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A Sustainable Business Framework Using Solar and Bio-Energy to Instate Incessant Power in Rural India: Optimal Scheduling, Smart Metering, and Economic Viability

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ABSTRACT In this paper, a profitable strategy of utilizing solar and bio-energy available in a rural location for meeting the energy deficit is discussed. The proposed model can provide 24-hour continual power supply to the vicinity without the need for any battery. The land requirement is minimal in the proposed model making it cost-effective for implementation. The paper provides a step by step procedure to optimally size the solar and bio-power plants and schedule their operation for maximum utility. A programmable smart meter connected with a central system having a user-friendly control algorithm has also been proposed at every home for end-user profitability. The smart meter will indicate energy consumption in local home, its solar energy generation, vicinity power demand, current tariff of power usage, energy imported/exported and other required details. The proposed model is discussed in detail for comprising of two adjacent villages named Gaddikheri and Tajamajra in Rohtak (Haryana), North India (having 768 houses). The technical and financial analysis at this location is done using RETScreen expert software and the results are presented. The system is found to provide 24-hr power supply and also be profitable with the capital cost being recovered in less than 8 years time. Apart from this, the proposed system also provides other benefits like reduction in greenhouse gas emission (by 93%), auto power theft control, bio-fertilizers, and a clean environment.

INDEX TERMS Solar PV, biogas generator, green energy sources, renewable energy generation, smart grid, smart meter, smart home, energy management and scheduling, sustainable development, rural electrification, RETScreen expert.

I. INTRODUCTION

A. MOTIVATION AND PROBLEM DESCRIPTION

With an upsurge in energy demand the reliquiae fuels are diminishing day by day and hence the contemporary conventional sources like thermal are not ample enough to support the grid. Fossil fuels are also the predominant cause of greenhouse gas (GHG) emissions that vitiate the quality of life on this planet. Hence, it has necessitated shifting to renewable sources of energy to solve both these problems simultaneously. The renewable sources are sustainable if they are generated and utilized locally, which results in a microgrid/smart grid. To decrease/stop the people from immigrating to urban cities (due to lack of amenities, primarily due to intermittent/no power), the need for a microgrid in rural is more essential. This microgrid notion also aids better agricultural activities, which is the backbone of a country like India. In rural areas, the abundantly accessible renewable source is biogas(can be easily obtained through crop waste, animal husbandry). If power generation is done through biomass, it offers other benefits also like bio-fertilizers, clean waste disposal, biogas for domestic usage etc..

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B. LITERATURE REVIEW

[2]–[15], [17]–[20], [22], [25], [40], [46] have stated to use biogas for power generation but that is either used as peak power generation or as base power generation until the gas is fully utilised. Some of them used battery as backup power, which becomes expensive; while others don't have

any plan for backup power. Some authors have shown that it is more economical if solar and/or wind is used in combination with biogas to form the micro-grid [3], [5], [7], [10]–[12], [14]–[16], [18], [20], [23], [46]; depending on the location type it is suitable to use wind, solar, biogas for power generation but what if the stored battery power is consumed, grid is not available for much time. Also, most of these microgrids require separate locations for both solar and biogas power plants, and this may increase the land need inciting added capital expense. Optimal sizing of the system with different renewable sources based on availability and demand using various multi-objective functions are shown in [1], [2], [5]–[7], [9], [10], [15], [16], [18], [19], [22], [47], [48], [50], [51] but there are no provisions for exigencies. A business model to some extent is developed in [4], [5], [9], [11], [17], [21]–[23], [25], [28], [34], [52] but they either include spot market rate, cost of equipment or capital cost but lacks the real time cost of equipment, interest rate, incentive. The proposed model has all the factors according to the current market rates including capital cost, land, incentive, equipment, current electricity rate, risk factor, GHG emissions. Also there are provisions of peak tariff rate as well as low tariff rate in the night. Even there are provisions to make it handy so that the customer have the choice to shed their loads when they are generating power at peak time and supply it to the grid so that they can take economic benefit. After sizing the plant optimally, it is required to have forecast based strategy for scheduling the power in order to utilize it better. Authors in [3]–[6], [8], [19], [27], [28], [31], [32], [34], [53], [55]–[59], [68] have discussed different energy management strategies for various scenarios but they lack the emergency situations tackling process. Some authors have used smart meters [1], [26]–[29], [31]–[36], [53]–[55], [60]–[67] in which role of smart meter is to watch the energy export/import and consumption monitoring but the proposed model smart meter will act as controlling device in houses which not only have energy export/import, consumption monitoring but also act smartly according to the vicinity generation and load allotted. Also it will inform the owner that by switching these appliances they will have extra savings.

C. CONTRIBUTIONS

This paper offers the following contributions:

- A step by step methodology is developed to accomplish 24-hour electricity with emergency back-up using solar and bio-energy available in a region. For easy understanding, the proposed system is implemented in two adjacent villages named Gaddikheri and Tajamajra in Rohtak (Haryana) of North India and the details are presented.
- The method uses rooftop solar and proposes a biogas plant the sizing of which is done based on the location availability and requirements.
- The proposed system does not require battery or any other form of storage. Hence, the capital cost is curtailed.
- Depending on the grid availability and the load profile, strategy of energy scheduling in different parts of a day and different seasons of a year are proposed.
- Based on the actual market rates, the calculation of capital cost and interest rate for implementing a profitable system is proposed.
- A programmable smart meter is proposed to provide an optimal load management with price benefits to the consumer end. The profitability of the model is projected based on the tariff calculations.
- The economic viability of the entire system is concluded using RETScreen Expert software, and the results are presented.
- Apart from providing a consistent power supply, the proposed model will also provide benefits like bio-fertilizers for farms a clean and green village, low GHG emissions, extra income for farmers.

D. ARTICLE ORGANISATION

Section I introduces the work, the location and its attributes are provided in Section II. Section III gives a brief description of solar and bio-energy generation schemes, Section IV gives complete details of the proposed business model including the financial aspects. Section V talks about the other possible benefits of the proposed model and Section VI concludes the work.

II. PROPOSED RESEARCH METHODOLOGY

The flowchart of the proposed methodology is given in Fig. 1. As seen, the proposed strategy involves six steps for designing a micro grid at any given location. First step is the collection of data including the grid availability, load profile, energy deficit, Government incentives, climatic data etc. at the location. Second step involves the calculation of the solar and bio-energy potential in the region based on average irradiance and bio-waste respectively available in the location across different seasons of an year. Third step is the optimal sizing of rooftop-solar and bio-energy to cater for the location during off-grid periods. Energy is supplied from roof-top solar to the extent possible and rest of the requirement is met using bio-energy. Fourth step is to schedule the grid, solar, and bio-power plants optimally to provide 24-hour supply in all the months of an year. This also includes a provision for emergency backup using biogas. Fifth step is the programming of a smart meter installed at every house to achieve the optimal load management and to maximize the profitability at the consumer end. Sixth step is the financial analysis of the proposed system to check the profitability of the microgrid. This is done with real-time input costs of land, raw materials, rate of interest, transport cost, etc. of the location to get a realistic picture. All these steps have been implemented and explained in detail for a location of North India as given in subsequent sections.

III. LOCATION AND ITS ATTRIBUTES

Gaddikheri and Tajamajra are two adjoining villages located in Rohtak district, Haryana. They have 664 hectares of the

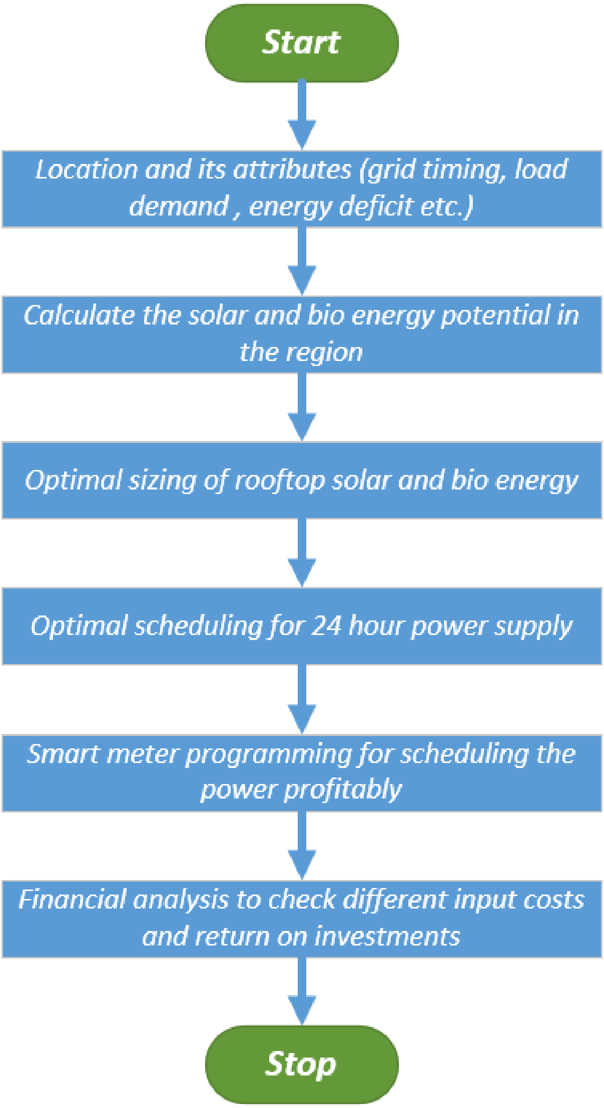


FIGURE 1. The Proposed methodological framework for sustainable micro-grid design at a given location.

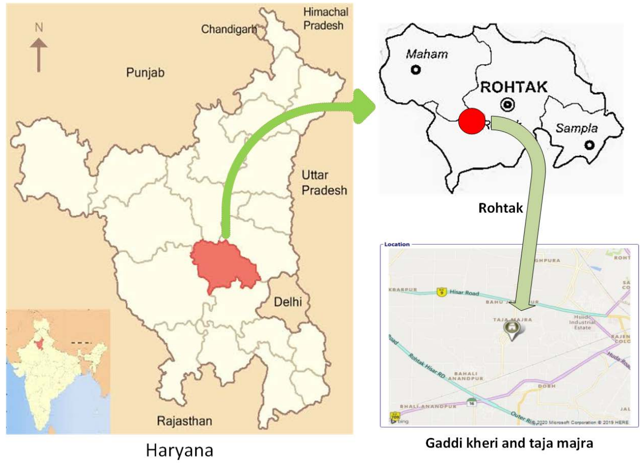


FIGURE 2. Location details of the proposed model.

