Energy scheduling of grid tied photovoltaic-wind-diesel-battery hybrid system for load management under real-time pricing mechanism using game theory

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Abstract: Integration of renewable distributed generations at the customer end has been proved to be successful for meeting today's exponentially growing energy demand in order to control the adverse effects of fossil fuel-fed energy sources. But inapt integration of renewable sources into electricity markets may lead to some prominent techno-economic challenges. There is a significant connection between the consumers and suppliers behavior along with their profits in the electricity markets. So, the optimal planning of power supply sources is increasingly becoming the area of interest for contemporary researchers. This paper presents a sophisticated system model and game theory methodology for determining the optimum electricity clearance price in the grid hourly, to maximize the system's best reliability for consumers and suppliers. It is found that an appropriate contribution of power supply sources results in significant benefits to suppliers and consumers.

Keywords: solar PV, wind power, energy storage system, game theory, electricity market price

1.Introduction

As renewable distributed generations and diesel generator (DG) power supply sources produce power at the load end, they generally inhibit the need of upgradation of existing power distribution systems which has a very constructive effect on energy infrastructure related economy. But proper allocation of renewable sources and DGs depends on load demand which is highly stochastic in nature. Thus the optimal allocation problem becomes a bit tough to solve in real time. In addition, cheaper energy can be provided to consumers with different price applications in different time periods [1-5].

Renewable energies have become an essential part of the utilization of distributed production systems. In the literature research, renewable energy sources have been integrated into Smart Grid. [6-13].

With the development of renewable energy sources, the need for energy storage systems to meet fluctuations in energy demand becomes more pronounced. Determining the charging and discharging times and duration of the storage system according to the need in the electric grid for the more efficient use of renewable energy sources is important for the continuity, quality and reduction of the cost of use [14-17]. Diesel Generator is also considered for emergency backup power supplier [18].

Normally, an electricity consumer's desire is to always purchase power at lower price. At the same time, electricity supplier's wish is for selling the power at a very higher price. At a time, both market participants profit can't be incorporated. A solution is required in order to escape from this problem by understanding the greediness of the situation. A game theory technique has been proposed to solve this problem with incorporating demand side management (DSM) [19-21].

Game theory method was presented here for determining the optimum electricity clearance price in the grid hourly, to maximize the system's best reliability for consumers and suppliers. For solving this problems, seasonal varying load and time as well as seasonal generation variation (wind and solar) curve was considered. The prepared model is made available for daily operation by using solar radiation, wind speed and air temperature values at one-hour intervals. The contributions of this work are summarized as follows.

a) A multi-objective optimization framework is proposed for determining the optimum electricity clearance price in the grid hourly, to maximize the system's best reliability for consumers and suppliers.
b) Game theory technique has been explored to solve the optimization problem

c) The coordination of solar PV/wind power/battery storage/ DG and grid is investigated.

d) Uncertainties existing in the system are fully addressed.

The remainder of this paper discusses the details of the model, DSM & game theory followed by a set of case study conducted & simulation results.

2.Modelling of the system

Solar photovoltaic and wind energy are the renewable energy sources considered as suppliers for two suppliers (supplier-1 & supplier-2). Besides the above, batteries, DG (diesel generator) and grid are also measured as back-up power suppliers for two suppliers. In day, load demand during winter and summer season of Bhubaneswar and Dhenkanal area of Odisha, India has been considered as consumer-1 & consumer-2 respectively. The Schematic diagram of the system is shown in Figure 1.

2.1.Modelling of supplier

The solar irradiation, wind speed and ambient temperature data at Dhenkanal and Bhubaneswar are collected from the Indian Meteorological Department, Govt.of India during both summer and winter season for the year 2018. Each supplier's modelling is defined below.

2.1.1.Solar Photovoltaic System

The mathematical model studies given in the references [14-15] were the source of the studies of the modeling of solar PV.

$$P_{pv-DC} = A_{pv} * \eta_{pv} * \eta_{pt} * N_{pv} * f_{manu} * f_{cell} * \eta_{pv-INV} * E_{ir}(t) \quad (1)$$

$$P_{pv-AC}(t) = P_{pv-DC}(t) * \eta_{INV} * \eta_{INV-SB} \quad (2)$$

The solar irradiation and respective ambient temperature during a typical summer and winter day are shown in Figure 2.

