Impacts of Energy Storage on Short Term Operation Planning Under Centralized Spot Markets

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***Abstract*—Energy Storage Systems (ESS) are an alternative to provide flexibility in power system operation. ESS have been foreseen as crucial technologies to facilitate the transition to a low-carbon energy matrix that integrates higher level of renewable variable energy resources.**

In this paper, the integration of grid-scale ESS in short term operational planning under a centralized cost-based electricity market is analyzed through an adapted stochastic unit commitment formulation to provide energy arbitrage, primary or/and secondary reserve. Several computational simulations are performed in a realistic study case to discuss techno-economic effects of ESS integration in detail. Results obtained show that value of storage is increased when ESS jointly provide different services. Additionally, ESS enable greater participation of renewables into generation mix, while reducing impacts on flexible power plants. Influence of ESS in marginal price signals is also discussed. The undertaken discussion provides insight information for agents in liberalized markets.

***Index Terms*—Energy storage systems (ESS), operating reserves, renewable energy, stochastic programming, unit commitment, wind power.**

I. Introduction

BINDING targets for greenhouse gas reductions over the next decades have been set by governments worldwide. It is expected that the share of electricity generation from variable renewables—such as wind, photovoltaic, tidal and wave power—will increase rapidly [1]. The natural variability of such technologies arise unprecedented challenges to the energy systems. For instance, the short term planning and operation of power systems will demand greater flexibility in order to maintain the balance between supply and demand in this new paradigm [2], [3].

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Energy Storage Systems (ESS)—among other options, such as demand-side management, improved forecasting or cross-border interconnection—are highlighted by several studies as a crucial technology to mitigate the challenges of the transition to a low-carbon energy matrix that integrates higher level of variable energy resources [3]–[7]. ESS are suitable for a broad spectrum of applications associated with integration of renewable energy providing more flexibility into the grid. In [8] and [9] authors present an extensive up-to-date review of storage technologies, identifying numerous potential applications. From the current technologies, Pump Hydro Storage (PHS), Compressed Air Energy Storage Systems (CAES) and certain batteries technologies, such Li-on and Flow batteries are the most suitable for bulk applications, with longer-term storage capacities ranging from hours to days.

ESS advantages, combined with the accelerating rate of cost reductions and technological development of some emerging technologies, and governmental incentive programs, permit to anticipate that there will be increasing levels of ESS in the near future. Despite advantages of ESS, it is challenging to assess the economic value that can be reached by using storage on each application [6]. Active research has been conducted to study impacts of ESS on power system operation and economic value coupled with renewables integration. Single or multiple applications have been studied using simplified dispatch models, historical market data to maximize net profit, or unit commitment formulations [10]–[17].

Nevertheless most of the models founded in the literature to study the value streams of ESS, determine their optimal bids in the energy market to maximize profit obtained, assuming forecasts of energy and ancillary services prices for next day operation. In such market structures, value of storage depends on agents' strategies within the market, which difficult assessment of ESS value, since assumptions on price profiles may not be valid. Additionally, such models neglect the effect that storage may have in the market operation—especially in medium-sized power systems—which is reflected in the influence of ESS operation on market prices.

In cost-based energy spot markets, system operating decisions are centrally established and coordinated by the System Operator (SO) in a cost-based basis, with the purpose of minimize expected operational costs. In such conditions, operating decisions for ESS are no longer determined following individual agents revenue maximization, but established on an overall efficiency target to maximize social-welfare. This situation enables to clearly determine potential benefits in social-welfare obtained by introducing ESS into the system operation.

This paper presents an exhaustive analysis of repercussions of grid-scale ESS in a real thermal power system under a centralized spot market. An ESS model is adapted in a two-stage stochastic unit commitment (UC) formulation. To account for ESS capabilities, relevant technical constraints are introduced to provide energy arbitrage, primary and secondary reserve during power system operation. The evaluation of synergies between energy arbitrage and the provision of secondary reserve from ESS is performed in the Chilean Northern Interconnected Power System (SING).

Several UC simulations are performed to discuss techno-economic effects of ESS integration in detail. The authors study storage capabilities to incorporate greater levels of renewables into generation mix, while reducing impacts on flexible power plants. Economic effects such as reduction of system operational costs and impacts on energy marginal price are shown. The undertaken discussion provides insight information for agents in liberalized market, showing how value of storage is increased when ESS jointly provide different services.

II. Approaches for Evaluating ESS Value

Different models are found in literature to assess the value of ESS. They differ in the market modeling considerations, and can be classified into two trends. On the one hand, ESS is assumed not having influence on the market (price-taker), so energy prices are considered as an exogenous parameters in the model. In such cases, operation is carried out according to a profit maximization objective.

On the contrary, the second group considers that ESS influence price signals within the market. Hence, operation of the entire system, along with ESS, is determined under a single procedure, embedded into the system scheduling model (UC).

A. Profit Maximization Models (Price-Taker)

As mentioned, evaluation of ESS is in some cases carried out by considering an agent's profit maximization objective. In [11] authors introduce market prices and wind generation uncertainty in a two-stages stochastic model to obtain a joint day-ahead market bid (purchase or sale) of a PHS coupled with a wind farm. Other authors [14] propose a statistical method to obtain the optimal operation of a PHS that is capable to maximize energy profit and compensate wind power forecast errors given a confidence interval. The model considers that the power generated or consumed while pumping must take into account the possible deviations contained within the confidence interval. Additionally, the operating schedule considers that ESS must reserve energy capacity to cover accumulative addition of imbalances; energy stored should be enough to cover cumulative underproduction, and reservoir should not be full to cover overproduction cases.

