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 NOx 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.

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/m²/day [9]. Depending on geographical location, the global solar radiation in the Kingdom varies between a minimum of 4493W/m²/day to a maximum of 7014W/m²/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 interconnected 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 multijobjective 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/m²) and are given by equations (1) and (2) respectively

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

\[ P_s = \eta A_s S W \] (2)

In (1) and (2), \( P_m \) is the panel power rating, \( \tau \) is the drift in panel temperature per °C, \( \eta \) is the collector efficiency and \( A_s \) is the collector area in m².

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

\[ P_w = \frac{1}{2} a_c \rho A_v V_w^3 W \] (3)

where, \( a_c \) is the aerodynamic coefficient of wind turbine which depends on the turbine speed and wind speed, \( \rho \) is the air density, \( A_v \) is the surface swept in m² 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 developed power, the characteristic of wind power with wind speed is summarized in Table I.

<table>
<thead>
<tr>
<th>Wind Speed (V_w, m/s)</th>
<th>Wind Power (P_w, W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V_w ≤ V_{min}</td>
<td>0</td>
</tr>
<tr>
<td>V_{min} &lt; V_w &lt; V_1</td>
<td>Useful Power</td>
</tr>
<tr>
<td>V_1 ≤ V_w &lt; V_2</td>
<td>P_{w1}</td>
</tr>
<tr>
<td>V_2 ≤ V_w &lt; V_3</td>
<td>P_{w2}</td>
</tr>
<tr>
<td>V_3 ≤ V_w &lt; V_{max}</td>
<td>P_{w3}</td>
</tr>
<tr>
<td>V_{max} ≤ V_w</td>
<td>P_w</td>
</tr>
<tr>
<td>V_w ≥ V_{max}</td>
<td>0</td>
</tr>
</tbody>
</table>

Where \( V_1, V_2 \) and \( V_3 \) (\( V_{min} < V_1 < V_2 < V_3 < V_{max} \)), 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 \( F_i(P_{gi}) \) in $/h is represented by a quadratic equation such as;

\[ F_i(P_{gi}) = \sum_{i=1}^{N_g} a_i + b_i P_{gi} + c_i P_{gi}^2 \] (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 \( i^{th} \) generator and \( N_g \) is the number of the generators.

Main emissions in thermal power plants are SO₂ and NOₓ. The emission of SO₂ depends on fuel consumption and has the same form as the fuel cost function. The emission of NOₓ is related to many factors such as the temperature of the boiler and content of the air. The emission \( F_i(P_{gi}) \) in ton/h of SO₂ and NOₓ pollutants is a function of generator output and can be expressed as;

\[ F_i(P_{gi}) = \sum_{i=1}^{N_g} a_i + \beta_i P_{gi} + \gamma_i P_{gi}^2 + \lambda_i e^{\delta_i P_{gi}} \] (5)

where, the coefficients \( \alpha_i, \beta_i, \gamma_i, \lambda_i \) and \( \delta_i \) are emission coefficients of the \( i^{th} \) 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_s). 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_a) of sun light.

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

\[ P_D = P'_D - (P_s + P_{w}) \pm P_{st} \] (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.,

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

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

$$P_{gi}^{\min} \leq P_{gi} \leq P_{gi}^{\max}, \quad i=1, 2, \ldots, N_g  \hfill (8)$$

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

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

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

$$(P_s + P_w)_d \leq xP_D^a  \hfill (10)$$

- 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.

$$P_{st} \leq y\sum_{i=1}^{N_s} (P_s + P_{wi})_g - (P_s + P_{wi})_d  \hfill (11)$$

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

$$\sum_{T_a} P_{st} \leq \sum_{T_a} P_{st}  \hfill (13)$$

Now the optimization problem can be summarized as;

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

Subjected to;

$$P_D^a + P_L - \sum_{i=1}^{N_g} P_{gi} = 0  \hfill (16)$$

$$P_{gi}^{\min} \leq P_{gi} \leq P_{gi}^{\max}, \quad i=1, 2, \ldots, N_g  \hfill (8)$$

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

$$(P_s + P_w)_d \leq xP_D^a  \hfill (10)$$

$$P_{st} \leq y\sum_{i=1}^{N_s} (P_s + P_{wi})_g - (P_s + P_{wi})_d  \hfill (11)$$

$$\sum_{T_u} P_{st} \leq \sum_{T_u} P_{st}  \hfill (12)$$

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        |                |                |                |                |                |                |
|                | $a$  | $b$  | $c$  | $\alpha$ | $\beta$ | $\gamma$ | $\lambda$ | $\delta$ | $\beta$ | $\gamma$ | $\lambda$ | $\delta$ |
| $P_{g1}$  | 10   | 200  | 100  | 4.091 | -5.554 | 6.490 | 2x10^{-4} | 2.857 |
| $P_{g2}$  | 10   | 150  | 120  | 2.543 | -6.047 | 5.638 | 5x10^{-4} | 3.333 |
| $P_{g3}$  | 20   | 180  | 40   | 4.258 | -5.094 | 4.586 | 1x10^{-4} | 8   |
| $P_{g4}$  | 10   | 100  | 60   | 5.326 | -3.55  | 3.380 | 2x10^{-4} | 2   |
| $P_{g5}$  | 20   | 180  | 40   | 4.258 | -5.094 | 4.586 | 1x10^{-4} | 8   |
| $P_{g6}$  | 10   | 150  | 100  | 6.131 | -5.555 | 5.151 | 1x10^{-4} | 6.667 |

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

$$0.05\, pu \leq P_{gi} \leq 1.5\, pu; \quad i=1, 2, \ldots, 6  \hfill (14)$$

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 $C_N$.  