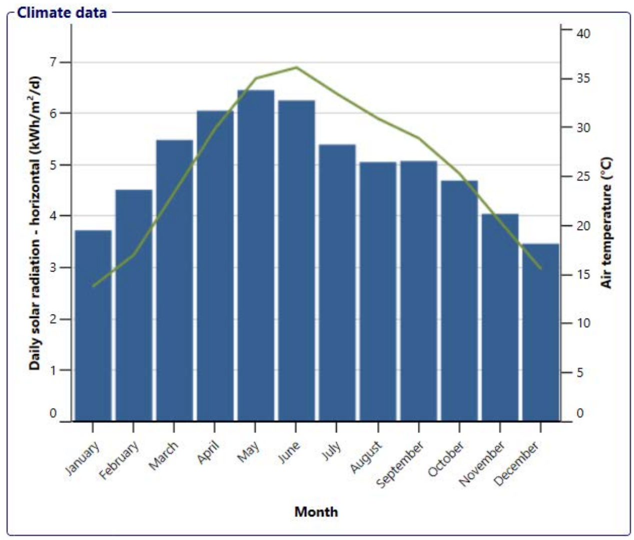


FIGURE 3. Monthly solar irradiance (kWh/m^2/d) and temperature (° C) of the proposed location.

tract, which is equal to 1640 acres. They have 768 independent houses (including a local hospital), one senior secondary government school and overall inhabitants of 3997 as per population census of 2011. It also has HSIIDC (Haryana State Industrial and Infrastructure Development Corporation Ltd.) industrial area within a 2 km radius. The villages have nearly 2868 faunae (cows and buffaloes). The topographical location is given in Fig. 2. The average annual temperature of the area is 25.8° Celcius (Fig. 3), whereas the average annual rainfall is 603.23 mm. As given in Table 1.

A. TYPICAL VILLAGE LOADS

The different types of loads used in the homes are listed in Table 2. These have been categorized based on usage like round the clock, continual, seasonal etc. and hence the load demand varies at different times of the day and with seasons. These loads have to be met based on power availability, user demand, and spot rate (based on peak/off-peak period).

B. GRID POWER AVAILABILITY

As per Haryana Govt. policy, the villages are supplied with grid power for a total of 16 hrs from 1900 to 0700 (12 hours) and 4 hours in rotating schedule (9 am to 1 pm or 1 pm to 5 pm) as shown in Fig. 4. There is no power for the remaining 8 hr duration. During this period, power has to be supplied through the available renewable sources.

C. GOVT. INCENTIVES

The central and state govt. offers various incentives in the form of waived transmission and distribution charges, reactive power charges, tax and interest rate rebates, subsidies on installation costs etc. for renewable installations. The detailed description of these incentives is available in [69], [70].

TABLE 1. Climatic data (monthly air temperature, humidity, precipitation, solar radiation, atmospheric pressure, wind speed, earth temperature, heating degree days, cooling degree days) of the proposed location for plant; source:NASA.

	Unit	Climate data location	Facility location	Source
Latitude		28.9	28.9	
Longitude		76.6	76.5	
Climate zone		1B - Very hot - Dry		NASA
Elevation	m	227	225	NASA – Map
Heating design temperature	°C	6.9		NASA
Cooling design temperature	°C	36.0		NASA
Earth temperature amplitude	°C	23.2		NASA

Month	Air temperature	Relative humidity	Precipitation	Daily solar radiation - horizontal	Atmospheric pressure	Wind speed	Earth temperature	Heating degree-days 18 °C	Cooling degree-days 10 °C
	°C	%	mm	kWh/m²/d	kPa	m/s	°C	°C-d	°C-d
January	13.8	37.4%	14.26	3.72	99.0	2.9	13.2	130	118
February	17.0	35.1%	22.96	4.51	98.8	3.0	16.8	28	196
March	23.4	26.8%	11.47	5.48	98.4	3.2	23.7	0	415
April	29.9	19.0%	10.80	6.05	98.0	3.3	31.1	0	597
May	35.0	19.2%	25.42	6.45	97.6	3.7	36.8	0	775
June	36.1	31.8%	69.30	6.25	97.2	3.7	38.2	0	783
July	33.4	53.7%	147.87	5.39	97.2	3.4	34.8	0	725
August	30.9	65.7%	174.84	5.05	97.4	2.9	31.6	0	648
September	28.9	61.9%	103.80	5.07	97.8	2.6	29.1	0	567
October	25.3	41.9%	12.40	4.69	98.4	2.3	24.8	0	474
November	20.4	32.8%	3.60	4.04	98.8	2.5	19.3	0	312
December	15.6	34.1%	6.51	3.46	99.0	2.7	14.6	74	174
Annual	**25.8**	**38.3%**	**603.23**	**5.01**	**98.1**	**3.0**	**26.2**	**233**	**5,784**
Source	NASA	NASA	NASA	NASA	NASA	NASA	NASA	NASA	NASA
Measured at					m	10	0		

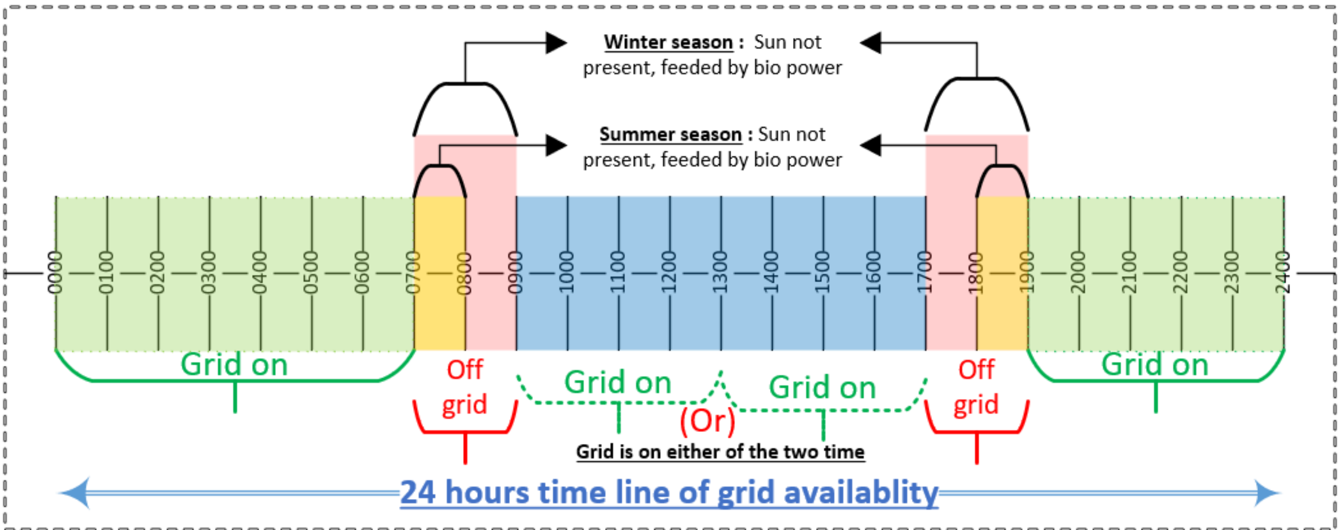


FIGURE 4. 24 hours timeline of power to be supplied in the village based on the grid timing schedule.

IV. CALCULATE THE SOLAR AND BIO ENERGY POTENTIAL IN THE REGION

From the description provided in Section III-B, the target villages have a power cut for 8 hrs in a day. The renewable sources are required to provide power in this period at least. The solar and bio availability in the region is calculated as below:

A. SOLAR AVAILABILITY

As shown in Table 1, the average daily solar irradiance in a year is 5.01 kWh/m^2/d. From the data, solar availability in the region can be divided into two categories; one where the solar is abundantly available called good solar days and the other where solar is sparsely available called sparse solar days.

1) Good solar days – (March to September) Irradiance is above 5 and the average irradiance is 5.67 kWh/m^2/d. Average temperature is 31° C. Sun is available from 0800 to 1800 hrs. There is ample solar power available for powering homes as well as for exporting to the grid/industries.
2) Sparse solar days - (October to February) Irradiance is below 5 kWh/m^2/d, and the average irradiance is 4.84 kWh/m^2/d. Sun is available from 0900 to 1700 hrs. Partial or full shading can occur due to the

TABLE 2. Typical loads used in the village.

Appliance	Wattage	Qty	Total load	Remarks
Refrigerator	150 W	1	150 W	Round the clock
LED bulb	15 W	4	60 W	Continual
Television	60 W	1	60 W	Continual
Fan	60 W	2	120 W	Seasonal
Room cooler	150 W	1	150 W	Seasonal
Juicer mixer	500 W	1	500 W	Intermittent
Washing machine	1000 W	1	1000 W	Intermittent
Water pump	800 W	1	800 W	Periodical
AC	1500 W	1	1500 W	Rarely Available

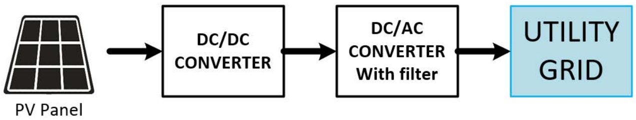


FIGURE 5. Typical solar power generation and supply to the grid through PV panel.

winter season. The average temperature is 18.42° C. The available power may not be sufficient for self-sustenance.

B. BIO AVAILABILITY

With the available 2868 animals(Average dung of cow and buffalo per day taken as 12 kg); total biogas production per day is estimated to be 1376 m^3(With about 60% methane (CH_4) content on average), which is equivalent of 7544.3 kWh of power. Assuming 35% efficiency in the generator, 2640.5 kWh of electricity can be produced per day. The detailed conversion process with relevant calculations is shown in the next section.

V. OPTIMAL SIZING OF ROOFTOP SOLAR AND BIO ENERGY

The solar/bio energy profile in the region indicates that neither of these can fulfil this requirement alone. Hence, a hybrid system with solar and bio is required to meet the requisites. A brief description of energy generation from solar and biogas is provided in this section.

A. SOLAR PHOTOVOLTAICS (PV)

The block diagram of power generation from solar PV is given in Fig. 5. It consists of PV panels, a dc/dc converter for voltage boosting and maximum power extraction, and a dc/ac converter with filter for grid connection. Battery is not included in the system. At night time when the solar power is unavailable, the system can be used for reactive power compensation. The output power of PV array is given by

$$P_{PV} = N \times V_{mpp} \times I_{mpp} \times \eta_1 \times \eta_2 \tag{1}$$

where P_{PV} is the power generated by PV array, N is the number of PV panel, V_{mpp} and I_{mpp} are the voltage and current at the maximum powerpoint, η_1 and η_2 are the efficiencies of both the converters respectively.

The output of a PV system varies with temperature and irradiance which can vary throughout the day. Hence, the power output is intermittent.

B. BIO POWER GENERATION

The biogas industry's major purpose is to reduce fossil fuel usage, thereby reducing global warming. Among the different possible biomass usage techniques, anaerobic digestion has a number of benefits, including the following:

- Biogas is a carbon-neutral energy source produced by anaerobic digestion.
- In comparison to aerobic processes, biomass sludge production is minimised. 10% of garbage is turned into mud, while 90% is converted into biogas.
- After digestion, the residue is nutrient-dense and may be used as fertiliser in agriculture.
- Energy recovery technologies that are more cost effective and less impactful on the environment than other biological processes.

