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Energy-efficient and environmentally friendly power dispatch by trigeneration with renewable energy and energy storage

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Abstract: The importance of energy-efficient power generation that effectively utilizes the available fossil fuels is increasing due to the gradual decline in fossil fuel reserves. Furthermore, concern about global warming has led to rapid growth in renewable energy and energy storage technologies. This trend is encouraging power utilities to effectively exploit the use of renewable energy resources (RESs) and energy storage facilities (ESFs) for power supply systems. In this regards, trigeneration in the presence of RESs and ESFs can play an important role for efficient and clean power dispatch. This paper discusses the optimum power dispatch using a hybrid power plant consisting of trigeneration-based thermal plants, RES-based plants, and energy storage facilities. Mathematical modeling of such a dispatch problem is formulated and the analysis is carried out using MATLAB simulations. Results show that considerable reduction in fuel utilization and pollutants emission can be achieved using such hybrid plants by using the optimum power dispatch proposed here.

Key words: Energy storage, optimization, pollutants emission, power dispatch, renewable energy, renewable penetration level, trigeneration

1. Introduction

Uninterrupted, economical, and sustainable electrical energy supply is essential for economic and social development. Electrical utilities strive to provide a sustainable, uninterrupted, and secure energy supply while limiting the amount of pollutants emitted from power plants. Global primary energy consumption is increasing rapidly due to population growth, development, and globalization and industrialization trends. Meanwhile, billions of people are facing a lack of primary energy for even their basic needs [1]. Thus, the global demand for fossil fuels for electricity generation is increasing while the reserves of these fossil fuels are decreasing [2]. A conventional coal-fired power plant designed to generate electricity wastes about 60% of the fuel energy as heat loss [3]. Hence, effective and optimal utilization of available energy resources is essential to accommodate future energy needs. The trend of global energy demand of different primary energy resources, in million tons of oil equivalent (Mtoe), is illustrated in Table 1.

About 86% of global primary energy needs are met by fossil fuel-based thermal power plants and thus such power plants are the main source of global greenhouse gas (GHG) emission [4]. Almost 1000 kg/MWh of GHG emission occurs during the generation of electricity from fossil fuel-based plants. The increased concentration of GHG in the atmosphere is causing a gradual rise in the global temperature. In 2013, the atmospheric

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Table 1. Global energy demand by sources in Mtoe [1].

Energy source	Year			
	1980	2000	2008	2020
Fossil fuel	6133	8032	10,192	11,824
Nuclear	186	676	723	920
Renewable	909	1311	1552	2021
Total world	7228	10,018	12,467	14,765

CO_2 concentration reached almost 400 ppm [2]. It has been suggested that more than 450 ppm of GHG concentration can result in severe damage to the environment [2]. It is estimated that every year about 300,000 people die globally due to the pollutants emitted from fossil fuel-based plants [5]. Power utilities are thus under considerable pressure to utilize the available renewable energy resources (RESs) in order to reduce the amounts of GHG emissions.

Gradual developments are taking place in renewable power generation and energy storage technologies [6]. At the end of 2012, the global installed capacity of renewable power units exceeded 1500 GW. It has been suggested that renewable sources can provide about 13% of global energy demand by the year 2020 and about 14.5% by the year 2040 [2]. When RES generation is available and in off-peak periods, a part of the renewable power produced can be stored and can be used to supply consumers during the periods when RES generation is unavailable. Hence, energy storage facilities (ESFs) can help to increase the renewable energy penetration level in the grid while using intermittent and distributed renewable resources. Effective use of available RESs and ESFs along with conventional power plants can reduce the dependence on fossil fuel-based power production and thus help to minimize pollutant emissions significantly.

