INVITED PAPER

Microhybrid Electricity System for Energy Access, Livelihoods, and Empowerment

This article reports a technoeconomic feasibility and sustainability analysis for a hybrid microgrid in India based on local solar PV and biomass resources.

By Madalsa Singh and P. Balachandra

ABSTRACT | Ensuring reliable and affordable access to modern energy services, especially for the poorer and deprived section of the population, is a basic requisite for sustainable development. Given that a majority of the energy-deprived population lives in rural regions of developing countries, an effective rural electrification is critical for bridging the rural–urban divide. Building on energy access intervention, implementing productive energy services can influence the next stages of development through livelihood activities, microenterprises, lifestyle energy services, value-added activities, survival irrigation, and so on. Social benefits of access to healthcare, education, and longer productive hours have an equally important impact on sustainable development. In India, for example, 240 million people lack electricity access. While grid extension in India is on the rise through various government programs, specific rural problems of low energy demand, poor rural economy, inaccessible terrain, and low purchasing power can render grid extension expensive and inefficient. Microgrid electricity systems, especially with hybrid renewable energy resources, can be a good alternative for addressing above-mentioned challenges. India enjoys high solar intensity, and the predominantly agrarian rural society has enough biomass resources, abundant cattle dung, forest foliage, and agricultural waste. A solar–biomass hybrid electricity system can solve the problem of intermittency of solar. Such a hybrid electricity system is being implemented in a remote Indian unelectrified village for electricity access, livelihoods, and economic empowerment. In this paper, we report the technoeconomic feasibility and sustainability analysis of this hybrid system. The system consists of 30-kW solar photo voltaic (PV) and 20-kW biomass gasifier modules. Energy demand and resource availability are estimated with inputs from extensive stakeholder discussions and field surveys, and they account for daily and seasonal variations in both supply and end uses and availability and productive hours. The expected temporal electricity demand is estimated for households, community, irrigation, and commercial needs. The technoeconomic feasibility is assessed using hybrid optimization model for electric renewable energy (HOMER). Furthermore, opportunities for the development of productive uses and their expansion through a sustainable business model are explored.

KEYWORDS | Electricity access; hybrid power systems; microgrid; rural areas; sustainable development.

I. INTRODUCTION

Ensuring reliable and affordable access to modern energy services, especially for poorer and deprived section of population, is a basic requisite for the sustainable development of a country. Given that most of the energy-deprived population lives in rural regions of developing countries, an effective rural electrification serves as a stepping stone for bridging the rural–urban divide. Home to the largest rural population in the world, rural electrification in India is an important step to contributing to the country's overall socioeconomic development. With 77 million households or 365 million people living without electricity as per

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the 2011 Census [1], relying only on grid extension to electrify remote and rural areas becomes difficult and expensive. While grid extension in India is on the rise through various government programs, specific rural problems of low energy demand, poor rural economy, inaccessible terrain, and low purchasing power can render grid extension costly and inefficient. In addition, these remote rural areas face multifaceted issues: lack of government attention of various schemes, poor access to markets, and expensive infrastructure. They are often inhabited by the tribal and marginalized population who are most vulnerable to climate change. Also, the latest estimate of 239 million people lacking electricity access in 2016 by the International Energy Agency (IEA) suggests that India still lags significantly behind the target of universal electricity access [2]. India's rural energy challenges, hence, operate on three levels: prevalence of large-scale energy poverty, expansion of energy systems to bridge over urban–rural divide and accelerate economy, and work toward mitigating climate change on global levels. The best outcome would be to achieve all three, without compromising on any [3]. Specifically, in the Karnataka state, where we plan to implement the proposed system, about 229 000 rural households remain unelectrified despite the recent push toward electrification [4]. Chamarajanagar, the district under which the proposed village Indiganatha falls, has 48.16% area covered by forest with many unelectrified, geographically remote villages that are most suited for distributed systems [5].

Decentralized distributed technologies are expected to play an important role in global electrification efforts, especially in remote rural areas. According to IEA, by 2030, the decentralized systems are expected to be the most cost-effective solutions for over 70% of those who gain access to electricity in rural areas [2]. In addition, about 60% of the access will be from renewable energy sources with offgrid and minigrid systems providing almost half of the new access facilitated by information and communication technology and innovative business models. This is favorable news for India for its Intended Nationally Determined Contributions to the Paris Agreement in achieving 40% of its electricity from nonfossil fuels [6] as 93% of all installed minigrid and offgrid systems would use renewable energy and subsequently reduce dependence on fossil fuels. India enjoys rich solar resources and there is high potential for biomass sources in the forms of agrarian waste, cattle refuse, and forest foliage, which makes hybrid decentralized renewable energy a sustainable and desirable option. Hybrid electricity systems based on renewable energy sources are becoming popular as such systems can achieve higher efficiencies and lesser capacity shortages as compared to single-source systems. Furthermore, hybrid systems address limitations in fuel availability, reliability, emissions, and economics [7].

Access to electricity at the lower rungs of energy ladder in developing countries can result in better health, higher productivity, increased employment for both men and women, more schooling hours for girls and boys, increased farm income through mechanization, cleaner rural environment, and increased per capita income while reducing poverty [8], [9]. An empirical study of farm productivity in Haryana in India indicated that even after factoring in a moderate price increase to improve power supply, small-scale farmers could increase their income by 50% [10]. Along with an increase in income, electricity in villages helps in access to healthcare, education, and longer working hours that have an immense impact on sustainable development. As part of Sustainable Development Goals, SDG 7 focuses on bringing sustainable, affordable, and modern energy carriers for solving the problems of energy access [11]. SDG 7 also positively complements other nonenergy goals and efforts to ensure access to modern energy, increase deployment of renewable sources, and accelerate the pace of energy efficiency improvements, which should benefit broader sustainable development agenda. However, there are instances where tradeoffs could emerge [12]. In a study conducted in Uttar Pradesh and Bihar, India, Rockefeller Foundation found that consumers with productive loads increased significantly from 0 to 2970 in two years, and microenterprises, in general, have benefitted from the minigrid with 60% owners reporting improved lighting conditions, increased appliance ownership, and ease in business operations [13]. Despite studies and demonstration on technological and economic benefits of minigrids increasing in recent times, there remains a lack of understanding of the real social impacts of minigrids on the community and customers they serve, partly due to cost of collecting such data. Evaluative methods should also include a variety of methods—both qualitative and quantitative—like semistructured interviews with users and managers, transect walks, photographic evidence, and observations [14].

