal, "Robust Optimization of Storage Investment on Transmission Networks," *IEEE Trans. Power Syst.*, vol. 30, no. 1, pp. 531–539, Jan. 2015.
[4] H. Pandžić, Y. Wang, T. Qiu, Y. Dvorkin and D. S. Kirschen, "Near-Optimal Method for Siting and Sizing of Distributed Storage in a Transmission Network," *IEEE Trans. Power Syst.*, vol. 30, no. 5, pp. 2288–2300, Sept. 2015.
[5] P. Xiong and C. Singh, "Optimal Planning of Storage in Power Systems Integrated With Wind Power Generation," *IEEE Trans. Sust. Energy*, vol. 7, no. 1, pp. 232–240, Jan. 2016.
[6] R. F. Blanco, Y. Dvorkin, B. Xu, Y. Wang and D. S. Kirschen, "Optimal Energy Storage Siting and Sizing: A WECC Case Study," *IEEE Trans. Sust. Energy*, vol. 8, no. 2, pp. 733-743, April 2017.
[7] Y. Dvorkin *et al.*, "Ensuring Profitability of Energy Storage," *IEEE Trans. Power Syst.*, vol. 32, no. 1, pp. 611–623, Jan. 2017.
[8] E. Nasrolahpour, S. J. Kazempour, H. Zareipour, and W. D. Rosehart, "Strategic Sizing of Energy Storage Facilities in Electricity Markets," *IEEE Trans. Sust. Energy*, vol. 7, no. 4, pp. 1462–1472, Oct. 2016.
[9] Y. Dvorkin, "Can Merchant Demand Response Affect Investments in Merchant Energy Storage?," *IEEE Trans. Power Syst.*, vol. PP, no. 99, pp. 1-1.
[10] T. Qiu, B. Xu, Y. Wang, Y. Dvorkin, and D. S. Kirschen, "Stochastic Multistage Coplanning of Transmission Expansion and Energy Storage," *IEEE Trans. Power Syst.*, vol. 32, no. 1, pp. 643–651, Jan. 2017.
[11] S. Dehghan and N. Amjady, "Robust Transmission and Energy Storage Expansion Planning in Wind Farm-Integrated Power Systems Considering Transmission Switching," *IEEE Trans. Sust. Energy*, vol. 7, no. 2, pp. 765–774, April 2016.
[12] Y. Dvorkin, R. Fernandez Blanco Carramolino, Y. Wang, B. Xu, D. Kirschen, H. Pandžić, J. P. Watson, and C. A. Silva-Monroy, "Co-planning of Investments in Transmission and Merchant Energy Storage," *IEEE Trans. Power Syst.*, early access.
[13] D. Pudjianto, M. Aunedi, P. Djapic and G. Strbac, "Whole-Systems Assessment of the Value of Energy Storage in Low-Carbon Electricity Systems," *IEEE Trans. Smart Grid.*, vol. 5, no. 2, pp. 1098-1109, March 2014.
[14] R. S. Go, F. D. Munoz, J. P. Watson, "Assessing the economic value of co-optimized grid-scale energy storage investments in supporting high renewable portfolio standards," *Applied Energy*, vol. 183, pp. 902-913, December 2016
[15] W. Qi, Y. Liang, Z. J. M. Shen, "Joint Planning of Energy Storage and Transmission for Wind Energy Generation," *Operations Research*, vol. 63, no. 6, pp. 1280-1293, December 2015
[16] D. Pozo, J. Contreras, E. Sauma, "If you build it, he will come: Anticipative power transmission planning," *Energy Economics*, vol. 36, pp. 135-146, March 2013

[17] California Independent System Operator, Transmission Economic Assessment Methodology (TEAM), available at: https://www.caiso.com/Documents/ TransmissionEconomicAssessmentMethodology.pdf, June 2004
[18] B. Zeng and L. Zhao, "Solving two-stage robust optimization problems using acolumn-and-constraint generation method," *Op. Res. Let.*, vol. 41, no. 5, 2013, pp. 457–461.
[19] E. Nasrolahpour; J. Kazempour; H. Zareipour; W. D. Rosehart, "Impacts of Ramping Inflexibility of Conventional Generators on Strategic Operation of Energy Storage Facilities," *IEEE Trans. Power Syst.*, early access.
[20] H. Pandžić, Y. Dvorkin, T. Qiu, Y. Wang, and D. Kirschen, Unit Commitment under Uncertainty GAMS Models, University of Washington, Seattle, USA. [Online]. Available at: www.ee.washington.edu/research/real/gamscode.html
[21] J. Dupacova, N. Growe-Kuska, and W. Romisch, "Scenario reduction in stochastic programming: An approach using probability metrics," *Math. Program.*, vol. 95, pp. 493-511, 2003.

Kristina Pandžić (S'13) received her B.Sc. and M.Sc. degrees from the University of Zagreb Faculty of Electrical Engineering and Computing, Croatia, in 2012 and 2014, respectively. She is employed at the University of Zagreb Faculty of Electrical Engineering and Computing as a research and teaching assistant pursuing her doctoral degree. Her fields of interest include planning, operation, and economics of power and energy systems.

Hrvoje Pandžić (S'06-M'12-SM'17) received his M.E.E in 2007 and PhD in 2011 from the University of Zagreb Faculty of Electrical Engineering. From 2012 to 2014, he was a Postdoctoral Researcher with the University of Washington, Seattle, WA, USA. Currently, he is an Assistant Professor with the University of Zagreb Faculty of Electrical Engineering and Computing. His research interests include planning, operation, control, and economics of power and energy systems.

Igor Kuzle (S'94-M'97-SM'04) is a Professor at the University of Zagreb Faculty of Electrical Engineering and the head of the Department of Energy and Power Systems. He was the project leader for more than 60 technical projects for industry and electric power utilities. In period 2010-2015 he was the IEEE PES Chapter Representative for Central Europe and Scandinavia in IEEE Region 8.

His scientific interests include problems in electric power systems dynamics and control, maintenance of electrical equipment, smart grids as well as power system analysis and integration of renewable energy sources.