Power System Integration of Renewable Energy

Mahdi Emadaleslami

I. INTRODUCTION

With the increasing energy crisis, environmental issues, and excessive energy consumption, renewable energy sources such as wind and photovoltaic (PV) are becoming crucial in the power system. However, the unpredictable fluctuation of wind and solar causes significant challenges in incorporating the uncertainties into power system. Therefore, it is usually required to use extra spinning reserve or energy storage system (ESS) to offset the variability in the energy generated by renewable sources, which increases the operation cost at the same time. Compared to the spinning reserve operation cost, ESS is among the most efficient and compatible technologies for an improved power system operation and control with generated electricity based on renewable energy.

Considering th power system with renewable sources and ESS as shown in Fig. 1, the purpose of the economic dispatch is to schedule the outputs of all available generation units in the power system such that the production cost is minimized while system constraints are satisfied. Also it can be explained as the process of allocating generation among the committed units such that the constraints are satisfied and the energy requirements are minimized. Furthermore, the economic power dispatch for interconnected power system can be explained as the process of finding the total real and reactive power schedule of each power plant in such a way as to minimize the operating cost. This means that the generator's real and reactive power is allowed to vary within certain limits so that it can meet the demand with minimum fuel cost. This is called the optimal power flow. The optimal power flow is used to optimize the power flow solution of large scale power system. This is done by minimizing selected objective functions while maintaining an acceptable system performance in terms of generators capability limits and the output of the compensating devices [1].

Generally, economic dispatch can be classified into two categories. One is static dispatch, which searches the optimal solution in each separated time period, without taking the relationships among different periods into account; the other is dynamic dispatch [2], which considers the coupling in the time domain, such as ramp rate constraints for thermal units, charge/discharge behavior of ESS, and renewable variability. The results of dynamic economic dispatch are more effective. Integrated with battery energy storage units [3], microgird becomes a strong coupling system in the time domain. In this regard, A dynamic economic dispatch method considering unit commitment is proposed based on the wind speed forecasting and chance-constrained programming in [4], [5]. [5] formulates a short-term forward electricity market-clearing problem with stochastic security capable of accounting for non-dispatchable and variable wind power generation sources. The application of these methods will be better to describe the fluctuation of wind and PV generation and its impact.

In this study, we aim to investigate the integration of renewable energy sources into a sample power grid. As shown in Fig. 1, we consider all loads and power generators connected to one single bus and propose a dynamic economic dispatch method to find the optimal control strategy for the system in finite time period. The objective is to minimize the cost of energy production and Co_2 emissions while meeting the uncertainties of demand and renewable generation

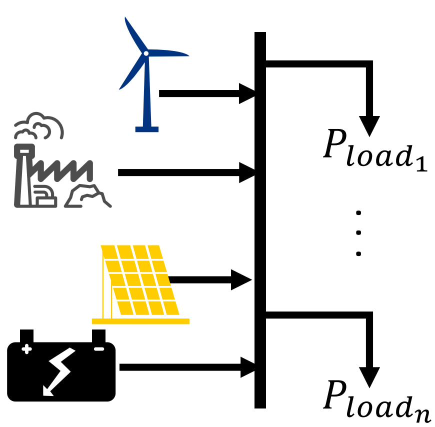

Fig. 1. Concept of power system dispatch with renewable sources and ESS

units. In this regard, we consider four scenarios and in each scenario we try to add complications to the problem to make it more realistic. So that in the fourth scenario, in addition to considering the uncertainty of the load and renewable resources, storage degradation and efficiency losses, are also modeled.

The remainder of the report is organized as follows. In Section II, the model of components including PV arrays, WTs, diesel generators, ESS, and loads, along side the optimization objective function and constraints are presented. Section III presents simulation results. Finally, Section VI concludes the study with a summary and future directions.

II. Problem Furmulation and Modeling

A. Objective Function

The presented discussion aims to address the production cost and carbon emission minimization.

1) *Production cost minimization:* The objective function of the optimal power generation output to minimize the production cost is presented in (1):

$$\min_{p_{i,t}} \sum_{t\in\tau} \sum_{i\in G} F_i(p_t^i) \tag{1}$$

Where $F_i(p_t^i)$ represents the cost function of the ith generating unit (in $\$/h$), p_t^i represents the real output of the ith generating/storing units at time t (in MW), τ *and* G are Set of time horizon and generating units respectively.