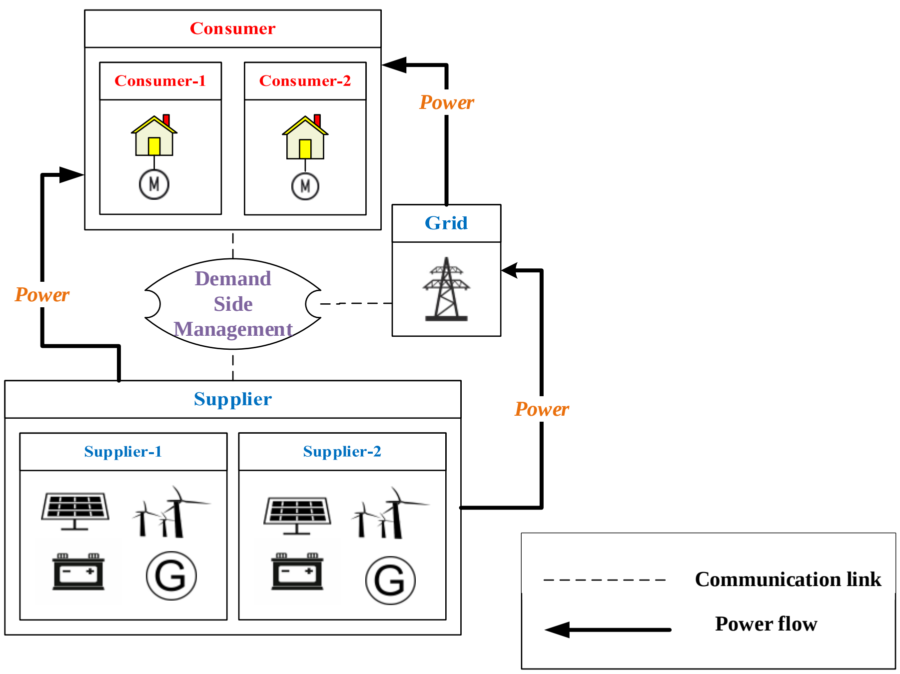

Figure1. Schematic diagram of the system

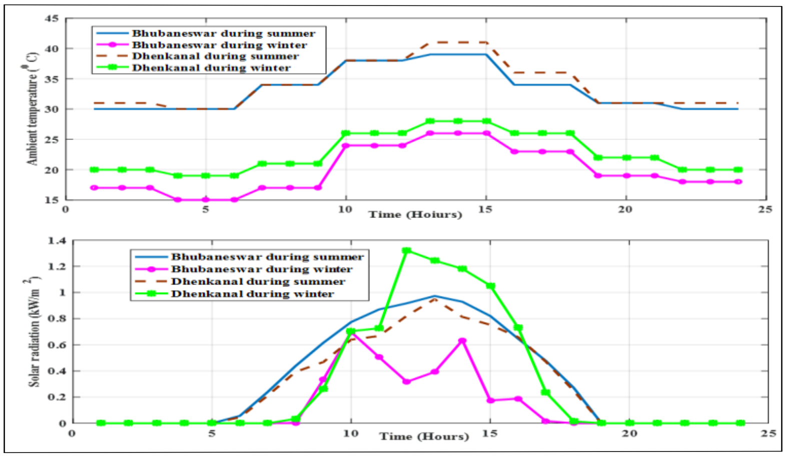

Figure2. Ambient temperature and solar radiation in a day during summer and winter

2.1.2.Wind Power Generation System

The mathematical model studies given in the references [16] have been the source of the studies of the modeling of wind power generation.

$$P_w = \begin{cases} 0 & v < v_{cut\ in}, v > v_{cut\ out} \\ v^3\left(\frac{P_{rated}}{v^3{}_{rated} - v^3{}_{cut\ in}}\right) - P_{rated}\left(\frac{v^3{}_{cut\ in}}{v^3{}_{rated} - v^3{}_{cut\ in}}\right) & v_{cut\ in} \le v < v_{rated} \\ P_{rated} & v_{rated} \le v \le v_{cut\ out} \end{cases} \quad (3)$$

Wind speed extracted during a typical summer & winter day at Bhubaneswar and Dhenkanal are shown in Figure 3.

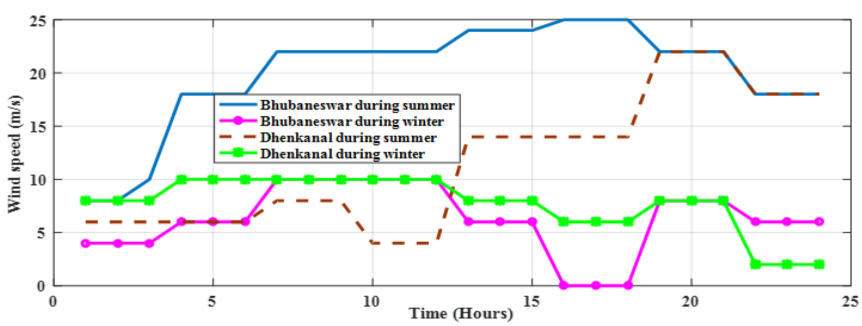

Figure3. Wind speed in a day during summer and winter

2.1.3.Diesel Generator (DG)