Trigeneration is one of the options for the effective utilization of primary energy resources. It facilitates the combined production of electricity as well as heating and cooling power from a single primary energy source simultaneously, resulting in a more efficient use of energy resources [7]. As noted earlier, a significant amount of heat energy is wasted in conventional power plants since such plants are designed to produce electricity only. However, in trigeneration, the heat produced as a by-product of electricity generation is used to obtain heating and cooling powers. Thus, the fuel utilization efficiency is increased in trigeneration plants. Moreover, the method also considerably reduces the amount of GHG pollutants emission. A trigeneration plant consists of a cogeneration side and a cooling side. The cogeneration side generates electricity and heat [8,9] while the cooling side produces the required cooling power. For this purpose, the absorption chillers are mainly used to convert some portion of waste heat to the cooling power [10].

In order to increase their overall efficiency and effectiveness, an efficient operating schedule is needed for committed trigeneration plants. Power dispatch techniques are used to find the best operating schedule for the committed units while meeting the load demand without affecting any unit or system constraints [11]. Several optimum power dispatch problems have been discussed in the literature for conventional power plants [12–15]. However, the key contribution of this paper is the modeling of the optimum power dispatch scheduling problem for a hybrid power plant that consists of fossil fuel-based trigeneration units and RES-based generation units along with energy storage facilities. It is shown that such dispatch methods can help reduce the amounts of fuel utilization as well as the resulting pollutants emissions. In order to illustrate the benefits of the proposed approach, energy-efficient and environmentally friendly power dispatch (EEEFPD) optimization is carried out for minimizing both the amounts of fuel used and the amounts of emissions, simultaneously.

In the proposed method, the optimization is carried out using a genetic and sequential quadratic programming (GA-SQP)-based hybrid algorithm in MATLAB simulations. The sequential quadratic programming (SQP) algorithm outperforms other nonlinear programming methods in terms of accuracy, efficiency, and percentage of successful solutions [16]. However, the SQP is not preferred to find a global minimum solution in many complex problems as it suffers from a tendency to converge to local optimal values. In such cases, a GA-SQP hybrid algorithm gives the accurate global minimum solution. In this approach, such global or near-global optimum results are first obtained by the genetic algorithm (GA) method. These values are used as the initial solutions for SQP to find the overall global optimum solution. Thus, SQP acts as a tuner algorithm to the GA-based optimization method [17]. The paper provides complete details of the model, the method of solution, and results and analysis.

2. Methodology

During operation period T of power dispatch, wind power may or may not be available throughout the period. Furthermore, solar power can be produced only for a certain part of time period T. Let T_{sa} and T_{su} represent the available and unavailable periods, respectively, of solar insolation during 24 h. Figure 1 represents typical variations in daily solar insolation. The production of wind power depends on the availability of the wind speed during periods T_{sa} and T_{su}. The variations in the wind power produced (P_w) with changes in the wind speed (W) can be represented in such a way that the wind plant produces a constant power for a certain range of wind speeds. Let $W_{\min}$ and $W_{\max}$ be the minimum and maximum wind speed for the smooth operation of the wind turbine, respectively. Let W_1, W_2, and W_3 be the different levels of wind speeds available per day such that $W_{\min} < W_1 < W_2 < W_3 < W_{\max}$. Moreover, P_{wmin}, P_{w1}, P_{w2}, and P_{w3} are the wind powers corresponding to the abovementioned wind speeds, respectively. The characteristics of wind power with wind speed are given in Table 2. During the period of available RESs, the maximum possible amount of renewable power is extracted from the solar and wind plants. A part of this produced renewable power is dispatched to meet a specified share of the total demand, and the excess renewable energy is stored during this period. This stored energy is used to meet a predefined share of the total demand during the period of unavailable RESs.