However, anaerobic digestion produces greenhouse gases including CO_2, methane, and nitrous oxide. As a result, certain actions should be made to limit emissions. For example, using a flare that doesn't emit methane, covering tanks, improving the efficiency of combined heat and power (CHP) units, optimising the usage of electric power and maximising thermal energy are all ways to reduce greenhouse gas emissions. Electricity generation from anaerobic digestion is done in two stages as shown in Fig. 6. In stage 1, biogas is formed from the anaerobic digestion of animal manure, waste from agro-based farms and industry as well as slaughterhouses. The biogas power in stage 1, P_{gas} is given as

$$P_{gas} = T_f \times T_d \times T_g \tag{2}$$

where T_f is the total number of animals, T_d is the total dung per animal, T_g is the per kg dung to biogas equivalent (0.04). High calorific biogas can be obtained either scrubbing it with Sodium Hydroxide (NaOH) or with activated carbon. Harmful components especially hydrogen sulfide (H_2S) must be removed before feeding biogas to the generator as it shortens engine life. This biogas is converted into electricity in stage 2. The electrical energy, E_{bio} generated in stage 2 is

$$E_{bio} = \frac{P_{gas} \times C_{vg} \times \eta}{C_{ve}} \tag{3}$$

where C_{ve} is the calorific value of electricity (860 kcal/kWh), C_{vg} is the calorific value of biogas (4713 kcal/m^3), and η is the thermal efficiency of the plant ($\approx$ 35%). From this, the bio-power plant size, P_{bio} is determined as

$$P_{bio} = \frac{E_{bio}}{T_H} \tag{4}$$

where T_H is total number of hours the plant is operated.

The average calorific value of biogas is about 21-23.5 MJ/m^3, which means that one m^3 of biogas equals to 0.5-0.6 liter diesel fuel or energy content correspond to 6 kWh. However, due to conversion losses, one m^3 of biogas can be converted only to around 1.7 kWh.

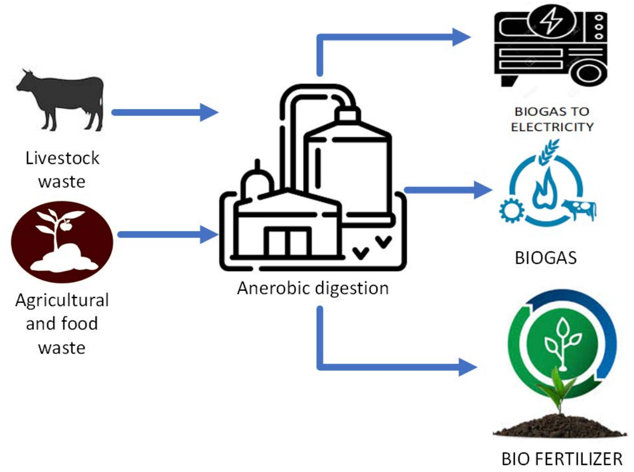


FIGURE 6. A biogas plant and its possible different outputs.

1) ENERGY REQUIREMENT FOR HEATING THE SLURRY

The energy required for heating the slurry in the digester can be calculated by using the formulae below.

$$Q_T = m * c * (T2 - T1) \tag{5}$$

Q_T = Energy required for heating the slurry in Kilo-joule(kJ)
m = mass of slurry in Kilo-gram(Kg).
c = specific heat of slurry in KJ/Kg°C.
T2 = desired temperature of slurry in °C.
T1 = current temperature of slurry in °C.

$$m = (V) * (\rho) \tag{6}$$

V = volume of the digester in m^3
ρ = density of slurry in Kg/m^3

$$\rho = \rho_1 + \rho_2 \tag{7}$$

ρ_1 = density of water = 1000 Kg/m^3; ρ_2 = density of cow dung = 0.13 Kg/m^3
equating in (2)

$$\rho = (1000 + 0.13) = 500\ Kg/m^3 \tag{8}$$

Specific heat of slurry=specific heat of water (4.2Kj/Kg°C) + specific heat of cow dung (2.8Kj/Kg°C)/2 = 3.5Kg/Kg°C

2) FAVOURABLE TEMPERATURE FOR METHANE GENERATION

The temperature of the digester determines the time period for which the biomass can be kept in a digester. Eg for two weeks (slurry/organic waste) holding period 50°C is needed while at 15°C, it can be held for two months. The average is around one month. To calculate the size of the digester, scale the amount of material kept in the digester per day and then multiply by 30. The range for anaerobic digestion is 0°C to 65°C. The microbial activity takes place in the optimum temperature range of 29°C to 35°C. Below 15°C, less gas is produced.

TABLE 3. Proposed power plant sizing of both solar and biogas.

Power plant		
Power system - total		
Capacity	1,851	kW
Electricity	3,381	MWh
Fuel consumption - total		
Biogas	1,75,419	m^3
Photovoltaic - 1.536 MW		
Capacity	1,536	kW
Electricity	2,554	MWh
biogas 315kw		
Capacity	315	kW
Electricity	828	MWh
Fuel type	Biogas	
Consumption	1,75,419	m^3

C. SYSTEM CONFIGURATION

The proposed system model is shown in Fig. 7. To meet the energy requirements in the villages, it is proposed to have a hybrid renewable energy plant involving solar and biogas. It is economical to have one large biogas power plant based on raw-material availability. Further, it is recommended to use roof top solar in every home since all the houses in these villages have unoccupied roofs. This waives the land cost and also provides many other benefits.

D. PROPOSED PLANT SIZING

Based on the topographical and demo-graphical data of the location, the plant sizing is done in a straightforward manner as follows:

- Taking the standard (Haryana) Govt. assigned load of 2 kW into account and the typical load of a village house as in Table 2 solar panels of 2 kW rating are proposed to be installed in every house. From 768 houses, the maximum output power would be 1.536 MW (2 kW*768).
- The bio-power plant sizing is done assuming that all the available raw-materials are used for generating power. From the available resources, an estimated maximum power of 2.64 MWh units per day is available. For continuous operation of 8 hours, the size of the bio power plant would be 0.315 MW (2.64 MWh/8H).

The considered plant size and the generated power information from each of the sources is presented in Table 3.

VI. OPTIMAL SCHEDULING FOR 24 HOUR POWER SUPPLY

The grid power supply is available for 16 hours in the villages with timings from 1900 to 0700 hrs. In the afternoon, it is available for 4 hours on a rotating basis as shown in Fig. 4. In order to supply the villages with power for 24 hours and to effectively utilize the plant, proper scheduling needs to be done. To meet the emergency requirements of the village

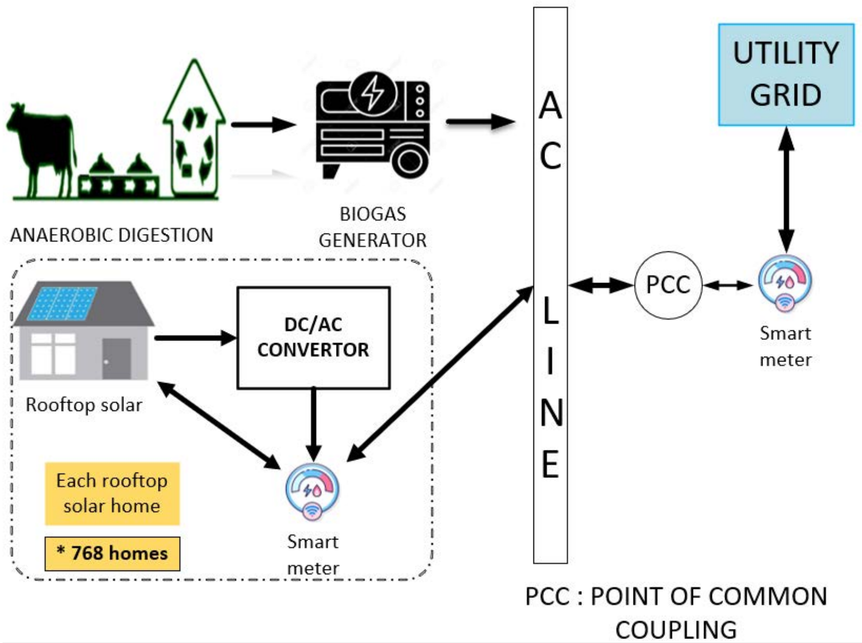


FIGURE 7. Proposed model (graphical view).

(like hospitals), it is proposed to permanently store the biogas required to supply the emergency loads for 24 hrs. This will act like storage and will be used only in emergency cases when no other source is available. Different operating modes are possible based on the availability of biogas, solar, and grid. For example, mode 1 denotes all three sources are absent (only emergency power is available) and mode 8 denotes all the sources are available. Similarly, other modes are obtained as shown in Table 4. Power scheduling is proposed based on all possible modes in a day as follows:

1) 1900-0700: During this timings, normally grid power is available. Solar power would be unavailable (night time). It is preferable to use the grid supply in this time as it will be cheaper (Mode 2). If biogas is available in excess, then only it will be used (Mode 6).
2) 0700-0800, 1800-1900 in Summer and 0700-0900, 1700-1900 in Winter: During these timings, neither grid nor solar is available. In this period, biogas power is fully utilized to supply all the houses with limited amounts until other sources become available (Mode 5). If biogas reserve is depleted till emergency levels, load shedding is done and only emergency loads are supplied (Mode 1).
3) 0800-1800 in Summer and 0900-1700 in Winter: In this period, solar is available. If grid is also available, excess solar and bio power if available (after supplying local loads) may be supplied to the grid/industries (Mode 4 and 8) whichever is profitable. If grid is unavailable, the solar and bio power after supplying the local loads is given to the nearby industries at the spot rate.
4) Biogas other than emergency needs to be completely used every 24 hrs to pave way for storing the gas generated in the subsequent day. Any other contingency will have to fall in any one of the above 8 modes of operation. Depending on the mode, decision may be taken.

The complete 24 hr operation as discussed is summarized in Table 5. Further, it is proposed to use smart meters in every home integrated with a centralized monitoring and control system for:

- Proper utilization of sources and loads in all 8 modes of operation.
- Calculation of power transferred to the grid and locally used by the consumer.
- Alerting the consumer about the current tariff, generation, and load position at every instant in their home as well as in their vicinity so that they can take a profitable decision.
- Allowing the consumer to know about their allocated quota of power during Mode 5.

The connection diagram of centralized monitoring and control system integrated with all the generation units and smart meters installed at every home is shown in Fig. 8. The next section shows the working of a smart meter in different source and load scenarios.

VII. SMART METER PROGRAMMING FOR SCHEDULING THE POWER PROFITABLY

Smart meters installed at every house are connected to one main centralised monitoring and control located at a distinct location. The respective communications will be either SCADA based/wireless depending on the equipment type. Real-time data collecting improves efficiency, lowers costs, and streamlines processes. With so many assets to manage, obtaining accurate data may be difficult. SCADA systems allow controllers obtain data and manage equipment.

