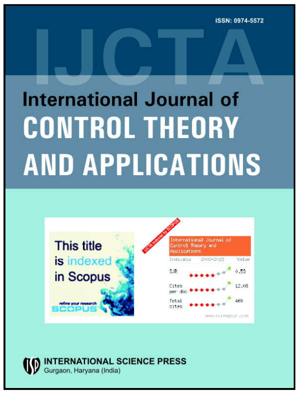

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Short Term Scheduling of Rural Residential Electricity Demand by A Smart Micro Grid

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Abstract: This paper presents strategy to achieve energy sustainability at a minimum cost, by day ahead scheduling of the aggregated residential load, connected through Smart Green Micro Grid, managed by Microgrid Central Controller (MGCC). The proposed MGCC performs the role of a facilitator to convey demand response policy of a utility company to the customers, obtain forecasting of availability and cost of renewable sources installed on load side, and get demand pattern from the consumers. This demand pattern is analysed, classified, and optimized for maximum profit in an energy exchange with the central smart grid. The optimization is carried out by the means of Hybrid Particle Swarm Optimization technique (HPSO) that deals with a hybrid type of data variables i.e. binary particles and continuous particles. The MGCC takes care of the battery state of charge (SOC) control, as well as scheduling of power generated by renewable resources on the load side with the customers (viz. Solar and biomass gasifier), so as to earn the maximum profit.

Keywords: Smart grid, particle swarm optimization, microgrid, solar PV, biomass gasifier, demand response.

1. INTRODUCTION

Sustainable electrical energy access in rural areas of the India is a critical factor in the nation's sizable and comparable development, as still today about 70% [1] of population lives in the villages. And 32898 out of 593731 inhabited villages India are still un-electrified [2].Technological development, health, education, information and improvement of standard of living in-turn brings job prospects in villages and restricts migration of the population from the rural to the urban areas of the country [3][5].

Microgrid is known as a network integrating energy resources and loads at the local level while functioning in synchronized or islanded mode with the central grid. It provides the most effective way for the rural electrification [6]. India has huge potential of generating electricity out of solar energy. The daily average solar energy incident over India varies from 4 to 7 kWh/m^2 with the sunshine hours ranging between 2300 and 3200 per year, depending upon location [7]. Biomass Gasifier has an advantage of easy availability of the biomass in India, added to which, reliability of supply is a key quality with such power plant in coordination to solar PV.

S. Abu, et al. [8] presented study of an alternative concept of producing energy using small scale generators integrated into microgrid in the close proximity to the energy users. I.Maity, et al. [10] presented rural residential load scheduler based on game theory. M.Marwali, et al. [11] proposed short term scheduling of integrated thermal and PV generation including battery storage. Augmented Lagrange Relaxation and Dynamic programming are employed for the solution. X. Guan, et al. [12] discussed the method to minimize the overall energy cost of electricity and natural gas over the entire scheduling horizon using the time-of-use (TOU) electricity price. Thus though above literature creates strong base of modelling, optimization and scheduling of Distributer Energy Resources (DER), load disaggregation and optimization is not attempted. M.Castillo-Cagigal, et al. [16] developed remote monitoring and control mechanism for optimization of energy generated, using solar PV with storage. Although optimization using "self consumption factor" was carried out to reduce energy drawn from the grid, utility perspective of peak shaving using TOU/RTP is not considered. J. Zhao, et al. [17] designed an optimum schedule for plug-in-Hybrid Vehicle (PHEV) using PV and battery storage based on agent based model simulation framework. While considering various consumer behaviours for PHEV charging/discharging under demand response program, household load pattern is considered non-responsive to the TOU or RTP. A. Chaurey, et al. [18] carried out techno-economical analysis to search usefulness of Solar Home System compared to off grid PV powered micro grid system for the purpose of rural electrification. Whereas opportunity of tapping and integrating other renewable sources in villages such as biomass energy using gasifier or use of demand response were not explored. D.R.Thiam, et al. [19] shown that the decentralized PV to be most cost effective than extending the grid connections to remote rural areas. Authors have carried out energy consumption survey was taken but scheme for demand response is not targeted for optimization. T. Som, et al. [23] suggested that the biomass gratifier in addition to the solar PV may be used for the purpose of cost reduction; it reduces the cost by 8.1% compared to the Solar PV with fuel cells. A.P. Agalgaonkar, et al. [24] developed economic analyser for optimum sizing of distributed generator powered micro grid but disaggregation and scheduling of shiftable loads in not attempted. T. Logenthiran, et al. [25] effectively demonstrated generation scheduling scheme of micro grid in islanding mode in real time optimized operation but considers only islanding mode. Thus does not include benefit to consumers out of export of excess energy with micro grid to the utility.

This paper emphasizes empowering rural consumers by aggregating their demand and energy generated by micro generators (i.e. kW level roof top solar PV and biomass gasifier). Thus enabling them to play in to and earn profit from the energy market. The micro grid and the central smart grid ensure the sustainable energy and reduction in energy cost. Particle Swarm Optimization (PSO) based algorithm coded to achieve maximum profit in energy exchange with the utility.

The loads are disaggregated and classified as (I) time constraint loads (i.e. non-shiftable or non-deferrable): that to be ON/OFF at particular time and manually operated viz. lighting, TV, AC etc. and (II) time flexible loads (i.e. shiftable or deferrable): which may be operated to the time zone having a minimum rate of energy during the day (viz. automatic machines including washing machine, flourmill, water pump etc). Micro grid energy is supposed to be managed by MGCC that targets optimization to obtain maximum profit in energy exchange with the grid during the day and customers are empowered to play an important role in energy market.

2. PROBLEM DEFINITION AND MATHEMATICAL FORMULATION

The problem involves mixed integer optimization that estimates and schedules functioning of distributed energy resources, load and/or storage day ahead. This aims to the commonly targeted agenda of the community viz. maximum profit and reliability. Each consumer connected to the micro grid is asked for such one day load utilization profile. According to which common agenda are drawn.