2) *Carbon emission minimization:* The objective function of the optimal power generation output with repect to carbon emissions is presented in (2):

$$\min_{p_{i,t}} \sum_{t\in\tau} \sum_{i\in G} C_{i,t}^E * p_t^i \tag{2}$$

Where $C_{i,t}^E$ represents the corresponding carbon emissions of each power source to generate 1 p.u. of electricity at time t.

3) *Joint cost and carbon emissions minimization:* The joint cost and carbon emissions objective function of the optimal power generation is presented in (3), μ is the monetizing coefficient for carbon emissions.

$$\min_{p_{i,t}} \sum_{t\in\tau} \sum_{i\in G} F_i\left(p_t^i\right) + \mu * C_{i,t}^E * p_t^i \tag{3}$$

Several constraints, such as the power balance, and output power generation limits, shall be satisfied as follow:

$$\sum_{i\in G} p_t^i = p_t^{Load} \qquad \forall t \in \tau \tag{4}$$

$$\underline{p_t^i} \leq p_t^i \leq \overline{p_t^i} \tag{5}$$

Where $\overline{p_t^i}$, $\underline{p_t^i}$, and p_t^{Load} are the maximum, minimum generating power of unit i at time t, and grid demand at time t, respectively .

B. Demand

A load profile for the system demand is randomly calculated for 24 hours time horizon. in the simulation different values for maximum demand are considered to study the performance of different generating unit.

C. Photovoltaic Array

The output power of the PV array is proportional to solar radiation, which can be calculated using the following equation [6]:

$$p^{pv} = \frac{G}{G_{STC}} * p_{rated}^{pv} * \eta_{conv}^{pv} \tag{6}$$

Where G is perpendicular radiation at the surface of the PV arrays (W/m^2), and η_{conv}^{pv} is the efficiency of the DC/DC converter of the arrays, which is considered to be 100%. Also, p_{rated}^{pv} and G_{STC} are the rated power of each PV array and solar radiation at the standard test condition, which are taken as 5 kW and 1000 (W/m^2), respectively.the generation power of a PV Farm according to irradiation can be approximately calculated. The production cost of a PV Farm with fixed cost of \$25/MW over time is as follows:

$$F\ \ (p_t^{pv}) = \sum_{t\in\tau} 25 * p_t^{pv} \tag{7}$$

D. Diesel Generators

The production cost of a diesel generator is a quadratic function of rated power and cost coefficients as follows [6]:

$$F\ \ (p_t^{G}) = \sum_{t\in\tau} \alpha_i * {p_{i,t}^{G}}^2 + \beta_i * p_{i,t}^{G} + \delta_i \tag{8}$$

Also each diesel generator should satisfy the following Ramp up/down constraints:

$$\begin{aligned} p_t^G - p_{t+1}^G &\le\ 0.2 * \overline{p_t^i} \qquad \forall t \in \tau \\ p_{t+1}^G - p_t^G &\le 0.2 * \overline{p_t^i} \qquad \forall t \in \tau \end{aligned} \tag{9}$$

E. ESS

Due to the stochastic nature of both the demand and supply sides, a 150 MWh lead-acid ESS is considered in this study with a maximum charging/discharging power of 50 MW. To guarantee a long ESS lifetime, the state of charge (SoC) of the ESS should satisfy the following constraint [7]:

$$\begin{gathered} \underline{SoC_t} \le SoC_t \le \overline{SoC_t} \qquad \forall t \in \tau \\ SoC_t = SoC_{t-1}(1-\sigma) - \gamma P_{dch}(t) + \frac{P_{ch}(t)}{\gamma} \quad \forall t \in \tau \end{gathered} \tag{10}$$

Where SoC_t is the SOC of ESS at time t. $\overline{SoC_t}$ and $\underline{SoC_t}$ are the maximum and minimum SOC limits of the ESS which are taken as %100 and %10, repectively. $P_{dch}(t)$, $P_{ch}(t)$, σ, γ are the discharging, charging, self discharge rate, and efficiency factor of the ESS, respectively. The output power of ESS at time t, p_t^{Ess}, and energy production cost is as follows, with fixed cost of \$20/MW over time:

$$\begin{gathered} p_t^{Ess} = P_{dch}(t) - P_{ch}(t)\ \ \forall t \in \tau \\ F\ \ (p_t^{Ess}) = \textstyle\sum_{t\in\tau} 20 * p_t^{Ess} \end{gathered} \tag{11}$$