Expanding energy access in rural and poor communities is not an easy task. Complex geography, lower income levels, diffused population, and low demand levels make electricity provision more challenging in rural areas compared to urban regions in India. Poor connectivity, dominant poverty, low purchasing power, and below average electricity consumption levels make any private interventions unprofitable and unattractive. Rural poor, despite gaining these services through government expanded grid, find it difficult to pay the connection fees and procure necessary appliances [15]. Hence, the next steps should not only be focused on the minimalist approach of providing electricity through subsidized energy infrastructure but also create economic linkages to contribute to economic and human development and should be turned into a driver of productivity, income generation, and socioeconomic transformation, adopting the "EnergyPlus" approach promoted by the United Nations Development Programme [16], [17]. Implementing productive energy services along with energy access can influence the next stages of development through livelihood activities, microenterprises, lifestyle energy services, value-added activities, farm mechanization, and irrigation services. To achieve that, a multipronged approach of unique business models, operational incentives, tapping into global climate financing, and developing an institutional mechanism that provides both community-driven equity and organized delivery is needed [18], [19]. Adopting this approach, the Indian Institute of Science in Bengaluru, India, is in the process of implementing a hybrid microgrid system, a hybrid of solar photo voltaic (PV) and biomass gasifier-based electricity generation, for providing electricity access to people in a remote village.

This paper examines the technoeconomic feasibility of such a microgrid system consisting of 30 kW of solar PV and 20 kW of biomass gasifier-based electricity generation to be implemented in a remote village of Indiganatha in the Chamarajanagar district in Karnataka, India. Energy resource estimation is done through NASA's Surface Meteorology and Solar Energy database on Global Horizontal Irradiance for solar energy potential, and extensive field surveys were conducted for biomass availability [20]. The expected temporal electricity demand is estimated for households, community, irrigation, and commercial needs. The data have been triangulated through field visits and using village characteristics in India. Both energy demand and resource availability have been estimated, keeping daily and seasonal variations in end uses and productive hours. A technoeconomic feasibility of this hybrid system is assessed using a hybrid optimization model for electric renewable energy (HOMER) software, which optimizes capital/operational cost, demand, and resource distributions [21]. Furthermore, business models using mobile and payment technologies are explored for sustainable expansion.

In this paper, we have attempted to advance the methodology for demand estimation for determining the capacity of the offgrid hybrid systems for locations that are completely unelectrified. We have used a bottom-up methodology that includes probabilistic time of use along with comprehensive stakeholder consultations for generating temporal demand profiles across various end-use sectors (households, commercial, community, and irrigation) and accounting for gender and other prospective developmental priorities of the village (microenterprises, energy services for health, education and safety, and livelihoods). Furthermore, discussions on biomass resource estimation, framework of implementation, and possible business models are novel, and this should serve as a comprehensive primer for practitioners, researchers, and policymakers.

II. FIELD SURVEY AND CHOICE OF LOCATION

Indiganatha is a small village/hamlet in Kollegala Taluk in Chamarajanagar District of Karnataka State, India (latitude 11.98 and longitude 77.65). It is part of Mahadeshwarabetta (MM Hills) Panchayath and belongs to Mysore Division. Nestled in one of the plains of MM hills, Indiganatha can be reached only through a seasonal road that traverses risky mountainous terrain. The village is unelectrified and relies on kerosene for lighting and biomass for cooking/heating. Extensive survey through structured questionnaire, focused group discussions, and interviews were conducted for achieving three objectives as follows.

1) Obtain village characteristics to estimate electricity demand, variety of end-uses/appliances needed, and main sectors of the economy.
2) Find out the potential of different types of biomass.
3) Understand various socioeconomic activities of the village to find out enterprising potential.

A. End-Use Demand and Economy

Indiganatha village consists of 160 households with an average family size of 5. The village consists of a primary school where most children study till the fifth standard. There are several makeshift shops scattered around provide small goods for daily requirements, food items, and so no. Agriculture is the main occupation with an average landholding of 2–3 acres and rain-fed. Most farmers grow Ragi (*Eleusinecoracana*) and Hyacinth (*Hyacinthus*) and can grow cotton (*Gossypium*), horse gram (*Macrotylomauniflorum*), and Ground nut (*Arachis hypogeal*) when water is available. Water availability with irrigation pump sets, if provided, can be a huge benefit to the farmers, as currently most produce is used for domestic consumption and very less makes it to the market for sale. Indiganatha families use firewood for cooking and kerosene lamps for lighting, which are unreliable and polluting. Children desire for efficient and brighter sources of lighting in schools and home to study longer. Absence of lighting on the streets also raises security concern and women and girls of the village cannot venture out beyond sunset. Street lighting, hence, was identified as beneficial for security and mobility by the villagers.