The mathematical model studies given in the references [18] were the studies' source of the modeling of wind power generation. The cost function is expressed as below.

$$C_{dgi,t} = a_i\left(Pdg_i(t)\right)^2 + b_i\left(Pdg_i(t)\right) + c \quad (4)$$

For supplier-1 & 2 coefficients of cost function are a_1 = - 0.0067, b_1 = 0.3333, c_1 = 0, and a_2= -0.0085, b_2 = 0.4972, c_2 = 0 respectively. The rated capacity of the DGs for supplier-1 & 2 are 20 and 30 kW respectively.

2.1.4.Battery Energy Storage System

The SOC for each hour is determined as given below [15].

$$SOC_i(t+1) = SOC_i(t) - Pbat_i(t) * \frac{del\ t}{E_{bat}} \quad (5)$$

where E_{bat}= 2 kWh and *delt*=1 hour .SOC_{min} and $SOC_{max}$of battery are taken as 20% and 80% respectively.

2.2.Modelling of Consumer

The load demand in a day of Bhubaneswar and Dhenkanal area of Odisha, India has been considered as consumer-1 & consumer-2 respectively during both summer and winter season as shown in Figure 4 and 5 .

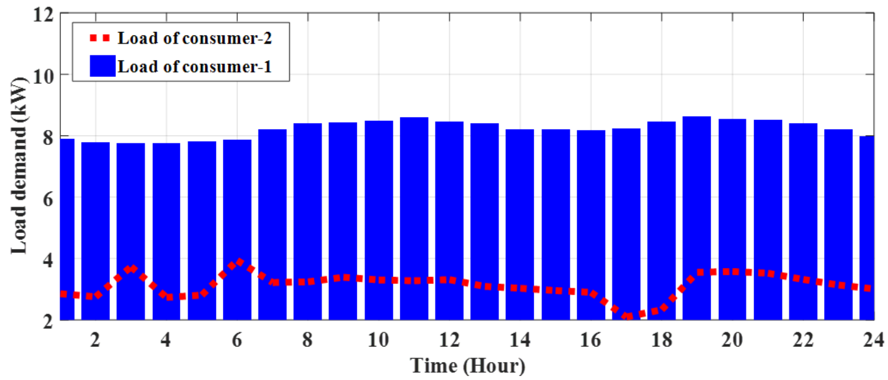

Figure 4. Load demand of consumer 1 & 2 in a day during summer

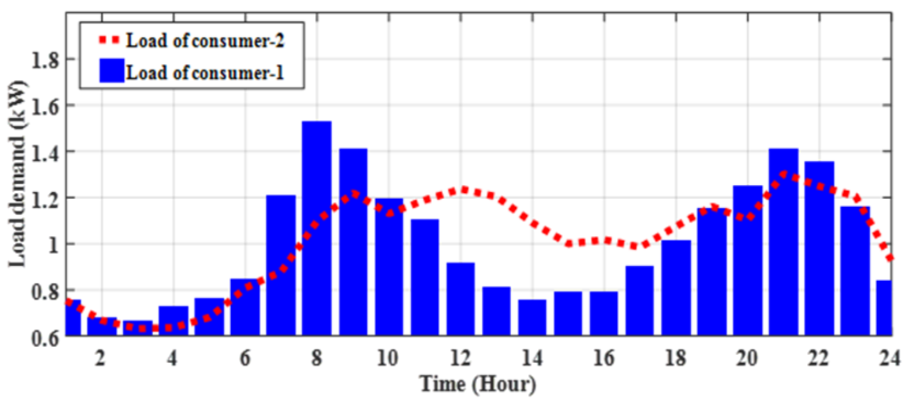

Figure 5. Load demand of consumer 1 & 2 in a day during winter

3.Demand Side Management Strategy

One of the primary approaches of the DSM is to regulate consumers' consumption levels according to the price levels in the electricity market. The concept of DSM provides a relationship between supplier and consumer that runs with mutual benefit. Application of DSM strategies comprises abundant earnings for a great number of beneficiaries in the electricity market. Hence, this advance and grand profitable plan is implemented here for maintaining stability in the electricity market [22-25]. The DSM strategy controls the overall function of the system. By the means of DSM strategy, consumer generates their optimized load demand as per the suitability of the price levels in the electricity market. The optimized load demand is fulfilled by the coalition of all suppliers. If there is any power deficit condition arises, then grid is available to feed power to the consumers. If there is any power surplus condition arises, then renewable suppliers provide their surplus power to the grid. In this way, DSM strategy maintains stability in the electricity market.