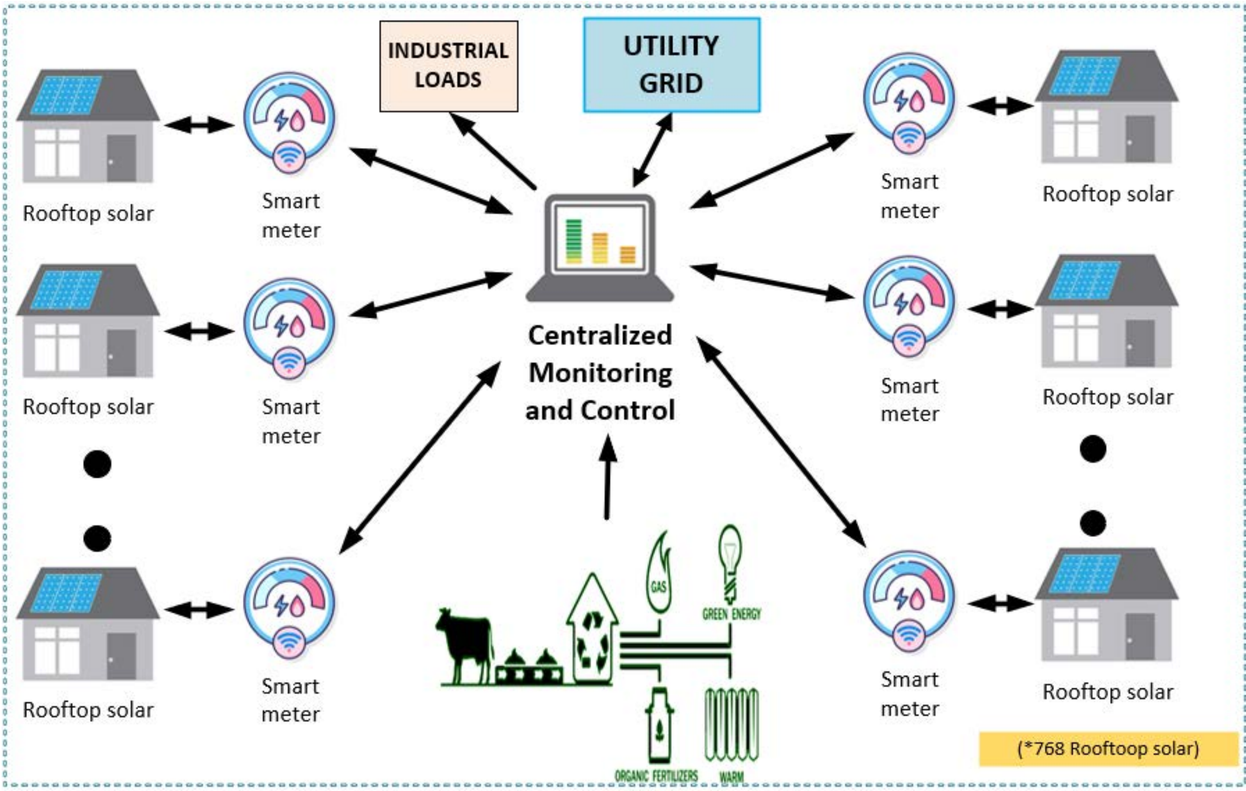


FIGURE 8. Integrated model of villages with centralized monitoring and control.

SCADA is a sophisticated control system for collecting, analysing, and visualising data from equipment. The home smart meters shows the actual load, demand, individual generation and tariff to the consumer on its application of smart phones so that individual can take further actions on load shedding on individual basis. All the performances of the individual smart meters and individual housing loads can be monitored and controlled; necessary instructions to be sent to the connected individual. The central controller connected to these units are required to perform the following operations

- Exchange the power availability and load data with the consumer and central controller.
- In mode 5, with off-grid and no solar available, power has to be supplied through biogas only. Of the available 2640 kWh of bio-energy, about 240 kWh is kept for emergency loads, so that it can run the 10 kW hospital load in the vicinity for at least 24 hours. The remaining 2400 kWh of energy need to be delivered for at-least 4 hrs (in winter). 2400 kWh of energy is conservatively distributed to supply for ≈7.6 hrs so that it can also help in contingencies if any. If no contingency occurs, the excess power will be delivered to the grid at other times. During this period 2400 kWh/7.6 = 315 KW of power is available. If this is divided evenly among the houses considering a realistic 85% loading of the bio-generator, each house would get a quota of Pquota, P_q = 350 W. The flowchart of operation is shown in Fig. 9. If any house needs more power, the smart meter through the central controller will fetch this power from other houses having lower utilization of their P_q. If no extra power is available, load shedding of the particular house is done by the integrated smart meter after alerting the consumer.
- In other modes of operation, smart meter chooses the appropriate option to maintain the supply-load equilibrium giving preference to the default option selected by the consumer and/or making profits to the consumer. The flow-chart for the same is given in Fig. 10.
- The operation of the central controller in various modes is presented in Fig. 11. The figure is self-explanatory and uses the flow-charts shown in Fig. 9 and 10 for operating in different modes.

A. SMART HOME

Home automation/Domotics is the connection of home appliances over network (LAN/Wi-fi) for remote accessing, controlling, management and interconnection of devices. Different sensors are used.

1) Temperature sensor: to measure the temperature inside and outside of a home. Depending on the required temperature, smart meter sends signal to device for increasing or decreasing cooling/ heating.
2) Environment sensor: for detecting inactivity of an electrical appliance.
3) Lighting sensor: to switch on/off lights based on ambient light.

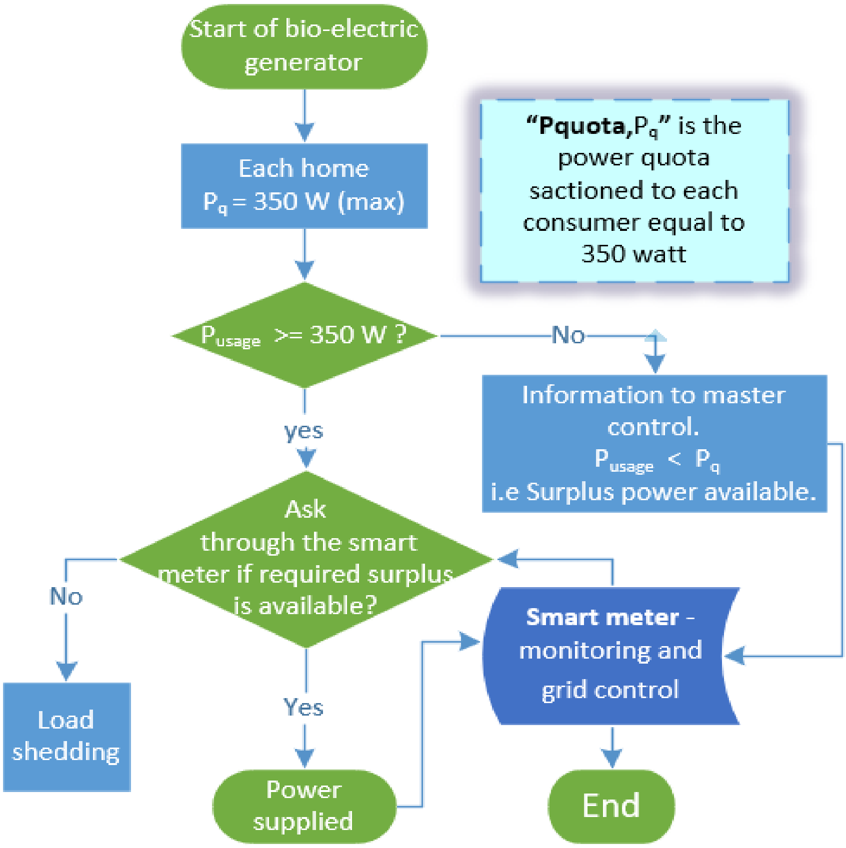


FIGURE 9. Flowchart of bio electric generator usage in mode 5 by smart meter connected to central controller.

These sensors collect utilization data, device usage time, energy consumption of different devices and sends to smart meter which in-turn sends it to the consumer. A smart plug is installed for old appliances so as to connect to the smart home as well as getting and transmitting usage, energy consumed to the user for real time control. As loads are distinguished on the basis of their frequency of usability as in Table 2 then saving of power and hence lowering the energy demand. Time-Tariff specific scheduling can be done to shift the load from peak to off peak time. In night time, when the demand/cost of electricity is low, loads like washing machines, electric vehicle charging can be scheduled in a smart home.

VIII. FINANCIAL ANALYSIS TO CHECK DIFFERENT INPUT COSTS AND RETURN ON INVESTMENTS

RETScreen Expert software is managed under the CanmetENERGY Varennes Research Centre of Natural Resources Canada, a department of the Government of Canada. The team has technical support from principal partners including NASA's Langley Research Center and others. The financial analysis of the proposed model is done using this software.

The power-plant is designed in RETscreen expert by keeping constraints like energy production cost, fuel cost of biogas, different solar PV module available, inverters, operating time, power-plant of 1.536 MW solar rooftop is designed and similarly a 315 kW biogas power-plant is designed keeping all the constraints in mind. Currency units are taken in canadian dollar (CAD). The calculated capital and running costs of the different units are provided first and then are the plant economic details.

1) SOLAR ENERGY SYSTEM CAPITAL & MAINTENANCE COSTS

- Capital cost as per Haryana govt. in rooftop installation is 739.65536 CAD (1 Canadian Dollar ≈0.75 US Dollar) per kW but it has been considered as 1233 CAD per kW (to include the cost of smart meters and other equipment). Operational and maintenance cost is considered as 33 CAD/kW per year. Solar panel different parameters are given in Table 6. The plant is of fixed type inclined at 29° according to the location. The panels taken are 19% efficient. Different factors like efficiency, losses, different cost, export rate, converter size are all taken into consideration while designing the plant as depicted in Table 6.
- The roofs of the village houses are considered as space for installation. If per house 2 kW solar installation(*768 houses) is considered then total plant size would be 1.536 MW.

