Economic and Environmental Dispatch at Highly Potential Renewable Area with Renewable Storage

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***Abstract*—Economic/Environmental Dispatching (EED) is an important multiobjective optimization problem to decide the amount of generation to be allocated to each thermal generating unit including renewable sources so that the total cost of generation and emission of polluting gases is minimized without violating system constraints. Here, the problem is EED of hybrid power system including solar, wind and storages of renewable energies. High potential renewable area ensures the availability of renewable sources in some extent. A consistent optimum EED can be obtained by extracting maximum renewable energy during their availability and using them for both available and unavailable periods with the aid of their storages. This paper illustrates the optimization of EED with renewable storage using MATLAB simulations. The simulations have been done using IEEE-30 test bus (with 6 generators) data.**

***Index Terms*—EED, energy storage, multiobjective, optimization, renewable energy, solar power, wind power.**

I. Introduction

The power dispatch problem is to find the optimum operating policy for committed units in order to meet the load demand while satisfy all unit and system equality and inequality constraints. Minimizing the fuel cost is the objective of traditional economic dispatch (ED) problems. The existing energy production is not economically clean. About 63% of world electricity is obtained by burning fossil fuels and 40% of which is from coal-fired electric power stations. Most of the coal-fired power stations are built two decades before and emit 80-85% of NO_x generated by utilities. Some older power plants operate with a pollution rate up to 70 to 100 times greater than the new plants [1], [2]. Due to the increase of public awareness on environmental protection, the utilities have been forced to use renewable sources with hybrid power system and to modify their operation strategies in order to reduce the pollution and atmospheric emission of power plants. Economic / environmental dispatch (EED) is the proposed alternative for the same.

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EED distributes active and renewable production among the power stations to meet the minimization of both fuel cost and pollutant emissions simultaneously [3], [4]. In EED, the amount of dispatching renewable power is calculated, based on the data conveyed by the Environmental Information Systems and Load Dispatch Centers, using any commercially available software package [2]. It is better to treat EED as a multiobjective problem instead of treating it as a single objective problem [5]. Several literatures described EED as a multiobjective problem with solar or wind or both of them [3], [6].

Renewable energy resources depend on the climate data such as the wind speed, solar radiation, and temperature. The uncertainty and the variation of the renewable resources create issues in EED problems. Different methodologies were illustrated in several articles to overcome these issues [3], [4]. One of the methods is to treat renewable power as a negative load and formulate demand equation in this basis [3], [7], [8]. The uncertainty in the availability of solar irradiation is less in the high potential solar areas. Saudi Arabia is one of the examples for such areas. The country is part of a vast, rainless region that receives about 6-7 $kWh/m^2/day$ [9]. Depending on geographical location, the global solar radiation in the Kingdom varies between a minimum of $4493W/m^2/day$ to a maximum of $7014W/m^2/day$ with the minimum and maximum duration of sunshine varying between 7.4 and 9.4 hours. Other Middle East countries, some part of India, Australia etc are also examples of high potential solar areas. The prediction of wind power at a particular location in a certain period of day is not possible due to the uncertainty in the availability of wind speed. Wind does not blow at a point or steadily moves from one direction; it continues blowing from one point to another point. Installing a number of inter connected wind turbines in the passage of wind will ensure the availability of wind power at some extend.

The renewable generation technologies and energy storage systems are sufficiently developed and are widely used for economical and environmental friendly dispatch. In such dispatch the renewable energy system and energy storage system are effectively interconnected with the existing power plants. Some of energy storage systems are described in [10]-[13]. Production and storage of renewable energy at off-peak times, and in times when there would be a surplus of its availability, also reuse this stored energy during its unavailable periods will make the EED optimization more effective.