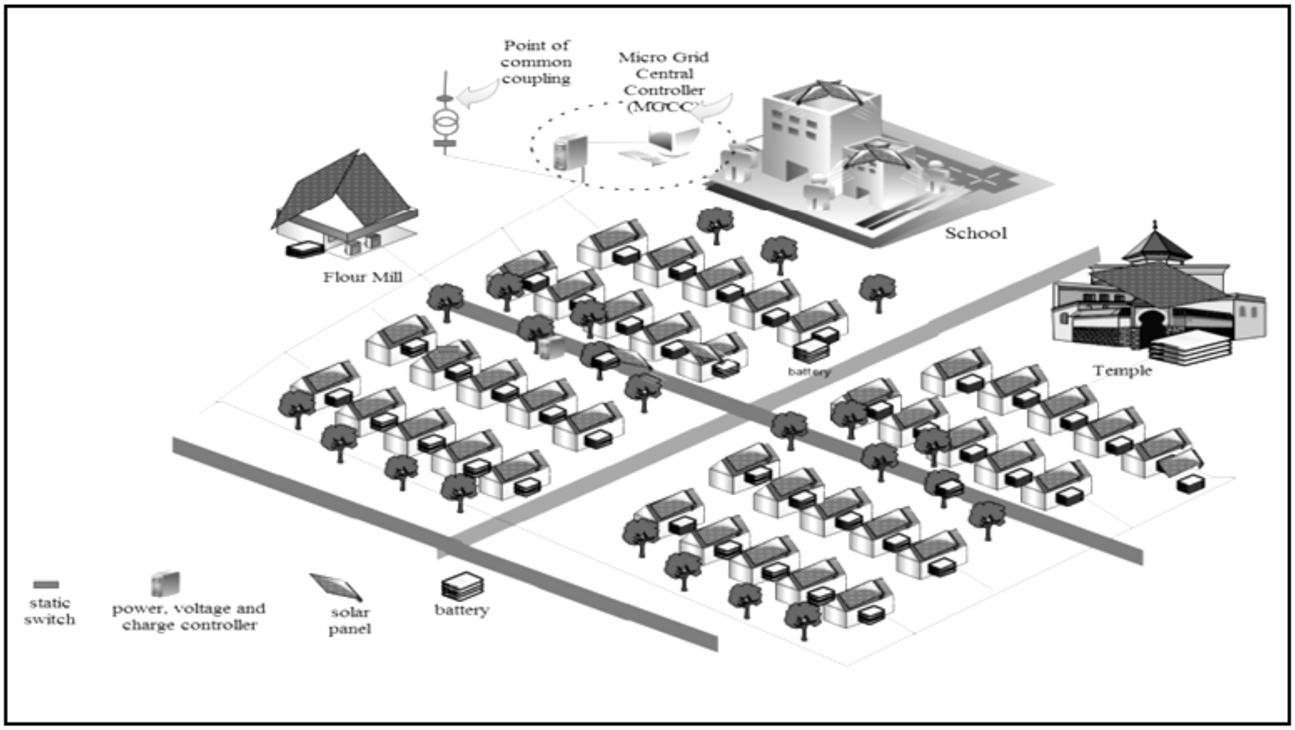

Figure 1: Case Study community Layout

Figure.1represents an example for a community micro grid controlled by Micro grid Central Controller (MGCC), which works in synchronism with utility grid. Diverse categories of loads as residential, temple, school, and community flourmill considered in this study is as per surveyed from Nava-Sudambada village, Gujarat State, India.

Figure. 2 depicts each node details of a domestic consumer equipped with DER (viz. solar PV, biomass gasifier), battery storage interconnected by micro grid. Micro Grid Central Energy Controller communicates with utility grid and community connected load.

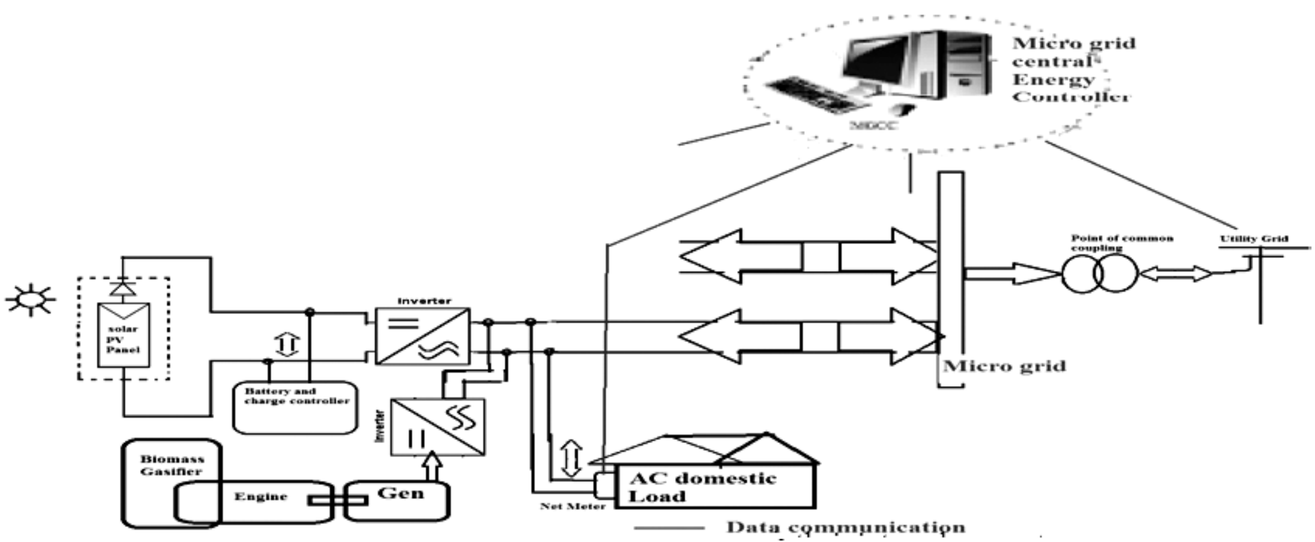

Figure 2: Micro Grid and its components with their internal connectivity

The basic functionality of MGCC is formulated to obtain maximum profit in the energy exchange day-wise basis as follows:

Notations for the formulation are as follows:

t	Time instant (hr)
T	Total length of time horizon (24 hrs)
i	Home count
G_t	Forecast solar radiation at hour't'.
$P_{PV}(G_t)$	Incidence solar radiation to energy conversion function of PV generator defined by (3).
G_{std}	Solar radiation in the standard environment set as 1000 W/m^2.
G_c	Critical radiation point set.
P_{sn}	Equivalent rated power output of the PV generator (in kW).
$Pcb^{\min}$	Lower limit of the state of charge for battery.
pcb_t	State of charge of battery at instant't'.
eb^{min}	Energy consumption of the critical loads (in kWh).
eb^{max}	Maximum energy capacity of the battery (in kWh).
$P_{b,t}$	Battery power (in kW), at tth instant.
$P_{PV,t}$	Power generated by at tth instant (in kW).
$P_{l,t}$	Total load optimized connected to the micro grid at instant't.'
$P^{opt}_{l,i,t}$	Optimally scheduled load demand on the bases of priority of demand at instant't' and rate of energy to be drawn from the grid of home 'i'.
$\alpha_{r,t}$	Rate of electrical energy at time 't'.
$\alpha_{rg,t}$	Tariff declared by utility for electrical energy at time't' for drawing energy from grid.
$\alpha_{rmg,t}$	Tariff declared by utility for electrical energy at time't' for supplying energy from micro grid to utility.
pcb^{min}	Lower limit of the state of charge for battery.
pcb_t	State of charge of battery at instant't'.
eb^{min}	Energy consumption of the critical loads (in kWh).
eb^{max}	Maximum energy capacity of the battery (in kWh).
η_b	Charging/discharging efficiency of battery.
x_i	ith particle of the population.
v_i	Velocity vector.
d	1, 2 ... D dimension of space.
c_1, c_2	Two positive acceleration coefficients.

R_1, R_2	Uniformly distributed random numbers in [0, 1].
w	Linearly decreasing function of the iteration index.
$w_{\max}$, $w_{\min}$	Initial and final weights.
$P_{bio,t+1}$	Output power of biomass for next instant.
P_{bio}	Output rating of biomass based generator (in kW),
$u\_bio,_{t+1}$	Availability of the gasifier.
$\tau_{up,t}$	Up time counter. (Hr)
$\tau_{dn,t}$	Down time counter. (Hr)
τ_{up}^{Max}	Maximum up time. (Hr)
τ_{dn}^{Min}	Minimum down time. (Hr)
α_{bmr}	Cost of biomass in Rs/kWh.

Scheduling of the load is done to achieve maximum profit, this in-turn leads towards objective function:

$$Maximize\sum_{t=1}^{T}(((P_{PV,t}+P_{b,t})-P_{l,t})\cdot\alpha_{r,t}-(P_{bio,t}\cdot\alpha_{bmr})) \tag{1}$$

Subjected to:

Solar power generation capacity constraints:

$$P_{PV}^{Min}\le P_{PV,t}\le P_{PV}^{Max}\ \text{Where t = 1, 2, ...T} \tag{2}$$

Power output of the solar PV can be mathematically formulated as [21], and 22],

$$P_{PV}(G_t)=\begin{cases}P_{Sn}\left(\dfrac{(G_t)^2}{G_{std}\cdot G_c}\right) & 0<G_t<G_c \\ & & t=1,2,\ldots T \\ P_{Sn}\dfrac{G_t}{G_{std}} & G_t>G_c\end{cases} \tag{3}$$

Where, G_t = Radiation in W/m^2 at the instant of time‘t’ as.

G_{std} = Solar radiation in the standard environment set as 1000 W/m^2

G_c = Certain radiation point set as 150 W/m^2 [11, 21, 22]

Battery control constraints:

Initial charge: [12]

$pcb_{,1}$ Initial charge (4)

State of charge dynamics

$$pcb_{,t+1} = pcb_{,t} + \frac{P_{b,t} \cdot t}{eb^{\max}} \tag{5}$$

State of charge constraint

$$pcb^{\min} = \frac{eb^{\min}}{eb^{\max}} \le pcb_{,t} \le 1 \tag{6}$$

State of battery: charging/discharging:

$$P_{b,t} = \begin{cases} -P_{b,t} \cdot \eta_b & P_{b,t} < P_b^{Max} \\ P_{b,t} \cdot \eta_b & P_{b,t} < P_b^{Min} \end{cases} \qquad t = 1, 2, \ldots T \tag{7}$$

Total load optimized connected to the micro grid at instant‘t’

$$P_{l,t} = \sum_{t=1}^{T} \left(\sum_{i=1}^{I} P_{l,i,t}^{opt} \right) \tag{8}$$

Where,

$P_{l,i,t}^{opt}$ = optimally scheduled load demand on the bases of priority of demand at instant ‘t’ and rate of energy to be drawn from the grid of for ‘i’

$$P_{l,i,t}^{opt} = P_{l,i,t}^{\min} < P_{l,i,t}^{opt} < P_{l,i,t}^{\max} \tag{9}$$

Rate of power at time‘t’: $\alpha_{r,t}$

$$\alpha_{r,t} = \begin{cases} \alpha_{rg,t} & (P_{PV,t} + P_{b,t}) < P_{l,t} \\ \alpha_{rmg,t} & (P_{PV,t} + P_{b,t}) > P_{l,t} \end{cases} \qquad t = 1, 2, \ldots T \tag{10}$$

Biomass power output: Scheduled output power from biomass gasifier based system to be constrained by the maximum up/down timing as per requirement of the system (discussed in section IV).

$$P_{bio,t+1} = P_{bio} \cdot u\_bio_{,t+1} \qquad t = 1, 2, \ldots T \tag{11}$$

$$u_{bio,t+1} = \begin{cases} 0 & \tau_{up,t} \ge \tau_{up}^{Max} \\ 1 & \tau_{dn,t} \ge \tau_{dn}^{Min} \end{cases} \tag{12}$$

3. DAY-AHEAD SCHEDULING USING HYBRID PSO

The scheduling problem that needs to determine two types of decision variables: i) Flexible load demand to be scheduled or not, at given instant (ON/OFF). ii) Battery power available at instant ‘t’.