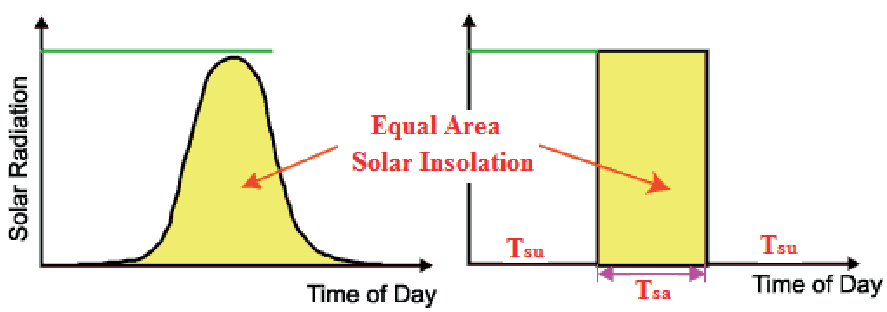

Figure 1. Daily solar insolation.

Table 2. Characteristics of wind power with wind speed.

Wind speed (W)	Wind power (P_w)
$W < W_{\min}$	0
$Wmin < W < W_1$	P_{wmin}
$W_1 < W < W_2$	P_{w1}
$W_2 < W < W_3$	P_{w2}
$W_3 < W < W_{\max}$	P_{w3}
$W > W_{\max}$	0

3. Problem formulation

In this analysis, the generated renewable power $(P_R)_g$ is considered as a variable load due to the intermittent nature of its availability. Thus, this power is deduced from the total demand (P_D^t). Moreover, the stored renewable power (P_{st}) is added to the total demand while the delivered renewable power (P_{dl}) is deducted from it. Let P_{sg} and P_{wg} be the amount of solar and wind power generated, respectively. Thus, the actual demand (P_D^a) to be dispatched by the trigeneration plants can be represented as:

$$P_D^a = P_D^t - (P_R)_g + P_{st} - P_{dl}, \tag{1}$$

$$(P_R)_g = P_{sg} + P_{wg}. \tag{2}$$

Moreover, the combined cooling, heating, and electric power output of the ith trigeneration plant can be expressed as:

$$P_{ti} = IBP_{ti}[\eta_{et} + (1 - x_1)\eta_{th} + x_1\eta_{ct}]. \tag{3}$$

In Eq. (3), IBP_{ti} is the boiler input power of the ith trigeneration plant. Moreover, η_{et}, η_{ht}, and η_{ct} are the conversion efficiencies of the trigeneration system for the electricity, heating, and cooling powers and x_1 represents the percentage of heat used to produce the cooling effect.

The minimization of the amounts of fuels used and the amounts of pollutant emissions are the main objectives of the considered EEEFPD problem. Hence, fuel utilization and emission functions of the committed units are considered as the objective functions. Using curve-fitting methods, the approximate expressions for overall fuel utilization function by trigeneration $F_{fut}(P_{ti})$ can be derived and is expressed in t/h as [18,19]:

$$F_{fut}\left(P_{ti}\right) = \sum_{i=1}^{N_{ti}} \left(\left(a_{ti}P_{ti}^3 + b_{ti}P_{ti}^2 + c_{ti}P_{ti} + d_{ti}\right)\right), \tag{4}$$

where P_{ti} is the output power by trigeneration and a_{ti}, b_{ti}, c_{ti}, and d_{ti} are fuel utilization coefficients of the ith trigeneration unit.

The amounts of pollutant emissions from a trigeneration plant depend on the boiler efficiency, the amount of fuel used, and the contents of carbon, sulfur, and nitrogen in the fuel. The amounts of pollutant emissions by trigeneration can be calculated using basic stoichiometric calculations and ultimate analysis of the used fuels [19]. The approximate expressions for overall emissions by the trigeneration plant in the presence of renewable energy can be expressed in t/h as:

$$F_{et}\left(P\right) = \sum_{i=1}^{N_{ti}} \left(\alpha_{ti}P_{ti}^3 + \beta_{tt}P_{ti}^2 + \gamma_{ti}P_{ti} + \delta_{ti}\right) + \sum_{r=sg,wg} (\chi_r P_r), \tag{5}$$

where P is the combined power output of the committed units. $\alpha_{ti}, \beta_{ti}, \gamma_{ti}$, and δ_{ti} are the emission coefficients of the ith trigeneration plant. Moreover, χ_{sg} and χ_{wg} are the emission coefficients of the solar and wind plants, respectively.