F. Wind Turbine Generator

The generation power of a WT can be written as a function of the wind speed as follows [6]:

$$p^{WT} = \begin{cases} 0 & \nu_w \le \nu_{ci}, \nu_w \ge \nu_{co} \\ p_{rated}^{WT} * \left(\dfrac{\nu_w - \nu_{ci}}{\nu_r - \nu_{ci}}\right)^3 & \nu_{ci} < \nu_w \le \nu_r \\ p_{rated}^{WT} + (\nu_w - \nu_r) * \dfrac{p_{co}^{WT} - p_{rated}^{WT}}{\nu_{co} - \nu_r} & \nu_r < \nu_w \le \nu_{co} \end{cases} \tag{12}$$

Where, p^{WT} is the output active power level of the WT. p_{rated}^{WT} and p_{co}^{WT} are the output power level of the WT at the rated and cut-out speeds, respectively. ν_w, ν_r, ν_{ci} and ν_{co} are the measured, rated, cut-in, and cut-out wind speeds in m/s, respectively [6]. The parameters WT, including the cut-in, cutout, and rated wind speeds and the rated power, are 3:5, 25, and 12:5 m/s and 120 MW, respectively. The production cost of a WT is as follows, with fixed cost of \$20/MW over time:

$$F\ \ (p_t^{WT}) = \sum_{t\in\tau} 20 * p_t^{WT} \tag{13}$$

III. RESULTS AND DISCUSSION

The system that includes two conventional thermal units, a wind turbine, ESS and a photovoltaic farm is analyzed in this study. A day is divided into 24 hourly dispatch periods. The forecasted load profile of wind, photovoltaic system and demand are showed in Fig.2. The characteristics of thermal units and Renewable units are provided in Table I. Co_2 Emisssion information are based on [8].Four cases are considered and in each cases we try to add complications to the problem to make it more realistic. In the first case, base model, The rated power of WT, ESS,PV farm, and maximum system demand are 40 MW, 10 MW, 50 MW, and 100 MW, respectively. In all other case, The rated power of WT,PV farm, and maximum system demand are 120 MW, 150 MW, and 300 MW,respectively. ESS capacity for case two and three is considered 50 MW and for case four is considered 150 MW.

TABLE I
CHARACTERISTICS OF GENERATING UNITS

Type	α_i	β	δ_i	Co_2 Emisssion (g Co_2/kwh)	Pmin (MW)	Pmax (MW)
Wind Turbine	0	20	0	11	0	120
PV	0	25	0	0	0	150
Coal-based Generator (G_1)	1.5	10	30	980	10	100
Gas-based Generator (G_2)	2	12	20	465	0	100

