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Online Management of MicroGrid with Battery Storage Using Multiobjective Optimization

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***Abstract*— This paper presents a generalized formulation for determining the optimal operating strategy and cost optimization scheme as well as reducing the emissions of a MicroGrid (MG). Multiobjective (MO) optimization is applied to the environmental economic problem of the MG. The proposed problem is formulated as a nonlinear constrained MO optimization problem. Prior to the optimization, system model components taken from real manufactural data are constructed. The model takes into consideration the operation and maintenance costs as well as the reduction in emissions of NOx, SO_2, and CO_2 . The MG considered in this paper consists of a wind turbine, a micro turbine, a diesel generator, a photovoltaic array , a fuel cell, and a battery storage. The optimization is aimed at minimizing the cost function of the system while constraining it to meet the costumer demand and safety of the system. The results demonstrate the efficiency of the proposed approach to satisfy the load and to reduce the cost and the emissions in one single run.**

***Index Terms*— microgrid, multiobjective optimization, load management , wind turbine, photovoltaic, diesel generator, (PEM) full cell, microturbine, battery storage.**

I. Introduction

THE need for more flexible electric systems, changing regulatory and economic scenarios, energy savings and environmental impact are providing impetus to the development of MGs, which are predicted to play an increasing role in future power systems [1]. One of the important applications of the MG units is the utilization of small-modular residential or commercial units for onsite service. The MG units can be chosen so that they satisfy the customer load demand at compromise cost and emissions all the time.

The management of the MG units requires an accurate environmental economic model to describe the operating problem taking into account the output power production. Such a model is discrete and nonlinear in nature, hence optimizations tools are needed to extract the best compromise solution between the operating costs and emission.

When designing the MGs, special attention should be given to the MG central controller. The MG central controller uses the information from local electrical and thermal needs, power quality requirement, electricity and fuel costs, emission reduction, etc to compute the amount of the power taken from the main utility [2].

Significant research has been conducted in the areas of MGs, which may have many different sizes and forms; some model architectures have been proposed in the literature such as [2], [3]. Communication infrastructure operating between the power sources to solve the optimization problem for the fuel consumption have been proposed in [1]. A rational method of building MGs optimized for cost and subject to reliability constraints have been presented in [4].

Solving the environmental economic problem in the power generation has received considerable attention. An excellent overview on commonly used environmental economic algorithms can be found in [5]. The environmental economic problems have been effectively solved by the goal programming method [6], the classical technique [7], and fuzzy satisfaction-maximizing approach [8]; however, the computing speed of these solutions is unsatisfactory for online applications.

Several strategies have been reported in the literature related to the operation cost as well as minimization emission of MG. In [1] the optimization is aimed at reducing the fuel consumption rate of the system while constraining it to fulfil the local energy demand (both electrical and thermal) and provide a certain minimum reserve power. The problem has been treated as a single objective problem by neither considering the emission not the operation and maintenance costs. This formulation, however, has a severe difficulty in getting the trade-off relations between cost and emission. A linear programming based optimization procedure in which the objectives are considered one at a time was presented in [9]. Since the environmental economic problem is a highly nonlinear optimization problem, conventional optimization methods that make use of the derivatives and gradients are not able to locate or identify the global optimum. On the other hand, many mathematical assumptions such as analytic and differential objective functions have to be given to simplify, the problem. Additionally, this approach does not give any information regarding the trade-offs involved.

Our optimization method incorporates an explicit cost minimization criterion applied to the MG architecture as well as minimizing the emission. The formulation in this work seeks the most environmental economical generation to satisfy the load demand and the constraints. The problem is decomposed into several stages, starting with building the system model, which is an important stage to understand the problem. The next stage is the algorithm developed by the authors. The algorithm consists of determining at each iteration the optimal use of the resources available, such as wind speed, temperature, and irradiation as they are the inputs to the model. If the produced power from the wind turbine and the photovoltaic cell is less than the load demand then the algorithm goes to the next stage which is the use of the other alternative sources according to the load amount and the objective function of each one.

In this paper, we rigorously study the MG components in

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terms of accuracy and efficiency of having a system model based on the costs of fuel, operation and maintenance, as well as the emission reduction. The system model clearly has the potential to explain the environmental/ecomomic problem significantly better than before. However, developing the system model imposes studying minimization of the cost and reducing the emissions of the system. Thus, it is important that the problem of minimization the cost and reducing the emissions as well as serving the load of the MG be investigated.

