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# Lowering Weighted Average Cost Of Generation By Optimizing Operating Time: A Study From Pakistan

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***Abstract*—With rapidly increasing electricity demand globally, it is crucial to manage the electricity load during peak hours. Fossil fuel-based emission prone generators are often used to fulfill demand during peak hours, which results in an increase in the cost of generation. Demand side management (DSM) is a well-known technique to manage the flexible load. However, it requires increased compatibility with renewable resources, which are cheap but inherently intermittent. Along with financial benefits, electricity management through enhanced incorporation of renewables will also reduce the sum of emissions. In this paper, we use convex optimization to simulate energy consumption, according to the merit order, in Pakistan's power sector. The simulation framework will be used to find optimal amount of load that can be shifted from an hour, using equilibrium optimization under given constraints. The results depict that the power sector can gain massive financial and environmental benefits using realistic DSM parameters.**

***Keywords*—WACG, DSM, ToU pricing, emissions, Circular debt**

## I. Introduction

The share of electricity in global energy usage is rapidly increasing. From 13% in 2010 [1] [2] the conversion of energy to electricity before use has increased to 40% in 2020 [3] worldwide. In recent years, there has been a significant disruption in the transport sector with the advent of electric vehicles. The number of electric vehicles worldwide is increasing at a growth rate of 4% annually [4]. There has been a rapid increase of 14.8% [5] in electricity consumption in households due to wider availability of various electronic devices for several household activities.

Given the current trends and experts' forecasts, dependency on electricity in small households to large industries is projected to increase. In 2030, it is expected that the share of electricity in energy usage will increase to 80% globally [6]. This high dependency requisites a robust power system to deliver energy in the form of electricity seamlessly and in the most cost-effective manner.

The situation is even more critical for developing countries where electricity usage is rapidly increasing and there is a need for new solutions to keep the power sector stable with low-cost electricity supply. One way to achieve this is by installing renewable sources of generation such as solar photovoltaic and wind turbines. As there is no fuel cost associated with both sources of generation, the generated electricity is cheap.

However, both of these sources are inherently intermittent and create problems in balancing for system operator. The problem of high electricity usage and intermittency can be solved by controlling demand to some extent.

Demand side management (DSM) is a technique used to gain some control over electricity demand in return for cheaper rates and guarantee of uninterrupted supply. Typically, as the electricity demand in a power system increases, the system operator often needs to activate fossil fuel-based peaking power plants that increase the cost of electricity provided to end consumer [7]. However, by just marginally reducing the load during peak hours and shifting it to off-peak hours the electricity cost can be reduced substantially. In conventional DSM, the cost of electricity generation is the only consideration from respective power plant. However, there is another cost associated with emissions that needs to be accounted.

The system operator considers economic dispatch while managing electricity generation to fulfill demand. A merit order list is devised to prioritize power plants with low electricity generation rates. However, there is also environmental dispatch, which is not usually considered [8] [9] in countries like Pakistan. In environmental dispatch, the emissions by each power plant are considered and the order is devised accordingly [10].

In this paper, it is proposed that both economic and environmental dispatch shall be considered. By using equilibrium optimization technique, an optimal scenario is calculated for a day to marginally shift electricity demand and find minimum economic plus environmental cost while keeping constant the total energy consumed. Case study of Pakistan, a developing country, is considered with discussion on field results and a strong strategy proposed towards the end.

## II. Literature Review

This paper gives general background of DSM as well as its expansion in the field of power system management based on existing research. The following literature presents the review and relevance of each method for Demand Side Management in a power system network.

In [11] the authors investigate the effects of reduction of VRE (Variable Renewable Electricity) production for heating. Since VRE requires high penetration of variable load, the transfer of generation to renewables sources directly it not possible. Many operational problems in power grids occurs due to this variable load. To fulfill this variability in VRE generation, price-based Demand side management (DSM) can be used to provide flexibility.

In [12] the paper introduces a DSM (Demand Side Management) framework that forecasts temperature set points and charge /discharge patterns of battery for the purpose of energy storage and optimization of energy costs. Load on electric grid and its respective emissions can be reduce by using DSM techniques in conjunction with market tariff. DSM with direct load control, load limiter and price-based DSM techniques can alleviate the load on grid and hence minimize the operating cost.