Multiple value streams from ESS are also evaluated in profit maximization models. Kazempour [12] propose to obtain the energy, spinning and regulation reserves bids simultaneously to maximize profit, considering a price taker PHS. Uncertainty of activation of reserves and its impact on energy stored is modeled in the energy constraints, by considering fixed probabilities. The minimum level reached by the PHS must be, in each period, greater than scheduled reserves for next period. Such considerations are crucial to be introduced, since reserve activations could, in the worst conditions, extinguish energy stored. In [13] a model to co-optimize a CAES revenue from energy arbitrage, spinning and non-spinning reserve is studied for several U.S. markets. Study assumes that all the spare capacity is contracted successfully in the market, but it does not internalize the effect of deviations in the energy stored aforementioned.

In order to account for schedule deviations due to reserve activation in real time operation, other authors such as Thatte *et al.* [15] consider that all scheduled regulation up and down reserves sold in the market affects the energy stored, assuming that activation certainly occurs in each period.

B. ESS Into System Scheduling Models (UC)

Along with difficulties encountered in profit maximization models to take into account reserve activation from ESS, technical impacts of storage in power system operation, such as commitment of generating units, are barely evaluated. However, some authors have been working in modeling ESS into system scheduling process to incorporate these phenomena's.

In [10] the storage value to provide standing reserve in the future UK system is assessed using a simple priority list to schedule generation, and a linear model for real time dispatch. Value of storage is driven by wind installed and flexibility of the generation mix.

To evaluate impacts of ESS on system scheduling, Daneshi *et al.* [16] extend a previous SCUC model to study several impacts of integrate CAES into energy, regulation, spinning and non-spinning reserves. However, uncertainty of wind power is not considered into the reserves determination. Reserves are considered in the power limits of generating/pumping load. Similarly, in [17] a two-stage algorithm to solve a min-max robust UC optimization is presented to obtain a schedule for thermal generators that are capable of minimizing costs under worst case inter-hour wind power fluctuations when considering a PHS.

III. Stochastic UC Model Including ESS

The particular challenge of including ESS into day-ahead scheduling process is to guarantee that sufficient energy will be available in the ESS to provide energy and reserves when required. Most of models aforementioned avoid or simplify this issue, but in cost-based energy spot market this point turns out to be critical. In such market structures, system operating decisions are centrally established and coordinated by the SO. Hence, reserve activation must be considered during the scheduling process. Thus, in order to determine the value of storage, it is necessary to account for ESS storage limitations.

A two-stage stochastic UC formulation, that incorporates ESS for energy arbitrage and spinning reserves into the day-ahead market clearing process, is proposed to evaluate the contribution of storage into power system operation. The notation used in the formulation is described in Table I.

A. Stochastic UC Formulation

The proposed stochastic approach (1)–(31) minimizes the expected operation, start/stop, and unserved energy costs, over a set of representative scenarios (1), subject to power

TABLE I
UC NOTATION

Notation	Definition
G	Set of all generation units, $g \in G$
G^{SL}	Sub set of slow start units. G^{SL}
G^{FS}	Sub set of fast start units
E	Set of all ESS, $e \in E$
S	Set of all scenarios, $s \in S$
$\overline{P_g}$	Maximum capacity limit for generator g
$\underline{P_g}$	Minimum capacity limit for generator g
β_g	Variable cost generator g
C_g^{Start}	Start-up cost generator g
C_g^{Stop}	Stop cost generator g
G_g^{UP}	Up ramp limit generator g
G_g^{DN}	Down ramp limit generator g
$\overline{W}_t^s$	Available wind power, hour t, scenario s
$\overline{S}_t^s$	Available solar power, hour t, scenario s
π^s	Probability of occurrence, scenario s
l_t	System load, hour t
$\overline{E_e}$	Maximum storage capacity, ESS e
$\underline{E_e}$	Minimum required level stored energy, ESS e
$\overline{d_e}$	Maximum discharge capacity, ESS e
$\overline{c_e}$	Maximum charge capacity, ESS e
$\eta_{d,e}$	Discharge efficiency, ESS e
$\eta_{c,e}$	Charge efficiency, ESS e
$P_{t,g}^s$	Power output, generator g, hour t, scenario s
$SR_{t,g}^{UP}$	Up spinning reserve, generator g, hour t
$SR_{t,g}^{DN}$	Down spinning reserve, generator g, hour t
$TR_{t,g}^{UP}$	Non-spinning reserve, generator g, hour t
W_t^s	Wind power output, hour t, scenario s
S_t^s	Solar power output, hour t, scenario s
Ws_t^s	Wind power spillage, hour t, scenario s
Ss_t^s	Solar power spillage, hour t, scenario s
U_t^s	Unserved energy, hour t, scenario s
$E_{t,e}^s$	Energy stored, ESS e, hour t, scenario s
$c_{t,e}^s$	Charging level, ESS e, hour t, scenario s
$d_{t,e}^s$	Discharging level, ESS e, hour t, scenario s
$SR_{t,e}^{UP}$	Up spinning reserve, ESS e, hour t
$SR_{t,e}^{DN}$	Down spinning reserve, ESS e, hour t
$u_{t,g}^s$	Unit Commitment, generator g, hour t, scenario s
$v_{t,g}^s$	Start-up flag, generator g, hour t, scenario s
$b_{t,g}^s$	Turn-off flag, generator g, hour t, scenario s
$C_{op}(p_{t,g}^s)$	Operation cost, generator g, hour t, scenario s
$C_{start}(v_{t,g}^s)$	Start-up cost, generator g, hour t, scenario s
$C_{stop}(b_{t,g}^s)$	Shut-down cost, generator g, hour t, scenario s
$C_{ENS}(U_t^s)$	Unserved energy cost, hour t, scenario s

supply balance (2) and capacity constraints including spinning and non-spinning reserves (3)–(10). Optimal reserves for uncertainty management (9), (10) are determined as pre-post disturbance balances as in [18]. Index s = 0 indicates the pre-disturbance (or error-free) scenario, whereas the scenarios indexed by s>0 are the post-disturbance (or error) scenarios.