B. Biomass Potential

1) *Wood:* For estimating potential biomass resources, woody biomass (wastes from forests and plantations, foliage, and straw) and soft biomass (agricultural, commercial, and animal waste) were surveyed for weekly consumption and extrapolated for the year. Approximately 251 ton of wood is collected by 110 households annually, with a reported collection of 20 kg of wood every two days or three times a week. The estimations were made after deliberating through the questionnaire and weighing of some sample loads collected. On average, 2282 kg of wood is collected and consumed per year per household.
2) *Straw:* Since it is difficult to ascertain the exact amount of straw available from the farmland, an indirect method was employed to arrive at the straw yield. Amount of grain produced in the village is calculated from the sacks of grain obtained in a year, usually at 100 kg per sack. Straw content from the grain can be calculated from straw-to-grain

Table 1 Woody and Nonwoody Biomass Resource Estimation

Parameters	Units and assumptions	Total
Total Population	Number	511
Total Straw	tonne/year (@100kg/sack)	156.8
Total Cattle	Number	365
Buffaloes (of total cattle)	Number (out of total cattle)	150
Total Manure	tonne/year (@7kg/day)	932.6
Total Wood	tonne/year (@60kg/week)	251.1
Land holding	Acres	221.4
Households	Number	110
Wood/Household	kg/year/unit household	2,282
Cattle/household	Number/unit household	3.32
Straw/household	kg/year/unit household	1,426
Land holding/household	acres/unit household	2.01
Straw/landholding	kg/year/acre	708.2
Land holding/household	acres/unit household	2.01

ratio, which is assumed to be 2:1, i.e., for every 1 kg of grain 2 kg of straw is available. A higher ratio is taken as most people in Indiganatha practice rain-fed subsistence agriculture resulting in lower grain yields and more straw content. The total straw yield over a reported 221.45 acres of land was 157 ton in a year.

3) *Manure:* The cattle in the village are usually left to fend/graze for themselves in the nearby forest in the presence of caretaker. The potential to collect and use manure becomes higher if a method is devised for centralized manure collection and utilization for biogas production. Assuming a modest value of 7 kg/day/cattle or 2555 kg manure/year/cattle, the total manure potential could be estimated at 932.58 tons per year. Manure contributed by each household is approximately 8477 kg manure/year/household. Table I provides details of the survey findings.

C. Potential for Microenterprises

Despite its geographic remoteness, the people of Indiganatha are enterprising. The community has invested money in intervillage transport and road maintenance, and many people travel long distances for part-time jobs. Few people also rear cattle and goat for meat, dairy, and transportation. Cattle rearing for dairy and meat is a big source of income and insurance during lean agricultural months. People facilitate transport to other towns and villages through pooled investments in a jeep, which ferries people to-and-fro and returns are awarded in proportion to respective investments. Families in villages have community spirit and share food, fuel, and firewood in times of need. Many have small shops to cater to the needs of pilgrims. Indiganatha satisfied most of our predetermined characteristics: the size of the settlement is large enough to design a medium capacity microgrid without land constraints, rich availability of biomass resources and high solar irradiation throughout the year, low chances of grid extension in foreseeable future due to mountainous geography, and the enterprising nature of the residents which would ensure that energy access would enable economic development through entrepreneurial activities.

III. HYBRID SYSTEMS AND METHODOLOGY

Microgrids, which typically operate below 100-kW capacity and cover a radius of 3–8 km, can power small villages with residential, community, and commercial loads in remote areas [22]. Here, an isolated microgrid providing power to the local consumers is considered, which may be expanded and/or connected to the grid later. Kollegala Taluk of Chamarajanagar, where Indiganatha is situated, also has one of the highest numbers of projects implemented by the government of India under which eight hamlets within which 546 below poverty line (BPL) households and 155 street lights are being electrified with the help of decentralized distributed technologies using solar PV [23]. In the future, these distributed technologies are likely to be connected to the electricity grid that could help enhance grid reliability during outages and increase customer "uptime," reduce costs of generation by connecting intermittent solar generation with the grid as backup, boosting the overall system efficiency by utilizing excess electricity, and optimize assets to aid the distressed state distribution companies.

A. Solar PV System

The proposed solar system consists of a flat plate PV array with a rated capacity of 30 kW, lifetime of 25 years, and derating factor of 80%. With enough wasteland available at the periphery of the village, the PV system can be easily installed. However, since Indiganatha is located in the dustier part of the state, proper cleaning of the PV panels would be required at regular intervals. Village labor can be tapped for it to do the same.

B. Biomass Gasifier System

A 20-kW small-scale biomass gasifier-based electricity system, with a lifetime of 25 years and the minimum load ratio of 50%, is proposed. Indiganatha, with abundant potential for woody and nonwoody biomass, will use a biomass gasifier system developed by the Indian Institute of Science to meet its needs. Gasification is a thermochemical process wherein biomass combustion occurs under substoichiometric conditions in a reactor called gasifier (air/pure oxygen/steam, or carbon dioxide as reactants), and the product is a combustible gaseous mixture of H_2, CO, CO_2, and CH_4. The mixture is called producer gas, which can be used in internal combustion engines and alternators for electricity generation [24], [25].

C. Hybrid Energy System Optimization

Modeling and designing of a hybrid microgrid are done through HOMER, a software package developed by National Renewable Energy Labs, USA [21]. HOMER is for optimization, simulation, and technoeconomic feasibility

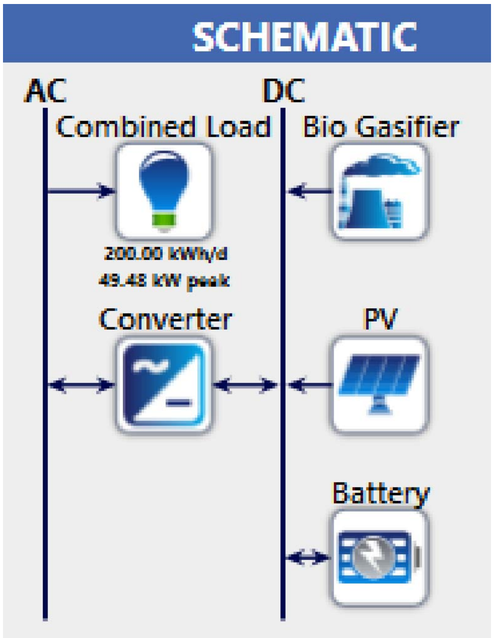

Fig. 1. *Schematic of the hybrid renewable energy system.*

of the system by considering energy demand and supply for every hour throughout the year. While there are several studies [26]–[31], using HOMER software for studying the feasibility of microgrids, both in developing and developed countries, few have looked at extensive local renewable energy resources, location-specific socioeconomic characteristics, financing, and climate change mitigation potential at the project level.