The second objective of this paper deals with solving the optimization problem which uses several scenarios to explore the benefits of having optimal management of the MG. The exploration is based on the minimization of running costs and reducing the emissions, then it is extended to cover a load demand scenario in the MG. It will be shown that by developing a good system model, we can use an optimization technique to solve the optimization problem accurately and efficiently.

II. System Model

The MG architecture studied is shown in Fig 1. It consists of a group of radial feeders, which could be part of a distribution system. There is a single point of connection to the utility called Point of Common Coupling (PCC). The feeders 1 and 2 have sensitive loads which should be supplied during the events. The feeders also have the microsources consisting of a photovoltaic (PV), a wind turbine (WT), a fuel cell (FC), a microturbine (MT), a diesel generator, and a battery storage. The third feeder has only traditional loads. The static switch (SD) is used to island the feeders 1 and 2 from the utility when events happenen. The fuel input is needed only for the DG, FC, and MT as the fuel for the WT and PV comes from nature. To serve the load demand and charge the battery, electrical power can be produced either directly by PV, WT, DG, MT, or FC. Each component of the MG system is modeled separately based on its characteristics and constraints. The characteristics of some equipment like wind turbines and diesel generators are available from the manufacturer. A charger controller is required to limit the depth of discharge of the battery, to limit the charging current supplied to the battery, and to prevent overcharging, while making use of the power from the other microsources when it is available.

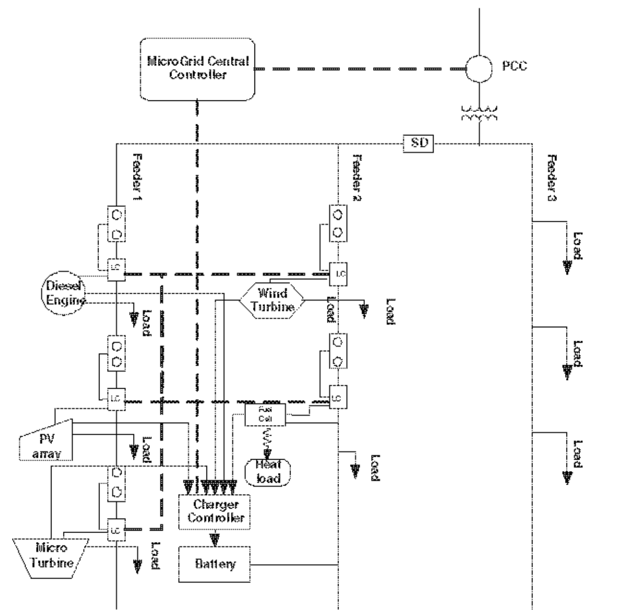

Fig. 1. MicroGrid Architecture.

III. System Components

A. Wind Turbine

The following is the model used to calculate the output power generated by the wind turbine generator [11]:

$$\begin{cases} P_{WT} = 0, & V < V_{ci} \\ P_{WT} = aV^2 + bV + c, & V_{ci} < V < V_r \\ P_{WT} = P_{WT,r}, & V > V_{co} \end{cases} \quad (1)$$

where $P_{WT,r}$, V_{ci}, and V_{co} are the rated power, cut-in and cut-out wind speed respectively. Furthermore, V_r, and V are the rated and actual wind speed.

We modeled the commercial wind turbine AIR403 power curve according to equation (1), with the actual power curve obtained from the owner's manual. The parameters in model (1) are as follows: a = 3.4; b = -12; c = 9.2; $P_{WT,r}$ = 130 watt; V_{ci} = 3.5 m/s; V_{co}= 18 m/s; V_r =17.5 m/s.

B. Photovoltaic Cell

The output power of the module can be calculated as [12]:

$$P_{PV} = P_{STC}\frac{G_{ING}}{G_{STC}}(1 + k(T_c - T_r)) \quad (2)$$

where:

P_{PV}	The output power of the module at Irradiance (G_{ING}),
P_{STC}	The Module maximum power at Standard Test Condition (STC),
G_{ING}	Incident Irradiance,
G_{STC}	Irradiance at STC 1000 (W/m^2),
k	Temperature coefficient of power,
T_c	The cell temperature,
T_r	The reference temperature.