$$Min\ f(x) = \sum_s \pi^s \left[\sum_t \sum_g [C_{op} + C_{start} + C_{stop}] + C_{ENS} \right] \quad (1)$$

subject to the following constraints:

$$\Sigma_g P_{t,g}^s + W_t^s + S_t^s + U_t^s + \Sigma_e \boldsymbol{d_{t,e}^s} = l_t^s + \Sigma_e \boldsymbol{c_{t,e}^s} \quad \forall s, t \quad (2)$$

$$W_t^s + Ws_t^s = \overline{W}_t^s \quad \forall s, t \quad (3)$$

$$S_t^s + Ss_t^s = \overline{S}_t^s \quad \forall s, t \quad (4)$$

$$P_{t,g}^0 + SR_{t,g}^{UP} \le u_{t,g}^0 \cdot \overline{P_g} \quad \forall t, g \quad (5)$$

$$P_{t,g}^0 - SR_{t,g}^{DN} \ge u_{t,g}^0 \cdot \overline{P_g} \quad \forall t, g \quad (6)$$

$$P_{t,g}^s \le u_{t,g}^s \cdot \overline{P_g} \quad \forall t, g, s > 0 \quad (7)$$

$$P_{t,g}^s \ge u_{t,g}^s \cdot \overline{P_g} \quad \forall t, g, s > 0 \quad (8)$$

$$SR_{t,g}^{UP} \ge P_{t,g}^s - P_{t,g}^0 \quad \forall t, g \notin G^{FS}, s > 0 \quad (9)$$

$$SR_{t,g}^{DN} \ge P_{t,g}^0 - P_{t,g}^s \quad \forall t, g \notin G^{FS}, s > 0 \quad (10)$$

$$TR_{t,g}^{UP} \le \left(1 - u_{t,g}^0\right) \cdot \overline{P_g} \quad \forall t, g \in G^{FS} \quad (11)$$

$$TR_{t,g}^{UP} + SR_{t,g}^{UP} \ge P_{t,g}^s - P_{t,g}^0 \quad \forall t, g \in G^{FS}, s > 0 \quad (12)$$

$$P_{t,g}^s \le P_{t-1,g}^s + u_{t-1,g}^s \cdot G_g^{UP} + \overline{P_g} \cdot \left(1 - u_{t-1,g}^s\right) \quad \forall t, g, s \quad (13)$$

$$P_{t,g}^s \ge P_{t-1,g}^s - u_{t,g}^s \cdot G_g^{DN} - \overline{P_g} \cdot \left(1 - u_{t,g}^s\right) \quad \forall t, g, s \quad (14)$$

$$v_{t,g}^s = v_{t,g}^s \left(u_{t-1,g}^s, u_{t,g}^s\right) \quad \forall t, g, s \quad (15)$$

$$b_{t,g}^s = b_{t,g}^s \left(u_{t-1,g}^s, u_{t,g}^s\right) \quad \forall t, g, s \quad (16)$$

$$u_{t,g}^s, v_{t,g}^s, b_{t,g}^s \in \{0, 1\} \quad \forall t, g, s \quad (17)$$

$$\left(u_{t,g}^s, v_{t,g}^s, b_{t,g}^s\right) \in \Omega \quad \forall t, g, s \quad (18)$$

$$u_{t,g}^s = u_{t,g} \quad \forall t, g \in G^{SL}, s \quad (19)$$

Note that wind and solar spillage are considered explicitly in the model (3), (4) and load shedding is allowed at a high Value of Lost Load (VOLL), in order to assure schedule feasibility. Ramping constraints for thermal generators are included in (13), (14). For the sake of simplicity, startup and shutdown flags are summarized in (15) and (16) respectively, along with other constraints such as minimum up and downtime constraints summarized in the subset Ω. Commitment decisions of slow start units, such as coal-fired units, are considered first stage decisions. Therefore, the variable **u** remains identical across all scenarios. This is included through non-anticipativity constraints (19). The above consideration not only represents the limited of flexibility of certain technologies to accommodate intraday variability, but also the compromise with the risk aversion of the SO.

Incorporation of ESS into the stochastic UC problem (20)–(31), modifies power supply balance (2) introducing charging $(\boldsymbol{c_t^s})$ and discharging $(\boldsymbol{d_t^s})$ process variables. Main technical constraints of storage are related to energy balance in the ESS (20), charging and discharging capacity limits (21), (22), as well as maximum and minimum levels of storage (23), (24). Boundary condition is considered in (25). Note that hourly charge and discharge power levels are included in the power supply balance (2).

$$E_{t+1,e}^s = E_{t,e}^s + \eta_{c,e} \cdot c_{t,e}^s - d_{t,e}^s / \eta_{d,e} \quad \forall t, e, s \quad (20)$$

$$d_{t,e}^s \le \overline{d_e} \quad \forall t, e, s \quad (21)$$

$$c_{t,e}^s \le \overline{c_e} \quad \forall t, e, s \quad (22)$$

$$E_{t,e}^s \le \overline{E_e} \quad \forall t, e, s \quad (23)$$

$$E_{t,e}^s \ge \underline{E_e} \quad \forall t, e, s \quad (24)$$

$$E_{1,e}^s = E_{NT+1,e}^s \quad \forall t, e, s \quad (25)$$

In case that the ESS provides jointly energy arbitrage and spinning reserves, constraints (26)–(31) are needed.