The fuel cost increases with the increase of the outputs of the given thermal generating units and the amount of emission is also very high for higher values of output [14]. Thus, distributing the renewable energies throughout the operating periods instead of using them only during their available period will help to reduce both cost and emission to some extent. This distribution can be achieved using suitable storage devices. It also helps to day-night weather based approach for economic dispatch [1]. In this paper, the EED is formulated as multiobjective problem with renewable sources and their storages. Discussion on renewable power is given in Section II. The definitions and formulation of problems are described in section III and the results are discussed in section IV.

II. Renewable Energy

In this paper, only solar and wind power is considered. Wind power is produced by wind turbines and solar power can be produced either by solar panels, solar thermal plants, or both. The maximum solar power produced by solar panels and the approximate solar power developed by solar thermal plants are proportional to solar irradiation (S W/m^2) and are given by equations (1) and (2) respectively

$$\mathrm{P_s} = \mathrm{P_m}\frac{\mathrm{S}}{1000\mathrm{W/m^2}}\left[1-\tau\left(\mathrm{T_{cell}}-25\right)\right]\ \mathrm{W} \quad (1)$$

$$p_s = \eta A_c S\ \mathrm{W} \quad (2)$$

In (1) and (2), P_m is the panel power rating, τ is the drift in panel temperature per ^{o}C, η is the collector efficiency and A_c is the collector area in m^2.

The mechanical power recovered by a wind turbine can be written as;

$$P_w = \frac{1}{2}a_c\rho A_s V_w^3\ \ \mathrm{W} \quad (3)$$

where, a_c is the aerodynamic coefficient of wind turbine which depends on the turbine speed and wind speed, ρ is the air density, A_s is the surface swept in m^2 and V_w is the wind speed in m/s.

In order to limit the variance in the useful power produced due to varying wind speed, the production of wind power is designed in such a way that it is constant for a certain range of wind speeds. Also, wind turbines are designed to develop a nominal Power P_n with a nominal wind speed V_n. Wind speed higher than V_n causes mechanical overloads in the turbine. To avoid mechanical overloading and to limit the variance in the developed power, the characteristic of wind power with wind speed is summarized in Table I.

TABLE I: Wind Power variation with Wind Speed

Wind Speed (V_w m/s)	**Wind Power (P_w W)**
$V_w \le V_{min}$	0
$V_{min} < V_w < V_n$	Useful Power
$V_1 \le V_w < V_2$	P_{w1}
$V_2 \le V_w < V_3$	P_{w2}
$V_3 \le V_w < V_n$	P_{w3}
$V_n \le V_w \le V_{max}$	P_n
$V_w \ge V_{max}$	0

Where V_1, V_2 and V_3 ($V_{min} < V_1 < V_2 < V_3 < V_n < V_{max}$), are the different level of wind speed available per day and P_{w1}, P_{w2} and P_{w3} are the corresponding values of useful power developed.

III. Problem Formulation

The main objective of EED is to minimize both fuel cost and the emissions of polluting gases by extracting maximum power from the renewable sources. The objective functions are fuel cost and emission functions.

The fuel cost function $F_f(P_{gi})$ in \$/h is represented by a quadratic equation such as;

$$F_f\left(P_{gi}\right) = \sum_{i=1}^{N_g} a_i + b_i P_{gi} + c_i P_{gi}^2 \quad (4)$$

In (4), the coefficients a_i, b_i and c_i are the appropriate cost coefficients for individual generating units, P_{gi} is the real power output of the ith generator and N_g is the number of the generators.

Main emissions in thermal power plants are SO_2 and NO_x. The emission of SO_2 depends on fuel consumption and has the same form as the fuel cost function. The emission of NO_x is related to many factors such as the temperature of the boiler and content of the air. The emission $F_e(P_{gi})$ in ton/h of SO_2 and NO_x pollutants is a function of generator output and can be expressed as;

$$F_e\left(P_{gi}\right) = \sum_{i=1}^{N_g} \alpha_i + \beta_i P_{gi} + \gamma_i P_{gi}^2\ + \lambda_i e^{\delta_i P_{gi}} \quad (5)$$

where, the coefficients α_i, β_i, γ_i, λ_i and δ_i are emission coefficients of the ith generating unit.