The main constraints applicable for the EEEFPD problem considered here are as follows:

- ♦ The actual power demand is distributed among the thermal units committed for the dispatch. Hence, the actual demand and the transmission power loss should be covered by the total power generation in order to ensure the power balance. Thus,

$$P_D^a + P_L - \sum_{i=1}^{N_{ti}} P_{ti} = 0. \tag{6}$$

♦ The required electrical, heating, and cooling power demands should equal the total demand. Thus,

$$P_D^t = P_e + P_h + P_c, \tag{7}$$

where P_e, P_h, and P_c are the electrical, heating, and cooling power demands, respectively. Here it is assumed that:

$$P_e = x_2 P_D^t, \tag{8}$$

$$P_h = \frac{1 - x_2}{1 + x_1} P_D^t, \tag{9}$$

$$P_c = \frac{x_1 - x_1 x_2}{1 + x_1} P_D^t, \tag{10}$$

where x_2 is the electrical share of the demand.

♦ The real power generation by any committed conventional or renewable unit must be restricted to its lower and upper limits. Thus,

$$P_{ti}^{\min} \leq P_{ti} \leq P_{ti}^{\max}, \tag{11}$$

i=1, 2, ..., N_{ti},

$$P_r^{\min} \leq P_r \leq P_r^{\max}, \tag{12}$$

r = sg and wg.

♦ Transmission loss of the system is positive, i.e.

$$P_L = P^T B P + B_0 P + B_{00} > 0, \tag{13}$$

where B, B0, and B00 are the traditional loss coefficients.

♦ RES-based generation plants and the ESF together provide a certain share of the demand during the operation periods. Thus,

$$(P_R)_d \leq x P_D^t, \tag{14}$$

$$(P_R)_d = \begin{cases} P_{wd} + P_{sd}; during T_{sa} period \\ P_{wd}; during T_{su} period \end{cases}, \tag{15}$$

where P_{wd} and P_{sd} are the dispatched solar and wind powers, respectively, and x is the renewable penetration level.

- P_{st} is the difference between the total power extracted from the renewable sources and the dispatched renewable power during its available period T_a. Let T_{st} and T_{dl} be the storage and delivery of ESF periods, respectively. The amount of total energy delivered, E_{dl}, by the storage facilities during the T_{dl} period must not exceed the total energy stored, E_{st}, during the T_{st} period plus the balance of stored energy from the last operation period E_{st}^L. Thus, for an operation period T:

$$E_{dl} \leq E_{st} + E_{st}^L, \tag{16}$$

$$E_{dl} = \sum_{t=1}^{T_{dl}} (P_{dl} T_{dl}), \tag{17}$$

$$E_{st} = \sum_{t=1}^{T_{st}} (P_{st} T_{st}), \tag{18}$$

$$P_{st} \leq \frac{\int_t \left[(P_R)_g - (P_R)_d \right] dt}{\int_t dt}; \quad t \in T_{st}, \tag{19}$$

and

$$P_{dl} \leq y P_{st}; \quad during T_u. \tag{20}$$

The value of y is selected to guarantee that there is no complete discharge of the ESF at the end of the T_u period. The value of y depends on the length of the storage and delivery periods. It is large for longer storing and shorter delivering periods and vice versa. Thus, it is proportional to the ratio of T_a to T_u and the total power demand. Hence, $y \propto \frac{T_a}{T_u} P_D^a$.

Thus, the EEEFPD optimization problem can be expressed as:

Minimize $\{F_{fut}(P_{ti}), F_{et}(P)\}$,

subjected to the constraints given in Eqs. (6) through (16).