$$d^0_{t,e} + SR^{UP}_{t,e} \leq \overline{d_e} + c^0_{t,e} \quad \forall t, e \tag{26}$$

$$c^0_{t,e} + SR^{DN}_{t,e} \leq \overline{c_e} + d^0_{t,e} \quad \forall t, e \tag{27}$$

$$SR^{UP}_{t,e} \geq d^s_{t,e} - d^0_{t,e} - \left(c^s_{t,e} - c^0_{t,e}\right) \quad \forall t, e, s \tag{28}$$

$$SR^{DN}_{t,e} \geq c^s_{t,e} - c^0_{t,e} - \left(d^s_{t,e} - d^0_{t,e}\right) \quad \forall t, e, s \tag{29}$$

$$E^0_{t,e} + SR^{DN}_{t,e} \leq \overline{E_e} \quad \forall t, e \tag{30}$$

$$E^0_{t,e} - SR^{UP}_{t,e} \geq \underline{E_e} \quad \forall t, e \tag{31}$$

The model assumes that the ESS is capable to change, in a short interval, between charge/discharge modes. In this way, it is possible to offer spinning reserves on a greater extent. Theoretically, the ESS may provide twice their power capacity for either up or down spinning reserve. For instance, if the ESS is charging at full capacity, it can deviate from this schedule to provide up spinning reserve by interrupting the charge process. If more reserve is required from the ESS, this may change the operation mode starting to discharge at maximum discharging rate. Thus, the ESS would be reducing the load of the system an increasing the generation, contributing with a net effect of twice its power capacity. Similar analysis applies for the case of changing from discharge to charge mode and provide down reserves. This depends on the energy available at the ESS as well as the operating point (charging/discharging power). Constraints (26)–(29) resume the ESS possibility to exploit this flexibility.

In addition to the power constraints that account for reserve capacities, it is necessary to consider that the ESS has a limited energy capacity to provide these scheduled reserves if they are activated during real time operation. Sufficient energy has to be reserved to provide down reserves, when compensating overfrequency events (e.g. overproduction periods from renewables). Likewise, a minimum energy level is required provide up reserves, during underfrequency events. This is assured through constraints (30) and (31) allowing ESS to cover worst-case foreseen deviations in every period.

Moreover, it is important to consider that deviations may occur persistently, leading to a cumulative activation of reserves. Through a deterministic energy requirement, the schedule obtained may be far from optimal. On the contrary, introduction of a set of scenarios into the stochastic UC formulation, like presented in this work, enables to account for cumulative deviations to be absorbed by the ESS and generating units, since scenarios represent the intraday dynamics of the load, wind and solar power.

Hence, the present model (1)–(31) allows assuring that enough energy is available at the ESS in order to provide reserve, for a given charging/discharging pattern determined in the day-ahead market.

IV. Realistic Case Study and Simulation Approach

To evaluate potential benefits of different configurations of ESS into the short term operation planning, computational simulations were carried out in the Chilean Northern Interconnected Power System (SING). The ESS model (20)–(30) was incorporated into UC Stochastic model implemented under GLPK [19] and solved using CPLEX 12.1 with a gap of 0.01% on an Intel i7, 3.0-GHz processor with 8 GB of RAM. The UC Stochastic model has been validated over several case studies, by comparing results with those obtained with the commercial PLEXOS software package [20]. The transmission network is not modeled, so load and generation balance is made at a single node.

A conformation of 64 generating units was used for developing a techno-economic model of the SING. Simulations consider 3800 MW peak load, wind power installed capacity of 1275 MW, and solar power installed capacity of 725 MW, representing a future expected system matrix for the year 2024, where 20% of the electricity comes from renewables. To the date, the SING is mainly thermal, and the technology mix consists predominantly of coal units, with large up/down time, and a high-minimum stable operating point, without cross-border interconnections. Additionally, it counts with a high penetration of FS units, incorporated since the uncertainty of fuel availability experienced in the past.

A. Services and ESS Configurations

To maximize contribution of storage into power system operation requires evaluating multiple value streams from ESS. The integration of ESS in short term operation planning under cost-based energy spot markets is then, analyzed by covering three kinds of services. Firstly, primary reserve is evaluated considering 20-min full rated storage capacity over different rated power, ranging from 10 up to 80 MW.

Energy arbitrage and provision of secondary reserve are also evaluated for different configurations of rated power and storage capacity. Here, technical constraints were introduced in the stochastic UC formulation to jointly provide energy arbitrage and secondary reserve ancillary services from grid-scale ESS during power system operation. Then, an evaluation of synergies between energy arbitrage and the provision of secondary reserve from ESS is performed for the SING.

B. Wind and Solar Scenarios

Most of works in the subject consider wind power forecasting information along with scenario reduction techniques in order to obtain a reduced and representative number of wind power scenarios. In this work, historical wind-speed measurements and hard-partitioning *K-Medoids* clustering [21], [22] is adopted, along with [23] to account for the smoothing effect of aggregated power generation from planned wind farms. Local wind power representative and realistic patterns, along with their probabilities of occurrence, are obtained. Results are scaled linearly to represent different wind power installed capacity within geographical zones. Scenarios are determined within a monthly period, which is enough to capture daily and seasonal wind patterns in the northern Chile. It is important to remark that the clustering process is conducted in different seasons to preserve the seasonal effects of wind power along the year. Fixed probabilities are used for each season after the clustering process. The study does not incorporate a detailed modeling of the stochastic process.

