Energy Storage System to Facilitate High RE Penetration: A Techno-economic Benefit Analysis

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***Abstract*- Ambitious targets for climate-change mitigation and energy sufficiency lead to rising share of renewable energy (RE) in generation mix. With future market scenario and potential of large-scale deployment, major contribution is provided by solar and wind RE sources. However, their intermittent nature not only increases the variability and uncertainty in power system but also deteriorates its performance in many technical and economic aspects such as frequent load & RE curtailment, decreased capacity utilization and increased operating cost of conventional generating units. For smooth integration of RE, grid planners need to ensure that enough flexible options are available down the road that will help to maintain system reliability without deteriorating the performance of conventional units. In this regard, this paper formulates a security-constrained unit commitment (SCUC) problem for a whole year in rolling horizon and performs techno-economic benefit analysis of energy storage system (ESS) to facilitate high RE integration. System benefits are accounted in-terms of reduced system operating cost, increased RE penetration & capacity utilization factor, and reduced CO_2 emissions.**

Keywords - Capacity utilization factor, energy storage system, RE integration, reserve, uncertainty

I. Introduction

Transition towards decarbonization of energy system coupled with the issues of declined fossil fuel require proliferation of renewable energy (RE) sources in power sector. Looking at future market projections and owing to large-scale deployment capability, intermittent solar and wind RE generation indicate high growth rate in this era. However, their intermittent nature poses additional challenges to system operators besides demand supply balancing. In traditional power system the major challenge in real time system operation is to meet demand supply balance and retain sufficient reserve to handle contingency. The challenges that occur during structural matching of supply with demand in high RE scenario are reduced capacity credits, decreased plant load factor of dispatchable generating units and excess generation [1].

High penetration of intermittent RE generation increases variability and uncertainty in the power system. Operational constraints such as minimum stable generation and minimum up & down time limit frequent cycling of conventional power plants and cause recurrent RE or load curtailment. Moreover, uncertainty associated with renewable generation calls for additional reserve capacity in the system. These challenges increase overall operating cost incurred to system operator. Therefore, there is need to opt a solution that can consume as well as deliver power whenever required. With high ramping capability and quick response time, energy storage system (ESS) is emerging as a potential candidate for future flexibility portfolio. Being a carbon-free source, it can play an important role to support decarbonization of electrical sector and simultaneously improve the operation flexibility of grid. However, it is a capital-intensive solution.

ESS can provide multiple grid services at various time scale such as energy shifting, peak shaving, load following and regulation services [2, 3]. Line of research to maximize the profit that can be procured from these different grid services to justify its high capex to ESS owner are short-run basis [4]. However, it is equally important to analyses its impact on power system reliability and performance of other dispatchable units in order to introduce it in system level policies & planning [5].

Therefore, from system perspective, a study is required to quantify and monetize its benefits to the system by scheduling it with other generating units for long-run. For this, unit commitment problem is to arrange over a longer period of study and long-term study of chronological short-term system operations need to be performed. This arrangement will help to capture significant diurnal and seasonal variation of RE and load. Also, chronology will help to establish minimum up and down time constraints of conventional units. In this regard, this paper formulates security-constrained unit commitment (SCUC) problem for a whole year and performs techno-economic benefit analysis of ESS in high RE scenario. By running simulation for a whole year, diurnal variation of RE and load can be captured. By analyzing yearly performance of system, benefits of integrating ESS are accounted in-terms of reduced system operating cost, increased RE penetration & its capacity utilization factor, and reduced CO_2 emissions. Moreover, a comparison of monetized system benefits and life-cycle cost of ESS is performed to satisfy its economic viability in system. Following cases are considered for the studies

Case-I: Base case; without RE and energy storage integration.

Case-II: With RE integration; additional reserve from conventional generating units to address RE uncertainty.

Case-III: With RE and energy storage; Storage is participating in balancing and reserve services with conventional generating units.

Detailed problem formulation of proposed model is explained in section II. Data preparation is presented in section III. Analysis on different cases is demonstrated in section IV. Section V concludes the proposed work.

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II. Problem Formulation

This paper proposes a yearly unit commitment model split into hourly time steps. To reduce the computation burden, problem is split into weekly optimization subproblems that runs for whole year recursively in rolling horizon. Optimization runs for 168+1 hours that covers 1 week and 1 extra hour as a look ahead (overlap) period as shown in Fig. 1. Final values (Status and output of all generating resources) of optimization of previous week (w-1) become the initial values of optimization of next week (w). Out of 169 hours only first 168 hours are conserved.