D. System Components and Cost

As stated earlier, the hybrid system consists of solar PV panels producing 30 kW and biomass gasifier modules of 20 kW. The system consists of combined electric load, solar resources, biomass resources, and system components such as solar PV arrays, biomass gasifier modules, storage battery (12 A, 200 Ah), and a converter. Fig. 1 shows the schematic for the system. Costs of components (Table II) are collected from independent manufacturers, wholesale market, and in-house survey. The project lifetime is taken as 25 years, and for a financial feasibility analysis, a discount rate of 10% and an inflation rate of 5% are used (observed standard rates in India). The fixed and variable costs are site-specific and would vary with geography of operations.

E. Development of Sectorwise Load Profiles

Load profiles were developed in three steps: first, studies of villages with similar socioeconomic, geographic, and electricity end use were used for reference [32], [33]. These provided a basic skeleton for demand profile for areas on lower rung of energy access. Second, information was gathered from field visits to houses, consultation with existing enterprises, and prospective demand surveys. The demand surveys included plans to provide lighting in primary school, street lighting, new paper bag making center, and provision of water heater and fridge for storing vaccination. Finally, a time-dependent probabilistic distribution of loads was generated to model the varying demand across the day to reflect the end uses. The profiles are developed using conventional methods and adopting a bottom-up analysis for various segments of customers with small populations typical of minigrid operations. This includes an analysis of the number of consumers for each type of electricity operations, devices, and appliances which will be used and their typical loads, and the probability that they will be in use at a given time of the day [34]. For example, lights will usually be on in evenings and nights, fans have lesser usage during winters and higher during summers, and paper bag making, cold storage, school, and health center would be continuous loads during their time of use.

The loads are divided into domestic (households), commercial, community, and irrigation sectors. Domestic loads comprised of 160 households with appliances, charging plug, and lighting, as given in Table III. Commercial loads comprised of three commercial shops, one cold storage plant (prospective), one paper-bag making center (prospective), two mixing units (prospective), and one milling unit (prospective). Community loads comprised of a school, a health center with end uses like water cooling and heating facilities (prospective) and street lighting (prospective). Irrigation loads accommodated three water pumps for dry season (except monsoons). An hourly temporal electricity demand profile is created across sectors. While there will be uncertainties and variabilities in load profiles that can be refined once more, information about load, time of use, and diversity of demand is received through smart meters. For initial planning, a 10% day-to-day variability is assumed.

Months have been divided into summer (March–July), monsoon (August–October), and winter (November–February). As can be seen in Figs. 2(a)–5(a), a uniform distribution of electricity demand for specific services of households, commercial, irrigation, and community is assumed. Seasonal changes that are considered are like the presence of more cooling facilities during summer, longer duration electricity demand in the evening during winters due to early sunsets, and zero irrigation loads during monsoons as the village is adequately rain-fed during those months.

Table 2 Costs of System Components

System Components	Size	Number	Capital Cost (US $)	Replacement Cost (US $)	O&M Cost (US $)	Lifetime (years)
PV Array	1kW	30	968.75/kW	968.75/kW	25/kW	25
Biomass gasifier	20kW	1	1533.46/kW	0/kW	0.01/kWh	25
Battery	200 Ah, 12V	120	284/Battery	220/Battery	6.0/Batt/year	5
Converter	1 kW	40	117/kW	117/kW	3.0/kW/year	15

Source: In-house survey among manufacturers

Table 3 Rating and Requirements of Appliances Across Sectors in Different Seasons

Load Sector	Appliances	Watts	Quantity per household or connection	No. of households or connections	Summer usage (hours/day)	Winter Usage (hours/day)	Monsoon Usage (hours/day)
				Domestic			
Households	LED bulbs	7	3	160	8	10	8
	TV	70	1	160	3	4	4
	Fan	45	1	160	8	0	8
	Radio	15	1	160	4	4	4
	Phone Charger	4	1	160	6	6	6
				Commercial			
Shops	LED Bulbs	7	3	3	5	5	5
	Fan	45	1	3	10	0	10
Small cold storage plant		6000	1	1	5	2	
Paper-bag making	LED Bulbs	7	8	1	6	5	6
	Fans	45	2	1	6	0	6
Mixer	Mixer	500			5	5	5
Milling unit		11000	1	1	5	5	5
				Community			
School	LED bulbs	7	8	1	8	8	8
	Fan	45	5	1	8	0	8
Heath Center	LED Bulbs	7	20	1	6	8	6
	Fan	45	10	1	8	0	8
	Fridge	475	1	1	4	4	4
	Water heater	1000	1	1	6	6	6
Street Light	LED bulbs	10	30	-	8	8	8
				Agriculture			
Fields	Water pump	3730	1	3	7	4	0

Similarly, daily load profiles have been constructed considering feedback received during surveys of villagers. As shown in Fig. 2(b), household loads form a double-humped shape. First, spike occurs during afternoon signifying women's interest in entertainment and resting after they finish their chores at home. A second spike during the late evening is when family reconvenes after their days, which includes entertainment and lighting. Commercial loads, as per Fig. 3(b), show high consumption during the business hours, and community loads, as per Fig. 5(b), show high consumption during the day (schools, health center, and paper-bag center) and low but constant consumption at night (for street lighting). Irrigation has been simplified to be running for a few hours every day for the farming community across the village as shown in Fig. 4(b) as the water can be stored in existing storage and harvesting ponds.

F. Energy Resource Estimation

Solar energy potential for Indiganatha village located at 11° 98' N' and 77° 65' E was taken from NASA Surface Meteorology and Solar Energy Database [20]. The annual average solar radiation was 5.13 kWh/m^2/day and the average clearness factor was 0.524 (Fig. 6). Highest clearness is seen during the months of February–May because of low fog and low cloud cover which reduces during late summer and monsoon season due to cloud and rain activity. Through field visits, household surveys, and waste disposal estimates mentioned before, availability of 407.89 ton of woody biomass/year was estimated. There is a seasonal variation as monsoons record for higher forest foliage than a drier season; however, for the present analysis, we assume 34 ton of potential biomass availability per day.