4.Problem Formulation

For optimum hourly electricity price, a combination of multi-objective function can be framed by taken into account of both profits of consumers and suppliers, and which can be described as:

4.1.Objective function

4.1.1.Objective function for consumer

The electricity purchase cost of consumers can be minimized by controlling the load demand. Of consumer.For the consumer objective function can be given as:

$$MinF_i = \sum_{t=1}^{t=24} \lambda_t(P_l) * P_{li,t} \quad (6)$$

$$\lambda_t(P_l) = \theta * P_l(t) - \beta \quad (7)$$

4.1.2.Objective function for supplier

Cost of Power selling should be more than the cost of power generating in order to provide profit to the supplier's. The objective function of supplier can be given as:

$$MaxF_i = \sum_{t=1}^{t=24} (Revenue_{i,t} - Cost_{i,t}) \quad (8)$$

The supplier includes 4 entities (battery energy storage system, diesel generator, solar PV system, and wind turbine). The revenue function of supplier can be given as:

$$Revenue_{i,t} = \lambda_t(P_l) * [Pw_{i,t} + Ps_{i,t} + Pdg_{i,t} + Pbat_{i,t}] \quad (9)$$

Battery power can be negative or positive as per their SOC. The supplier's cost function is expressed as:

$$Cost_{i,t} = C_w(Pw_{i,t}) + C_s(Ps_{i,t}) + C_{dg}(Pdg_{i,t}) + C_{bat}(Pbat_{i,t}) \quad (10)$$

Power generation cost, maintenance and Installation of renewable energy sources (C_w & C_s) and cost of the battery energy storage system, C_{bat} = 0 are assumed to be negligible.

The objective function of supplier can be given as:

$$MaxF_i = \sum_{t=1}^{t=24} (Revenue_{i,t} - Cost_{i,t}) \quad (11)$$

$$F_i = \sum_{t=1}^{t=24} \lambda_t(P_l) * [Pw_{i,t} + Ps_{i,t} + Pdg_{i,t} + Pbat_{i,t}] - [C_w(Pw_{i,t}) + C_s(Ps_{i,t}) + C_{dg}(Pdg_{i,t}) + C_{bat}(Pbat_{i,t})] \quad (12)$$

4.2.Constraints

Objective function is optimized satisfying inequality and equality constraints.

4.2.1 Equality constraints

$$Pw_{i,t} + Ps_{i,t} + Pdg_{i,t} + Pbat_{i,t} + Pg_{i,t} = Pl_{i,t} \quad (13)$$

4.2.2 Inequality constraints

$$k_1Pb_i(t) \le Pl_i(t) \le k_2pb_i(t) \quad (14)$$

$$Pw_{i,min} \le Pw_i(t) \le Pw_{i,max} \quad (15)$$

$$Ps_i(t) \le Ps_{i,max} \quad (16)$$

$$Pdg_{i,min} \le Pdg_i(t) \le Pdg_{i,max} \quad (17)$$

$$Pbat_{i,min} \le Pbat_i(t) \le Pbat_{i,max} \quad (18)$$

$$SOC_{i,min} \le SOC_i(t) \le SOC_{i,max} \quad (19)$$

$$SOC_{i,end} \le SOC_{i,24} \quad (20)$$

$$P_{pv\_AC,i,min} \le P_{pv\_AC,i}(t) \le P_{pv\_AC,i,max} \quad (21)$$

$$|Pg_{i,t}| \le 1/10 \times [Pw_{i,t} + Ps_{i,t} + Pdg_{i,t} + Pbat_{i,t}] \quad (22)$$

5. Game Theory

The suppliers and consumers are reconstructing themselves to reap benefits, in order to meet the ever growing energy demands. But to fulfil the objective of both market participants (supplier and consumer) is a challenging task. Game Theory is one of the best approach , which can be used to find equilibrium point between two market participants in a conflicting situation. Although many design theories focus on reducing the impact of these sub-optimal choices, game theory as a branch of applied mathematics provides a auspicious solution to resolve conflicts of interest. Supplier and consumer are two players in this game and the result depends upon the individual strategy of the players. Games can be classified according to the number of players and the payoff. Classification of games can be done as per interactions of players such as: Cooperative game, non cooperative game (Nash).