In [13] the Demand Side flexibility is investigated to reduce the loss of potential useful wind energy (surplus energy) in Ireland. In this study, the impact of Price-Based Demand Response is analyzed for two industrial electricity consumers to increase the use of surplus wind energy by shifting their working hours to off-peak hours. It is a win-win situation, because through this manner the consumers can save their average unit price of electricity by shifting their demand to a time that offers electricity at a lower price, resulting in high consumption of wind energy. DSM is more efficient than energy storage because DSM does not require storage of energy. Research indicates that curtailing peak hours demand has little or no benefit until we use it in off-peak hours by using DSM. During off-peak hours intermittent resources can be used for soft loads.

In [14] the research presents mathematical statistics and DSM efficiency algorithms to provide benefits to both the consumers and the energy companies in the era of private electricity markets. Incentive-based DSM and smart metering advanced outputs generated by modern statistical approaches and customer feedback are used to calculate results. This approach will help consumers to choose their power supplier with the most promising conditions and can assess and manage their power consumption and reduce energy costs. The owners of distributed generation can get maximum profit by controlling maintenance and operational costs because the demand of energy is elastic. Energy companies can also gain more profit since the load curve will be smooth and provide durability to grid components.

In [15] the paper emphasizes on the impact of energy efficiency on the electricity demand profile. It uses two strategies of DSM; one is Energy efficiency, and the other is Demand Response to achieve the objective. The paper studies the demand profiles of Swiss' household appliances (i.e., cooking stocks, light bulbs etc.) based on time of use data, using a developed bottom-up model. The results show that there should be policies to improve the energy efficiency to reduce the total energy demand and peak load demand.

In [16] a novel framework is proposed, which calculates the effective DP (Dynamic Pricing) to assist DSM within a Smart Grid (SG) environment. The framework is divided into two parts. A set of generic formulas is developed using Particle Swarm-Heuristic Optimization (PSO) technique, to best define the critical demand and inform the customers about this, under system conditions in first phase of the model. The main objective of this optimization is to minimize operational cost, while maintaining the underlying system constraints. In the second phase of the model, the proposed composite time incentive based pricing technique of DSM is introduced, in which the consumers can be encouraged or penalized according to the threshold situation. Consumers provide responsible feedback of their energy usage and hence save their electricity bills. By reducing peak demand, energy companies can manage their congestions in transmission system caused by peak demand.

In [17] the authors developed an Energy Management System (EMS) for Smart Micro Grid (SMG) using time of use (ToU) price balancing DSM technique and two-level genetic algorithm (GA) optimization technique, to reduce the SMG costs, $CO_2$ emissions' cost and Peak to Average Ratio (PAR). The communication between SMG, EMS and control center is achieved by IoT technology. In first level of optimization, the SMG appliances are scheduled using ToU pricing principle. While in second, an optimal and efficient controller system is developed by improving PID based H Infinity controller, to control and regulate the SMG voltage and frequency. PID based H Infinity controllers are used to provide robustness and disturbance attenuation [18].

In [19] the authors emphasize on priority-oriented DSM considering the priority defined by customers, hence achieving the customers' satisfaction. Multiple optimization techniques are used to alleviate the rebound peaks by solving multiple Knapsack problem (maximize the profit). The meta-heuristic optimization techniques of Genetic Algorithm (GA), Binary Particle Swarm Optimization (BPSO), Enhanced Differential Evolution (EDE) and Optimal Stopping Rule (OSR) are used. Simulations are performed on three different appliances to test their strategy and results are shown.

In [20] the study implements Multi Objective Evolutionary Algorithm to overcome the issues faced by power companies, consumers, and distribution authorities. A communication mechanism is developed to connect the Smart grid home area with local renewable energy resources to reduce the peak to average ratio and stress on grid.

In [21] the authors investigate the issues associated with deregulations in the electricity markets due to the intermittent energy resources such as wind and solar. The developed system uses the economic potential of DSM to reduce the fluctuations 3 in the energy price in deregulated markets due to variable energy resources. DSM with Energy Informatics System is combined to design an efficient information system, which evaluates the real-world scenarios that reduce the total expenditures of retailers and diminish uncertainties in energy prices.

## III. Methodology

In this section, the problem statement and various components of proposed solution are explained.