The optimization is carried out with MATLAB simulation using GA-SQP-based hybrid algorithms. In this study, the GA is used as the main algorithm, whereas SQP is used as a tuner algorithm.

4. Results and discussion

The EEEFPD optimization problem is carried out using the data given in Tables 3 and 4. The emission coefficients of solar and wind plants are considered as 0.45 t/MWh and 0.26 t/MWh, respectively [13].

Table 3. Fuel utilization coefficients and power limits (MW) of thermal units [19].

Gen.	a	b	c	d	P^{min}	P^{max}
1	2×10^{-7}	-2×10^{-4}	0.269	3.0	10	85
2	2×10^{-7}	-2×10^{-4}	0.269	3.0	10	85
3	2×10^{-7}	-2×10^{-4}	0.250	2.8	10	60
4	6×10^{-8}	-7×10^{-5}	0.105	1.1	10	55

Table 4. Emission coefficients of thermal units [19].

Gen.	α	β	γ	δ
1	3×10^{-7}	-3×10^{-4}	0.451	5.0
2	3×10^{-7}	-3×10^{-4}	0.451	5.0
3	-3×10^{-7}	8×10^{-4}	0.341	5.0
4	2×10^{-7}	-2×10^{-4}	0.332	3.7

The analysis is carried out for a particular operation day. The assumed wind speed ratio W_p (the ratio of actual to maximum wind speeds) as well as solar and wind powers generated are as shown in Figure 2. It is considered that reliable solar irradiation is available from 0700 to 1700 hours as is usually the case in many countries. The wind power generated corresponding to different wind speed ranges, $W_p < 0.2$, $2 \leq W_p < 0.4$, $0.4 \leq W_p < 0.8$, and $W_p \geq 0.8$, are 0 MW, 25 MW 35 MW, and 40 MW, respectively, as shown in Figure 2. The maximum solar and wind powers generated are assumed as 45 MW and 40 MW, respectively.

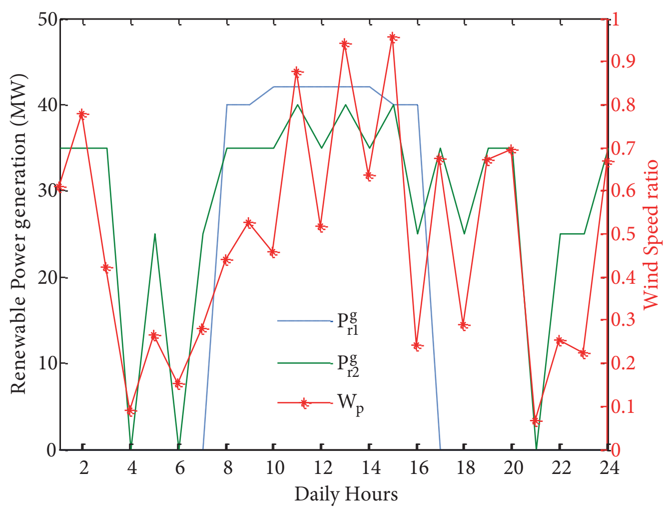

Figure 2. Renewable power generation and wind speed ratio for the considered day of operation.

The power generation of each unit of the hybrid plant can be determined by the EEEFPD optimization in such a way that a specified power demand can be met by least fuel consumption and least possible emissions. Hence, the amounts of fuel utilization and pollutants emission are reduced with this approach. The optimum power dispatch with trigeneration is analyzed here by considering two case studies. In case 1, only thermal units are utilized, while in case 2 a hybrid plant consisting of thermal and RES-based plants and ESF units is considered. The optimum variations of dispatched power outputs of each generation unit with daily power demands for case 1 are given in Table 5. It is clear from the results of this table that the fourth generation unit is more efficient and contributes a greater share of the total power demand while the contributions of the first two units are comparatively smaller due to their higher emission characteristics.