IV. RESULTS AND DISCUSSION

A. Technoeconomic Feasibility Analysis Through HOMER

The initial proposition of working with hybrid solar and biomass gasifier systems for meeting the seasonal and diurnal variations in electricity demand was successfully optimized. Final architecture comprises of 30-kW solar PV array, 20-kW biomass gasifier modules, 40-kW converter,

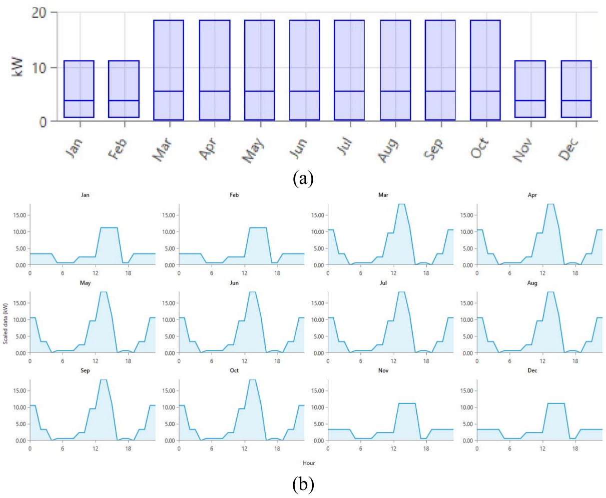

Fig. 2. ***(a) Monthly demand profiles for households. (b) Daily load profiles for households.***

Table 4 Summary Cost of Hybrid System

Total Net Present Lifecycle Cost (US$)	250,077
Levelized Cost of Electricity (US$/kWh)	0.217
Operating Cost per year (US$)	14,146

and 120 strings of 1-kWh lead–acid storage batteries. Zero capacity shortage was achieved in the system. Cost summary details of the above-mentioned architecture are given in Tables IV and V.

The system was optimized at a levelized cost of energy (COE) of \$0.217/kWh. A higher battery backup has been provided to manage intermittency, high peak load, and variable nature of solar resource. Fuel costs for biomass gasifier modules are assumed to be \$23 for a ton of biomass, which would be a source of income for women who are currently involved in the collection of firewood, straw, and wood-based resources for their domestic needs and can collect the agrarian waste, forest foliage, and firewood for the gasifier. In addition, more biomass resource can be easily sourced from the wastelands near the villages and animal dung [24].

Despite having higher production capacity, PV records for lower electricity production percentage, largely due to the intermittency of solar. PV production peaks to 29.3 kW in summer months with the highest solar irradiation and drops to 0 kW at night, which explains a low mean. Biomass gasifier, which can operate throughout the year, works according to the deficit between the total load and the output of solar at a given time of the day in a season. The highest electricity load of the system occurs at a peak demand of 38.33 kW, while the minimum of 0.063 kW is recorded at night (Table VI). Other crucial aspects to be noted are the unmet demand, capacity shortage, and excess electricity production (Table VII). The system has been overdesigned for high reliability and quality.

It achieved zero capacity and energy shortages, which required a significant number of battery backups. The current trend of decreasing battery costs and increasing long-term storage can help to reduce battery storage cost and help bring down the COE of renewable electricity systems [35]. Significant excess electricity generation (14%) is helpful in the case of variations in time step (durations for appliances), day-to-day demand, operating reserve constraints, and be further utilized in future, if demand grows.

Mitigating climate change, one of the three energy access objectives, is also a crucial component of the study. Rural India's per capita green house gases (GHG) emissions for households that use electricity and kerosene for lighting is estimated at 26 kgCO_2e per year per person [36]. In the present case, the entire system powering 160 households would produce a total of 20.13-kg CO_2e per year (Table VIII), which is a significant improvement in combating emissions. Such low levels of emissions are possible since biomass will be sourced sustainably resulting in zero emissions. Black carbon is also a powerful absorber of sunlight and the second largest climate warmer today after carbon dioxide. One-tenth of the fuel burned in kerosene lamps to light up houses is converted to black carbon which impacts both GHG and household air pollution (HAP) [37]. The hybrid system replaces the currently used inefficient kerosene lamps in Indiganatha with no particulate matter emission or unburned hydrocarbons.

HAP, attributed to household's emissions of particulates, carbon monoxide, sulfur dioxide, and nitrogen oxides, is the single most important environmental health risk factor worldwide, and 60% of all

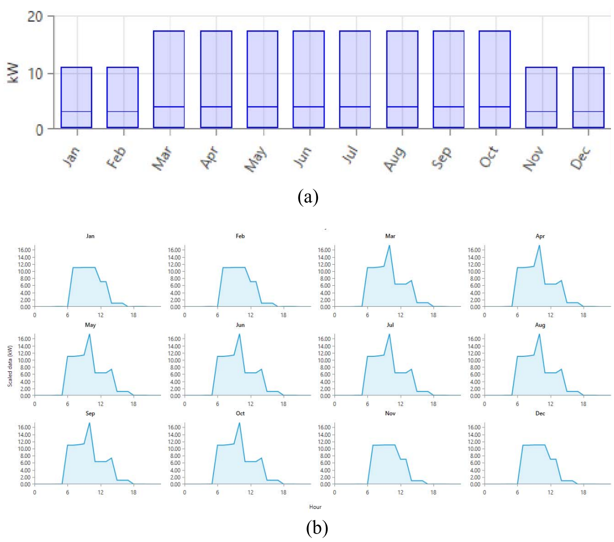

Fig. 3. ***(a) Monthly demand profiles for commercial use. (b) Daily load profiles for commercial use.***