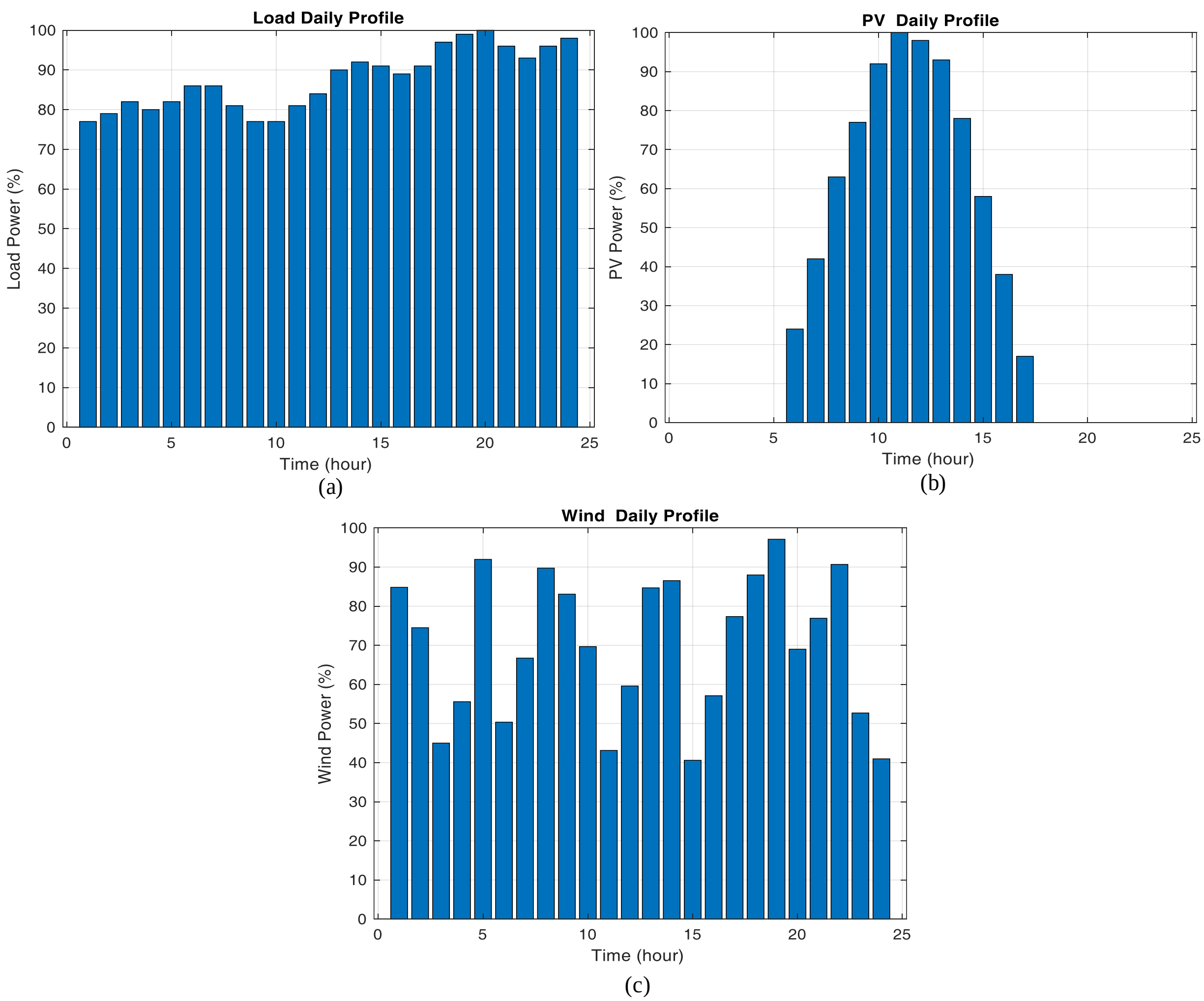

Fig. 2. (a) Daily Load profile. (b) Forcasted Daily PV profile. (c) Forcasted Daily WT profile

A. Case 1: Base Model

According to the assignment description, in this case we consider a grid with fixed generating WT, ESS,PV units and Total demand of 100 MW. The objective is to minimize the production cost. Since the objective function and constraints are all linear, GLPK solver is used for optimization. Results are provided in Table II. As can be seen in the base case all the grid demand is satisfied and no power mismatch occurs.

TABLE II
RESULT OF CASE 1

Generation unit (MW)					Total Geenration (MW)	Total Demand (MW)	Total Cost ($)
Wind	PV	ESS	G1	G2			
40	50	10	-	-	100	100	2250

B. Case 2: Production cost & Co_2 emission

In this case, we add 2 thermal generating units with different generation costs to the problem to make it more comprehensive. In addition, we increase the capacity of renewable sources and the amount of network Demand. By considering thermal units, we can further investigate the impact of Co_2 emissions in Economic Dispatch problem. The objective is to minimize the production cost and Co_2 emissions. According to the equation (8) the cost function of thermal units has a quadratic form; therefore, Ipopt solver is used for optimization. Considering the monetizing coefficient as $0.1, the results are provided in Table III. As can be seen grid demand is satisfied in each scenario and no power mismatch occurs. However, Co_2 consideration in the objective function prompts the G1 unit to produce less compared to the G2 unit since its Co_2 emission is higher according to Table I.

TABLE III
RESULT OF CASE 2

Objective	Generation unit (MW)					Total Geenration (MW)	Total Demand (MW)	Total Cost ($)
	Wind	PV	ESS	G1	G2			
Cost only	120	150	50	46	34	400	400	13554
Cost+ Emission	120	150	50	23.93	56.07	400	400	19585.55

C. Case 3: Demand, Wind, and PV variability

In this case, we assume that Demand,Wind, and PV change over 24h horizon with a known Profile. Similar to Case 2, The objective is to minimize the production cost and Co_2 emissions. According to the equation (9) Ramp up/down constraints are also considered for Termal units. Ipopt solver is used for optimization. Considering the monetizing coefficient as $0.1, the results for 24h horizon are provided in Table IV. Fig. 3 shows the power output of the generation units throughout 24h horizon.