### *A. Problem Statement*

The expected load profile for the next 24 hours is calculated using inhouse forecasting tools [22] that are in use of the government of Pakistan. Fulfilling the high ramped electricity demand without any intervention results in elevated economic and environmental cost. To meet the peak-demand, power plants are needed that require huge capital to actualize. Hence, there is a need for DSM to limit electricity demand without reducing the total energy consumed during a given interval.

The following parameters are considered when shifting energy from peak hours to off-peak hours:

- Marginal Generator unit price
- Emissions from Thermal Power Plants
- Socio-Economic cost

By considering the above parameters, we apply the optimization techniques and propose the following solution:

### *B. Demand Side Management*

To reduce the demand in any time interval, the load is shifted to another interval with less demand. To achieve this, flexible loads are determined that can be scheduled with the discretion of postponing their operations anytime. In this study, it is assumed that a marginal percentage of load during any time interval can be shifted. However, the total energy consumed during the whole-time horizon remains almost same.

### *C. Overall System*

Using the allowed percentage of forecasted load that can be shifted in any hour, a search space is created for the Equilibrium Optimization (EO) to randomly place its particles in an n-dimension space defined by n number of intervals in a time horizon. A simple check ensures that the load profile suggested by each particle randomly matches the original load profile. This helps in ensuring that the total energy consumed stays the same and the load is only shifted between intervals.

After this first setup, the EO starts the process by calculating the economic and environmental cost of generation for each particle using dispatch optimization model. The particles gradually move towards the optimal solution after several iterations. EO stops after the allocated number of iterations are completed. The final answer is reported in the form of a new load profile, which will have the same amount of energy as original but with shifted loads and maximum reduction in cost.

## IV. Equilibrium Optimization

Equilibrium optimization is a new technique that has shown better results than other popular optimization methods. With particles acting as search agents, equilibrium optimization does an excellent job of exploration, exploitation, and local minima avoidance [23]. In this study, EO is used to find the best possible load profile that reduces cost of generation.

EO takes six parameters: the load profile (Load_profile_MW), the lower bound of load (lb), the upper bound of load (ub) which are vector variables, the merit order (merit order) in the form of data frame parameter, number of particles (number_of_particles) which is a numeric variable and number of iterations (max_iter) which is also a numeric variable. Details are provided by the following equation (1):

$$EO(L_t^u, L_t^l, MO, L_t, np, max\_iter) \qquad (1)$$

Where $\boldsymbol{Lt}$ is a Load Profile of a day and described as following equation (2):

$$L_t = L_1, L_2, L_3, \ldots, L_T \qquad (2)$$

Here T denotes the total hours in a day, i.e., T=24.

Similarly, $L_t^u$ and $L_t^l$ are upper and lower bound of original load respectively and are described as equation (3, 4):

$$L_t^u = L_t + \alpha(L_t) \qquad (3)$$

$$L_t^l = L_t - \alpha(L_t) \qquad (4)$$

Where $\alpha$ is the percentage of energy that can be shifted.

Moreover, *MO* is merit order consisting of Power Plant Names, their respective capacity, generation tariff and emission tariff as shown in fig 1. *np* is the number of particles for population building for EO and *max_iter* is the maximum number if iterations for EO to generate the optimal load profile. *CVXR* is used as an objective function for cost minimization.