On the solar power patterns, most photovoltaics and concentrated solar power generation projects are located near the Atacama Desert. The entire zone is characterized by the highest solar radiation on the planet with very predictable resources, with nearly non-existence cloud cover. In this way, solar power profiles are considered deterministic, seasonally variable, and uniform throughout the region.

C. Performance Evaluation

To benchmark quantitative advantages of an ESS in the SING, a comparison has been carried out between operational conditions of the system considering a penetration of 20% for 2024. As mentioned, computational simulations have considered the provision of different services and configurations (rated power and storage capacity) to determine real contribution of adding multiple value streams from ESS. To characterize the expected system behavior over one year period, 36 representative segments of 72 hours were chosen considering variations in wind and solar power patterns, maintenance program and demand growth, to reflect operational conditions and reducing computational effort. Specific conditions of the SING were taken into consideration to define selected segments: flat demand profile since 90% of electricity consumption comes from mining industry, and seasonal behavior of wind and solar patterns. Load data provided from the System Operator (CDEC-SING[1]) is used during computational simulations carried out in this study.

The general procedure of the evaluation framework consists of the following steps:

1) Wind and solar power scenarios are generated along with their probabilities as explained in Section IV-B.
2) UC is solved at segment $i+1$, considering initial boundary conditions from segment i, using probability distribution of cluster generated in step 1.
3) Expected operating costs resulting from step 2 are computed as the sum of each scenario, weighted by the probability distribution generated in step 1.
4) Results from segment $i+1$ are evaluated considering its duration within the year examined.

V. Results

Firstly, a detailed analysis of daily operational impacts is presented for a particular day, emphasizing in the intraday operational decisions. Secondly, results of consecutive stochastic UC simulations for a full year were performed to evaluate the economic effects and the correspondence with the operation of an ESS in the SING. Additionally, sensitivity analysis were performed, in order to understand impacts of ESS under different circumstances.

A. Daily Operational Impacts

A detailed analysis of the short term operational effects of ESS is presented. Fig. 1 shows the aggregated solar and wind power scenarios used in the example. To facilitate analysis and conceptual understanding, results obtained by solving UC are presented by gathering units according to their combustion fuel.

[1]http://www.cdec-sing.cl (in Spanish)

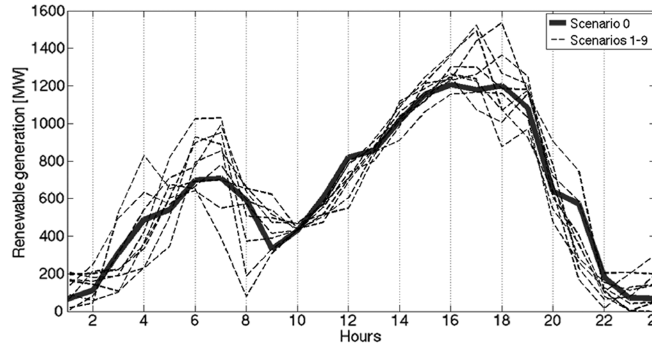

Fig. 1. Renewable generation scenarios for daily analyses.

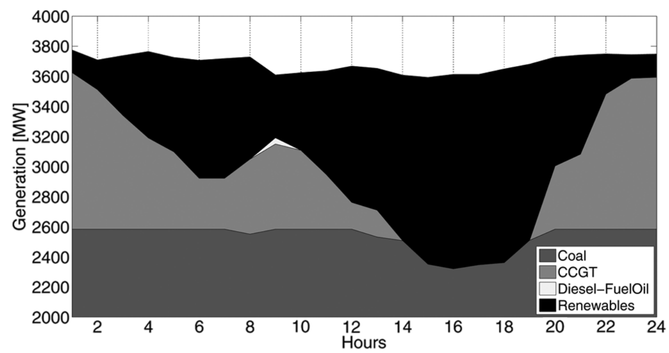

Fig. 2. Day-ahead schedule (without ESS).

As UC is performed, Fig. 2 shows the day-ahead schedule obtained for the SING **without ESS**. Coal units exhibit long start-up times, so are rarely shut-down during the SING operation. On the other hand, CCGT (gas-fired) and Fast-Start units (diesel or fuel-oil) are expected be used with an intensive cycling operation, showing the important role of these technologies to handle wind and solar fluctuations. In fact, the importance of turn-off and start-up decisions, as shown in hours 14 and 20, is reflected in a more flexible operation of the power system, enabling an appropriated integration of renewables into the SING.

The introduction of an ESS has different impacts on system operation, depending on the services provided by the storage facilities. Fig. 3 illustrates operating schedule obtained when introducing an ESS of 100 MW–600 MWh used for **energy arbitrage only**. Results show that coal-fired units reduce their participation in the load-following process (hours 14 to 19). Similarly, CCGT (hours 13–14) and fast-start (hour 9) units tend to decrease their usage. Start-up and shut-down schedule of CCGT units is affected by the introduction of the ESS. Thus, an overall reduction in equivalent operating hours (EOH) is achieved as a result of lower variability in net-demand.

Fig. 4 shows ESS charge/discharge profile and corresponding renewable generation. Note that charging process is carried out when cost-efficient generators are available—in situations of low net-demand or high power generation from renewables—replacing relative importance of fast-start units to face renewables variability and lack of predictability.