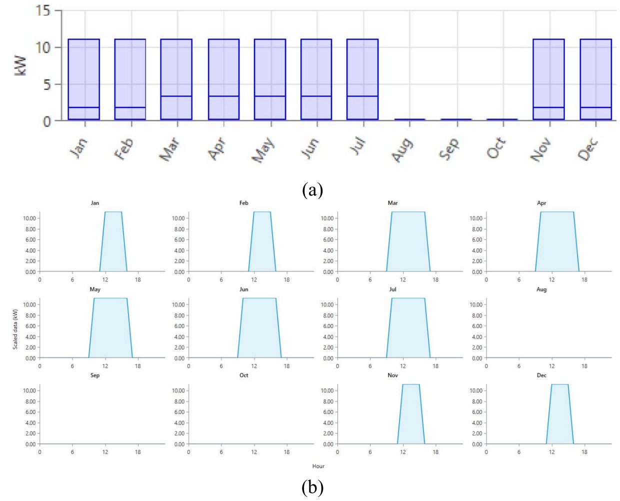

Fig. 4. ***(a) Monthly demand profiles for irrigation water pumping. (b) Daily load profiles for irrigation water pumping.***

premature deaths attributed to it occur among women and children [38]. Since HAP disproportionately affects women and children, efficient appliances replacing traditional fuels and inefficient combustion for lighting and heating would provide greater household health and productivity.

Notwithstanding all the above-mentioned benefits of electricity access to the village households and to the environment, the financial feasibility as well as long-term revenue sustainability appear unfavorable to the stakeholders. The overall COE at \$0.217/kWh is about 2.50 times the average cost of electricity supply in India (at Indian rupees 65/\$). For the poor households of Indiganatha village, this price would be extremely unaffordable. Furthermore, a modest 15% rate of return on investment will make the electricity price more expensive to the consumers. Even with an assumption that the households would be responsible only for the recovery of operational cost, which is at \$0.111/kWh, the system seems financially unsustainable. The poor will find even this price unaffordable. It is important that a mechanism needs to be developed whereby the household electricity prices are cross subsidized by making the commercial and irrigation end uses to pay higher prices.

Thus, to make the whole hybrid system financially sustainable, the capital investment needs to be sourced from either government or donor agencies and the operational cost to be recovered by adopting a differential electricity pricing for household and productive end uses. It is also important that some profit margin is built into the pricing structure to ensure long-term substance of the system. The following sections present discussions on some of the possible alternatives to achieve these objectives.

Table 5 Componentwise Breakup of Life-Time Costs

Component	Capital (\$)	Replace-ment (\$)	O&M (\$)	Fuel (\$)	Total (\$)
Biomass Gasifier	30,769	0	15,262	23,310	69,341
120 kWh Lead Acid Battery	34,080	61,051	10,394	0.00	105,525
Flat plate PV	29,063	0.00	10,827	0.00	39,890
System Converter	4,680	2,329	1,732	0.00	8,741
Distribution/ Connection	23,075	0	3,505	0	26,580
System	121,667	63,380	41,720	23,310	250,077

B. Mainstreaming Offgrids/Microgrids—An Ecosystem Analysis

A critical factor to note across studies involving HOMER is that technologies, solutions, and equipment can deliver clean, reliable, and affordable energy in the most demanding geographies, but the main innovation challenge is building the supporting commercial models and enabling the environment that can encourage the deployment of these solutions and that they work effectively in the long run. For this, the following section deals with three main themes. First, three-tiered innovations in framework, financing, and final mile connection are suggested with institutionalized collaborations. Second, a landscape of business models is studied to make comparative and focused analysis. Third, a business model is proposed for the Indiganatha village site.

1) Three-Tiered Ecosystem Analysis:

a) Framework—Policy and regulatory: Various governance side risks that ventures face while expanding into rural energy access fields such as political, policy, and revenue risks need to be considered [39]. Political- and country-specific risks involving appropriation and theft can be addressed through better governance, law and order, and village-level rolling security checks. Policy and implementational risks around abrupt changes in policy or failure of implementation plans need more consistency within state, central, and international guidelines. Revenue risks arising from nonpayment by customers or low demand can be fixed by innovative billing and metering models like village-level guarantee funds or pay-

Table 6 Summary of Electricity Production by Sources and System

	Unit	PV	Biomass Gasifier	System
Electricity Production	kWh/Year	45,676	81,455	127,131
Percentage production	%	35.93	64.07	100
Maximum Output	kW	29.3	20	38.3
Minimum Output	kW	0	10	0.063
Mean output	kW	5.21	12.53	11.109

Table 7 Technoeconomic Parameters of the System

Configurations	Unit	Optimized Design
Solar PV	kW	30
Biomass gasifier modules	kW	20
Battery storage	kW hour	120
Converter	kW	45
Total capital cost	US $	121,667
Total replacement cost	US $	63,380
Total annual capital cost	$/year	13,404
Total annual replacement cost	$/year	6,982
Total annual O&M cost	$/year	4,596
Total annual fuel cost	$/year	2,568
Total annual cost	$/year	27,551
Total operating cost	$/year	14,146
Unit cost of energy	$/kWh	0.217
Unit operating cost of energy	$/kWh	0.111
Solar PV Electricity Generation	kWh/year	45,676
Biomass gasifier Electricity Generation	kWh/year	81,455
Total Electricity Generation	kWh/year	127,131
Generation shortage	kWh/year	0
Unmet load	kW	0
Excess Electricity	kWh/year	17,760

as-consume subscriptions. It is pointed out that at the lack of effective policies and programs, poor institutional framework, ineffective governance structure, misdirected focus and targets, ineffective delivery mechanism, and lack of simulated private market as the main policy and regulatory barriers are currently plaguing Indian rural energy market. These are amplified in the context of decentralized renewable systems due to their resource, implementation, business, and investment complexities and hence require initial capital and revenue support. Rural Energy Access authorities, at central and state levels, have been suggested to be leadership institutions [19]. Furthermore, they can serve at the focal point to bring energy management, repairing, and maintenance of micro-grid energy systems through various skilling and apprenticeship schemes of the government. Furthermore, they will have an important role in providing clear information about distributed energy systems, and highlighting the advantages with respect to health, education, and opportunities.

b) Finance: IEA estimates investments to the tune of $30 billion per year required to achieve universal household access by 2030 under SDG [2]. Financing energy access, especially through distributed renewable energy systems, is tougher since the sector is new and not well understood by investors, and financing automatically comes under government funds or philanthropic donations/trusts. Bhattacharya [40] divides offgrid financing into: 1) project level financing that can be done through equity or debt from government, asset-based lending, nonrecourse lending, and supplier credits and 2) end-use-level financing through small-scale lending, microcredit, leasing arrangements, and revolving funds. The focus, however, has moved to end-use demand-side financing of the users. Sustainable end-use financing is also preferred to make it more commercially scalable.