As can be seen in Table IV, the grid demand is met at all hours except 23 and 24. Also, according to the Renewable curtailment column, it is clear that in some hours such as 14, 15, and 16, a significant amount of renewable resource generation is unused. If we could have stored this amount of unused power with the help of an ESS, we might have been able to solve the power mismatch problem in the 23rd and 24th hours. We further investigate this issue in Case 4. Despite the low generation cost of renewable resources compared to thermal units, Renewable curtailment occurs because the Ramp up/down constraints of thermal units hamper the full employment of renewable resources.

TABLE IV
RESULT OF CASE 3

Time (h)	Generation unit (MW)					Total Geenration (MW)	Total Demand (MW)	Curtailment (MW)	
	Wind	PV	ESS	G1	G2			Wind	PV
1	101.78	0	50	55.40	34	254.1	254.1	0	0
2	85.04	0	49.05	71.03	55.57	260.7	260.7	4	0
3	54	0	50	91.04	75.58	270.6	270.6	0	0
4	66.68	0	50	80.5	66.81	264	264	0	0
5	110.35	0	50	61.07	49.17	270.6	270.6	0	0
6	60.42	36	50	76.18	61.19	283.8	283.8	0	0
7	77.85	59.3	49.27	56.18	41.19	283.8	283.8	2	4
8	100.49	61.18	48.25	36.18	21.2	267.3	267.3	7	33
9	99.46	87.28	49.98	16.18	1.2	254.1	254.1	0	28
10	83.61	108.97	50	11.36	0.16	254.1	254.1	0	29
11	51.74	150	50	15.04	0.52	267.3	267.3	0	0
12	71.52	144.19	50	11.34	0.16	277.2	277.2	0	3
13	96.75	116.75	48.92	27.64	6.94	297	297	5	23
14	98.23	81.85	48.93	47.64	26.94	303.6	303.6	6	35
15	48.72	87	50	67.64	46.94	300.3	300.3	0	0
16	68.53	57	50	64.64	53.53	293.7	293.7	0	0
17	92.82	25.5	50	72.71	59.27	300.3	300.3	0	0
18	105.57	0	50	92.14	72.39	320.1	320.1	0	0
19	116.53	0	50	82.97	77.2	326.7	326.7	0	0
20	82.8	0	50	100	97.2	330	330	0	0
21	92.29	0	50	97.25	77.26	316.8	316.8	0	0
22	97.06	0	49.25	80.59	80	306.9	306.9	12	0
23	63.23	0	50	100	100	313.23	316.8	0	0
24	49.16	0	50	100	100	299.16	323.4	0	0

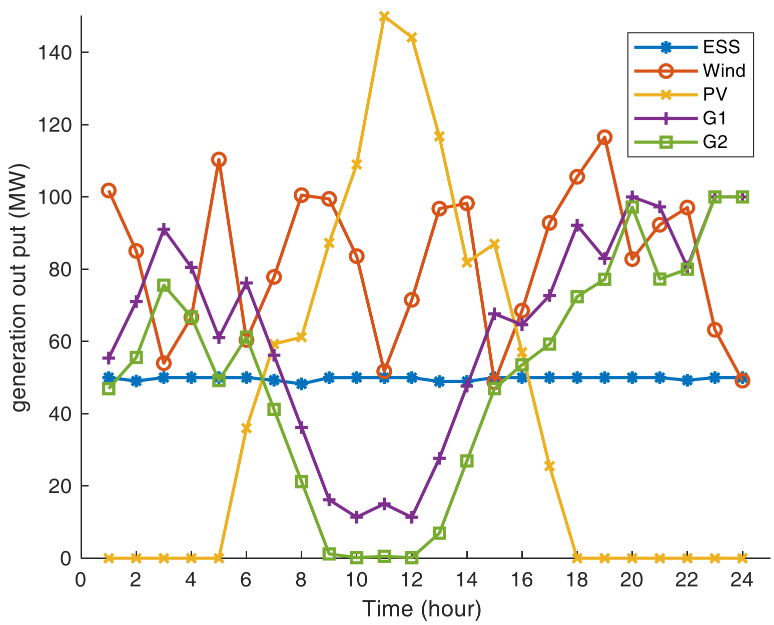

Fig. 3. Power output of generating units in case 3 throughout 24h horizon.