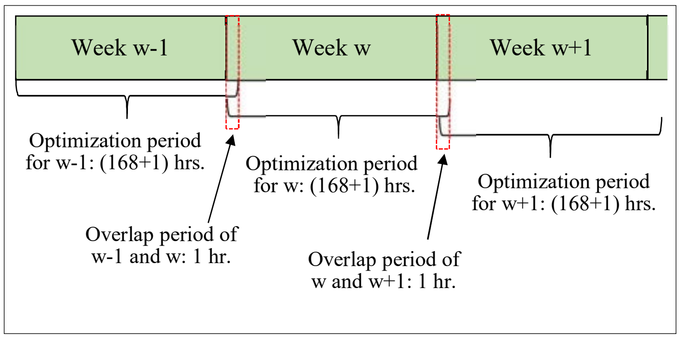

Fig. 1. Rolling horizon of optimization with overlap period between consecutive weeks

A. Objective function

Problem minimizes the total power system operating cost F^{op} defined in terms of sum of all cost components such as fixed operation and maintenance (O&M) cost C_g^{fx}, variable O&M cost C_g^{vr}, Start-up cost C_g^{su} and shut-down cost C_g^{sd} of conventional generating units, emission cost EC for CO_2 emission, penalty for load curtailment PLC, solar curtailment PSC & wind curtailment PWC and reserve allocation cost RAC as given in (1). Here, positive variable $P_{g,t}$ is the power output and $v_{g,t}$, $x_{g,t}$, $y_{g,t}$ are the binary variables to show commitment, start-up and shut-down status respectively of unit g at time t. $L_{b,t}^{ct}$, $P_{s,t}^{ct}$, $P_{w,t}^{ct}$ are the amount of load, solar and wind curtailed respectively. RS_t^u is the total up reserve and E_g is the amount of CO_2 emission per MWh for unit g.

$$
\begin{aligned}
Min\ F^{op} = & \sum_{g,t} (C_g^{fx} v_{g,t} + C_g^{vr} P_{g,t} + C_{g,t}^{su} x_{g,t} + C_{g,t}^{sd} y_{g,t}) \\
& + \sum_{b,t} L_{b,t}^{ct} PLC + \sum_{s,t} P_{s,t}^{ct} PSC + \sum_{w,t} P_{w,t}^{ct} PWC \\
& + \sum_{t} RS_t^u \mathrm{RAC} + \sum_{g,t} P_{g,t} E_g EC
\end{aligned} \quad (1)
$$

B. Operational Constraints of Generators

All generating units operate and simultaneously conserve up and down reserves $RS_{g,t}^u$ and $RS_{g,t}^d$ within their minimum and maximum operating limits as given in (2) and (3). Here, $\underline{P}_g$ and $\overline{P}_g$ are the minimum and maximum operating limits of generating unit g respectively.

$$P_{g,t} - RS_{g,t}^d \geq \underline{P}_g v_{g,t} \qquad \forall g, \forall t \quad (2)$$

$$P_{g,t} + RS_{g,t}^u \leq \overline{P}_g v_{g,t} \qquad \forall g, \forall t \quad (3)$$

Ramp-up and Ramp-down constraints

Constraints (4) and (5) elucidate that the power output and reserve at each time stamp depends on generators' ramp up rate RR_g^u and ramp down rate RR_g^d limits. Also, units start shut-down process and end start-up process with minimum stable generation $\underline{P}_g$.

$$P_{g,t} - P_{g,t-1} + RS_{g,t}^u \leq RR_g^u v_{g,t-1} + \underline{P}_g x_{g,t} \qquad \forall g, \forall t \quad (4)$$

$$P_{g,t-1} - P_{g,t} - RS_{g,t}^d \leq RR_g^d v_{g,t} + \underline{P}_g y_{g,t} \qquad \forall g, \forall t \quad (5)$$