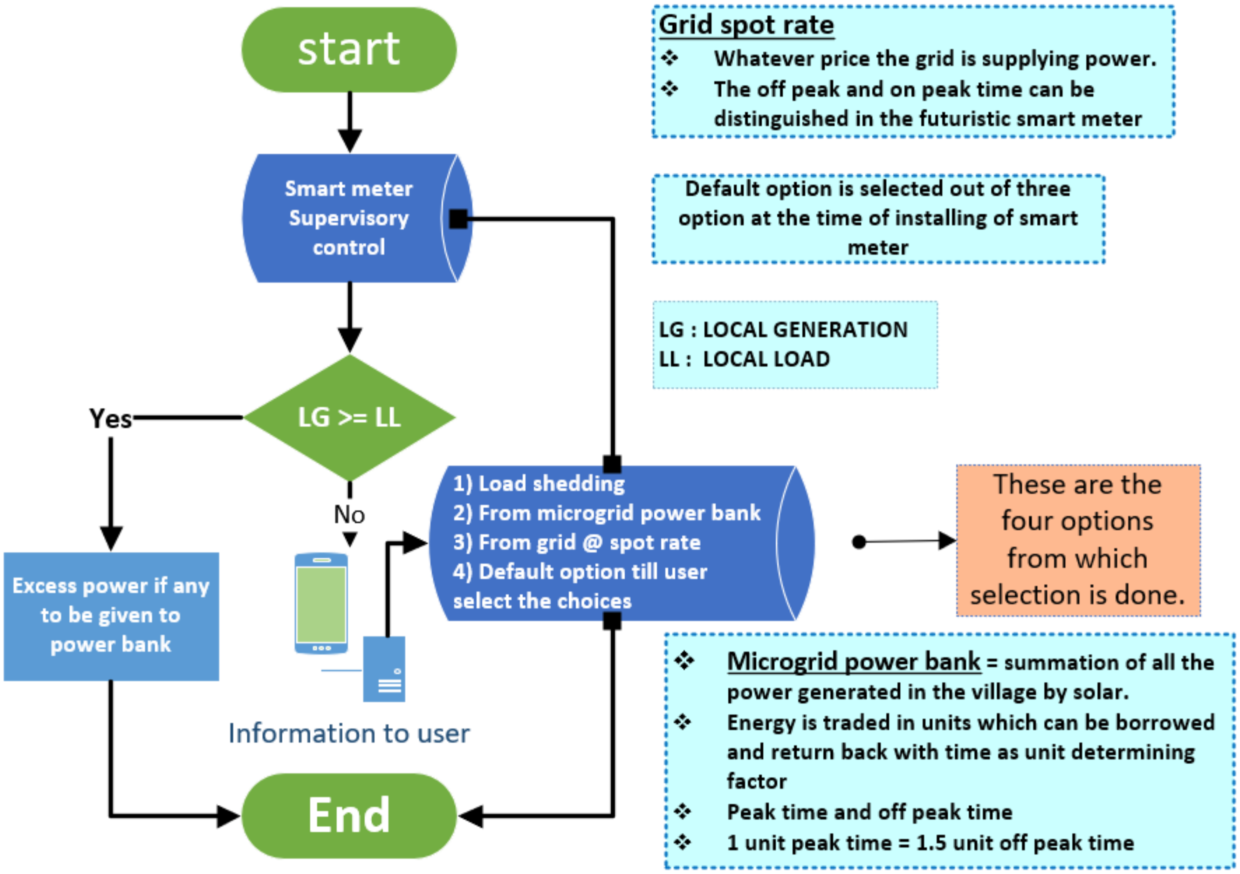


FIGURE 10. Flowchart of smart meter operation and its tie-up with the load scheduling and optimisation.

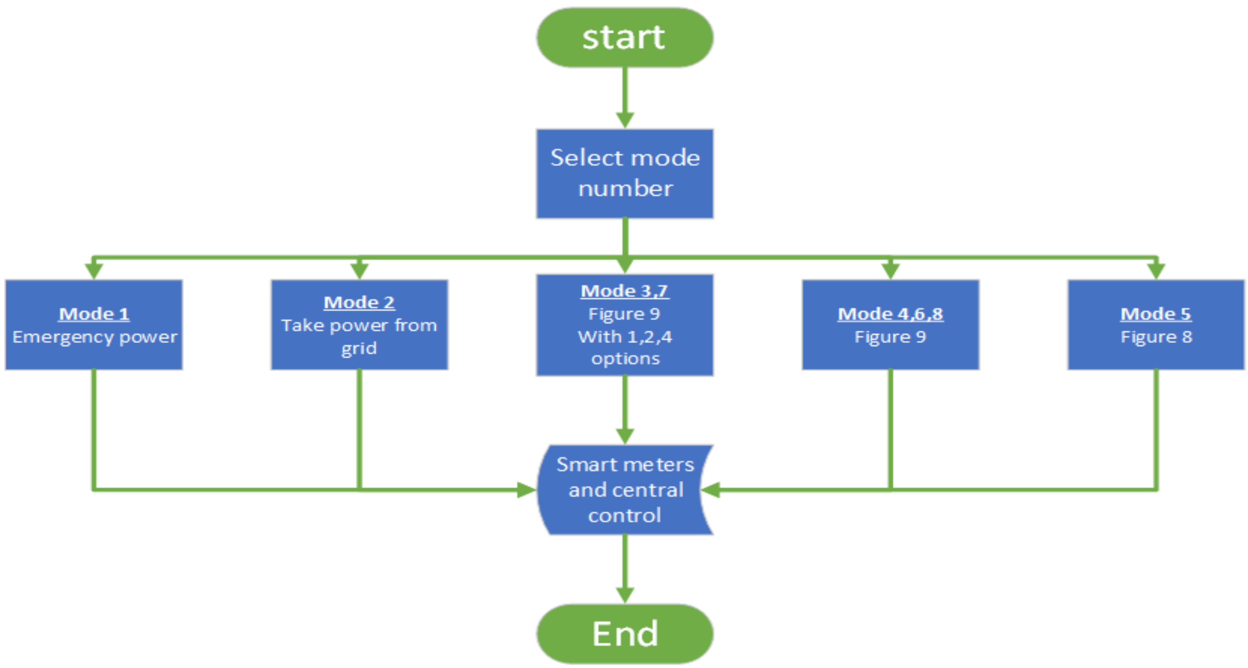


FIGURE 11. Central monitoring and control flowchart(refer table 4 for modes).

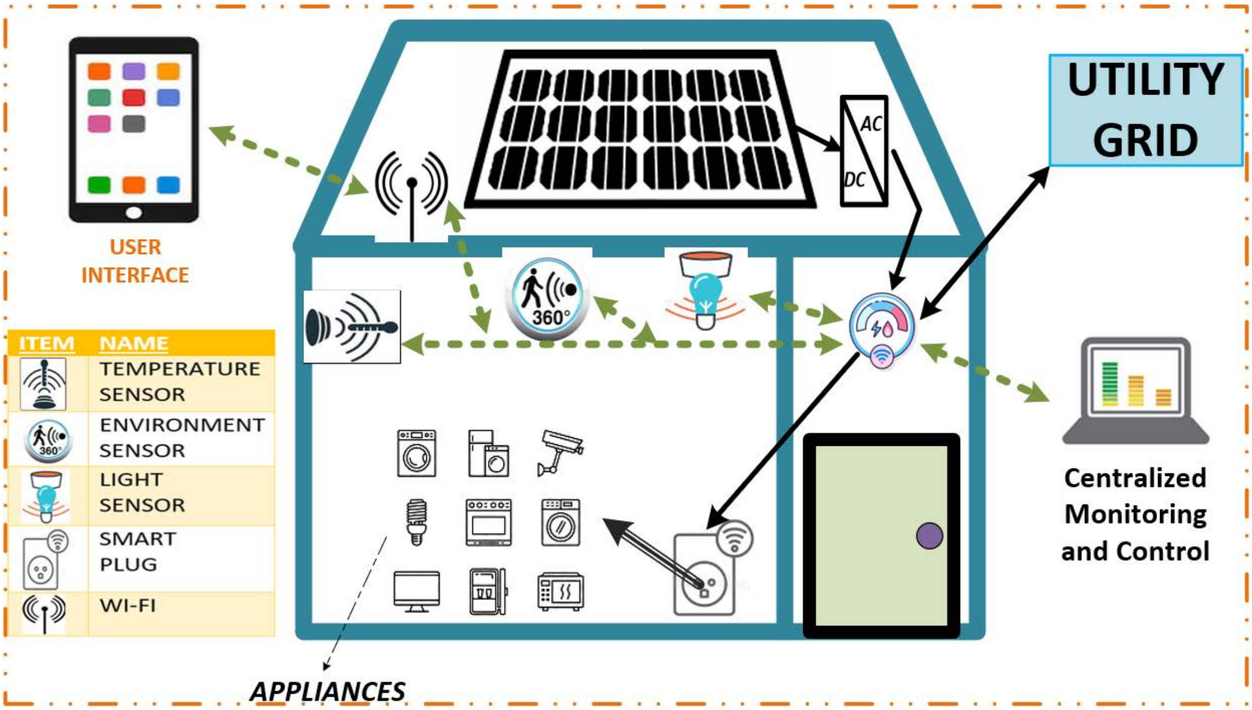
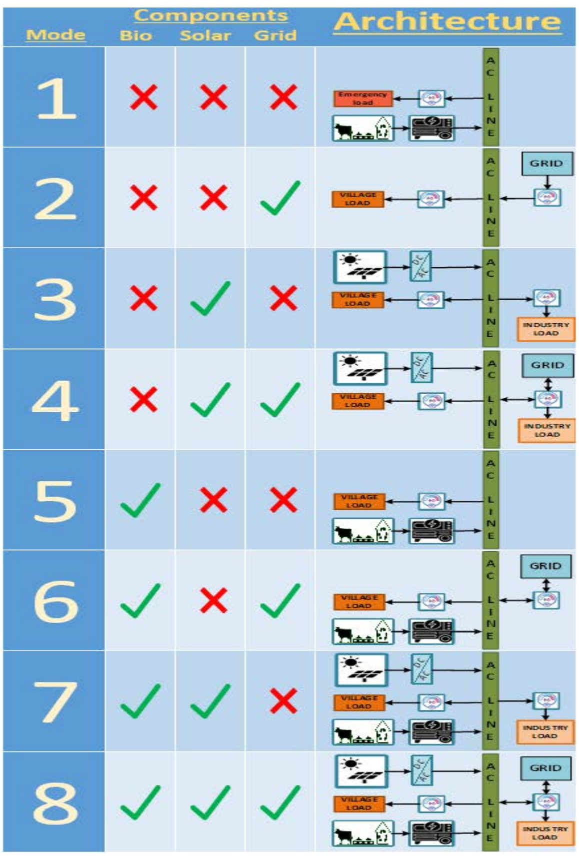


FIGURE 12. Proposed Smart Home for optimal resources utilisation.

TABLE 4. Different modes of operation of proposed model.



Mode	Components: Bio	Components: Solar	Components: Grid	Architecture
1	✗	✗	✗	Emergency load; AC LINE
2	✗	✗	✓	VILLAGE LOAD; AC LINE; GRID
3	✗	✓	✗	VILLAGE LOAD; AC LINE; INDUSTRY LOAD
4	✗	✓	✓	VILLAGE LOAD; AC LINE; GRID; INDUSTRY LOAD
5	✓	✗	✗	VILLAGE LOAD; AC LINE
6	✓	✗	✓	VILLAGE LOAD; AC LINE; GRID
7	✓	✓	✗	VILLAGE LOAD; AC LINE; INDUSTRY LOAD
8	✓	✓	✓	VILLAGE LOAD; AC LINE; GRID; INDUSTRY LOAD

TABLE 5. Proposed scheme for 24 hours uninterrupted operation.