The presence of RES-based power units and the ESF along with thermal units results in better scheduling results since RES-based units contribute comparatively negligible amounts of pollutant emissions. By the use of a hybrid plant, a significant value of renewable penetration is assured by the presence of the ESF throughout the operation period. For case 2, the results of EEEFPD optimization with daily load demand are given in Table 5. The maximum value of renewable penetration considered here is taken as 25%. If the amount of total renewable

Table 5. Results of EEEFPD optimization for case 1.

Time (h)	1	4	7	10	13	16	19	22	24
P_D^t (MW)	100	140	260	220	155	240	270	230	115
P_{g1} (MW)	10	17.27	85	85	32.30	85	85	85	10
P_{g2} (MW)	10	10	63.49	22.63	10	43.01	73.77	32.81	10
P_{g3} (MW)	26.44	60	60	60	60	60	60	60	41.75
P_{g4} (MW)	55	55	55	55	55	55	55	55	55
Fuel (t/h)	27.29	37.06	67.67	57.33	40.96	62.57	70.19	59.97	30.92
Emission (t/h)	54.87	71.26	122.93	105.49	77.82	114.3	127.3	109.92	60.76

generation exceeds 25% of the total demand, only 25% of the demand is dispatched from the renewable units while the remaining renewable power produced is stored. However, for a particular time of operation, if the renewable power is either zero or less than 15% of the demand, the storage units deliver the power in order to ensure 15% of the renewable penetration level. Hence, the RES and ESF units together guarantee that $\geq$15% but $\leq$25% of the total demand is supplied by these units at any time of operation.

It can be noted from Figure 2 and Table 6 that at 0700 hours, the amount of solar power is zero and that of wind power is only 25 MW. Hence, to meet 15% of the 260 MW demand, about 13 MW is supplied by the ESF. However, at 1600 hours, the available amounts of solar and wind powers are 40 MW and 25 MW, respectively, and the dispatched powers to meet 25% of the 240 MW demand from these units are 31.2 MW and 25 MW, respectively. The remaining 9.8 MW power is stored as shown in Figure 3.

Table 6. Results of EEEFPD optimization for case 2.

Time (h)	1	4	7	10	13	16	19	22	24
P_D^t (MW)	100	140	260	220	155	240	270	230	120
P_{g1} (MW)	10.00	10.00	73.98	40.17	10.00	61.57	80.12	68.33	10.00
P_{g2} (MW)	10.00	10.00	34.72	10.00	10.00	10.00	48.19	10.00	10.00
P_{g3} (MW)	12.93	45.67	59.93	60.00	41.39	59.56	48.52	59.63	26.23
P_{g4} (MW)	55.00	55.00	55.00	55.00	55.00	55.00	55.00	55.00	55.00
P_{sd} (MW)	00.00	00.00	00.00	28.60	20.15	31.20	00.00	00.00	00.00
P_{wd} (MW)	13.00	00.00	25.00	28.60	20.15	25.00	35.00	25.00	14.95
P_{dl} (MW)	00.00	21.00	14.00	00.00	00.00	00.00	05.50	09.50	00.00
Fuel (t/h)	24.02	31.84	57.79	42.98	30.84	48.23	60.06	49.91	27.24
Emission (t/h)	50.79	62.30	106.86	85.69	65.23	94.13	110.82	93.58	55.70

Let us assume that F_{fut}^1 and F_{et}^1 are the amounts of fuel used and pollutant emissions in case 1, respectively, and the respective values in case 2 are F_{fut}^2 and F_{et}^2. Then the percentage savings of fuel used ($\%\Delta F_{fut}^2$) and percentage reduction in pollutant emissions ($\%\Delta F_{et}^2$) are expressed as:

$$\%\Delta F_{fut}^2 = (1 - \frac{F_{fut}^2}{F_{fut}^1})x100, \tag{21}$$

$$\%\Delta F_{fet}^2 = (1 - \frac{F_{et}^2}{F_{et}^1})x100. \tag{22}$$

The variations of the amounts of fuel used and pollutant emissions with daily load curve are shown in Figure 4 for case 2. In this case, for a demand of 240 MW, the amount of fossil fuel utilized is approximately 48 t/h,