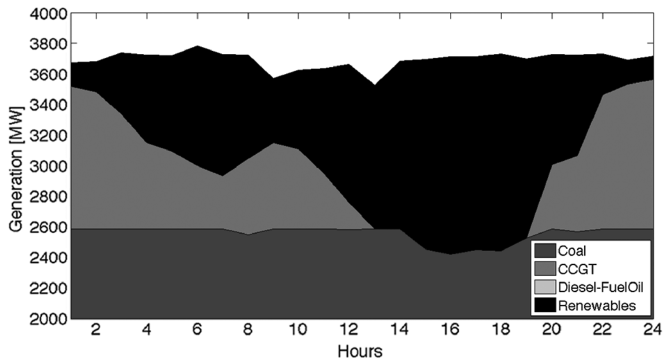

Fig. 3. Day-ahead schedule (with ESS in energy arbitrage mode).

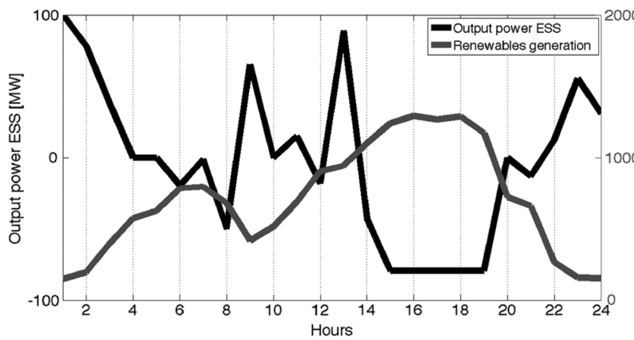

Fig. 4. ESS operating schedule v/s renewable generation (with ESS in energy arbitrage mode).

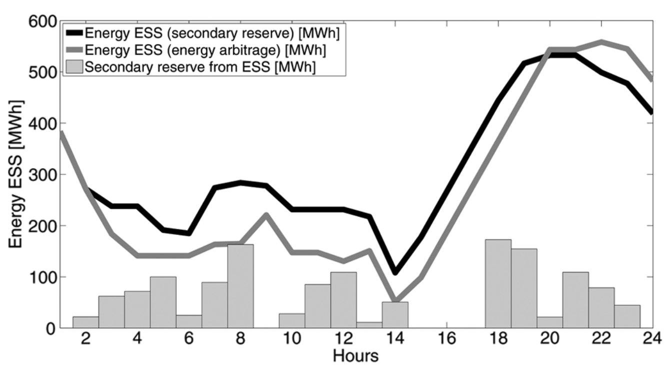

Fig. 5. Daily charge/discharge pattern of ESS for different services.

As shown, the introduction of an ESS implies a modification in the system operation when used for energy arbitrage. This leads to a more efficient operation of the SING, reducing operational costs in about 0.5%.

Nevertheless, the solely energy arbitrage application does not exploit the whole potential of ESS. When including an ESS to jointly provide **energy arbitrage and secondary reserve**, reductions in operational costs are even greater, reaching 1.1% in savings.

As shown in Fig. 5, when ESS jointly provides energy arbitrage and secondary reserve (black line), the stored energy profile is modified. The ESS must be scheduled to either charge or discharge it if needed to provide up or down secondary reserve. Thus, stored energy remains in a narrower band between maximum and minimum limits (30), (31). It is also important to notice that in hour 18 the ESS provides 173 MW of secondary up reserve, which is greater than the charge/discharge capacity (100 MW), as discussed in Section III.

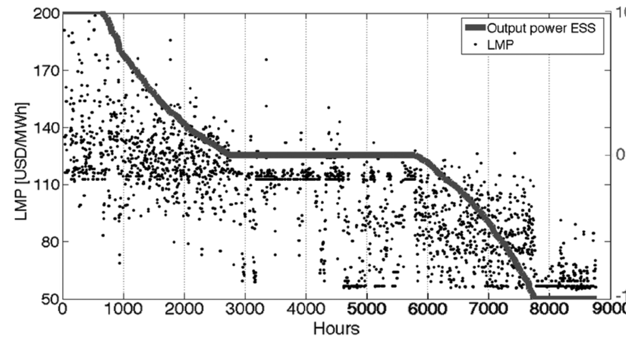

Fig. 6. Charge/discharge pattern of ESS v/s marginal prices.

In brief, results show that when the ESS participates in the power supply balance, peaking generation, from diesel, fuel-oil and CCGT units (with higher operation costs), is transferred to the ESS. On the contrary, the provision of secondary reserve from coal units, with high opportunity costs (with lower operation costs), is allocated to the ESS. Thus, operational cost savings are achieved by transferring provision of services from less efficient units (with higher operation costs in the case of energy, or higher opportunity cost in case of reserves) to the ESS.

B. Yearly Operational Results

To verify reductions in operational costs, the same ESS configuration (100 MW–600 MWh) was used for operational simulation of the SING in 2024. Following the evaluation framework proposed in Section IV, results show that when operating the ESS for **energy arbitrage and the provision of secondary reserve**, a reduction of about 1.15% is reached. Such savings are directly associated with a greater use of cost-efficient generating technologies. Coal-fired units increase its share in the generation mix in about 1.15%. Meanwhile, diesel and fuel oil generators significantly decrease their generation level. Reductions reached 10% for CCGT and fuel oil-units, whereas almost 40% of diesel generation is avoided. Since coal units have lower operational costs, this shift in the primary energy use results in a reduction in the overall system operation costs.