C. Case 4: Storage degradation & efficiency loss

In this case, we assume that a ESS with maximum capacity of 150 Mwh, discharge/charge rate of 50 MWh and 0.95 efficiency is available. by using a storage over 24h horizon we expect to reduce the renewable curtailment. Similar to Case two and three, The objective is to minimize the production cost and Co_2 emissions. ESS is modeled according to the equation (10). solver is used for optimization. Considering the monetizing coefficient as \$0.1 and maximum demand of 310 MW, the results for 24h horizon are provided in Table V. Negative values in the Table means the ESS is charging. the Fig. 4 shows the power output of the generation units throughout 24h horizon.

TABLE V
RESULT OF CASE 4 WITH MAXIMUM DEMAND OF 310 MW AND 150 MWH ESS

Time (h)	Generation unit (MW)					Total Geenration (MW)	Total Demand (MW)	Curtailment (MW)	
	Wind	PV	ESS	G1	G2			Wind	PV
1	101.78	0	-21.5149	83.4	75.03	238.7	238.7	0	0
2	89.39	0	-3.14345	83.51	75.14	244.9	244.9	0	0
3	53.99	0	20.50882	95.5	84.2	254.2	254.2	0	0
4	66.68	0	1.671718	95.51	84.13	248	248	0	0
5	110.35	0	-7.47491	79.29	72.03	254.2	254.2	0	0
6	60.42	36	6.704073	82.49	80.99	266.6	266.6	0	0
7	80.06	63	0.00298	62.5	61.04	266.6	266.6	0	0
8	107.67	94.5	-34.6266	42.5	41.05	251.1	251.1	0	0
9	99.68	115.5	-27.2844	22.51	28.29	238.7	238.7	0	0
10	83.61	138	-29.4786	18.22	28.36	238.7	238.7	0	0
11	51.74	150	-0.01027	19.95	29.42	251.1	251.1	0	0
12	71.52	147	-6.83542	19.51	29.2	260.4	260.4	0	0
13	101.62	139.5	-17.8341	26.78	28.93	279	279	0	0
14	103.83	117	-30.7001	46.77	48.3	285.2	285.2	0	0
15	48.72	87	11.35185	66.76	68.28	282.1	282.1	0	0
16	68.52	57	-12.8049	85.97	77.21	275.9	275.9	0	0
17	92.82	25.5	-0.18555	86.49	77.48	282.1	282.1	0	0
18	105.57	0	0.742622	100	94.39	300.7	300.7	0	0
19	116.53	0	-0.00444	100	90.38	306.9	306.9	0	0
20	82.8	0	32.25652	100	94.95	310	310	0	0
21	92.29	0	10.47441	100	94.84	297.6	297.6	0	0
22	108.81	0	-0.04413	95.39	84.14	288.3	288.3	0	0
23	63.23	0	39.47751	100	94.89	297.6	297.6	0	0
24	49.16	0	50	100	100	299.16	303.8	0	0

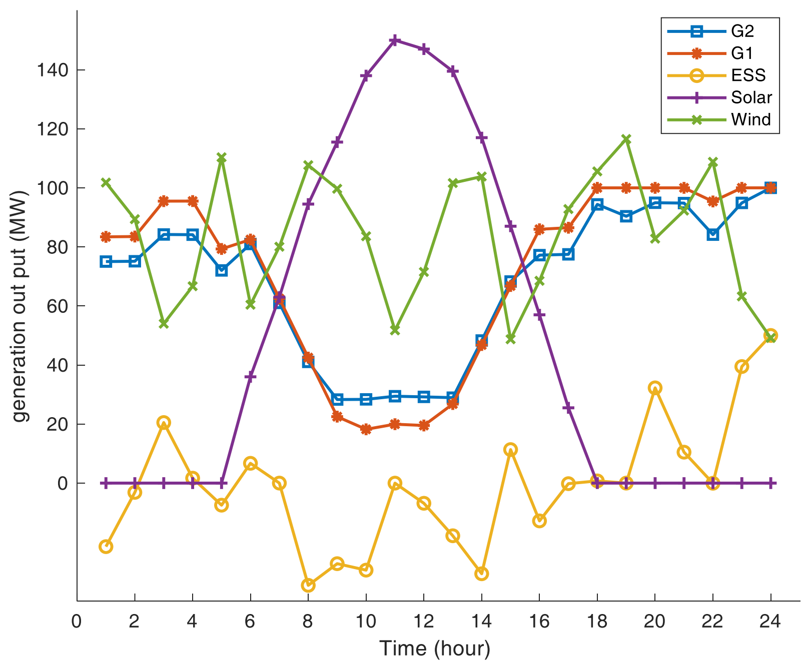

Fig. 4. Power output of generating units in case 4 throughout 24h horizon.