No	Timings	Mode used	Comments
1	1900-0700 (all days) **Grid available**	2nd	Electricity would be cheaper at night. The future is of the time-specific tariffs (off and on-peak).
		6th	Load can be fulfilled by grid and biogas plant. If the sufficient load is not there that power can be supplied back to grid.(rarely happens)
2	0700-0800 & 1800-1900 <u>*Summer*</u> 0700-0900 & 1700-1900 <u>*Winter*</u> **Grid and Solar not available**	5th	Biogas produced can be used to run the 315-kW bio-electric powerplant with each home (total 768 homes) capable of running 350 WPH. (***ECONOMICAL MODE)***
		1st	If any unavoidable circumstances occur, then **EMERGENCY MODE** can be used.
3	0800-1800 <u>*Good Solar*</u> 0900-1700 <u>*Sparse Solar*</u> **Grid and Solar available**	4th	Rooftop solar power is consumed in the homes after that remnant can be supplied to the grid from net-metered smart meter.
		8th	There is not ample space to store biogas, then bio-electricity is also supplied to the grid.
4	0800-1800 <u>*Good Solar*</u> 0900-1700 <u>*Sparse Solar*</u> **Grid not available**	3rd	The village load is sufficient enough to consume the power of the solar power generated wholly. ***(SELF-SUFFICIENT VILLAGE)*** or else if remaining power is there that can be supplied to the industry at the spot rate.
		7th	Firstly, the village load is met up and if extra power is available that can be supplied to the industry at the spot rate or biogas is stored.

- Plant life is taken as 20 years. The govt. provides subsidy of 30%, which is, however, not considered to cater for other costs if any such as cost of slurry tanks, collector trucks for biowaste, fetilizer trucks to transport organic fertilizers.

TABLE 6. PV system parameters used for simulation of model.

Resource assessment		
Solar tracking mode		Fixed
Slope	°	29
Azimuth	°	0
Show data		
Photovoltaic		
Type		mono-Si
Power capacity	MW	1.5361
Manufacturer		Vikramsolar
Model		mono-Si - 60-SOM Prime-1500V - 310W
Number of units		4,955
Efficiency	%	19%
Nominal operating cell temperature	°C	45
Temperature coefficient	% / °C	0.4%
Solar collector area	m²	8,084
Miscellaneous losses	%	5%
Inverter		
Efficiency	%	97%
Capacity	kW	1,536
Miscellaneous losses	%	1%
Summary		
Capacity factor	%	19%
Initial costs	$/kW	1,200
	$	18,43,260
O&M costs (savings)	$/kW-year	33
	$	50,690
Electricity export rate		Electricity export rate - monthly
	$/kWh	0.11
Electricity exported to grid	MWh	2,554
Electricity export revenue	$	2,81,040

TABLE 7. Biogas generator system parameters.

Other - Single fuel			
Fuel selection			
Fuel type		Biogas - m³	
Fuel rate	$/m³	0.10	
Other			
Power capacity	kW	315	
Availability	%	30%	2,628 h
Manufacturer		Stirling	
Model		SD4 gasification	
Number of units			
Heat rate	kJ/kWh	3,560	
Fuel required	kW	312	
Initial costs	$/kW	1,629	
	$	5,13,135	
O&M costs (savings)	$/kW-year	91.96	
	$	28,967	
Fuel consumption	m³	1,75,419	
Fuel cost	$	17,542	
Electricity export rate		Electricity export rate - monthly	
	$/kWh	0.11	
Electricity exported to grid	MWh	828	
Electricity export revenue	$	91,106	

2) BIO ENERGY SYSTEM CAPITAL & MAINTENANCE COSTS

- Plant is setup according to the Haryana govt. rates and the size of plant is 315 kW according to the calculations done. The biogas to electricity plant parameters taken is shown in Table 7. In a financial year, out of 8760 hrs it is run for 2628 hrs (nearly 30%) as discussed.

TABLE 8. Economics of power-plant i.e factors like initial cost, annual cost, saving, revenue generated and net yearly cashflow.

Costs | Savings | Revenue			
Initial costs			
Initial cost	100%	$	23,56,395
Total initial costs	**100%**	**$**	**23,56,395**
Yearly cash flows - Year 1			
Annual costs and debt payments			
O&M costs (savings)		$	79,657
Fuel cost - proposed case		$	8,771
Debt payments - 15 yrs		$	2,23,464
Total annual costs		**$**	**3,11,892**
Annual savings and revenue			
Electricity export revenue		$	3,74,925
GHG reduction revenue		$	0
Other revenue (cost)		$	0
CE production revenue		$	0
Total annual savings and revenue		**$**	**3,74,925**
Net yearly cash flow - Year 1		**$**	**63,033**

The different parameters like power capacity, bio-fuel required, biogas consumption, other costs are all taken into consideration while designing the model. Expected power from bio energy decreases by 50-75% in winter (November-February). This is also included in the estimation.

- Capital cost is calculated as 1626728.78 CAD per MW, whereas operational and maintenance cost is 97309.96 CAD per MW per year.
- Plant life is taken as 20 years. The Haryana govt provides a subsidy of 40% for the biogas electric plant, which is, however, not considered to cater for any other costs like construction of transmission lines to the nearby industries, purchase of slurry and biowaste collector trucks.
- The running cost of biogas plant will also include the collection of biowaste from homes, manpower required and their collection in the biogas plant. However, plants side product is biofertilizer, organic manure which can lumpsum the amount of collecting that to biogas plant. e.g trucks, manpower used for collecting biowaste can be again used to sell the bio manure and fertilizer and it is much costlier than the cost of collecting that. However, these things are ignored on account of profit earned by whole system.

3) PLANT ECONOMICS

- The plant size is given in Table 3 with overall capacity of 1.851 MW having solar and biogas generation.
- The economics of the power-plant with revenues, debts, export rate, yearly cash flow is given in Table 8 whereas the cumulative cash flow is given in Fig. 13. All the costs are in CAD. Different risk impacts like debt ratio, debt term, maintenance charges, fuel (biogas) cost are shown in Fig. 14. As shown, the business is profitable because the electricity export rate (income) is greater than the input costs.

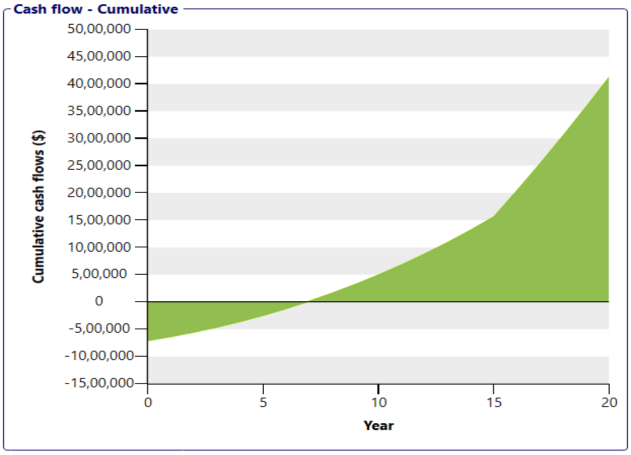


FIGURE 13. Cumulative cash flow of the proposed model.

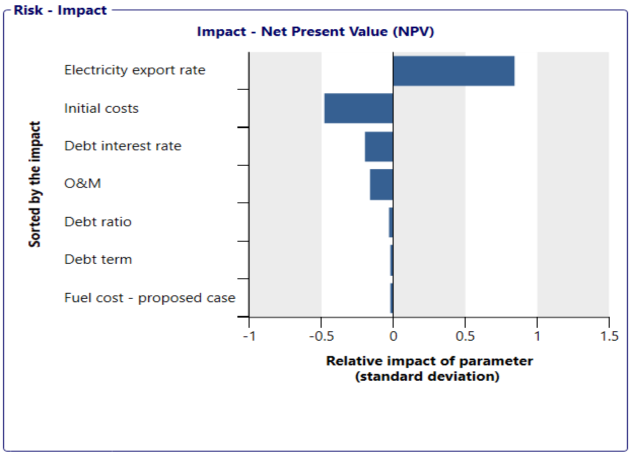


FIGURE 14. Risk impact of the plant.

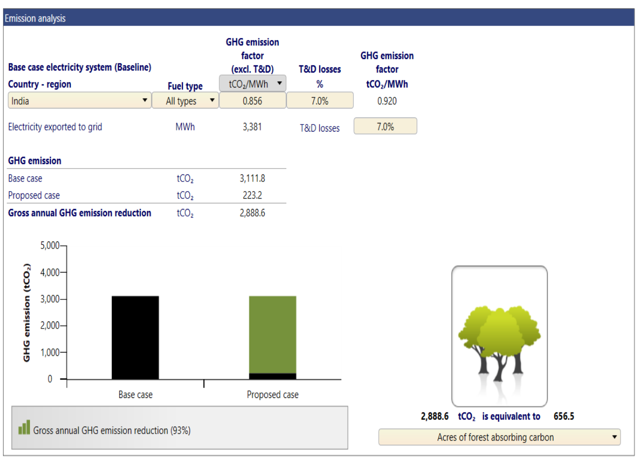


FIGURE 15. GHG reduction using proposed model.

IX. OTHER BENEFITS OF THE PROPOSED MODEL

Apart from offering a profitable business model, the proposed system also offers innumerable other benefits like

- Reduction in greenhouse gases by up to 93%, as shown in Fig. 15.
- Power theft is mitigated since the consumer is the supplier for solar power and can earn money out of it. Also, the smart meter connected to the centralized unit can detect this easily by comparing the supply and load data obtained from the meters.
- Since the generation and distribution are in the same location, the line losses in the system are minimal.
- The slurry produced from the biogas digester is an excellent food for the fisheries as well as it can be used as biofertilizer in farms leading to organic farming.
- Promotes cleanliness by utilizing the daily waste and converting it to power.
- There is no chemical waste since batteries are not used.