The first decision variable needs binary details (1/0) while the later one continuously varying non-binary variable (i.e. continuous variable). Such problem can be solved by Hybrid Particle Swarm Optimization (HPSO) [14], which involves continuous as well as binary decision variables (particles).

3.1. Particle formulation

The swarm generated for this problem incorporates two sub swarms i) swarm of binary particles and ii) swarm of continuous variable particles. The swarm containing continuous variables, for battery power status, initialized with uniformly distributed random numbers $[P_{b1},...,P_{bT}]$ within P_b^{Max} and P_b^{Min}. For binary variables representing scheduling binary status [1/0] for washing machine flourmill and biomass gasifier $u_{wm1},...,u_{wmT}$, $u_{fm1},...,u_{fmT}, u_{bio1},...,u_{bioT}$, respectively, an additional operator is needed to account for the distinct nature of these variables and those are initialized from randomly initialized velocity. Once the binary variables are initialized, those should check for the feasibility (the minimum up-down constraints for load).

Thus each string of swarm contains total 72 particles. First 24 continuous variable particles, while next 48 (25 to 72) are binary particles i.e. swarm = $[P_{b1},...,P_{bT}, u_{wm1},...,u_{wmT}, u_{fm1},...,u_{fmT}, u_{bio1},...,u_{bioT}]$

3.2. Algorithmic steps

Swarm, number of variables, swarm sizes, times dimension initialized and defined by the set of randomly generated particles within limits.

Repair algorithm fixes the time-constrained variables ON for their ON periods, must-run loads for whole time horizon. Washing machine and flour mill are defined as flexible load without time constraint.

Fitness function is constructed for calculating the objective function wherein the profit is calculated.

PSO is run to search for the optimal scheduling for the day ahead by scheduling flexible loads, so as to obtain minimum cost to be paid for the consumption, and maximum earning by selling power in peak period, and ultimately obtaining maximum profit.

3.3. Feasibility test for the solution

To achieve the maximum profit, the PSO may opt to schedule flexible load demands for minimum time in OFF-peak periods, hence repair algorithm for the flexible demand keeps it ON for the minimum on time expected for the satisfactory operation of particular load.

4. CASE STUDY

A survey was carried out at the Nava Sudamda village near Limbdi (Figure.3) in Surendranagar District, Gujarat state, India, for the residential energy demand patterns. The survey was carried out to estimate approximate use of the energy in 40 homes, a school, a temple and a flourmill for all the three seasons.

Annual income of the home ranges from Rs. 50,000 to Rs. 1,50,000 they mainly depend on cotton farming. These homes are getting 17Hrs electricity per day as an indirect demand response agreement. The residential energy demand profile for typical summer(June), winter(Dec) and monsoon(Aug) are shown in Figure 4, Figure 5 and Figure 6.

Similarly load demand for the temple and school were surveyed for all the four seasons. The solar irradiation data was obtained from the India Metrological Department [online] of the well-known nearest location Limbdi town, using the aforesaid data, power generated for 1 kW PV panel is plotted (Figure. 7)

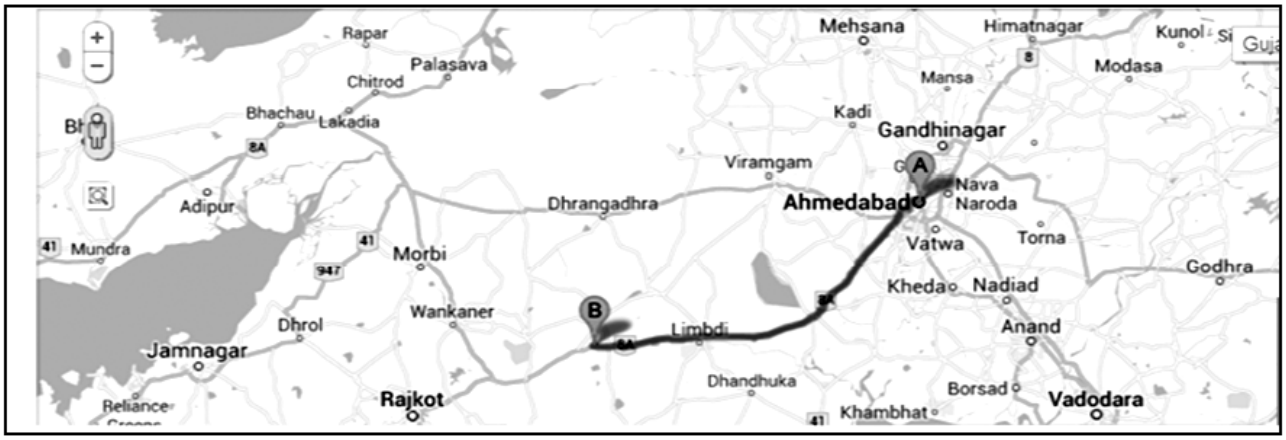

Figure 3: Location of the village in the map of Gujarat state, India [26]