Fig. 6 shows the charge/discharge pattern of the ESS, for each hour for the yearly simulation, and corresponding energy price observed (black dots). Positive output power indicates discharging mode of the ESS, as shown in right hand y-axis. In turn, negative values are related to charging process. Expected energy prices for 2024 are about 101 USD/MWh, which represents a 20% increase of current prices. High volatility in prices is related to the massive penetration of renewable energy by the year of study. Note the correlation between charge/discharge with low/high prices, showing the expected behavior of the ESS to maximize social-welfare. ESS is charged when low prices occurs (77 USD/MWh on average), while discharging when high prices takes place (132 USD/MWh on average).

Other impacts in the operation of the SING with the introduction of an ESS are related to a decrease in the variations on net demand, reduction in start-up and shut-down events for CCGT, diesel and fuel-oil units, and reduced participation of coal-fired and CCGT units in the load-following process. It is expected that introduction of the studied ESS decreases EOH

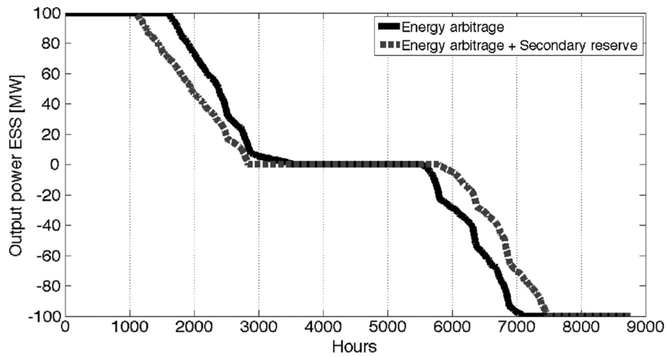

Fig. 7. Yearly charge/discharge duration curve of ESS considering different services.

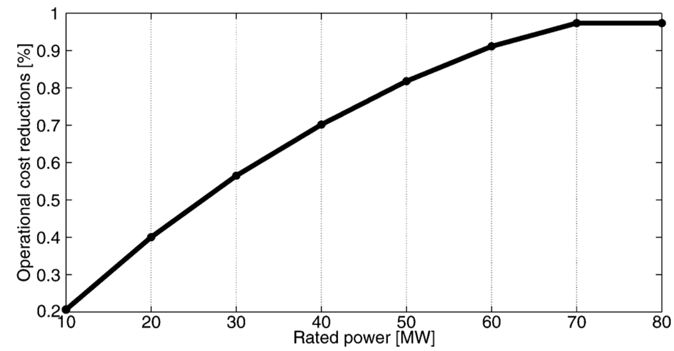

Fig. 8. Cost reductions when including ESS in primary reserve provision.

by approximately 20% for CCGT units. The quantitative impacts illustrated before, may have a bearing in reducing maintenance cost, improving power plants availability, maximizing periods of operation between inspections and overhauls, while extending components lifetime.

The type of services provided by the ESS defines how storage is handled by the SO to perform an efficient system operation as in Section V-A. Fig. 7 shows the variation in the yearly charge/discharge duration curve when the ESS provides energy arbitrage, and then jointly secondary reserve. To provide secondary reserve from the ESS, not only is necessary to store enough energy, but also operate with a lower charge/discharge rate to increase output power when required. As expected, lower charge/discharge power is used by the ESS when jointly provides energy arbitrage and secondary reserve.

Note that results obtained are based on day-ahead market decisions under a stochastic unit-commitment approach. The proposal involves ESS to participate in both markets (real-time and day-ahead). The challenge is to take into account the way storage utilizes its energy during the day to face uncertainties in real-time operation and to assure that there will be enough energy stored to coupe with it. If real-time operation differs from what was considered in the day-ahead market, reserves has to be deployed to maintain the system in a normal operation state (using secondary reserves to provide secondary frequency control).

Under the proposed two-stage stochastic UC, several scenarios are considered to account for deviations from the day ahead forecast. Since these scenarios are included into the scheduling process, the computational simulations carried out include expected costs of system reaction to forecast errors, through the corrective actions—deployment of scheduled secondary and tertiary reserves. These actions correspond to what is expected to happen in real time operation, once uncertainty is revealed and the real time wind and solar power generation occurs. Note that savings in operational costs are expected cost reductions.

C. Sensitivity Analysis

Further analyses were carried out to understand impacts of ESS under different circumstances. Simulations cover three different aspects: provision of primary reserve from ESS, effects in energy prices depending on different ESS configurations (rated power and storage capacity), and various renewable integration levels.

Fig. 8 shows reductions in operational costs when incorporating an ESS to provide exclusively primary reserve. It has been found that by installing 70 MW in primary reserve, savings in operational costs are similar to those obtained when operating an ESS of 100 MW–600 MWh but providing energy arbitrage and secondary reserve. Nevertheless, storage capacity in the first case is much lower, requiring 24 MWh to provide a reliable service. Thus, the value of storage in the SING is greater for primary reserve rather than energy arbitrage and secondary reserve. Note that this result may vary across different power systems.

Computational simulations indicate that 1% in savings (from yearly operational costs) represents almost 10 MUSD. Considering an investment cost of 2250 USD/kWh, such reduction represents almost a 25% of total capital cost of a 70 MW facility providing exclusively primary reserve. Such results show an attractive scenario for incorporating ESS to provide such service in the SING. However, it is important to remark that evaluation of ESS benefits must be performed in the long-term. This means that if results for one year simulation produce an overestimation of long-term expected benefits, evaluation will lead to a sub-optimal storage capacity.