X. CONCLUSION

This paper proposed a six step strategy for providing 24-hour power supply by installing and scheduling a solar and bio energy-based renewable power plant at a given location. The proposed strategy has been implemented for two villages, Gaddikheri, and Tajamajra in North-India. The current data of grid, solar, and bioenergy available in the location is used, and a model with minimum plant size/investment is proposed. It is proposed to use the rooftops of individual houses for solar plant installation, thereby saving land and its cost. The land can be taken having an agreement with the rooftop holder either on profit sharing or rent or lease basis. Also, it is proposed to have a single biogas generation plant for the two villages. The power generation through various sources (grid, solar, bio) are scheduled for all the 24 hrs according to the availability and user needs. All possible modes of operation are considered. An emergency backup is kept throughout in the form of biogas for delivering power to emergency loads in the villages for 24 hrs. A futuristic approach is employed using off-peak and on-peak spot rate differentiation. The impact on the generation in different seasons is also considered for making the schedules. This framework eliminated the need for other energy storage devices like batteries. Smart meter is proposed at every home, which is connected with the central controller. These regulate the power generated to various homes/industrial loads automatically for maximum profitable utilization. The smart meters are also connected with end-user smartphones for real-time data and provides them with the flexibility to check their usage and earn profits. A smart home can also be realized by using these smart meters for real-time control of appliances in every home according to consumer requirements. The financial feasibility of the proposed system is checked using RETScreen Expert software using realistic data from the location, technical data, and existing Govt. norms. The proposed system is not only beneficial from a business point of view but also for the society and environment by providing many other benefits. The wastage of the proposed model is also beneficial for providing biofertilizers for the fields. In this manner, the proposed framework can be extended to any other location for profitable generation, utilization, and distribution of electrical power using renewable sources.

REFERENCES

[1] R. Dias, J. C. Scaramutti, C. D. Arrojo, and H. A. Nastta, "Considerations on the role of smart meters in the incorporation of renewable energy sources through microgrids," in *Proc. IEEE Central Amer. Panama Conv. (CONCAPAN XXXIV)*, Nov. 2014, pp. 1–5, doi: 10.1109/CONCAPAN.2014.7000442.

[2] W. Gu, C. Li, and M. Gu, "Study on the wind/biogas integration system for power generation and gas supply," in *Proc. World Non-Grid-Connected Wind Power Energy Conf.*, Sep. 2009, pp. 1–4.

[3] L. Novosad and Z. Hradilek, "Combination of biogas station and photovoltaic power plant operation," in *Proc. 20th Int. Sci. Conf. Electr. Power Eng. (EPE)*, May 2019, pp. 1–6, doi: 10.1109/EPE.2019.8777954.

[4] Y. Cao, J. Wei, C. Li, B. Zhou, L. Huang, G. Feng, and H. Yang, "Optimal operating control strategy for biogas generation under electricity spot market," *J. Eng.*, vol. 2019, no. 18, pp. 5183–5186, Jul. 2019, doi: 10.1049/joe.2018.9311.

[5] J. D'Rozario, S. Shams, S. Rahman, A. Sharif, and E. Basher, "Cost effective solar-biogas hybrid power generation system," in *Proc. IEEE Int. Conf. Ind. Technol. (ICIT)*, Mar. 2015, pp. 2756–2760.

[6] A. Kumar, A. R. Singh, Y. Deng, X. He, P. Kumar, and R. C. Bansal, "Multiyear load growth based techno-financial evaluation of a microgrid for an academic institution," *IEEE Access*, vol. 6, pp. 37533–37555, 2018.

[7] C. S. Lai and M. D. McCulloch, "Sizing of stand-alone solar PV and storage system with anaerobic digestion biogas power plants," *IEEE Trans. Ind. Electron.*, vol. 64, no. 3, pp. 2112–2121, Mar. 2017.

[8] J. Jansa, Z. Hradilek, and P. Moldrik, "Energy supplied from biogas power station to the distribution network," in *Proc. 16th Int. Sci. Conf. Electr. Power Eng. (EPE)*, May 2015, pp. 575–578.

[9] M. A. Ehsan, C. K. Das, and M. Hasan, "Biogas based chain business: A road to sustainable rural development," in *Proc. 4th Int. Conf. Develop. Renew. Energy Technol. (ICDRET)*, Jan. 2016, pp. 1–5.

[10] P. Anand, M. Rizwan, and S. K. Bath, "Sizing of renewable energy based hybrid system for rural electrification using grey wolf optimisation approach," *IET Energy Syst. Integr.*, vol. 1, no. 3, pp. 158–172, Sep. 2019. Accessed: Oct. 5, 2020.

[11] C. S. Kwok, S. Krishnan, B. H. Tesfagergis, and H. Yao Hsu, "Feasibility study of using photovoltaic (PV), wind and biogas renewable energy system in South Australia household to maximize the energy production from renewable sources," in *Proc. Adv. Sci. Eng. Technol. Int. Conf. (ASET)*, Mar. 2019, pp. 1–5.

[12] A. Rajani, R. Darussalam, R. I. Pramana, and A. Santosa, "Simulation of PV—Biogas integration on hybrid power plant using HOMER: Study case of superior livestock breeding center and forage of animal feed (BBPTU—HPT) Baturraden," in *Proc. Int. Conf. Sustain. Energy Eng. Appl. (ICSEEA)*, Nov. 2018, pp. 69–74.

[13] Y. Manabe, R. Hara, H. Kita, K. Takitani, T. Tanabe, S. Ishikawa, and T. Oomura, "Cooperation of energy storage systems and biogas generator for stabilization of renewable energy power plants," in *Proc. IEEE PES ISGT Eur.*, Oct. 2013, pp. 1–5.

[14] K. Longyun, Z. Yanning, and C. Binggang, "Wind-solar-biogas renewable energy distributed power system," in *Proc. Int. Conf. Clean Electr. Power*, Jun. 2009, pp. 798–799.

[15] M. M. Tanim, N. A. Chowdhury, M. M. Rahman, and J. Ferdous, "Design of a photovoltaic-biogas hybrid power generation system for Bangladeshi remote area using Homer software," in *Proc. 3rd Int. Conf. Develop. Renew. Energy Technol. (ICDRET)*, May 2014, pp. 1–5.

[16] M. N. M. Nasir and J. Mutale, "Optimal sizing of solar FV/battery and biogas generator in remote microgrid," in *Proc. 51st Int. Univ. Power Eng. Conf. (UPEC)*, Sep. 2016, pp. 1–6.

[17] A. Gupta, R. P. Saini, and M. P. Sharma, "Design of an optimal hybrid energy system model for remote rural area power generation," in *Proc. Int. Conf. Electr. Eng.*, Apr. 2007, pp. 1–6.

[18] S. Arafa, "Renewable energy solutions for development of rural villages and desert communities," in *Proc. Int. Conf. Clean Electr. Power (ICCEP)*, Jun. 2011, pp. 451–454.

[19] X. Zhang, R. Sharma, and Y. He, "Optimal energy management of a rural microgrid system using multi-objective optimization," in *Proc. IEEE PES Innov. Smart Grid Technol. (ISGT)*, Jan. 2012, pp. 1–8.

[20] V. Imcharoenkul and S. Chaitusaney, "Optimal hybrid renewable energy system considering maximum profit from electricity sale," in *Proc. 16th Int. Conf. Electr. Eng./Electron., Comput., Telecommun. Inf. Technol. (ECTI-CON)*, Jul. 2019, pp. 305–308.

[21] N. S. Savic, V. A. Katic, N. A. Katic, B. Dumnic, D. Milicevic, and Z. Corba, "Techno-economic and environmental analysis of a microgrid concept in the university campus," in *Proc. Int. Symp. Ind. Electron. (INDEL)*, Nov. 2018, pp. 1–6.

[22] A. Gupta, R. P. Saini, and M. P. Sharma, "Modelling of hybrid energy system for off grid electrification of clusters of villages," in *Proc. Int. Conf. Power Electron., Drives Energy Syst.*, Dec. 2006, pp. 12–15.

[23] P. Anand, S. K. Bath, and M. Rizwan, "Design and development of stand-alone renewable energy based hybrid power system for remote base transceiver station," *Int. J. Comput. Appl.*, vol. 169, no. 6, pp. 34–41, Jul. 2017, doi: 10.5120/ijca2017914776.

[24] M. J. Loza-Lopez, E. N. Sanchez, and R. Ruiz-Cruz, "Microgrid laboratory prototype," in *Proc. Clemson Univ. Power Syst. Conf.*, Mar. 2014, pp. 1–5, doi: 10.1109/PSC.2014.6808120.

[25] A. Gupta, R. P. Saini, and M. P. Sharma, "Hybrid energy system for remote area—An action plan for cost effective power generation," in *Proc. IEEE Region 3rd Int. Conf. Ind. Inf. Syst.*, Dec. 2008, pp. 1–6, doi: 10.1109/ICIINFS.2008.4798396.

[26] A. S. Metering, S. Visalatchi, and K. K. Sandeep, "Smart energy metering and power theft control using arduino & GSM," in *Proc. 2nd Int. Conf. Converg. Technol. (I2CT)*, Apr. 2017, pp. 858–961, doi: 10.1109/I2CT.2017.8226251.

[27] G. R. Barai, S. Krishnan, and B. Venkatesh, "Smart metering and functionalities of smart meters in smart grid—A review," in *Proc. IEEE Electr. Power Energy Conf. (EPEC)*, Oct. 2015, pp. 138–145, doi: 10.1109/EPEC.2015.7379940.

[28] W. Luan, D. Sharp, and S. LaRoy, "Data traffic analysis of utility smart metering network," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Jul. 2013, pp. 1–4, doi: 10.1109/PESMG.2013.6672750.

[29] V. G. Vilas, A. Pujara, S. M. Bakre, and V. Muralidhara, "Implementation of metering practices in smart grid," in *Proc. Int. Conf. Smart Technol. Manage. Comput., Commun., Controls, Energy Mater. (ICSTM)*, May 2015, pp. 484–487, doi: 10.1109/ICSTM.2015.7225465.

[30] P. Kalkal and V. K. Garg, "Transition from conventional to modern grids: Modern grid include microgrid and smartgrid," in *Proc. 4th Int. Conf. Signal Process., Comput. Control (ISPCC)*, Sep. 2017, pp. 223–228, doi: 10.1109/ISPCC.2017.8269679.

[31] I. F. Siddiqui, S. U.-J. Lee, A. Abbas, and A. K. Bashir, "Optimizing lifespan and energy consumption by smart meters in green-cloud-based smart grids," *IEEE Access*, vol. 5, pp. 20934–20945, 2017, doi: 10.1109/ACCESS.2017.2752242.

[32] R. Morello, C. De Capua, G. Fulco, and S. C. Mukhopadhyay, "A smart power meter to monitor energy flow in smart grids: The role of advanced sensing and IoT in the electric grid of the future," *IEEE Sensors J.*, vol. 17, no. 23, pp. 7828–7837, Dec. 2017, doi: 10.1109/JSEN.2017.2760014.

[33] S. N. Islam, M. A. Mahmud, and A. M. T. Oo, "Relay aided smart meter to smart meter communication in a microgrid," in *Proc. IEEE Int. Conf. Smart Grid Commun. (SmartGridComm)*, Nov. 2016, pp. 128–133, doi: 10.1109/SmartGridComm.2016.7778750.

[34] E. J. Palacios-Garcia, E. Rodriguez-Diaz, A. Anvari-Moghaddam, M. Savaghebi, J. C. Vasquez, J. M. Guerrero, and A. Moreno-Munoz, "Using smart meters data for energy management operations and power quality monitoring in a microgrid," in *Proc. IEEE 26th Int. Symp. Ind. Electron. (ISIE)*, Jun. 2017, pp. 1725–1731, doi: 10.1109/ISIE.2017.8001508.