(a) Cooperative game theory

In the Cooperative game theory case, all participants work together to establish a coalition to achieve a common shared goal. Here, every player knows the strategy of other player. They cooperate with each other for findingthe necessary solution answer, because cooperation can lead to an improvement in compensation. For example, in chess, each player knows everything about the game . As a result of Game Theory, an equilibrium solution is obtained. That solution is called as “Nash Equilibrium” and It's called "John Nash," the creator of Game Theory. Getting the Nash equilibrium point is a very difficult and challenging task if the number of players exceed to more than two. It is noteworthy to mention that at Nash equilibrium no player can obtain profit through changing its own strategy unilaterally.

(b) Non-cooperative game theory

In this Game Theory, each and every playerare always focused on their self-interest , so they can achieve their objective. They donot have prior knowledge about their strategy of competitors.This approach aims constantly to meet the objective function of the individual without considering their effect on the strategy of another player.

5.1. Application of Game Theory Approach to Solve the Problem

Renewable power integration with versatile electricity price signifies the need of power management in smart grids. Here, the renewable suppliers not only provide power to the consumers but also sell their excess generation to the grid. The additional feature of the proposed system is the plug and play activity of the DGs and battery storage.

Game theory method was presented for determining the optimum electricity clearance price in the grid hourly, to maximise the system's best reliability for consumers and suppliers.The electricity suppliers and consumers are considered as the two players. The consumers are allowed to regulate and manage their own load demand with respect to the electricity price variation for minimizing the electricity purchase cost. Consumers focus on their profit. So, non-cooperative game technique is applied to study and control the consumer’s behavior [26-28]. Total optimized load demand is fulfilled by forming a coalition among all the suppliers. The non-cooperative game between the suppliers as well as consumers gives Nash Equilibrium point for every hour which includes the optimized electricity price [29-30].

6. Results and Discussions

Game theory is applied to solve the problem using the required data of summer & winter season of Odisha, India.

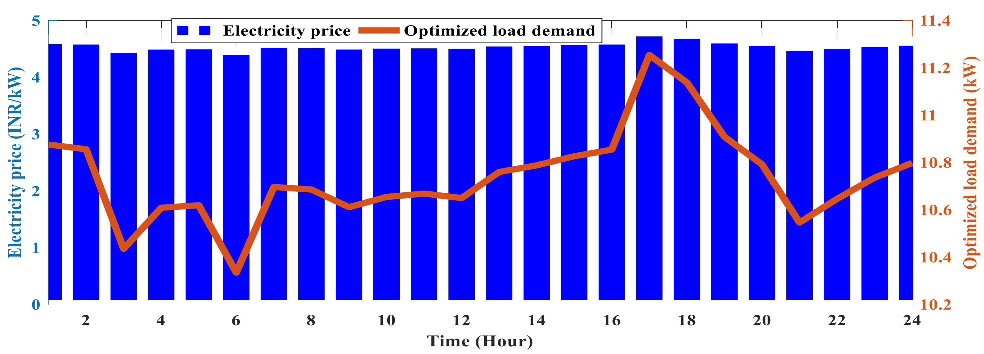

Figure 6. Optimized load demand and Electricity price during summer

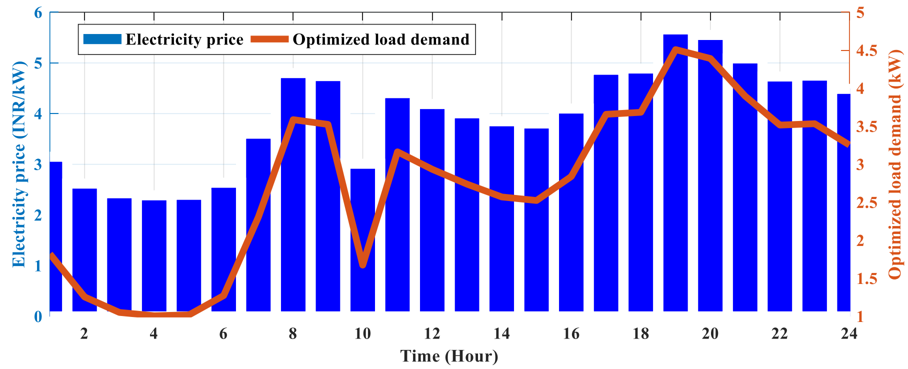

Figure 7. Optimized load demand and Electricity price during winter

From Figure 6 & 7, it is observed that the electricity price is directly proportional to the optimized load demand. Optimum hourly electricity price in a day is determined keeping in view of both suppliers and consumers interest. Both the market participants shall be benefitted by implementing this TOU electricity price mechanism. The consumers have to pay the electricity price for electricity consumption according to their use of electricity. The hourly clearing electricity price for 24 hours for summer and winter season are shown in Table 1.