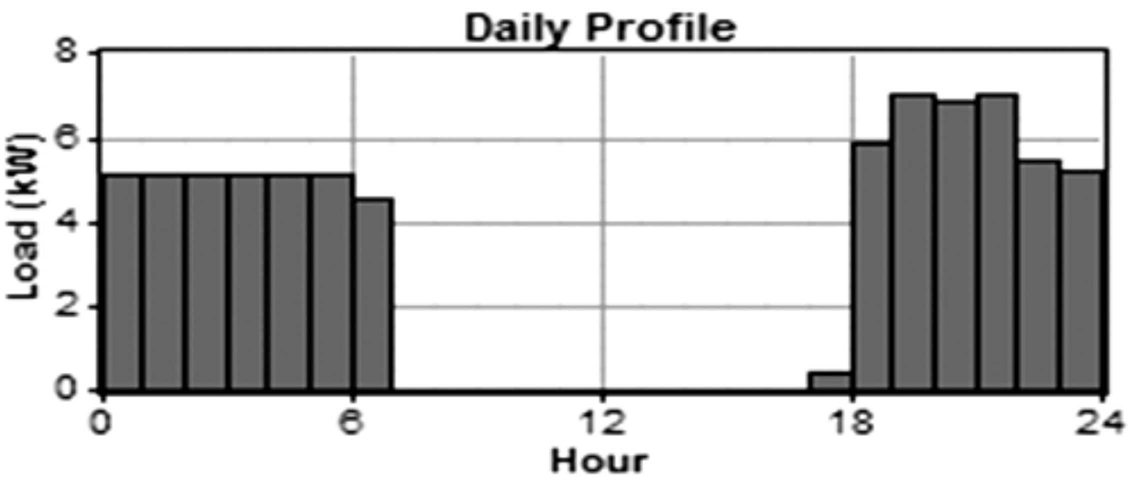

Figure 4: Residential Load Profile of in hot summer

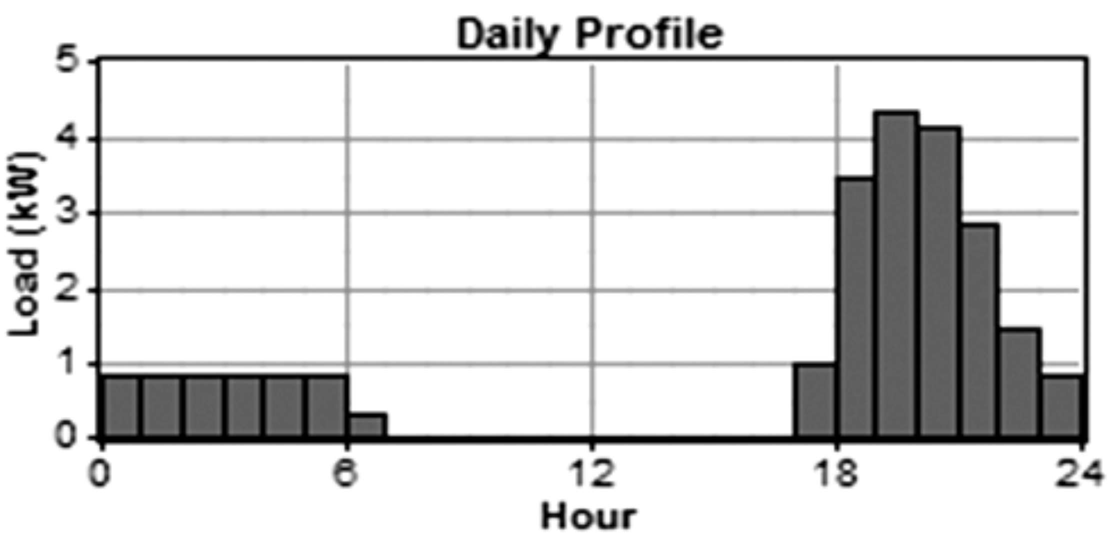

Figure 5: Residential Load Profile of in winter

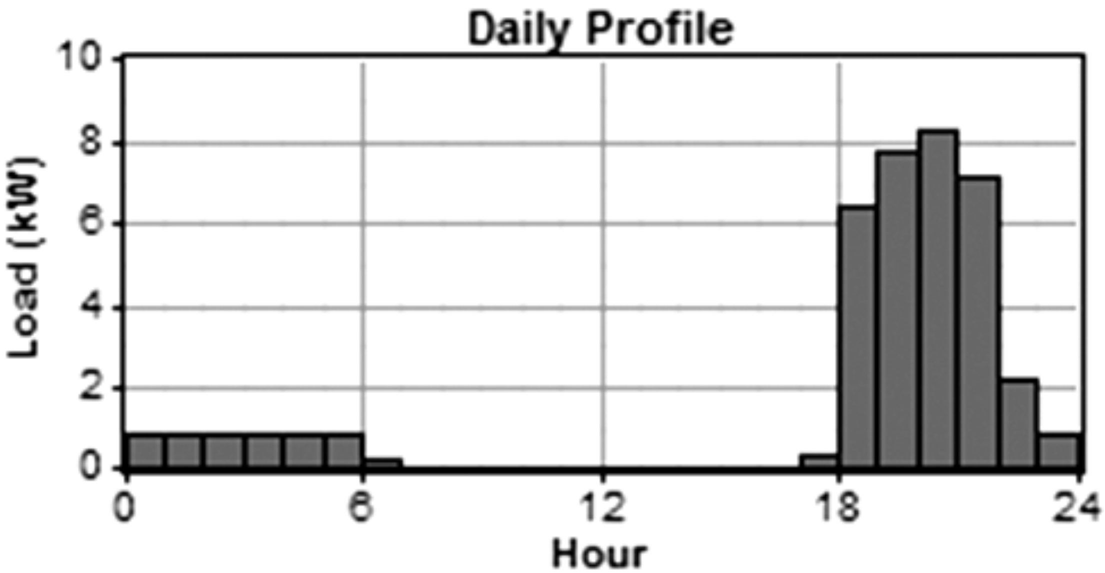

Figure 6: Residential Load Profile of in monsoon

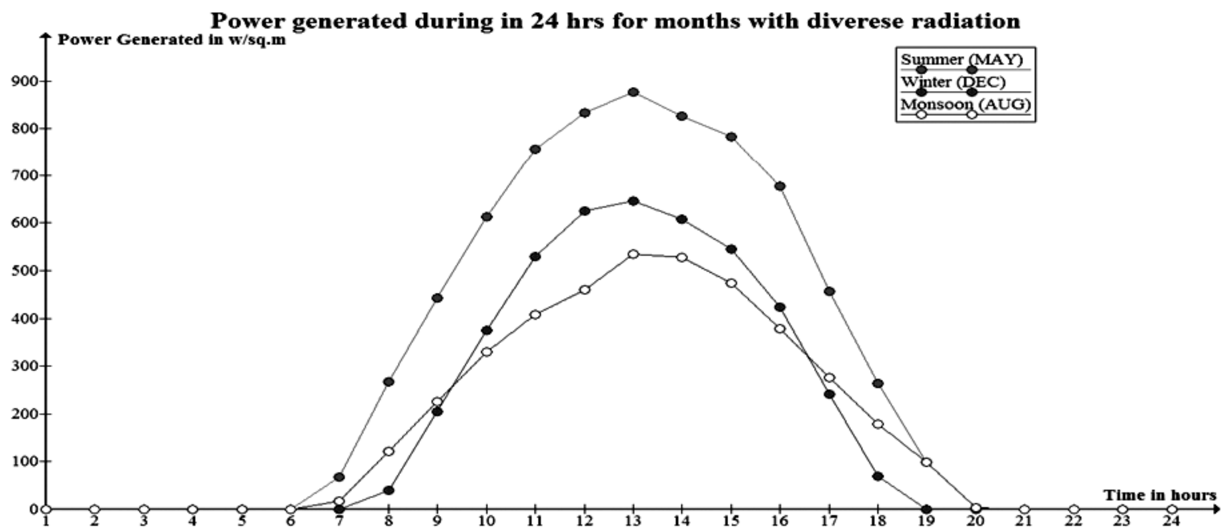

Figure 7: Solar Power generated by 1kW panel per day by PV panel in three seasons

Biomass based generation is being proven as a potential source of reliable energy generation, because agricultural waste and residues are easily and in ample amount available in rural areas.

While considering the case of the village "Nava Sudamda", the major plantation is of cotton plants that can provide waste as stem segments of the plant, unproductive cotton seeds, lint and segments of leaves etc. Employing gasifier in microgrid adds reliability in the system as it generates energy using cheaper bio-waste/garbage. Gasifier rating begins at 10 kW level which is suitable for scheduled operation in module of 10-50kW as per the demand.

Generally start and stop time of low rating biomass gasifier is limited to 10-15 minutes. While maintenance of about half an hour after each continuous run for 8-12 Hrs. These constraints are required to be taken care by MGCC.

Particle Swarm Optimization technique is used to obtain load schedule aiming to achieve maximum profit considering seasonal effects on load profiles, pattern of solar irradiation based power output of the PV generators, biomass based generator and battery storage constraints.