[35] M. Tasdighi, H. Ghasemi, and A. Rahimi-Kian, "Residential microgrid scheduling based on smart meters data and temperature dependent thermal load modeling," *IEEE Trans. Smart Grid*, vol. 5, no. 1, pp. 349–357, Jan. 2014, doi: 10.1109/TSG.2013.2261829.

[36] X. Zhang, L. Guo, H. Zhang, L. Guo, K. Feng, and J. Lin, "An energy scheduling strategy with priority within islanded microgrids," *IEEE Access*, vol. 7, pp. 135896–135908, 2019, doi: 10.1109/ACCESS.2019.2942399.

[37] B. Washom, J. Dilliot, D. Weil, J. Kleissl, N. Balac, W. Torre, and C. Richter, "Ivory tower of power: Microgrid implementation at the University of California, San Diego," *IEEE Power Energy Mag.*, vol. 11, no. 4, pp. 28–32, Jul. 2013, doi: 10.1109/MPE.2013.2258278.

[38] A. G. Skowronska-Kurec, S. T. Eick, and E. T. Kallio, "Demonstration of microgrid technology at a military installation," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Jul. 2012, pp. 1–2, doi: 10.1109/PESGM.2012.6344923.

[39] J. Sachs and O. Sawodny, "A two-stage model predictive control strategy for economic diesel-PV-battery island microgrid operation in rural areas," *IEEE Trans. Sustain. Energy*, vol. 7, no. 3, pp. 903–913, Jul. 2016, doi: 10.1109/TSTE.2015.2509031.

[40] M. Zhou and Z. Zou, "Design of an intelligent control system for rural biogas engineering," in *Proc. 2nd IEEE Adv. Inf. Manage., Commun., Electron. Autom. Control Conf. (IMCEC)*, May 2018, pp. 1636–1639, doi: 10.1109/IMCEC.2018.8469547.

[41] A. K. N. Reddy, "Lessons from the Pura community biogas project," *Energy Sustain. Develop.*, vol. 8, no. 3, pp. 68–73, Sep. 2004.

[42] S. Mahapatra, H. N. Chanakya, and S. Dasappa, "Evaluation of various energy devices for domestic lighting in India: Technology, economics and CO_2 emissions," *Energy Sustain. Develop.*, vol. 13, no. 4, pp. 271–279, Dec. 2009.

[43] I. Govender, G. A. Thopil, and R. Inglesi-Lotz, "Financial and economic appraisal of a biogas to electricity project," *J. Cleaner Prod.*, vol. 214, pp. 154–165, Mar. 2019, doi: 10.1016/j.jclepro.2018.12.290.

[44] M. N. Pérez-Camacho, R. Curry, and T. Cromie, "Life cycle environmental impacts of biogas production and utilisation substituting for grid electricity, natural gas grid and transport fuels," *Waste Manage.*, vol. 95, pp. 90–101, Jul. 2019, doi: 10.1016/j.wasman.2019.05.045.

[45] R. Bedoić, F. Jurić, B. Ćosić, T. Pukšec, L. Čuček, and N. Duić, "Beyond energy crops and subsidised electricity—A study on sustainable biogas production and utilisation in advanced energy markets," *Energy*, vol. 201, Jun. 2020, Art. no. 117651, doi: 10.1016/j.energy.2020.117651.

[46] R. M. de Azevedo, W. S. Brignol, L. N. Canha, and D. Maguerroski, "Operational impact of the complementarity between photovoltaic solar and biogas generation sources on distribution network systems," in *Proc. 51st Int. Univ. Power Eng. Conf. (UPEC)*, Sep. 2016, pp. 1–6, doi: 10.1109/UPEC.2016.8114013.

[47] A. de Araujo Cavalcanti, F. de Assis dos Santos Neves, G. M. de Souza Azevedo, and A. T. de Almeida Filho, "Performance evaluation of micro- and minidistributed photovoltaic systems using data envelopment analysis," *IEEE J. Photovolt.*, vol. 9, no. 6, pp. 1806–1814, Nov. 2019, doi: 10.1109/JPHOTOV.2019.2930053.

[48] A. Kumar, A. R. Singh, Y. Deng, X. He, P. Kumar, and R. C. Bansal, "A novel methodological framework for the design of sustainable rural microgrid for developing nations," *IEEE Access*, vol. 6, pp. 24925–24951, 2018, doi: 10.1109/ACCESS.2018.2832460.

[49] A. Kumar, A. R. Singh, Y. Deng, X. He, P. Kumar, and R. C. Bansal, "Integrated assessment of a sustainable microgrid for a remote village in hilly region," *Energy Convers. Manage.*, vol. 180, pp. 442–472, Jan. 2019, doi: 10.1016/j.enconman.2018.10.084.

[50] A. Kumar and R. C. Bansal, "A review of multi criteria decision making (MCDM) towards sustainable renewable energy development," *Renew. Sustain. Energy Rev.*, vol. 69, pp. 596–609, Mar. 2017, doi: 10.1016/j.rser.2016.11.191.

[51] R. D. Prasad, R. C. Bansal, and A. Raturi, "Multi-faceted energy planning: A review," *Renew. Sustain. Energy Rev.*, vol. 38, pp. 686–699, Oct. 2014, doi: 10.1016/j.rser.2014.07.021.

[52] D. Gregoratti and J. Matamoros, "Distributed energy trading: The multiple-microgrid case," *IEEE Trans. Ind. Electron.*, vol. 62, no. 4, pp. 2551–2559, Apr. 2015, doi: 10.1109/TIE.2014.2352592.

[53] E. J. Palacios-Garcia, Y. Guan, M. Savaghebi, J. C. Vasquez, J. M. Guerrero, A. Moreno-Munoz, and B. S. Ipsen, "Smart metering system for microgrids," in *Proc. 41st Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, Nov. 2015, pp. 3289–3294, doi: 10.1109/IECON.2015.7392607.

[54] E. Rodriguez-Diaz, E. J. Palacios-Garcia, M. Savaghebi, J. C. Vasquez, J. M. Guerrero, and A. Moreno-Munoz, "Advanced smart metering infrastructure for future smart homes," in *Proc. IEEE 5th Int. Conf. Consum. Electron. Berlin (ICCE-Berlin)*, Sep. 2015, doi: 10.1109/ICCE-BERLIN.2015.7391260.

[55] S. Lee, B. Kwon, and S. Lee, "Joint energy management system of electric supply and demand in houses and buildings," *IEEE Trans. Power Syst.*, vol. 29, no. 6, pp. 2804–2812, Nov. 2014, doi: 10.1109/TPWRS.2014.2311827.

[56] S. D. Manshadi and M. E. Khodayar, "Resilient operation of multiple energy carrier microgrids," *IEEE Trans. Smart Grid*, vol. 6, no. 5, pp. 2283–2292, Sep. 2015, doi: 10.1109/TSG.2015.2397318.

[57] G. P. Holdmann, R. W. Wies, and J. B. Vandermeer, "Renewable energy integration in Alaska's remote islanded microgrids: Economic drivers, technical strategies, technological niche development, and policy implications," *Proc. IEEE*, vol. 107, no. 9, pp. 1820–1837, Sep. 2019, doi: 10.1109/JPROC.2019.2932755.

[58] H. Wang, X. Tong, F. Li, and B. Ren, "Research on energy management and its control strategies of microgrid," in *Proc. Asia–Pacific Power Energy Eng. Conf.*, Mar. 2011, pp. 1–5, doi: 10.1109/APPEEC.2011.5749146.

[59] R. BiYing, T. XiangQian, S. XiangDong, and Z. Qi, "Research on the control strategy of energy management system for low capability microgrid," in *Proc. IEEE Power Eng. Autom. Conf.*, Sep. 2011, pp. 441–444, doi: 10.1109/PEAM.2011.6134978.

[60] F. Yang, X. Feng, and Z. Li, "Advanced microgrid energy management system for future sustainable and resilient power grid," *IEEE Trans. Ind. Appl.*, vol. 55, no. 6, pp. 7251–7260, Nov. 2019, doi: 10.1109/TIA.2019.2912133.

[61] C. Feng, Y. Wang, K. Zheng, and Q. Chen, "Smart meter data-driven customizing price design for retailers," *IEEE Trans. Smart Grid*, vol. 11, no. 3, pp. 2043–2054, May 2020, doi: 10.1109/TSG.2019.2946341.

[62] Y. Wang, Q. Chen, T. Hong, and C. Kang, "Review of smart meter data analytics: Applications, methodologies, and challenges," *IEEE Trans. Smart Grid*, vol. 10, no. 3, pp. 3125–3148, May 2019, doi: 10.1109/TSG.2018.2818167.

[63] G. Sun, Y. Cong, D. Hou, H. Fan, X. Xu, and H. Yu, "Joint household characteristic prediction via smart meter data," *IEEE Trans. Smart Grid*, vol. 10, no. 2, pp. 1834–1844, Mar. 2019, doi: 10.1109/TSG.2017.2778428.

[64] S. N. A. U. Nambi, E. Pournaras, and R. V. Prasad, "Temporal self-regulation of energy demand," *IEEE Trans. Ind. Informat.*, vol. 12, no. 3, pp. 1196–1205, Jun. 2016, doi: 10.1109/TII.2016.2554519.

[65] S. N. A. U. Nambi, S. A. Uttama, and R. V. Prasad, "Toward the development of a techno-social smart grid," *IEEE Commun. Mag.*, vol. 54, no. 11, pp. 202–209, Nov. 2016, doi: 10.1109/MCOM.2016.1600077cm.

[66] C.-H. Lo and N. Ansari, "The progressive smart grid system from both power and communications aspects," *IEEE Commun. Surveys Tuts.*, vol. 14, no. 3, pp. 799–821, 3rd Quart., 2011, doi: 10.1109/SURV.2011.072811.00089.

[67] M. Alizadeh, A. Scaglione, and G. Kesidis, "Scalable model predictive control of demand for ancillary services," in *Proc. IEEE Int. Conf. Smart Grid Commun. (SmartGridComm)*, Oct. 2013, pp. 684–689, doi: 10.1109/SmartGridComm.2013.6688038.

[68] P. R. Thimmapuram and J. Kim, "Consumers' price elasticity of demand modeling with economic effects on electricity markets using an agent-based model," *IEEE Trans. Smart Grid*, vol. 4, no. 1, pp. 390–397, Mar. 2013, doi: 10.1109/TSG.2012.2234487.

[69] *CBIP*. Accessed: Oct. 2, 2020. [Online]. Available: http://www.cbip.org/

[70] *Biogas*. Accessed: Oct. 2, 2020. [Online]. Available: https://vikaspedia.in/energy/energy-production/bio-energy/biogas

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