Table 1.Hourly clearing electricity price in a day during summer & winter season

Time (Hour)	Electricity price (INR/kWh) for summer	Electricity price (INR/kWh) for winter
1	4.6661	3.1492
2	4.6589	2.6197
3	4.5078	2.4295
4	4.5701	2.3888
5	4.5739	2.3986
6	4.4715	2.6365
7	4.6016	3.6039
8	4.5977	4.7996
9	4.5709	4.7412
10	4.5865	3.0112
11	4.5916	4.4043
12	4.5848	4.1891
13	4.6244	4.0065
14	4.6345	3.8492
15	4.6483	3.8057
16	4.6584	4.1007
17	4.8021	4.8652
18	4.7604	4.8902
19	4.6779	5.6610
20	4.6359	5.5518
21	4.5476	5.0892
22	4.5836	4.7327
23	4.6158	4.7498
24	4.6381	4.4883

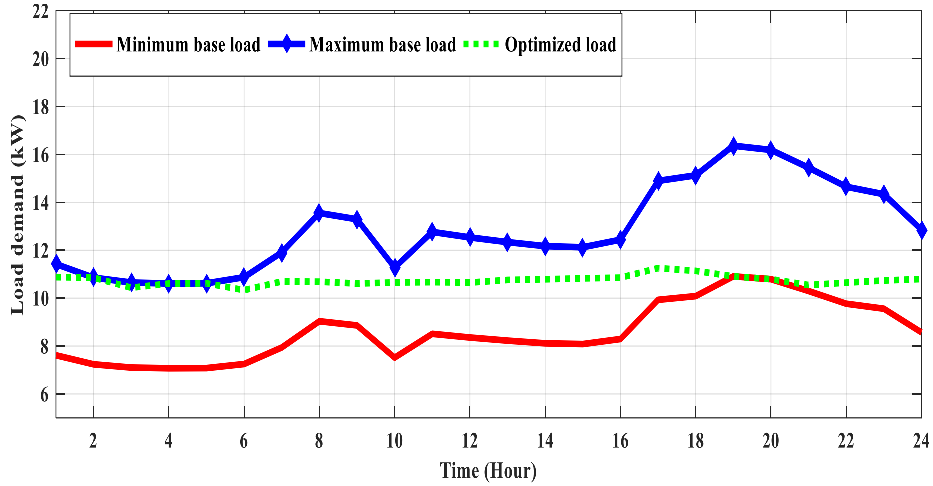

Figure 8. Load demand curve of consumer during summer