Minimum up and Minimum down time constraints

Constraints (6) - (11) force the generators to satisfy minimum up time M_g^{ut} and minimum down time M_g^{dt} during the decision of unit commitment. Here, v_g^0 is the status of generating unit g at time $t = 0$. Equation (6) ensures the minimum up time if the total "ON" hours of any unit at $t = 0$ i.e. S_g^0, are less than minimum up time. And similarly (9) ensures minimum down time if the total "OFF" hours at $t = 0$ i.e. D_g^0, are less than required one. Equation (7) and (10) impose the constraints for all possible sets of consecutive hours of size M_g^{ut} and M_g^{dt} respectively. Equation (8) implements the minimum up time constraint for the last $M_g^{ut} - 1$ hours and forces the unit to remain committed till the last hour of optimization period T, if it is started-up in any of these hours. Similarly, equations (11) forces the unit to remain de-committed till the last hour, if it is shut-down during any hours from last $M_g^{dt} - 1$ hours.

$$\sum_{t=1}^{\lambda_g} (1 - v_{g,t}) = 0 \quad (6)$$

$$\sum_{t=h}^{h+M_g^{ut}-1} v_{g,t} \geq M_g^{ut} x_{g,t} \qquad \forall h = \lambda_g + 1 \ldots T - M_g^{ut} + 1 \quad (7)$$

$$\sum_{t=h}^{T} (v_{g,t} - x_{g,t}) \geq 0 \qquad \forall h = T - M_g^{ut} + 2 \ldots T \quad (8)$$

Where, $\hbar_g = Min[T,(M_g^{ut} - S_g^0)v_g^0]$

$$\sum_{t=1}^{\hbar_g} v_{g,t} = 0 \quad (9)$$

$$\sum_{t=h}^{h+M_g^{dn}-1} (1-v_{g,t}) \ge M_g^{dt} y_{g,t} \quad \forall h = \hbar_g + 1 ... T - M_g^{dt} + 1 \quad (10)$$

$$\sum_{t=h}^{T} (1-v_{g,t} - y_{g,t}) \ge 0 \quad \forall h = T - M_g^{dt} + 2 ... T \quad (11)$$

Where, $\hbar_g = Min\,[\mathrm{H},(M_g^{dt} - D_g^0)(1-v_g^0)]$

Unit status constraints

Equation (12) calculates the committed status of units and constraint (13) ensures their non-simultaneous start-up and shut-down.

$$v_{g,t} = v_{g,t-1} + x_{g,t} - y_{g,t} \quad \forall g, t > 1 \quad (12)$$

$$x_{g,t} + y_{g,t} \le 1 \quad \forall g, \forall t \quad (13)$$

C. Renewable related constraint

Generation and curtailment of solar and wind units can be modelled by equation (14) and (15). Here, $P_{w,t}^g$ & $P_{s,t}^g$ are generation, $P_{w,t}^{ct}$ & $P_{s,t}^{ct}$ are curtailment and $P_{w,t}^{av}$ & $P_{s,t}^{av}$ are available wind and solar respectively at time t.

$$P_{w,t}^g + P_{w,t}^{ct} \le P_{w,t}^{av} \quad \forall w, \forall \mathrm{t} \quad (14)$$

$$P_{s,t}^g + P_{s,t}^{ct} \le P_{s,t}^{av} \quad \forall s, \forall t \quad (15)$$

D. Energy storage system (ESS) related constraints

The state of charge of ESS can be defined by equation (16) and (17). Where, $\underline{SOC_{st}}$ and $\overline{SOC_{st}}$ are the minimum and maximum level of state of charge. P_{st_ch} & P_{st_di} and η_{st_ch} & η_{st_di} are charging & discharging power outputs and efficiencies of ESS. $l_{st,t}$ and $m_{st,t}$ are the binary variables to enable charging and discharging of ESS. Up and down reserves provided by ESS and its charging-discharging power are constrained under minimum and maximum power limits as shown in (18) – (21). For provision of reserve by ESS, four new variables are introduced: 1) $RS_{st\_ch}^d$: downward reserve provided by increasing charging power 2) $RS_{st\_ch}^u$: upward reserve provided by decreasing charging power 3) $RS_{st\_di}^u$: upward reserve provided by increasing discharging power 4) $RS_{st\_di}^d$: downward reserve provided by decreasing discharging power.