Wind is available throughout the day at different locations with varying speed and sun light is available only for a particular duration of the day. The aim is to extract maximum amount of power from solar reactor during its available period (T_a). Some part of renewable power generated during this period is stored using some available storage devices. This stored power is delivered during unavailable period (T_u) of sun light.

The power extracted from the renewable source varies and can be considered as a variable load. Therefore this power (P_s+P_w) is deducted from the total demand $\left(P_D^t\right)$ and also the stored power (P_{st}) is added to it (during T_a) or subtracted from it (during T_u), to obtain the actual demand $\left(P_D^a\right)$, which is distributed among the available generating units. The net actual demand is expressed as;

$$P_D^a = P_D^t - \left(P_s + P_w\right)_g \pm P_{st} \quad (6)$$

where, P_s and P_w are solar and wind power generated respectively. The positive sign is applicable during the storage whereas the negative sign is used during the delivery periods.

There are some constraints that can be formulated as follows:

- The total power generation, renewable power that have to be considered and also stored power must cover the actual demand and the power loss (P_L) in transmission lines so as to ensure power balance, i.e.

$$P_D^a + P_L - \sum_{i=1}^{N_g} P_{gi} = 0 \quad (7)$$

- The generated real power of i^{th} unit is restricted by the lower limit P_{gi}^{min} and the upper limit P_{gi}^{max},

$$P_{gi}^{min} \le P_{gi} \le P_{gi}^{max} \text{, i=1, 2, ….., Ng} \quad (8)$$

- Active power loss of the transmission line is positive, i.e.,

$$P_L > 0 \quad (9)$$

- The dispatched amount of renewable power is limited to some part (x) of the total actual demand, i.e.

$$(P_s + P_w)_d \le xP_D^a \quad (10)$$

- The stored power is the difference of the total extracted and dispatched amount of renewable power during T_a. During T_u, it must not exceed some part (y) of the total stored renewable power of T_a period. Moreover, the sum of total power delivered from the storage devices during T_u must not exceed the total power stored during T_a,

$$P_{st} \le (P_s + P_w)_g - (P_s + P_w)_d \text{ ; during Ta} \quad (11)$$

And,

$$P_{st} \le y\sum_{T_a} (P_s + P_w)_g - (P_s + P_w)_d \text{ ; during Tu} \quad (12)$$

where, $y \propto \frac{T_a}{T_u} P_D^a$ in such a way that;

$$\sum_{T_u} P_{st} \le \sum_{T_a} P_{st} \quad (13)$$

Now the optimization problem can be summarized as;

$$\text{Minimize} \left(F_f(P_{gi}), F_e(P_{gi})\right)$$

Subjected to;

$$P_D^a + P_L - \sum_{i=1}^{N_g} P_{gi} = 0$$
$$P_{gi}^{min} \le P_{gi} \le P_{gi}^{max}$$
$$P_L > 0$$
$$(P_s + P_w)_d \le xP_D^a$$
$$P_{st} \le (P_s + P_w)_g - (P_s + P_w)_d$$
$$P_{st} \le y\sum_{T_a} (P_s + P_w)_g - (P_s + P_w)_d$$
$$\sum_{T_u} P_{st} \le \sum_{T_a} P_{st}$$

The simulations of the above multiobjective EED problem with given constraints were performed using MATLAB and the results are discussed in the next section.

IV. Results and Discussions

The MATLAB simulations were carried out using the data of the standard IEEE 30 bus test system [3], [5]. Here, two case studies were considered: Case A, during T_a and Case B, during T_u. Three sub cases such as; (i) without renewable & storage, (ii) with renewable only and (iii) with both renewable and storage were investigated. Let E_N, E_R, and $E_{R\&S}$ be the values of emission per hour and C_N, C_R, and $C_{R\&S}$ the fuel cost per hour corresponding to these three sub cases. The values of the fuel and emission coefficients are given in Table II.