India's wrongly targeted subsidy burden that is to the tune of $485 billion can be relaunched as operational incentives in the form on Energy Access Funds [19]. Furthermore, budgetary allocations, Green Climate Fund finance, and donations can be a part of the national fund. Credit through private sector, rolling credit, and microfinance institutions and cooperatives are possible avenues. Local banks, in a newly vitalized carbon finance market, have begun issuing foreign currency dominated masala bonds and green bonds for transitioning to a low-carbon economy [41]. Microfinance intervention for below poverty households for energy access with twin-expertise institutions with both energy and financial management skills, along with community involvement, can be an option [42].

c) Final mile connection: Microenterprise and minienterprise are potential business worth of $4 billion, serving 30 million households [43]. With better technology and subsidized capital costs, the market size would be much larger. Three possible business solutions can be put in place.

1) *A commercial enterprise model with financial viability without public sector financial support.* These enterprises innovate on unique cost and revenue structures to reduce their revenue risk of nonpayment. Prepaid meters help avoid payment difficulties with the standard 30-day billings and provide direct control to people over their electricity use as demonstrated in Zambia [44]. The same models are being employed by Husk Power, India, and Shared Solar, Mali. District Energy Access Funds [19], or community trusts can be used to provide collective guarantee to pay for the services. This fund/trust can also help individuals obtain access to microcredit to pay for their individual connection costs [39].
2) *Semicommercial enterprises, with public–private partnerships or state subsidization with high community-based arrangements.* A unique feature of the decentralized renewable energy system, as demonstrated by Indiganatha, is that the full value chain of the system can be sourced in the village—fuel sourcing, connection, sales, billing, and collection. Women, who already collect traditional fuels for their household energy needs, can source fuel to feed the biomass gasifier modules; connections in proximity to the consumer can be done through simple distribution wires;

Table 8 Emissions Analysis of the Hybrid System

Quantity	Value (kg/year)
Carbon Dioxide	20.13
Carbon Monoxide	0.22
Unburned Hydrocarbons	0.00
Particulate Matter	0.00
Sulfur Dioxide	0.00
Nitrogen Oxides	0.14

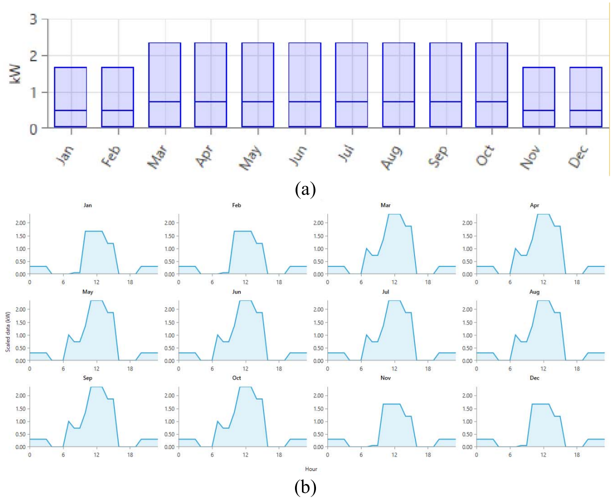

Fig. 5. ***(a) Monthly demand profiles for community use. (b) Daily load profiles for community use.***

maintenance and repairs through skill training under Rural Energy Access Agencies to help better services and provide employment; billing and revenue collections through village-level panchayat/group of elders to guarantee payments. This creates a stream of revenue within the village and provides a sense of ownership to the community.

3) *Noncommercial delivery through public sector or donors.* However, these would be less financially sustainable due to lower income of consumers and would incur higher operating, maintenance costs. In addition, consumers with a lesser sense of ownership, and no local earning options, would not be able to pay on time or maintain the structure.

2) Survey of Business Models in High-Impact Countries: While financing from multilateral and bilateral development institutions has historically made up a significant portion of the financial commitments to energy access, especially electricity access in high-impact countries [45], individual customized business models with market focus are now coming up. Entrepreneurs working in the space utilize social trust, informal community networks, and extent of technological reach to tweak their practices to self-sustain. Despite the high upfront initial costs to the rural customers, according to the latest IEA analysis [2], decentralized systems are the most cost-effective solutions for over 70% of those who expected to gain access in rural areas. By 2030, renewable energy sources are expected to power over 60% of new access, and offgrid and minigrid systems to provide the means for almost half of new access, underpinned by new business models using digital and mobile technologies. The market for offgrid renewable electricity remains so vast and it is unlikely that the industry will ever depend on one business model. Some applications may lean strongly upon one model but could vary by geography, resource mix, regulatory structure, financial options, and availability of vendors. From the high diversity of these models to choose from, the most suitable for high-impact countries are pay-as-you-go (PAYG), operation and maintenance contracts, utility-led development, community-owned financing and maintenance, and design, build, operate, own, and maintain (DBOOM) and utility-in-a-box (UiB). Infrastructure ownership, operations and maintenance, and capital ownership would greatly depend on what kind of model of delivery is chosen. Microgrids can be similar to public good built on community land that is owned by the village community and operated and maintained by local skilled labor, or it can be part of the portfolio of service provider built on land leased or bought from community or private individuals. A myriad of ownership, maintenance, and financing scheme can be developed with hybridization across the broad categories. A few of them are discussed as follows.