$$\underline{SOC_{st}} \le SOC_{st,t} \le \overline{SOC_{st}} \quad \forall st, \forall t \quad (16)$$

$$SOC_{st,t} = SOC_{st,t-1} + (P_{st\_ch,t}\eta_{st\_ch} - P_{st\_di,t} / \eta_{st\_di}) \quad (17)$$

$$P_{st\_ch,t} + RS_{st\_ch,t}^d \le \overline{P_{st}} l_{st,t} \quad (18)$$

$$P_{st\_ch,t} - RS_{st\_ch,t}^u \ge \underline{P_{st}} l_{st,t} \quad (19)$$

$$P_{st\_\mathrm{di},t} + RS_{st\_\mathrm{di},t}^u \le \overline{P_{st}} m_{st,t} \quad (20)$$

$$P_{st\_\mathrm{di},t} - RS_{st\_\mathrm{di},t}^d \ge \underline{P_{st}} m_{st,t} \quad (21)$$

Inclusion of constraints (22) and (23) ensures that sufficient state of is ensured while scheduling upward and downward reserve by ESS.

$$SOC_{st,t} - (RS_{st\_ch,t}^u \eta_{st\_ch} + RS_{st\_di,t}^u / \eta_{st\_di}) \ge \underline{SOC_{st}} \quad (22)$$

$$SOC_{st,t} + (RS_{st\_ch,t}^d \eta_{st\_ch} + RS_{st\_di,t}^d / \eta_{st\_di}) \le \overline{SOC_{st}} \quad (23)$$

E. Reserve Related Constraints

Total up reserve is the sum of up reserve from conventional generating units and up reserve from ESS, and should be equal to the sum of 50% of the capacity of biggest generating units and 2.5 times the standard deviation of solar and wind generation σ_s and σ_w to cater uncertainty as given in (24). Total down reserve is kept equal to the amount of total up reserve as given in (25).

$$RS_t^u = \sum_g RS_{g,t}^u + \sum_{st} (RS_{st\_\mathrm{ch,t}}^u + RS_{st\_\mathrm{di,t}}^u \mathrm{t}) = 0.5 * Max(\overline{P_g}) + 2.5 * (\sigma_s + \sigma_w) \quad (24)$$

$$RS_t^d = \sum_g RS_{g,t}^d + \sum_{st} (RS_{st\_\mathrm{ch,t}}^d + RS_{st\_di,t}^d) = RS_t^u \quad (25)$$

F. Network security related constraints

Power flow at time t from line connecting bus n to bus nn i.e. $F_{n,nn,t}$, can be calculated from (26). Where, $\gamma_{n,nn}$ is the admittance of line and ϕ is the load angle. Security constraints (27) and (28) ensures the load angle and power flow within their minimum and maximum limits at every time step. Here, $tlc_{n,nn}$ is line capacity connected with bus n & nn and S_{base} is the base capacity of the system.

$$Fw_{n,nn,t} = \gamma_{n,nn}(\phi_n - \phi_{nn})\mathrm{S}_{base} \quad (26)$$

$$-\pi/3 \le \phi_n - \phi_{nn} \le \pi/3 \quad (27)$$

$$-tlc_{n,nn} \le fw \le tlc_{n,nn} \quad (28)$$

G. Power balance

Equality constraint (29) matches the total power entering at any bus with total power leaving.

$$\sum_{g \in g_b, t} P_{g,t} + \sum_{w \in w_b, t} P_{w,t} + \sum_{s \in s_b, t} P_{s,t} + \sum_{st \in st_b, t} P_{st\_di,t} + L_{b,t}^{ct} = \sum_{nn \in nn_b} Fw_{n,nn,t} + L_{b,t} + \sum_{st \in st_b, t} P_{st\_ch,t} \quad (29)$$

H. Modelling of planned outage

As the security constraints unit commitment (SCUC) is performed for whole year, planned outage of each conventional generating unit except nuclear power plants is considered for annual overhauling and maintenance; 2 weeks for units ≤ 50 MW and 3 weeks for units > 50 MW.

III. DATA PREPARATION

Study is carried out on IEEE RTS 24 bus system, that consists 32 generating units including thermal (coal, gas, nuclear) hydro power plants. Network detail, yearly load profile at every bus and emission coefficient of the generating units are taken from [6]. Annual peak load of the system is 2850 MW. Yearly load profile has been generated by:

1) Calculating weekly peak in percentage of annual peak.
2) Calculating daily peak load in percentage of weekly peak (same for a particular day of every week)
3) Calculating hourly load in percentage of daily peak (hourly profile is different for every season and type of day – week day or weekend)
4) Bus wise distribution of hourly load profile (percentage of distribution is same for every hour)