TABLE II: Generator Cost and Emission Coefficients

	Cost				Emission			
	a	b	c	α	β	γ	λ	δ
P_{g1}	10	200	100	4.091	-5.554	6.490	2x10-4	2.857
Pg2	10	150	120	2.543	-6.047	5.638	5x10-4	3.333
Pg3	20	180	40	4.258	-5.094	4.586	1x10-6	8
Pg4	10	100	60	5.326	-3.55	3.380	2x10-3	2
Pg5	20	180	40	4.258	-5.094	4.586	1x10-6	8
Pg6	10	150	100	6.131	-5.555	5.151	1x10-5	6.667

The lower and upper limits of generated active power of each generator are given as;

$$0.05pu \le P_{gi} \le 1.5pu \text{ ; i=1, 2, ….., 6} \quad (14).$$

During T_a period, a high intensity of solar radiation and wind with less or high speed is available and one must extract maximum power from the renewable source during this period. About 30% of total demand is dispatched from this extracted power and the remaining part is stored. Therefore both emission and cost are independent of stored energy during this period. Fig. 1 shows that, E_R decreases with increase in demand while E_N decreases up to a certain amount of demand and when demand increases it also increases rapidly. Also C_R for a given demand is always less than C_N.

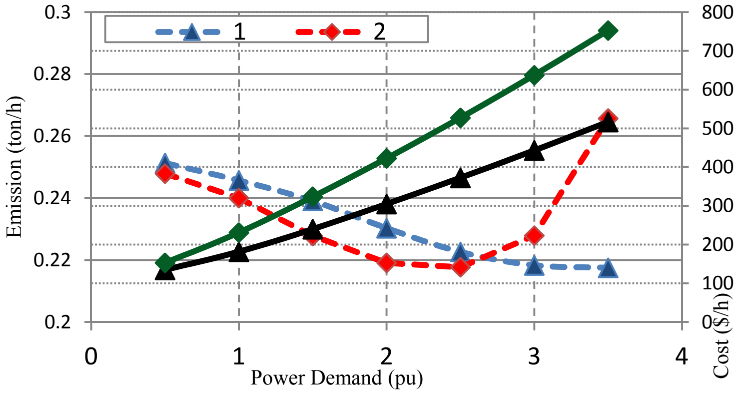

Fig. 1. Variation of Emission & Cost with Power Demand during T_a. 1. E_R, 2. E_N, 3. C_R & 4. C_N