C. Diesel Generator Costs

The fuel cost of a power system can be expressed mainly as a function of its real power output and can be modeled by quadratic polynomial [13], The total $\$/h$ DG fuel cost $C_{DG,i}$ can be expressed as:

$$C_{DG,i} = \sum_{i=1}^{N}(d_i + e_i P_{DG,i} + f_i P_{DG,i}^2) \quad (3)$$

where N is the number of generators, d_i, e_i, and f_i are the coefficients of the generator, $P_{DG,i}$ is the diesel generator i output power (kW), $i = 1, 2, ..., N$ assumed to be numerically known.

Typically, the constants d_i, e_i, and f_i are given by the manufacturer. From the data sheet [14] and equation (3) the parameters are obtained as follows: $d_1 = 0.4333$, $e_1 = 0.2333$, and $f_1 = 0.0074$.

D. Fuel Cell Cost

The efficiency of any fuel cell is the ratio between the electrical power output and the fuel input, both of which must be in the same units (W), [15]. The fuel cost for the fuel cell is calculated as:

$$C_{FC} = C_{nl} \sum_{J} \frac{P_J}{\eta_J} \tag{4}$$

where
C_{nl} is the natural gas price to supply the fuel cell, P_J is the net electrical power produced at interval J, and η_J is the cell efficiency at interval J.

To model the technical performance of PEM fuel cell, a typical efficiency curve is used to develop the cell efficiency as a function of the electrical power and used in equation (4) [16].

E. Microturbine Cost

The economic model is similar to the FC model. Unlike the FC, the efficiency of the MT increases with the increase of the supplied power [17].

Due to lack of detailed information, the curves of the MT are rescaled to be suitable for a unit with less than 4kW rating. These curves are used to derive the electrical efficiency as functions of the electrical power to be used in the economic model of the MT.

F. Battery Model

Batteries are electrochemical devices that store energy from other AC or DC sources for later use. The power from the battery is needed whenever the PV or/and WT are insufficient to supply the load, or when both the microsources and the main grid fail to meet the total load demand. On other hand, there will energy stored in the battery whenever the supply from the microsources exceeds the load demand.

When determining the state of charge for an energy storage device, two constraint equations must be satisfied at all times. First, because it is impossible for an energy storage device to contain negative energy, the maximum state of charge ($\mathrm{SOC_{max}}$) and the minimum state of charge ($\mathrm{SOC_{min}}$) of the battery are 100 % and 20 % of its AH capacity, respectively. The constraints on battery SOC:

$$SOC_{\min} \leq SOC \leq SOC_{\max} \tag{5}$$

Finally, in order for the system with a battery to be sustained over a long period of time, the battery SOC at the end must be greater than a given percentage of its $SOC_{\max}$. In this study the percentage assumed to be 90%.

IV. Proposed Objective Function

The major concern in the design of an electrical system that utilizes MG sources is the accurate selection of output power that can economically satisfy the load demand, while minimizing the emission. Therefore the system components are required to:

1.Minimize the operation cost (\$/h).

2. Minimize the emissions (kg/h).

3. Ensure that the load is served according to the certain constraints.

A. Operating Cost

The objective function is developed according to the following requirements to minimize the operating cost in $\$/h$ of the MG:

$$F(P_i) = \sum_{i=1}^{N} (C_i F_i + OM_i + SC_i) \tag{6}$$

where
$F(P_i)$ The operating cost of the generating unit i in $\$/h$,
C_i Fuel costs of the generating unit i in $\$/l$ for the DG, and in $\$/kWh$ for FC and MT
F_i Fuel consumption rate of a generating unit i,
OM_i Operation and maintenance cost of a generating unit i in $\$/h$,
SC_i Start up cost of the generating unit i in $\$/h$,
P_i Decision variables, representing the real power output from generating unit i in kW.

where P_i is the real power output vector of the ith generator and is defined as: P_i= P_{FC}, or P_{MT}, or P_{DG}.