As can be seen in Table V, the employment of a rechargeable ESS has enabled us to reduce renewable curtailment to zero,but the grid demand is still not satisfied at the 24th hour. This is because the maximum capacity of the employed ESS is 150 GWh. If we further increase the ESS capacity to 300 MWh with a charge/discharge rate of 100 MWh, we can supply the grid with a maximum demand of 330 MW for 24h horizon as shown in Table VI.

TABLE VI
RESULT OF CASE 4 WITH MAXIMUM DEMAND OF 330 MW AND 150 MWH ESS

Time (h)	Generation unit (MW)					Total Geenration (MW)	Total Demand (MW)	Curtailment (MW)	
	Wind	PV	ESS	G1	G2			Wind	PV
1	101.78	0	-24.9192	94.21	83.03	254.1	254.1	0	0
2	89.39	0	-5.93128	94.21	83.03	260.7	260.7	0	0
3	53.99	0	23.56857	100	93.04	270.6	270.6	0	0
4	66.69	0	4.274014	100	93.04	264	264	0	0
5	110.35	0	-7.35685	88.7	78.9	270.6	270.6	0	0
6	60.42	36	6.63956	93.53	87.21	283.8	283.8	0	0
7	80.06	63	0	73.53	67.21	283.8	283.8	0	0
8	107.67	94.5	-36.5582	53.53	48.15	267.3	267.3	0	0
9	99.68	115.5	-56.938	47.7	48.15	254.1	254.1	0	0
10	83.61	138	-63.3621	47.7	48.15	254.1	254.1	0	0
11	51.74	150	-30.2936	47.7	48.15	267.3	267.3	0	0
12	71.52	147	-37.1733	47.7	48.15	277.2	277.2	0	0
13	101.62	139.5	-39.9754	47.7	48.15	297	297	0	0
14	103.83	117	-40.9627	65.06	58.67	303.6	303.6	0	0
15	48.72	87	0.855218	85.06	78.67	300.3	300.3	0	0
16	68.53	57	-0.94761	89.57	79.55	293.7	293.7	0	0
17	92.82	25.5	0	96.92	85.06	300.3	300.3	0	0
18	105.57	0	22.12833	100	92.4	320.1	320.1	0	0
19	116.53	0	17.76789	100	92.4	326.7	326.7	0	0
20	82.8	0	54.80013	100	92.4	330	330	0	0
21	92.29	0	32.10885	100	92.4	316.8	316.8	0	0
22	108.81	0	5.689292	100	92.4	306.9	306.9	0	0
23	63.23	0	61.16757	100	92.4	316.8	316.8	0	0
24	49.16	0	81.83793	100	92.4	323.4	323.4	0	0

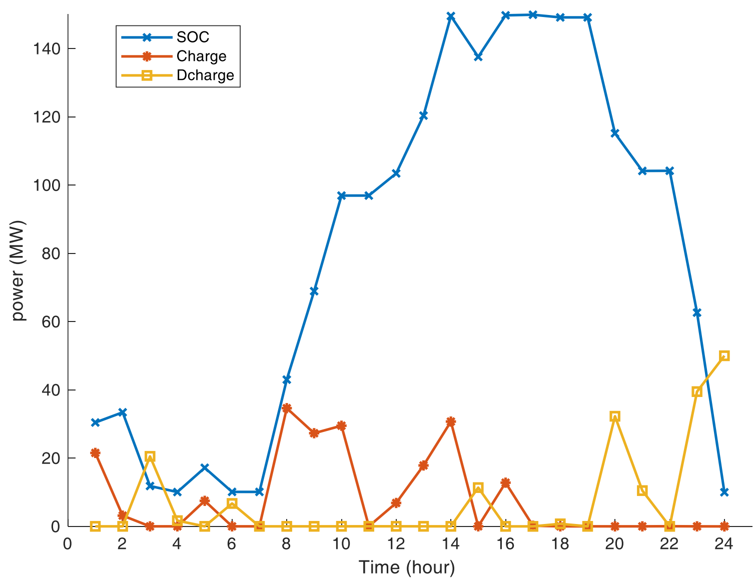

Fig. 5. SoC, Charge, and Discharge of the ESS in case 4 throughout 24h horizon.