| Power_plant | Capacity_MW | Unit_cost_Rs_per_MWh | Emission_Cost_g_per_MWh | PLANT.TYPE1 | Unit_cost_Dollar_per_MWh | Emission_Cost_Dollar_ |
|---|---|---|---|---|---|---|
| SEPCOL | 135 | 0 | 961000 | IPPS FOSSIL FUEL | 0 | |
| HCPC | 140 | 0 | 480000 | IPPS FOSSIL FUEL | 0 | |
| JAPAN | 120 | 0 | 961000 | IPPS FOSSIL FUEL | 0 | |
| DAVIS | 13 | 0 | 480000 | IPPS FOSSIL FUEL | 0 | |
| RESHMA.POWER | 97 | 0 | 961000 | IPPS FOSSIL FUEL | 0 | |
| GULF.POWER | 84 | 0 | 961000 | IPPS FOSSIL FUEL | 0 | |
| ROUSCH | 450 | 196.1738892 | 480000 | IPPS FOSSIL FUEL | 1.241606894 | |
| PORT.QASIM.COAI | 1320 | 5063.33848 | 980000 | IPPS FOSSIL FUEL | 32.04644608 | |
| UCH | 586 | 5426.241551 | 480000 | IPPS FOSSIL FUEL | 34.34330096 | |
| H.B.SHAH | 1230 | 6638.318871 | 566000 | IPPS FOSSIL FUEL | 42.0146764 | |
| CHINA.HUBCO.CO. | 1320 | 6726.373257 | 980000 | IPPS FOSSIL FUEL | 42.57198264 | |
| SAHIWAL..COAL..H | 1320 | 6993.159418 | 980000 | IPPS FOSSIL FUEL | 44.26050264 | |
| BHIKKI..QATPL. | 1230 | 7248.272981 | 566000 | IPPS FOSSIL FUEL | 45.87514545 | |
| BALLOKI | 1223 | 7522.288523 | 566000 | IPPS FOSSIL FUEL | 47.60942103 | |
| SAIF | 225 | 7893.6702 | 480000 | IPPS FOSSIL FUEL | 49.95993797 | |
| HALMORE | 225 | 8072.368322 | 480000 | IPPS FOSSIL FUEL | 51.09093874 | |
| ORIENT | 225 | 8094.735649 | 480000 | IPPS FOSSIL FUEL | 51.23250411 | |

*Figure 1: Sample merit order list*

## V. Dispatch optimization model

CVXR is used to minimize the cost of generation $CG$ and the cost of environment $CE$ by using optimal load profile generated by EO. The object function of CVXR is defined as equation (5):

$$\min\left(\sum_{t=1}^{T} C_{G_t} + \sum_{t=1}^{T} C_{E_t}\right) \qquad (5)$$

Where T is the time horizon and in our case T=24.
The cost of generation can be calculate using equation (6):

$$C_G = PP_a * GT \qquad (6)$$

Similarly, the cost of environment can be calculate using equation (7):

$$C_G = PP_a * ET \qquad (7)$$

Where, $\boldsymbol{PPa}$ is the generation of active power plant, GT is its generation tariff and ET is its emission tariff.

*A. Constraints*

1. Power plants cannot generate more energy than their respective capacity, so following constraint is required as represented in equation (8):

$$PP_a \leq Capacity_{PP} \qquad (8)$$

Where $Capacity_{PP}$ is the capacity of active power plant.

2. The second constrained is the energy conservation. The sum of generation from all the power plants should be equal to system load at that time and can be described as following equation (9):

$$\sum_{i=1}^{N} PP_{a_i} == L_t \qquad (9)$$

Where N is the number of active power plants.

3. The third constraint is that the power plants should be generating electricity at a minimum of 50 % of their capacity. This is represented in equation (10):

$$PP_a \geq Capacity_{PP} * 0.5 \qquad (10)$$

*B. WACG Modeling*

To calculate WACG, it is important to consider both types of payments. Other that capacity payments it is also equally important to consider energy payments. The sum of both is divided by energy utilization as shown in following equation (11):

$$WACG = \frac{CP + EP}{EU} \qquad (11)$$

The above equation is a generalization which does not fully capture the situation in Pakistan. The above equation needs to be modified to model payments in Pakistan. To compute WACG, in case of Pakistan equation (12) is used.

$$WACG = \frac{CP + \sum_{x=1}^{n} EPx}{\sum_{x=1}^{n} EUx}, n \leq z \qquad (12)$$

Where x is the index of each power plant according to the merit order that goes up to n, number of power plants that are operational at any given time and the total number of power plants available is denoted by z. To approximate monthly payments equation (13) is used.

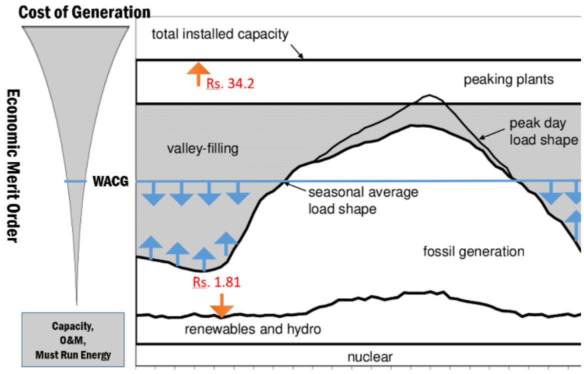


*Figure 2: Reducing WACG*

$$WACG = \sum_{h=1}^{720} \frac{CP + \sum_{x=1}^{n} EPx}{\sum_{x=1}^{n} EUx}, n \leq z \qquad (13)$$

According to the above equation it is important to note that to decrease WACG, energy consumption should be increased in valley periods as shown in figure 2. By shifting load from the peak timings to the valley intervals, WACG can be decreased to get an overall benefit [24]. This phenomenon is depicted in figure 3.