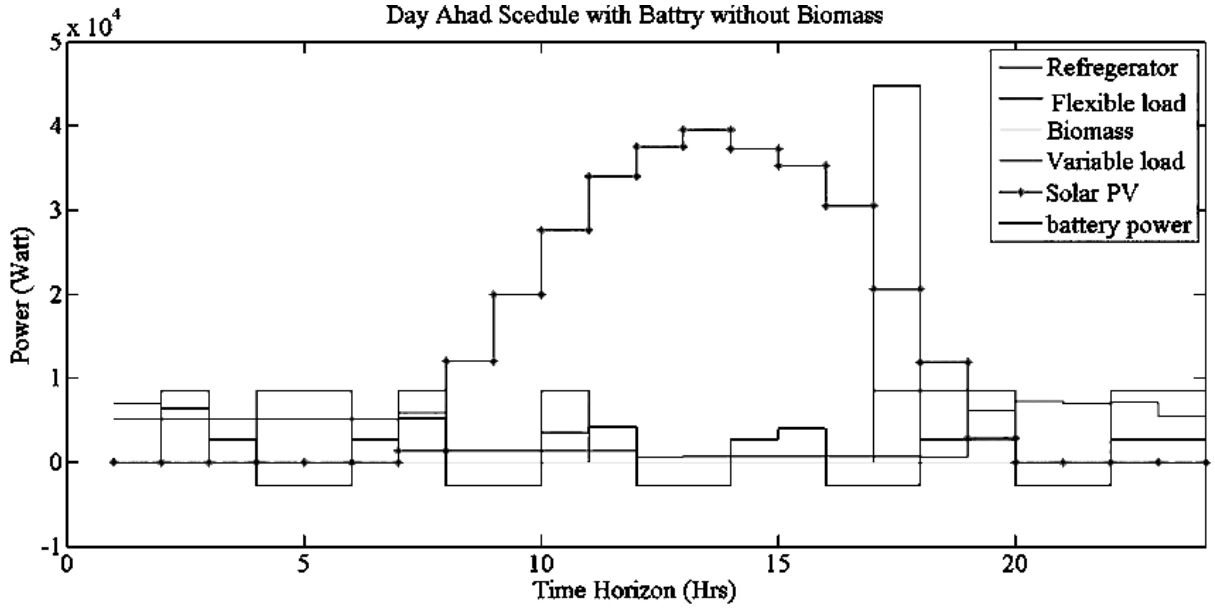

Figure 8: Day Ahead Schedule using Solar PV and battery

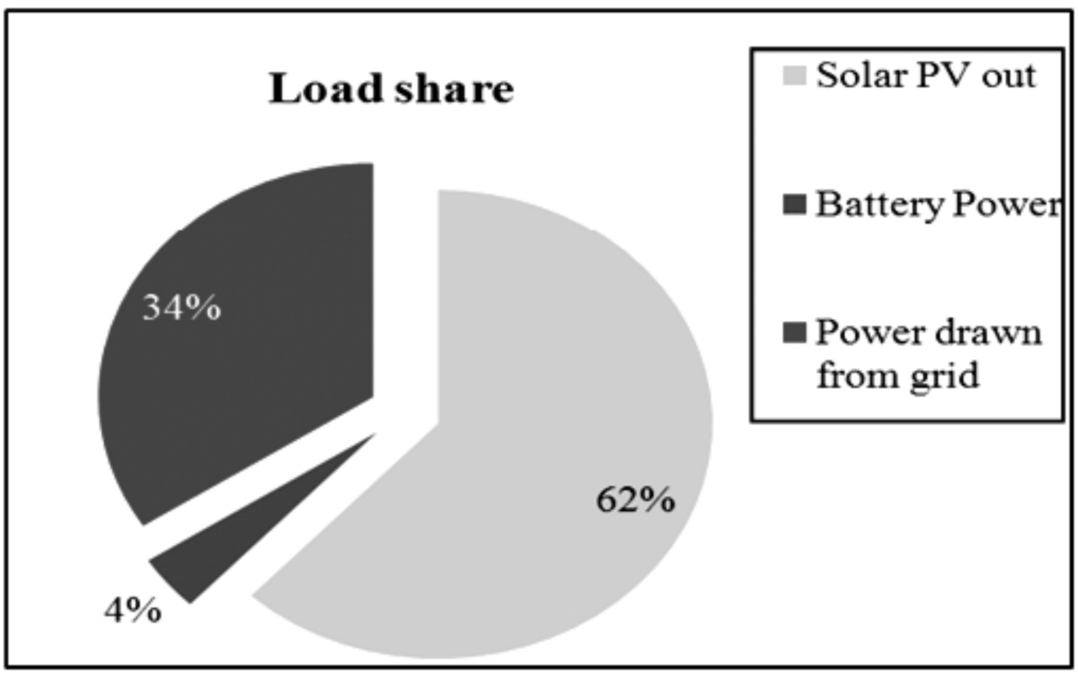

Figure 9: Load Shared by solar PV, Battery and Grid

The MGCC schedules loads targeting not only to have minimum energy bill for energy drawn from grid, but also to earn more by selling energy to the grid during the daylong energy exchange.

The results are plotted for the convergence and optimized scheduling of the loads varying different parameters to ensure and validate the behaviour of the algorithm.

Figure.8 shows the load distribution and Figure.9 shows load shared by Solar PV, battery and the grid while, Figure.10 shows convergence. For summer season, the convergence plot gives schedule with the maximum