Fig. 5 depicts the SoC, charge, and discharge of the 150 MWH ESS throughout the 24h horizon. With the PV unit coming into operation from 8 to 14, the ESS is charged with the excess power from the PV and wind units. Later, particularly from 20 to 24, when the demand exceeds the generation capacity, the ESS discharges to help the generation side meet the grid demand.

VI. Conclusion

In this study, we proposed a dynamic economic dispatch method to find the optimal control strategy for a system consisting of energy storage, renewable generations, and thermal units over a period of 24 hours. The objective is to minimize the cost of energy production and Co_2 emissions while meeting the intermittency of demand and renewable generation. in this regard, four cases are studied. According to case four, energy storage employment provides us with an opportunity to utilize the curtailed renewable power generation during off-peak hours in peak hours, especially at night when PV generation is not available. Finally, Our further works are as below:

1. As can be seen in Figure 5, the energy storage at 4th and 5th hours is simultaneously charged and discharged, which is technically wrong. To avoid simultaneous charging and discharging, binary variables can be used in future studies, which adds more complexity to the problem.
2. In this work, we did not consider the adverse effects of repeatedly charging/discharging of the energy storage on its lifetime; however, the intermittent generation of renewable units cause energy storage to be repeatedly charged and discharged to supply the grid demand, which will decrease the energy storage lifetime. Therefore, we can try to improve the energy storage lifetime.
3. In this study, we considered that all production units have %100 reliability when needed. But, in real-life conditions, this is not necessarily true, where some Photovoltaic Arrays in a PV farm might be unavailable. Therefore, in future studies we should consider the Probability of equipments unavailability.
4. In this work, we didn't consider the network topology. By considering the network topology we can further study the network loss and reliability and therefore develop a multi-objective optimization problem, which is more comprehensive.

References

[1] V. Bhattacharjee and I. Khan, “A non-linear convex cost model for economic dispatch in microgrids,” *Appl. Energy*, vol. 222, pp. 637–648, Jul. 2018, doi: 10.1016/J.APENERGY.2018.04.001.

[2] M. Basu, “Dynamic economic emission dispatch using nondominated sorting genetic algorithm-II,” *Int. J. Electr. Power Energy Syst.*, vol. 30, no. 2, pp. 140–149, Feb. 2008, doi: 10.1016/J.IJEPES.2007.06.009.

[3] F. Carastro, M. Sumner, and P. Zanchetta, “An enhanced shunt active filter with energy storage for microgrids,” *Conf. Rec. - IAS Annu. Meet. (IEEE Ind. Appl. Soc.*, 2008, doi: 10.1109/08IAS.2008.270.

[4] R. Doherty and M. O’Malley, “A new approach to quantify reserve demand in systems with significant installed wind capacity,” *IEEE Trans. Power Syst.*, vol. 20, no. 2, pp. 587–595, May 2005, doi: 10.1109/TPWRS.2005.846206.

[5] F. Bouffard and F. D. Galiana, “Stochastic security for operations planning with significant wind power generation,” *IEEE Power Energy Soc. 2008 Gen. Meet. Convers. Deliv. Electr. Energy 21st Century, PES*, 2008, doi: 10.1109/PES.2008.4596307.

[6] H. R. Baghaee, M. Mirsalim, G. B. Gharehpetian, and H. A. Talebi, “Reliability/cost-based multi-objective Pareto optimal design of stand-alone wind/PV/FC generation microgrid system,” *Energy*, vol. 115, pp. 1022–1041, Nov. 2016, doi: 10.1016/J.ENERGY.2016.09.007.

[7] E. Fouladi, H. R. Baghaee, M. Bagheri, and G. B. Gharehpetian, “Power Management of Microgrids including PHEVs Based on Maximum Employment of Renewable Energy Resources,” *IEEE Trans. Ind. Appl.*, vol. 56, no. 5, pp. 5299–5307, Sep. 2020, doi: 10.1109/TIA.2020.3010713.

[8] “CO2 Emissions from Different Energy Sources.” https://www.energy.gov/eere/wind/articles/how-wind-can-help-us-breathe-easier#:~:text=In general%2C lifecycle greenhouse gas,2%2FkWh for natural gas.