Different Cost and operating parameters are taken as per assumptions given in [7] and [8] respectively. As SCUC runs for a whole year, planned outage of each conventional generating unit has been considered for yearly maintenance and overhauling [6]. Cost of reserve allocation is referred from [9]. Data for solar power generation and wind speed are taken from [10] and [11] respectively. Fig. 2 and fig. 3 show diurnal and hourly variations in a monthly profile of solar and wind respectively. Capacity utilization factor (CUF) for wind is 0.48 and for solar is 0.21. Total RE penetration is 40% out of which solar is 12.5% and wind is 27.5% that gives 1000 MW capacity of each, calculated as given in (30) [12]. Solar and wind power plants are assumed to be installed at bus 7, 12, 15, 16 & 23, and distributed with equal capacity of 200MW at each bus. To integrate energy storage system, with total capacity of 300 MWh, 60 MW/60 MWh battery energy storage system is considered at each bus where RE plants have been installed.

$$Capacity\ of\ solar/wind = \frac{penetration * average\ load}{CUF\ of\ solar/wind} \tag{29}$$

Cost analysis of energy storage

Operating cost SC_{st} of battery is taken as its availability cost per MWh of discharge energy and can be calculated as given in [13]:

$$SC_{st} = \frac{Battery\ replacement\ cost}{E_{st}^{tc}} \tag{30}$$

Here, E_{st}^{tc} is the total lifetime cycling capacity of battery storage system which is a function of its rated capacity RC_{st}, depth of discharge DOD_{st} and rated life time RL_{st} in no. of cycles that it can last as given in (32) [14]. Cost of battery replacement in case of vanadium redox flow battery is taken as \$364.44 per kWh, depth of discharge is taken as 80% and its rated life time is 10,000 cycles.

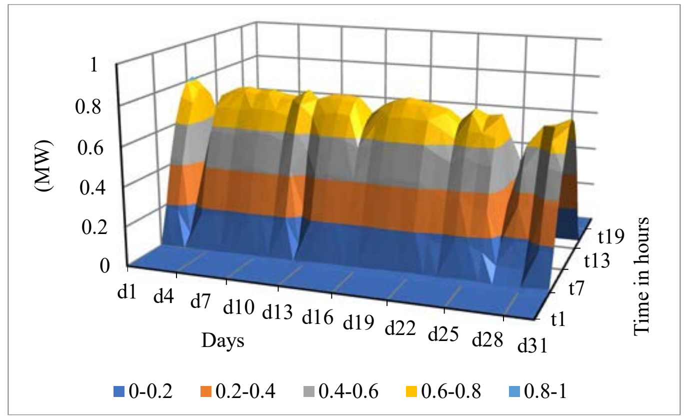

Fig. 2. Diurnal variation in solar power generation (profile of one month)

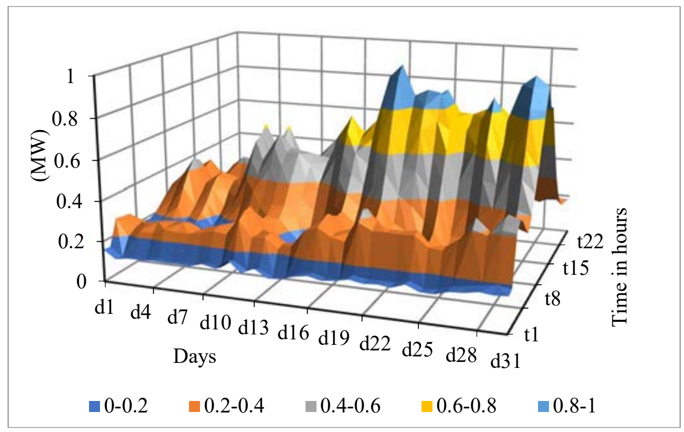

Fig. 3. Diurnal variation in wind power generation (profile of one month)

$$E_{st}^{tc} = RC_{st} DOD_{st} RL_{st} \tag{31}$$

The proposed mixed integer problem (MIP) is formulated using GAMS 24.2.3 and solved using CPLEX solver on Intel® Xenon® CPU E5-2699 v3 @ 2.30 GHz 2.29 GHz (2 Processors) with 32 GB RAM.

IV. RESULT ANALYSIS

Case-I: A demand supply balanced condition is achieved by scheduling only conventional units while conserving required amount of reserve to meet any contingency as shown in Fig. 4.