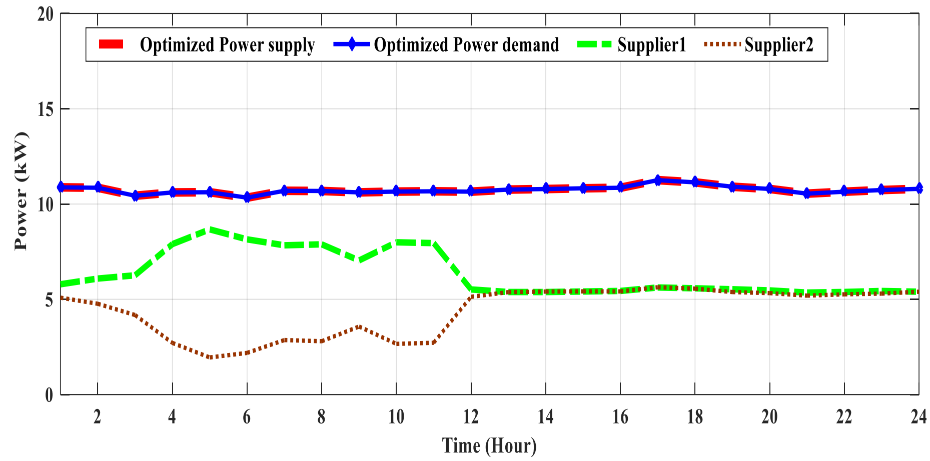

Figure 9. Supply and demand strategy after optimization during summer

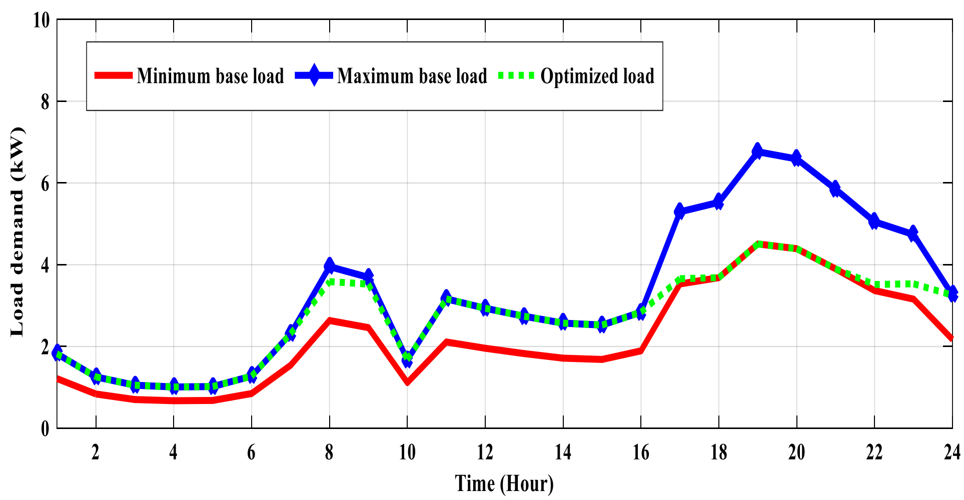

Figure 10. Load demand curve of consumer during winter

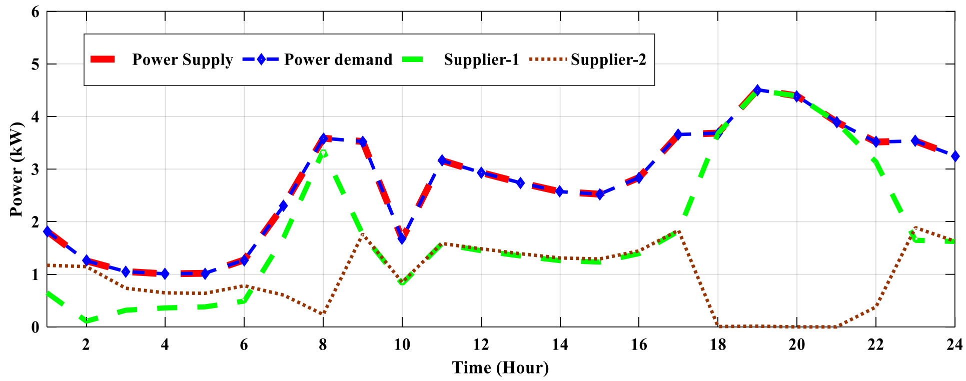

Figure 11. Supply and demand strategy after optimization during winter

Figure 8 & 10 indicate that, the optimized load demand is within minimum and maximum base load demand during summer and winter respectively. Figure 9 & 11 show that, the consumers' schedule demand is efficiently fulfilled by supplier-1 and supplier-2 coalition during summer and winter respectively.