The operating and maintenance cost of the generating unit i (OM_i) is assumed to be proportional to the produced energy, where the proportional constant is (K_{OM}) [16].

$$OM_i = K_{OM} \sum_{i=1}^{N} P_i \tag{7}$$

The values of the K_{OM} for different generation units are as follows:
$K_{OM}(DE)$ = 0.01258 \$/kWh
$K_{OM}(FC)$ = 0.00419 \$/kWh
$K_{OM}(MT)$ = 0.00587 \$/kWh.
The start up cost depends on the time the unit has been off before it is started up once again [18]:

$$SC_i = \sigma_i + \delta_i \left[1 - \exp\left(\frac{-T_{off,i}}{\tau_i}\right)\right] \tag{8}$$

where σ_i is the hot start up cost, δ_i the cold start up cost, τ_i the unit cooling time constant and $T_{off,i}$ is the time a unit has been off.

B. Emission Level

The atmospheric pollutants such as sulphur oxides SO_2, carbon oxides CO_2, and nitrogen oxides NOx caused by fossil-fueled thermal units can be modeled separately. The total kg/h emission of these pollutants can be expressed as [19]:

$$E(P_i) = \sum_{i=1}^{N} 10^{-2}(\alpha_i + \beta_i P_i + \gamma_i P_i^2) + \zeta_i \exp(\lambda_i P_i) \quad (9)$$

where α, β , γ, ζ, and λ are nonnegative coefficients of the ith generator emission characteristics.

For the emission model introduced in [5] and [19], we propose to evaluate the parameters α, β , γ, ζ, and λ using the data available in [20]. Thus, the emission per day for the DG, FC, and MT is estimated, and the characteristics of each generator will be detached accordingly.

System Constraints:

Power balance constraints: To meet the active power balance, an equality constraint is imposed

$$\sum_{i=1}^{N} P_i - P_L + (P_{PV} + P_{WT} + P_{batt}) = 0 \quad (10)$$

where

P_L The total power demanded in kW,

P_{PV} The output power of the photovoltaic cell in kW,

P_{WT} The output power of the wind turbine in kW .

P_{batt} The output power of the battery storage kW .

Generation capacity constraints: For stable operation, real power output of each generator is restricted by lower and upper limits as follows:

$$P_i^{\min} \leq P_i \leq P_i^{\max}, i = 1, ..., N \quad (11)$$

where

$P_i^{\min}$ Minimum operating power of unit i,

$P_i^{\max}$ Maximum operating power of unit i.

Each generating unit has a minimum up/down time limits (MUT/MDT). Once the generating unit is switched on, it has to operate continuously for a certain minimum time before it is switched off again. On the other hand, a certain stop time has to be terminated before starting the unit. These constraints most not be violated These constraints are formulated as continuous running/stop time constraint as follows [18]:

$$\begin{aligned} \left(T_{t-1,i}^{on} - MUT_i\right)(u_{t-1,i} - u_{t,i}) \geq 0 \\ \left(T_{t-1,i}^{off} - MDT_i\right)(u_{t-1,i} - u_{t,i}) \geq 0 \end{aligned} \quad (12)$$

where $T_{t-1,i}^{off}/T_{t-1,i}^{on}$ is the unit off/on time, while $u_{t-1,i}$ denotes the unit off/on $[0, 1]$ status.

Finally the number of starts and stops ($\varepsilon_{start-stop}$) should not exceed a certain number ($N_{\max}$).

$$\varepsilon_{start-stop} \leq N_{\max} \quad (13)$$

V. IMPLEMENTATION OF THE ALGORITHM

When designing MGs, several goals could be set, including reduction in emissions and generation cost. To achieve this, it is important to highlight all factors influencing the main goal. The following items summarize the key characteristics of the implemented strategy:

- Power output of WT is calculated according to the relation between the wind speed and the output power.
- Power output of PV is calculated according to the effect of the temperature and the solar radiation that are different from the standard test condition.
- Since the WT and PV deliver free cost power (in terms of running as well being emission free), the output power is treated as a negative load, so the load which is the difference between the actual and microsource output can be determined if the output from PV and WT is smaller than the load demand.
- The power from the battery is needed whenever the PV and WT are insufficient to serve the load. Meanwhile the charge and discharge of the battery is monitored.
- Calculate the net load.
- Choose serving the load by other sources (FC or MT or DG) according to the objective functions.