Case-II: Solar and wind RE sources have been integrated in the system with total penetration of 40%. Power output and reserve by conventional generating units and RE generation is shown in Fig. 5. Due to insufficient operational flexibility of system, high amount of solar and wind curtailment occurs in the system as shown in Fig. 6. To provide required balancing, conventional units need to be in committed state, though at partial load. Also, to cater uncertainty of solar and wind, conventional units need to keep increased amount of reserve as shown in Fig 5 and forces other units to be in committed state to supply required energy. This increases overall system operating cost.

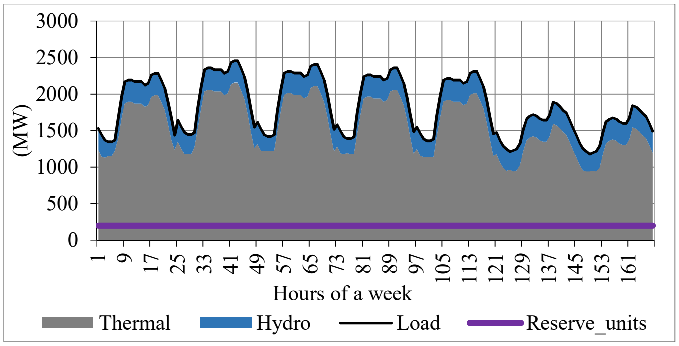

Fig. 4. Power output and reserve by conventional generating units in case I (profile of a week)

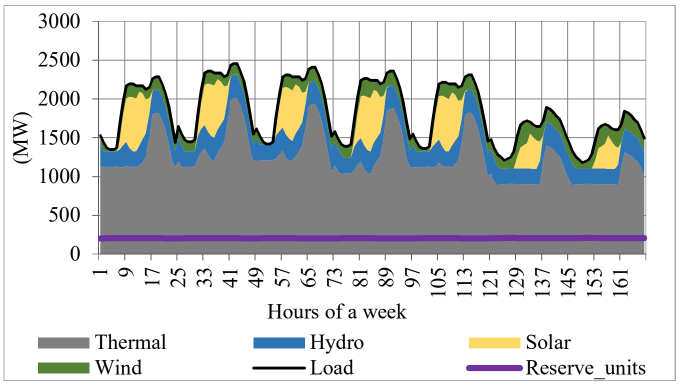

Fig. 5. Power output and reserve by conventional generating units and RE generation in case II (profile of a week)

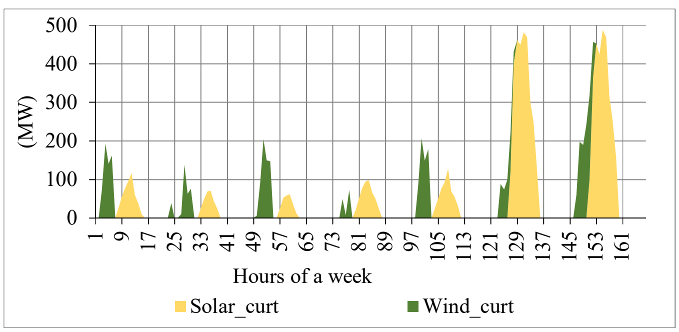

Fig. 6. Solar and wind curtailment in case II (profile of a week)

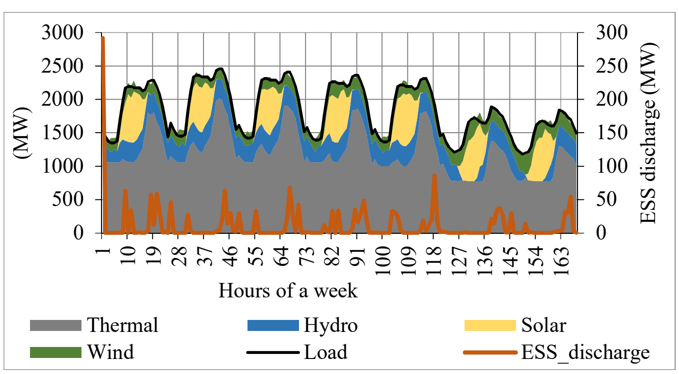

Fig. 7. Power output by conventional generating units, RE generation and storage discharge in case III (profile of a week)