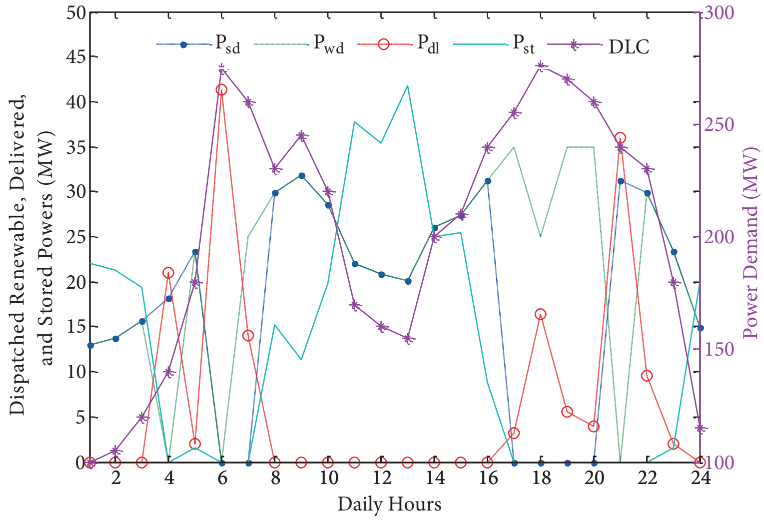

Figure 3. Variation of dispatched renewable, delivered, and stored powers with daily load.

while in case 1, this amount was more than 60 t/h. Similarly, at this demand, the amounts of pollutants emitted for case 1 and case 2 are about 94 t/h and 114 t/h, respectively. The variations of percentage savings in the amounts of fuel utilized and the percentage reduction of pollutant emissions with demand are shown in Figure 5 for the considered case studies. Case 2 provides more than 10% savings in fuel utilization and more than 50% reduction in the pollutant emissions during the complete operation periods. In the considered scenario, the power demand during the period of available solar power is comparatively less, and thus more savings in fuel utilization and emissions are possible due to high renewable penetration. Moreover, during such periods, the rate of power storage is also high.

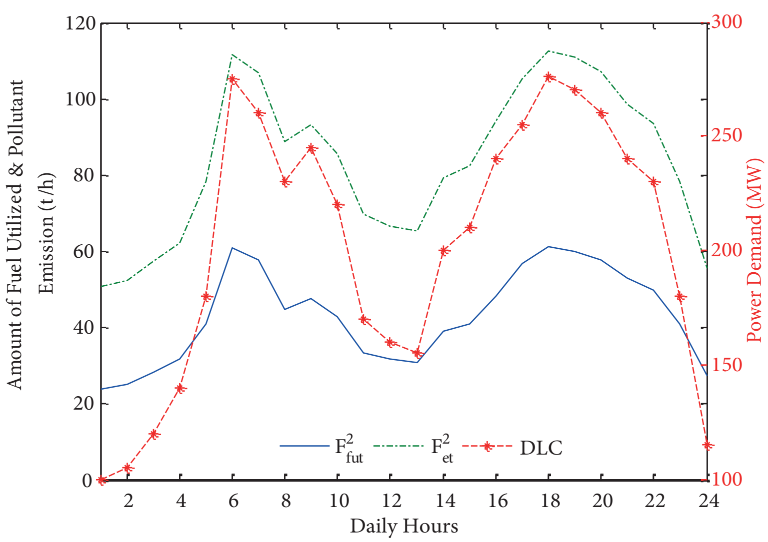

Figure 4. Variation of amount of fuel used and pollutant emissions with daily load in case 2.