VI. MULTIOBJECTIVE OPTIMIZATION

Multiobjective optimization is a method to find the best solution between different, usually conflicting objectives. In the MO optimization problem we have a vector of objective functions. Each objective function is a function in the decision (variable) vector [21]. Mathematically the environmental/ecomomic problem is formulated as follows:

Find the output generator power vector $\mathbf{P} = [P_1, P_2, ..., P_N]'$ that minimizes the function:

$$F(\mathbf{P}) = \{CF(P_i), E(P_i)\} \quad (14)$$

Subject to

$$h_k(\mathrm{P_i}) = 0 \qquad k = 1, ..., q \quad (15)$$

$$g_j(\mathrm{P_i}) \leq 0 \qquad j = 1, ..., p \quad (16)$$

$$P_i^{\min} \leq P_i \leq P_i^{\max}, \qquad \forall_i = 1, ..., N \quad (17)$$

where the number of the objective functions $\geq$2, *and* $F(P_i) : R^n \to R$. The vector of objective functions is denoted by $\mathrm{F}(\mathbf{P}) = (F(P_1), F(P_2), ..., F(P_k))^T$. The decision variable vector $\mathbf{P} = (P_1, P_2, ..., P_N)^T$ consists of all design variables in the problem and may be bounded. The collection of the equality constraints, $\mathrm{H}(\mathbf{P}) = (h_1(P_1), h_2(P_2), ...h_q(P_i))^T$, is an equality constraint vector, and similarly the inequality constraint vector, $\mathrm{G}(\mathbf{P}) = (g_1(P_1), g_2(P_2), ...g_p(P_i))^T$ is less or equal to zero.

VII. RESULTS AND DISCUSSION

At first, the optimization model described in the previous section is applied to a time-varying load demand varying between 4 kW to 14 kW. The available power from the PV and the wind generators were used first. The inputs to the wind turbine model and the model of the photovoltaic cell were obtained from measured data [10].

In order to explore the extreme points of the trade-off surface two different cases have been considered: case 1 when the emission objective is only considered. Case 2 when the operation cost is considered. Table I shows the best results when the operational cost and emission objectives are optimized individually. Convergence of operation cost and emission objectives in different time of the day are shown in Fig. 2.

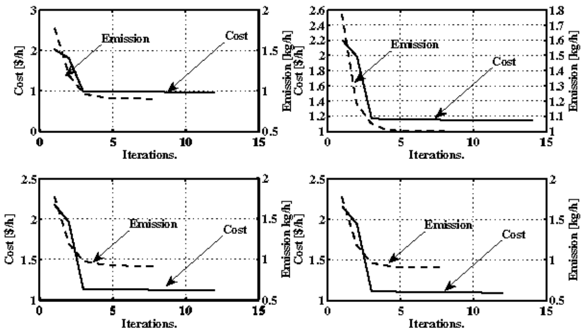

Fig. 2. Convergence of cost and emission objective functions in different time of the day.

Next the problem is solved as a MO optimization problem where both the operation cost and emission are optimized simultaneously. The diversity of the Pareto optimal set over the trade-off surface is shown in Fig 3. The trade off relation can be obtained by minimizing the function [5]:

$$C = \theta CF + (1 - \theta)E \tag{18}$$

subject to constraints in the above section.

The value θ =1.0 implies minimum operating cost and we obtain the optimum solution of the operating cost objective. As the importance of the emission objective increases ($\theta > 0$) then the optimum solution will move toward the emission objective value. When θ =0.0, it implies minimum emission and we obtain the optimum solution of the emission objective. C is minimized for successive values of θ to cover the entire range from 0 to 1. It is clear that for non-dominated solution points an improvement in one objective requires degradation of the other objective.

The distribution of the non-dominated solutions in the Pareto-optimal front using the MO optimization for different time of the day is shown in Fig 3. Because our proposed model is highly nonlinear and it has different characteristics as each generator has different behavior in the operating cost, it is clear that the solutions are diverse and acceptably distributed over the trade-off curve.

Figure 3 shows the diversity of the Pareto set over the trade-off surface. The operating costs of the non-dominated solutions thus appear to be inversely proportional to their emissions. It can seen that the Pareto optimal set has a number of non-dominated solutions. Out of them, two nondominated solutions that represent the best cost and best emission. This demonstrates the potential and effectiveness of the proposed approach to solve MO optimization problem of the MG model. It can be concluded that the proposed approach is capable of exploring more efficiently and noninferior solutions of OM optimization problems. The set of power curves found by the optimization algorithm as shown in Fig 4. These curves are plotted against time. It is observed in this figure when the battery reached the SOC minimum limit it is considered as a load and let the other sources to charge the battery and server the load.