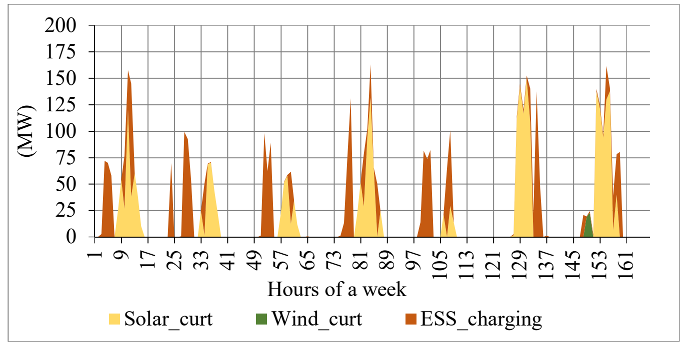

Fig. 8. Solar & wind curtailment and storage charging in case III (profile of a week)

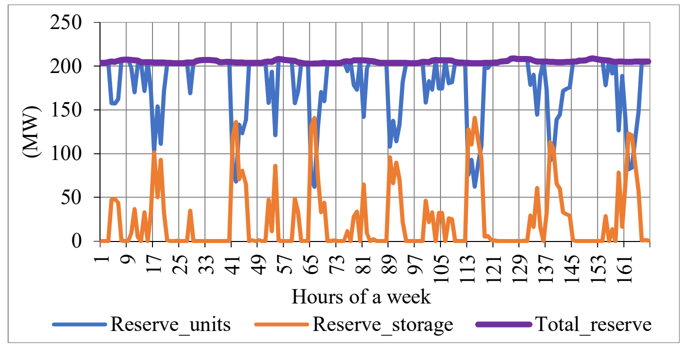

Fig. 9. Participation of conventional units and ESS in reserve services (profile of a week)

Case-III: Battery energy storage system of total capacity 300 MW is integrated into the system with RE. ESS provides required balancing and improves operational flexibility by discharging during peak load hours as depicted from Fig. 7. Curtailed RE is stored in the ESS as represented in Fig. 8. Comparison of Fig. 6 and Fig. 8 shows huge reduction in RE curtailment. This increases penetration of RE in the system and subsequently reduces CO_2 emission. Plant load factor of conventional generating is increased by participation of storage in reserve services as shown in Fig. 9.

A comparison of different performance and economic indicators for case II and case III for 52 weeks simulation is presented in Table I. Results indicate that ESS improves system reliability by decreasing load curtailment in a significant amount. It improves performance of RE units by reducing their curtailment and increasing their capacity utilization factor and subsequently helps to penetrate more renewables in the system. Total CO_2 emission was 3309248T in base case (case I) which has been reduced by 28.69% in case II and 30.11% in case III. This reduces overall operating cost of the system. Decreased operating cost in case III indicates economic viability of captive-intensive ESS in the system. Here, the cost of solar and wind curtailment has been taken as $ 0.5 per MWh and $0.7 per MWh respectively [15]. Operating cost of storage has been calculated as explained in section III. Fixed operating cost of RE and variable operating cost of storage is not included in objective function (1) to allow their participation in scheduling and added exogenously to compute overall operating cost of the system. Table I summarizes all technical benefits of integrating ESS into the system and monetizes them by adding their respective cost in total operating cost.

TABLE I. COMPARISON OF PERFOMANCE AND ECONOMIC INDICATORS FOR CASE II and CASE III

Indicators	**Case II (With RE integration)**	**Case III (With RE and ESS integration)**
CUF of Solar (%)	12.55%	16.92%
CUF of Wind (%)	40.80%	45.12%
RE Penetration (%)	30.47%	35.33%
CO2 Emission: (T)	2359543	2312612
Total load curtailment (MWh)	1308	79
Total solar curtailment (MWh)	683878	301574
Total wind curtailment (MWh)	496553	119560
Total Operating Cost ($) (Fixed and variable O & M cost of conventional generating units, fixed O & M cost of RE & penalty for RE curtailment, reserve allocation cost, emission cost, O & M cost of ESS	215,233,401.86	208,867,929.11

V. CONCLUSION

To show economic viability of captive-intensive ESS and monetize its benefits to system, a security constraint unit commitment problem has been formulated in presented work for a complete year. Results indicate that integration of ESS improves technical performance of other generating units (conventional and RE) and helps to decarbonize power sector by increasing RE penetration in the system. ESS increases the operational flexibility and provide more capacity credits by displacing less flexible nuclear power units. These benefits will increase in future as there is continuous innovation and fall in cost of ESS technologies.

This work can be extended to obtain an optimal generation portfolio for future power system by considering different energy storage systems and comparing their benefits.

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