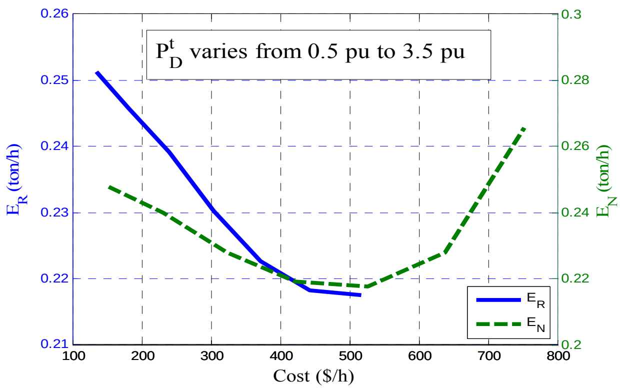

Fig. 2. Variation of Emission with cost during T_a

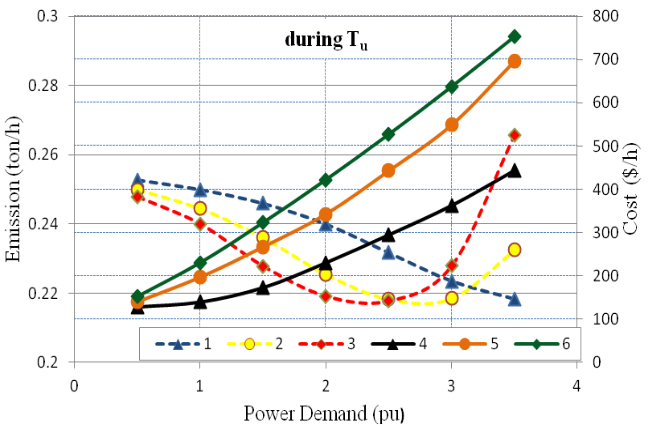

Fig. 3. Variations of Emission & Cost with Power Demand during Tu. 1. $E_{R\&S}$, 2. E_R, 3. E_N, 4. $C_{R\&S}$, 5. C_R & 6. C_N

The variation of emission with respect to cost is shown in Fig. 2. Comparing Fig. 1 & Fig. 2, it is clear that, 2.7 pu demand can be met with a cost of 400 $/h with renewable sources while only 1.9 pu can meet without the renewable sources. However, the amount of emission is about 0.22 ton/h in both cases.

During T_u, both wind power and stored power are available. Due to the uncertainty of the wind speed, the dispatch amount of renewable power is less (about 20% total demand) as compared in case A. Considering 1 pu of stored power during this period, the dispatch amount of stored power is correlated to both demand and T_u duration. The results are summarized in Figs. 3 and 4. It is clear that, the fuel cost per hour is as $C_{R\&S} < C_R < C_N$ for a given amount of demand and emission per hour is $E_{R\&S} < E_R < E_N$ for higher values of demand.

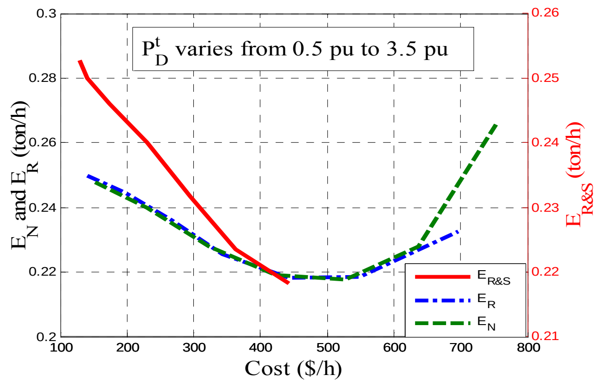

Fig. 4. Variation of Emission with cost during T_u

Percentage reductions in fuel cost per hour with renewable power %ΔC_R $(1-C_R/C_N)x100$ and that of emission %ΔE_R $(1-E_R/E_N)x100$ with renewable power during T_a are given in Table III. The %ΔC_w is increased with increase in demand while, for low demand, the amount of emission with renewable power is slightly higher than the amount of emission without renewable power. However, for higher demand, the %ΔE_R is increased.

TABLE III: REDUCTION IN COST AND EMISSION DURING T_A

P^t_D (pu)	(%ΔC_R)	(%ΔE_R)
0.5	11.86	-1.37
1	21.52	-2.38
1.5	25.89	-4.96
2	27.92	-5.11
2.5	29.38	-2.25
3	30.49	4.21
3.5	31.37	18.14

Similarly, the percentage reductions in fuel cost with renewable power %ΔC_R and with both renewable & storage power %$\Delta C_{R\&S}$ and that of emission with renewable power %ΔE_R and with both renewable & storage %$\Delta E_{R\&S}$ during T_u are given in Table 4.

During T_u, at demand 3.5 pu, about 7.5% of cost and 12.5% of emission are reduced with renewable power only while the cost and emission reductions are about 40% and 18% respectively using both renewable and storage power. The percentage reduction in cost decreases with decrease in demand in both cases. However, the emission is slightly higher in these cases than the dispatch of power without storage and renewable for low demands, but the percentage reduction in emission is always more for higher demand.