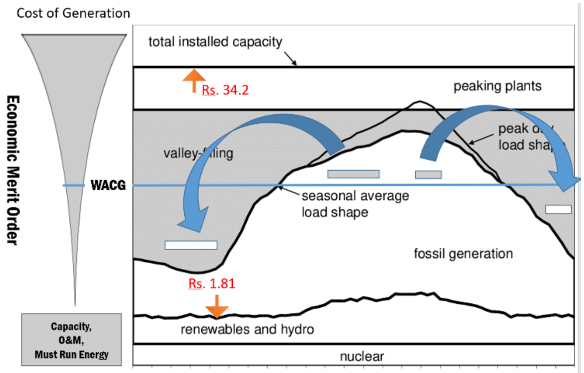


*Figure 3: Shifting load from peak to off-peak hours*

## VI. Results

To show the proposed solution in action, an example of Pakistan is used. A 24-hour load profile of Pakistan for a typical day is selected. The demand side management is only allowed for ±10 % of the total load at each hour. The National Dispatch and Control Center (NTDC) provides the economic merit order [25]. The environmental cost is calculated using the given fuel type for each power plant in merit order.

After shifting 10% of the load from peak hours to off peak hours, the original load profile and the shifted load profile is shown in figure 4. The green color represents the load that is subtracted from that particular hour and red color shows the load that is added to that particular hour.

*Figure 4: Actual vs shifted load*

### A. *Economic and Environmental Dispatch*

The economic merit order is a list of available power plants sorted according to the cost of electricity generation calculated in Rs/kWh. The environmental merit order is also calculated in Rs/kWh. The emissions of a power plant are aggregated to calculate the monetary value of damage to environment, which can be seen in figure 5.

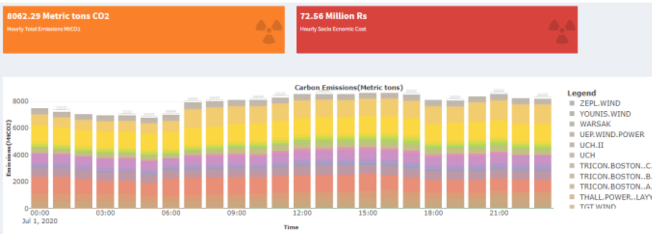

*Figure 6: Emissions as monetary value*

Given the expected load profile, the system operator decides which power plants shall be operational given the merit order. With that in place, the cheapest power plants are prioritized. Using simple convex optimization, an algorithm is created to calculate the economic and environmental cost of electricity generation. The respective generation and cost analysis is shown in figure 6.

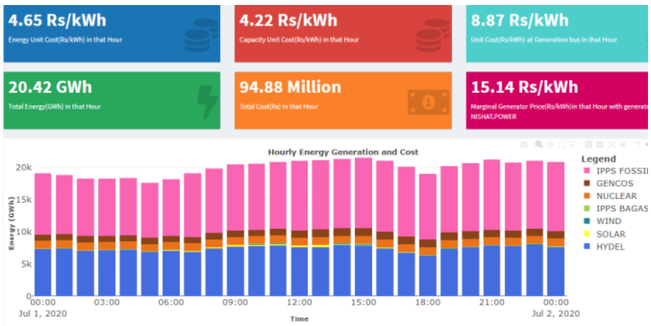

*Figure 7: Generation & cost analysis*

Generation tariff is comprised of two components. One is energy component and other is capacity component. On July 01, 2020, at 3pm price of the energy component was RS.4.76/kWh and the capacity component was Rs.4.22/kWh. Aggregate of these two, which is generation tariff, is Rs.8.98/kWh. On this particular hour of the day, total generation was 21.44 GWh and its costed Rs.102.12 million While the marginal generator price is Rs.15.14/kWh. This is shown in figure 7.