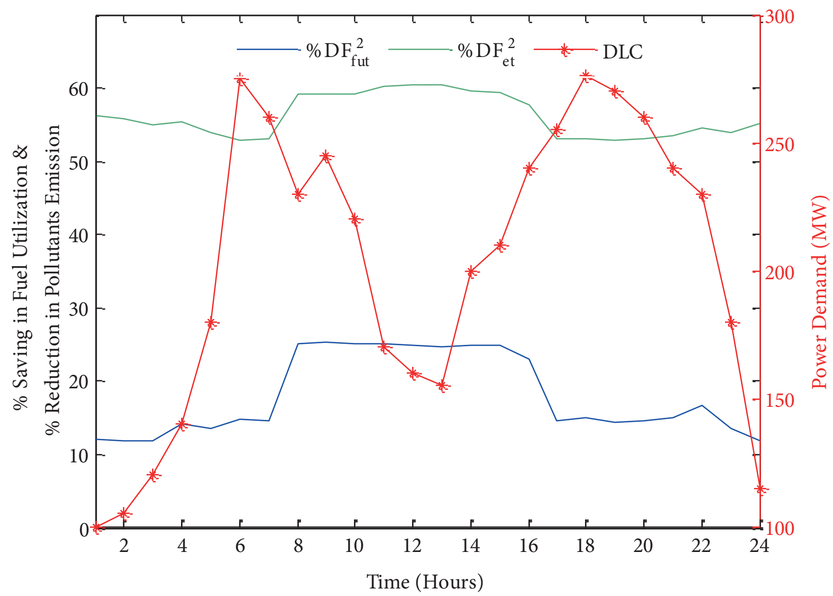

Figure 5. Percentage variations of fuel used and pollutant emissions with daily power demands.

Figure 6 shows the variation of stored and delivered energies versus the hours of operation. At 0700 hours, the delivered energy is about 500 MWh and it remains constant until 1700 hours. This means that no power is dispatched from the ESF during this period since renewable generation units contribute enough renewable power to meet the specified share of the power demands. Moreover, stored energy increases during this period due to the addition of further energy during each operation interval. However, from 1700 to 2200 hours, the amount of energy storage is almost zero, while a significant amount of energy is delivered by the ESF. The ESF provides 350 MWh of energy at the start of this day's operation, whereas at the end of this day, this balance amounts to 1500 MWh of stored energy in the ESF, which is used for the next day's operation.

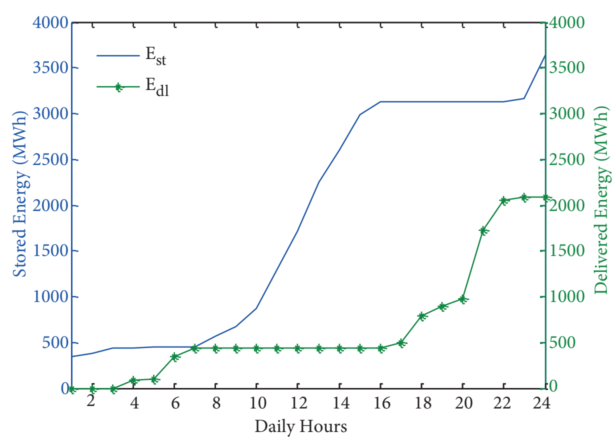

Figure 6. Variation of energy stored and delivered versus the hours of operation.

5. Conclusion

Trigeneration is one of the efficient methods for power generation, and the utilization of RESs is essential for clean power production. The problem of optimization of the amounts of fuel used and pollutant emissions by trigeneration plants in the presence of renewable energy and energy storage facilities was formulated and analyzed in this paper. Analysis was carried out by MATLAB simulation using a GA-SQP algorithm. Without the use of ESFs the efficient utilization of RESs is not possible throughout the operation periods. Concern about clean and energy efficient power generation is increasing rapidly and hence the proposed approach can play a significant role in future power generation. The analysis showed that with the aid of proper scheduling a significant reduction in pollutant emissions and savings in the amount of fuel used are possible.

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