TABLE IV: REDUCTION IN COST AND EMISSION DURING T_U

P_D^t (pu)	(%$\Delta C_{R\&S}$)	(%ΔC_R)	(%$\Delta E_{R\&S}$)	(%ΔE_R)
0.5	15.45	8.12	-1.98	-0.85
1	39.22	14.64	-4.17	-1.86
1.5	46.34	17.47	-7.99	-3.64
2	45.34	18.84	-9.54	-2.92
2.5	44.04	15.98	-6.43	-0.28
3	43.13	13.89	1.931	4.12
3.5	41.15	7.53	17.84	12.50

Fig. 5 shows the percentage change in Cost (% ΔC) and Emission (% ΔE) for a given daily load curve. It is clear that more than 40% of fuel cost is saved during T_u with both storage & renewable sources, while the saving is less than 20% when only renewable sources are considered. And almost 35% of fuel cost can be saved during T_a with renewable sources. Also, the percentage change in emission is high for higher demand and can be negative for lower demands.

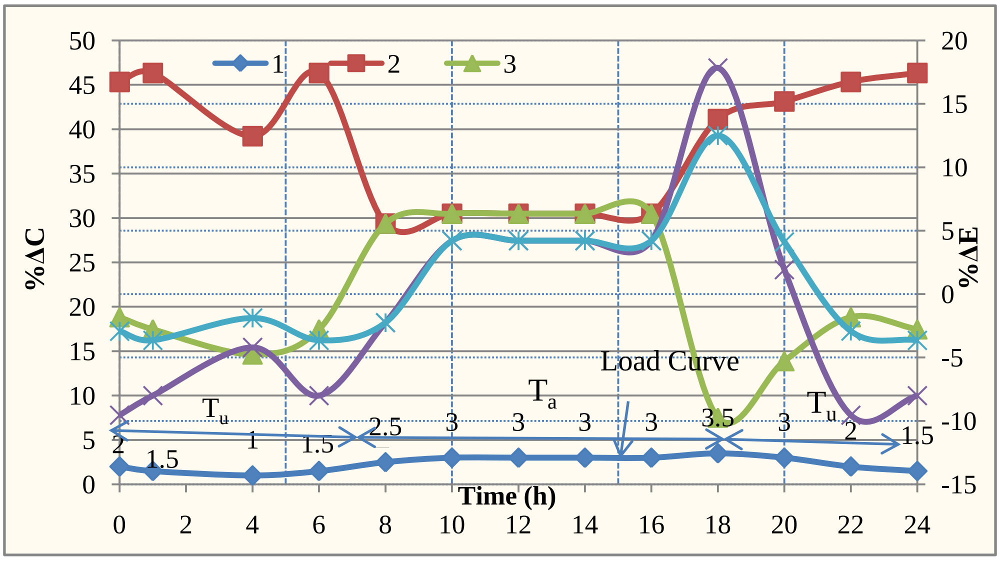

Fig. 5. Percentage change in Emission and Cost with Load Curve
1. Load (pu), 2. % $\Delta C_{R\&S}$, 3. % ΔC_R, 4. % $\Delta E_{R\&S}$ and 5. % ΔE_R

V. CONCLUSION

In this paper EED problem is formulated for a hybrid system which includes thermal generating units, solar, wind and renewable storage. Analysis is carried out using MATLAB simulation for a high irradiation solar region. Results show that, the renewable storage helps to extend advantage of clean energy sources into unavailable solar radiation periods. The optimized results are compared for both available and unavailable periods of sun light. From the analysis it is concluded that if less amount of extracted renewable power is required to optimal dispatch at low values of power demand, thereby large values of energy can be stored at low demand during the solar power available periods. High cost of storage device and uncertainty of renewable sources will reduce the reliability of this approach. Further research should be carried out in order to solve the problems related to the interconnection of number of renewable resources and to develop storage devices with lower cost.

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