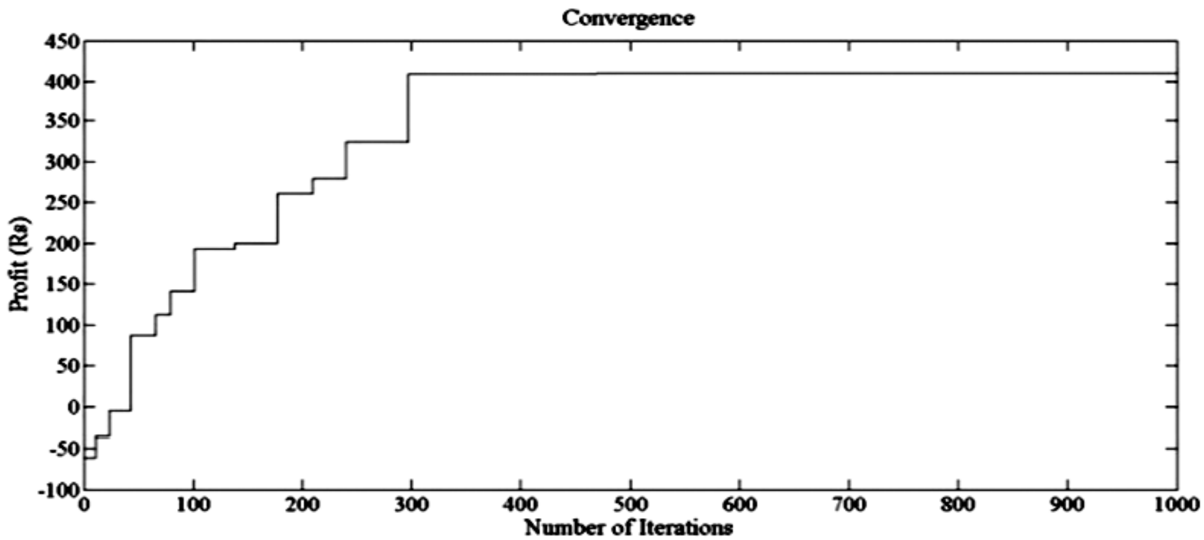

Figure 10: Convergence of objective function

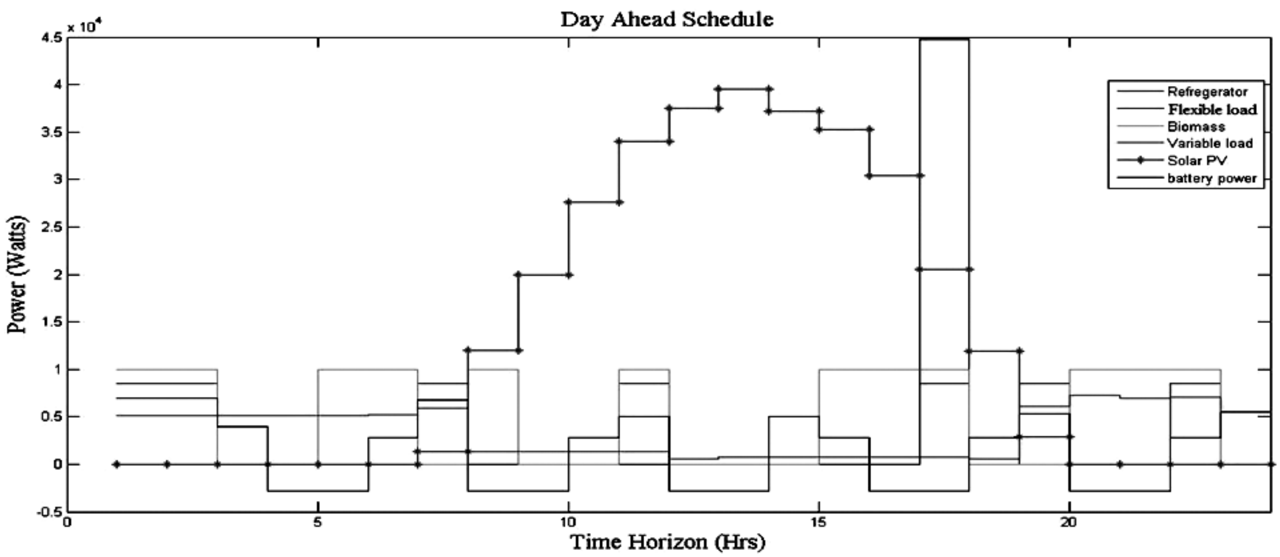

Figure 11: Load Distribution optimum schedule after inclusion of biomass gasifier

profit of Rs.410.8 per day for the residential load, without using biomass gasifier. Figure 11 shows the initial load distribution using biomass gasifier while Figure.12 shows the load shared by different sources, and battery storage.

The load shared by different sources depict that 10kW biomass gasifier shares 20% of load ,while batteries are getting charged so as to have more share from the batteries, consequently power drawn from the grid is reduced to 22% from 34% ,thus achieves the profit of Rs.948/day.

Figure 13 shows convergence plot, represents load schedule that achieves the maximum profit of Rs.948 per day for the residential area on introduction to the biomass gasifier. Thus inclusion of Biomass gasifier reduces dependency on utility grid by 12% and profit gets more than the double compared to case without using gasifier.