1) *Pay-as-you-go:* Like how cellular phone air-time is sold, PAYG plans allow customers to access prepaid electricity as per their desired plan or quota. This is most suited to customers with low and variable income, where the risk of irregular payments for services is high [46]. Payment chunks can be smaller, and households can have more autonomy over their consumption, spending, and savings. There can be greater flexibility if companies wish to increase the frequency of money collection (weekly, fortnightly, and monthly) or incorporate various means for payment (smart cards or mobile money or payments through a local agent). Payments often can be made in smaller amounts than would otherwise be possible, and customers have greater control over their consumption and thus of their expenditure.
2) *Utility-led development:* A key trend observed is partnerships between utility giants and solar systems and offgrid companies. This is a mutually beneficial relationship as offgrid companies benefit from stronger cash flows and balance sheets of the utility companies and the latter access markets, products, and retail clients in a new geography. French gas utility company Engie acquired a Ugandan home solar systems company, Fenix International, which uses PAYG model to reach out to customers, and in process unlocked a massive commercial debt market

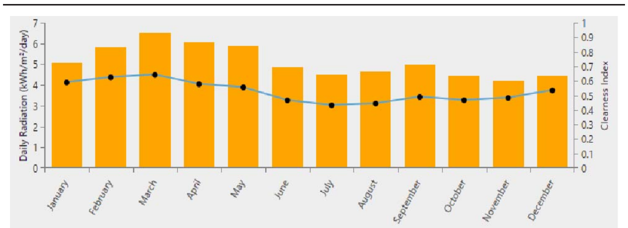

Fig. 6. ***Global horizontal irradiation for Indiganatha; accessed from NASA surface metrology and solar energy database on February 21, 2017.***

for the energy access market [47]. Another French utility company, Électricité de France joined hands with offgrid electrique to offer solar plants in rural West Africa [48].

3) *Community-financed microgrid with operational and maintenance contracts:* Financed at a village level through national, state, or local funds, community-owned and -financed microgrids can be an alternative. They are unique since the ownership of the microgrid can tap into local structures of governance and leadership and synchronizing payments through household-level collections. However, in high-impact countries, where local level funds are inadequate, special energy access funds would be needed for the upfront costs [36]. In addition, operational and maintenance (O and M) contracts, from utilities or vendors, can be designed to maintain optimum performance while having utilized the small revenue streams. These would be beneficial for low-income communities where skilled labor and engineering expertise are rare [49].
4) *DBOOM and utility-in-a-box:* Another recent development is DBOOM where a single company designs, builds, operates, owns, and maintains a single integrated solution. Siemens has demonstrated complete turnkey capabilities of financing, consulting, advanced grid technology, generation assets, O and M, and an adapted supervisory control and data acquisition system sized for microgrid management. While it provides one-stop solutions, the approach is limited to companies that provide a range of electrical and software capabilities [50]. A smaller and more versatile version is seen in the upcoming concept of UiB—a solar plus battery integrated system—that has been deployed in India [50]. This solar plus battery unit, with retrofits, also incorporate an additional biomass gasification system and with drastically reduced costs.

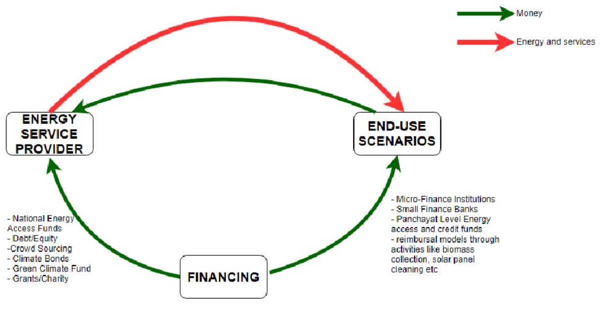

Fig. 7. ***Proposed revenue model.***

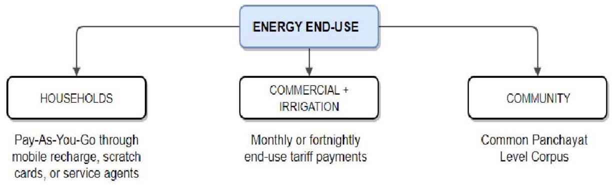

Fig. 8. ***Proposed business model.***

3) Proposed Business Model for Indiganatha: For the project at Indiganatha, we propose the following simplified revenue (Fig. 7) and business models (Fig. 8). The modalities of it work on two levels—at the end-use level and the other on the ecosystem level. At the end-use level, it has been divided into three: households, commercial and irrigation, and community. Community includes all the common electricity usage of the village—street lights, panchayat hall, school, and so on.

For households, it is proposed to use a PAYG prepaid subscription plan that can be suited to individual households needs. These can be activated via mobile, subscription coupons, or visiting the local shop in the village. The upfront installation charges would have to be provided by the household.

For commercial and irrigation end use, a monthly or fortnightly consumption tariff can be used. Cross subsidization by charging a higher tariff for commercial and irrigation use can be explored. The timing of the payment of commercial subscribers can be determined based on the nature of business and the flexibility of payment.

V. CONCLUSION

This paper explored the techno, economic, and social feasibility of a hybrid solar PV and biomass gasifier system to be put up in the unelectrified village of Indiganatha. The flow of this paper works in three parts: resource estimation through exploratory survey, load profile construction with the aid of village characteristics and personalized interviews with stakeholders, and optimization and assessment of technoeconomic feasibility, system efficiency, and emissions through HOMER software. The results indicate that the optimally designed hybrid system can reliably and continuously meet the dynamic demand from multiple end uses. Next, a business model is proposed for the implementation of this hybrid microgrid as a private enterprise based on insights from existing business models, financing projects, and final mile implementation. The findings suggest that a public–private partnership that actively supports cost sharing and recovery of operational cost is critical for the success of such hybrid systems. Future research is needed to study the impact of grid extension on distributed generation to assess high-load applications in hybrid microgrids and to find sustainable financing models to help them mainstream. ■

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