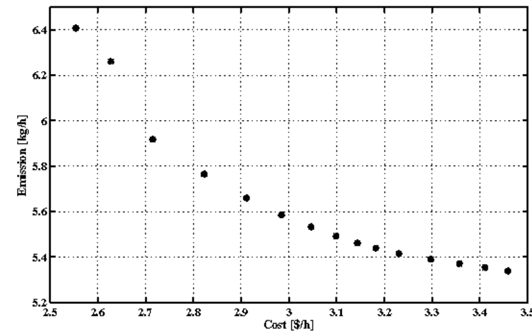

Fig. 3. Trade- off in cost and emission.

TABLE II
THE BEST SELECTION OF THE POWER GENERATORS OF THE MG USING MULTIOBJECTIVE OPTIMIZATION

Load Demand [kw]	3.5971	4.5352	10.7113	13.7614
Fuel Cell [kw]	1.5534	1.8634	2.2691	2.7773
Microturbine [kw]	2.0437	2.6718	3.4952	4.0000
Diesel Engine [kw]	0.0000	0.0000	4.9469	6.9841
Operating cost[$/h]	0.9099	1.0335	3.3741	4.5216
Emissions[kg/h]	0.9999	1.5175	5.0677	7.9068

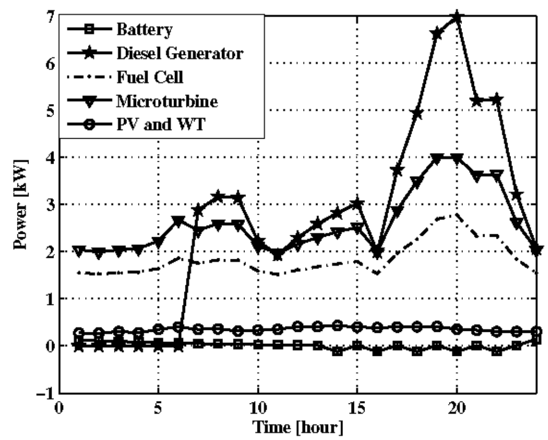

Fig. 4. The hourly power curves.

Table II and Fig 4 confirm that the MO optimization technique has made reasonable selections in the total cost and emission per day comparing with the result in Table I. The selections were not so straightforward, because of the existing of the start-stop time limit constraints which have a big effect on the performance of the algorithm. It can be seen that the load was served perfectly.

VIII. CONCLUSION.

A model to determine the optimum operation of a MG with respect to load demand and environmental requirement is developed constructed and presented. The optimization

TABLE I
THE BEST SELECTION OF THE POWER GENERATORS OF THE MG

	Case 1				Case 2			
Load Demand [kw]	3.5971	4.5352	10.7113	13.7614	3.5971	4.5352	10.7113	13.7614
Fuel Cell [kw]	1.2635	1.3968	2.2740	2.7908	3.5971	4.0000	3.7113	4.0000
Microturbine [kw]	1.4906	1.7607	3.5385	4.0000	0.0000	0.5352	0.0000	2.7614
Diesel Engine [kw]	0.8430	1.3777	4.8987	6.9706	0.0000	0.0000	7.0000	7.0000
Operating cost[$/h]	1.1730	1.4113	3.1592	4.3238	0.8937	1.0262	4.4885	4.5342
Emissions [kg/h]	0.9038	1.2611	5.0674	7.9067	2.4694	3.1228	7.2447	8.5904

problem includes a variety of energy sources that are likely to be found in a microgrid: a fuel cell, a diesel engine, a microturbine, a PV arrays, a wind generator, and a battery storage. Constraint functions are added to the optimization problem to reflect some of the additional considerations often found in a small-scale generation system. From the results obtained, it is clear that from the optimal power operating costs and emissions curves for the MG that the optimization works very well and can give the optimal power strategy to the generators after taking into account the operating cost and emission objective functions for each of them. The responses are effected by several variables including weather conditions, emissions operation & maintenance, start up costs, and of course, the actual power demand.

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