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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 $T_a$.

Percentage reductions in fuel cost per hour with renewable power $\%\Delta C_R (1 - C_R / C_N) \times 100$ and that of emission $\%\Delta E_R (1 - E_R / E_N) \times 100$ with renewable power during $T_a$ are given in Table III. The $\%\Delta C_w$ 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 $\%\Delta E_R$ is increased.

<table>
<thead>
<tr>
<th>$P_D^t$ (pu)</th>
<th>$%\Delta C_R$</th>
<th>$%\Delta E_R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>11.86</td>
<td>-1.37</td>
</tr>
<tr>
<td>1</td>
<td>21.52</td>
<td>-2.38</td>
</tr>
<tr>
<td>1.5</td>
<td>25.89</td>
<td>-4.96</td>
</tr>
<tr>
<td>2</td>
<td>27.92</td>
<td>-5.61</td>
</tr>
<tr>
<td>2.5</td>
<td>29.38</td>
<td>-2.25</td>
</tr>
<tr>
<td>3</td>
<td>30.49</td>
<td>4.21</td>
</tr>
<tr>
<td>3.5</td>
<td>31.37</td>
<td>18.14</td>
</tr>
</tbody>
</table>

Similarly, the percentage reductions in fuel cost with renewable power $\%\Delta C_R$ and with both renewable & storage power $\%\Delta C_{R&S}$ and that of emission with renewable power $\%\Delta E_R$ 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>
<thead>
<tr>
<th>$P_D^i$ (pu)</th>
<th>(%ΔC_R&amp;S)</th>
<th>(%ΔC_R)</th>
<th>(%ΔE_R&amp;S)</th>
<th>(%ΔE_R)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>15.45</td>
<td>8.12</td>
<td>-1.98</td>
<td>-0.85</td>
</tr>
<tr>
<td>1</td>
<td>39.22</td>
<td>14.64</td>
<td>-4.17</td>
<td>-1.86</td>
</tr>
<tr>
<td>1.5</td>
<td>46.34</td>
<td>17.47</td>
<td>-7.99</td>
<td>-3.64</td>
</tr>
<tr>
<td>2</td>
<td>45.34</td>
<td>18.84</td>
<td>-9.54</td>
<td>-2.92</td>
</tr>
<tr>
<td>2.5</td>
<td>44.04</td>
<td>15.98</td>
<td>-6.43</td>
<td>-0.28</td>
</tr>
<tr>
<td>3</td>
<td>43.13</td>
<td>13.89</td>
<td>1.931</td>
<td>4.12</td>
</tr>
<tr>
<td>3.5</td>
<td>41.15</td>
<td>7.53</td>
<td>17.84</td>
<td>12.50</td>
</tr>
</tbody>
</table>

Fig. 5 shows the percentage change in Cost (% $\Delta C$) and Emission (% $\Delta E$) 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.

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.

REFERENCES


F. R. Pazheri received his B.Tech. degree in Electrical & Electronics Engineering from the Calicut University, India in 2001 and M. Tech. degree in Electrical Engineering from Kerala University, India in 2004. He is pursuing PhD in Power System Scheduling from UniversitiTeknologi Malaysia. He has authored over 20 research papers. He was with MES College of Engineering, India from 2005 to 2006 and with College of Engineering, Thalassery, India from 2006 to 2009. Currently he is Lecturer in “Saudi Aramco Chair in Electrical Power” at King Saud University, KSA. (e-mail: fpazheri@hotmail.com)

M. F. Othman received his M. Eng (Elec.) in Power System Control from Universiti Teknologi Malaysia (UTM) in 1996 and PhD in Control System from The University of Sheffield, UK in 2004. He has authored over 30 research papers. Presently he is the Senior Lecturer and principle researcher of Artificial Intelligence Research Group at Centre for Artificial Intelligence & Robotics, Faculty of Electrical Engineering, Universiti Teknologi Malaysia (UTM).

N. H. Malik graduated with B.Sc. in E.E from UET, Lahore in 1973, MASc in Electrical Engineerin from University of Windsor, Canada in 1977 and received Ph.D. from the University of Windsor, Canada in 1979. He has authored over 150 research papers and four books. Presently he is Chair Professor of “Saudi Aramco Chair in Electrical Power”, Electrical Engineering Department, King Saud University, KSA.

Safoora O. K. received her B.Tech. degree in Electronics & Communication Engineering from the Cochin University of Science and Technology, India in 2005. She has authored 4 research papers. Currently she is Assistant Professor in Electronics and Communication Engineering Department at College of Engineering Thalassery, Kerala, India.