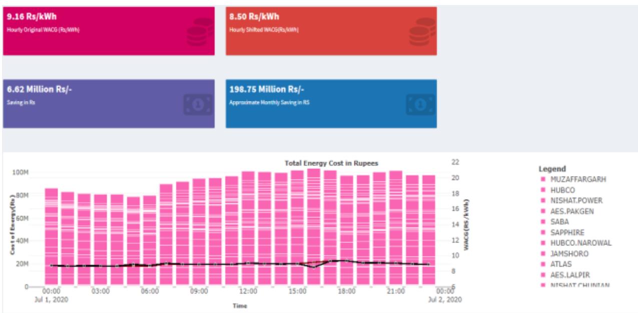

*Figure 8: Reducing WACG by load shifting*

### B. *Reducing Generation Cost*

Reduction in WACG by shifting 10% energy from peak hours to off peak hours on July 01, 2020. WACG shifted from Rs.9.16/kWh to Rs.8.50 /kWh, saved Rs.6.62 million in a day, and approximately Rs.198.75 million in a month as shown in figure 8.

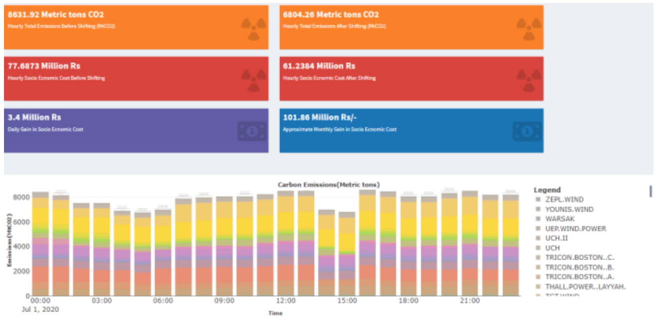

*Figure 5: Reducing socio-economic cost by energy shifting*

Reduction in Emissions by shifting 10% of the load from emissions' peak hours to emissions' off-peak hours on July 01, 2020. Reduction in emissions from 8631.92 M tons to 6804.26 M tons saved Rs.3.4 million in socio economic cost daily and Rs.101.86 million monthly.

## VII. Discussion

This section is divided into recommendations that are expected to help Pakistan power sector stop inflation of circular debt and even help in reducing its volume. The recommendations are based on the analysis shown in this study.

### A. *Smart Metering*

One of the most important technologies that is lacking in power sector of Pakistan is smart metering. Without detailed information about electricity consumption, it is not possible to regulate peak demand and apply any demand side management techniques. In order to install smart meter for all categories of consumers it is important that utility companies devise a plan to provide subsidy for financial support. Other than residential customers, smart metering makes simple sense given the scale of revenue generated from industrial and commercial customers.

With the smart meters in place, utility companies can better manage the electricity consumption pattern. Smart metering will allow deeper control over electricity consumption [26].

### B. *Incentivized Tariff*

The next step in this scheme is to introduce tariff-centric interventions. In 2021, the government introduced a lower tariff in winter to encourage electricity consumption to improve the load factor. This was not the best strategy, given that the more than half of the energy consumption in Pakistan is residential and for heating purposes in winter people in Pakistan uses natural gas which is much cheaper than electricity. However, instead of winter lower tariffs, peak and off-peak hours tariffs should have been introduced and

### C. New Flexible Loads

Using smart meter data and customer behavior analysis, flexible loads can be identified. By working with the customers, flexible loads can be managed to optimize WACG. Using this approach customers will also benefit by reducing their monthly electricity bill and by providing better service to the customers. Industrial and commercial customers have a high potential of flexible loads identification. Residential customers can also be further categorized according to their consumption pattern and made part of this demand side management plan.

## VIII. Conclusion

Pakistan's power sector is under pressure of circular debt and mismanagement. Without proper planning and introduction of radical solutions, it is not possible to sustain the energy sector. One important metric that should be considered in WACG as it governs the payments that are made to the generation power plants. In this paper, we propose techniques and recommendations that will help lower WACG by shifting peak load to off-peak hours. The quantified benefits of this intervention are also calculated. By installing smart meters, introducing new tariff schemes and controlling flexible loads, it is possible to create a sustainable environment in the power sector.

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