The influence of ESS on energy prices is another important aspect to evaluate when studying integration of storage into power systems. Fig. 9 illustrates duration curves for energy prices when incorporating ESS with different rated power—considering the same storage capacity of 600 MWh. Results show that the greater the rated power of the ESS, the flatter the energy prices in the system. The reduction in energy prices volatility is an important aspect for developers of renewable energy projects. The tradeoff between higher prices at peak production levels versus lower prices in low generation periods, involves changes in energy sales. Thus, this is an interesting topic that needs to be studied further, since ESS could be a financial driver to bring more renewables into the grid. This suggests that price-taker assumptions, in profit maximization models, needs to be aware of potential influence of ESS in energy prices.

The future development of wind and solar power would modify the benefits obtained by the introduction of an ESS. Thus, sensitivity analyses were carried out considering different installed capacities from both technologies into the SING. A

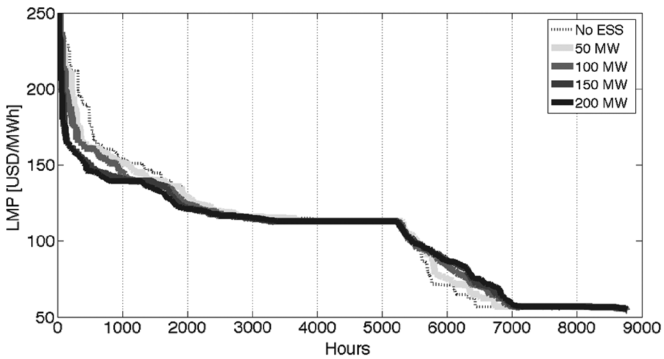

Fig. 9. Variations in marginal prices under different ESS configurations.

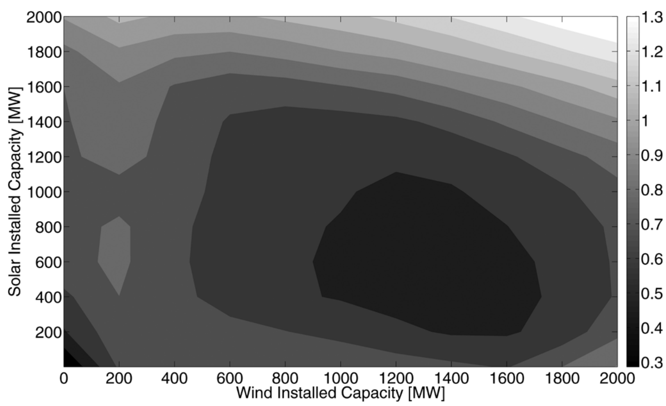

Fig. 10. Cost reductions (%) for different solar and wind installed capacities.

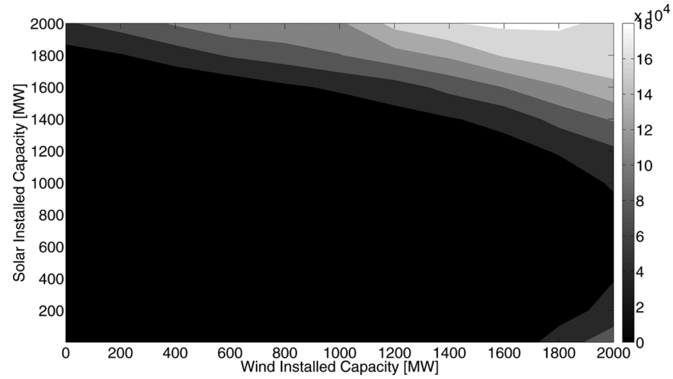

Fig. 11. Wind and solar spillage reductions (MWh) for different installed capacities.

configuration of 100 MW–600 MWh was operated providing energy arbitrage and secondary reserve. As illustrated in Fig. 10, cost reductions are greater as installed capacity from wind and solar power increases, or in other words, as net demand becomes more variable and less predictable. Note that in the case of the SING, despite that demand presents a flat pattern, the introduction of renewables causes a variation in net-demand. Given the characteristics of wind and solar resources within the system, the increased variation in net-demand is exacerbated when considering higher level of wind and solar generation. A more variable system increases potential of ESS in technical and economic terms.

Additionally, ESS gives more flexibility into the grid, allowing a greater participation of renewables into generation mix. As shown in Fig. 11, important yearly wind and solar spillage reductions are obtained—depending on renewables installed capacity. In short, ESS becomes more relevant when installed capacity of variable renewable technologies is greater.

VI. Conclusions

The maximization of storage value will likely require multiple value streams from ESS. Analyses of simultaneous applications that internalize the technical characteristics of ESS are covered in this paper.

The integration of ESS in short term operation planning under centralized spot markets is analyzed, by covering three kinds of services: energy arbitrage, primary reserve and secondary reserve. To analyze impacts of introducing ESS into power system operation, the Chilean Northern Interconnected Power System was used as a test bed.

According to the results, ESS turns out to be an efficient way to provide primary reserve, since storage replace provision of this service from less expensive generating units, with high opportunity costs to provide reserve.

An evaluation of synergies between energy arbitrage and the provision of secondary reserve from ESS was also performed. Results reveal that jointly provision doubles the value of storage. The impact of an ESS in the energy market is reflected in a less variable operation of traditional generating units, while reducing thermal power plants equivalent operating hours, improving system adequacy.

The authors show the influence of ESS in energy prices. This suggests the need to revisit profit maximization models when high levels of storage are analyzed. Additionally, it has been found that ESS becomes more relevant when installed capacity of variable renewable technologies is greater.

Future work entails the discussion optimal sizing of ESS in power systems. Similarly, further analyses on ESS's lifetime should be carried out depending on the considered storage technology.

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