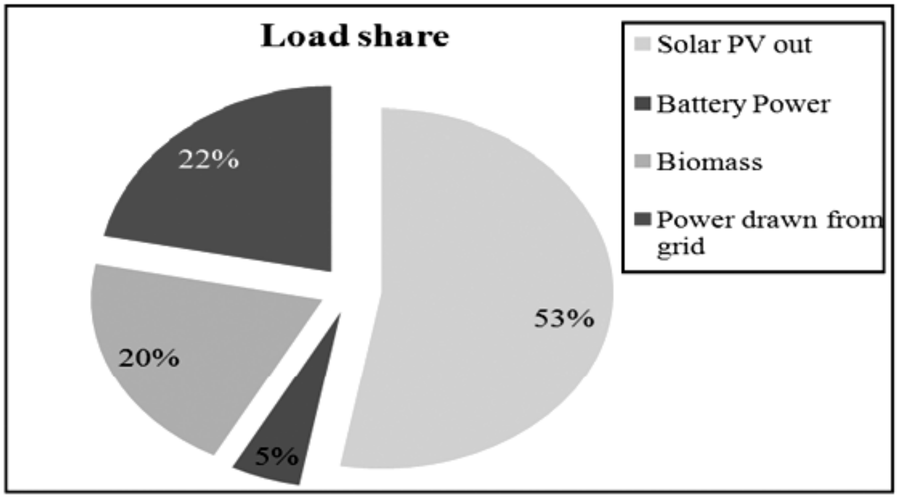

Figure 12: Load Shared by solar PV, Battery and Grid

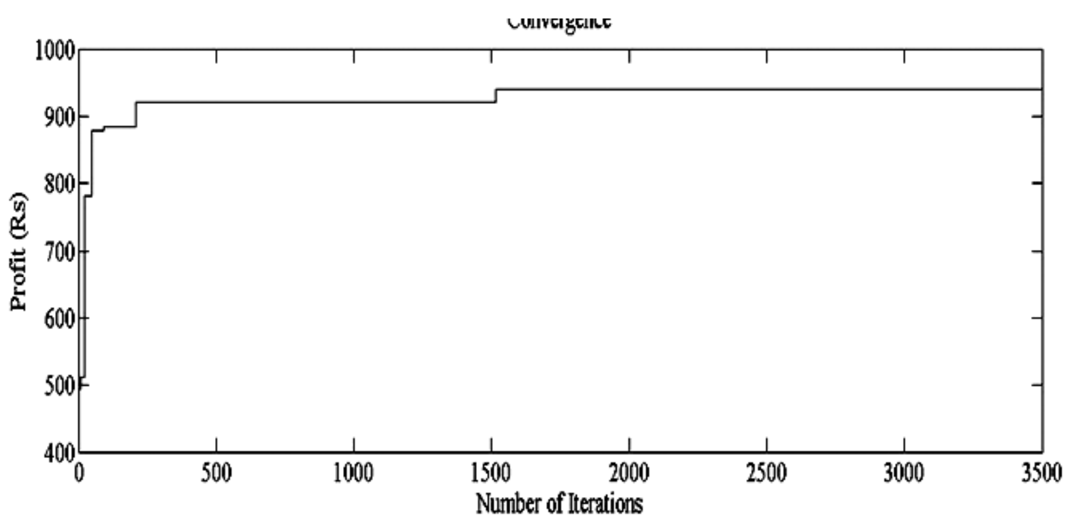

Figure 13: Final Convergence of objective function with biomass gasifier

5. CONCLUSION

Thus the paper proposed a way towards giving right to people to manage their energy utilization as per their comfort and will by taking part in energy market. The concept of microgrid Central Controller provides aggregated residential load demand to the utility company that is optimized with HPSO. It enables to provide maximum profit to the customers in day to day energy exchange with the grid. Customers are having installed rooftop solar panel, biomass gasifier and battery connected to microgrid.

The present case study has involved preparation of schedule of the load demand of the residents of a village. Profit is calculated with general tariff rate based on Time of Use type strategic values, if Power purchase agreement is done with the utility company, more profit can be obtained.

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