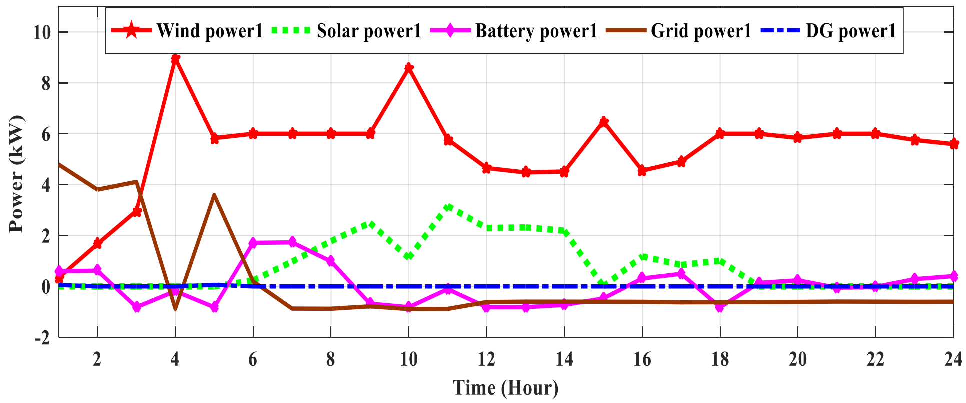

Figure 12. Contribution of power of supplier1 during summer

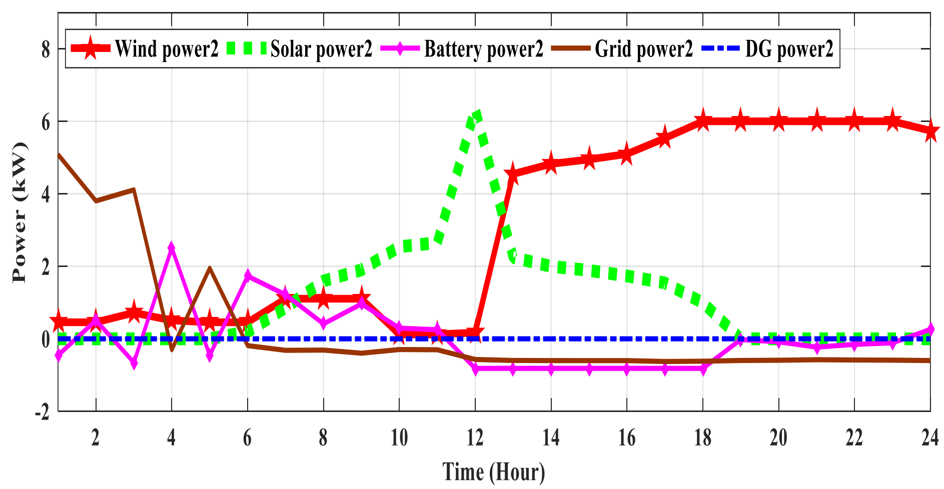

Figure 13. Contribution of power of supplier 2 during summer

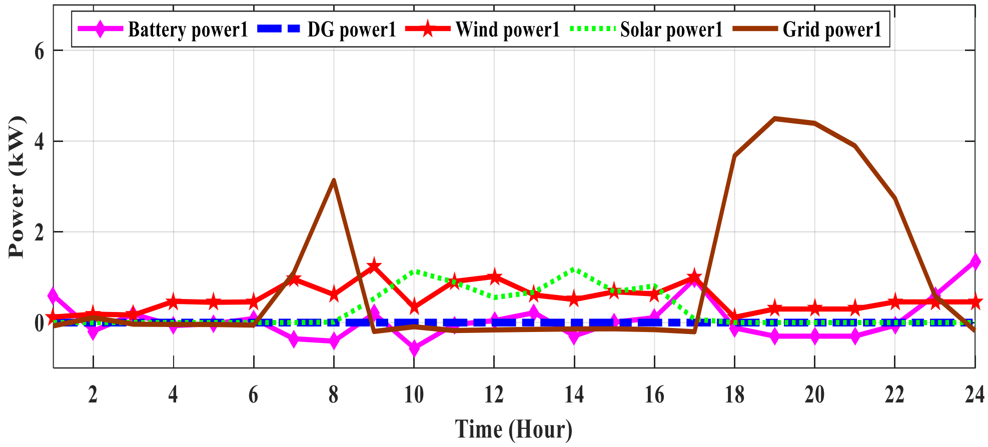

Figure 14. Contribution of power of supplier1 during winter

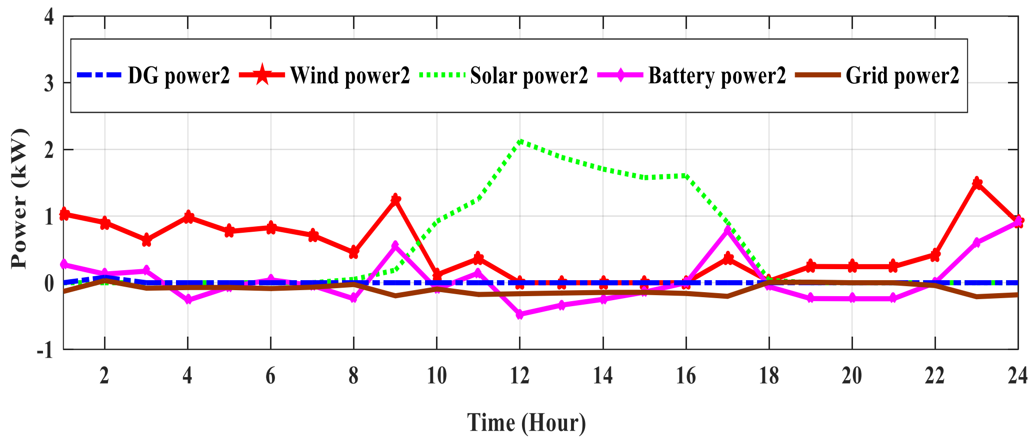

Figure 15. Contribution of power of supplier 2 during winter

Figure 12 & 14 for supplier-1 and Figure 13 & 15 for supplier-2 show the contribution of power to meet the optimized load demand of consumers during summer and winter season. Negative grid power indicates that, the extra generated surplus power of renewable suppliers is sold to the grid.

7. Conclusion

This study proposes the technique of game theory in electricity grid for determining optimum hourly clearing electricity price. In this study two seasons, i.e. winter as well as summer were considered. There is a significant connection between the consumers and suppliers behavior along with their profits in the electricity markets. A decision maker should take into consideration the strategies that have been chosen by his competitors. After analyzing the results of all cases using game theory technique, thiswas observed that the optimal hourly clearing electricity market price of grid gives the profit to both suppliers and consumers simultaneously with satisfying all constraints of the system.

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